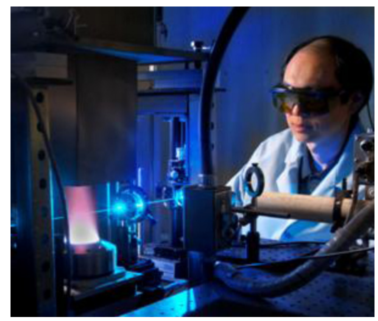
CLEAN COAL RESEARCH PROGRAM

United States Department of Energy | Office of Fossil Energy

2012 TECHNOLOGY READINESS ASSESSMENT
—ANALYSIS OF ACTIVE RESEARCH PORTFOLIO

Pathway for readying the next generation of affordable clean energy technology

—Carbon Capture, Utilization, and Storage (CCUS)



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OFFICE OF FOSSIL ENERGY

NETL

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EXECUTIVE SUMMARY

Consistent with ongoing efforts to supply policy makers with clear information in a form more amenable for them to gauge the maturity of carbon capture, utilization, and storage (CCUS) technologies, the National Energy Technology Laboratory (NETL) has undertaken an assessment of its "key technologies." The De*partment of Energy-Fossil Energy Technology Readiness Assessment Guide* (DOE-FE Guide[1]) served as the basis for a comprehensive and formal evaluation of the maturity of NETL's key technologies. This effort involved a three-step process:

- Establish a standard set of benchmarks
- Conduct a formal assessment of the ongoing research and development (R&D) efforts being supported by FE's Clean Coal Research Program (CCRP) using the Technology Readiness Level (TRL) evaluation discipline
- Publicly report the results of the TRL evaluation

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

- *Carbon Capture* develops technologies to lower the costs of carbon capture from both pre-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.
- *Advanced Energy Systems* focuses on developing advanced combustion systems, advanced gasification systems, stationary power fuel cells, advanced fuels, and improved gas turbines for future coal-based combined-cycle plants that are cleaner, more efficient, and capture carbon.
- *Crosscutting Research* develops technologies for improving the efficiency and environmental performance of advanced coal power systems through the use of modeling, advanced simulation techniques, novel sensors, process control, and advanced materials.

These subprograms are further subdivided into major Technology Areas and each Technology Area—which consists of multiple projects—is organized to pursue the development of key technologies.

Once engineering-scale models or prototypes have been tested in a relevant environment, technologies within the R&D portfolio can be advanced to the CCS/CCUS Demonstrations program area, where they are tested at scale to advance their readiness for commercial deployment. Technology availability for advancement is based on technology performance expectations, funding availability, demonstration program area priorities, and other factors. Although research and development projects typically focus on a single key technology, the demonstration projects frequently serve as a platform to advance multiple key technologies.

As of July 2012, there are over 400 active projects within the CCRP RD&D portfolio. This portfolio has a value of approximately \$16.3 billion composed of a \$5.9 billion DOE share and \$10.4 billion private-sector share. The entire portfolio of R&D projects was reviewed and considered as part of the Technology Readiness Assessment (TRA) process. However, not all of projects in the CCRP's active R&D portfolio were deemed suitable for a formal evaluation, based on the criteria set forth in the DOE-FE Guide. Many small projects were excluded based on cost (that is, ones that represent relatively small investments). Also, projects that are focused on only simulations and/or analyses were not generally selected for assessment. Consequently over 90 percent of the total value of the R&D component of the CCRP portfolio was included, and the results of this formal TRA are presented in this report.

The flow of technology development that is employed by the CCRP to accomplish its mission to develop technology and make it ready for potential commercial deployment is depicted in Figure ES-1 below. The CCRP is fundamentally an applied research program, and because TRL 1 reflects basic research, the CCRP is generally focused on advancing technology from TRL 2 through TRL 6 for the CCUS and Power Systems R&D program area.

Although this report focuses primarily on the TRA of the CCUS and Power Systems program area, an overview of the TRA approach to technologies in the CCS/CCUS Demonstration program area is presented in the latter portion of this report.

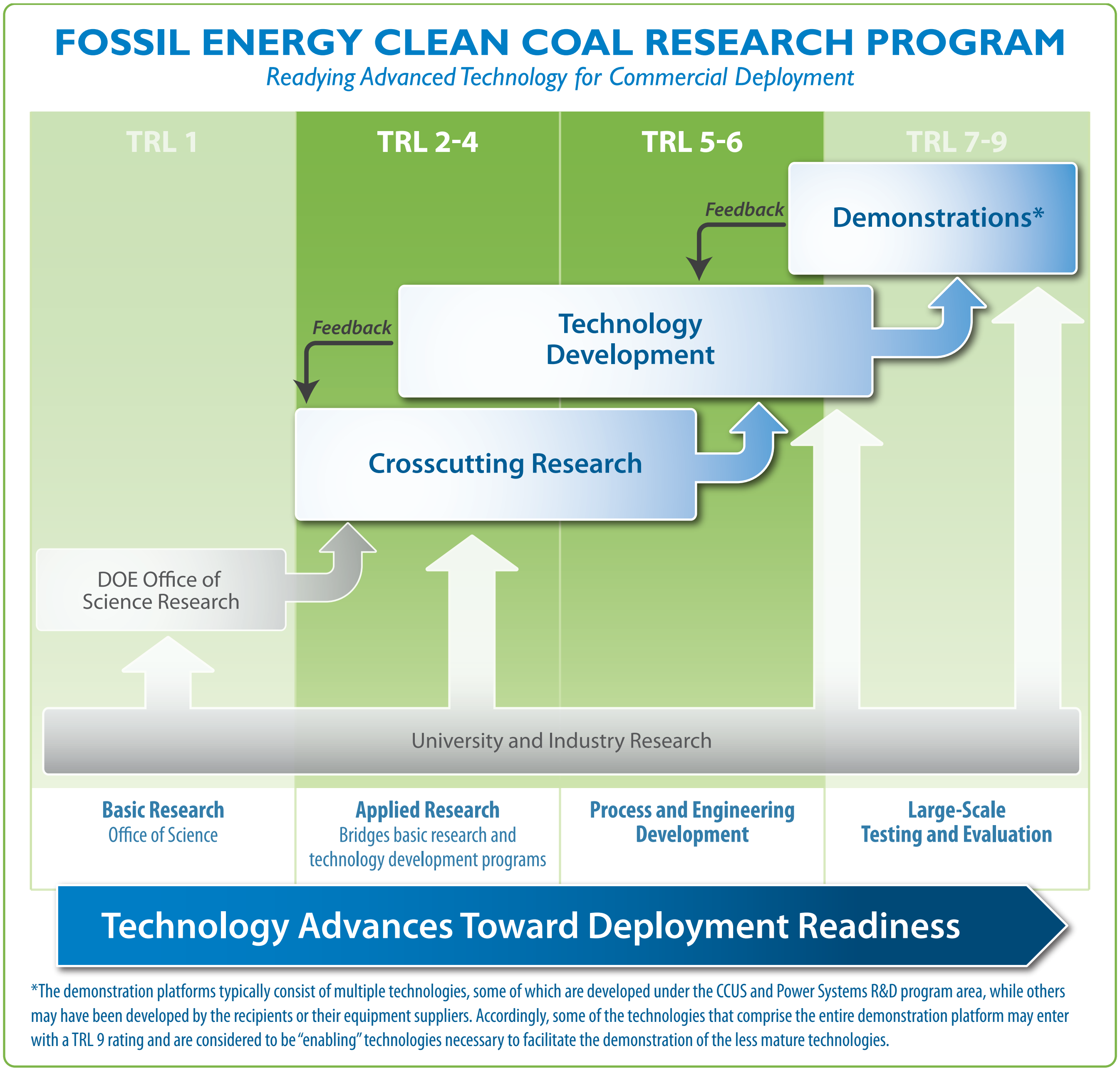


Figure ES-1: CCRP—Flow of Technology Advancement

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."[2] 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[3] provided the foundation for the assessment of CCRP R&D projects conducted by NETL.

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% final scale (e.g., complete technology process has undergone bench-scale testing using synthetic flue gas composition at a scale of approximately 1–100 scfm).
5	Laboratory-scale similar-system validation in a relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Prototype is defined as less than 5% final scale (e.g., complete technology has undergone bench-scale testing using actual flue gas composition at a scale of approximately 1–100 scfm).
6	Engineering/pilot-scale prototypical system demonstrated in a relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. Pilot or process-development-unit scale is defined as being between 0 and 5% final scale (e.g., complete technology has undergone small pilot-scale testing using actual flue gas composition at a scale equivalent to approximately 1,250–12,500 scfm).
7	System prototype demonstrated in a plant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Final design is virtually complete. Pilot or process-development-unit demonstration of a 5–25% final scale or design and development of a 200–600 MW plant (e.g., complete technology has undergone large pilot-scale testing using actual flue gas composition at a scale equivalent to approximately 25,000–62,500 scfm).
8	Actual system completed and qualified through test and demonstration in a plant environment	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include startup, testing, and evaluation of the system within a 200–600 MW plant CCS/CCUS operation (e.g., complete and fully integrated technology has been initiated at full-scale demonstration including startup, testing, and evaluation of the system using actual flue gas composition at a scale equivalent to approximately 200 MW or greater).
9	Actual system operated over the full range of expected conditions	The technology is in its final form and operated under the full range of operating conditions. The scale of this technology is expected to be 200–600 MW plant CCS/CCUS operations (e.g., complete and fully integrated technology has undergone full-scale demonstration testing using actual flue gas composition at a scale equivalent to approximately 200 MW or greater).

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; of the over 400 active projects, 285 met the criteria for conducting a formal TRA. In addition, 34 projects under the University Training and Research (UTR) Technology Area of the Crosscutting Research subprogram were deemed significant enough to receive a "tabletop" review by the NETL Technology Manager (see page 101 of this report for more details). The evaluation teams gathered pertinent information, conducted an independent analysis, assessed their findings, reached team consensus, and documented the results of their evaluation that included 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-2 below.

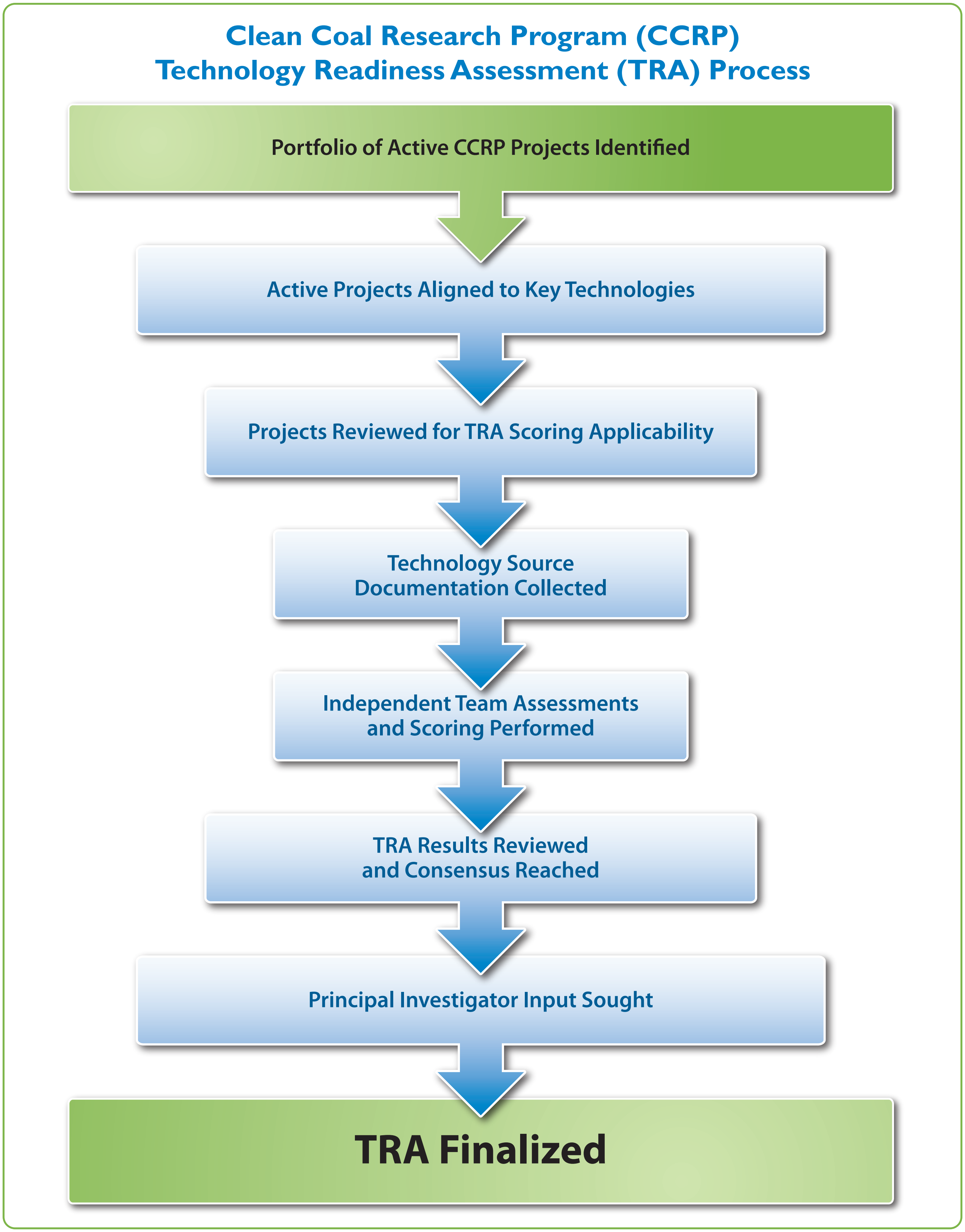


Figure ES-2: CCRP TRA Process Diagram

Summary of R&D Results

In summary, 285 active R&D projects were evaluated and consensus was achieved with the Principle Investigators for all of the ratings. A summary of the TRL ratings by subprogram is provided in Table ES-2. The UTR portfolio as a whole (34 additional projects) is consistent with TRL scores of 2 and 3. More detail regarding the individual key technologies can be found in Table 7 through Table 20 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 1	TRL 2	TRL 3–4	TRL 5–6	TRL 7–9	
Carbon Capture	0	8	39	7	0	54
Carbon Storage	0	0	56	15	1	72
Advanced Energy Systems	0	5	92	7	0	104
Crosscutting Research	0	9	34	12	0	55
Total	**0**	**22**	**221**	**41**	**1**	**285**

As shown in Figure ES-1, R&D technologies that achieve a TRL rating of 6 or 7 are strong candidates for advancement into the CCS/CCUS Demonstrations program area to continue the process of readying them for potential commercial use. In addition, R&D technologies that achieve a TRL rating of 5 may be considered for large-scale testing advancement. As shown in Table ES-2, 42 CCUS and Power Systems R&D technologies received TRL scores of 5–7.

CCS/CCUS DEMONSTRATIONS

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

DOE is addressing the key challenges that confront the wide-scale industrial deployment of CCS/CCUS technologies by sponsoring large-scale demonstrations of key R&D technologies including the cost-effective capture, utilization, and storage of carbon dioxide (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 CO2 from industrial sources that produce a variety of commodities, including power. The captured CO_2 is then stored and/or utilized.

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

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

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

Figure ES-3 presents the key technologies being advanced through each Technology Area.

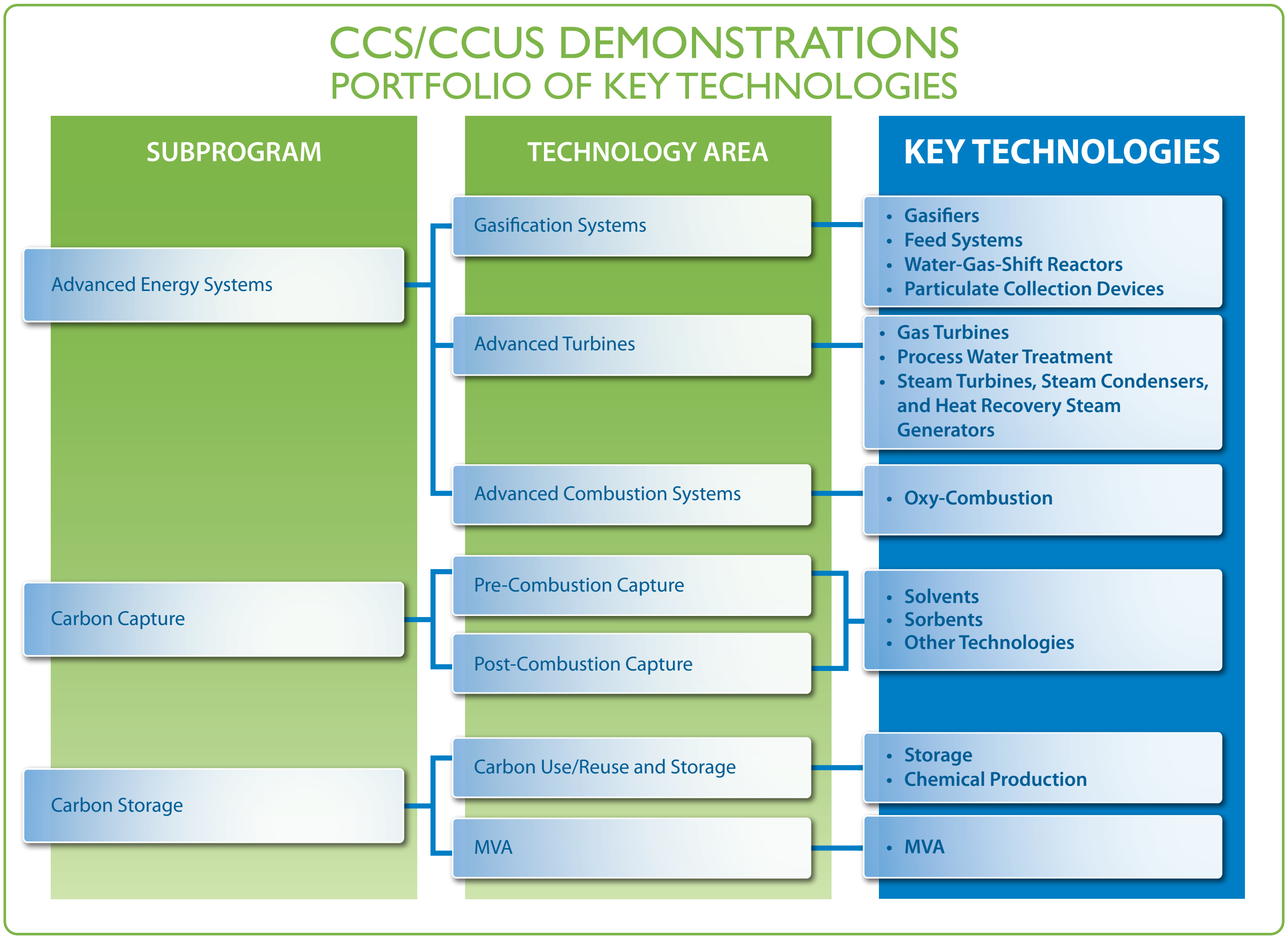


Figure ES-3: CCS/CCUS Demonstrations Portfolio of Key Technologies

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

The TRA discipline is a new practice within the CCRP. Since it is the goal of the demonstration program to advance technologies to the point of commercial readiness (i.e., TRL 9), the TRA methodology would be most useful in assessing the status of technologies once the demonstration concludes, thus serving as a tool for aiding future investment decisions that may be needed to advance specific technologies to a condition of commercial readiness. As a result, an appropriate time to conduct the TRA would be as part of the Post Project Assessment (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 CCUS 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/CCUS Demonstrations section of this report.

CONCLUSION

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

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

INTRODUCTION AND PURPOSE

FOSSIL ENERGY PROGRAM DRIVERS

Today the energy resources that fuel our nation's economy are 83 percent fossil-based, with coal playing a significant role. Of the roughly 100 quads of energy our economy consumes each year, our coal and natural gas resources satisfy nearly one-half of this demand while affordably producing over two-thirds of our electricity. All segments of U.S. society rely heavily on America's existing multibillion-dollar investment in its highly reliable and affordable fossil-based utility, industrial, commercial, transportation, and residential energy infrastructure. However, the continued use of coal faces a strategically important challenge. While demand for electricity continues to escalate, there are significant public concerns regarding coal-based emissions, particularly carbon dioxide (CO_2) and its relation to climate change. This is a global issue that requires worldwide attention, and advanced technological solutions are required.

To meet this challenge, 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 2011 Strategic Plan[4] and the fiscal year 2012 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

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

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

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 [Environmental Protection Agency] and Energy Information Administration assessments of recent climate and energy legislative proposals show that, if available on a cost-effective basis, CCS can over time play a large role in reducing the overall cost of meeting domestic emissions reduction targets. By playing a leadership role in efforts to develop and deploy CCS technologies to reduce 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."

Secretarial Goals

In concert with the President's goals, Energy Secretary Chu has identified four distinct DOE-specific goals that generally guide management and technology investments applicable to all of its research, development, and demonstration (RD&D) programs. The Secretary's first goal—catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies—applies directly to the clean coal technologies portion of the CCRP.

DOE Strategic Plan

In May 2011, DOE issued its Strategic Plan (updated February 13, 2012),[5] which provides the following additional guidance to the CCRP.

Mission

DOE's mission is to ensure America's security and prosperity by addressing its energy, environmental, and nuclear challenges through transformative science and technology solutions.

Goals

- Goal 1: Catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies
- Goal 2: Maintain a vibrant U.S. effort in science and engineering as a cornerstone of our economic prosperity with clear leadership in strategic areas

CCRP Alignment with the Department's Goals and FY 2012 Agency Performance Plan

Long-Term Performance Goals

- *Carbon Capture/Post-Combustion* – Conduct laboratory through pilot-scale tests of advanced post-combustion capture technologies that show, through engineering and systems analyses studies, continued achievement toward the goal of 90 percent CO_2 capture at no more than a 35 percent increase in cost of electricity (COE).
- *Carbon Capture/Pre-Combustion* – Conduct laboratory through pilot-scale tests of advanced pre-combustion capture technologies that show, through engineering and systems analyses studies, continued achievement toward the goal of 90 percent CO_2 capture at no more than a 10 percent increase in COE.
- *Carbon Storage* – Inject 9.0 million (cumulative since 2009) metric tons of CO_2 in large-volume field test sites to demonstrate the formations' capacity to permanently, economically, and safely store carbon dioxide.

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 carbon capture, utilization, and storage (CCUS) 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's Office of Clean Coal 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 May 2011 DOE Strategic Plan and supports the achievement of DOE's mission and applicable goals by deploying a strategy focused on the following:

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

The CCRP is responsive to the FE Office of Clean Coal's Strategic Plan, which defines program goals, objectives, and technology roadmaps for coal-related efforts. At a more discrete level, the CCRP complies with Federal assessment mechanisms, including the Government Performance and Results Act (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) CCUS and Power Systems R&D and (2) CCS/CCUS Demonstrations. Each program area has specific goals that contribute to DOE's carbon reduction portfolio, either through direct capture and storage of greenhouse gases 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 CCUS and Power Systems R&D program area, since technologies that are components of demonstrations 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/CCUS with coal-fired power generation at commercial scale needs to be demonstrated, and the permanence and safety of CO_2 storage must be assured. Capital and operating costs must be significantly reduced so that CCS/CCUS technology can be deployed on both new and existing facilities for a wide range of fuel types and geological storage settings. Overcoming these challenges requires not only adequate funding, but innovative strategies that must be developed in conjunction with the private sector and DOE's academic partners. To achieve this end, DOE is addressing the key challenges that confront the wide-scale commercial deployment of CCS/CCUS through industry/government/academic cooperative research on cost-effective capture, storage, and power-plant efficiency-improvement technologies.

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

- *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.
- *Advanced Energy Systems* focuses on developing advanced combustion systems, advanced gasification systems, stationary power fuel cells, advanced fuels, and improved gas turbines for future coal-based combined-cycle plants that are cleaner, more efficient, and capture carbon.
- *Crosscutting Research* develops technologies for improving the efficiency and environmental performance of advanced coal power systems through the use of modeling, advanced simulation techniques, novel sensors, process control, and advanced materials.

FE's advanced research can be categorized into 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.

To reduce the incremental capital and operating costs of applying CCS/CCUS to existing plants, the CCRP is developing advanced, next-generation post-combustion carbon-capture and compression technologies. The key technology components under development for retrofitting the existing fleet include advanced CO_2 compression and carbon-capture approaches akin to those being pursued for advanced plants.

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 CCUS. The funding of revolutionary research for CCUS will help the United States realize continued improvement in power-generation technology and potentially transform U.S. energy infrastructure.

PURPOSE

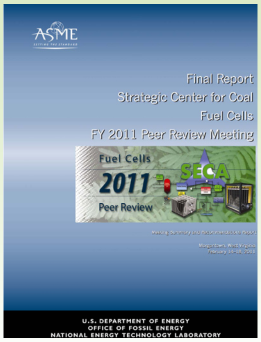
NETL developed standard benchmarks and performed assessments of key technologies within its research portfolio. This report provides a summary of the analysis that was conducted and the findings that resulted.

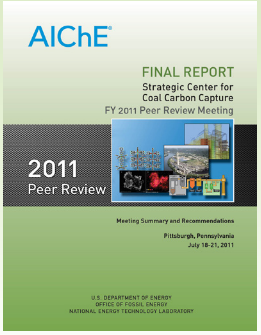
Although NETL has not previously conducted Technology Readiness Assessments (TRAs) of its technologies in its research portfolio, the organization has a long and rich history of performing various allied forms of technology assessments, including rigorous, comprehensive independent Peer Reviews of the technologies under investigation. The associated sidebar provides additional details concerning these efforts and depicts examples of recent products.

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 President's Management Agenda, Office of Management and Budget (OMB) bulletins and circulars on Peer Reviews, and the U.S. Department of Energy's Strategic Plan, biannual Peer Reviews are performed. FE routinely commissions the independent review of Technology Areas in accordance with the Department's Guide for Managing General Program Evaluation Studies to assess the status of the research, accomplishments, and planned activities. Peer Reviews conducted by independent experts from the American Society of Mechanical Engineers (ASME), American Institute of Chemical Engineers (AIChE), and the International Energy Agency (IEA) have been completed spanning all program areas of the CCRP. The results of these reviews and a summary of the findings developed by review panels can be found on the NETL website under Technologies > Coal and Power Systems; these results are routinely posted and made publicly available as new reviews are completed. All recommendations and action items resulting from these reviews are evaluated, addressed, and resolved via the development of detailed mitigation strategies and actions that are recorded and tracked through completion. Peer Reviews improve the overall quality of the technical aspects of R&D activities and enhance project-related activities such as utilization of resources, project and financial management, and commercialization. In addition, Peer Reviews allow the DOE to gain industry acceptance of the SCC Office of Coal and Power Systems' program R&D efforts by communicating the goals and objectives that are supported by their various program portfolios. More information can be found at: http://www.netl.doe.gov/technologies/coalpower/peer-review/index.html

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





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."[2] 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 research and development 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[3] 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[1]) 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 2012 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 that separate TRL readiness terminology and scales be developed to guide the assessment. Refer to Table 1 for TRL definitions and descriptions for advanced power-generation systems and to Table 2 for technologies for carbon storage. Although the definitions imply a linear progression in technology advancement, the use of advanced simulation may support a nonlinear progression where technology development bypasses or skips a TRL.

Table 1: DOE-FE Plant Technology TRL Definitions and Descriptions

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

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

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

i 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 is depicted in Figure 1.

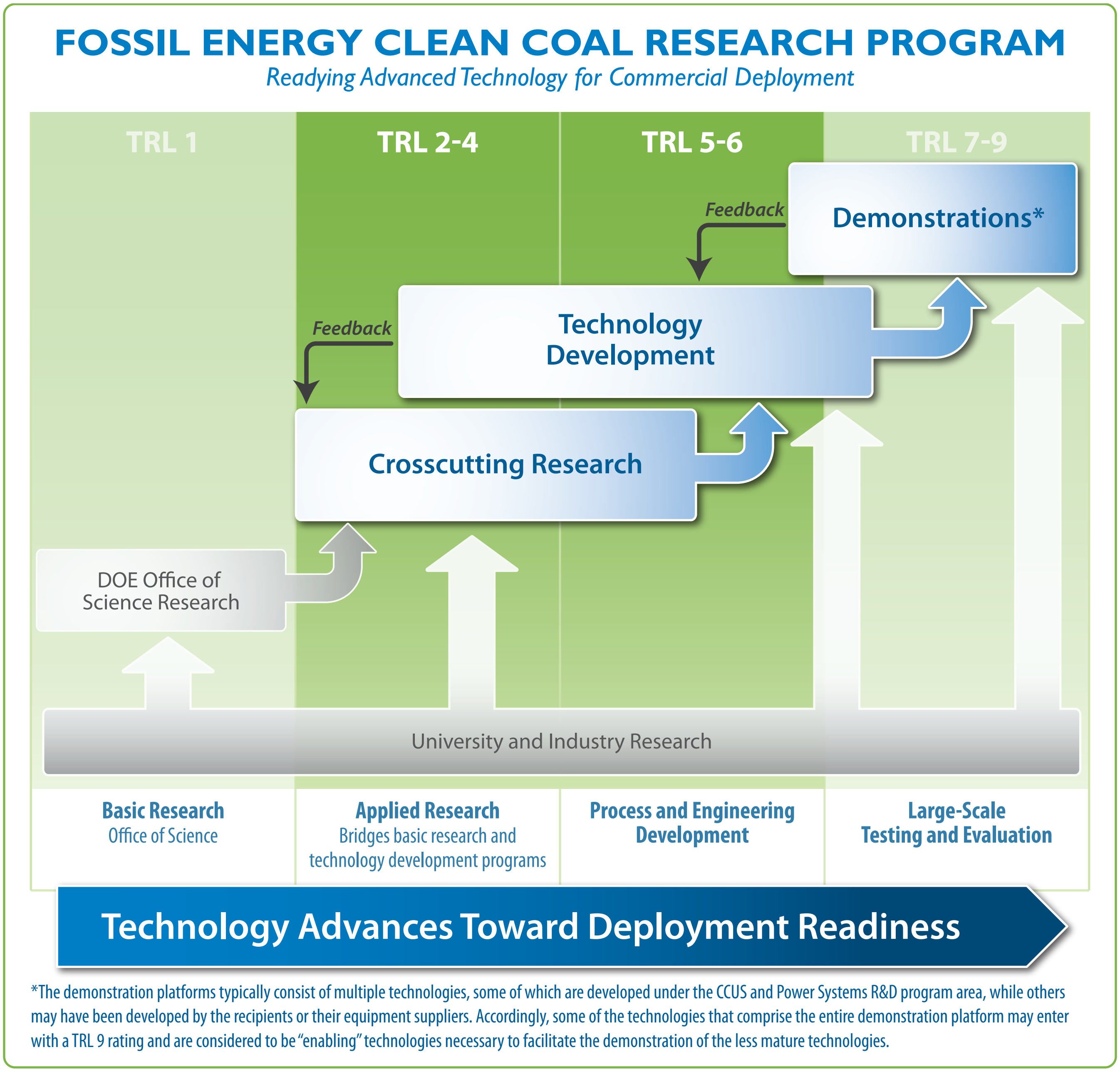


Figure 1: Schematic of DOE/FE Technology Readiness Levels

NETL's TRA focused on "key technologies" and is organized consistent with the budget structure approved via the FY 2012 congressional budget appropriations. The CCRP is thus subdivided into four distinct areas: Carbon Capture, Carbon Storage, Advanced Energy Systems, and Crosscutting Research, as depicted in Figure 2.

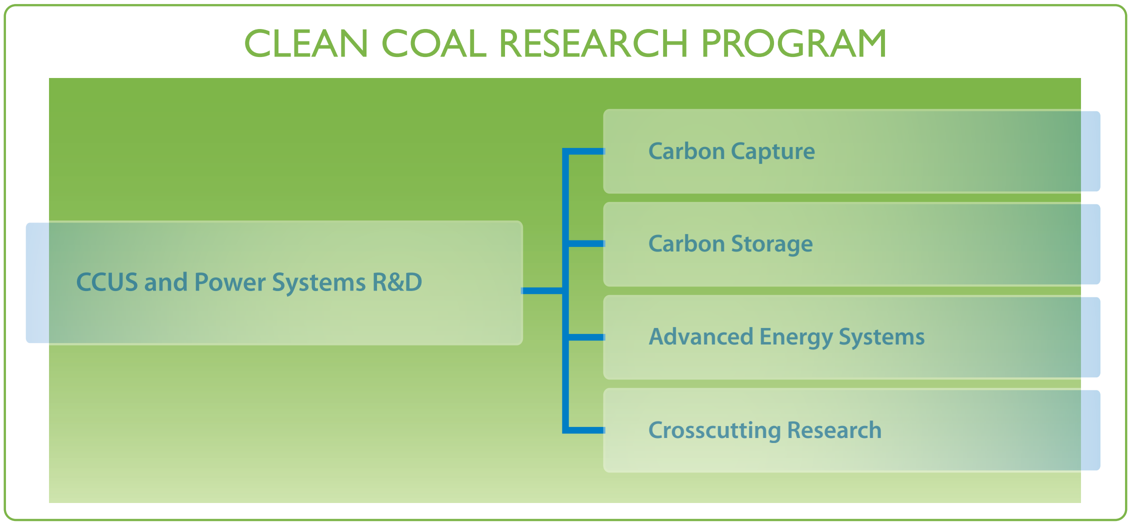


Figure 2: Fossil Energy Clean Coal Research Program FY 2012 Budget Structure

As of July 2012, there are over 400 active projects within the CCRP RD&D portfolio. This portfolio has a value of approximately $16.3 billion composed of a $5.9 billion DOE share and $10.4 billion private-sector share. The entire portfolio was examined to identify projects and individual key technologies that were deemed to warrant a formal TRL evaluation. A two-stage screening process was applied. First, project costs and DOE investment potential were reviewed according to the criteria defined in Table 1 of the DOE-FE Guide (see Table 3 below).

Table 3: TRA Technology Risk-Related Selection Criteria

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

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

Table 4: TRA Technology-Related Selection Criteria

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

The selected projects were organized by the areas noted above: Carbon Capture, Carbon Storage, Advanced Energy Systems, and Crosscutting Research. This structure provided a standard means for capturing selected projects and graphically showing how they map to a budgeted program area. The Carbon Storage structure is provided as an example in Figure 3.

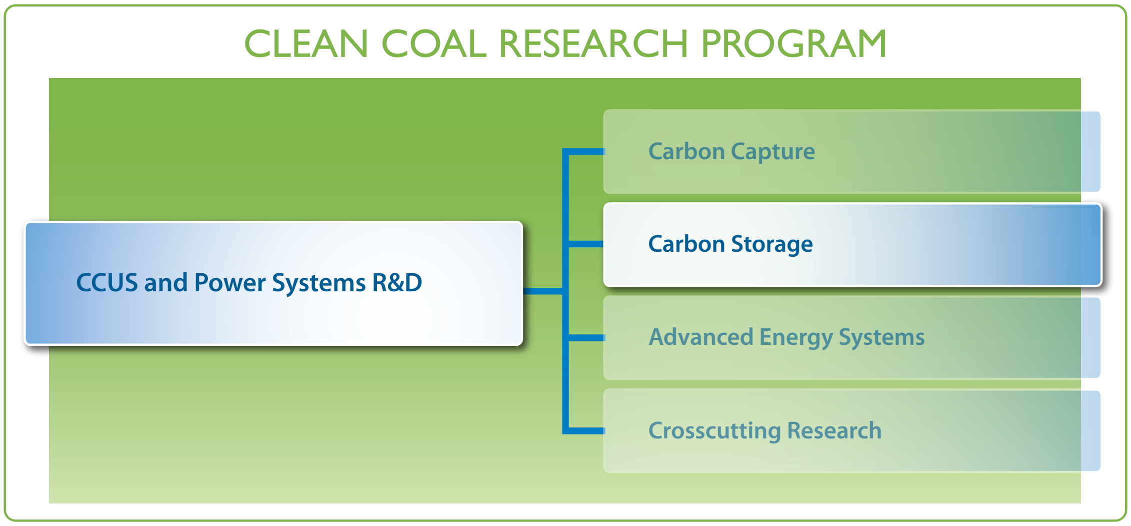


Figure 3: Carbon Storage Component of the Fossil Energy Clean Coal Research Program

The CCRP is divided into Technology Areas. Figure 4 provides an example, showing that Monitoring, Verification, Accounting, and Assessment was one of four Carbon Storage Technology Areas. "Key technologies," such as the four shown for Monitoring, Verification, Accounting, and Assessment in Figure 4, were associated with each Technology Area, and projects being performed related to those key technologies were assessed to establish an appropriate current state of technology readiness (i.e., TRL score). In addition, a relevancy statement has been developed for each project that concisely documents the expected contribution to program goals. These statements contain project objectives, the reason the project objectives are important to achieving program goals, and the research approach being taken to accomplish project objectives.

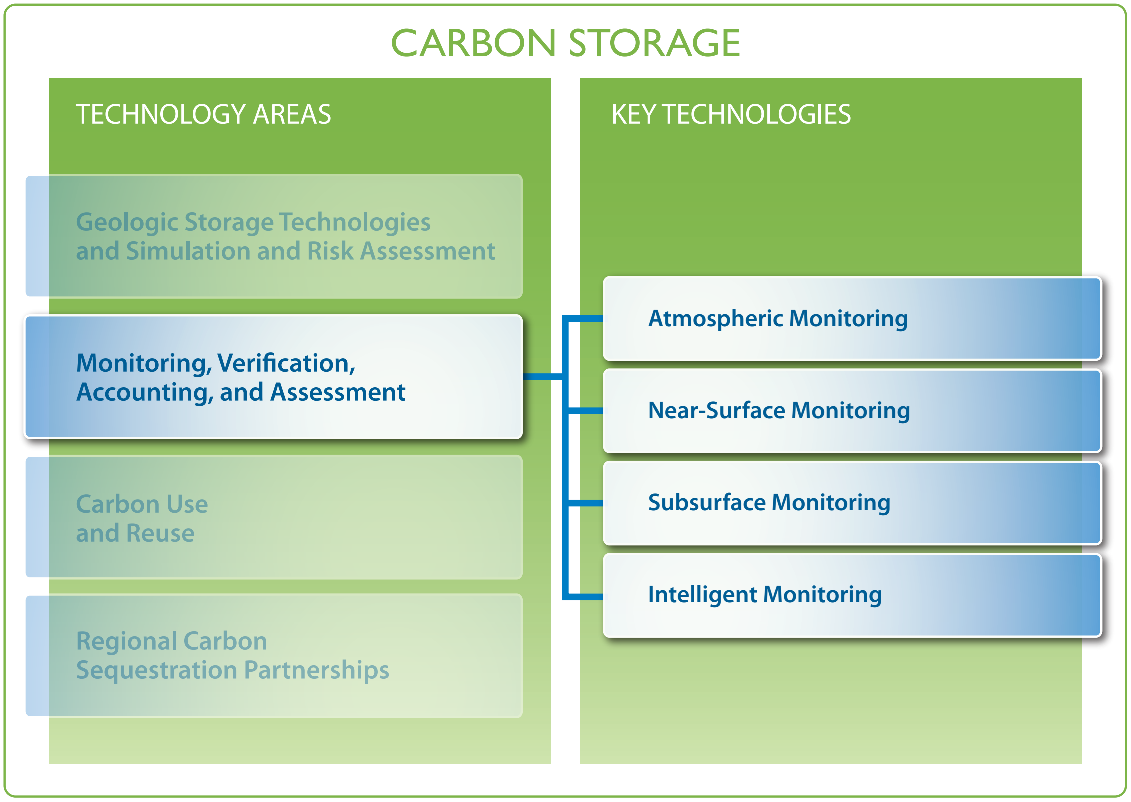


Figure 4: Example of Technology Area and Key Technologies Subdivision

The nature of the CCUS and Power Systems R&D portion of the CCRP is to pursue research at the lower and mid-level range of the readiness scale. As such it is common for a project to be focused on a single "key technology." The goal of the assessment effort is to identify the current state of readiness of the key technologies being pursued across the R&D portion of the CCRP. The detailed technology assessment and scoring followed the process depicted in Figure 5 below and described in a subsequent narrative.

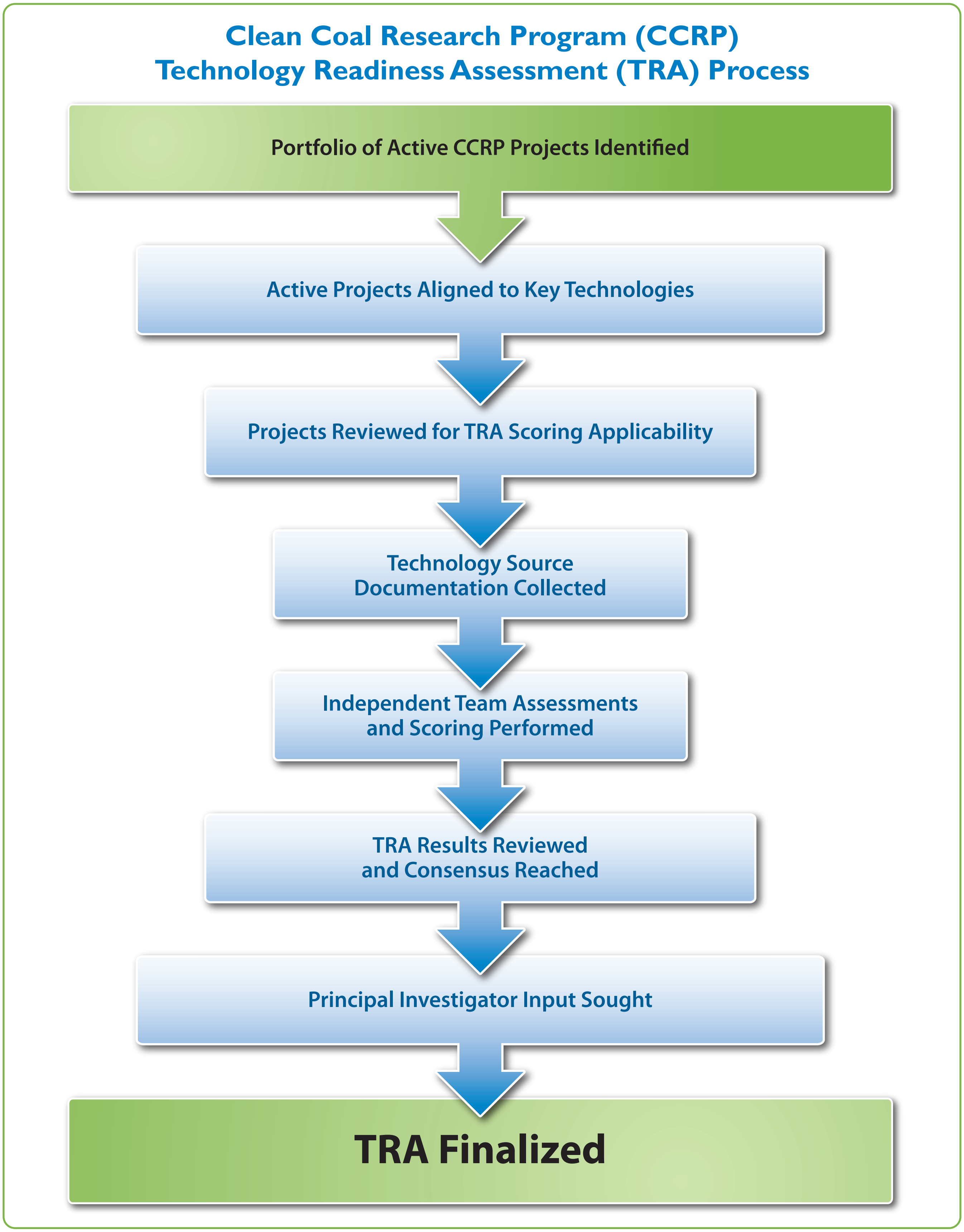


Figure 5: Process Flow for Conducting TRA

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

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

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

ii 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 285 active R&D projects within the portfolio of key technologies being advanced by the CCRP (34 additional UTR projects received a tabletop review, see page 101). Additionally, consensus was established for all of the 285 active project ratings. A summary of the TRL ratings as aligned with their respective key technologies is provided in Table 5.

Table 5: CCRP R&D Key Technologies TRL Summary

CCUS and Power Systems R&D	Technology Area	Key Technology	Number of R&D Projects					Total
			TRL 1	TRL 2	TRL 3–4	TRL 5–6	TRL 7–9	
Carbon Capture	Post-Combustion Capture	Solvents		2	14	2		18
		Sorbents		1	8	4		13
		Membranes		2	8	1		11
	Pre-Combustion Capture	Solvents		1	1			2
		Sorbents		1	3			4
		Membranes		1	5			6
		Subtotal Carbon Capture	**0**	**8**	**39**	**7**	**0**	**54**
Carbon Storage	Geologic Storage Technologies and Simulation and Risk Assessment	Wellbore			1			1
		Mitigation			2			2
		Fluid Flow, Pressure, and Water Management			14	1		15
		Geochemical Impacts			5			5
		Geomechanical Impacts			9			9
		Risk Assessment			3			3
	Monitoring, Verification, Accounting, and Assessment	Atmospheric Monitoring				2		2
		Near-Surface Monitoring			1	2		3
		Subsurface Monitoring			11			11
		Intelligent Monitoring			2			2
	Carbon Use and Reuse	Chemicals			4			4
		Mineralization/Cement			2			2
		Polycarbonate Plastics			1			1
	Regional Carbon Sequestration Partnerships	Clastics (deltaic, fluvial deltaic, fluvial/alluvial, strandplain, turbidite, eolian, and shelf clastic)			1	6	1	8
		Carbonates (shallow shelf and reef)				3		3
		Coal and Shale				1		1
		Subtotal Carbon Storage	**0**	**0**	**56**	**15**	**1**	**72**

Table 5: CCRP R&D Key Technologies TRL Summary

CCUS and Power Systems R&D	Technology Area	Key Technology	Number of R&D Projects					Total
			TRL 1	TRL 2	TRL 3–4	TRL 5–6	TRL 7–9	
Advanced Energy Systems	Advanced Combustion Systems	Oxy-Combustion			5	2		7
		Chemical Looping			2	1		3
		Advanced Materials			11	1		12
	Gasification Systems	Feed Systems			3			3
		Gasifier Optimization and Plant Supporting Systems		1	5	1		7
		Syngas Optimization Systems		1	4			5
	Hydrogen Turbines	H_2 Turbines				2		2
		Oxy-Fuel Turbines for EOR and Power			1			1
		Combustion Systems			6	0		6
		Materials and Material Architectures			6			6
		Aerodynamics and Heat Transfer			7			7
	Coal and Coal-Biomass to Liquids (Fuels)	Advanced H_2 Membranes		2	11			13
		Coal-Biomass to Liquids		1	15			16
	Solid Oxide Fuel Cells	Anode Electrolyte Cathode (AEC) Development			10			10
		Atmospheric Pressure Systems			2			2
		Pressurized Systems			1			1
		Alternative AEC Development			3			3
		Subtotal Advanced Energy Systems	**0**	**5**	**92**	**7**	**0**	**104**
Crosscutting Research	Plant Optimization Technologies	Sensors and Controls		3	11	6	0	20
		Water-Emissions Management and Controls			1	4		5
		Dynamic Systems Modeling		2	1	1		4
		High-Performance Materials and Modeling		1	5			6
	Coal Utilization Sciences	Dynamic Systems Modeling		1	7			8
		Carbon Capture Simulation			1			1
		Carbon Storage Risk Assessment			2	1		3
		Innovative Energy Concepts		2	5			7
		High-Performance Materials and Modeling			1			1
		Subtotal Crosscutting Research	**0**	**9**	**34**	**12**	**0**	**55**
		Total	**0**	**22**	**221**	**41**	**1**	**285**

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

Table 6: Carbon Capture and Carbon Storage TRL 5–7 Portfolio Summary

CCUS R&D	Technology Area	Key Technology	Number of TRL 5–7 Technologies	Technology Assessment Summary
Carbon Capture	Post-Combustion Capture	Solvents	2	Solvent-based CO_2 capture involves chemical or physical absorption of CO_2 from flue gas into a liquid carrier. One of these technologies is integrating waste heat recovery into an existing 25-MW pilot amine-based CO_2 capture process and the other is designing, building, and operating a 1-MW equivalent pilot plant.
		Sorbents	4	Solid sorbents, include sodium and potassium oxides, zeolites, carbonates, amine-enriched sorbents, and MOFs. These technologies range from bench-scale tests and validation in relevant environments to pilot-scale testing using a 1-MW equivalent slipstream at an operating coal-fired power plant. These include technologies being developed at the National Carbon Capture Center.
		Membranes	1	Membrane-based CO_2 capture uses permeable or semi-permeable materials that allow for selective transport and separation of CO_2 from flue gas. This technology is being developed at a 1-MW pilot-scale equivalent testing capacity at the National Carbon Capture Center.
		Subtotal Carbon Capture	**7**	
Carbon Storage	Geologic Storage Technologies and Simulation and Risk Assessment	Fluid Flow, Pressure, and Water Management	1	Computer simulations of CO_2 flow and pressure increases are used to design injection operations. This technology development effort is providing an understanding of the enhancement of coal-bed methane production and geologic injection limitations to achieve safe, commercial geologic CO_2 storage by actively injecting CO_2 and recovering methane and then developing models and analyses on reservoir effects.
	Monitoring, Verification, Accounting, and Assessment	Atmospheric Monitoring	2	Atmospheric CO_2 monitoring provides assurance that there are no leaks of stored CO_2 to the atmosphere. These technologies are developing field-deployed remote and noninvasive monitoring tools to quantify CO_2 storage and leakage and developing and validating a scanning eye-safe diode laser-based Differential Absorption Lidar under in-situ conditions.
		Near-Surface Monitoring	2	Near-surface monitoring includes sampling and analysis of soil gas for CO_2, natural chemical tracers or introduced tracers, and geochemical analysis of groundwater samples. These technologies are focused on in-field, continuous, non-invasive soil carbon canning system and verification and accounting of carbon sequestration using a field ready 14C isotopic analyzer.
	Regional Carbon Sequestration Partnerships	Clastics	7	Storage reservoirs collectively referred to as clastics are derived primarily from sand deposited in a variety of depositional environments. These technology focused efforts are focused on assessing and validating regional clastic reservoirs as a potential CCUS option either by preparing for or by current active injection of CO_2 at project end.
		Carbonates	3	Carbonate deposits include isolated banks with flat tops and walls that slope steeply down into the ocean (reef), and continental shelf deposits, and ramp-like shelves that slope into shallow ocean basins (shallow shelf). These three technology development efforts are focused on assessing and validating regional carbonate reservoirs as a CCUS option by preparing for eventual injection of CO_2 at project end.
		Coal and Shale	1	In coal, CO_2 is adsorbed into the matrix and locked in place while shale is very fine grained rock with low permeability. This technology development effort is assessing and validating coal/shale as a potential CCUS option by preparing for an eventual ECBM injection test at project end.
		Subtotal Carbon Storage	**16**	

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

Conclusions

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

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

CARBON CAPTURE

Although commercially available 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. There are three primary reasons: (1) they have not been demonstrated at the large scale necessary for power plant application, (2) the parasitic loads required to support CO_2 capture would significantly decrease power generating capacity, and (3) if successfully scaled up, they would not be cost-effective at their current level of process development.

FE is investigating a broad portfolio of CO_2-capture research pathways in two general Technology Areas—*Post-Combustion Capture* and *Pre-Combustion Capture*. Post-combustion systems are designed to separate CO_2 from the flue gas—primarily nitrogen—produced by fossil fuel combustion in air. 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 and other industrial CO_2 sources. Pre-combustion systems are designed to separate CO_2 from H_2 and other constituents in the syngas produced at integrated gasification combined cycle (IGCC) power plants. Pre-combustion capture is mainly applicable to IGCC power plants and refers to removal of the CO_2 from the syngas prior to its combustion for power production.

CARBON CAPTURE

POST-COMBUSTION CAPTURE

OVERVIEW

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 pulverized coal (PC) power plants that capture CO_2 produced as part of the combustion process.

DOE/FE Goals

The DOE/FE goals for the Post-Combustion Capture Technology Area are to achieve at least 90 percent CO_2 capture at costs that represent less than a 35 percent increase in the total COE for PC power plants compared to those same plants without carbon capture and storage.

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. Cost-effective post-combustion capture technologies are therefore critical to ensuring the long-term viability of coal-fired power generation, which will remain a principal source of secure U.S. electricity for many decades. 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. Cost-effective post-combustion capture technologies will provide the United States with the ability to use low-cost domestic coal supplies in a carbon-constrained fuels market.

Critical Technology Area Challenges

Critical technology challenges related to post-combustion capture include improving the performance and cost of capture materials (solvents, sorbents, and membranes), decreasing parasitic loads, effective integration with other power plant processes, scaleup to industrial scale, and reducing the impacts of other flue gas contaminants on the CO_2 capture process.

Technology Readiness Assessment—Key Technologies

The Post-Combustion Capture Technology Area, supported by the Clean Coal Research Program, is organized into the three portfolios of key technologies depicted in Figure 6.

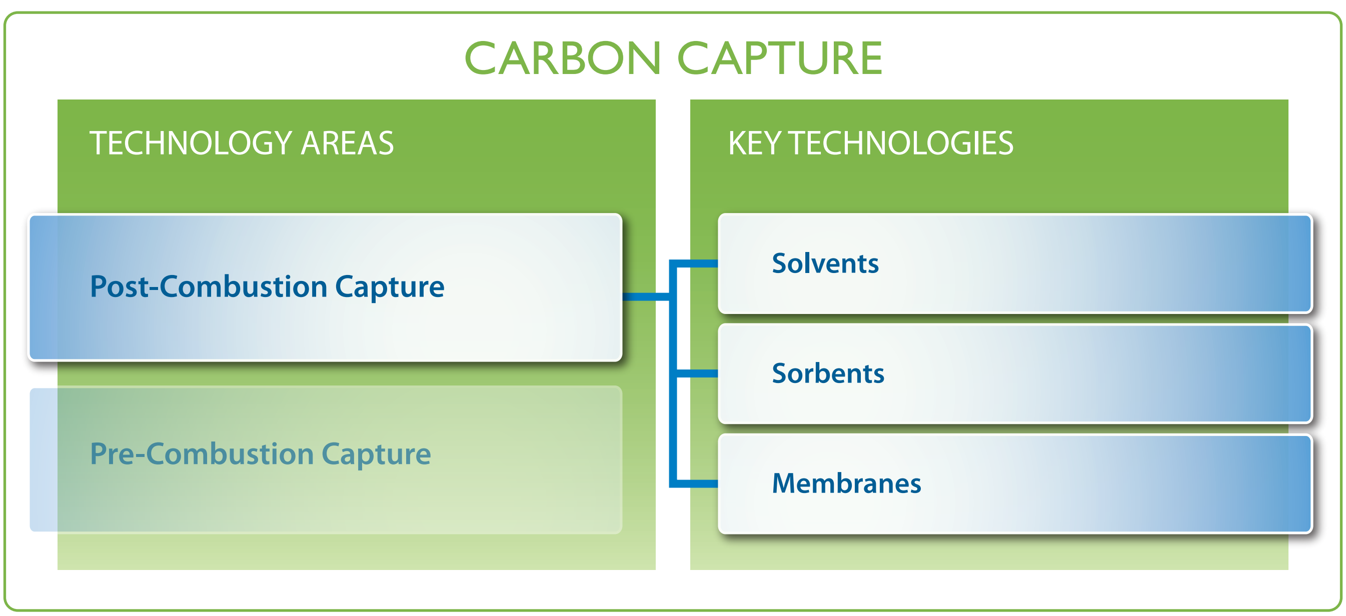


Figure 6: Post-Combustion Capture Key Technologies

Projects Assessed

Technology readiness has been assessed based on a review of individual research projects currently underway in each key technology. FE has considerable research underway to improve post-combustion capture in three key technologies:

- Solvents
- Sorbents
- Membranes

The TRLs of 42 projects were assessed in the Post-Combustion Capture Technology Area: 18 in Solvents, 13 in Sorbents, and 11 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.

The large number of projects being undertaken in the Post-Combustion Capture Technology Area reflects the importance of capture research in meeting GHG reduction goals. There are commercially available CO_2 capture technologies that are being used in various industrial applications. However, these technologies are not ready for widespread deployment on coal-based power plants for three principal reasons: (1) the technologies have not been demonstrated at a large enough scale necessary for power plant application, (2) the parasitic loads (steam and power) required to support CO_2 capture would significantly decrease power generating capacity, and (3) if successfully scaled up, the technologies would not be cost-effective at current levels of process development.

The results of the assessment of the scoring analysis are shown in Table 7, which also presents relevancy statements documenting the expected contribution of each project to program goals.

TECHNOLOGY AREA—QUALITATIVE SUMMARY OF TECHNOLOGY READINESS LEVEL

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 Post-Combustion Capture Technology Area spans a body of ongoing work with individual technologies at different levels of development. As such, the overall readiness of the Technology Area is represented by the status of the individual projects evaluated in the portfolio, which have TRL scores ranging from 2 to 6.

KEY TECHNOLOGIES—TECHNOLOGY READINESS ASSESSMENT

Key Technology—Solvents

Post-combustion solvent-based CO_2 capture involves chemical or physical absorption of CO_2 from flue gas into a liquid carrier. 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. 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.

Eighteen projects within the CCRP Post-Combustion Capture portfolio focus on improving solvent-based CO_2 capture. The current TRL of this key technology spans a range of 2–6, consistent with the status of the individual technologies embedded within these projects.

Key Technology—Sorbents

Solid sorbents—including sodium and potassium oxides, zeolites, carbonates, amine-enriched sorbents, and metal organic frameworks—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 no water is present, 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 equipment designs that are tailored to the sorbent characteristics.

Thirteen projects within the CCRP portfolio focus on improving sorbent-based capture. The current TRL of this key technology spans a range of 2–5, consistent with the status of the individual technologies embedded within these projects.

Key Technology—Membranes

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, palladium, 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, and tolerance to contaminants in combustion flue gas.

Eleven projects within the CCRP Post-Combustion Capture portfolio focus on improving membrane-based capture. 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.

PORTFOLIO OF POST-COMBUSTION CAPTURE PROJECTS

The composite results of the technology readiness assessment for the Post-Combustion Capture Technology Area are presented in the following table.

Table 7: Post-Combustion Capture Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—Solvents				
FC26-07NT43091	University of Notre Dame	Ionic Liquids: Breakthrough Absorption Technology for Post-Combustion CO_2 Capture	3	Develop a new ionic liquid absorbent and accompanying process that overcome viscosity and capacity issues impacting cost and performance of ionic liquids by via "proof-of-concept" exploration and laboratory-/bench-scale testing of a variety of ionic liquid formulations.
NT0005498	University of Illinois	Development and Evaluation of a Novel Integrated Vacuum Carbonate Adsorption Process	3	Develop an integrated vacuum carbonate absorption process to improve absorption kinetics and lower regeneration costs by evaluating process parameters, identifying an absorption rate acceleration catalyst, and developing an additive for reducing regeneration energy.
ED33EE	Lawrence Berkeley National Laboratory	Development of Chemical Additives for CO_2 Capture Cost Reduction	3	Develop a solvent system that integrates amine, potassium carbonate, and ammonium solvents to enhance solvent absorption and reduce regeneration cost through bench-scale investigation of novel solvents.
FE0004274	3H Company, LLC	Post-Combustion CO_2 Capture for Existing PC Boilers by Self-Concentrating Amine Absorbent	3	Evaluate the feasibility of a self-concentrating absorbent capture process to determine capture costs and energy savings generated through use of an innovative material and process by developing an engineering design supported by laboratory data and economic justification.
FE0004228	Akermin, Inc.	Advanced Low Energy Enzyme Catalyzed Solvent for CO_2 Capture	3	Demonstrate the performance of an advanced carbonic anhydrase-enzyme-potassium carbonate solvent to improve sorption kinetics and decrease costs by conducing bench-scale testing to develop immobilized carbonic anhydrase enzymes to accelerate potassium carbonate uptake rates.
FE0005799	ION Engineering, LLC	Novel Solvent System for Post-Combustion CO_2 Capture	4	Develop an ionic liquid/amine mixture to realize cost and performance improvements through combination of two solvent systems by conducting bench-scale testing of an amine-based solvent with an ionic liquid instead of water as the physical solvent, greatly reducing the regeneration energy.

Table 7: Post-Combustion Capture Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
FE0004360	University of Illinois	Bench-Scale Development of a Hot Carbonate Absorption Process with Crystallization-Enabled High-Pressure Stripping for Post-Combustion CO_2 Capture	3	Evaluate the hot carbonate absorption process with crystallization-enabled, high-pressure stripping to determine process costs and technical feasibility by conducing lab-/bench-scale analyses of thermodynamic and kinetic data associated with major unit operations.
FE0005654	URS Group, Inc.	Evaluation of Concentrated Piperazine for CO_2 Capture from Coal-Fired Flue Gas	4	Investigate the use of aerosol formation in amine-based systems to decrease capture costs and energy use by conducting process analyses initially at a 0.1-MW scale and then scaled to 0.5 MW for testing at DOE's National Carbon Capture Center.
FE0007502	General Electric Company	Bench-Scale Silicone Process for Low-Cost CO_2 Capture	3	Enable a practical technology path for the use of a novel silicone solvent-based capture system that meets cost and performance goals via bench-scale analysis of process kinetic and mass transfer information and development of a manufacturing plan for the aminosilicone solvent.
FE0007466	Battelle Memorial Institute	CO_2 Binding Organic Liquids Gas Capture with Polarity-Swing-Assisted Regeneration	3	Develop a capture technology that couples nonaqueous, switchable organic solvents with a polarity-swing-assisted regeneration process to lower temperatures and energies for CO_2 separation by performing bench-scale analyses to determine process design parameters for eventual scaleup.
FE0007716	Babcock & Wilcox Power Generation Group, Inc.	Optimized Solvent for Energy-Efficient, Environmentally Friendly Capture of Carbon Dioxide at Coal-Fired Power Plants	3	Characterize and optimize the formulation of a novel solvent to lower capture costs by identifying blends that will improve overall solvent and system performance through bench-scale thermodynamic and kinetic analyses of concentrated piperazine blends with other organic compounds.
FE0007567	Carbon Capture Scientific, LLC	Development of a Novel Gas Pressurized Stripping-Based Technology for CO_2 Capture from Post-Combustion Flue Gases	2	Develop a novel gas pressurized stripping process to reduce CO_2 compression needs and the regeneration energy penalty through bench-scale tests of individual process units and computer simulations to predict the gas pressurized stripping column performance under different operating conditions.
FE0007741	Novozymes North America, Inc.	Low-Energy Solvents for Carbon Dioxide Capture Enabled by a Combination of Enzymes and Ultrasonics	3	Develop a capture system that combines a carbonic anhydrase enzyme with low-enthalpy solvents and novel ultrasonically enhanced regeneration to improve capture efficiency, economics, and sustainability by designing, building, and testing an integrated bench-scale system.
FE0007525	Southern Company Services, Inc.	Waste Heat Integration with Solvent Process for More Efficient CO_2 Removal from Coal-Fired Flue Gas	6	Develop a viable heat integration method to improve capture cost and performance by integrating a waste heat recovery technology (high-efficiency system) into an existing 25-MW pilot amine-based CO_2 capture process and evaluating improvements in energy performance.
FE0007528	Neumann Systems Group, Inc.	Carbon Absorber Retrofit Equipment	4	Design, construct, and test an absorber that uses proven nozzle technology and an advanced solvent to reduce process equipment footprint and cost by conducting pilot-scale performance tests on 0.5-MW slipstream using a three-stage absorber unit and a best available technology CO_2 stripper unit.
FE0007453	Linde, Inc.	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	Refine a previously developed technology to reduce regeneration energy requirements by designing, building, and operating a 1-MW equivalent pilot plant using a novel amine-based solvent along with process and engineering innovations.
FE0007395	University of Kentucky	Application of a Heat-Integrated Post-Combustion CO_2 Capture System with Hitachi Advanced Solvent into an Existing Coal-Fired Power Plant	4	Develop a process using a two-stage stripping concept combined with an innovative heat integration method that utilizes waste heat to reduce costs through use of an improved power plant cooling tower by testing the process in a 0.7-MW slipstream pilot-scale system.
2012.01.05	National Energy Technology Laboratory	ORD Carbon Capture Field Work Proposal—Task 5: Post-Combustion Solvents	2	Develop technologies to capture 90% of the CO_2 produced by an existing coal-fired power plant with less than a 35% increase in to the COE as a critical step in reducing greenhouse gas emissions from fossil fuel-based processes by improving solvent working capacity, reducing sensible heat and heat of vaporization, and reducing the environmental impacts of solvent slip and degradation.

Table 7: Post-Combustion Capture Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—Sorbents				
NT0005578	SRI International	Development of Novel Carbon Sorbents for CO_2 Capture	5	Develop a novel carbon-based sorbent with moderate thermal regeneration requirements to evaluate the cost and performance capabilities of a low-cost sorbent via bench-scale parametric experiments involving fixed-bed adsorption and regeneration to determine optimum operating conditions.
NT0005497	TDA Research, Inc.	Low-Cost Sorbent for Capturing CO_2 Emissions Generated by Existing Coal-Fired Power Plants	4	Evaluate a low-cost alkalized alumina sorbent to determine the value of low-cost materials on capture cost and performance via bench-scale testing of a moving-bed capture system where adsorption and regeneration characteristics of the sorbent will be tested using actual flue gas.
FE0007804	Georgia Tech Research Corporation	Rapid-Temperature Swing Adsorption Using Polymeric/Supported Amine Hollow Fiber Materials	3	Develop a rapid temperature swing adsorption (TSA) process to evaluate cost and performance benefits of a novel hybrid capture approach via bench-scale testing of a module containing hollow fibers loaded with supported adsorbents surrounding an impermeable layer that allows for cooling and heating.
FE0007603	University of North Dakota	Evaluation of Carbon Dioxide Capture from Existing Coal-Fired Plants by Hybrid Sorption Using Solid Sorbents	3	Develop hybrid solid sorbent technology to decrease capture costs and energy use via bench-scale testing of a system that utilizes novel process chemistry, a low-cost method of heat management, and contactor conditions that minimize sorbent-CO_2 heat of reaction and promote fast CO_2 capture.
FE0007948	InnoSepra LLC	Novel Sorption-Based CO_2 Capture Process	3	Develop a sorption-based technology using a combination of novel microporous materials and process cycles to determine the impacts of this unique combination on capture costs and performance via bench-scale testing of system components using actual coal-based flue gas.
FE0007707	Research Triangle Institute	Bench-Scale Development of an Advanced Solid Sorbent-Based Carbon-Capture Process for Coal-Fired Power Plants	3	Develop an advanced process using molecular basket sorbents (MBS) to evaluate the viability of MBS by developing fluidizable MBS production techniques, collecting critical process engineering data, and testing a continuous bench-scale MBS capture system using coal-fired flue gas.
FE0007639	W. R. Grace & Co	Bench-Scale Development and Testing of Rapid Pressure Swing Absorption for Carbon Dioxide Capture	3	Develop a rapid pressure swing absorption (PSA) process to evaluate concept cost and performance benefits by testing a bench-scale system using a low-cost, structured adsorbent with low pressure drop, high mass-transfer rates, high capacity, and high availability that will enable large feed throughputs.
FE0007580	TDA Research, Inc.	Low-Cost High-Capacity Regenerable Sorbent for Carbon Dioxide Capture from Existing Coal-Fired Power Plants	3	Develop a low-cost, high-capacity CO_2 adsorbent to demonstrate its technical and economic viability through sorbent evaluation and optimization, development of sorbent production techniques, and bench-scale testing of the process using actual flue gas.
FE0004343	ADA-Environmental Solutions, Inc.	Evaluation of Solid Sorbents as a Retrofit Technology for CO_2 Capture	5	Refine the conceptual design of a commercial solid sorbent-based, post-combustion CO_2 capture technology to facilitate future scaleup efforts through process modeling and pilot-scale testing using a 1-MW equivalent slipstream at an operating coal-fired power plant.
FE0000493	Ramgen	Ramgen Supersonic Wave Compression and Engine Technology	4	Develop a supersonic shock wave compression technology to decrease carbon capture and storage costs and energy use through the design and testing of unique stationary power plant compressor products based upon aerospace shock wave compression theory.
FC26-05NT42650	Southwest Research Institute	Novel Concepts for the Compression of Large Volumes of Carbon Dioxide	5	Design a compression system that decreases power consumption and capital costs through the development of a semi-isothermal compression process with cooling via an internal cooling jacket or refrigeration to liquefy CO_2 so that its pressure can be increased using a pump, rather than a compressor.
NT0000749	Southern Company Services, Inc.	National Carbon Capture Center at the Power Systems Development Facility	5	Develop the capability to evaluate a broad range of capture technologies to facilitate scaleup of cost-effective technologies through testing of processes for pre-combustion CO_2 capture, post-combustion CO_2 capture, and oxy-combustion.
2012.01.06	National Energy Technology Laboratory	ORD Carbon Capture Field Work Proposal—Task 6: Post-Combustion Sorbents	2	Develop technologies to capture 90% of the CO_2 produced by an existing coal-fired power plant with less than a 10% increase in to the COE by improving sorbent CO_2 working capacity and hydrophobicity, decreasing heat capacity, and increasing chemical and mechanical stability.

Table 7: Post-Combustion Capture Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—Membranes				
FE0004278	American Air Liquide, Inc.	CO_2 Capture by Subambient Membrane Operation	4	Develop a capture system using subambient temperature with a commercial hollow-fiber membrane to evaluate cost and performance impacts of a hybrid capture approach via bench-scale testing that demonstrates high selectivity/permeance and mechanical integrity and long-term operability at low temperatures.
FE0004787	Gas Technology Institute	Hybrid Membrane/Absorption Process for Post-Combustion CO_2 Capture	3	Develop a hybrid capture technology that combines solvent absorption and a hollow-fiber membrane to leverage capture cost and performance advantages of two different capture technologies through bench-scale testing on synthetic and actual flue gas to evaluate mass transfer and regeneration.
FE0007514	General Electric Company	High-Performance Thin-Film Composite-Hollow-Fiber Membranes for Post-Combustion Carbon Dioxide Capture	3	Develop high-performance thin-film polymer-composite hollow-fiber membranes to improve system performance via bench-scale testing to tune the properties of a novel phosphazene polymer and decrease costs through development of innovative fabrication techniques.
FE0007632	The Ohio State University Research Foundation	Novel Inorganic/Polymer Composite Membranes for CO_2 Capture	3	Develop a design and manufacturing process for new membranes to improve system performance through bench-scale testing of a membrane with a thin selective inorganic layer embedded in a polymer structure and decrease costs through development of a continuous manufacturing process.
FE0007531	William Marsh Rice University	Combined Pressure, Temperature Contrast, and Surfaced-Enhanced Separation of CO_2 for Post-Combustion Capture	3	Develop a novel gas absorption process to improve capture cost and efficiency through bench-scale testing of a combined absorber/stripper with a very high-surface-area ceramic foam gas-liquid contactor with basic and acidic functional groups for enhanced mass transfer.
FE0007553	Membrane Technology and Research, Inc.	Low-Pressure Membrane Contactors for Carbon Dioxide Capture	3	Develop a new type of membrane contactor (or mega-module) to decrease capture costs, energy use, and system footprint through bench-scale testing of a module with a membrane area that is 500 square meters, 20–25 times larger than that of current modules used for CO_2 capture.
FE0007634	FuelCell Energy, Inc.	Electrochemical Membrane for Carbon Dioxide Capture and Power Generation	3	Demonstrate the ability of an electrochemical membrane-based system (molten carbonate fuel cell) to simultaneously capture CO_2 and deliver additional electricity to the grid through bench-scale testing of an 11.7 m^2-area electrochemical membrane system for CO_2 capture, purification, and compression.
FE0005795	Membrane Technology and Research, Inc.	Pilot Testing of a Membrane System for Post-Combustion CO_2 Capture	5	Scaleup a high-permeance membrane and process design to determine parameters for further scaleup and demonstration of the membrane-based system through small pilot-scale testing of a 1-MW equivalent capacity membrane skid at the National Carbon Capture Center.
12036	Idaho National Laboratory	Bench-Scale High-Performance Thin-Film-Composite Hollow-Fiber Membranes for Post-Combustion Carbon Dioxide Capture	3	Develop high-performance thin film polymer composite hollow-fiber membranes to improve system performance via bench-scale testing to tune the properties of a novel phosphazene polymer and decrease costs through development of innovative fabrication techniques.
2012.01.07	National Energy Technology Laboratory	ORD Carbon Capture Field Work Proposal—Task 7: Post-Combustion Membranes	2	Develop technologies to capture 90% of the CO_2 produced by an existing coal-fired power plant with less than a 10% increase in to the COE by increasing membrane selectivity and permeability, as well as overcoming the low-partial-pressure driving force for CO_2 associated with the process.
2012.01.08	National Energy Technology Laboratory	ORD Carbon Capture Field Work Proposal—Task 8: Oxygen Production	2	Develop technologies that overcome the energy penalties associated with conventional cryogenic separation and emerging ion-transport membrane (ITM) technologies and focusing on the development of novel approaches that yield high-purity oxygen.

CARBON CAPTURE

PRE-COMBUSTION CAPTURE

OVERVIEW

Pre-combustion capture is applicable to IGCC plants, where coal is converted into syngas (a mixture of H_2 and carbon monoxide) by applying heat under pressure in the presence of steam and a limited amount of oxygen (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.

DOE/FE Goals

The DOE/FE goals for the Pre-Combustion Capture Technology Area are to achieve at least 90 percent CO_2 capture at costs that represent less than a 10 percent increase in the total COE for IGCC power plants compared to those same plants without carbon capture and storage.

Benefits

FE estimates that current state-of-the-art pre-combustion CO_2 capture technology on a new IGCC power plant would increase the COE by approximately 40 percent and derate plant net generating capacity by as much as 20 percent. New cost-effective pre-combustion capture technologies therefore are critical components of IGCC power production, which can contribute to the long-term viability of coal-fired power generation. Cost-effective pre-combustion capture technologies will enhance the ability of the United States to use low-cost domestic coal supplies in a carbon-constrained fuels market.

Critical Technology Area Challenges

Physical solvent-based technologies are currently being used in industrial applications for pre-combustion CO_2 capture. However, these solvent-based processes have several disadvantages, including loss of pressure during regeneration and requirement of a low operating temperature, thus requiring cooling of the syngas prior to CO_2 absorption, followed by reheating to the gas turbine inlet temperature.

Critical technology challenges related to pre-combustion capture include improving the performance and cost of capture materials (solvents, sorbents, and membranes), decreasing parasitic loads, scaleup to industrial scale, and reducing the impacts of syngas contaminants on the CO_2 capture process.

Technology Readiness Assessment—Key Technologies

The Pre-Combustion Capture Technology Area, supported by the Clean Coal Research Program, is organized into the three portfolios of key technologies depicted in Figure 7.

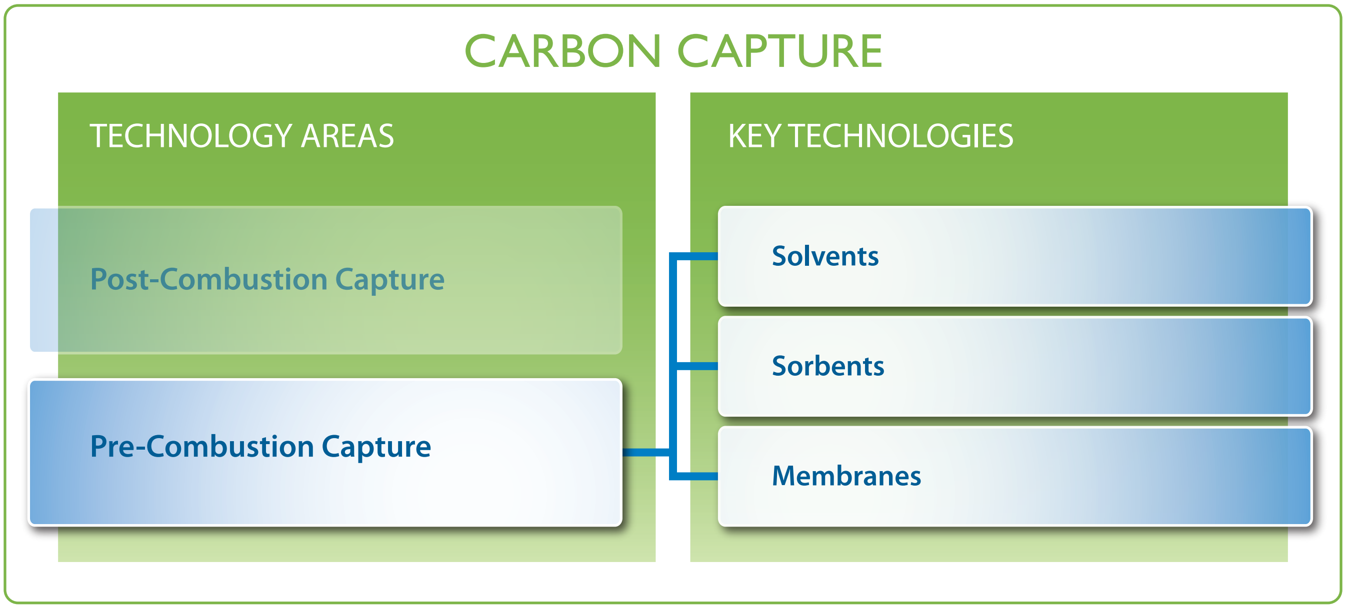


Figure 7: Pre-Combustion Capture Key Technologies

Projects Assessed

Technology readiness has been assessed based on a review of individual research projects currently underway in each key technology. FE has considerable research underway to improve pre-combustion capture in the three key technologies:

- Solvents
- Sorbents
- Membranes

Twelve projects were assessed in the Pre-Combustion Capture Technology Area: two in Solvents, four in Sorbents, and six 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.

The results of the assessment of the scoring analysis are shown in Table 8, which also presents relevancy statements documenting the expected contribution of each project to program goals.

TECHNOLOGY AREA—QUALITATIVE SUMMARY OF TECHNOLOGY READINESS LEVEL

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 4.

KEY TECHNOLOGIES—TECHNOLOGY READINESS ASSESSMENT

Key Technology—Solvents

Pre-combustion solvent-based CO_2 capture involves chemical or physical absorption of CO_2 from flue gas into a liquid carrier. 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 a high CO_2 loading at a higher temperature to improve IGCC efficiency.

Two projects within the CCRP Pre-Combustion Capture portfolio met the scoring criteria of the TRA and focus on improving solvent-based CO_2 capture. The current TRLs for this technology are 2 and 4.

Key Technology—Sorbents

Solid sorbents—including sodium and potassium oxides, zeolites, carbonates, amine-enriched sorbents, and metal organic frameworks—are also 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.

Four projects within the CCRP Pre-Combustion Capture portfolio focus on improving sorbent-based capture. The current TRLs of this key technology span a range of 2–4, consistent with the status of the individual technologies embedded within these projects.

Key Technology—Membranes

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. 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.

There are several technical barriers that must still be overcome to reduce the cost and improve the performance of membrane systems. 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. Six projects within the current CCRP Pre-Combustion Capture portfolio focus on improving membrane-based capture. The current TRLs of this key technology span a range of 2–4 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

PORTFOLIO OF PRE-COMBUSTION CAPTURE PROJECTS

The composite results of the technology readiness assessment for the Pre-Combustion Capture Technology Area are presented in the following table.

Table 8: Pre-Combustion Capture Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—Solvents				
FE0000896	SRI International	CO_2 Capture from Integrated Gasification Combined Cycle Gas Streams Using the Ammonium Carbonate-Ammonium Bicarbonate Process	4	Develop a technology using a high-capacity, low-cost aqueous ammoniated solvent to meet cost and performance goals through bench-scale proof-of-concept testing followed by small pilot-scale testing using a slipstream of coal-derived syngas.
2012.01.02	National Energy Technology Laboratory	ORD Carbon Capture Field Work Proposal—Task 2: Pre-Combustion Solvents	2	Develop technologies with a pre-combustion programmatic goal to capture 90% of the CO_2 produced by an existing coal-fired power plant with less than a 10% increase in to the COE as a critical step in reducing greenhouse gas emissions from fossil fuel-based processes by developing solvents with increased CO_2 working capacity and hydrophobicity to prevent the absorption of water and promote CO_2 capture at temperatures consistent with those of gas cleanup technology.
Key Technology—Sorbents				
FE0000469	TDA Research, Inc.	A Low-Cost, High Capacity Regenerable Sorbent for Pre-Combustion CO_2 Capture	4	Develop a low-cost, high-capacity sorbent to demonstrate its technical and economic viability by optimizing chemical/physical properties, scaling up production, and conducting long-term testing with simulated syngas containing contaminants and eventually with actual syngas.
FE0000465	URS Group, Inc.	Evaluation of Dry Sorbent Technology for Pre-Combustion CO_2 Capture	3	Develop high-temperature/pressure/loading capacity sorbents that combine the water-gas-shift reaction with CO_2 removal to minimize energy efficiency impacts by combining process simulation modeling and bench-scale sorbent molecular and thermodynamic analyses.
FE0001323	New Jersey Institute of Technology	Pressure Swing Absorption Device and Process for Separating CO_2 from Shifted Syngas and Its Capture for Subsequent Storage	3	Develop a cyclic pressure-swing-adsorption-based process that produces purified hydrogen at high pressure and a highly purified CO_2 stream to enable economic evaluation for potential larger scale use through process/equipment development/testing and data analysis to facilitate scaleup.
2012.01.03	National Energy Technology Laboratory	ORD Carbon Capture Field Work Proposal—Task 3: Pre-Combustion Sorbents	2	Develop technologies to capture 90% of the CO_2 produced by an existing coal-fired power plant with less than a 10% increase in the COE as a critical step in reducing greenhouse gas emissions from fossil fuel-based processes by developing sorbents with improved CO_2 working capacity, increased hydrophobicity, low heat capacity, and increased chemical and mechanical stability at elevated temperatures consistent with those of gas cleaning technologies.
Key Technology—Membranes				
FE-10-002	Los Alamos National Laboratory	High-Temperature Polymer-Based Membrane Systems for Pre-Combustion CO_2 Capture	3	Develop a polymer membrane technology that operates over a broad range of conditions to improve capture cost and performance through bench-scale testing of multiple structures, deployment platforms, and sealing technologies with high selectivity/permeability and chemical/mechanical stability.
FE0001322	University of Minnesota	Hydrogen Selective Exfoliated Zeolite Membranes	3	Develop a silica molecular-sieve membrane to decrease capture system costs by lowering fabrication costs and enhancing long-term stability through hydrothermal stability tests of exfoliated silicate powders and bench-scale membrane testing under shifted syngas conditions with simulated feed.
FE0001181	Pall Corporation	Designing and Validating Ternary Pd Alloys for Optimum Sulfur/Carbon Resistance	3	Develop an optimized Pd alloy that is tolerant to contaminants while retaining high hydrogen flux and selectivity to decrease costs and facilitate warm gas cleaning by employing a combinatorial material design approach for rapid, high-throughput screening of ternary alloys.
FE0000470	Arizona State University	Pre-Combustion Carbon Dioxide Capture by a New Dual-Phase Ceramic Carbonate by a New Dual-Phase Ceramic Carbonate Membrane Reactor	4	Develop a dual-phase ceramic-carbonate membrane to enable a one-step process for combined water-gas-shift/CO_2 separation with the potential to lower capture costs by synthesizing stable, high-permeance/selectivity membranes and fabricating tubular membranes/modules.

Table 8: Pre-Combustion Capture Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
FE0000646	Gas Technology Institute	Pre-Combustion Carbon Capture by a Nanoporous, Superhydrophobic Membrane Contactor Process	4	Develop a gas/liquid membrane contactor concept to evaluate potential cost savings through laboratory and bench testing using pure gases, a simulated water-gas-shifted syngas stream, and a slipstream from a gasification-derived syngas.
2012.01.04	National Energy Technology Laboratory	ORD Carbon Capture Field Work Proposal—Task 4: Pre-Combustion Membranes	2	Develop technologies to capture 90% of the CO_2 produced by an existing coal-fired power plant with less than a 10% increase in the COE as a critical step in reducing greenhouse gas emissions from fossil fuel-based processes by developing membranes with increased permeability and selectivity toward CO_2 as well as increased mechanical stability and performance at high temperatures and pressures.

CARBON STORAGE

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

- Store large volumes of CO_2 in different classes of deep geologic formations that provide the field experience to develop and validate technologies that will support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
- Develop and validate technologies to measure and account for 99 percent of injected CO_2 in the injection zones.
- Develop technologies to improve reservoir storage efficiency while assuring containment effectiveness.
- Develop Best Practice Manuals for site selection, characterization, site operations, and closure practices.

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 site development, reservoir engineering, monitoring, well construction, and operations. Many of these technologies are applicable to storage with and without enhanced hydrocarbon recovery.

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 *Regional Carbon Sequestration Partnerships*, all of which are addressing the critical challenges associated with geologic storage. These four Technology Areas sponsor early applied research at laboratory scale, validate promising technologies at pilot scale, and support large-scale, large-volume injection field projects at precommercial 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. The Regional Carbon Sequestration Partnerships and other small- and large-volume field tests, where validation of various CCUS technology options and their efficacy are being confirmed, represent the development of the infrastructure necessary for the deployment of CCUS.

CARBON STORAGE

GEOLOGIC STORAGE TECHNOLOGIES AND SIMULATION AND RISK ASSESSMENT

OVERVIEW

DOE's Geologic Storage Technologies and Simulation and Risk Assessment (GS_RA) 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.

DOE/FE Goals

The DOE/FE goals for the GS_RA Technology Area are to (1) develop capabilities to quantify storage capacity within ±30 percent accuracy and (2) support development of protocols to account for greater than 99 percent of all injected CO_2.

Benefits

Results of GS_RA 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. GS_RA tools and techniques will improve injection operations and reservoir storage efficiency, and will assure permanent storage at lower cost. GS_RA methods also provide the capabilities to assess and mitigate any potential releases.

Critical Technology Area Challenges

Critical technology challenges related to GS_RA include improving material and construction techniques to ensure long-term integrity of wellbores exposed to CO_2, and mitigation techniques for existing wellbores; improvement of field methods to optimize storage capacity and ensure containment; and enhanced simulation tools to improve predictions and enhance performance of geologic storage.

Technology Readiness Assessment—Key Technologies

The GS_RA Technology Area, supported by the Clean Coal Research Program, is organized into the six key technologies depicted in Figure 8.

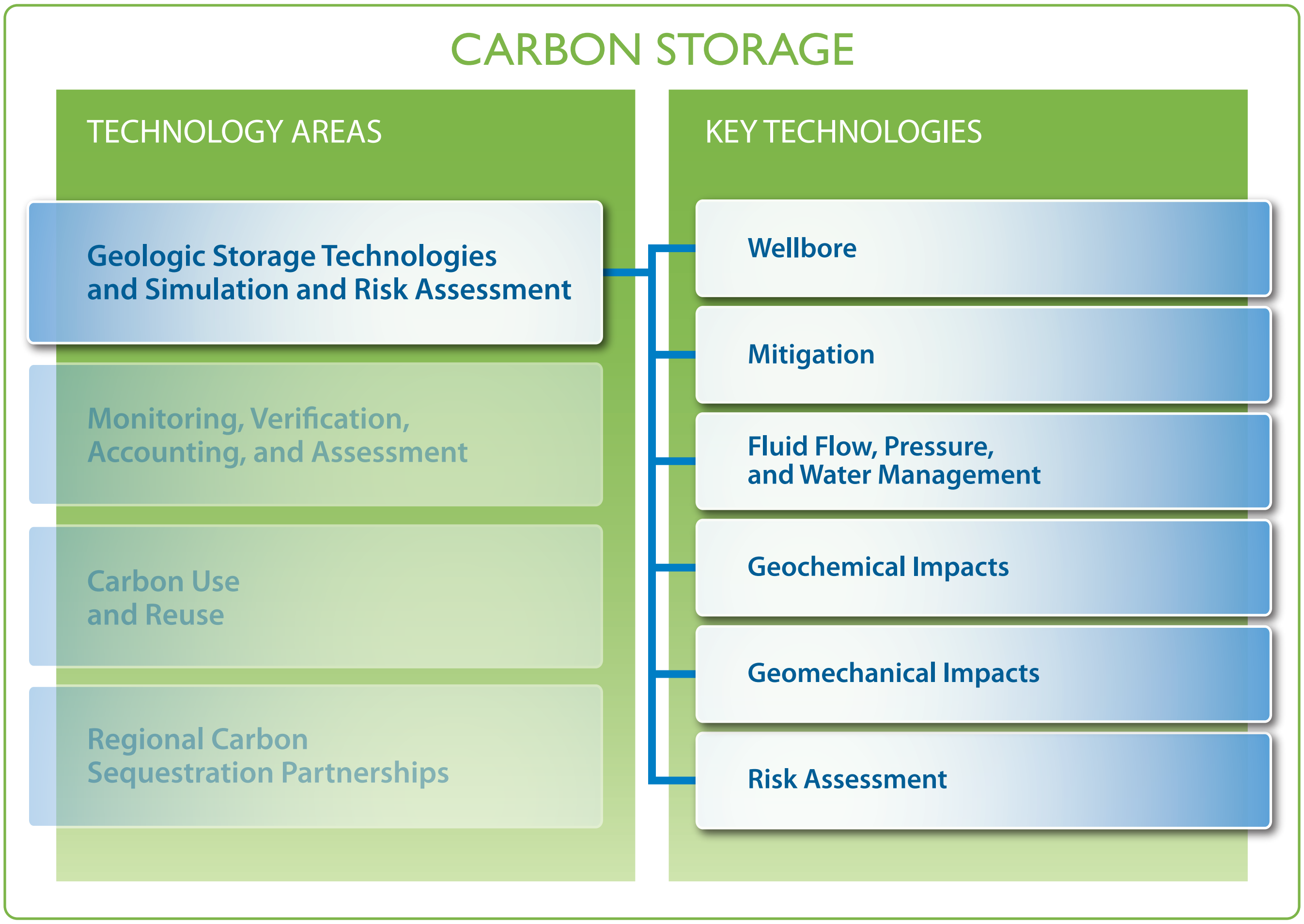


Figure 8: Geologic Storage Technologies and Simulation and Risk Assessment Key Technologies

Projects Assessed

Technology readiness has been assessed based on a review of the individual research projects currently underway in each of the six key technologies:

- Wellbore
- Mitigation
- Fluid Flow, Pressure, and Water Management
- Geochemical Impacts
- Geomechanical Impacts
- Risk Assessment

The Technology Readiness Levels of 35 projects were assessed in the GS_RA Technology Area: 1 in Wellbore; 2 in Mitigation; 15 in Fluid Flow, Pressure, and Water Management; 5 in Geochemical Impacts; 9 in Geomechanical Impacts, and 3 in Risk Assessment. In addition, the Crosscutting Research subprogram is sponsoring a research effort related to overcoming barrier science and technology issues associated with the development of GS_RA technology. 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.

The results of the assessment of the scoring analysis are shown in Table 9, which also presents relevancy statements documenting the expected contribution of each project to program goals.

TECHNOLOGY AREA—QUALITATIVE SUMMARY OF TECHNOLOGY READINESS LEVEL

The critical technology challenges related to GS_RA require development of a portfolio of technologies encompassing six key technologies. The ongoing research associated with this body of work comprises a diverse collection of technologies, and the overall readiness of the GS_RA technology is represented by the status of the individual projects evaluated in the portfolio, which have TRL values ranging from 3 to 6.

KEY TECHNOLOGIES—TECHNOLOGY READINESS ASSESSMENT

Key Technology—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 and the efficient use of the reservoir storage space.

One project within the CCRP GS_RA portfolio focused on improving wellbore technologies was assessed. Consistent with the status of this project, the current TRL of this key technology is 3.

Key Technology—Mitigation

Permanent CO_2 storage relies on the presence of a competent geologic seal 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.

Two projects within the CCRP GS_RA portfolio focused on improving mitigation technologies were assessed. The current TRLs of these two projects are 3 and 4.

Key Technology—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 and causes increases in water pressure. In some circumstances, removal of water may be required to keep pressures within operational limits.

Fifteen projects within the CCRP GS_RA portfolio focused on improving fluid flow, pressure, and water management technologies were assessed. The current TRL of this key technology spans a range of 3–6 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

Key Technology—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.

Five projects within the CCRP GS_RA portfolio aimed at improving capabilities to assess geochemical impacts were assessed. The current TRL of this key technology is a 3 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

Key Technology—Geomechanical Impacts

Injection of CO_2 will occur at pressures above the existing reservoir pressure and the pressure increase will cause the rock to deform or move slightly 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.

Nine projects within the CCRP GS_RA portfolio aimed at improving capabilities to assess geomechanical impacts were assessed. The current TRLs of these projects are 3 and 4 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

Key Technology—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 CCRP GS_RA 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.

PORTFOLIO OF GS_RA PROJECTS

The composite results of the technology readiness assessment for the GS_RA Technology Area are presented in the table below.

Table 9: Geologic Storage Technologies and Simulation and Risk Assessment Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—Wellbore				
DE-FE0004542	Clemson University	Proof of Feasibility of Using Wellbore Deformation as a Diagnostic Tool to Improve CO_2 Sequestration	3	Evaluate the feasibility of using wellbore deformations as a diagnostic tool to detect and assess changes in geologic formations due to CO_2 storage and improve the efficiency and safety of CO_2 sequestration by identifying data correlations and developing evaluation techniques from field data.
Key Technology—Mitigation				
DE-FE0004478	Montana State University	Advanced CO_2 Leakage Mitigation Using Engineered Biomineralization Sealing Technologies	4	Develop a biomineralization-based technology to seal flow or leakage pathways near wellbores to maximize injectivity and the effectiveness of CO_2 storage by conducting meso-scale lab experiments on various rock types under actual field conditions.
DE-FE0001132	Missouri University of Science and Technology	Geomechanical Simulation of CO_2 Leakage and Caprock Remediation	3	Develop a new approach to simulate caprock leakage and remediation at a shallow CO_2 injection site to improve leakage detection, CO_2 containment through coupled reservoir and multiscale geomechanical modeling of caprock leakage risk, and experimental remediation studies.
Key Technology—Fluid Flow, Pressure, and Water Management				
DE-FE0001034	Battelle Memorial Institute	Simulation Framework for Regional Geologic CO_2 Storage Infrastructure Along Arches Province	4	Develop an advanced simulation framework to evaluate regional geologic storage deployment in the Arches province for optimal CO_2 storage by using Midwest Regional Carbon Sequestration Partnership field data in basin-scale coupled simulations to determine infrastructure needed for large-scale CO_2 storage.
DE-FE0000988	Colorado School of Mines	Simulation of Coupled Processes of Flow, Transport, and Storage of CO_2 in Saline Aquifers	3	Develop a comprehensive tool to assess geologic CO_2 storage to cost-effectively evaluate its long-term performance and risks by modeling nonisothermal multiphase flow and the effects of geochemical and geomechanical processes.
DE-FE0004381	Indiana University	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	Assess and reduce uncertainties in model predictions of CO_2 plume migration and trapping modes to enhance understanding of CO_2 containment and storage by reservoir-scale multiphase flow and reactive-mass-transport modeling calibrated using 4D seismic data.

Table 9: Geologic Storage Technologies and Simulation and Risk Assessment Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
DE-FE0001161	New Mexico Institute of Mining and Technology	Analytical-Numerical Sharp-Interface Model of CO_2 Sequestration and Application to Illinois Basin	3	Evaluate the seismic and environmental consequences of large-scale CO_2 injection in sedimentary basins to achieve safe, commercial geologic CO_2 storage by developing a basin-scale model of the injection formation and overlying aquifers using existing data sets.
DE-FE0004962	University of Texas at Austin	Inexpensive Monitoring and Uncertainty Assessment of CO_2 Plume Migration	3	Develop a prototype modular computational approach to inexpensively model and monitor CO_2 plumes during injection for cost-effective, safe geologic CO_2 storage by using injection data to model plume location, and validate models using synthetic and field data sets.
DE-FE0004630	Colorado School of Mines	Validation of Models Simulating Capillary and Dissolution Trapping	3	Develop a new understanding of the effects of reservoir heterogeneity on trapping mechanisms to improve CO_2 storage capacity of geologic reservoirs by conducting intermediate-scale laboratory experiments and using the results to update storage modeling codes.
DE-FE0000749	Princeton University	Basin-Scale Leakage Risks from Geologic Carbon Sequestration: Impact on CCS Energy Market Competiveness	3	Integrate the commercial potential of geologic CO_2 storage with subsurface liabilities for safe, cost-effective large-scale storage by quantifying basin-scale leakage risk, impacts on subsurface resources, and modeling geochemical reactions leading to wellbore/caprock leakage.
DE-FE0004566	University of Kansas	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	Develop new volumetric curvature tool to delineate subtle structural features for cost-effective geologic CO_2 storage by using well drilling data from a deep saline carbonate aquifer to verify the tool and update model predictions of CO_2 flow and containment.
FC26-01NT41148	CONSOL Energy, Inc.	Enhanced Coalbed Methane Production and Sequestration of CO_2 in Unmineable Coal Seams	6	Provide an understanding of the enhancement of coalbed methane production and geologic injection limitations to achieve safe, commercial geologic CO_2 storage by developing models and sensitivity analyses of the effect of reservoir parameters on methane production and CO_2 injection.
FEW0174	Lawrence Livermore National Laboratory	Advancing the State of Geologic Sequestration Technologies Toward Commercialization—Task 1: Fresh Water Generation from Aquifer-Pressured Carbon Storage	3	Assess the technical and economic impact of brine regeneration through Active CO_2 Reservoir Management to minimize formation-pressure buildup and increase reservoir storage capacity by analyzing various methods of freshwater recovery.
DE-FE0004832	University of Wyoming	Maximization of Permanent Trapping of CO_2 and Co-Contaminants in the Highest Porosity Formations of the Rock Springs Uplift	3	Improve our understanding of mixed supercritical CO_2 storage in the Rock Springs Uplift to determine the technical and economical feasibility of CO_2 injection in the target formation by developing a dynamic model for the region.
FWP-58159	Pacific Northwest National Laboratory	Capture and Sequestration Systems Support—Task 1: Sequestration in Basalt Formations	4	Determine commercial-scale injection strategies, CO_2 fate and transport, and characterization methods for basalt to provide a path forward for commercial use of basalt formations for CO_2 storage by continued analysis of basalt formations and development of novel characterization techniques.
FWP ESD09-056	Lawrence Berkeley National Laboratory	Consolidated Sequestration Project—Task 5: Large Scale Hydrological Impacts of CO_2 Geologic Storage	3	Continued evaluation of large-scale hydrological and environmental impacts of geologic carbon storage to better understand brine pressurization and migration of CO_2 flow by developing a high-performance regional-scale simulation model for a multisite project in the Basal Aquifer in the Northern Plains.
FWP ESD09-056	Lawrence Berkeley National Laboratory	Consolidated Sequestration Project—Task 4: Sim-SEQ	3	Evaluate and compare different field test models and measurements by applying them to one specific field test site (SECARB Cranfield Phase III Site) and further identify improvements and document lessons learned to improve future modeling efforts.
2012.02.00	National Energy Technology Laboratory	NETL Carbon Storage Field Work Proposal—Task 4: Estimates of Storage Potential	3	Refine existing and develop new EOR and CO_2 storage-capacity-assessment methodologies to improve storage predictive accuracy to $\pm 30\%$ through incorporation of reservoir properties and storage efficiency uncertainties in field case studies and production datasets.

Table 9: Geologic Storage Technologies and Simulation and Risk Assessment Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—Geochemical Impacts				
DE-FE0004510	Fusion Petroleum Technologies, Inc.	Experimental Design Applications for Modeling and Assessing Carbon Dioxide Sequestration in Saline Aquifers	3	Evaluate various factors (e.g., heterogeneity, reactions, faults, seal integrity) affecting the characterization, design, and operation of saline aquifer storage sites for more cost-effective CO_2 storage using modeling (uncertainty analyses and response surface methods).
FE-10-001	Los Alamos National Laboratory	LANL Sequestration Activities, Field Work Proposal—Task 1: CO_2-Water-Rock Interactions and the Integrity of Hydrodynamic Seals	3	Develop a basic understanding of the effects of CO_2-water interactions on wellbore integrity to improve the containment of injected CO_2 by field studies from analog sites and experiments, and use these results to develop a numerical model for wellbore performance risk assessment.
FEW0174	Lawrence Livermore National Laboratory	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	3	Develop an understanding of the role of heterogeneity in carbonate reservoirs to transition CO_2-EOR operations to storage sites and to improve CO_2 storage capacity by using coupled simulations and experimental studies of the effects on heterogeneity on dissolution.
FWP-58159	Pacific Northwest National Laboratory	Capture and Sequestration Systems Support—Task 2: Cosequestration	3	Develop cosequestration methods and technologies capable of storing CO_2 and minor contaminants in subsurface formations supporting the commercialization of carbon storage at near-zero cost by identifying associated R&D needs and developing low-cost technologies and multicomponent gas analysis tools.
2012.02.00	National Energy Technology Laboratory	NETL Carbon Storage Field Work Proposal—Task 3: Fundamental Processes and Properties	3	Validate laboratory determination of CO_2 reaction kinetics and fluid properties to improve prediction of fluid behavior and evaluation of CO_2 storage sinks through studies of variance in kinetic data for mineral dissolution reactions at relevant in-situ pressure and temperature conditions.
Key Technology—Geomechanical Impacts				
FE-10-001	Los Alamos National Laboratory	LANL Sequestration Activities, Field Work Proposal—Task 3: Systems Model Development and Science for Geologic CO_2 Sequestration	4	Investigate water generation during injection and CO_2 migration in overlying formations to improve CO_2 storage and containment of reservoirs by developing system-level models for brine production and treatment and by experimental and modeling studies of CO_2 flow in shallow aquifers.
DE-FE0000730	Colorado School of Mines	CO_2 Saline Storage Demonstration in Colorado Sedimentary Basins: Applied Studies in Reservoir Assessment and Dynamic Processes Affecting Industrial Operations	3	Address applied issues in reservoir characterization and large-scale CO_2 injection in deep saline aquifers to develop guidelines to minimize the risk of commercial CO_2 storage by using theory, modeling, and lab and field studies linking chemistry, geomechanics, and microbiology.
DE-FE0004844	New Mexico Institute of Mining and Technology	Nature and Dynamics of the Reservoir/Caprock Contact and Implications for Carbon Storage Performance	3	Analyze and assess the caprock/storage formation interface for more effective CO_2 containment by developing coupled modeling of the leakage of fluids across mudrock/sandstone interfaces using data from outcrop analogs and core samples
DE-FE0004375	Yale University	Integrated Experimental and Modeling Studies of Mineral Carbonation as a Mechanism for Permanent Carbon Storage in Mafic/Ultramafic Rocks	3	Assess the potential of carbon sequestration into mafic and ultramafic rocks via in-situ carbonate mineralization to determine their technical and economical feasibility for CO_2 storage through geochemical and geomechanical testing and modeling.
DE-FE0004956	University of Texas at Austin	Influence of Local Capillary Trapping on Containment System Effectiveness	3	Develop a method to identify and quantify the extent of capillary trapping of CO_2 in heterogeneous geologic storage formations to better locate trapping systems and reduce risks associated with long-term CO_2 storage by performing laboratory experiments and testing improved numerical simulations.
DE-FE0001560	Advanced Resources International	The Coal-Seq III Consortium: Advancing the Science of CO_2 Sequestration in Coal Seam and Gas Shale Reservoirs	3	Verify and validate CO_2 storage mechanisms in coal reservoirs to advance the potential application of carbon sequestration in coal seams by developing and testing three advanced geochemical and geomechanical modules.

Table 9: Geologic Storage Technologies and Simulation and Risk Assessment Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
DE-FE0004633	Advanced Resources International, Inc.	Assessment of Factors Influencing Effective CO_2 Storage Capacity and Injectivity in Eastern Gas Shales	3	Assess factors influencing effective CO_2 storage capacity and injectivity in organic shale formations to better understand CO_2 trapping mechanisms, storage permanence, and capacity estimates in gas shales by developing and validating improved shale-formation models and monitoring techniques.
DE-FE0004731	Stanford University	Interdisciplinary Investigation of the CO_2 Sequestration in Depleted Shale Gas Formations	3	Examine the physical and chemical processes associated with CO_2 storage in organic-rich shales to determine the feasibility of geologic CO_2 sequestration in depleted shale gas reservoirs by conducting a series of multiscale, multiphysics, interdisciplinary laboratory, and theoretical studies.
2012.02.00	National Energy Technology Laboratory	NETL Carbon Storage Field Work Proposal—Task 2: Flow Properties of Reservoirs and Seals	3	Identify impacts of CO_2 injection on storage capacity, injectivity, and permanence to improve storage potential assessments and predictions of subsurface behavior through laboratory and numerical studies of CO_2-brine-rock interactions and physical property alteration.
Key Technology—Risk Assessment				
DE-FE0001112	Headwaters Clean Carbon Services LLC	Comprehensive, Quantitative Risk Assessment	3	Develop and apply a novel process-based risk-assessment tool integrated with various inputs to improve understanding of geologic CO_2 containment by using a failure mode effects and analysis-based approach to quantify and predict site-specific risk impacts.
DE-FE0001164	GoldSim Technology Group	Development of a Software Framework for System-Level Carbon Sequestration Risk Assessment	3	Extend a probabilistic simulation framework to better simulate risk in geologic CO_2 storage projects to improve confidence in risk assessment and CO_2 containment by developing comprehensive, integrated system-level risk assessments.
DE-FE0001563	University of Texas at Austin	Developing a Comprehensive Risk-Assessment Framework for Geological Storage of CO_2	3	Quantitatively analyze business and technical risks due to CO_2 geologic storage in deep saline aquifers to understand and mitigate CO_2 containment risks by using statistical techniques, expert inputs, and by developing inexpensive, non-proprietary mathematical risk models.

CARBON STORAGE

MONITORING, VERIFICATION, ACCOUNTING, AND ASSESSMENT

OVERVIEW

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 in conjunction with verification and accounting protocols to provide a high level of confidence that injected CO_2 remains permanently stored in geologic storage formations.

DOE/FE Goals

The DOE/FE goals for the MVA Technology Area are to (1) achieve a level of accountability such that greater than 99 percent of injected CO_2 can be credited and contribute to the economic viability of a storage project and (2) improve a project developer's ability to more confidently quantify storage capacity.

Benefits

MVA capabilities will be critical to ensuring the long-term viability of carbon capture and storage—satisfying both technical and regulatory requirements. MVA tools and protocols also provide the capabilities to support CO_2 credit trading, should a domestic program be established. An additional benefit of the research efforts will be to reduce MVA costs.

Critical Technology Area Challenges

Critical technology challenges related to MVA include improving the ability of techniques to quantitatively measure the amount of CO_2 as a function of location in the subsurface as well as any possible releases; developing robust, flexible accounting protocols for diverse geologic settings; and reducing the cost of near- and long-term monitoring.

Technology Readiness Assessment—Key Technologies

The MVA Technology Area, supported by the Clean Coal Research Program, is organized into the four portfolios of key technologies depicted in Figure 9.

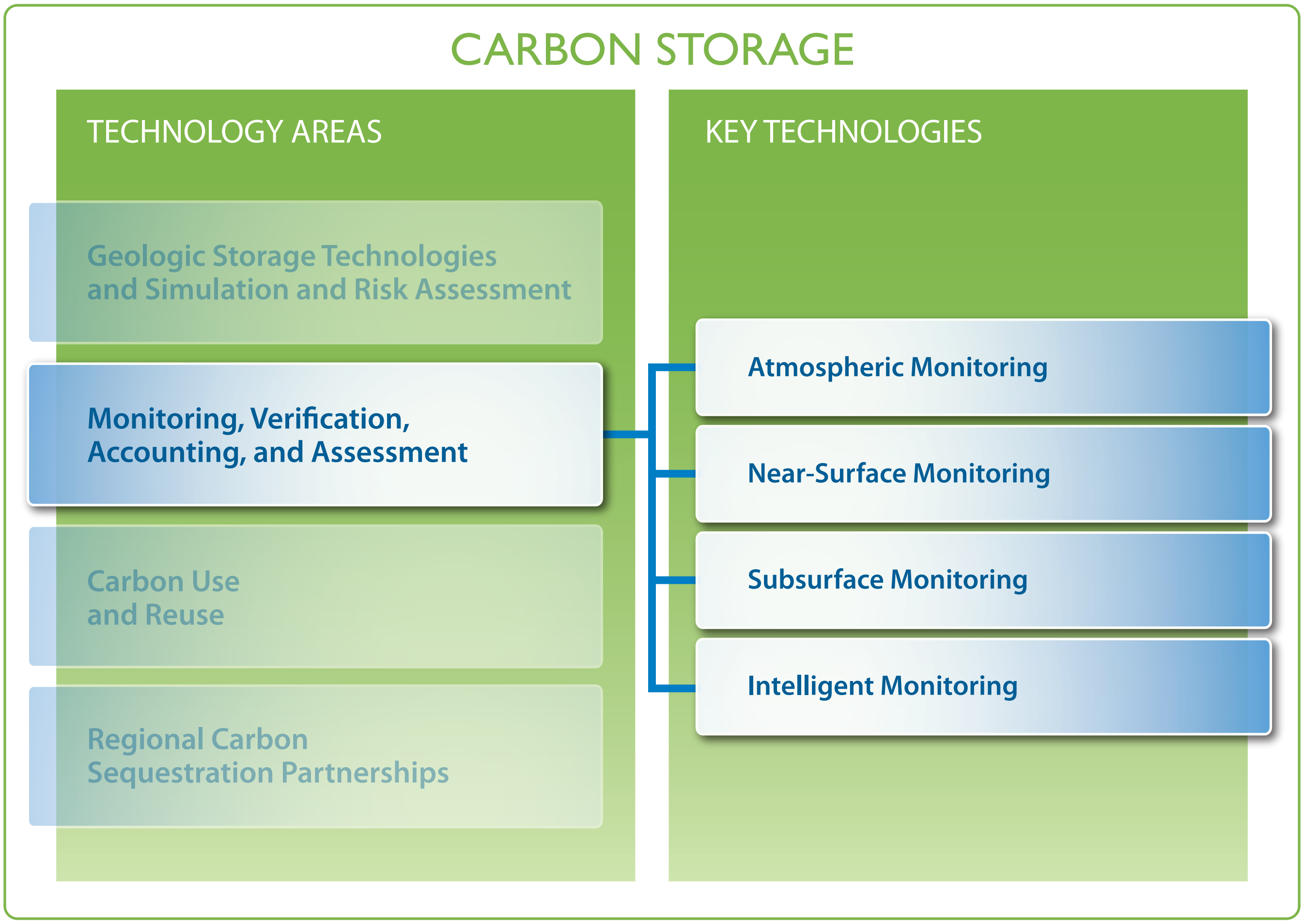


Figure 9: Monitoring, Verification, Accounting, and Assessment Key Technologies

Projects Assessed

Technology readiness has been assessed based on a review of individual research projects currently underway in each key technology. FE has considerable research underway to improve various MVA techniques in the four key technologies:

- Atmospheric Monitoring
- Near-Surface Monitoring
- Subsurface Monitoring
- Intelligent Monitoring

The TRLs of 18 projects were assessed in the MVA Technology Area: 2 in Atmospheric Monitoring, 3 in Near-Surface Monitoring, 11 in Subsurface Monitoring, and 2 in Intelligent Monitoring. In addition, the Crosscutting Research subprogram is sponsoring a research effort related to overcoming barrier science and technology issues associated with the development of MVA technology (discussed in the Crosscutting Research subprogram section). 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.

One reason for the large number of projects in the Subsurface Monitoring key technology is the need for improved technologies around the wellbore, near the wellbore, and across the entire storage field. In addition, a variety of technologies will likely be required to effectively track plume migration in different storage formations that vary considerably. FE has identified 11 different storage formations that need to have solutions for monitoring CO_2.

The results of the assessment of the scoring analysis are shown in Table 10, which also presents relevancy statements documenting the expected contribution of each project to program goals.

TECHNOLOGY AREA—QUALITATIVE SUMMARY OF TECHNOLOGY READINESS LEVEL

The critical technology challenges related to MVA require development of a portfolio of technologies encompassing the four key technologies. The ongoing research associated with this body of work comprises a diverse collection of technologies with individual technologies at different levels of development. The overall readiness of the MVA technology emerges as a range of TRL values from 3 to 5.

KEY TECHNOLOGIES—TECHNOLOGY READINESS ASSESSMENT

Key Technology—Atmospheric Monitoring

Above-ground (atmospheric) CO_2 monitoring provides assurance that there are no leaks that would pose a risk to the environment or the population, or loss of stored CO_2 to the atmosphere. 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.

Two projects within the CCRP MVA portfolio that focus on improving atmospheric monitoring technologies were assessed. The current TRL of this key technology is 5, consistent with the status of the two individual technologies embedded within these projects.

Key Technology—Near-Surface Monitoring

Near-surface CO_2 monitoring techniques also provide assurance that there are no leaks that would pose a risk to the environment or the population. 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.

Three projects within the CCRP MVA portfolio that focus on improving near-surface monitoring technologies were assessed. The current TRL of this key technology spans a range of 3–5, consistent with the status of the individual technologies embedded within these projects.

Key Technology—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; satellite based measurements such as interferometric synthetic aperture radar (InSAR); and geophysical techniques, including seismic, gravity, and electrical methods.

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.

Seismic geophysical methods have been highly developed for petroleum industry applications and provide the highest resolution of all geophysical methods. The FE portfolio in this area includes four projects that will provide important improvements in seismic methods for application to CO_2 storage.

The FE portfolio includes six projects that are developing nonseismic and geochemical techniques to provide additional information on CO_2 trapping and geochemical reactions. These techniques can also be combined with seismic data to better track the movement of CO_2 in the subsurface.

The FE portfolio contains one project that is using wireline well logging as the basis of a new method to evaluate the risk of wellbore leakage.

In summary, 11 projects within the CCRP MVA portfolio that focus on improving subsurface monitoring technologies were assessed. The current TRLs of this key technology are 3 and 4 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

Key Technology—Intelligent Monitoring

Intelligent monitoring systems are computer-based methods capable of gathering data from various monitoring sources, analyzing and interpreting those data, and then automatically activating process control functions or recommending actions to an operator. Such systems afford the possibility of real-time decision making, which will decrease the risk and increase the cost-effectiveness of CO_2 storage operations. Certain technologies are low-cost but can serve as indicators of release, while others may be deployed only after an event has been identified. Research is needed to develop these intelligent systems that would inform project developers of the capabilities of different MVA technologies and when to apply each.

Two projects within the CCRP MVA portfolio aimed at developing high-confidence intelligent monitoring systems for leak detection was assessed. This key technology has a TRL of 3.

PORTFOLIO OF MVA PROJECTS

The composite results of the technology readiness assessment for the MVA Technology Area are presented in the table below.

Table 10: Monitoring, Verification, Accounting, and Assessment Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—Atmospheric Monitoring				
FE-10-001	Los Alamos National Laboratory	LANL Sequestration Activities, Field Work Proposal—Task 2: Development and Deployment of MVA Tools	5	Advance the state-of-the-science of geological sequestration of CO_2 by developing and field testing remote and noninvasive monitoring tools to quantify CO_2 storage and leakage to assure safe, effective, and long-term geologic sequestration.
DE-FE0001156	Montana State University	Development and Deployment of Eye-Safe Scanning Differential Absorption LIDAR (DIAL) for Spatial Mapping of Carbon Dioxide for MVA at Geologic Sequestration Sites	5	Perform MVA of stored CO_2 over large areas and for extended periods by developing and validating a scanning eye-safe diode laser-based DIAL in order to determine possible CO_2 leakage to the atmosphere at geologic carbon sequestration sites.
Key Technology—Near-Surface Monitoring				
13W0205-AACH133	Brookhaven National Laboratory	In-Field Continuous Noninvasive Soil Carbon Scanning System	5	Develop a novel soil analysis method that surpasses current state-of-the-art chemical analysis through dry combustion by designing and testing a gamma ray spectroscopy soil analysis instrument capable of providing safe, rapid, and nondestructive monitoring of carbon-dioxide seepage from underground reservoirs.
DE-FE0001580	University of Miami	Combining Space Geodesy, Seismology, and Geochemistry for Monitoring, Verification, and Accounting of CO_2 in Sequestration Sites	3	Develop a low-cost methodology for assessing the fate of injected CO_2 by integrating data from space geodesy, seismology, and geochemistry and assessing the cost and efficacy of these procedures to better monitor sequestered CO_2 in deep geologic repositories.
DE-FE0001116	Planetary Emissions Management Inc.	Near-Surface Leakage Monitoring for the Verification and Accounting of Geologic Carbon Sequestration Using a Field-Ready 14C Isotopic Analyzer	5	Develop a high-precision, low-cost method to directly track fossil fuel CO_2 by modifying and field testing a carbon-14 analyzer based on Planetary Emissions Management's multi-isotopic Global Monitor Platform to detect potential leakage of geologically sequestered CO_2.
Key Technology—Subsurface Monitoring				
DE-FE0001159	Stanford University	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	Improve seismic data interpretation for monitoring of CO_2 in the subsurface by developing experimentally based, CO_2-optimized rock-fluid models to ensure that injection fields and abandoned wells are not leaking, and verify the quantity of CO_2 injected.
DE-FE0004522	Paulsson Inc.	Development and Test of a 1,000 Level 3C Fiber-Optic Borehole Seismic Receiver Array Applied to Carbon Sequestration	3	Improve characterization of storage sites and tracking of CO_2 in the subsurface by designing, building, and testing a next-generation downhole seismic system using fiber-optic geophone technology deployed on drill pipe to provide high-resolution seismic imaging and monitoring technologies for CO_2 storage projects.

Table 10: Monitoring, Verification, Accounting, and Assessment Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
DE-FE0001160	University of Wyoming	Feasibility of Geophysical Monitoring of Carbon-Sequestrated Deep Saline Aquifers	3	Determine if seismic waveform inversion can accurately predict and account for post-injection CO_2 saturation by analyzing the feasibility of combining reservoir flow simulation with 3D, multicomponent seismic-waveform modeling to accurately predict CO_2 plume movements within deep saline aquifers.
DE-FE0001317	University of Texas at Austin	Improving the Monitoring, Verification, Accounting, and Assessment of CO_2 Sequestered in Geologic Systems with Multicomponent Seismic Technology and Rock Physics Modeling	3	Improve the cost-effectiveness of 3D surface seismic technology for monitoring storage sites by combining multicomponent seismic technology including cable-less technology and rock physics modeling to provide a superior scientific technique for accomplishing CO_2 MVA tasks.
DE-FE0001040	Schlumberger Carbon Services	Quantification of Wellbore Leakage Risk Using Nondestructive Borehole Logging Techniques	3	Develop a new method to evaluate the risk of wellbore leakage by 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.
DE-FE0004847	Columbia University	Radiocarbon as a Reactive Tracer for Tracking Permanent CO_2 Storage in Basaltic Rocks	3	Develop and field test a method to use 14C as a reactive tracer to monitor geochemical reactions and to evaluate the extent of mineral trapping in basaltic rock storage sites by geochemical analysis of collected samples to provide validation of CO_2 mineral trapping and containment.
FWP ESD09-056	Lawrence Berkeley National Laboratory	Consolidated Sequestration Project—Task 6: CO_2 SINK Collaboration	4	Enhance the knowledge of the movement and behavior of CO_2 by conducting distributed-thermal-perturbation-sensor measurements in observation boreholes and developing rock-physics models to increase public confidence and enable the commercialization of geologic carbon sequestration.
FEW0174	Lawrence Livermore National Laboratory	Advancing the State of Geologic Sequestration Technologies Toward Commercialization—Task 3: Injection and Reservoir Management, The Role of Injected Induced Mechanical Deformation and Geochemical Alteration in Salah CO_2 Storage Project	4	Identify key factors related to CO_2 isolation at In Salah by studying the reactive chemistry of the brine-CO_2-reservoir-caprock-wellbore system and the geomechanical effects of large-scale injection on crustal deformation and fault leakage hazards to improve field performance of predictive and monitoring capabilities and standards.
FEW0174	Lawrence Livermore National Laboratory	Advancing the State of Geologic Sequestration Technologies Toward Commercialization—Task 4: Snøhvit CO_2 Storage Project	3	Enhance key factors needed for continued CO_2 injection at Snøhvit by researching the geomechanical effects of injection on rock deformation and fault leakage hazards, and developing a monitoring program focused on potential CO_2/brine migration to the seafloor to improve field performance of predictive and monitoring capabilities and standards.
DE-FE0001535	Columbia University	Tagging Carbon Dioxide to Enable Quantitative Inventories of Geological Carbon Storage	3	Provide a quantitative method to verify the amount of CO_2 stored by geologic sequestration by 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.
FWP ESD09-056	Lawrence Berkeley National Laboratory	Consolidated Sequestration Project—Task 2: GEOSEQ	4	Investigate fundamental geochemical and petrophysical processes related to geologic CO_2 storage by predicting injectivity and capacity of saline formations and depleted gas reservoirs and lab-test innovative, high-resolution methods for monitoring CO_2 in the subsurface to gain knowledge of carbon dioxide storage processes and mechanisms.
Key Technology—Intelligent Monitoring				
DE-FE0001163	West Virginia University	In-Situ MVA of CO_2 Sequestration Using Smart Field Technology	3	Develop a software package that autonomously cleanses and summarizes raw data collected from in-situ pressure gauges and prepares those data for processing and analysis to estimate the location and amount of CO_2 leakage from a carbon storage reservoir to better understand, monitor, and assure CO_2 storage permanence, leakage detection, and response.
2012.02.00	National Energy Technology Laboratory	NETL Carbon Storage Field Work Proposal—Task 5: Verifying Storage Performance	3	Design an intelligent monitoring network for tracking the fate of subsurface CO_2 capable of signaling CO_2 intrusion, predicting locations of high-probability CO_2 leakage, and tracking deep CO_2 pressure plumes through technology development and integration, laboratory experiments, and modeling.

CARBON STORAGE

CARBON USE AND REUSE

OVERVIEW

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. Carbon use and reuse is an important component in carbon storage and some of the applicable technologies 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 currently underway.

DOE/FE Goals

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.

Benefits

The concept of converting a waste to a valued product and possibly accelerating the implementation of carbon capture and storage has attracted interest worldwide. However, an adequate portfolio of opportunities and technologies for creating products from CO_2 needs to be developed. Some benefits of carbon use and reuse are quantifiable in terms of tons of CO_2 sequestered but have uncertain value, such as the value of reducing CO_2 emissions to the atmosphere. Other benefits include:

- Increasing energy security by reducing oil imports
- Improving balance of payments for international trade
- Providing U.S. industry with potentially low-cost options for reducing GHG emissions

Critical Technology Area Challenges

Critical challenges identified in this Technology Area include the cost-effective use of CO_2 as a feedstock for chemical synthesis or its integration into preexisting products. The efficiency (CO_2 integration reaction rate and the amount of CO_2 sequestered in a product) and energy use (the amount of energy required to utilize CO_2 in existing products) of these utilization processes also represent a critical challenge.

Technology Readiness Assessment—Key Technologies

The Carbon Use and Reuse Technology Area, supported by the Clean Coal Research Program, is organized into the three key technologies depicted in Figure 10.

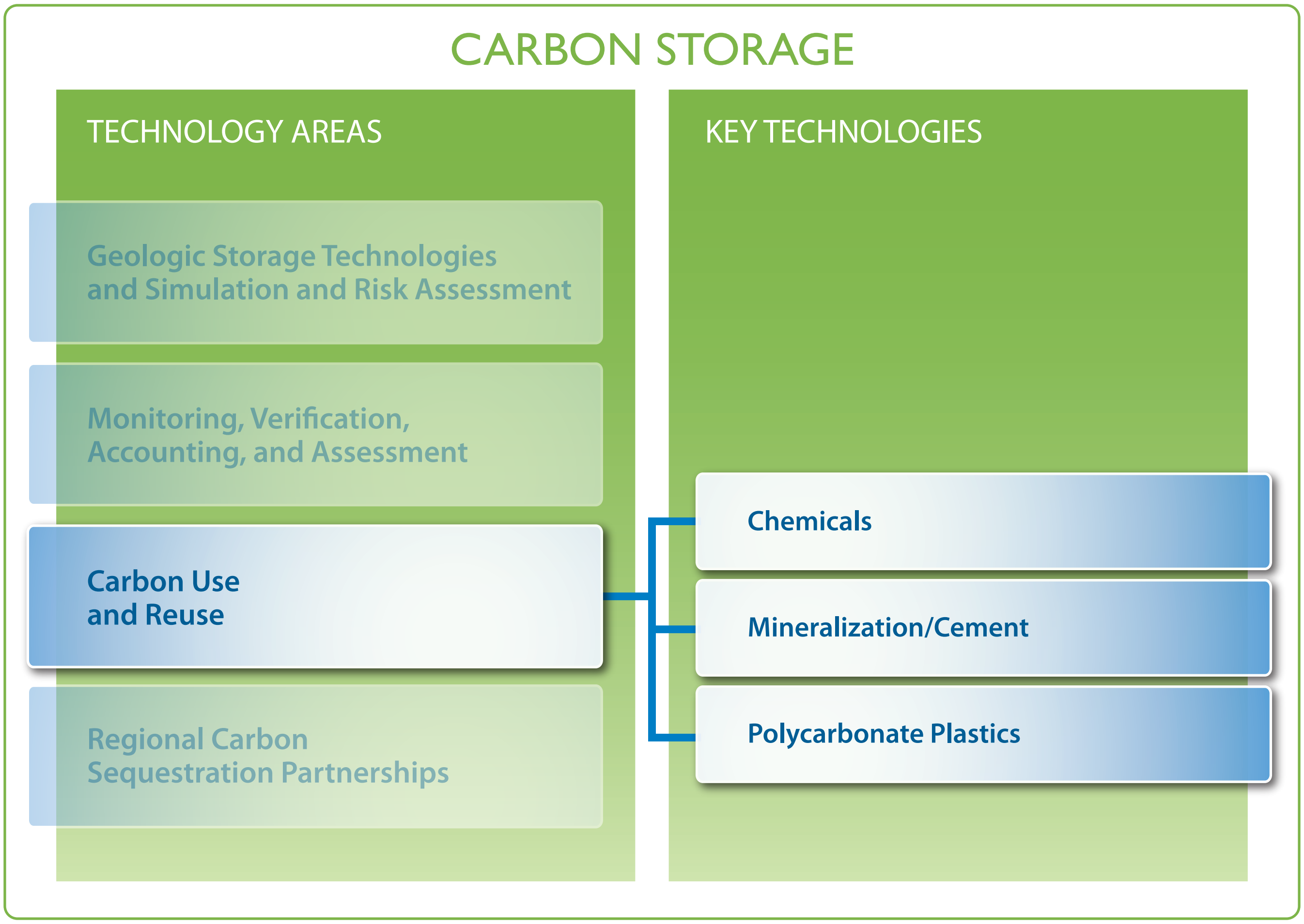


Figure 10: Carbon Use and Reuse Key Technologies

Projects Assessed

Technology readiness has been assessed based on a review of the individual research projects currently underway in each of the three key technologies:

- Chemicals
- Mineralization/Cement
- Polycarbonate Plastics

In total, the Technology Readiness Levels of seven projects were assessed in the Carbon Use and Reuse Technology Area: four in Chemicals, two in Mineralization/Cement, and one in Polycarbonate Plastics. The research and development contribution of each project to the program is captured as part of the analysis below.

The results of the assessment of the scoring analysis are shown in Table 11, which also presents relevancy statements documenting the expected contribution of each project to program goals.

TECHNOLOGY AREA—QUALITATIVE SUMMARY OF TECHNOLOGY READINESS LEVEL

The critical technology challenges related to carbon use and reuse require development of 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 carbon use and reuse technology emerges as a range of TRL values.

The Carbon Use and Reuse Technology Area spans a diverse body of ongoing work that contains individual technologies that reside at similar levels of development. As such, the overall readiness of the Carbon Use and Reuse Technology Area is represented by the status of the individual projects evaluated in the portfolio, each of which has a TRL of 3.

KEY TECHNOLOGIES—TECHNOLOGY READINESS ASSESSMENT

Key Technology—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.

Four projects within the CCRP 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.

Key Technology—Mineralization/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 calcium carbonate ($CaCO_3$) 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 CCRP Carbon Use and Reuse portfolio that focus on improved mineralization/cement technologies were assessed. The current TRL of this key technology is 3, consistent with the status of the individual technologies embedded within these projects.

Key Technology—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.

The CCRP Carbon Use and Reuse portfolio includes one polycarbonate plastics project that is assessing the viability of CO_2 reduction with ethylene using a molybdenum catalyst to produce acrylic acid. The current TRL of this key technology is 3.

PORTFOLIO OF CARBON USE AND REUSE PROJECTS

The composite results of the technology readiness assessment for the Carbon Use and Reuse Technology Area are presented in the following table.

Table 11: Carbon Use and Reuse Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—Chemicals				
DE-FE0004271	Massachusetts Institute of Technology	Integrated Electrochemical Processes For CO_2 Capture and Conversion to Commodity Chemicals	3	Evaluate the potential of integrating CO_2 as a raw material into a chemical reaction process used to produce commodity chemicals resulting in reduced greenhouse gas emissions by synthesizing organic carbonate molecules, engineering assessment of the process, and conducting life-cycle analyses of the process.
FWP-49607	Argonne National Laboratory	Life Cycle Water Consumption for CCS	3	Evaluate water removal options from geological formations targeted for injected CO_2 to determine environmental costs and benefits by using a process life-cycle assessment approach for their net carbon sequestration, net water consumption/production, and total energy consumption.
DE-FE0004224	PhosphorTech Corporation	Nanobased Photocatalyst Structure for CO_2 Reforming by Sunlight	3	Develop and demonstrate a novel CO_2 catalytic structure and conversion process utilizing solar energy to enhance the process economics and move toward achieving the DOE target net cost by optimizing a low-cost solution manufacturing process and a higher cost vacuum-deposition process.

Table 11: Carbon Use and Reuse Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
DE-FE0004329	Research Triangle Institute	Conversion of CO_2 into Commercial Materials Using Carbon Feedstocks	3	Evaluate the potential for converting CO_2 into carbon monoxide for use in producing marketable chemicals and reducing greenhouse gas emissions by conducting carbon reaction experiments in a laboratory and performing simulations to evaluate process economics.
Key Technology—Mineralization/Cement				
DE-FE0004285	McGill University	Beneficial Use of Carbon Dioxide in Precast Concrete Production	3	Develop a precast concrete curing process that uses CO_2 as a reactant to accelerate strength gain, improve durability, and reduce energy consumption and greenhouse gas emissions by designing and testing carbonated concrete blocks and panels and performing short-term and long-term evaluation of carbonated products.
DE-FE0004222	Solidia Technologies, Inc.	Utilization of CO_2 in High-Performance Building and Infrastructure Products	3	Develop a process that uses a CO_2-consuming inorganic binder as a substitute for Portland cement in concrete to reduce the energy required to make Portland cement and resultant greenhouse gas emissions while sequestering large amounts of CO_2 by a laboratory/engineering process study.
Key Technology—Polycarbonate Plastics				
DE-FE0004498	Brown University	Chemical Fixation of CO_2 to Acrylates Using Low-Valent Molybdenum Sources	3	Evaluate the potential for utilizing and storing CO_2 in acrylate compounds by analyses to expand the range of molybdenum complexes capable of coupling CO_2 and ethylene, and design and preparation of an optimized molybdenum catalyst for a bench-scale reaction.

CARBON STORAGE

REGIONAL CARBON SEQUESTRATION PARTNERSHIPS

OVERVIEW

DOE has created a network of seven Regional Carbon Sequestration Partnerships (RCSP) to help develop the technology, infrastructure, and regulations to implement large-scale CO_2 sequestration in different regions and geologic formations within the nation. The RCSP 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. 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.

DOE/FE Goals

The DOE/FE goals for the RCSP Technology Area are to conduct small- and large-scale field tests to (1) develop and validate technologies that will support industry ability to predict CO_2 storage capacity in geologic formations to within ±30 percent, (2) develop and validate technologies to demonstrate that 99 percent of injected CO_2 remains in the injection zones, and (3) support the development of Best Practice Manuals for site selection, characterization, site operations, and closure practices.

Benefits

Knowledge and experience gained from small- and large-scale field tests in different depositional environments will determine the systems best suited for geologic storage on a regional basis, which is critical to the broad, large-scale deployment of carbon capture and storage throughout the United States. Small- and large-scale field tests provide understanding of the impacts of different depositional systems on flow, injectivity, containment, and capacity. Field tests also validate simulation models and determine the effectiveness of the technologies needed to monitor CO_2 in the different storage formations. RCSPs are also working to develop human capital, encourage stakeholder networking, support regulatory policy development, develop carbon mitigation plans, and enhance public outreach and education throughout the United States.

Critical Technology Area Challenges

Critical technology challenges in the RCSP research area include (1) proving adequate injectivity, available storage capacity, and storage permanence across the range of major reservoir classes, and (2) 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.

Technology Readiness Assessment—Key Technologies

The RCSP Technology Area, supported by the Clean Coal Research Program, is organized into four key technologies as depicted in Figure 11.

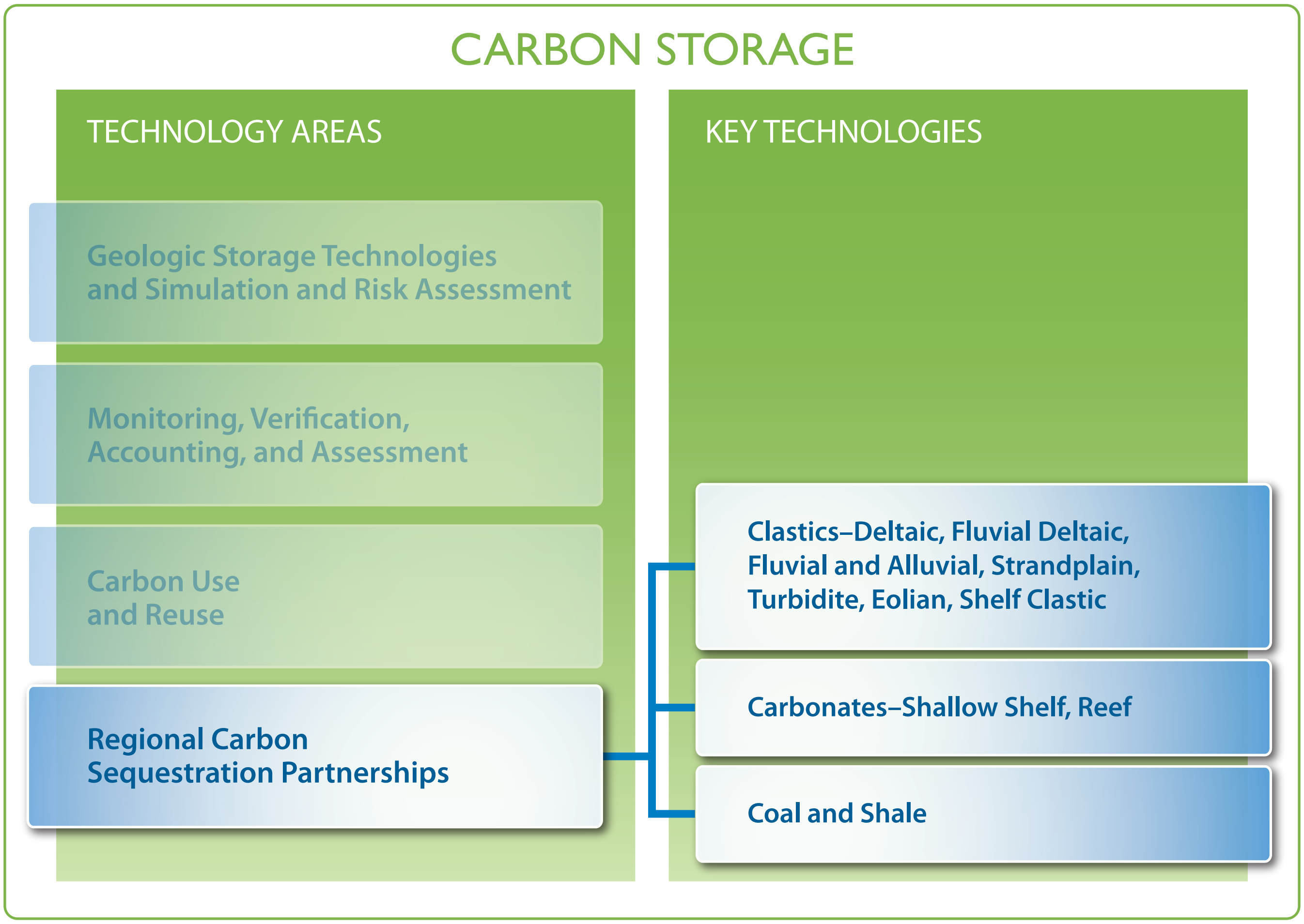


Figure 11: Regional Carbon Sequestration Partnerships Key Technologies

The four key technologies encompass 11 major types of geologic storage reservoir classes. The Clastics key technology includes seven classes of storage reservoirs: deltaic, fluvial deltaic, fluvial/alluvial, strandplain, turbidite, eolian, and shelf clastic. The Carbonates key technology includes two reservoir classes: shallow shelf and reef. The Coal and Shale key technology includes coal and shale reservoirs (shale is also a common seal for a storage reservoir).

Projects Assessed

Technology readiness has been assessed based on a review of the individual research projects currently underway in three of the four key technologies:

- Clastics (including deltaic, fluvial deltaic, fluvial/alluvial, strandplain, turbidite, eolian, and shelf clastic)
- Carbonates (including shallow shelf and reef)
- Coal and Shale

In total, the Technology Readiness Levels of 12 projects were assessed in the RCSP Technology Area—8 in Clastics, 3 in Carbonates, and 1 in Coal and Shale key technologies. Current projects target a subset of the 11 major types of geologic storage reservoir classes due to budgetary constraints and test site availability. Testing of all 11 major reservoir classes is planned because the effectiveness of CO_2 injection and storage operations and the ability of technologies to monitor and simulate CO_2 storage will differ among geologic reservoir classes.

The results of the assessment of the scoring analysis are shown in Table 12, which also presents relevancy statements documenting the expected contribution of each project to program goals.

TECHNOLOGY AREA—QUALITATIVE SUMMARY OF TECHNOLOGY READINESS LEVEL

Addressing the critical technology challenges related to the RCSP area requires a portfolio of technologies encompassing 11 major reservoir classes represented by 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 RCSP Technology Area emerges as a range of TRL values.

The RCSP Technology Area involves integrated system testing and validation of technology components at different levels of development. The overall readiness of the RCSP Technology Area is therefore best represented by the status of the individual projects evaluated in the portfolio, which have TRL scores ranging from 3 to 7.

KEY TECHNOLOGIES—TECHNOLOGY READINESS ASSESSMENT

Key Technology—Clastics

The seven storage reservoirs collectively referred to as clastics, are derived primarily from sand deposited in a variety of depositional environments. These environments include river deltas (deltaic), river channels (fluvial), beaches (strandplain), offshore submarine fans (turbidite), and desert dunes (eolian). The deposits formed in these different environments have distinct and unique internal architectures that control fluid flow within the reservoir.

Eight projects within the CCRP RCSP portfolio focused on assessing and validating clastic reservoirs as a CCUS technology option were assessed. The current TRL of this key technology spans a range of 3–7, consistent with the status of the individual technologies embedded within these projects.

Key Technology—Carbonates

Most carbonate rock of interest for CO_2 storage is derived from the growth and demise of organisms that live in oceans on continental shelves. Shapes of 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). As compared to clastic sedimentation, carbonate sedimentation is much more influenced by faulting, fracturing, precipitation, and solution channels after initial deposition. In carbonates there are far fewer recognizable trends in direction of fluid flow imposed by the initial deposition system.

Three projects within the CCRP RCSP portfolio focused on assessing and validating carbonate reservoirs as a CCUS technology option were assessed. The current TRL of this key technology is 5, consistent with the status of the individual technologies embedded within these projects.

Key Technology—Coal and Shale

Coals are deposited over a narrow range of depositional sedimentary environments, including swamps, marshes, and flood plains. While CO_2 storage in clastics and carbonates is accomplished primarily by occupying pore space, in coal, the CO_2 is adsorbed into the matrix and locked in place. Shale, deposited in a wide variety of environments, including lakes, river channels, deltas, near-shore and open-ocean marine environments, is characterized by very fine grained rock with low permeability. Shales are the seals 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 seams.

One project within the CCRP RCSP portfolio focused on assessing and validating coal/shale as a CCUS technology option was assessed. The current TRL of this key technology is 5, reflecting the TRL score of this project.

PORTFOLIO OF RCSP PROJECTS

The composite results of the technology readiness assessment for the RCSP Technology Area are presented in the table below.

Table 12: Regional Carbon Sequestration Partnerships Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—Clastics (Deltaic, Fluvial, Alluvial, Strandplain, Turbidite, Eolian, Lacustrine, Shelf)				
NT42587	Montana State University	Big Sky Regional Carbon Sequestration Partnership—Phase III	5	Demonstrate that selected formations are viable, safe targets for sequestration of a large fraction of regional CO_2 emissions to develop the foundation for future development of regional CO_2 capture and storage by safely, permanently, and economically storing over two million tons of CO_2.
NT42588	Illinois State Geological Survey	Midwest Geological Sequestration Consortium—Development Phase: Large-Scale Field Test	6	Assess carbon capture, transportation, and geologic carbon storage options to establish a regional project-development model by performing a fully integrated demonstration of monitored geological carbon storage in the largest capacity saline reservoir in the Illinois Basin.
FC26-05NT42590	Southern States Energy Board	Anthropogenic Injection—Phase III	6	Develop the necessary framework and infrastructure for large-scale CO_2 storage and MVA in the Southeast region to identify and evaluate potential opportunities and technologies for the future commercialization of carbon storage by safely transporting, injecting, and monitoring CO_2 into the Citronelle Field.
FC26-05NT42590	Southern States Energy Board	SECARB Early Test Injection—Phase III	7	Expand the characterization of geologic sinks and evaluate opportunities for injectivity, capacity, and storage of CO_2 in the Southeast region in order to demonstrate that CO_2 capture and sequestration is a viable option for mitigating GHG emissions by long-term injection and MVA efforts at the Cranfield site.
FC26-05NT42589	Battelle Memorial Institute	Midwest Regional Carbon Sequestration Partnership—Phase III	5	Assess the technical potential, economic viability, and public acceptability of carbon storage within the Midwest region to promote the reduction of CO_2 emissions while simultaneously preserving the industrial infrastructure and conducting a large-scale CO_2 sequestration test in the Michigan Basin site.
FC26-05NT42592	University of North Dakota Energy & Environmental Research Center	Plains CO_2 Reduction Partnership Phase III—Bell Creek	5	Verify and validate CO_2 injection and monitoring technologies associated with EOR operations and production wells to develop a set of cost-effective MVA protocols for large-scale CO_2 storage by collaborating in an existing EOR operation.
FC26-05NT42591	New Mexico Institute of Mining and Technology	Southwest Regional Partnership on Carbon Sequestration—Phase III	5	Provide an assessment of the sources and potential sinks for CO_2 in the Southwest region to develop an optimum strategy for future commercial-scale sequestration projects subject to the regional constraints by conducting field tests and identifying the most promising carbon-sequestration technologies and infrastructure concepts available for the region.
FC26-05NT42593	California Energy Commission	West Coast Regional Carbon Sequestration Partnership—Regional Characterization	3	Develop a comprehensive assessment of the sources and potential sinks for CO_2 in the West Coast to identify the most cost-effective, technically feasible, and publicly acceptable options for terrestrial and geologic carbon sequestration in the region by conducting CO_2 storage tests in depleting gas reservoirs, saline formations, and terrestrial storage areas.
Key Technology—Carbonates (Shallow Shelf, Reef)				
FC26-05NT42592	University of North Dakota Energy & Environmental Research Center	Plains CO_2 Reduction Partnership—Phase III: Fort Nelson	5	Verify and validate CO_2 storage information and technology to provide regional information critical to GHG management by conducting a CO_2 storage demonstration utilizing the region's carbonate saline formations for large-scale injection of CO_2.
DE-FE0006823	Blackhorse Energy, LLC	South Louisiana Enhanced Oil Recovery/Sequestration Demonstration Project	5	Demonstrate the capabilities of emerging MVA and site characterization technologies in order to establish that CO_2 can be sequestered safely in Gulf Coast Reservoirs by monitoring CO_2 behavior and migration in an EOR project.
DE-FE0006821	University of Kansas	Small-Scale Field Test Demonstrating CO_2 Sequestration in Arbuckle Saline Aquifer and by CO_2-EOR at Wellington Field, Sumner County	5	Advance the science and practice of sequestration to better define regional best practices for MVA, characterization, modeling, remediation, and risk management by performing a CO_2 injection operation in the Midcontinent Arbuckle Saline Aquifer.

Table 12: Regional Carbon Sequestration Partnerships Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—Coal and Shale				
DE-FE0006827	Virginia Polytechnic Institute and State University	Central Appalachian Basin Unconventional (Coal/Organic Shale) Reservoir Small-Scale CO_2 Injection Test	5	Determine the injectivity of CO_2 into unmineable coal seams and shale to better understand the effect of matrix swelling on injectivity and ECBM in the Central Appalachian Basin by performing an ECBM injection test and a Huff and Puff in a Devonian Shale gas well.

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 synthesis gas (syngas) that can in turn be converted into electricity, chemicals, hydrogen, and liquid fuels to suit market needs.

Hydrogen 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

OVERVIEW

Advanced combustion power generation from fossil fuels involves combustion in oxygen rather than air, or oxygen-fired combustion. This type of system eliminates the introduction of nitrogen (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 nitrogen in the flue gas simplify separation of the CO_2 for storage or beneficial use, providing the potential for oxygen-fired combustion to be a low-cost alternative for electricity generation with carbon capture and storage. The Advanced Combustion Systems Technology Area research effort is focused on new high-temperature materials and the continued development of oxygen-fired combustion technologies.

DOE/FE Goals

The DOE/FE goal for the Advanced Combustion Systems Technology Area is to develop oxygen-fired power-generation systems that achieve at least 90 percent CO_2 capture at costs that represent less than a 35 percent increase in the total COE compared to current PC power-generation plants without carbon capture and storage.

Benefits

Advanced combustion systems offer the potential for cost-effective carbon capture from PC power-generation facilities. FE estimates that the deployment of current state-of-the-art capture technology on a new PC power plant would increase the 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. New cost-effective power-generation technologies with CO_2 capture therefore are critical components of PC power production, which can contribute to the long-term viability of coal-fired power generation. Cost-effective advanced combustion technologies will enhance the ability of the United States to use low-cost domestic coal supplies in a carbon-constrained fuels market.

Critical Technology Area Challenges

Oxygen-fired combustion systems are not cost-effective at the current level of process development because of factors that include the capital cost and energy consumption for a cryogenic air separation unit (ASU), boiler air infiltration that dilutes the flue gas with nitrogen, and excess O_2 contained in the concentrated CO_2 stream. In addition, flue gas recycle (≈70–80 percent) is necessary for an oxy-combustion retrofit to existing air-fired boilers in order to approximate the boiler combustion and heat transfer characteristics of combustion with air.

Critical technology challenges related to advanced combustion systems to address these issues include improving the performance and cost of oxygen production technologies, improving boiler design to take advantage of higher flame temperatures associated with combustion in oxygen and lower gas volumes associated with nitrogen exclusion, development of advanced materials capable of withstanding the high temperatures and more corrosive oxygen-fired environment, and CO_2 purification processes that take advantage of the unique characteristics of the flue gas generated in oxygen-fired combustion systems.

Technology Readiness Assessment—Key Technologies

The Advanced Combustion Systems Technology Area, supported by the Clean Coal Research Program, is organized into the three portfolios of key technologies depicted in Figure 12.

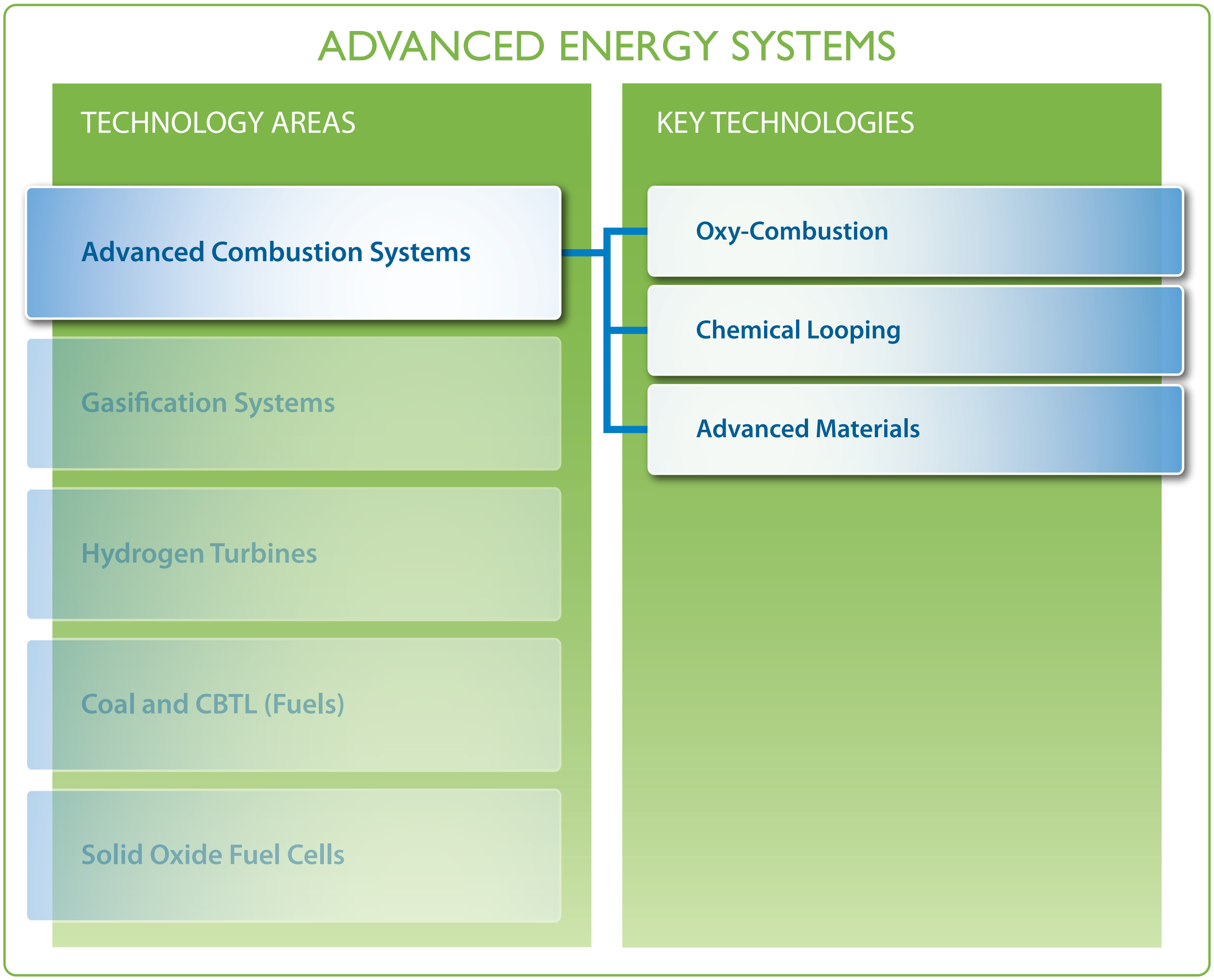


Figure 12: Advanced Combustion Systems Key Technologies

Projects Assessed

Technology readiness has been assessed based on a review of individual research projects currently underway in each key technology. FE has considerable research underway to improve advanced combustion power generation in three key technologies:

- Oxy-Combustion
- Chemical Looping
- Advanced Materials

In total, the Technology Readiness Levels of 22 projects were assessed in the Advanced Combustion Systems Technology Area: 7 in Oxy-Combustion, 3 in Chemical Looping, and 12 in Advanced Materials. 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.

The results of the assessment of the scoring analysis are shown in Table 13, which also presents relevancy statements documenting the expected contribution of each project to program goals.

TECHNOLOGY AREA—QUALITATIVE SUMMARY OF TECHNOLOGY READINESS LEVEL

The critical challenges related to advanced combustion 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 advanced combustion 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.

KEY TECHNOLOGIES—TECHNOLOGY READINESS ASSESSMENT

Key Technology—Oxy-Combustion

Oxy-combustion using currently available technology is applicable to new and existing conventional PC-fired power plants. Today's oxy-combustion system consists of a conventional supercritical PC boiler, a cryogenic ASU, substantial flue gas recycle, and conventional flue gas purification and CO_2 compression. This equipment is already available at the scale necessary for power plant applications. Key process principles, such as air separation and flue gas recycle, have been proven in the past.

The most significant barrier to the use oxy-combustion technology is the high cost, much of it associated with the cryogenic ASU. The cryogenic oxygen separation process is the only option currently available at production scale that can meet typical power plant demands. It is a mature and well-understood technology. However, the current state-of-the-art cryogenic separation process consumes over 200 kWh of electricity per ton of O_2 produced. A 500-MW oxygen-fired power plant would require 12,000 tons of oxygen per day, and cryogenic oxygen separation thus represents a significant energy penalty.

Seven projects within the CCRP Advanced Combustion Systems portfolio focus on improving oxy-combustion systems. The current TRL of this key technology spans a range of 3–6, consistent with the status of the individual technologies embedded within these projects.

Key Technology—Chemical Looping

Chemical-looping combustion (CLC) is a transformational technology that involves the use of a metal oxide or other compound as an O_2 carrier to transfer O_2 from the combustion air to the fuel, avoiding direct contact between fuel and combustion air. The products of combustion (CO_2 and H_2O) are kept separate from the rest of the flue gases. Chemical looping splits combustion into separate oxidation and reduction reactions. The metal oxide releases the O_2 in a reducing atmosphere and the O_2 reacts with the fuel. The metal is then recycled back to an oxidation chamber where the metal is regenerated by contact with air. Researchers are investigating several metal oxides for use as the O_2 carrier including calcium, iron, nickel, copper, and manganese.

A key advantage of the CLC process is that no separate ASU is required, and CO_2 separation takes place during combustion. Elimination of the ASU and incorporation of efficiencies available from CLC provide the potential for the process to meet cost and performance goals. Key R&D issues that need to be addressed to advance the development of chemical-looping systems include solids handling challenges and O_2 carrier capacity, reactivity, and attrition.

Three projects within the CCRP Advanced Combustion Systems portfolio focus on improving CLC systems. The current TRL of this key technology spans a range of 3–5, consistent with the status of the individual technologies embedded within these projects.

Key Technology—Advanced Materials

An advanced combustion system would incorporate advanced ultra-supercritical (A-USC) steam conditions rather than supercritical conditions used in current designs as well as cosequestration of CO_2 with other emissions. Today's supercritical boilers operate at steam conditions of approximately 3,500 psia and 1,000 °F. A-USC conditions are 4,000 psig and 1,350–1,400 °F. Depending on actual steam conditions, A-USC plant efficiencies are generally 3–4 percentage points higher than those of comparable supercritical plant designs. This results in a direct reduction of CO_2 emissions per net megawatt of power generated, reducing the penalty of carbon capture. However, advanced steam conditions are limited by the availability and/or cost of materials that can withstand increasingly aggressive conditions. In addition, advanced materials are needed to allow for cosequestration of CO_2 and other contaminants. Many of the advanced materials and coatings that support A-USC conditions and cosequestration are still in the R&D stage of development and at varying levels of maturity.

Advanced materials research is being pursued in the following areas: characterization of materials corrosion in advanced combustion boilers; development of advanced alloys for A-USC boiler and steam turbine components; advanced alloy design, development, and manufacturing processes for A-USC boiler and steam turbine components; alloy optimization for ultra-supercritical (USC) (650 °C) boiler and steam turbine components; and computational modeling of USC and A-USC materials.

Twelve projects within the current CCRP Advanced Combustion Systems portfolio focus on improving advanced materials. The current TRL of this key technology spans a range of 3–5 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

PORTFOLIO OF ADVANCED COMBUSTION SYSTEMS PROJECTS

The composite results of the technology readiness assessment for the Advanced Combustion Systems Technology Area are presented in the following table.

Table 13: Advanced Combustion Systems Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—Oxy-Combustion				
FC26-07NT40388	Praxair, Inc.	Oxy-Combustion Oxygen-Transport Membrane Development	3	Develop a system that integrates oxygen-transport-membrane air separation with oxy-combustion to determine if this system is competitive with other CO_2 capture processes through development of high-performance materials, testing/optimization of process configurations, and validation of manufacturing capabilities.
NT0005341	Praxair, Inc.	Near-Zero-Emissions Oxy-Combustion Flue Gas Purification	3	Develop a near-zero-emissions flue-gas-purification technology to facilitate the development of oxy-combustion systems through bench- and pilot-scale component testing on a vacuum pressure-swing-adsorption process.
NT0005290	Alstom	Oxy-Combustion Technology Development for Industrial-Scale Boiler Applications	6	Develop an oxy-combustion system designed for retrofit to T-fired boilers to advance technology by conducting pilot-scale tests on a 5-MW T-fired boiler to evaluate impacts of O_2/recycled flue gas ratio, injection of pure oxygen, injection direction, and firing system designs.
NT0005288	Reaction Engineering International	Characterization and Prediction of Oxy-Combustion Impacts in Existing Coal-Fired Boilers	5	Validate and refine computational fluid dynamic (CFD) tools for predicting the impacts of CO_2 recycle and burner feed design to determine the feasibility of developing an oxy-combustion retrofit by conducting experiments that evaluate flame characteristics and waterwall corrosion in a 1.2-MW pilot-scale coal-fired combustor.
FC26-06NT42811	Jupiter Oxygen Corporation	Jupiter Oxy-Combustion and Integrated Pollutant Removal for the Existing Coal-Fired Power-Generation Fleet	4	Demonstrate a high-flame-temperature technology to evaluate the feasability of cost-effective oxy-combustion power production through scaleup to a 5-MW pilot test facility.
2012.03.01	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities, Advanced Combustion Field Work Proposal—Task 2.1: Oxy-Combustion Environment Characterization, Fire-Side Corrosion	3	Evaluate the ability of current and/or novel materials to support oxy-combustion operations so that higher plant efficiencies can be achieved on coal with carbon capture by testing a wide range of commercial coupons at realistic fireside oxy-combustion conditions.
2012.03.01	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities, Advanced Combustion Field Work Proposal—Task 2.2: Oxy-Combustion Environment Characterization, Steam-Side Oxidation	3	Evaluate the ability of current and/or novel materials to support oxy-combustion operations so that higher plant efficiencies can be achieved on coal with carbon capture by testing a wide range of commercial coupons at realistic steam-side oxy-combustion conditions.
Key Technology—Chemical Looping				
NT0005286	Alstom	Chemical-Looping Combustion Prototype for CO_2 Capture	5	Develop a 1-MW CLC prototype to evaluate cost and performance of CLC technology through operation and testing of a system that includes a limestone oxygen carrier, a reducing reactor, an oxidation reactor, and process loops to transfer solids between the two reactors.
NT0005289	The Ohio State University Research Foundation	Coal Direct Chemical-Looping Retrofit for Pulverized Coal-Fired Power Plants with In-Situ CO_2 Capture	4	Demonstrate a subpilot-scale (25 kWth) coal direct chemical-looping system to advance a technology that offers efficient and cost-effective CO_2 capture by testing the unit using an iron oxygen carrier and various coals.
NT0005015	University of Utah	Clean and Secure Energy from Coal	3	Perform academic research tasks addressing issues associated with oxy-combustion and chemical looping to promote utilization of domestic coal resources for power generation through validation and uncertainty quantification based on tightly coupled simulation and experimental designs.

Table 13: Advanced Combustion Systems Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—Advanced Materials				
NT41175	Energy Industries of Ohio	Boiler Materials for Ultra-Supercritical Coal Power Plants	5	Develop materials for use in USC and A-USC boilers that work well with all types of coal to increase combustion efficiency through field exposure testing (via a steam loop) at A-USC service conditions.
FE0000234	Energy Industries of Ohio	Steam Turbine Materials for Ultra-Supercritical Coal Power Plants	3	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.
FWP-12461	Pacific Northwest National Laboratory	Joining of Advanced High-Temperature Materials	3	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.
AL-99-501-032	Ames Laboratory	Improved Atomization Processing for Fossil Energy Applications	3	Develop improved nozzles and powder formation techniques for applications to materials used in A-USC boilers to decrease costs of materials that will improve power plant efficiencies through a detailed analysis of atomization process responses to alloy and parameter modifications.
FEAA 109	Oak Ridge National Laboratory	Qualification of New, Commercial ODS Alloys for Use in Advanced Fuel Processes	3	Determine the viability of oxide dispersion-strengthened steel in USC boilers to increase efficiency of oxy-combustion systems through corrosion and fatigue testing under A-USC pressure, temperature, and gas composition conditions.
FEAA 106	Oak Ridge National Laboratory	Understanding Corrosion in Oxy-Fired Systems	3	Determine the temperature-dependent corrosion mechanisms of candidate high-temperature alloys and coatings in oxy-firing systems to facilitate the development of cost-effective oxy-combustion systems through corrosion testing under realistic combustion gas and ash/slag conditions.
FEAA107	Oak Ridge National Laboratory	Improving the Performance of Creep-Strength-Enhanced Ferritic Steels	3	Develop methods to improve the performance of creep-strength-enhanced ferritic steels to promote more efficient A-USC power production through fundamental and applied studies of the effects of heat treatment, welding, and process control on microstructural evolution and material properties.
AA-15-10-10	Argonne National Laboratory	Materials Research for Coal Conversion and Utilization Processes	3	Provide fundamental mechanistic information on structural and functional materials to advance low-emission, high-efficiency energy systems utilizing fossil fuels through experiments evaluating corrosion behavior, scale development/failure, and adhesion of several advanced steam-cycle materials.
FEAA 105	Oak Ridge National Laboratory	Bespoke Materials Surfaces	3	Develop a family of material coatings for coal-fired waterwall tube fireside protection that allows for higher temperature, more efficient power production through thermochemical/mechanical modeling, development of coating deposition methods, and testing of coatings under operational conditions.
FEAA069	Oak Ridge National Laboratory	Ultra-Supercritical Steam Cycle Turbine Materials	3	Contribute to the development of A-USC turbine materials to promote more efficient power production through development of high-temperature Ni-based alloy castings and evaluation of long-term performance including understanding modes of degradation.
2012.03.01	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities, Advanced Combustion Field Work Proposal—Task 4.1: Alloy Manufacturing and Process Development, Large-Scale Ni-Based Castings	4	Develop novel materials that support oxy-combustion operations so that higher plant efficiencies can be achieved on coal with carbon capture by testing a range of potential new materials at realistic oxy-combustion conditions.
2012.03.01	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities, Advanced Combustion Field Work Proposal—Task 4.3: Optimized Alloys for USC and A-USC Components	3	Develop novel materials that support USC and A-USC operations so that higher plant efficiencies can be achieved on coal with carbon capture by testing a range of potential new materials at realistic USC/A-USC conditions.

ADVANCED ENERGY SYSTEMS

GASIFICATION SYSTEMS

OVERVIEW

Gasification is used to convert a solid feedstock, such as coal, petroleum coke, or biomass, into a gaseous form, referred to as synthesis gas or syngas, which is primarily hydrogen and carbon monoxide. With gasification-based technologies, potential pollutants including CO_2 can be captured and sequestered or converted to useful byproducts. FE research supports development of advanced low-cost low-carbon energy-efficient electrical-generation technologies.

DOE/FE Goals

The DOE/FE goal for the Gasification Systems Technology Area is to support the development of advanced low-cost low-carbon energy-efficient electrical-generation technologies. The outcome of accomplishing this goal would be a gasification system whose cost represents less than a 13 percent increase in the COE compared to a 2003 baseline (i.e., COE at 9.4 cents/KWh in 2007 dollars) while achieving near-zero-emissions IGCC when coupled with a CCUS system.

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. 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 Technology Area Challenges

Critical technology challenges related to the Gasification Systems Technology Area include reducing gasification costs using low-rank coal, reducing capital costs while improving availability, and increasing plant efficiency:

- Conventional cryogenic air separation for oxygen production is a mature technology, with little opportunity remaining for significant improvements. To reduce capital costs and minimize the auxiliary power requirements to create oxygen, new advanced technologies, such as those based on ITMs, are needed.
- Gas separation processes that realize the full advantages of high-temperature gas cleaning technologies must occur at temperatures higher than in existing IGCC systems. Effective integration of components within advanced IGCC systems requires technologies that operate successfully within restricted temperature and pressure envelopes. For hydrogen separation, technologies that are capable of producing CO_2 at high pressure to avoid significant recompression costs would further enhance the economics.
- Significant improvements in key components such as coal feed systems and other components integral to the power system such as syngas cleanup are essential to efficiently utilize domestic coal resources, including western low-rank coal, at competitive power costs.
- Low operational availability of gasifiers and gasification-based technologies is one of the barriers to commercial deployment of IGCC.

Technology Readiness Assessment—Key Technologies

The Gasification Systems Technology Area, supported by the Clean Coal Research Program under Advanced Energy Systems, is organized into the three portfolios of key technologies depicted in Figure 13.

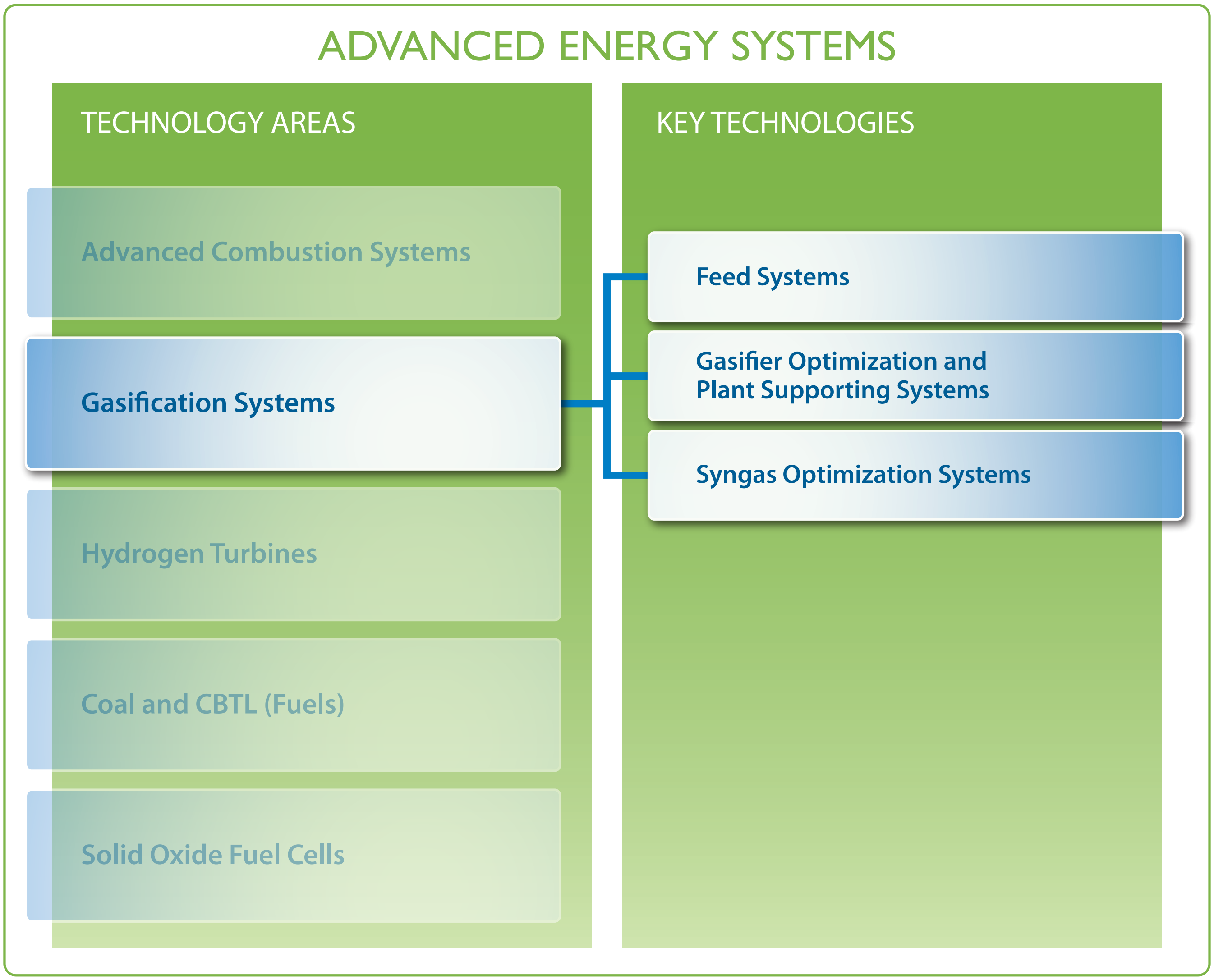


Figure 13: Gasification Systems Key Technologies

Projects Assessed

Technology readiness has been assessed based on the review of the individual research projects currently underway. FE research is focused on developing advanced technologies to reduce the cost and increase the efficiency of producing syngas, with carbon capture, in the three key technologies:

- Feed Systems
- Gasifier Optimization and Plant Supporting Systems
- Syngas Optimization Systems

In total, the Technology Readiness Levels of 15 projects were assessed in the Gasification Systems Technology Area, 3 in Feed Systems, 7 in Gasifier Optimization and Plant Supporting Systems, and 5 in Syngas Optimization Systems. In addition, the Crosscutting Research subprogram is sponsoring a significant research effort related to overcoming barrier science and technology issues associated with the development of advanced gasification technology. 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.

The results of the assessment of the scoring analysis are shown in Table 14, which also presents relevancy statements documenting the expected contribution of each project to program goals.

TECHNOLOGY AREA—QUALITATIVE SUMMARY OF TECHNOLOGY READINESS LEVEL

The critical challenges related to advanced gasification require developing a portfolio of technologies encompassing the three key areas, and the overall readiness of the ongoing research associated with this diverse collection of gasification technologies 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 5. Scores for the related Crosscutting Research efforts are discussed further under the Crosscutting Research subprogram.

KEY TECHNOLOGIES—TECHNOLOGY READINESS ASSESSMENT

Key Technology—Feed Systems

Utilizing the nation's large reserves of low-cost low-rank coals in IGCC systems is currently limited by the capabilities of available coal feed systems. Feed technologies are being developed to effectively, reliably, and economically feed low-rank coal into commercial IGCC systems. In addition, efficient and economical air separation technologies are pivotal to lower-cost IGCC power generation using any domestic coal resource.

Three projects within the CCRP Gasification Systems portfolio focused on improving feed systems were assessed. The current TRL values of this key technology are 3 and 4 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

Key Technology—Gasifier Optimization and Plant Supporting Systems

Experience from existing IGCC plants has identified gasifier refractory service lifetime as a significant issue. The refractory lining must endure many aggressive agents, including steam, hot coal slag, and strongly reducing conditions under elevated temperatures and pressures. Research and development will continue to investigate durable, low-cost refractory to reduce system costs. In addition, in an IGCC plant, syngas coolers enable high-efficiency operation, but plugging and fouling often reduce reliability. Improving the performance of the syngas cooler will improve the reliability of the gasification island and the overall availability of IGCC plants.

The harsh environment created in the gasification process represents a challenge for in-situ instrumentation to monitor gasifier operations. Sensors must perform their stated function while exposed to high temperatures, high pressures, a highly reducing atmosphere, and ash or slag. The end result is extremely short lives for critical instruments like the thermocouples used to optimize gasifier operation. Sensors are being designed to be more reliable and sensitive, and to enable better control of gasifier operation, potentially leading to increased efficiency and decreased downtime.

Seven projects within the CCRP Gasification Systems portfolio focused on improving gasifier optimization and plant supporting systems were assessed. The current TRL of this key technology spans a range of 2–5, consistent with the status of the individual technologies embedded within these projects.

Key Technology—Syngas Optimization Systems

To avoid the cost and efficiency penalties associated with cooling syngas streams to temperatures at which conventional gas cleanup systems operate, novel processes are being developed that operate at warm to high temperatures. Multicontaminant control research is being conducted at lab, pilot, and pre-commercial scale to develop technologies capable of removing trace levels of contaminants from warm syngas. Incorporation of warm to high-temperature syngas cleanup systems with sorbents capable of multicontaminant control will ensure meeting stringent environmental requirements and will preserve the high thermal efficiency of the IGCC system.

Membrane technologies are being developed to efficiently and economically separate hydrogen from syngas, which allows for more efficient capture of CO_2. Furthermore, process models are being developed and verified to accurately predict the performance of gas separation technologies. These models will also help to optimize the process design with an emphasis on capital costs and reliability as tradeoffs for the system and for the whole IGCC plant and provide for reliable scaleup of the technology. In addition, analysis will be performed to improve efficiency through optimization of integration with a gas turbine.

Five projects within the CCRP Gasification Systems portfolio focused on improving syngas optimization systems were assessed. The current TRLs of this key technology span a range of 2–4 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

PORTFOLIO OF GASIFICATION SYSTEMS PROJECTS

The composite results of the technology readiness assessment for the Gasification Systems Technology Area are presented in the following table.

Table 14: Gasification Systems Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—Feed Systems				
DE-FE0007977	Electric Power Research Institute	Liquid CO_2 Slurry for Feeding Low-Rank Coal Gasifiers	3	Confirm advantages of low-rank coal/liquid carbon dioxide slurries as gasifier feed to facilitate use of low-rank coal by performing techno-economic analysis of liquid CO_2 slurry feed through plant-wide technical and economic simulations and by developing a preliminary design and cost estimate.
FC26-04NT42237	Pratt & Whitney Rocketdyne	Development of Technologies and Capabilities for Coal Energy Resources	4	Develop a high-pressure dry feed pump for gasification processes to reduce cost, increase efficiency, and enable feeding of low-rank coal by constructing, operating, and testing a pre-commercial-scale prototype. Test results will validate models and provide data for a final benefits analysis.
FC26-98FT40343	Air Products and Chemicals, Inc.	ITM Oxygen Technology for Integration in IGCC and Other Advanced Power-Generation Systems	4	Develop a novel air separation technology for large-scale production of O_2 to reduce cost by nearly one-third compared to conventional cryogenic plants by scaling-up and demonstrating the ITM. Results will be used to validate technical and economic performance.
Key Technology—Gasifier Optimization and Plant Supporting Systems				
DE-FC26-08NT0000749	Southern Company Services, Inc.	National Carbon Capture Center at the Power Systems Development Facility	5	Develop technology to reduce the cost of advanced coal-fueled power plants with CO_2 capture by testing and supporting the evaluation of component technologies (i.e., coal feeders, hot-gas filter elements, sensors, and controls) at commercially relevant scales to validate performance.
DE-FE0007952	Reaction Engineering International	Mitigation of Syngas Cooler Plugging and Fouling	3	Develop a better understanding of syngas cooler plugging and fouling principles and formulate concepts for mitigation of syngas cooler plugging and fouling to improve gasification plant availability and cost by conducting experiments and CFD modeling to develop designs for deposit removal, with the most promising concepts validated during field testing.
DE-FE0007859	General Electric Company	Feasibility Studies to Improve Plant Availability and Reduce Total Installed Cost in IGCC Plants	2	Reduce the time to for IGCC plants to reach technological maturity to increase availability, efficiency, and to lower costs by performing techno-economic studies using cost and availability data to develop and improve operating methodologies, simulations, and control philosophies.
2012.03.03.02	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities Field Work Proposal—Task 2: Refractory Improvement	3	Develop database of slag properties (chemistry, viscosity, etc.) to provide understanding of refractory wear and potential wear mitigation methods by testing various slag materials against commercial and newly developed refractory materials.
2012.03.03.03	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities Field Work Proposal—Task 3: Conversion and Fouling	3	Develop reduced-order models as well as high-fidelity engineering models to allow improved carbon conversion efficiency and reduced convective syngas cooler fouling by performing tests to measure pyrolysis and gasification kinetics of relevant coal types used in power generation.
2012.03.03.04	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities Field Work Proposal—Task 4: Low-Rank Coal Optimization	3	Develop a framework for uncertainty propagation in system models to provide for better assessment for technology risk by developing a hierarchy of cofeed Transport Reactor Integrated Gasification (TRIG™) models with uncertainty quantification.
2012.03.03.06	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities Field Work Proposal—Task 6: AVESTAR Center	3	Continue to develop and apply dynamic simulation technology to allow for optimized IGCC plant operation with carbon capture (including a facility for personnel training) by developing fast dynamic reduced-order models and advanced process control strategies.

Table 14: Gasification Systems Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—Syngas Optimization Systems				
DE-FE0000489	Research Triangle Institute	High-Temperature Syngas Cleanup Technology Scaleup and Demonstration Project	4	Develop technologies for removal of the most significant coal contaminants from syngas integrated with carbon capture technology to improve thermal and environmental performance and reduce costs by constructing, operating, and testing a pre-commercial-scale high-temperature syngas cleanup unit.
FC26-05NT42469	Eltron Research, Inc.	Scaleup of Hydrogen-Transport Membranes for IGCC and FutureGen Plants	4	Develop a hydrogen-transport membrane (HTM) for H_2 separation and CO_2 capture to improve environmental performance and efficiency by designing and testing a pre-commercial module HTM system. Results will be used to update process models and for techno-economic analysis.
DE-FE0007966	TDA Research, Inc.	Advanced CO_2 Capture Technology for Low-Rank Coal IGCC Systems	3	Demonstrate viability of an IGCC plant designed to use low-rank coal, to increase efficiency and reduce cost, by conducting bench-scale experiments to optimize the integrated water-gas-shift catalyst/CO_2 capture system design, and use results to validate the increase in efficiency and reduced cost.
DE-FE0007759	Air Products and Chemicals, Inc.	Advanced Acid Gas Separation Technology for the Utilization of Low-Rank Coals	3	Demonstrate sour PSA technology as replacement for acid gas removal systems to reduce capital cost by >10% at 90% CO_2 capture and >95% CO_2 purity by testing the sour PSA/TSA unit on syngas derived from low-rank coal and using results to generate a pilot process design and to prepare a techno-economic assessment.
2012.03.03.05	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities Field Work Proposal—Task 5: Warm Gas Cleanup	2	Develop a novel warm-gas-cleanup reactor to allow for higher temperature gas cleanup in power plants, and thereby increased operation efficiencies, by testing and developing palladium sorbents for capture of trace metals.

ADVANCED ENERGY SYSTEMS

HYDROGEN TURBINES

OVERVIEW

The Hydrogen Turbines Technology Area supports a portfolio of projects addressing scientific and engineering challenges associated with the increased demands on turbine technology when using coal-derived hydrogen fuels. R&D efforts are focused on improving turbine components and subsystems that will ultimately lead to turbines with improved efficiency and lower cost of power production with IGCC with carbon capture.

DOE/FE Goals

The DOE/FE goal for the Hydrogen Turbines Technology Area is to demonstrate, through full-scale component testing, hydrogen-fueled gas turbine technology with a 3–5 percentage point efficiency increase and a 30 percent power increase above the hydrogen-fueled baseline machine. These advancements are associated with firing temperature increases culminating from full-scale combustion testing and advanced manufacturing trials for advanced hot-gas-component systems.

Benefits

Turbine technologies supported by this Technology Area will significantly improve the efficiency of coal-based IGCC applications, reduce capital costs, increase power output, and increase fuel flexibility. Taken together, these improvements will result in a reduced COE for IGCC with carbon capture and promote the wider adoption of this important technology. Oxy-fuel turbine technology has the potential to open new markets in EOR due to its fuel flexibility and ease of capturing CO_2.

Critical Technology Area Challenges

Critical technology challenges related to the Hydrogen Turbines Technology Area include developing high-temperature hydrogen-combustion systems with low emissions, increasing turbine inlet temperature, improving structural and coating material performance to withstand higher temperatures with longer life, reducing leakage, and improving airfoil cooling.

Technology Readiness Assessment—Key Technologies

The Hydrogen Turbines Technology Area, supported by the Clean Coal Research Program under Advanced Energy Systems, is organized into portfolios of the five key technologies depicted in Figure 14.

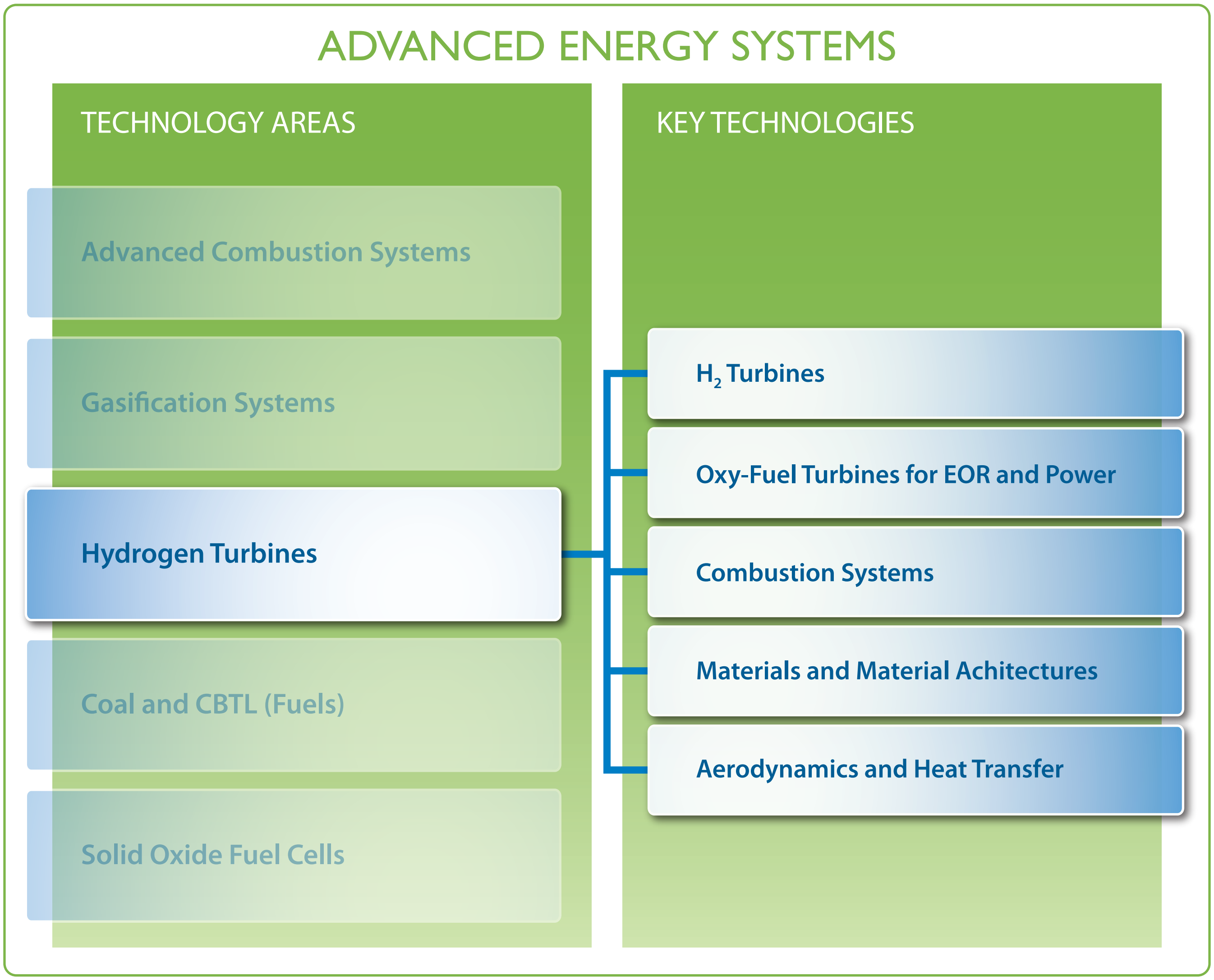


Figure 14: Hydrogen Turbines Key Technologies

Projects Assessed

Technology readiness has been assessed based on a review of the individual research projects currently underway in each key technology. FE research is focused on developing advanced technologies to reduce the cost and increase the efficiency and power output of turbines for IGCC applications with carbon capture in five key technologies:

- H_2 Turbines
- Oxy-Fuel Turbines for EOR and Power
- Combustion Systems
- Materials and Material Architectures
- Aerodynamics and Heat Transfer

In total, the Technology Readiness Levels of 22 projects were assessed in the Hydrogen Turbines Technology Area: 2 H_2 Turbines, 1 Oxy-Fuel Turbines for EOR and Power, 6 in Combustion Systems, 6 in Materials and Material Architectures, and 7 in Aerodynamics and Heat Transfer. In addition, the Crosscutting Research subprogram is sponsoring a significant research effort related to overcoming barrier science and technology issues associated with the development of advanced turbines technology. Scores for the related Crosscutting Research efforts are discussed further under the Crosscutting Research subprogram. 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.

The results of the assessment of the scoring analysis are shown in Table 15, which also presents relevancy statements documenting the expected contribution of each project to program goals.

TECHNOLOGY AREA—QUALITATIVE SUMMARY OF TECHNOLOGY READINESS LEVEL

The critical challenges related to advanced turbine development require developing a portfolio of technologies in five key areas. The overall readiness of the research associated with these five key areas was assessed and found to have a range of TRL values. The overall readiness of the Hydrogen Turbines Area is represented by the status of individual projects. The evaluation of this portfolio of projects produced TRL scores ranging from 3–5.

KEY TECHNOLOGIES—TECHNOLOGY READINESS ASSESSMENT

Key Technology—H_2 Turbines

The advancement and commercialization of power plants based on IGCC with carbon capture technology requires development of advanced turbines fueled by pure hydrogen. The work required for this key technology involves (1) applying fundamental knowledge to improve combustion, materials, and aerodynamics and heat transfer to actual turbine components and (2) developing components tested in realistic turbine environments, leading to practical engine applications.

Two projects within the CCRP Hydrogen Turbines portfolio focused on hydrogen turbine development were assessed. The current TRL value of this key technology is 5.

Key Technology—Oxy-Fuel Turbines for EOR and Power

Producing power and capturing low cost CO_2 for EOR from an oxy-fuel turbine based power presents an attractive proposition. Most CO_2 for EOR is supplied by pipelines that are not always available in proximity to either the sources of CO_2 or the areas of utilization. A system that can be remotely located and provide a non-pipeline source of CO_2 while also producing power would fill a gap in the current market for EOR.

One project within the CCRP Hydrogen Turbines portfolio that focuses on development of an oxy-fuel turbine for EOR and power was assessed. The current TRL value of this key technology is 4.

Key Technology—Combustion Systems

Turbine combustors using hydrogen fuels have significant challenges over natural gas combustion because hydrogen fuel varies in a few important ways:

- The density is very low compared to that of natural gas
- Specific energy content is much lower than that of natural gas
- Diffusivity is much higher than that of natural gas
- Hydrogen has a broad flammability range
- Laminar and turbulent flame speed of H_2 is much higher than that of other fuels

Turbine performance and design are based upon accurate models of flame characteristics and heat and air flow. Hydrogen and mixtures of gases, like syngas, deviate from established models built on hydrocarbon fuels and have limited data available for modeling. Experiments that investigate combustion dynamics, kinetics, flame speeds, flame shapes, and ignition properties provide data that will be used to develop or improve computational models that will aid in the development and verification of new combustor designs.

Six projects within the CCRP Hydrogen Turbines portfolio that focus on combustion systems were assessed. The current TRL values for this key technology are 3 and 4 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

Key Technology—Materials and Material Architectures

New materials or coatings with novel chemistries must be engineered to protect engine components and allow further increases in engine temperatures while resisting degradation from the exhaust of combusted hydrogen fuels. Efforts are focused on identifying candidate thermal barrier coating (TBC) architectures and material compositions with the proper thermal, mechanical, and chemical properties for use in reducing heat flux to combust transition pieces, stationary nozzles, and rotating airfoils.

Six projects within the CCRP Hydrogen Turbines portfolio that focus on materials and material architectures were assessed. The current TRL value of this key technology is 3.

Key Technology—Aerodynamics and Heat Transfer

Novel cooling strategies and advanced manufacturing methods for turbine airfoils are necessary to take turbine performance beyond the current state-of-the-art. In addition, increased understanding of the methods behind computational modeling tools used in cooling and airfoil design will lead to better tools and better designs.

Seven projects within the CCRP Hydrogen Turbines portfolio that focus on aerodynamics and heat transfer were assessed. The current TRL values of this key technology are 3 and 4.

PORTFOLIO OF HYDROGEN TURBINES PROJECTS

The composite results of the technology readiness assessment for the Hydrogen Turbines Technology Area are presented in the following table.

Table 15: Hydrogen Turbines Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—H_2 Turbines				
NT42644	Siemens Energy, Inc.	Advanced Hydrogen Turbine Development	4–5 [5]*	Develop advanced hydrogen-fueled-turbine machinery to increase efficiency and performance of IGCC systems by constructing and testing improved hydrogen combustion components, material systems, sensors, and manufacturing processes for advanced airfoil designs.
NT42643	General Electric Company	Advanced Hydrogen Turbine Development	5	Develop advanced hydrogen-fueled-turbine machinery to increase efficiency and performance of IGCC systems by constructing and testing improved hydrogen combustion components, materials, sensors, and airfoil designs.
Key Technology—Oxy-Fuel Turbines for EOR and Power				
NT42645	Clean Energy Systems, Inc.	Oxy-Fuel Turbomachinery Development for Energy-Intensive Industrial Applications	4	Develop novel oxy-fuel turbine technologies to demonstrate feasibility of industrial power generation with >99% CO_2 capture by modifying a commercial Siemens SGT-900 gas turbine for oxy-fuel operation and conducting validation tests.
Key Technology—Combustion Systems				
7-678402	Lawrence Berkeley National Laboratory	Low-Swirl Injectors for Hydrogen Gas Turbines in FutureGen Power Plants	4–5 [4]*	Adapt low-swirl combustion technology for use with hydrogen fuels to meet ultralow nitrogen oxide (NO_x) emission targets for IGCC systems by developing a conceptual low-swirl-injector prototype and conducting fundamental laboratory studies on premixed turbulent flame speeds.
NT0005054	Pennsylvania State University	Combustion Dynamics in Multinozzle Combustors Operating on High-Hydrogen Fuels	3	Develop physics-based flame-response models for the design of high-hydrogen combustors to improve the performance and reduce emissions from hydrogen combustion by utilizing research facilities to study combustion dynamics in multinozzle flame configurations.
FE0000752	Pennsylvania State University	An Experimental and Chemical Kinetics Study of the Combustion of Syngas and High-Hydrogen-Content Fuels	3	Advance understanding of the effects of water, CO_2, and other contaminants on ignition and combustion of high-hydrogen-content (HHC) fuels to develop guidelines for composition limits and operating characteristics that will improve the design and operability of hydrogen combustors by conducting laboratory experiments and chemical kinetic modeling.

Table 15: Hydrogen Turbines Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
FE0004679	Texas Engineering Experiment Station	Turbulent Flame Speeds and NO_x Kinetics of High-Hydrogen-Content Fuels with Contaminants and High Dilution Levels	3	Demonstrate validity of a comprehensive kinetics model to predict NO_x formation, flame speeds, and ignition behavior of HHC fuels for IGCC by conducting laboratory experiments in flame-speed and shock-tube facilities to improve existing kinetics models.
FE0007045	University of California, Irvine	Development of Criteria for Flameholding Tendencies Within Premixer Passages for High-Hydrogen-Content Fuels	3	Evaluate flameholding tendencies to develop design guides that will improve HHC fuel combustor design by conducting high-temperature, high-pressure experiments that simulate conditions in industrial-scale turbines.
FE0007099	Purdue University	Structure and Dynamics of Fuel Jets Injected into a High-Temperature Subsonic Crossflow: High-Data-Rate Laser Diagnostic Investigation	3	Develop a validation database for comparison with detailed numerical models to improve the operability of HHC combustors by conducting experiments using advanced laser diagnostics to probe the flow fields in a high-pressure gas turbine combustion facility.
Key Technology—Materials and Material Architectures				
FEAA070	Oak Ridge National Laboratory	Material Issues in IGCC/Hydrogen Turbines	3	Improve understanding of material issues in HHC-fueled turbines to reduce degradation and increase performance by studying the effect of water vapor contents during cycling, quantifying the benefit of adding doping elements to superalloys and bond coats, and characterizing microstructures of bond coat systems.
FE0004734	Louisiana State University System	Computational Design and Experimental Validation of New Thermal Barrier Systems	3	Develop a high-performance thermal barrier coating to improve the performance of HHC-fueled turbines by using high-performance computing simulations of an ab-initio molecular-dynamics-based design tool to screen and identify TBC systems with desired physical properties.
FE0004727	University of California, Irvine	Mechanisms Underpinning Degradation of Protective Oxides and Thermal-Barrier Coating Systems in HHC-Fueled Turbines	3	Evaluate the potential impacts of coal-derived syngas and HHC fuels on the degradation of turbine hot-section components to address turbine materials stability concerns by conducting tests in simulated syngas and HHC environments to evaluate materials evolution and degradation mechanisms.
FE0004771	The Research Foundation of State University of New York	Advanced Thermal Barrier Coatings for Operation in High-Hydrogen-Content-Fueled Gas Turbines	3	Improve science-based understanding of depositing bond coats and TBCs to create a pathway for reliable IGCC coating performance and provide new insight by conducting a systematic evaluation of multilayer coatings on nickel superalloys to determine properties, understand degradation mechanisms, and ultimately optimize performance and durability.
FE0000765	University of Texas at El Paso	Novel Hafnia-Based Nanostructured Thermal-Barrier Coatings for Advanced Hydrogen Turbine Technology	3	Develop hafnium-based TBCs to improve performance in IGCC by conducting experiments to optimize deposition parameters and chemical compositions, characterize microstructural, thermal, chemical, and physical properties, and ultimately quantify performance benefits.
2012.03.02	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities, Turbine Thermal Management Field Work Proposal—Task 3: Coatings and Materials Development	3	Develop integrated composite thermal-barrier coating systems to permit future land-based gas turbine power-generation engine operation at extreme temperatures (i.e., >1,400 °C) through development and manufacture of advanced and/or reduced-cost materials and through conduct of laboratory-scale, high- and/or extreme-temperature testing at near-commercial conditions to assess material performance.
Key Technology—Aerodynamics and Heat Transfer				
AL05205018	Ames Laboratory	Analysis of Gas Turbine Performance	3–4 [3]*	Advance turbine cooling strategies to improve cooling performance in industrial turbines by developing CFD-based analysis tools, examining the basis of experimental methods used to valid CFD analysis tools, and applying said tools to development of turbine technologies.
FE0006696	Florida Turbine Technologies, Inc.	Demonstration of Enabling Spar-Shell Cooling Technology in Gas Turbines	3–4 [4]*	Demonstrate Spar-Shell™ turbine airfoil technology to improve advanced gas turbine and IGCC system efficiency by designing, analyzing, fabricating, assembling, installing, and testing prototype airfoils to validate performance in a commercial turbine application.
FE0005540	University of Texas at Austin	Improving Durability of Turbine Components Through Trenched Film Cooling and Contoured Endwalls	3	Analyze shallow-trench film-cooling configurations and effects of deposition on endwall cooling configurations to improve the durability of turbine components by conducting wind-tunnel experiments that simulate turbine environments.
FE0004588	University of North Dakota	Environmental Considerations and Cooling Strategies for Vane Leading Edges in a Syngas Environment	3	Explore technology opportunities to improve the reliability of HHC fuels for gas turbines by analyzing the effects of free-stream turbulence level, geometry, deposition, and cooling on the heat load experienced by turbine vane leading edges.

Table 15: Hydrogen Turbines Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
2012.03.02	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities, Turbine Thermal Management Field Work Proposal—Task 2: Aerothermal and Heat Transfer	3	Develop advanced-internal-airfoil heat-transfer and film-cooling designs to permit higher temperature gas-turbine operation and therefore higher system operation efficiency by performing CFD modeling and conducting fundamental laboratory bench-scale testing as well as high-temperature testing at near-commercial conditions using coupon architectures.
2012.03.02	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities, Turbine Thermal Management Field Work Proposal—Task 4: Design Integration and Testing	3	Evaluate advanced ceramic matrix composites and oxide-dispersion-strengthened matrices for potential use in advanced land-based gas turbine engines and develop high-temperature validated laboratory bench-scale testing capabilities to assess the performance of these material systems as well as advanced internal-heat-transfer and film-cooling designs at near-commercial engine operating conditions.
2012.03.02	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities, Turbine Thermal Management Field Work Proposal—Task 5: Secondary Flow Rotating Rig	3	Design and construct a world-class secondary-flow rotating test facility that is focused on demonstrating improved rotaing-blade-platform sealing which ultimately reduces fuel burn and improves overall power-generation plant efficiencies through operation of the 1.5-staged turbine at conditions replicating modern gas-turbine engines.

NOTE:

* The the number in brackets represents the TRL score used for final tabulation purposes in the summary tables at the beginning of the report.

ADVANCED ENERGY SYSTEMS

COAL AND COAL-BIOMASS TO LIQUIDS (FUELS)

OVERVIEW

The Coal and Coal/Biomass-to-Liquids (C&CBTL) Technology Area R&D effort 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.

DOE/FE Goals

The Advanced Energy Systems subprogram goal is to support the development and demonstration of coal-based advanced energy production systems to produce ultraclean low-cost energy with near-zero emissions, including CO_2, with low water usage. In support of the Advanced Energy Systems goal, the focus of the C&CBTL Technology Area is twofold:

- Produce hydrogen from the gasification of coal or coal/biomass
- Produce liquid fuels from gasification of coal/biomass.

Benefits

Hydrogen can be used in advanced systems for efficient power generation with near-zero environmental emissions and with the potential to significantly reduce greenhouse emissions. Syngas produced via the gasification of coal and coal/biomass can be converted in chemical processes to liquid fuels that are cleaner burning than comparable petroleum products. High-hydrogen syngas can be refined to produce a variety of chemicals while facilitating the capture of carbon dioxide for storage. In addition, gasifiers can be made to operate at higher temperatures and pressures to make substitute natural gas directly from coal if warranted.

Critical Technology Area Challenges

The critical technical challenges facing the C&CBTL Technology Area cover a spectrum of issues that range from developing an understanding of chemical kinetics and reaction mechanisms of cogasification of coal/coal biomass mixtures to the design, construction, and testing of a pilot-scale H_2 production system.

Technology Readiness Assessment—Key Technologies

The C&CBTL Technology Area, supported by the Clean Coal Research Program, is organized into portfolios of the two key technologies shown in Figure 15.

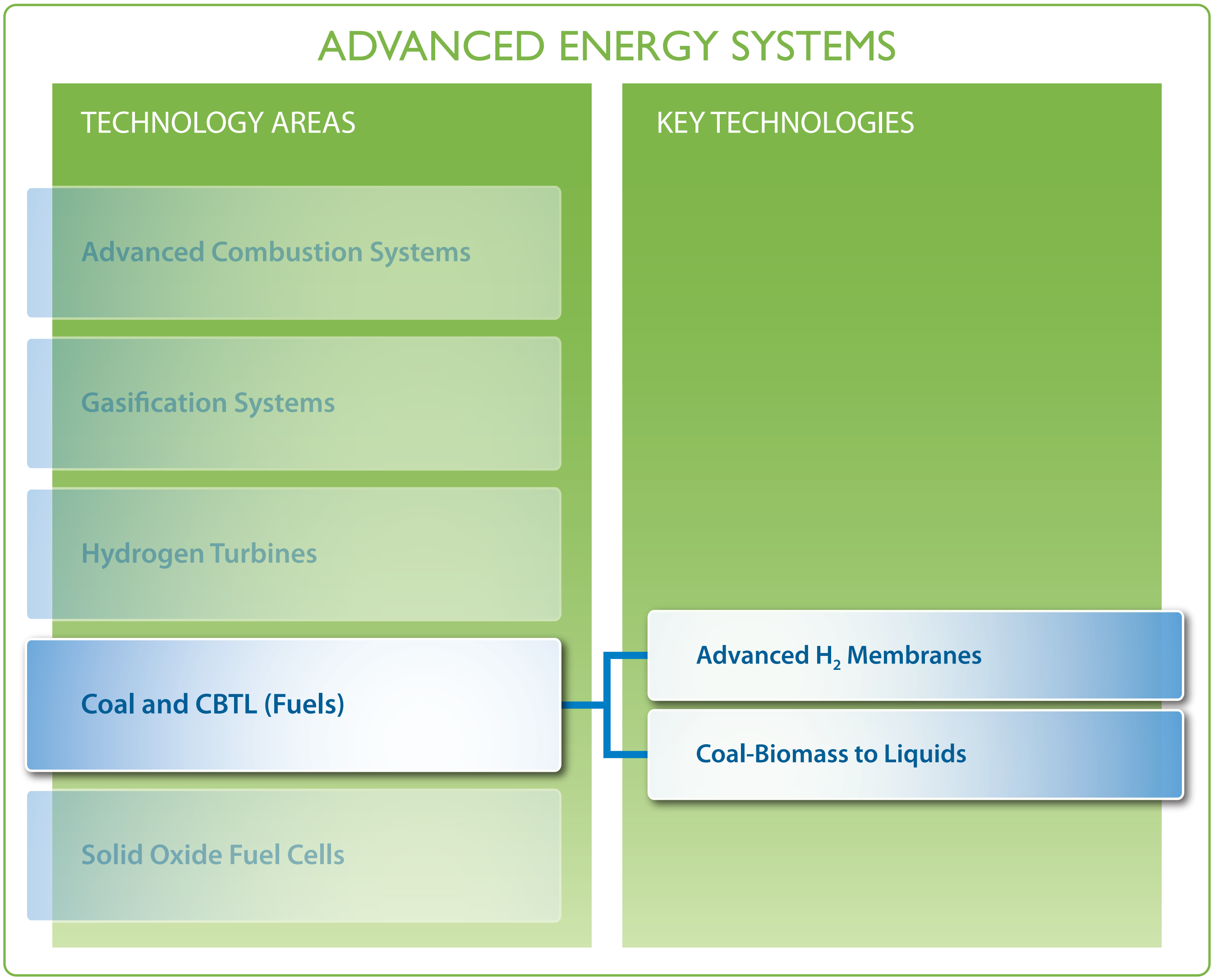


Figure 15: Coal and Coal-Biomass to Liquids (Fuels) Key Technologies

Projects Assessed

To successfully complete development of C&CBTL technology from the present state to the point of commercial readiness, the C&CBTL Technology Area efforts are focused on the two key technologies:

- Advanced H_2 Membranes
- Coal-Biomass to Liquids

Technology readiness has been assessed based on a review of individual research projects currently underway in each key technology. The C&CBTL Technology Area has a portfolio of 29 projects that were assessed: 13 projects in the Advanced H_2 Membranes key technology and 16 projects in the Coal-Biomass to Liquids key technology.

The results of the assessment of the scoring analysis are shown in Table 16, which also presents relevancy statements documenting the expected contribution of each project to program goals.

TECHNOLOGY AREA—QUALITATIVE SUMMARY OF TECHNOLOGY READINESS LEVEL

The mitigation strategy employed by the C&CBTL Technology Area to address technical challenges is to develop and maintain a diversified portfolio of near-term, mid-term, and long-term RD&D projects, including analytical studies, bench-scale experiments, and laboratory validation of prototypical components.

The portfolio includes (1) R&D projects to enhance the fundamental knowledge and understanding of reaction kinetics, (2) laboratory and bench-scale tests of hydrogen production systems, (3) component tests and validation, and (4) design studies that include the full engineering design of an advanced hydrogen transport membrane system. The TRL values of the projects within the C&CBTL Technology Area ranged from 2 to 4.

KEY TECHNOLOGIES—TECHNOLOGY READINESS ASSESSMENT

Key Technology—Advanced H_2 Membranes

This key technology supports the development of advanced hydrogen separation technology that, when integrated with IGCC and gas turbine technologies, can improve overall power-generation efficiency, reduce costs, and, in combination with CCUS and/or displacement of a portion of coal with biomass, will provide significantly reduced emissions for coal-based power plants. Activities include identifying new and novel membranes, bench-scale development of promising hydrogen separation technologies, and pilot-scale demonstrations of membrane technologies in operating gasifiers. TRL scores for the 13 projects in the Advanced H_2 Membranes key technology achieved scores ranging from 2 to 4.

Key Technology—Coal-Biomass to Liquids

The Coal-Biomass to Liquids key technology is advancing scientific knowledge of the production of liquid hydrocarbon fuels from coal/biomass mixtures. Activities support research for handling and processing of coal/biomass mixtures, ensuring these mixtures are compatible with feed delivery systems, identifying potential impacts on downstream components, catalyst and reactor optimization, and characterizing of the range of products and product quality from fuels conversion processes. TRL scores for the 16 projects in this key technology range from 2 to 4.

PORTFOLIO OF COAL AND COAL-BIOMASS TO LIQUIDS (FUELS) PROJECTS

The results of the Technology Readiness Assessment for the C&CBTL Technology Area are presented in the table below.

Table 16: Coal and Coal-Biomass to Liquids (Fuels) Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—Advanced H_2 Membranes				
FE0004908	Praxair, Inc.	Advanced Hydrogen Transport Membranes for Coal Gasification	4	Conduct R&D to scaleup current HTM technology to develop the design of a membrane hydrogen-separation unit capable of producing at least 4 tons/day of H_2 from syngas derived from coal or coal-biomass by testing a 2 lbs/day membrane module using coal-derived syngas.
FE0004895	Worcester Polytechnic Institute	Engineering Design of Advanced H_2/CO_2 Pd and Pd-Alloy Composite Membrane Separations and Process Intensification	4	Develop a cost-effective H_2 production and separation process that employs Pd and Pd-alloy membranes for use in water-gas-shift reactors by performing R&D leading to the demonstration of the process at the pre-engineering/pilot scale of 2 lbs/day of H_2.
FE0004967	United Technologies Corporation	Advanced Palladium Membrane Scaleup for Hydrogen Separation	4	Demonstrate the pilot-scale Pd/Cu alloy-based tubular membrane to establish a separator design basis for further scaleup by testing and quantifying the impact of gas composition, materials of construction, and temperature on performance and durability.
FE0004992	University of Wyoming Research Corporation	Pilot-Scale Water-Gas-Shift Membrane Device for Hydrogen from Coal	3	Demonstrate the feasibility and manufacturing practices of water-gas shift and H_2 separation in a small-scale device to maximize H_2 production from syngas by building and testing a 2 lbs/day pilot-scale system using coal-derived syngas as the input.
FE0000998	University of Nevada, Reno	Amorphous Alloy Membranes Prepared by Melt-Spin Methods for Long-Term Use in Hydrogen Separation Applications	3	Develop H_2 separation membranes using nonprecious metal alloys to provide a cost-effective, sulfur-tolerant method to separate H_2 from syngas by fabricating and testing melt-spun amorphous ribbons using alloys of nickel, zirconium, and other metals.
FE0001009	Colorado School of Mines	Nanoporous Metal-Carbide Surface-Diffusion Membranes for High-Temperature Hydrogen Separations	3	Develop and optimize novel nanoporous metal carbide membranes using molybdenum or tungsten for high-temperature hydrogen separations from coal synthesis gas by utilizing a low-temperature plasma-enhanced chemical-vapor-deposition process.

Table 16: Coal and Coal-Biomass to Liquids (Fuels) Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
FE0001050	Worcester Polytechnic Institute	Supported Molten-Metal Membrane for Hydrogen Separation	3	Develop supported molten-metal membranes using nonprecious metals for separating H_2 from syngas by developing fabrication procedures, fabricating the membranes, and conducting bench-scale testing for durability, H_2 permeability, and purity.
FE0001045	Ceramatec Inc.	Novel Ceramic Membrane System For Hydrogen Separation	3	Produce a prototype ceramic membrane that will separate hydrogen from coal-derived synthesis gas without the use of precious metals by fabricating multistacked wafers of ceramic or ceramic-composite materials.
FE0001057	Southwest Research Institute	Amorphous Alloy Membranes for High-Temperature Hydrogen Separations	3	Develop high-performance amorphous alloy membranes for high-temperature hydrogen separations to increase efficiency and lower the cost of clean hydrogen from coal-derived syngas by (1) advanced theoretical modeling of materials and (2) testing and evaluation.
FE0001293	University of Texas at Dallas	Integrated Water-Gas-Shift Membrane Reactors Utilizing Novel Nonprecious-Metal Mixed-Matrix Membranes	3	Develop novel nonprecious-metal mixed-matrix membranes based on zeolitic imidazolate frameworks (ZIF) to separate hydrogen from coal-derived syngas by characterizing ZIF materials and fabricating and testing membranes in flat, tubular, and hollow-fiber geometries.
2012.03.05.04	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities, Fuels Field Work Proposal—Task 4: Module Design	2	Develop robust materials that can withstand harsh environments of gas production to allow for flexible gasification plant operation in terms of power and valuable commodity production by developing new material membranes and catalysts that can generate the desired synthesis gas components and then separate them while resisting degradation due to possible contaminants in coal syngas.
2012.03.05.05	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities, Fuels Field Work Proposal—Task 5: Materials Development	2	Provide understanding of best IGCC plant operation conditions to guide targeted and cost-effective development of separation processes by applying both system-level and CFD-level analysis tools for determining optimal plant design and separation component configurations with complementary experimental work performed for CFD model comparison and validation.
2012.03.05.06	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities, Fuels Field Work Proposal—Task 6: Performance Verification Testing	3	Determine the performance of novel concepts for hydrogen enrichment at process-level conditions, and in particular chemical composition of products generated from these new systems, to verify progress toward meeting the goal of developing cost-effective separation technologies by experimentally testing membranes and systems developed under this Field Work Proposal.
Key Technology—Coal-Biomass to Liquids				
FC26-05NT42456	University of Kentucky	Production and Storage of Hydrogen from Coal Using C1 Chemistry	4	Develop an understanding of the chemical reaction processes to produce H_2 from natural gas, syngas derived from coal, and other feedstocks produced from coal-derived syngas by identifying, synthesizing, and experimentally testing candidate catalysts.
NT0005988	University of Kentucky	Coal Fuels Alliance: Design and Construction of an Early Lead Mini Fischer-Tropsch Refinery	3	Advance the design and construction of a Coal/Biomass-to-Liquids Process Development Unit to construct a facility to house test beds for evaluating new concepts for producing Fischer-Tropsch fuels by designing, procuring, and integrating subsystem components.
FC26-06NT42804	West Virginia University	Long-Term Environmental and Economic Impacts of Coal Liquefaction in China	2	Develop a working relationship with coal producers and users in China to better understand the development and implementation of Chinese direct liquefaction and other clean coal technologies by supporting communication and collaboration between the United States and China.
FE0000435	University of Southern California	Methanol Economy	3	Develop novel technologies to convert natural gas and anthropogenic CO_2 from fuels combustion into methanol and dimethyl ether by investigating two pathways (direct conversion and bi-reforming), and explore methods of efficiently capturing CO_2 for use in bi-reforming.
FE0005293	CoalTek Inc.	Development of Biomass-Infused Coal Briquettes for Cogasification	4	Demonstrate a microwave treatment process for briquetting coal and biomass to produce an economically viable single-stream feedstock suitable for cogasification by focusing on microwave processing, batch-scale production, and laboratory characterizations of briquettes.
FE0005339	Georgia Tech Research Corporation	Development of Kinetics and Mathematical Models for High-Pressure Gasification of Lignite-Switchgrass Blends	3	Develop a detailed understanding of pyrolysis and char gasification for lignite-switchgrass blends to build kinetic and mathematical models for predicting gasification behavior by gasifying blends of lignite-switchgrass in two reactor configurations.

Table 16: Coal and Coal-Biomass to Liquids (Fuels) Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
FE0005476	Virginia Polytechnic Institute and State University	Investigation of Coal-Biomass Catalytic Gasification Using Experiments, Reaction Kinetics, and Computational Fluid Dynamics	3	Characterize the chemical kinetics and reaction mechanisms of cogasification fuels to determine their key reactive properties by conducting bench- and pilot-scale gasification experiments over a range of temperatures and performing kinetic CFD modeling.
FE0005451	Virginia Polytechnic Institute and State University	Development of Advanced Systems for Preprocessing and Characterizing Coal-Biomass Mixtures as Next-Generation Fuels and Feedstocks	3	Develop engineered systems for manufacturing coal-biomass mixtures as solid briquettes suitable for transportation, storage, and direct cofeeding into gasifiers by determining the key reactive properties for coal-biomass mixed fuels.
FE0005349	Gas Technology Institute	R&D to Prepare and Characterize Robust Coal/Biomass Mixtures for Direct Cofeeding into Gasification	4	Develop hydrothermal carbonization technology to create biomass (pellets and briquettes) compatible with conventional coal equipment by utilizing a semi-continuous process development unit to treat biomass in hot pressurized water.
FE0001321	University of Florida	Novel Magnetically-Fluidized-Bed Reactor Development for the Looping Process: Coal-to-Hydrogen Production R&D	3	Determine the optimal reaction pathways, evaluate the kinetics, and characterize relevant properties to develop a chemical-looping reactor concept to generate high-purity streams of H_2 and CO_2 through bench-scale testing and simulation and modeling.
NT0006289	TDA Research Inc.	Investigation of Effects of Coal and Biomass Contaminants on the Performance of Water-Gas-Shift and Fischer-Tropsch Catalysts	3	Investigate the effects of contaminants present in syngas produced by biomass on catalyst activity and selectivity to determine a cost-effective procedure for maintaining catalyst effectiveness by measuring their deactivation kinetics in laboratory and bench-scale reactors.
FE0000507	GE Global Research	Demonstration of Pressurizing Coal/Biomass Mixtures Using Posimetric Solids Pump Technology	4	Demonstrate the posimetric pump for feeding coal and biomass mixtures into a pressurized gasifier to prove the ability to deliver up to 50 wt % mixtures in the absence of a carrier gas by testing the properties of the mixtures.
FE0002829	University of Texas at Arlington	Center for Renewable Energy Science and Technology (Advanced Fuels Research)	3	Develop new technologies to convert lignite to synoil and lignite to H_2 for the production of clean and low-cost energy by (1) characterizing, synthesizing, and evaluating catalysts and (2) investigating process optimization in bench- and pilot-scale tests.
NT42760	Research Triangle Institute	Coproduction of Substitute Natural Gas and Electricity Via Catalytic Coal Gasification	4	Develop and evaluate a catalytic gasification system to coproduce substitute natural gas and electricity from lignite or subbituminous coals by experimental bench-scale testing to demonstrate feasibility and optimize the process.
FE0003595	Crow Tribe of Indians	Montana Integrated Carbon-to-Liquids Demonstration Program	4	Demonstrate integrated carbon-to-liquids (ICTL) technology and conduct an assessment of biomass sources capable of recycling CO_2 from the ICTL to produce sample quantities of distillate fuels in a low-carbon-emitting process through the design and operation of a pilot-scale liquefaction facility.
DE-FE0002945	Viresco Energy, LLC	Utah Coal and Biomass-to-Fuel Pilot	4	Evaluate the steam hydrogasification reaction process to enhance conversion of carbonaceous material in a high-steam environment by designing and constructing process components to evaluate the process at both laboratory and pilot scale.

ADVANCED ENERGY SYSTEMS

SOLID OXIDE FUEL CELLS

OVERVIEW

The Solid Oxide Fuel Cells Technology Area research effort is focused on developing low-cost highly efficient solid-oxide-fuel-cell (SOFC) power systems that simultaneously produce electric power from coal with carbon capture when integrated with coal gasification.

DOE/FE Goals

The Advanced Energy Systems subprogram goal is to support the development and demonstration of coal-based advanced energy production systems to produce ultraclean low-cost energy with near-zero emissions, including CO_2, and low water usage. In support of the Advanced Energy Systems goal, the Solid Oxide Fuel Cells Technology Area has specific goals to:

- Establish the technology base to achieve the degradation rate, reliability, and low-cost manufacturing targets critical to the commercialization of SOFC technology.
- Develop and deploy technology that will demonstrate substantially improved power densities, reduced degradation rates, and more reliable and robust SOFC power systems.

Benefits

The integration of SOFC technology with advanced gasification systems and other advanced technologies being pursued by the companion Technology Areas 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 research subprogram. IGFC power systems are projected to achieve greater than 90 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 Technology Area Challenges

The key technical challenges facing the Solid Oxide Fuel Cells Technology Area cover a broad 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 associated with the SOFC include improving electrochemical performance, reducing long-term degradation rates, improving mechanical integrity, and reducing material costs.
- *Stacks* – issues include effective reactant flow distribution, thermal management, seals, mechanical integrity, understanding stack failure mechanisms, scaleup, and reducing cost.
- *Systems* – areas of importance include reducing the cost of high-temperature components, defining the operating envelope, integrating components and subsystems, and acquiring operational experience.

Technology Readiness Assessment—Key Technologies

The Solid Oxide Fuel Cells Technology Area, within the Advanced Energy Systems subprogram and supported by the Clean Coal Research Program, is organized into portfolios of the four key technologies shown in Figure 16.

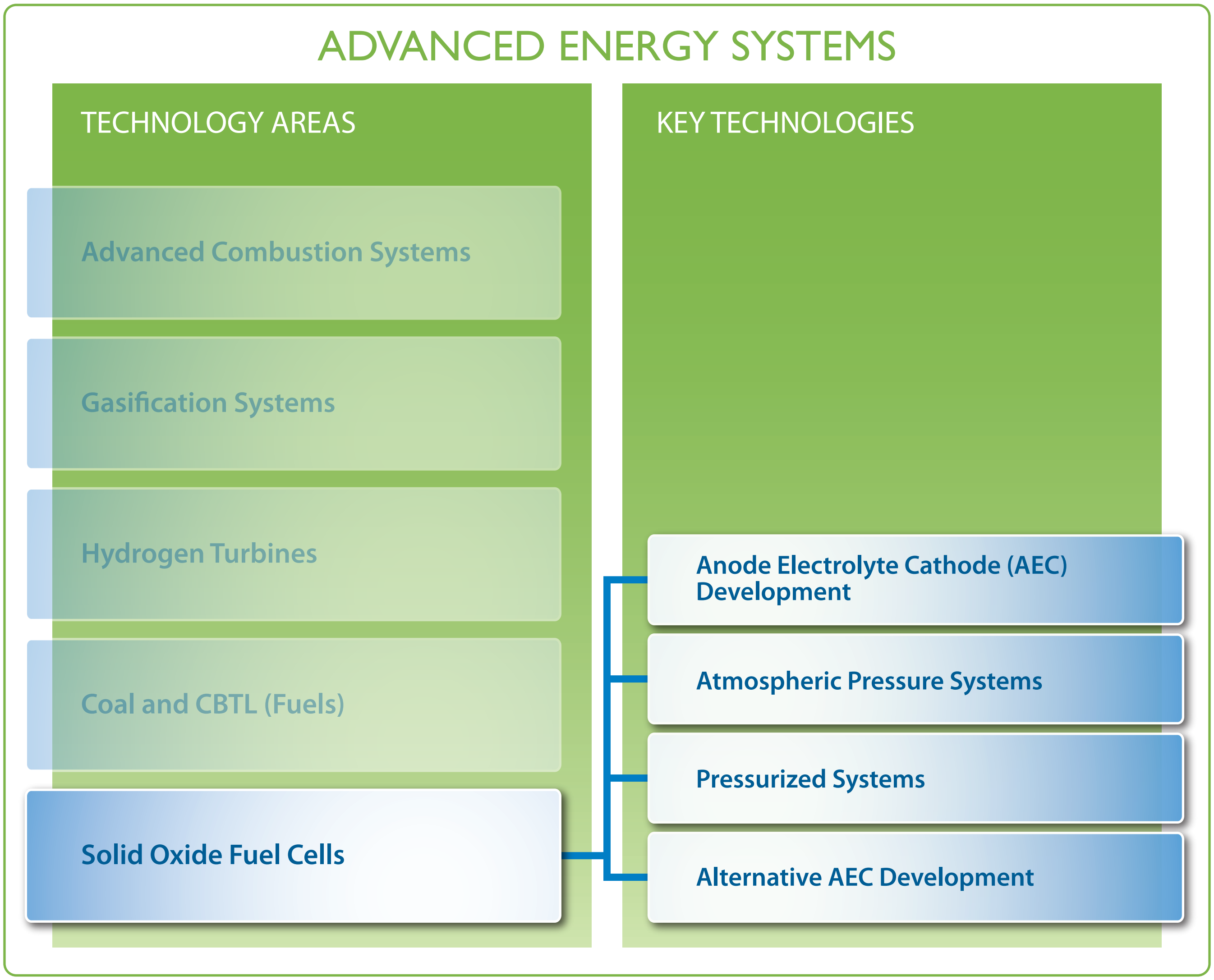


Figure 16: Solid Oxide Fuel Cells Key Technologies

Projects Assessed

To successfully complete the evolution of the SOFC technology from its present state to the point of commercial readiness, the Solid Oxide Fuel Cells Technology Area efforts are focused on four key areas:

- Anode Electrolyte Cathode (AEC) Development
- Atmospheric Pressure Systems
- Pressurized Systems
- Alternative AEC Development

Technology readiness has been assessed based on a review of individual research projects currently underway in each key technology. The Solid Oxide Fuel Cells Technology Area has a portfolio of 16 projects that were assessed: 10 projects in AEC Development, 2 in Atmospheric Pressure Systems, 1 in Pressurized Systems, and 3 in Alternative AEC Development. In addition, the Crosscutting Research subprogram is sponsoring a research effort related to overcoming barrier science and technology issues associated with the development of SOFC technology. 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.

The results of the assessment of the scoring analysis are shown in Table 17, which also presents relevancy statements documenting the expected contribution of each project to program goals.

TECHNOLOGY AREA—QUALITATIVE SUMMARY OF TECHNOLOGY READINESS LEVEL

The mitigation strategy employed by the Solid Oxide Fuel Cells Technology Area to address the above technical challenges is to develop and maintain a diversified portfolio of near-term, mid-term, and long-term RD&D projects, including laboratory-scale experiments and proof-of-concept system demonstrations to foster advancement of SOFC technologies for coal-based central station power systems.

The portfolio includes R&D projects to enhance the fundamental knowledge and understanding of cell kinetics, bench-scale stack tests, and the design of proof-of-concept power systems. The TRL scores of the projects within the Solid Oxide Fuel Cells Technology Area are 3 and 4.

KEY TECHNOLOGIES—TECHNOLOGY READINESS ASSESSMENT

Key Technology—AEC Development

The AEC Development subprogram, comprising universities, national laboratories, small businesses, and other R&D organizations, consists of projects that will lead to substantially improved power density and more reliable and robust systems. Research is focused on the technologies critical to the commercialization of SOFC technology, such as gas seals, interconnects, failure analysis, cathode performance, coal contaminants, fuel processing, and balance-of-plant components. AEC Development has a portfolio of 10 projects.

Within the SOFC, the performance of the cathode has a significant impact on stack and system performance and cost. However, the cathode is one of the least understood areas of the cell. Six projects are dedicated to addressing the technical challenges associated with the cathode and two others have one or more cathode-specific tasks. Theoretical and experimental work is underway to broaden the understanding of cathode science. All six projects focused on cathode science have a TRL of 3.

The remaining four projects are addressing the challenges associated with reliability and durability of materials and components, development of alternate materials, seals, and the effects of coal contaminants on anode performance. These projects are rated at a TRL of 3 or 4.

Key Technology—Atmospheric Pressure Systems

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 power systems. Activities include fabrication, testing, and post-test analysis of cells, integrating cells into stacks and the development and validation testing of progressively larger stacks (on the order of 10 kWe) to meet performance, reliability, endurance, and cost metrics. The two projects in this key technology have a current TRL of 4.

Key Technology—Pressurized Systems

SOFC demonstrate enhanced performance by increasing the cell pressure. Thus, IGFC systems with pressurized SOFC technology have the potential to achieve efficiencies approaching 60 percent (higher heating value) with greater than 90 percent carbon capture, near-zero emissions, and low water usage. The improved performance may be offset by increased costs, particularly those associated with the SOFC stack enclosure, additional operational risks, and a more complex integration with associated components and subsystems. The Pressurized Systems key technology is developing a deeper understanding on the behavior of the state-of-the-art SOFC material set under pressurized operation; quantifying the effect of pressure on cell performance, reliability, and degradation; and identifying and resolving the operational issues associated with pressuring the SOFC stack. Based on the cell, stack, and component tests that have been successfully completed, the sole project within this key technology has achieved a TRL of 4.

Key Technology—Alternative AEC Development

The Alternative AEC Development key technology evaluates, develops, and implements advanced technologies to reduce costs and to enhance robustness, reliability, and endurance of SOFCs. Research activities contribute critical information to assess the viability and benefits of new advanced cell and stack concepts (including alternative anodes, cathodes, electrolytes, materials, and configurations), advanced processing techniques, and novel fuel cell power systems. The Solid Oxide Fuel Cells Technology Area portfolio contains three projects within this key technology that is currently investigating, characterizing, and developing mitigation strategies for degradation mechanisms and investigating alternative cell manufacturing techniques. This technology has achieved TRL scores of 3 and 4.

PORTFOLIO OF SOLID OXIDE FUEL CELLS PROJECTS

The results of the Technology Readiness Assessment for the Solid Oxide Fuel Cells Technology Area are presented in the following table.

Table 17: Solid Oxide Fuel Cells Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—AEC Development				
49071	Argonne National Laboratory	SOFC Materials Research/ Synchotron	3	Develop an understanding of cathode surface phenomena to improve cell performance by measuring the atomic and chemical state of cathode materials under typical operating conditions to enable models for the design of high-performance cathode materials.
NT0004105	Carnegie Mellon University	Investigation of Cathode Electrocatalytic Activity Using Surfaced Engineered Thin-Film Samples and High-Temperature Property Measurements	3	Understand the role of atomic-scale surface chemistry and microstructure on cathodes to improve cathode performance by specifically targeting the O_2 uptake process by changing the base component material or adding a catalyst to the existing material set.
NT0006557	Georgia Tech Research Corporation	Theory, Investigation, and Stability of Cathode Electro-Catalytic Activity	3	Understand the role of cathode surface properties on SOFC performance to improve cathode activity by conducting analytical and laboratory-scale studies of alternate cathode materials and comparing the results with the known reactivity of base materials.
MSD-NETL-01	Lawrence Berkeley National Laboratory	SOFC Electrodes	3	Identify and develop candidate materials, architectures, and concepts to solve issues related to delamination and degradation of cathode-contact material by synthesizing, characterizing, and testing promising materials in relevant test geometries.
NT0004117	Massachusetts Institute of Technology	Chemistry of SOFC Cathode Surfaces: Fundamental Investigation and Tailoring of Electronic Behavior	3	Understand how physical, chemical, and electronic structures relate to cathode performance to propose improved cathode surfaces with enhanced electrochemical performance and low degradation by characterizing the surface properties of catalytic cathode materials.
NT0004115	Montana State University	Synchrotron Investigations of LSCF Cathode Degradation	3	Identify degradation mechanisms in cathode materials to improve cell performance and durability by modifying and characterizing the cathode/ electrolyte interface and correlating the modifications to the effects of overpotential, current, and gaseous environment.
FEAA066	Oak Ridge National Laboratory	Reliability of Materials and Components for Solid Oxide Fuel Cells	3	Characterize the thermomechanical properties of materials under typical operating to produce high-fidelity models to predict and assess cell and stack behavior and identify degradation mechanisms through lab-scale tests and analysis of experimental data.
FWP-40552	Pacific Northwest National Laboratory	SECA Core Technology Program	3–4 [4]*	Develop advanced cell and stack component materials and computational tools to increase performance, improve robustness, reduce degradation, and lower cost of SOFC cells and stacks, through lab-scale tests and benchmarking results against industry data.
NT0004104	Trustees of Boston University	Unraveling the Relationship Between Structure, Surface Chemistry and Oxygen Reduction	3	Understand the role of surface atomic and electronic structure in the oxygen-reduction reaction to provide guidance in improving cathode performance by acquiring surface-specific chemical and structural data using advanced analytical techniques.

Table 17: Solid Oxide Fuel Cells Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
FG02-06ER46299	West Virginia University	Direct Utilization of Coal Syngas in High-Temperature Fuel Cells	3	Identify the fundamental mechanisms of carbon deposition and coal-contaminant poisoning to establish the tolerance limits for the impurities for SOFCs operating on coal syngas by using experimental, theoretical, and modeling techniques.
Key Technology—Atmospheric Pressure Systems				
FC26-04NT41837	FuelCell Energy, Inc.	SECA Coal-Based Systems	4	Develop cell and stack technology with emphasis on performance, reliability, and cost to show progress toward demonstrating a proof-of-concept module through design and materials development and fabrication, testing, and post-test analysis of cells and stacks.
NT-0003894	UTC Power Corporation	Coal-Based IGFC Project—Phase I	4	Integrate smaller stacks into larger systems focusing on durability, reliability, cost, and manufacturability to validate scaled up operability and system performance by (1) building and testing a thermally self-sustaining stack and (2) system modeling and analysis.
Key Technology—Pressurized Systems				
FE-0000303	Rolls Royce Fuel Cell Systems, Inc.	SECA Coal-Based Systems	4	Develop cell and stack technology with a focus on performance enhancement to deliver a stack technically and economically suitable for aggregation into the proof-of-concept module by validating technology developments through system-level block testing.
Key Technology—Alternative AEC Development				
NT-0004109	General Electric Company	Performance Degradation of LSCF Cathodes	4	Develop mitigation strategies for degradation mechanisms and investigate alternate manufacturing techniques to improve cell performance and durability and reduce costs through electrochemical tests and micro-analytical techniques.
2012.03.04	National Energy Technology Laboratory	Task 2: Cell and Stack Degradation	3	Compile knowledge of degradation modes in anode/cathode/electrolyte and quantify relative importance to generate a predictive model describing modes of degradation applicable to cells and stacks by conducting direct cell testing in the laboratory.
2012.03.04	National Energy Technology Laboratory	Task 3: Cathode Engineering	3	Complete the development and performance evaluation of cathode materials and structure to improve cell power output by 30%, while maintaining cost and durability, by lab-scale cell tests and subsequent scaleup and testing in a complete cell stack

NOTE:

* The the number in brackets represents the TRL score used for final tabulation purposes in the summary tables at the beginning of the report.

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CROSSCUTTING RESEARCH

The Crosscutting Research subprogram serves as a bridge between basic and applied research by fostering the R&D of instrumentation, sensors, and controls targeted at reducing the costs and enhancing the availability and efficiency of advanced power systems. This subprogram area also develops computation, simulation, and modeling tools focused on optimizing plant design and shortening developmental timelines and other crosscutting issues, including plant optimization technologies, environmental and technical/economic analyses, and integrated program support. The Crosscutting Research subprogram consists of three Technology Areas:

Plant Optimization Technologies develops advanced sensors and controls, materials, and water- and emissions-related technologies for current and future applications in power plant and industrial facilities where harsh environment conditions are present and require novel control systems for optimization of operations.

Coal Utilization Sciences investigates immersive, interactive, and distributed visualization technology in the design of next-generation advanced energy systems. Additional support is offered for the optimization of the design and operation of important unit processes in advanced power-generation systems with high-performance computational modeling and simulation research. Carbon capture is addressed by modeling efforts that include storage and science-based risk quantification methodologies for specific CO_2 storage sites.

University Training and Research supports grants to U.S. colleges and universities with emphasis on longer term research in all Crosscutting Research R&D areas.

The common thread of the Crosscutting Research subprogram focus is breakthrough (enabling) technologies and novel applications that strive to balance high risk against the prospect of high payoff. Some of the key technologies overlap more than one of the previously discussed Technology Areas. The Crosscutting Research subprogram is developing advanced technologies to reduce the cost and increase the efficiency of power-generation facilities with carbon capture in eight specific pathways: sensors, controls, and novel concepts; dynamic systems modeling; high-performance materials and modeling; water-emissions management and controls; carbon capture simulation; carbon storage risk assessment; innovative energy concepts; and systems analyses and product integration.

CROSSCUTTING RESEARCH

PLANT OPTIMIZATION TECHNOLOGIES

OVERVIEW

The Plant Optimization Technologies (POT) Technology Area research effort is developing a portfolio of novel sensors and controls, water management, emissions control, dynamic systems modeling, and high-performance materials and modeling technologies to provide tools to enable rapid design and enhanced operation of power plants.

DOE/FE Goals

The DOE/FE goals for the POT Technology Area are to (1) lower sensor costs more than 20 percent over the cost of discrete sensors, (2) increase systems reliability by 5 percent or greater, (3) achieve systems efficiency gains of 4 percent or greater, (4) reduce forced outages by 5–10 percent, (5) mitigate the demand for surface water, (6) develop emissions sensors, (7) reduce the time required to develop new materials, and (8) reduce the time required for ASME Code approval of new materials.

Benefits

POT will be critical to ensuring the long-term viability of current and future power plants with and without carbon capture and storage—satisfying technical, economic, and regulatory requirements with lower emissions, greater efficiency, more reliability, and increased availability. An additional benefit of the research efforts will be to reduce future power plant capital costs.

Critical Technology Area Challenges

Critical technology challenges for the POT Technology Area are to improve efficiency and enhance the reliability and availability of power systems. Novel and new classes of sensors are needed to implement and optimize advanced fossil fuel-based power-generation systems. Future sensors and A-USC pressure-boundary components will require materials having unique thermal, chemical, and mechanical properties for advanced fossil-fuel-based power-generation plants. A reduction is needed in the time and costs to design and commercialize new materials for A-USC power plants and related applications. Advanced simulation techniques are needed to enable more rapid development of advanced highly efficient low-emissions power plants. Water supplies for current and future power production facilities are a concern along with toxic emissions and GHG capture.

Technology Readiness Assessment—Key Technologies

The POT Technology Area, supported by the Clean Coal Research Program, is organized into portfolios of four key technologies as depicted in Figure 17.

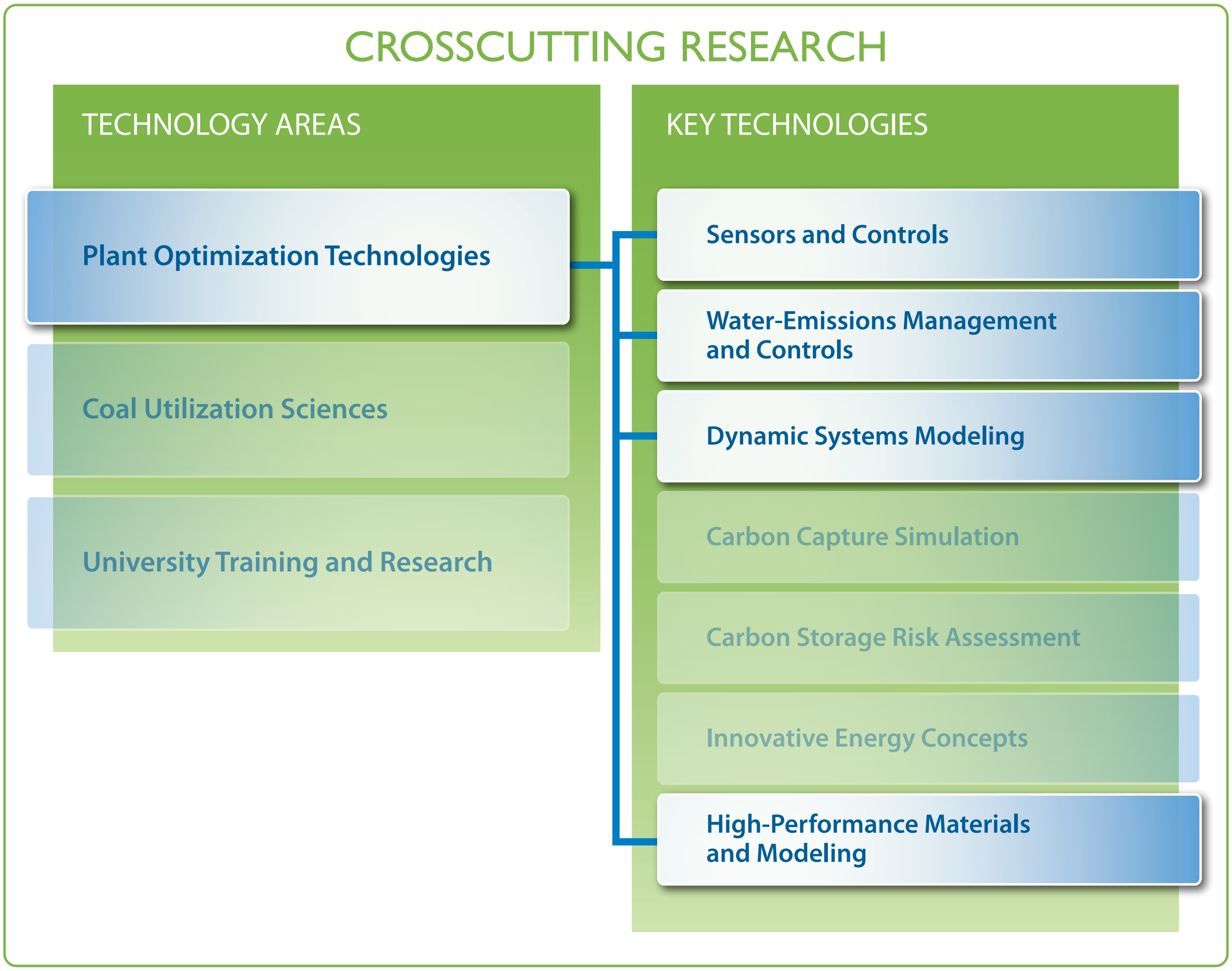

Figure 17: Plant Optimization Technologies Key Technologies

Projects Assessed

Technology readiness has been assessed based on a review of the individual research projects currently underway. This research effort is focused on four key technologies:

- Sensors and Controls
- Water-Emissions Management and Controls
- Dynamic Systems Modeling
- High-Performance Materials and Modeling

In total, the Technology Readiness Levels of 35 projects were assessed in the POT Technology Area: 20 in Sensors and Controls, 5 in Water-Emissions Management and Controls, 4 in Dynamic Systems Modeling, and 6 in High-Performance Materials and Modeling key technologies.

The large number of projects in the Sensors and Controls key technology in part reflects the critical need to develop better sensors and sensing strategies at an accelerated pace to exploit the significant potential to improve the efficiency and operations of advanced fossil energy systems.

The results of the assessment of the scoring analysis are shown in Table 18, which also presents relevancy statements documenting the expected contribution of each project to program goals. Solely funded by the Crosscutting Research subprogram, 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 allied Technology Areas considered in this report.

TECHNOLOGY AREA—QUALITATIVE SUMMARY OF TECHNOLOGY READINESS LEVEL

The critical challenges related to POT require a portfolio encompassing four key technologies. The ongoing research associated with this body of work comprises a diverse collection of technologies and the overall readiness of the POT Technology Area emerges as a range of TRL values.

POT contains individual technologies at different levels of development. As such, the overall readiness of the POT Technology Area is represented by the status of the individual projects evaluated in the portfolio, which have TRL scores ranging from 2 to 6.

KEY TECHNOLOGIES—TECHNOLOGY READINESS ASSESSMENT

Key Technology—Sensors and Controls

Novel sensors, controls, and other architectures are necessary to support the operation of future power-generation facilities that will have harsh environments with higher pressures and temperatures. These needs will be met by continued development in optical sensing, microsensors, novel sensor wireless and energy-harvesting technologies, advanced process control, and transformational sensing and information organization for process control.

The FE portfolio includes eight projects that focus on developing various sensors for condition monitoring of major power-generation components including gasifiers, gas combustion turbines, and boilers. One project is developing an embeddable sensor that uses a concept based on a pair of acoustic generating/detecting devices. These devices are integrated in an optical fiber with capabilities to provide comprehensive information about structural conditions including strain, temperature, and mechanical or chemical degradations such as cracking and corrosion. These sensors are expected to operate in a harsh environment with an extended life cycle and utilize laser, fiber optic, optical sapphire, and nanowire/file composite technologies.

The FE portfolio contains ten projects that are developing sensors for monitoring gas composition, high temperatures, and pressures, either singularly or simultaneously.

Two FE projects in high-density sensor network development and an imaging system for large-scale, cold-flow circulating fluidized beds (CFBs) will improve the efficiency, reliability, and environmental performance of coal-fueled power-generation systems.

In summary, 20 projects within the CCRP POT portfolio that focus on improving sensors and controls technologies were assessed. The current TRL of this key technology spans a range of 2–6, consistent with the status of the individual technologies embedded within these projects.

Key Technology—Water-Emissions Management and Controls

Surface water resources are subject to many residential and industrial demands. Alternate surface water sources such as wastewater and wetlands must be studied to assess the potential to assist in meeting future water needs. An alternate approach is to reduce demand for water by developing low-water-usage technologies. Air quality requirements are another important consideration for power-generation facilities, and novel sensors are necessary to measure and control GHG emissions and particulates to meet current and potential future regulations.

The FE portfolio includes one project that is developing innovative water treatment technology for scale prevention to improve performance of power-plant cooling towers and reduce water consumption by reducing fouling.

Three projects in the FE portfolio address reuse of treated municipal wastewater, impaired waters, and water vapor recovery by applying novel water treatments and membrane separation technology.

The FE portfolio includes one project that is investigating the benefits, costs, and limitations of using restored wetlands for power plant water reuse and as a tertiary treatment of wastewater treatment plant effluent prior to use in a power plant.

In total, five projects within the CCRP POT portfolio that focus on improving water-emissions management and controls technologies were assessed. The current TRL of this key technology spans a range of 4–6, consistent with the status of the individual technologies embedded within these projects.

Key Technology—Dynamic Systems Modeling

Computational modeling and simulation tools are necessary to guide the placement and networking of new advanced sensors capable of operation under the extreme temperature, pressure, and corrosive conditions found in coal-fueled power plants. Computational modeling for advanced sensing will facilitate research to monitor component condition and fault diagnosis in fossil energy systems to reduce forced outages and increase unit availability.

Plant modeling is developed to support critical understanding of plant operation and improvements in control-based performance gains. Continued harsh-environment sensor development and control system enhancements are necessary to address the needs for advanced power systems improvements.

In conjunction with computation expertise, plant optimization includes R&D in novel process control strategies that can manage high levels of process integration and inherent complexity associated with data from multiple sensors. Model-based process control for gasification and chemical-looping processes will be demonstrated virtually.

The complexity associated with process control of complex systems is being addressed through the use of both modeling and experimental techniques.

The FE portfolio includes one project that is developing model-based techniques aimed at enhancing the availability of a gasifier and radiant syngas cooler. This project incorporates information on sensors subjected to harsh conditions and uses a nonlinear model-based estimation algorithm to monitor refractory condition and radiant syngas-cooler fouling, and a nonlinear optimization algorithm for optimal sensor placement. Another project in the portfolio is focused on distributed sensor coordination and includes deriving criteria for assessing the impact of sensor locations and demonstrating the effectiveness and reconfigurability of sensors in response to a change in performance criteria.

Enhancement of performance of next-generation fossil energy power systems is being addressed by two FE portfolio projects focused on developing gasification and reaction kinetics simulation software capabilities and computational approaches for simulation and advanced control for hybrid combustion-gasification chemical looping.

A total of four projects within the CCRP POT portfolio that are focused on improving modeling and simulation 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.

Key Technology—High-Performance Materials and Modeling

Computational modeling and simulation tools are needed to guide the design of new materials capable of operation under extreme temperature, pressure, and corrosive conditions in future A-USC coal-fueled power plants. These tools will assist in decreasing the time and cost required to develop new materials compared to traditional trial-based methodologies.

The FE portfolio includes five projects that are developing computational and modeling capabilities for design of new materials and prediction of high-temperature alloy corrosion wastage and degradation. This information will speed development of new materials for critical high-temperature applications in advanced power plants.

One FE portfolio project is establishing the corrosion behavior of materials in an oxy-fuel environment to address issues with high-temperature structural and turbine service requirements.

In summary, six projects within the CCRP POT portfolio aimed at developing high-performance materials and modeling technologies were assessed. The current TRLs of this key technology are 2 and 3, consistent with the status of the individual technologies embedded within these projects.

PORTFOLIO OF PLANT OPTIMIZATION TECHNOLOGIES PROJECTS

The composite results of the technology readiness assessment for the POT Technology Area are presented in the table below.

Table 18: Plant Optimization Technologies Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement	Supported Program/ Technology Area
Key Technology—Sensors and Controls					
FE0007270	Case Western Reserve University	An Information Theoretic Framework and Self-Organizing Agent-Based Sensor Network Architecture for Power Plant Condition Monitoring	2	Develop an information theoretic framework for monitoring power plant conditions to help reduce forced outages 5–10% by incorporating distributed software agents and companion computational algorithms to maximize collection, transmission, aggregation, and conversion of data.	ACS GS HT
FE0001127	Missouri University of Science and Technology	Micro-Structured Sapphire Fiber Sensors for Simultaneous Measurements of High Temperature and Dynamic Gas Pressure in Harsh Environments	3	Develop unique single-crystal sapphire fiber sensors to measure temperature and gas pressure and contribute to a ≥10% gasification system efficiency gain by using a novel cladding and excitation techniques to assure signal integrity and sensor robustness.	ACS GS HT
NT42439	New Mexico Institute of Mining and Technology	Development of Nanocrystalline-Doped Ceramic-Enabled Fiber Sensors for High-Temperature In-Situ Monitoring of Fossil Fuel Gases	5	Develop sensors for monitoring of syngas in advanced power systems to contribute to ≥10% gasification system efficiency gain by designing, fabricating, and testing nanocrystalline ceramic films and silicalite layers on structured optical fibers.	ACS GS HT
FE0001249	Prime Research	Ultrahigh-Temperature Distributed Wireless Sensors	5	Develop an ultrahigh-temperature wireless sensor to help increase systems reliability ≥5%, by understanding radio frequencies, electromagnetic properties of materials, optimum electromagnetic design, and testing of packaged wireless sensors.	ACS GS HT SOFC
FE0005666	Siemens Energy	Conditioned-Based Monitoring of Turbine Blades Demonstrated in H-Class Engine	3	Develop a sensor suite to enable real-time, high-accuracy, remote monitoring of rotating turbomachinery and help achieve ≥10% turbine system efficiency gain by combining fast area sensors with point sensors connected to wireless transmitters.	ACS GS HT
NT0006833	Siemens Westinghouse Power Corporation	Condition-Based Monitoring of Turbine Combustion Components	5	Develop an integrated condition-monitoring system to contribute to system reliability increase ≥5% by developing direct measurement systems, software, and algorithms for a simulated test turbine.	ACS GS HT
FE0001180	Stanford University	Tunable Diode Laser Sensors to Monitor Temperature and Gas Composition in High-Temperature Coal Gasifiers	5	Improve measurement of temperature and gas composition to optimize gasifier output and gas turbine input and assist in a 2% plant efficiency gain, by designing, building, and testing a tunable diode laser sensor.	GS
NT0005654	Tech4Imaging	Development and Implementation of 3D, High-Speed Capacitance Tomography for Imaging Large-Scale, Cold-Flow Circulating Fluidized Bed	5	Enable more inexpensive exploration of options to contribute to a system efficiency ≥10% in producing power using cold-flow CFBs by developing a three-dimensional, high-speed capacitance tomography system for imaging large-scale CFBs.	ACS GS
FE0001241	University of Central Florida	Online In-Situ Monitoring Combustion Turbines Using Wireless Passive Ceramic Sensors	3	Develop a set of sensors to solve issues related to real-time turbine monitoring and contribute to system reliability increase >5%, by using high-temperature wireless passive ceramic and micro-electro-mechanical systems technologies.	ACS GS HT
FE0000870	University of Connecticut	Multifunctional Nanowire/Film Composites Based Bi-Modular Sensors for In-Situ and Real-Time High-Temperature Gas Detection	3	Develop high-temperature in-situ real-time gas sensors to facilitate the production of hydrogen from coal and help achieve system efficiency >10% by using a unique class of multifunctional metal oxide/perovskite core-shell composite nanostructures.	ACS GS HT

Table 18: Plant Optimization Technologies Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement	Supported Program/ Technology Area
FE0007379	University of Maine System	High-Temperature Wireless Sensor for Harsh Environment Condition Monitoring	2	Develop a novel high-temperature embedded wireless component-monitoring sensor to assist in reducing forced outages 5–10% by using prototype temperature sensors embedded in critical components at operating power plants.	ACS GS HT
FE0005703	Virginia Polytechnic Institute and State University	Distributed Fiber Optic Sensor for Online Monitoring of Coal Gasifier Refractory Health	3	Develop a high-temperature distributed sensing platform for monitoring a gasifier's refractory wall to help reduce forced outages 5–10% by placing the photonic crystal fiber sensor at the back side of the innermost gasifier liner.	GS
FE0007405	Virginia Polytechnic Institute and State University	Embedded Active Fiber Optic Sensing Network for Structural Health Monitoring in Harsh Environments	2	Develop a sensing network for structural health monitoring to provide real-time information on critical power plant components and help reduce forced outages 5–10% by using embedded active fiber optic technology.	ACS GS HT
NT0005591	Virginia Polytechnic Institute and State University	Multiplexed Optical Fiber Sensors for Coal-Fired Advanced Fossil Energy Systems	3	Develop a sensor network for measurement of strain, temperature, and pressure in supercritical and UCS boiler systems to help reduce forced outages 5–10% by packaging multiplexed IFPI fiber optic sensors and demonstrating performance in simulated conditions.	ACS
FT42441	Virginia Polytechnic Institute and State University	Novel Modified Optical Fibers for High-Temperature In-Situ Miniaturized Gas Sensors in Advanced Fossil Energy Systems	3	Develop modified optical fibers for high-temperature in-situ gas sensors to increase measurement capability and contribute to lowering sensor costs more than 20% over the cost of discrete sensors by developing a process to produce holes in optical fibers.	ACS GS HT
FT40685	Virginia Polytechnic Institute and State University	Single-Crystal Sapphire Optical Fiber Sensor Instrumentation	6	Develop and test a prototype temperature-measurement system to solve gasifier temperature-measurement issues and help increase gasifier system reliability ≥5% by using single-crystal-sapphire optical-fiber technology.	ACS GS HT
FE0005717	West Virginia University Research Corporation	Development of Self-Powered Wireless-Ready High-Temperature Electrochemical Sensors of In-Situ Corrosion Monitoring for Boiler Tubes	3	Develop in-situ corrosion-monitoring sensors to detect fireside corrosion on USC boiler tubes, generate a life prediction toolbox, and help reduce forced outages 5–10% by designing, constructing, and demonstrating initial performance of a prototype corrosion sensor.	ACS
AL-06-205-020	Ames Laboratory	High-Density Sensor Network Development	3	Develop understandings, algorithms, and control strategies to utilize sensor networks in power plants to help achieve efficiency gains of 2% by integrating work with the HYPER facility to demonstrate a proof-of-concept for high-density sensor networks.	ACS GS HT SOFC
FC26-08NT43291	University of North Dakota	EERC-DOE Joint Program on Research and Development for Fossil Energy-Related Resources	2–6 [4]*	Make FE systems nonpolluting and more efficient, capture and sequester GHGs, and integrate fossil and renewable energy sources to permit continued use of domestic fossil fuels as a mainstay of U.S. energy production by conducting basic, fundamental, and applied research.	ACS GS HT
FC26-08NT43293	University of Wyoming Research Corporation	DOE-WRI Cooperative Research and Development Program for Fossil Energy-Related Resources	2–7 [3]*	Develop, commercialize, and deploy technologies of value to assist industry with efficient, nonpolluting energy technologies and competitively meet requirements for clean fuels, chemical feedstocks, electricity, and water resources by conducting fundamental and applied research.	ACS GS HT
Key Technology—Water-Emissions Management and Controls					
NT0006644	Applied Ecological Services, Inc.	Wetland Water Cooling Partnership: The Use of Restored Wetlands to Enhance Thermoelectric Power Plant Cooling and Mitigate the Demand of Surface Water Use	6	Examine the use of restored wetlands to enhance and mitigate demand on conventional systems for power plant water reuse by investigating the benefits, costs, and limitations.	ACS GS

Table 18: Plant Optimization Technologies Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement	Supported Program/ Technology Area
NT0006550	Carnegie Mellon University	Use of Treated Municipal Wastewater as Power Plant Cooling System Makeup Water: Tertiary Treatment Versus Expanded Chemical Regimen for Recirculating-Water Quality Management	6	Examine the feasibility of using treated municipal wastewater as cooling system makeup water to reduce surface water demand by conducting experimental studies and economic and social analyses.	ACS GS
NT0005961	GE Global Research	Technology to Facilitate the Use of Impaired Waters in Cooling Towers	4	Make nontraditional water sources available for power plants with water shortage issues to allow operation at full capacity by utilizing effective water treatment technologies.	ACS GS
NT0005308	Drexel University	Application of Pulse Spark Discharges for Scale Prevention and Continuous Filtration Methods in Coal-Fired Power Plant	5	Develop the pulse-spark discharge water-treatment technology to prevent scale formation by precipitating dissolved mineral ions in circulating cooling water and removing precipitated mineral salts with a filter in a simulated laboratory cooling tower.	ACS GS
NT0005350	Gas Technology Institute	Transport Membrane Condenser for Water and Energy Recovery from Power Plant Flue Gas	6	Develop membrane separation technology to mitigate surface water demand and help achieve system energy efficiency gain of ≥10% by directly adding a part of the recovered water vapor to the boiler's feed water loop to replace expensive fresh makeup water.	ACS GS
Key Technology—Dynamic Systems Modeling					
FE0005712	GE Global Research	Model-Based Optimal Sensor Network Design for Condition Monitoring in an IGCC Plant	2	Identify an optimal sensor network design for IGCC plant condition monitoring and help reduce forced outages 5–10% by developing a model-based algorithm for sensor placement that considers refractory degradation and radiant syngas cooler fouling impacts on sensors.	GS
FE0000857	Oregon State University	Distributed Sensor Coordination for Advanced Energy Systems	2	Improve coordinated behavior in large sensor networks to provide a solution to a scalable and reliable sensor coordination issue and help increase systems reliability by ≥5% by deriving, implementing, and testing agent-objective functions.	ACS GS HT
FE0001074	Reaction Design	Package Equivalent Reactor Networks as Reduced-Order Models for Use with CAPE OPEN-Compliant Simulations	4	Develop simulation modeling software to provide an alternative to existing high-fidelity fluid-dynamics models and help achieve systems efficiency gains of ≥10% by integrating reduced-order models and computer-aided process engineering (CAPE)-open architecture.	ACS GS HT
FC26-07NT43095	Alstom Power, Inc.	Development of Computational Approaches for Simulation and Advanced Controls for Hybrid Combustion-Gasification Chemical Looping	5	Develop computational approaches for simulation and advanced controls to enable and contribute to increasing systems reliability ≥5% for chemical-looping plants by developing and testing advanced control algorithms.	ACS GS HT
Key Technology—High-Performance Materials and Modeling					
FE0005867	CFD Research Corporation	Computational Capabilities for Predictions of Grain Boundary Interactions Contributing to Degradation of Refractory Alloys	2	Improve computational capabilities for grain boundary interactions to predict behavior of refractory alloys and help reduce the time required to develop new materials up to 5 years by validating ReaxFF potentials capable of naturally accounting for grain boundaries and segregants.	ACS GS HT
FE0005868	University of Tennessee	Computational Design of Creep-Resistant Alloys and Experimental Validation in Ferritic Superalloys	3	Design and optimize a class of ferritic superalloys to improve the thermal efficiency and help reduce the time required to develop new materials by up to 5 years by developing computational tools for ternary alloys and phases.	ACS GS HT

Table 18: Plant Optimization Technologies Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement	Supported Program/ Technology Area
NT43097	The Babcock & Wilcox Company	Development of Computation Capabilities to Predict the Corrosion Wastage of Boiler Tubes in Advanced Combustion Systems	3	Develop computation capabilities to help develop better alloys and increase plant efficiency by developing accurate equations to predict the fireside corrosion of boiler tubing in the reducing and oxidizing zones as a function of a number of variables.	ACS
FE0005859	GE Global Research	Modeling Creep-Fatigue-Environment Interactions in Steam Turbine Rotor Materials for Advanced Ultra-Supercritical Coal Power Plants	3	Develop multiscale computational algorithms and guidelines to help reduce the time required to develop new materials ≤5 years and assist in reducing the time required for ASME Code approval ≤3 years by conducting bench-scale experiments on a steam turbine rotor superalloy.	ACS HT
AL-07-360-019	Ames Laboratory	Computational and Experimental Development of Novel High-Temperature Alloys	3	Develop a tool for rapid assessment of potential material formulations to find candidate materials for construction of high-temperature gas turbine components and reduce new material development time by performing comparisons using formation enthalpy data.	ACS GS HT
FWP-49640	Argonne National Laboratory	Corrosion and Mechanical Properties of Materials in Combustion and Mixed-Gas Environments	3	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.	ACS GS HT

NOTE:

* The the number in brackets represents the TRL score used for final tabulation purposes in the summary tables at the beginning of the report.

LEGEND:

ACS Advanced Combustion Systems
GS Gasification Systems
HT Hydrogen Turbines
SOFC Solid Oxide Fuel Cell

CROSSCUTTING RESEARCH

COAL UTILIZATION SCIENCES

OVERVIEW

The Coal Utilization Sciences (CUS) Technology Area research effort is developing modeling and simulation technologies intended to lead to a suite of products capable of designing and representing the operation of next-generation near-zero-emissions power systems such as gasification and oxy-combustion. These products are based on validated models and highly detailed representations of equipment and processes. Multinational laboratory efforts are being coordinated through the National Risk Assessment Partnership (NRAP) and Carbon Capture Simulation Initiative (CCSI) to focus on post-combustion capture of carbon, risk assessment, and integrated multiscale physics-based simulations.

DOE/FE Goals

The DOE/FE goals for the CUS Technology Area are to (1) develop high-fidelity computational reduced fluid dynamics models to aid in development of efficient fossil energy systems, (2) demonstrate sensor placement techniques to increase systems reliability by +5 percent or greater, (3) demonstrate multiscale dynamic optimization and smart sensor networks for systems efficiency gains of 4 percent or greater, (4) predict plant performance within 10 percent or less, (5) complete the CCSI toolsets to accelerate CCS and development of advanced energy systems with reduced risk, (6) develop and deploy the Risk Analysis and Decision Making Framework, (7) demonstrate the Risk Assessment and Management Framework for CCS/CCUS, (8) develop cost-efficient low-toxicity power electronics and energetic materials to improve reliability and stability of the grid, (9) develop, assess, and validate computational simulations/experiments to guide development of new materials and new sensors and controls to support high-performance magnetohydrodynamics combined cycles, pressure gained combustion, supercritical CO_2 power cycles, chemical looping, power electronics and energetic materials, (10) reduce the time required to develop new materials, and (11) reduce the time required for ASME Code approval of materials.

Benefits

New computer-aided design tools for virtual design groups will allow the use of information technology in next-generation advanced-fossil-power-systems modeling efforts to lower risks and ensure the long-term viability of carbon capture and storage. These research efforts will reduce power system, carbon capture and storage, as well as MVA costs.

Critical Technology Area Challenges

Critical technology challenges related to CUS include improving advanced simulation techniques that enable more rapid development of advanced highly efficient low-emissions power plants. This includes improved simulation of carbon-capture processes and the acceleration of CCUS. There is a need for evaluations, identification and quantification of the potential risks for carbon sequestration sites, and for cost estimates of the long-term liability associated with carbon sequestration. Also, enhanced design speed and cost reduction are needed for new technology development.

Future sensors and A-USC pressure-boundary components will need materials with unique thermal, chemical, and mechanical properties for advanced fossil-fuel-based power-generation plants. The time to design and commercialize new materials for A-USC power plants and related applications must be reduced. Refined assessments of advanced power-generation approaches are needed to guide work in the areas of grid-scale energy storage, chemical looping, supercritical CO_2 power cycles, magnetohydrodynamics combined cycles, and pressure-gain combustion.

Technology Readiness Assessment—Key Technologies

The CUS Technology Area, supported by the Clean Coal Research Program, is organized into portfolios of five key technologies as depicted in Figure 18.

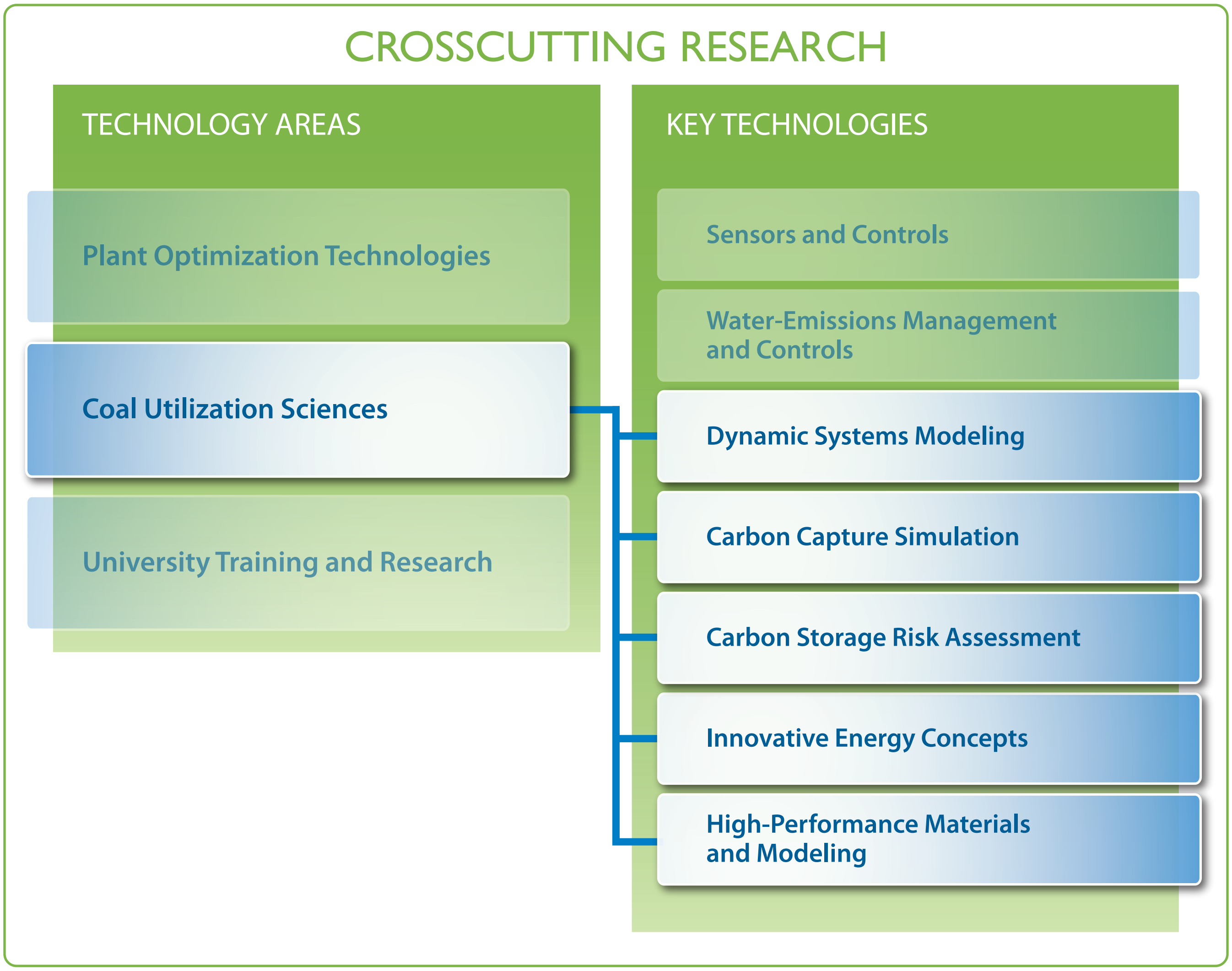

Figure 18: Coal Utilization Sciences Key Technologies

Projects Assessed

Technology readiness has been assessed based on a review of the individual research projects currently underway. FE has considerable research underway to improve various CUS techniques. This research effort is focused on five key technologies:

- Dynamic Systems Modeling
- Carbon Capture Simulation
- Carbon Storage Risk Assessment
- Innovative Energy Concepts
- High-Performance Materials and Modeling

In total, the Technology Readiness Levels of 20 projects were assessed in the CUS Technology Area: 8 in Dynamic Systems Modeling, 1 in Carbon Capture Simulation, 3 in Carbon Storage Risk Assessment, 7 in Innovative Energy Concepts, and 1 in High-Performance Materials and Modeling.

The Technology Areas supported by CUS projects and the results of the assessment of the scoring analysis are shown in Table 19, which also presents relevancy statements documenting the expected contribution of each project to program goals. Solely funded by the Crosscutting Research subprogram, 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 many allied Technology Areas.

TECHNOLOGY AREA—QUALITATIVE SUMMARY OF TECHNOLOGY READINESS LEVEL

The critical challenges related to CUS require a portfolio of technologies encompassing five areas. The ongoing research associated with this body of work comprises a diverse collection of technologies and the overall readiness of the CUS Technology Area emerges as a range of TRL values.

The CUS Technology Area contains individual technologies at different levels of development. As such, the overall readiness of the CUS Technology Area is represented by the status of the individual projects evaluated in the portfolio, which have TRL scores ranging from 2 to 4.

KEY TECHNOLOGIES—TECHNOLOGY READINESS ASSESSMENT

Key Technology—Dynamic Systems Modeling

Computational modeling and simulation tools are required to guide the placement and networking of new advanced sensors capable of operation under the extreme temperature, pressure, and corrosive conditions found in coal-fueled power plants. Computational modeling for advanced sensing will enable research to monitor component condition and fault diagnosis in fossil energy systems to reduce forced outages and increase unit availability.

Plant modeling is developed to support critical understanding of plant operation and improvements in control-based performance gains. Continued harsh-environmental sensor development and control system improvements are necessary to address the needs for advanced power systems improvements.

In conjunction with computation expertise, plant optimization will include R&D in novel process control strategies that can manage high levels of process integration and inherent complexity associated with data from multiple sensors. Model-based process control for gasification and chemical-looping processes will be demonstrated virtually.

The complexity associated with process control of complex systems is being addressed through the use of both modeling and experimental techniques. Sensor placement and virtual power plant modeling are critical to optimize power plant operations.

In summary, eight projects within the CCRP CUS portfolio focused on improving modeling and simulation technologies were assessed. The current TRL rating of this key technology spans a range of 2–4.

Key Technology—Carbon Capture Simulation

Post-combustion carbon capture simulation, risk assessment, and integrated multiscale physics-based simulations are essential for design, construction, and operation of future power-generation facilities. CCSI is developing a modeling toolset to simulate scaleup of a broad set of new carbon-capture technologies for the electric power-generation industry. The CCSI toolset is organized into ten elements that fall under three focus areas: physicochemical models and data, analysis and software, and industrial applications.

One project within the CCRP CUS portfolio focused on improving carbon capture simulation technologies was assessed. The current TRL of this key technology is 3.

Key Technology—Carbon Storage Risk Assessment

Carbon storage risk assessment is being addressed through the initiation of NRAP, a multilaboratory CCUS modeling effort. This collaborative effort will use best-in-class computational methods to accelerate CCUS development and craft robust methodologies for calculating defensible, quantitative, site-specific risk profiles and for integrating monitoring and mitigation strategies with risk minimization. The work is focused on R&D efforts to improve computational models/methodologies and quantify uncertainties to uncover the most important knowledge gaps associated with the long-term storage of CO_2 in the natural environment.

In summary, three projects within the CCRP CUS portfolio focused on improving carbon storage risk assessment technologies were assessed. The current TRL scores for this key technology are 3 and 4.

Key Technology—Innovative Energy Concepts

Innovative energy concepts are being pursued to lower cost and develop higher performance energy-storage technologies to address grid-scale energy storage in the power electronics and energetic materials focus area. Innovative energy concepts being evaluated include magnetohydrodynamics-combined cycles, pressure-gain combustion, chemical looping, and supercritical CO_2 power cycles. Complex, new advanced material structures will be tailored or tuned by developing a predictive multiscale computational framework. Multiphase flow research will be accelerated by development of improved algorithms and calculation routines that reduce solution times.

Seven projects within the CCRP CUS portfolio aimed at developing high-confidence innovative energy concepts were assessed. The current TRL of this key technology spans a range of 2–4.

Key Technology—High-Performance Materials and Modeling

Computational modeling and simulation tools are needed to guide the design of new materials capable of operation under extreme temperature, pressure, and corrosive conditions in future A-USC coal-fueled power plants. These tools will assist in decreasing the time and cost required to develop new materials compared to the use of traditional trial-based methodologies. A critical need is the development of chemistries that will form either protective chromia-oxide scales or alumina-oxide scales depending upon the application environment and performance requirements. Work also continues on development of Nb, Mo, Cr, and W alloys based on refractory metal elements to withstand the high temperatures and aggressive environments that are predicted for oxy-fuel turbines, hydrogen turbines, and syngas turbines.

One project within the CCRP CUS portfolio aimed at developing high-confidence, high-performance materials models for corrosion wastage was assessed. The current TRL of this key technology is 3.

PORTFOLIO OF COAL UTILIZATION SCIENCES PROJECTS

The composite results of the technology readiness assessment for the CUS Technology Area are presented in the table below.

Table 19: Coal Utilization Sciences Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement	Supported Program/ Technology Area
Key Technology—Dynamic Systems Modeling					
FE0005749	Texas Tech University	Model-Based Sensor Placement for Component-Condition Monitoring and Fault Diagnosis in Fossil Energy Systems	2	Improve sensor networks for monitoring gasification plant component health and diagnosing faults to help increase systems reliability by >5% by developing a two-tier (distributed and plant-level) sensor placement algorithm and enhancing models with incorporation of identified system level faults.	ACS GS HT
NT43098	University of Colorado	Development, Verification, and Validation of Multiphase Models for Polydisperse Flows	4	Upgrade Multiphase Flow with Interphase eXchanges (MFIX) to help predict plant performance <10% by deriving constitutive relations for a polydisperse solid phase, developing a drag law for polydisperse flows, and extending gas-phase turbulence models to account for polydisperse particles.	ACS GS HT
AL-00-470-001	Ames Laboratory	Technology Crosscut (Kinetic Theory of Multiphase Flow)	3	Further understanding of CFBs to provide underpinning for computer code construction and aid in developing energy systems with efficiency gains of 2% by performing analytical studies to enable theoretical estimates for transport coefficient analogues that parameterize computer simulations.	ACS GS HT
NT0005395	Alstom Power, Inc.	Process/Equipment Cosimulation of Oxy-Combustion and Chemical-Looping Combustion	3	Upgrade the APECS computational toolkit to allow systematic evaluations of various oxy-combustion and chemical-looping concepts by coupling user-defined functions and modifying an existing process model of a commercial chemical-looping facility.	ACS

Table 19: Coal Utilization Sciences Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement	Supported Program/ Technology Area
AL-00-470-002	Ames Laboratory	Coal Utilization Science (Development of Virtual Power Plants)	4	Develop virtual engineering tools to provide power plant designers and trainers with a robust computational environment and help predict plant performance <10%, by incorporating multibody physics, hotlinks to physics-based engines, and human interaction for optimization.	ACS GS HT
AL-07-450-004	Ames Laboratory	Coal Utilization Science (Virtual Advanced Power Training Environments)	4	Develop a set of advanced virtual power plant training environments to provide future operators with an improved understanding of the plant by integrating these tools into the training and research environment.	ACS GS HT
FEW0709	Sandia National Laboratories	Advanced Coal Combustion and Gasification Science	3	Develop fundamental information on the kinetics of advanced combustion and gasification systems to assist with design and commercialization and help achieve efficiency gains of 2% by obtaining experimental measurements of gasification kinetics of coal char at high temperature and pressure.	ACS GS
49629	Argonne National Laboratory	Fundamental Studies of Clay and Clay-Rich Mineral Reactions with H_2O-CO_2 Fluids: Applications to Geological Sequestration	3	Understand CO_2 injection interaction with swellable clay to enhance the predictive capability of geological sequestration models by integrating observations of key geochemical processes under simulated in-situ sequestration conditions.	ACS GS
Key Technology—Carbon Capture Simulation					
2012.04.02	Multiple Partners	Carbon Capture Simulation Initiative	3	Develop the CCSI toolset to accelerate commercialization of carbon capture technologies with reduced risk by increasing confidence in designs and reducing risk associated with incorporating multiple innovative technologies.	ORD
Key Technology—Carbon Storage Risk Assessment					
2012.04.03	National Energy Technology Laboratory	National Risk Assessment Partnership—Task 2: Develop a Methodology for Quantification of Site-Specific Risk Profiles	4–5 [4]*	Develop and apply a system-level methodology to support site-specific risk evaluations for the Risk Analysis and Decision Making Framework by using integrated assessment models consisting of reduced-order models based on detailed physical and chemical models with laboratory and field data.	ACS GS HT
2012.04.03	National Energy Technology Laboratory	National Risk Assessment Partnership—Task 3: Ensure the Science Base and Validity of the Methodology for Quantifying Site-Specific Risk Profiles	3	Develop the science base to quantify risk profiles associated with geologic carbon storage sites for the Risk Analysis and Decision Making Framework by performing assessments, simulations, and studies, developing Generation II groundwater models, and conducting laboratory experiments.	ACS GS HT
2012.04.03	National Energy Technology Laboratory	National Risk Assessment Partnership—Task 5: Develop Monitoring and Mitigation Strategies to Lower Uncertainties and Risk	3	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 by considering and assessing the variations expected across geologic sites.	ACS GS HT
Key Technology—Innovative Energy Concepts					
2012.04.01	National Energy Technology Laboratory	Innovative Process Technology, Field Work Proposal—Task 2: Sensors and Controls, Task 2.1 Raman Sensor Commercialization	4	Transfer the Raman gas sensor technology to the commercial sector for use in power generation by validation in a high-fidelity laboratory environment and via suitable licensing agreements for further development.	ACS GS HT
2012.04.01	National Energy Technology Laboratory	Innovative Process Technology, Field Work Proposal—Task 2: Sensors and Controls, Task 2.2 Sensor Materials	2	Develop materials to solve issues related to high-temperature and harsh-environment embedded sensing in advanced fossil energy applications by using nanocomposite thin films as functional optical sensor materials.	ACS GS HT

Table 19: Coal Utilization Sciences Composite Results

Agreement Number	Performer	Project Title	TRL	Relevancy Statement	Supported Program/ Technology Area
2012.04.01	National Energy Technology Laboratory	Innovative Process Technology, Field Work Proposal—Task 2: Sensors and Controls, Task 2.3 Sensors and Advanced Controls Testing in NETL's HYPER Facility	2	Develop an advanced control system to provide efficient control of future power plants based on stigmergy by coordinating testing of the advanced controls approach in the HYPER facility at NETL.	ACS GS HT
2012.04.01	National Energy Technology Laboratory	Innovative Process Technology, Field Work Proposal—Task 3: Power Electronics and Energetic Materials	3	Develop an integrated electrochemical architecture to enhance grid performance and provide extra energy during peak demand periods by conducting laboratory demonstrations on various batteries with new and novel Mg-based cathode materials.	ACS GS HT
2012.04.01	National Energy Technology Laboratory	Innovative Process Technology, Field Work Proposal—Task 4: Innovative Energy Concepts	3	Assess advanced energy concepts to potentially offset the penalty connected with CO_2 capture from existing power systems by using validated simulations to accelerate the development and deployment of potentially transformational systems.	ACS GS HT
2012.04.01	National Energy Technology Laboratory	Innovative Process Technology, Field Work Proposal—Task 5: Computational Materials, Integrated Materials Initiative	3	Develop a predictive multiscale computational framework to guide development of advanced, cost-effective materials for carbon capture and storage power systems by integrating multiscale computational approaches with focused validation experiments.	ACS GS HT
2012.04.01	National Energy Technology Laboratory	Innovative Process Technology, NETL Energy Systems Dynamics Activities Field Work Proposal—Task 6: Multiphase Flow	3	Enhance MFIX to address critical aspects of fossil-fuel energy production by reducing time to solution, improving basic understanding of polydisperse reacting flows and the methodology needed to reduce data sampling for uncertainty quantification.	ACS GS HT
Key Technology—High-Performance Materials and Modeling					
FE0005865	University of Missouri, Kansas City	Large-Scale Simulations of the Mechanical Properties of Layered-Transition-Metal Ternary Compounds for Fossil Energy Power System Applications	3	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 <5 years by modeling and performing laboratory testing of layered transition-metal carbides or nitrides.	ACS GS HT

NOTE:

* The the number in brackets represents the TRL score used for final tabulation purposes in the summary tables at the beginning of the report.

LEGEND:

ACS Advanced Combustion Systems
GS Gasification Systems
HT Hydrogen Turbines
ORD NETL's Office of Research and Development Supporting Science and Enabling Technologies projects

CROSSCUTTING RESEARCH

UNIVERSITY TRAINING AND RESEARCH

OVERVIEW

The University Training and Research (UTR) Technology Area awards grants to U.S. colleges and universities. There is an emphasis on longer term research across all Crosscutting Research R&D areas with a unique portfolio of Sensors and Controls, Dynamic Systems Modeling, and High-Performance Materials and Modeling technologies that provide tools and techniques to facilitate design of power plants with lower emissions, greater efficiency, increased reliability, and enhanced availability.

DOE/FE Goals

The DOE/FE goals for the UTR Technology Area are derived from the other two Crosscutting Research Technology Areas—Plant Optimization Technologies and Coal Utilization Sciences. The following is a summary of the goals:

- *Plant Optimization Technologies* – (1) lower sensor costs greater than 20 percent over discrete sensors, (2) increase systems reliability by 5 percent or greater, (3) achieve systems efficiency gains of 4 percent or greater, (4) reduce forced outages by 5–10 percent, (5) mitigate the demand for surface water, (6) develop emissions sensors, (7) reduce the time required to develop new materials, and (8) reduce time required for ASME Code approval of new materials.
- *Coal Utilization Sciences* – (1) develop high-fidelity computational reduced fluid dynamics to aid in development of efficient fossil energy systems, (2) demonstrate sensor placement techniques to increase systems reliability by 5 percent or greater, (3) demonstrate multiscale dynamic optimization and smart sensor networks for systems efficiency gains of 4 percent or greater, (4) predict plant performance within 10 percent or less, (5) complete the CCSI toolsets to accelerate CCUS and development of advanced energy systems with reduced risk, (6) develop and deploy the Risk Analysis and Decision Making Framework, (7) demonstrate the Risk Assessment and Management Framework for CCUS, (8) develop cost-efficient low-toxicity power electronics and energetic materials to improve reliability and stability of the grid, (9) develop, assess, and validate computational simulations/experiments to guide development of new materials and new sensors and controls to support high-performance magnetohydrodynamics combined cycles, pressure-gained combustion, supercritical CO_2 power cycles, chemical looping, power electronics, and energetic materials, (10) reduce the time required to develop new materials, and (11) reduce the time required for ASME Code approval of materials.

Benefits

UTR's pathways will develop technologies to:

- Sustain a national university program of research in energy and environmental science and engineering related to coal that focuses on innovative and fundamental investigations pertinent to coal conversion and utilization
- Provide a future supply of coal scientists and engineers through research exposure to coal technologies while advancing the science of clean energy from coal
- Improve our fundamental scientific and technical understanding of chemical and physical processes involved in the conversion and utilization of coal—one of our nation's most abundant natural resources—and its byproducts

UTR is divided into two components: University Coal Research (UCR) and Historically Black Colleges and Universities and Other Minority Institutions (HBCU/OMI).

UCR provides grants to U.S. universities to support fundamental research that cuts across FE's research focus areas and improves fossil energy technologies. The primary purpose of UCR is to improve the fundamental scientific and technical understanding of the chemical and physical processes involved in conversion and utilization of coal.

HBCU/OMI provides a mechanism for implementing cooperative research among HBCU/OMI institutions, the private sector, and Federal agencies. The central thrust of this effort is to generate fresh ideas and tap underutilized talent, define applicable fundamental scientific principles, and develop advanced concepts for generating new and improved technologies across the full spectrum of FE's R&D program areas.

Critical Technology Area Challenges

Critical technology challenges related to UTR are improvement of the efficiency and enhancement of the reliability and availability of power systems. Novel and new classes of sensors need to be developed to implement and optimize advanced fossil fuel-based power-generation systems. Future sensors and A-USC pressure-boundary components will require materials having unique thermal, chemical, and mechanical properties for advanced fossil fuel-based power-generation plants. A reduction is needed in the time and costs to design and commercialize new materials for A-USC power plants and related applications. Advanced simulation techniques are also needed to enable more rapid development of advanced highly efficient, low-emissions power plants.

Technology Readiness Assessment—Key Technologies

The UTR Technology Area, supported by the Clean Coal Research Program, is organized into portfolios of the three key technologies depicted in Figure 19.

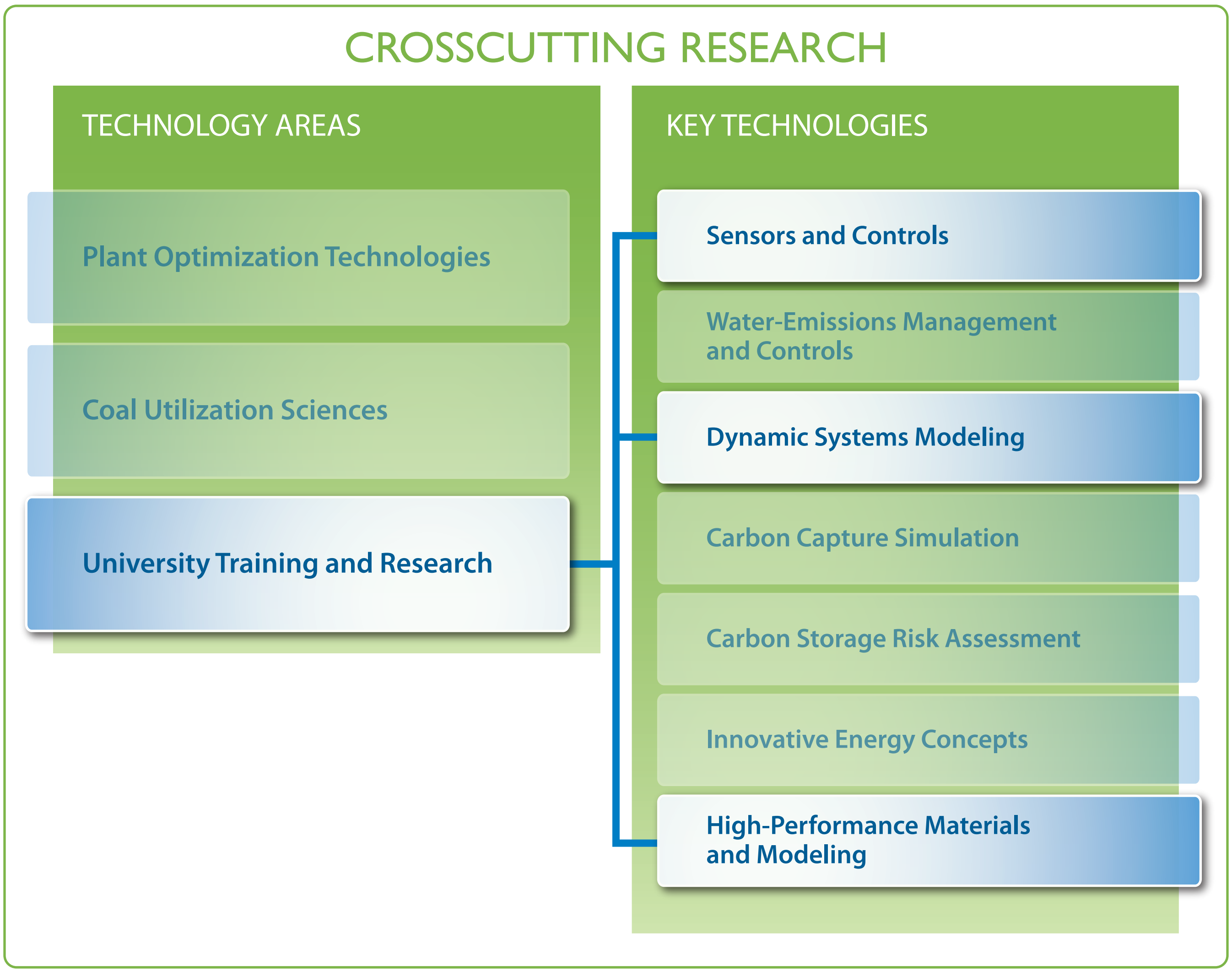

Figure 19: University Training and Research Key Technologies

Projects Assessed

UTR consists of 34 projects, each funded at less than $300,000. Therefore, the individual projects fall under the threshold for TRL assessment. However, because FE has considerable research underway to improve sensors and controls, computational modeling, and materials, the technology readiness for this Technology Area as a whole was assessed based on a Technology Manager review of the ensemble of individual research projects currently in the UTR portfolio. This research effort is focused on the three key technologies:

- Sensors and Controls—Control system development is viewed as an important enabling technology for the commercial deployment of advanced power-generation systems.
- Dynamic Systems Modeling—Work is in areas such as the development of theory and advanced computational models, the gathering of experimental data from physical systems or molecular dynamics simulations, and the validation of the models.
- High-Performance Materials and Modeling—New materials are required to significantly improve performance and reduce costs of existing and/or advanced coal-based power systems.

The Technology Areas supported by UTR projects and a summary of the individual projects is presented in Table 20 and shows the technical breadth of the effort. Solely funded by the Crosscutting Research subprogram, 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.

TECHNOLOGY AREA—QUALITATIVE SUMMARY OF TECHNOLOGY READINESS LEVEL

The critical technology challenges related to UTR require development of a portfolio of technologies encompassing three key technologies. The ongoing research associated with this body of work comprises a diverse collection of technologies and the overall readiness of UTR emerges as a range of TRL values. The overall readiness of the UTR research by its nature is fundamental to applied application toward fossil energy technical needs. Individual projects have received a tabletop review and the UTR portfolio as a whole is consistent with TRL scores of 2 and 3.

KEY TECHNOLOGIES—TECHNOLOGY READINESS ASSESSMENT

Key Technology—Sensors and Controls

Novel sensors, controls, and other architectures are necessary to support the operation of future power-generation facilities that will have harsh environments with higher pressures and temperatures. These needs will be met by continued development in optical sensing, micro sensors, novel sensor wireless and energy-harvesting technologies, advanced process control, and transformational sensing and information organization for process control.

The CCRP UTR portfolio has 11 projects focused on improving sensors and controls technologies.

Key Technology—Dynamic Systems Modeling

Computational modeling and simulation tools are required to guide the placement and networking of advanced sensors capable of operation under the extreme temperature, pressure, and corrosive conditions found in coal-fueled power plants. This computational modeling for advanced sensing will enable researchers to monitor component condition and fault diagnosis in fossil energy systems to reduce forced outages and increase unit availability.

Plant modeling is performed to develop critical understanding of plant operation and improvements in control-based performance gains. Continued harsh-environmental sensor development and control system improvements are necessary to address the needs for advanced power systems applications.

In conjunction with computation expertise, plant optimization will include R&D in novel process control strategies that can manage high levels of process integration and inherent complexity associated with data from multiple sensors. Model-based process control for gasification and chemical-looping processes will be demonstrated virtually.

The complexity associated with process control of complex systems is being addressed through the use of both modeling and experimental techniques.

The CCRP UTR portfolio has 12 projects focused on improving dynamic systems modeling technologies.

Key Technology—High-Performance Materials and Modeling

Computational modeling and simulation tools are needed to guide the design of new materials capable of operation under the extreme temperature, pressure, and corrosive conditions found in coal-fueled power plants. These tools will assist in decreasing the time and cost required to develop new materials compared to traditional trial-based methodologies.

A critical need is the development of chemistries that will form either protective chromia-oxide scales or alumina-oxide scales depending upon the application environment and performance requirements. Work also continues on development of alloys based on refractory metal elements (Nb, Mo, Cr, and W) to withstand the high temperatures and aggressive environments that are predicted for oxy-fuel turbines, hydrogen turbines, and syngas turbines.

The CCRP UTR portfolio has 11 projects focused on improving high-performance materials and modeling technologies.

PORTFOLIO OF UNIVERSITY TRAINING AND RESEARCH PROJECTS

The composite results of the technology readiness assessment for the UTR Technology Area are presented in the table below.

Table 20: University Training and Research Composite Results

Agreement Number	Performer	Project Title	Supported Program/ Technology Area
Key Technology—Sensors and Controls			
FE0007225	University of Texas at El Paso	Gallium Oxide Nanostructures for High-Temperature Sensors	ACS GS HT
NT0008022	University of Texas at El Paso	Investigation of WO_3-Based H_2S Sensor Materials for Coal Gasification Systems	ACS GS HT
FE0003780	University of Texas at San Antonio	Development of High-Temperature and High-Sensitivity Novel Chemical-Resistive Sensor	ACS GS HT
FE0007190	The Research Foundation of State University of New York	Heat-Activated Plasmonics-Based Harsh-Environment Chemical Sensors	ACS GS HT
NT0007918	The Research Foundation of State University of New York	Plasmonics-Based Harsh-Environment-Compatible Chemical Sensors	ACS GS HT
FE0007004	University of Central Florida	Wireless Passive Ceramic Strain Sensors for Turbine Engine Applications	ACS GS HT
NT0008062	University of Cincinnati	Development of Novel Ceramic Nanofilm Integrated Optical Sensors for Rapid Detection of Coal-Derived Synthesis Gas	ACS GS HT
FE0006947	The University of Utah	In-Situ Acoustic Measurements of Temperature Profiles in Extreme Environments	ACS GS HT
FE0007272	University of Washington	High-Temperature Thermoelectric Oxides Engineered at Multiple Length Scales for Energy Harvesting	ACS GS HT
FE0003859	University of Pittsburgh	Metal-Oxide Sensing Materials Integrated with High-Temperature Optical-Sensor Platforms for Real-Time Fossil Fuel Gas Composition Analysis	ACS GS HT
FE0003872	West Virginia University	High-Temperature Nanoderived Micro-H_2 and -H_2S Sensors	ACS GS HT
Key Technology—Dynamic Systems Modeling			
FE0007260	Florida International University	Development of a Two-Fluid Drag Law for Clustered Particles Using Direct Numerical Simulation and Validation Through Experiments	ACS GS HT
FE0003997	Illinois Institute of Technology	Computational Fluid Dynamic Simulations of a Regenerative Process for Carbon Dioxide Capture in Advanced Gasification-Based Power Systems	GS
FE0006932	Princeton University	Implementation and Refinement of a Comprehensive Model for Dense Granular Flows	ACS GS HT
FE0007520	Tuskegee University	Study of Particle Rotation Effect in Gas-Solid Flows Using Direct Numerical Simulation with a Lattice Boltzmann Method	ACS GS
FE0003742	University of Texas at El Paso	Investigation of Gas-Solid Fluidized Bed Dynamics with Nonspherical Particles	ACS GS
NT0008064	University of Texas at San Antonio	Use of an Accurate Direct Numerical Simulation Particulate Flow Method to Supply and Validate Boundary Conditions for the MFIX Code	ACS GS HT
NT43069	Georgia Tech Research Corporation	Prediction of Combustion Stability and Flashback in Turbines with High-Hydrogen Fuel	HT
FE0006946	Iowa State University	Uncertainty Quantification Tools for Multiphase Gas-Solid Flow Simulations Using MFIX	ACS GS HT
NT0007428	The Ohio State University Research Foundation	Process/Equipment Cosimulation on Syngas Chemical-Looping Process	ACS
FE0007450	The Regents of The University of Colorado	Quantifying the Uncertainty of Kinetic-Theory Predictions of Clustering	ACS GS HT
FE0003801	University of California, Merced	High-Fidelity Multiphase Radiation Module for Modern Coal Combustion Systems	ACS GS

Table 20: University Training and Research Composite Results

Agreement Number	Performer	Project Title	Supported Program/ Technology Area
NT0043326	Virginia Polytechnic Institute and State University	Experimental and Computational Investigations of Boundary Condition Effects on CFD Simulations of Thermoacoustic Instabilities	ACS GS
Key Technology—High-Performance Materials and Modeling			
NT0008066	North Carolina Agricultural and Technical State University	Bimetallic Nanocatalysts in Mesoporous Silica for Hydrogen Production from Coal-Derived Fuels	ACS GS
FE0007220	Southern University and A&M College System	An Integrated Study on the Novel Thermal Barrier Coating for Nb-Based High-Temperature Alloy	ACS GS HT
FE0003892	Clemson University	Multiscale Modeling of GB Segregation and Embrittlement in Tungsten for Mechanistic Design of Alloys for Coal-Fired Plants	ACS GS
FE0004007	Missouri University of Science and Technology	Ab Initio Modeling of Thermomechanical Properties of Mo-Based Alloys for Fossil Energy Conversion	ACS GS HT
NT0008089	University of Tennessee	Computational and Experimental Design of FE-Based Superalloys for Elevated Temperature Applications	ACS GS HT
NT0007636	University of Texas at Dallas	Novel Zeolitic Imidazolate-Framework Polymer Membranes for Hydrogen Separations in Coal Processing	ACS GS HT
FE0003693	Southern University and A&M College System	Computer Simulation and Experimental Validation on the Oxidation and Sulfate-Corrosion Resistance of Novel Chromium-Based High-Temperature Alloys	ACS GS HT
FE0003840	Carnegie Mellon University	High-Resolution Modeling of Materials for High-Temperature Service	ACS GS HT
FE0007377	University of Wisconsin System	Active Multiscale Computational Design and Synthesis of Protective Smart Coatings for Refractory Metal Alloys	ACS GS HT
FE0003798	Tennessee State University	Computational Studies of Physical Properties of Nb-Si Alloy	ACS GS HT
NT0001473	North Carolina Agricultural and Technical State University	Fabrication of Pd/Pd Alloy Films by Surfactant-Induced Electroless Plating	ACS GS HT

LEGEND:

ACS Advanced Combustion Systems

GS Gasification Systems

HT Hydrogen Turbines

CCS/CCUS DEMONSTRATIONS

OVERVIEW

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

DOE is addressing the key challenges that confront the wide-scale industrial deployment of CCS/CCUS technologies by sponsoring large-scale demonstrations of key R&D technologies including the cost-effective capture, utilization, and storage of CO_2 integrated with power-generation and industrial facilities. The CCS/CCUS 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/CCUS 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 MVA protocols to provide a high level of confidence that injected CO_2 remains permanently sequestered in geologic formations.

Today, demonstration of key CCS/CCUS technologies is being achieved via eight diverse power-generation and industrial platforms. These demonstration platforms represent various technology configurations, utilize a diverse set of feedstocks, produce a variety of commodities, and utilize the captured CO_2 for multiple purposes including chemical production, permanently storing the captured CO_2 in saline reservoirs, or EOR (by others). Figure 20 illustrates the relationship of these eight demonstration platforms to the four pathways and the three program components.

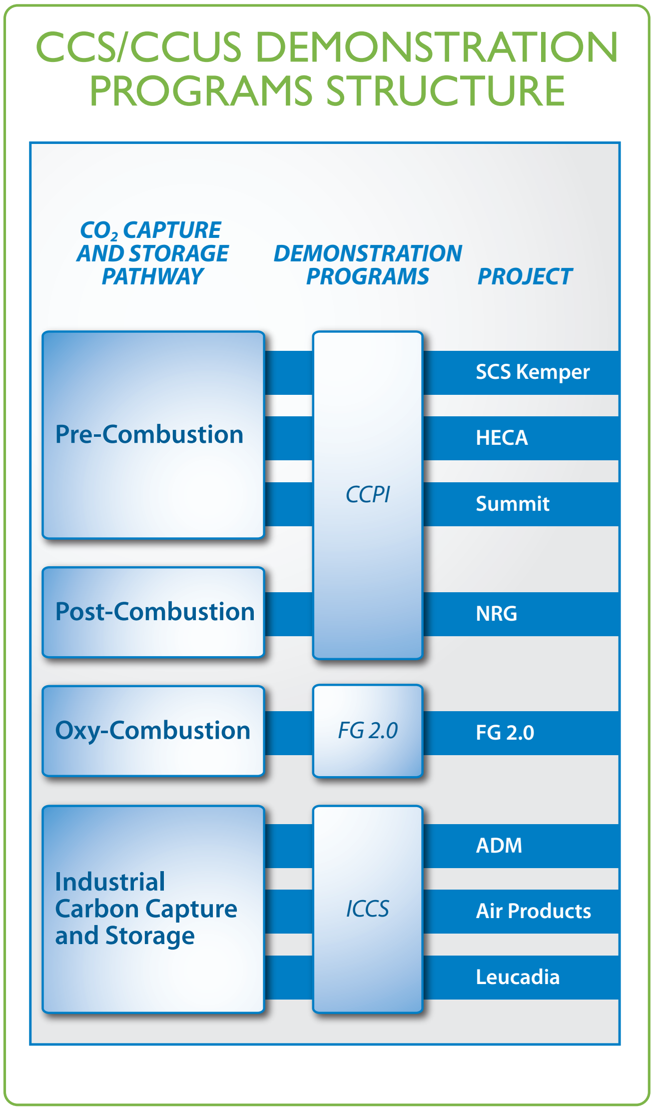

Figure 20: CCS/CCUS Demonstrations Program Structure

The eight demonstration platforms and their associated project(s) are described below.

Pre-Combustion

- *SCS-Kemper (CCPI)* – Lignite-fueled TRIG gasifier operating in a pressurized air-blown mode in an IGCC configuration. Electricity is generated via high-H_2 syngas-fired gas turbines and conventional steam turbines. Captured CO_2 will be used by others for EOR and sulfuric acid will be produced as a byproduct. Other systems/technologies being advanced via this commercial-scale integrated technology demonstration platform include: coal drying (fluidized bed), a coal-feed system (pressure decoupled advanced coal feeders), water-gas-shift reactors (at different operating conditions compared to current designs, with new catalysts, and in an IGCC configuration), particulate collection devices (barrier filters), an advanced gas turbine (Siemens F-class fired with a high-H_2 syngas), and pre-combustion hydrogen sulfide (H_2S) and CO_2 capture (Selexol™). Since this project was awarded under the CCPI-2 solicitation, which did not include a requirement for MVA, no MVA is associated with this project.
- *HECA (CCPI)* – Coal/petcoke-blend-fueled Mitsubishi Heavy Industries (MHI) two-stage gasifier, operating in a pressurized oxygen-blown mode in an IGCC/polygeneration configuration. Electricity is generated via a high-H_2 syngas-fired gas turbine and steam turbine technologies. Captured CO_2 will be used for production of urea and urea ammonium nitrate (UAN) and by others for EOR. Liquid sulfur will also be produced as a byproduct. Other systems/technologies being advanced via this integrated technology demonstration platform include: a coal/petcoke feeder, water-gas-shift reactors (in an IGCC/polygeneration configuration), a gas turbine (air-cooled MHI G-class fired with a high-H_2 syngas), pre-combustion H_2S and CO_2 capture (Rectisol), urea and UAN production (produced from an IGCC-derived syngas), and MVA.
- *Summit (CCPI)* – Powder River Basin (PRB) coal-fueled Siemens SFG-500 pressurized entrained-flow slagging reactor, functioning in an oxygen-blown mode in an IGCC/polygeneration configuration. Electricity is generated via a high-H_2 syngas-fired gas turbine and steam turbine technologies. Captured CO_2 will be used for production of urea and by others for EOR. Sulfuric acid will also be generated as a byproduct. Other systems/technologies being advanced via this integrated technology demonstration platform include: water-gas-shift reactors (operating in an IGCC/polygeneration configuration), an advanced gas turbine (Siemens F-class fired with a high-H_2 syngas and in an IGCC/polygeneration configuration), water treatment (reverse osmosis in a IGCC/polygeneration configuration), an advanced steam turbine (Siemens SST-900RD), air-cooled steam condensers integrated with Siemens SST-900RD steam turbines, a heat recovery steam generator (using high-H_2 fuel gas for duct firing), and MVA.

Post-Combustion

- *NRG (CCPI)* – Conventional pulverized coal-fired power-generation facility using PRB coal. Carbon capture and storage technology is being added to a 240-MW slipstream. Electricity is generated via traditional steam turbine and natural gas-fired turbine technologies. Captured CO_2 will be used by others for EOR. Other systems/technologies also being advanced via this commercial-scale integrated technology demonstration platform include post-combustion CO_2 capture and MVA.

Oxy-Combustion

- *FutureGen 2.0 (FG 2.0)* – Mixture of low- and high-sulfur coals combusted in an oxy-combustion boiler fully integrated with a large-scale (8,000 tons per day) ASU for power generation. Carbon dioxide is captured post-combustion, purified, and transported via pipeline for geologic storage in a saline formation. Associated systems/technologies being demonstrated in conjunction with this commercial-scale demonstration platform include: an ASU that is fully integrated with a steam turbine to help maximize plant thermodynamic efficiency, a sulfur removal circulating drying scrubbing system, cryogenic CO_2 compression and purification, and MVA.

Industrial Carbon Capture and Storage

- *ADM (ICCS)* – Commercial-scale corn-to-ethanol fermentation plant industrial facility. High-purity CO_2 will be dried using triethylene glycol technology, compressed, transported via pipeline and sequestered in a saline formation (Mt. Simon sandstone formation). Associated systems/technologies being advanced include commercial-scale demonstration of CO_2 transport from an existing industrial source, geologic sequestration (saline aquifer) of the CO_2, and MVA.
- *Air Products and Chemicals (ICCS)* – Commercial-scale steam methane reformers for a large-scale industrial hydrogen production facility. CO_2 will be captured via vacuum swing adsorption (VSA) and dried (triethylene glycol) to produce a high-purity (>98 percent) CO_2 stream and transported via pipeline to be used by others for EOR. The focus of this demonstration platform includes commercial-scale CO_2 capture from an industrial source using the VSA process and MVA.
- *Leucadia (ICCS)* – Petroleum coke-to-chemicals (methanol, hydrogen, and other byproducts) industrial facility. Captured CO_2 will be purified and transported via pipeline for EOR by others in Louisiana and Texas oilfields. The focus of this demonstration platform includes commercial-scale CO_2 capture from an industrial source and MVA.

Demonstration Program Area Goals

The CCRP is directly linked to and supports the achievement of DOE's mission and applicable goals, and is deploying a strategy focused on:

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

The above strategy mandates the need for demonstration platforms that enable the continued use of coal, while addressing climate change concerns and pursuing responsible transitional pathways to a sustainable energy future. Specifically, the performance goal of the CCS/CCUS Demonstrations program area is to "achieve initial operations of five commercial-scale demonstrations by 2015." Annual and quarterly milestones have been established under the Government Performance and Results Act (GPRA) to monitor and report progress toward achieving this performance goal.

Seven of the eight demonstration platforms (i.e., all except SCS-Kemper) receive Recovery Act funding, either exclusively or in addition to program funding. Accordingly, these seven platforms contribute to the achievement of the performance measures and metrics shown below in Table 21.

Table 21: FE R&D Recovery Act Performance Measures and Metrics

Performance Measure	Performance Metric
FE-1: Number and megawatt capacity of projects funded to capture CO_2 from anthropogenic sources.	8–10 projects, representing at least three CO_2 capture technologies applied to a minimum of five diverse industrial and power applications that offer substantial opportunity for future CO_2 reduction and totaling 750–2,000 MW equivalent
FE-2: Number of geological reservoirs characterized in detail and incremental CO_2 storage capacity verified as available for commercial development, in preparation for long-term storage and MVA.	10 geologic reservoirs representing at least five distinct types of reservoirs 0.3–1 billion metric tons of CO_2 storage capacity characterized
FE-3: Total number of students and professionals trained for future capture and storage industry.	100 students conducting over 40,000 research hours 500 professional development units or continuing education units
FE-4: Number of metric tons of CO_2 captured and stored per year.	5 million metric tons per year by 9/30/2015 with a demonstrated permanence of at least 99%
FE-5: Number of metric tons of CO_2 emissions avoided.[1]	7.5 million total metric tons by 9/30/2015
FE-6: Number of barrels of oil consumption displaced (crude oil equivalent).	4 million barrels of foreign oil displaced by 9/30/2015[2]

NOTES:
[1] Calculations equal carbon emission reductions.
[2] Equals allocation of 2 million metric tons of CO_2 to EOR.

Progress toward the achievement of the above performance measures and metrics is continually monitored and reported on a monthly basis. The SCS-Kemper project receives only program funding and does not contribute to the achievement of the Recovery Act goals.

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 70 projects have been awarded and 39 projects have been successfully completed. DOE's funding commitment has exceeded $1.7 billion, and its industrial partners have committed an additional $5.5 billion, representing over 75 percent of the overall project funding, well in excess of the 50 percent cost sharing required by law.

Public benefits from the CCS/CCUS 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 conservatively estimated to exceed $25 billion and continue to increase as additional technologies become commercial.

Critical Technology Area Challenges

Within the CCS/CCUS Demonstrations program area, the critical challenges relate to the demonstration of technologies at commercial scale. Some of these technologies 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/CCUS 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.

Key Technologies

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

- Gasification Systems
- Advanced Turbines
- Advanced Combustion Systems
- Pre-Combustion Capture and Post-Combustion Capture
- Carbon Use/Reuse and Storage
- MVA

Figure 21 links these Technology Areas to the related development pathways through the CCS/CCUS Demonstrations program areas and projects.

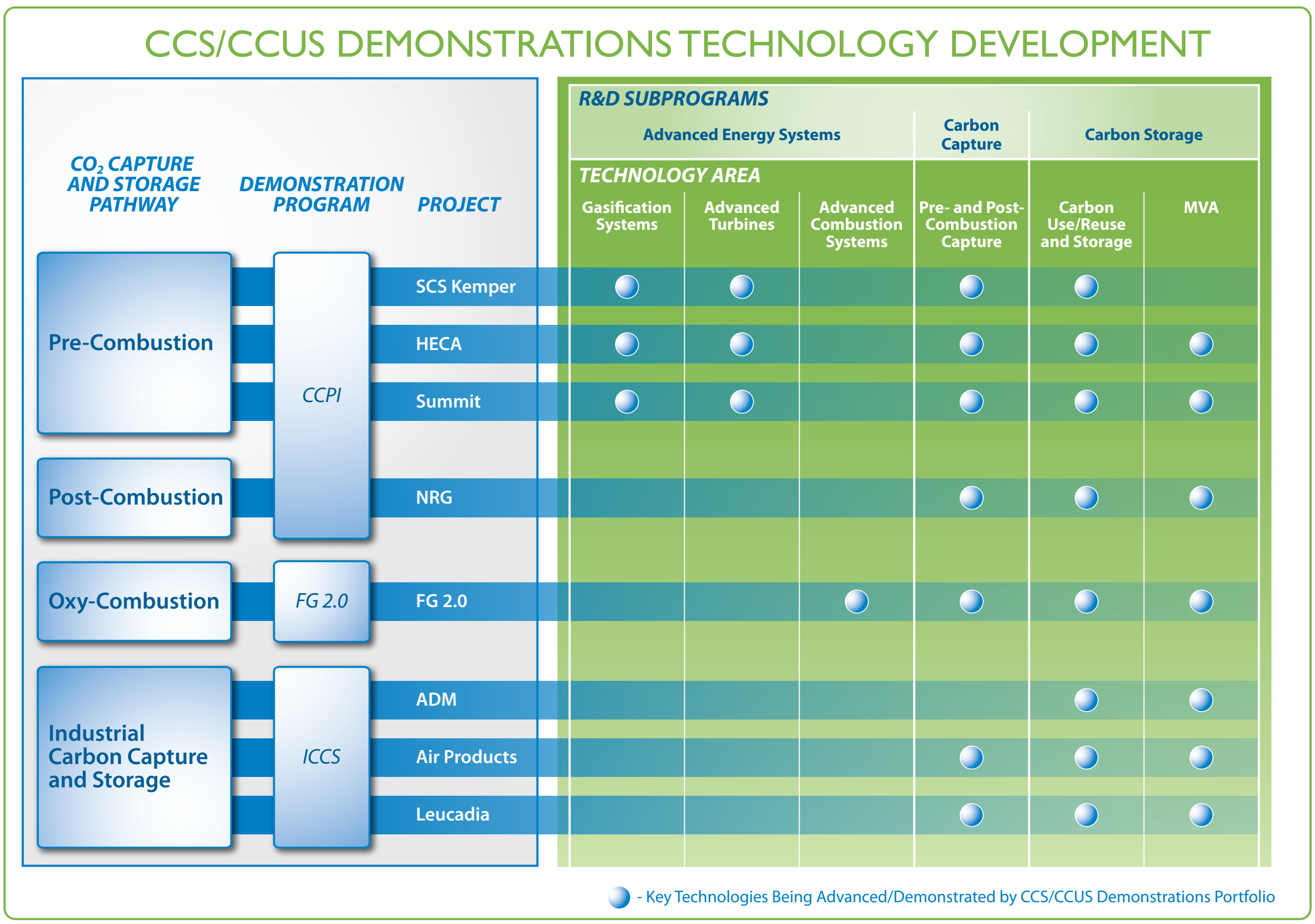

Figure 21: CCS/CCUS Demonstrations Technology Development

Figure 22 presents the key technologies being advanced through each Technology Area.

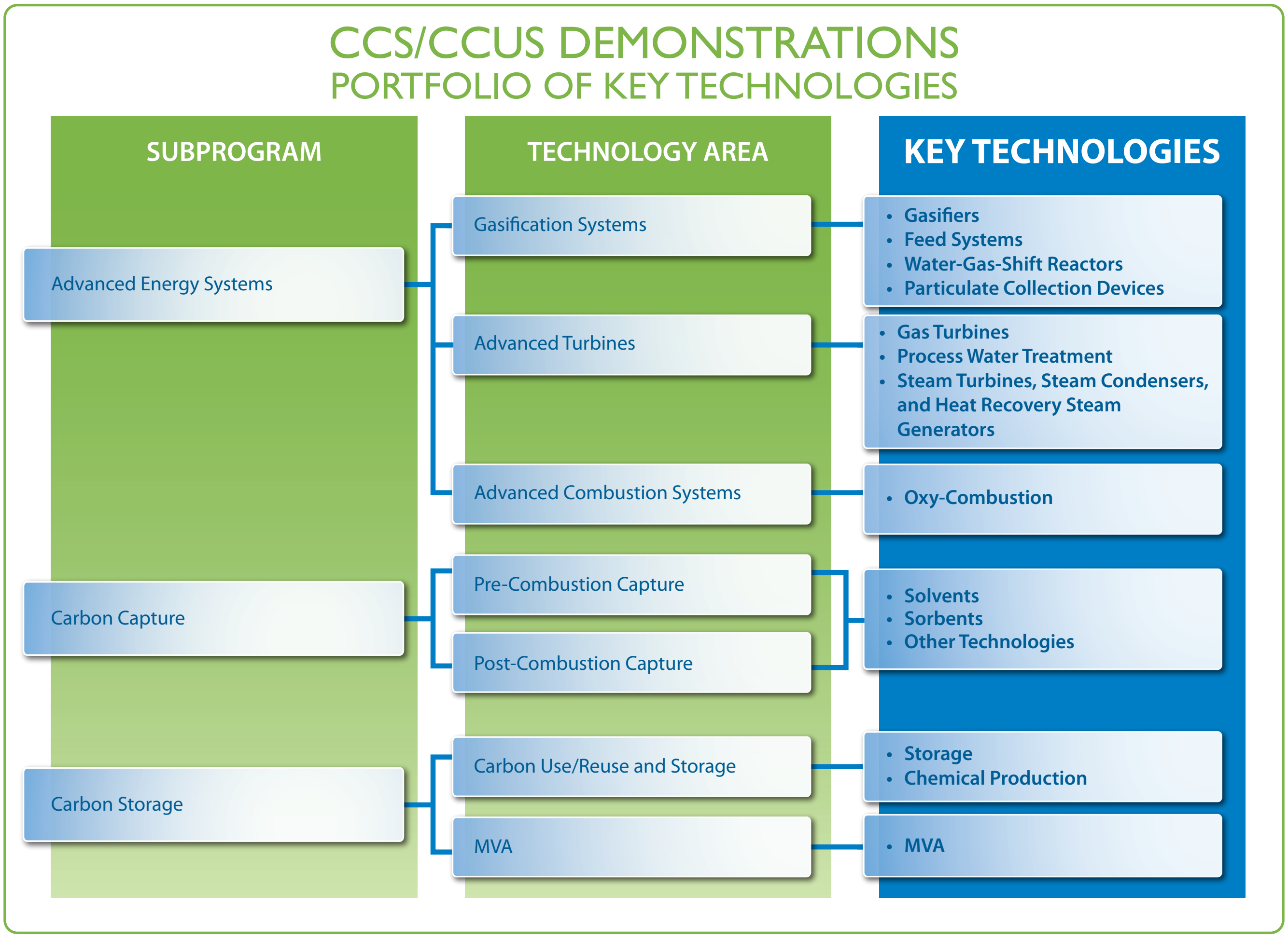

Figure 22: CCS/CCUS Demonstrations Portfolio of Key Technologies

CCS/CCUS DEMONSTRATION TECHNOLOGY

FE's CCUS and Power Systems R&D program area develops individual technologies to the point of demonstration readiness. In general, this corresponds to the following TRL rating levels:

- TRL 5—*laboratory-scale similar system validation in a relevant environment*
- TRL 6—*engineering/pilot-scale prototypical system demonstrated in a relevant environment*
- TRL 7—*system prototype demonstrated in a plant environment*

The CCS/CCUS 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 CCUS 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 comprise 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.

Technology Integration Risk

The integration of unproven and/or first-of-a-kind technologies into existing or new power or process plants can create significant risks to the achievement of the cost, schedule, and performance goals of a project. The degree of integration risk often directly influences the cost, schedule and performance margins that are applied to specific technologies and projects. These factors often increase significantly if the new technology is unproven at the scale being tested or "first-of-a-kind." This issue is a longstanding challenge in the business of technology development, being formally recognized and discussed in various publications dating back to the 1970s. A 1981 Rand Corporation report[6] on cost growth and performance shortfall concluded:

> It is widely recognized that commercially unproven technology may be the source of problems in design, construction, and startup that often cumulate in higher-than-expected final plant costs. Estimators may attempt to cover these costs by setting aside larger contingencies; however, standard estimating methods have usually proven unable to predict these added costs for pioneer plants with precision. These methods provide no adequate, systematic means of estimating plants that embody technologies, process steps, integrations, equipment, and the like, not previously demonstrated in a commercial plant. It is important to recognize, however, that a technology's being unproven is not a direct cause of underestimation. Instead, the culprit is the unforeseen design, engineering, construction or startup problems that technologies can run into that often require expensive redesign or repair.
>
> These first-of-a-kind costs may deter firms from introducing technologies that could provide public benefits. The deterrent effect will be especially strong where firms do not believe that they will be able to recapture their extraordinary costs from pioneering by obtaining a clear advantage over their competitors. When first-of-a-kind costs deter introduction of a technology that appears feasible and promises substantial social benefits, there is a strong rationale for Government assistance with the pioneer plant's costs.
>
> As discussed above, however, it is important to recall that having paid the first-of-a-kind costs does not automatically confer advantages. Accelerating the deployment of plants, and thus designing and constructing follow-on plants before the pioneer is up and operating, probably sacrifices many of the opportunities for learning. Although completing the design of a pioneer facility greatly reduces the risk of cost growth, the crucial performance risks are not reduced until the plant is up and operating well.
>
> Another aspect of commercialization strategy in which the cost growth and performance models have important implications is in the design of demonstration projects. In both equations, it is commercial use that distinguishes known from unknown technology. Having constructed pilot or other facilities to prove the technology at smaller scale does not alter this conclusion. Therefore, if demonstration projects are to significantly reduce cost growth and increase performance in the first commercial plant, they should at least be at a scale that allows the use of the same-size equipment that will be used in the commercial units.

The degree to which a key technology is successfully demonstrated or advanced is often dependent on the degree to which the risks associated with its integration into the demonstration platform have been sufficiently anticipated and mitigated in the designs and operation plans for the facility. The CCRP demonstration platforms consist of many technologies that have been proven at full scale. These technologies are typically integrated into the demonstration platform by an engineering, procurement, and construction (EPC) contractor during detailed design. With the expertise generally available within these types of firms, the risk associated with integrating these technologies into the overall design should be low. The EPC contractor may have the drawings and equipment specifications from previous successful projects and a high level of confidence that the new platform will only require minor modifications to these data.

On the other hand, if a key technology has only limited operating experience, is unproven at scale or is first-of-a-kind, the EPC contractor will view the integration risk as high, since vendor drawings and specifications—which are critical to achieving schedule, cost, and performance milestones—may not be available or completed in a timely manner. The integration of an unproven or first-of-a-kind technology into an otherwise replicable or nth design presents two important considerations. First, the risk associated with integration of the first-of-a-kind technology into an otherwise "standard" plant must be characterized and evaluated. Second, the impact of the operating parameters and conditions associated with an unproven technology on upstream and downstream equipment must also be evaluated.

The use of Federal funding is a means to share in the risk of developing technology and is required to better characterize and mitigate the cost, schedule, and performance issues associated with integration of these unproven technologies. Without this funding, industry may be unwilling to independently develop these technologies to the point of commercialization, and the expected benefits would not be realized.

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. The PPA typically is completed and issued after DOE receives the final report from the recipient.

Accordingly, the TRA was only completed for the CCUS and Power Systems R&D portion of the CCRP. However, consistent with FE's efforts to provide informative detail on CCRP projects, the following sections summarize the key technologies being advanced through the CCS/CCUS Demonstration program area's active demonstration platforms.

ADVANCED ENERGY SYSTEMS

Advanced Energy Systems, as represented in the CCS/CCUS demonstration platforms, includes three Technology Areas: Gasification Systems, Advanced Turbines, and Advanced Combustion Systems.

Technology Area—Gasification Systems

Gasification systems include the gasifier, innovative feed systems/technologies (i.e., dryers and feeders), as well as certain post-gasification processing and treatment of the resultant syngas (i.e., water-gas shift of the carbon monoxide/H_2O gas to produce H_2 and CO_2), high-temperature particulate collection devices (i.e., barrier filters), syngas cooling, and mercury removal systems.

Key Technology—Gasifiers

The Gasifier Technology Area includes development/demonstration of three different advanced gasification technologies:

- KBR TRIG air-blown transport gasifier fueled with lignite coals. While the transport reactor technology has been used for over 50 years in the petroleum refining industry, demonstration of this technology using a variety of coals has been limited to pilot scale (SCS-Kemper, CCPI).
- MHI oxygen-blown gasifier (pressurized entrained-flow slagging reactor with a two-stage operation), fueled using a blend of 75 percent coal and 25 percent petcoke, on a thermal basis. Although this gasifier has operated successfully for several years using air, there is limited operating experience with the MHI gasifier technology in an O_2-blown mode. In addition, operation of the MHI gasifier technology is currently unproven with a coal/petcoke blend fuel (HECA, CCPI).
- Siemens SFG-500, a dry-feed, pressurized O_2-blown entrained-flow gasifier. Further demonstration of this technology is required as part of an IGCC/polygeneration configuration (Summit, CCPI).

Key Technologies—Feed Systems, Water-Gas-Shift Reactors, and Particulate Collection Devices

Other integral gasifier-related technology components being demonstrated include dryers and feed systems of coal and/or coal/petcoke blends, water-gas-shift reactors, and particulate collection devices (i.e., barrier filters capable of operating at elevated temperatures). While a number of these component technologies have been commercially demonstrated in other applications (or at pilot scale), their performance at scale and/or in these specific applications has not yet been commercially demonstrated. For example, further demonstration is required for a pressure decoupled advanced coal (PDAC) feed system and water-gas-shift reactors (including associated catalysts) operating at lower than normal (i.e., demonstrated to date) H_2O/carbon monoxide ratios.

Technology Area—Advanced Turbines

Key Technology—Gas Turbines

The Advanced Turbines Technology Area includes the demonstration of three different gas turbines (and associated equipment/ systems) fired with high-H_2 syngas integrated into power only and IGCC/polygeneration configurations.

- Siemens F-class gas turbine—fired using a relatively high H_2/carbon monoxide ratio, and relatively low heat value of the syngas integrated in a power-generation configuration (SCS-Kemper, CCPI).
- MHI air-cooled (G-class) gas turbine—fired using a H_2-rich syngas and integrated in an IGCC/polygeneration configuration (HECA, CCPI).
- Siemens F-class gas turbine (in a separate demonstration)—fired using a high-H_2 syngas and integrated in an IGCC/polygeneration configuration (Summit, CCPI).

While gas turbines are commercially demonstrated technologies, most commonly fired with natural gas, they are not fully demonstrated using H_2-rich syngas, and/or integrated/operated in an IGCC/polygeneration configuration—requiring engineering modifications to combust the lower-heating-value fuel (compared to natural gas), differences in the volumetric flow rate of combusted gas through the turbine, and overall integration into the plant configuration to achieve optimal plant efficiencies.

Key Technologies—Process Water Treatment, Steam Turbines, Steam Condensers, and Heat Recovery Steam Generators

In addition to demonstrating these gas turbines, other associated technologies/systems being advanced in these different applications/plant configurations (i.e., power and IGCC/polygeneration) include process/supply water treatment (reverse osmosis), advanced steam turbines, air-cooled steam condensers, and heat recovery steam generators (HRSGs). While each of these component technologies has been commercially demonstrated in other applications, their performance at scale and/or integrated in these specific applications has not yet been commercially demonstrated. For example, this includes demonstrating successful operation of reverse osmosis water treatment technology in an IGCC/polygeneration configuration (Summit, CCPI), operating experience of Siemens SST-900RD reheat steam turbines at higher megawatt ratings (e.g., ≈182 MW), complete design integration/operation of air-cooled steam condensers (at planned scale) with Siemens SST-900RD reheat steam turbines, and HRSGs using high-H_2 fuel for duct firing.

Technology Area—Advanced Combustion Systems

Key Technology—Oxy-Combustion

The focus of Advanced Combustion Systems Technology Area, via FG 2.0, is currently focused on the demonstration of an oxy-fired combustion/boiler system. This advanced combustion system is defined to include the requisite coal feed systems, oxy-fired combustion boiler and gas recycle systems, and a fully integrated ASU.

In oxy-fuel combustion, the fuel is combusted with oxygen instead of air, with the benefit of producing a flue gas consisting predominately of CO_2 and water vapor, which is condensed via cooling. The hot flue gas can be used to produce steam (for electricity production), and, following post-combustion processing, the almost pure CO_2 flue gas is purified to required specifications for pipeline transport and ultimate geologic sequestration in a saline aquifer formation.

Associated key technologies also being advanced within the Advanced Combustion Systems Technology Area include the fully integrated ASU and steam turbine. While ASUs are commercially demonstrated technology, full-scale heat integration between the ASU and the steam turbine in this configuration has not been demonstrated. Successful demonstration of this heat integration is necessary to help maximize plant thermodynamic efficiency, from both technical and plant economic perspectives.

CARBON CAPTURE

Technology Areas—Pre-Combustion Capture/Post-Combustion Capture

Carbon Capture includes both the Pre-Combustion Capture and Post-Combustion Capture Technology Areas. Spanning these two Technology Areas are the four DOE-sponsored pathways for carbon capture and storage (i.e., Pre-Combustion, Post-Combustion, Oxy-Combustion, and Industrial Carbon Capture and Storage), and the advancement and/or demonstration of key technologies in three areas (i.e., Solvents, Sorbents, and Other Technologies).

As detailed below, five of the demonstration platforms are involved in advancing and/or demonstrating solvent-based CO_2 capture technologies (SCS Kemper/CCPI, HECA/CCPI, NRG/CCPI, Summit/CCPI, and Leucadia/ICCS). One ICCS demonstration platform (Air Products and Chemicals) is advancing and/or demonstrating sorbent-based CO_2 capture technology. One platform (FG 2.0) is advancing a capture technology that is neither solvent- nor sorbent-based and is characterized as "other" (cryogenic distillation technology for CO_2 capture). Lastly, CO_2 is being recovered directly from an industrial process (ADM).

Key Technology—Solvents

All four CCPI demonstration platforms are advancing solvent-based CO_2 capture technology. These platforms encompass three different configurations: (1) IGCC (SCS-Kemper), (2) post-combustion energy (NRG), and (3) IGCC/polygeneration (HECA and Summit).

The solvent-based CO_2 capture technologies being advanced include (1) Selexol and Rectisol, both of which are designed to capture both sulfur compounds and CO_2 from gas streams, and (2) Fluor EFG+, which is specific for CO_2 capture from flue gases produced by coal-fired power plants, refineries, and chemical plants.

In the IGCC and IGCC/polygeneration configurations, the synthesis gas, after the water-gas-shift reaction, is processed using either the Selexol or Rectisol technologies to capture the sulfur-containing compounds and CO_2. While Selexol and Rectisol are widely used commercial-scale technologies for the capture of sulfur compounds and CO_2, there are aspects that have not been commercially demonstrated at scale. These include (1) demonstration of the Selexol process integrated into an IGCC configuration (SCS-Kemper) with the TRIG gasifier, fueled with lignite coal, and producing a lower H_2/carbon-monoxide syngas than is typically the case and (2) demonstrations of the Rectisol technology integrated into an IGCC/polygeneration configuration (HECA and Summit), each using a different gasification technology and fuel blend.

In the one post-combustion configuration (i.e., NRG) within the CCPI, the Fluor EFG+ CO_2 capture technology is being advanced. The Fluor EFG+ is a commercially available technology; however, it has not yet been demonstrated at the scale of this project (flue gas slipstream sized for a 240-MW plant). Additionally, the demonstration is proposing a number of innovative technological advances to the Fluor EFG+ solvent technology and captured CO_2 processing equipment.

One of the ICCS demonstration projects (Leucadia) is also using Rectisol to recover sulfur/CO_2 from synthesis gas produced using a GE quench gasifier fueled with petroleum coke.

Key Technology—Sorbents

Within the CCS/CCUS Demonstrations program area, one ICCS demonstration platform (Air Products and Chemicals) is demonstrating sorbent-based CO_2 capture technology (VSA—CO_2 capture from a steam methane reforming facility). While, VSA is a well-demonstrated commercial technology, there are no commercial demonstrations of integrating this technology for CO_2 capture with a steam methane reforming facility.

Key Technology—Other Technologies

The CCS/CCUS Demonstrations program area is advancing oxy-combustion technology from which resultant CO_2 can be readily captured (CO_2 cryogenic purification) in one demonstration platform within FG 2.0.

The CO_2 cryogenic purification/drying technology being developed by Air Liquide is based on demonstrated chemical engineering processes. Configurations of the technology have been incorporated into a few oxy-combustion pilot plants (i.e., not commercial scale). Additionally, there are proposed designed modifications included in the FG 2.0 flowsheet to achieve the 1 million tonnes of CO_2/year (e.g., use of a membrane module, carbon monoxide vent stream control, CO_2 dryers), and other design options are being considered to achieve potential improvements in efficiency.

FG 2.0 is also demonstrating a dry-scrubbing sulfur removal technology. [Typically, sulfur compounds and CO_2 are captured using the same technology (e.g., Selexol, Rectisol) and are thus grouped with Carbon Capture]. The benefits of dry scrubbing include minimizing the water introduced into the process, which subsequently needs to be treated and reduces the operating efficiencies. While sulfur dry-scrubbing technology is a conventional process, further research is required to demonstrate that the technology can reduce sulfur to achieve regulatory emission standards in this application. Also, the reactor design could change because gas flow volume is reduced in an oxy-combustion process.

CARBON STORAGE

The Carbon Storage subprogram includes two Technology Areas: (1) Carbon Use/Reuse and Storage and (2) MVA.

Technology Area—Carbon Use/Reuse and Storage

Integral to the CCS/CCUS Demonstrations program area is the commercial-scale demonstration of CO_2 use/reuse and permanent storage. Two of the demonstration platforms are planning to use the captured CO_2 as a precursor for chemical production, and two of the platforms have proposed to permanently sequester the captured CO_2 in saline aquifers.

CO_2 injection for EOR is a commercial process, and six of the eight demonstration platforms are planning to use the captured CO_2 for EOR. Although the physical injection of the CO_2 is outside of the scope of the DOE-funded projects, the MVA aspects are included. The successful integration of CO_2 capture, EOR, and permanent storage remains a major focus area of the CCUS program.

Key Technology—Storage

Both the ADM and FG 2.0 projects intend to permanently store CO_2 in saline reservoirs and are extending the state-of-the-art of injection wells and characterization technologies.

The specific injection well and site characterization technologies required for the FG 2.0 project permit are not yet known, and technologies that may be further developed could include anything from known methodologies that have been tested at a smaller scale to mature technologies that have not been applied substantially to CO_2 injection applications. The Underground Injection Control Class VI permit requirements for the FG 2.0 project are not yet known and the possibility exists that mature technologies will be integrated with less mature technologies.

The CO_2 storage site for the ADM project will likely be one of the first U.S. storage facilities to be permitted under EPA's new Class VI regulations for a large-scale injection operation (over 1 million metric tons injected). The Midwest Geologic Sequestration Consortium large-scale injection project (which captures CO_2 from the ADM Ethanol Facility and has been injecting CO_2 in the vicinity of and into the same target formation as this ICCS injection project) has an existing injection well permitted as Underground Injection Control Class I (hazardous or non-hazardous industrial waste) and is built to satisfy expected Class VI (geologic carbon storage) requirements through U.S. EPA Region V. A Class VI permit has not been issued for this geographical area.

Key Technology—Chemical Production

Two of the demonstration projects (HECA and Summit) include the capture and purification of CO_2 as a chemical precursor for the production of urea and UAN, broadly used as agricultural fertilizers and as intermediates for producing other chemicals. While the production of urea (including ammonia, a urea precursor) in petrochemical facilities and ammonia from IGCC plants are commercially demonstrated technologies, there is no evident production of urea or UAN from IGCC plants.

Technology Area—MVA

Key Technology—MVA

Seven of the eight CCUS demonstration platforms evaluated include advancement of MVA technologies to ensure the permanent storage of CO_2. The one project not included (SCS-Kemper) was awarded under CCPI-2, which did not include an MVA requirement.

The seven platforms include three in CCPI-3, three in ICCS, and one in FG 2.0. Of the seven demonstrations, five will inject CO_2 for EOR and two will sequester CO_2 in saline aquifers.

Of the five EOR projects, four are planning injection of CO_2 into oil reservoirs in Texas and one in California. The MVA requirements for CO_2 injection for EOR have already been established by the Railroad Commission of Texas, Oil and Gas Division, and three of the four well injection permits have already been approved. While the injection permits are not yet available, it is anticipated that they include advancement of MVA technologies that either exist but have not been used for CO_2, or have been used but at a smaller scale.

Two of the demonstrations are planning CO_2 injection into saline aquifers. It is anticipated that the Class VI well permits for these demonstrations are likely to include mature elements of MVA technologies that are anticipated to be commercially available. The Class VI well permits are not available, it is expected that mature MVA technologies will be integrated with technologies of less maturity.

APPENDIX A

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REFERENCES

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APPENDIX B

LIST OF ABBREVIATIONS

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ADM	Archer Daniels Midland Company
AIChE	American Institute of Chemical Engineers
ARRA	American Recovery and Reinvestment Act of 2009
ASME	American Society of Mechanical Engineers
ASU	air separation unit
A-USC	advanced ultra-supercritical
°C	degrees Celsius
C&CBTL	Coal and Coal/Biomass-to-Liquids
$CaCO_3$	calcium carbonate
CAPE	computer-aided process engineering
CCPI	Clean Coal Power Initiative
CCRP	Clean Coal Research Program
CCS	carbon capture and storage
CCSI	Carbon Capture Simulation Initiative
CCUS	carbon capture, utilization, and storage
CFB	circulating fluidized bed
CFD	computational fluid dynamics
CLC	chemical-looping combustion
CO_2	carbon dioxide
COE	cost of electricity
Cr	chromium
DIAL	differential absorption LIDAR
DoD	Department of Defense
DOE	Department of Energy
DOE-FE Guide	Department of Energy-Fossil Energy Technology Readiness Assessment Guide
ECBM	enhanced coalbed methane
EOR	enhanced oil recovery
EPA	Environmental Protection Agency
EPAct	Energy Policy Act of 2005
EPC	engineering, procurement, and construction
°F	degrees Fahrenheit
FE	Office of Fossil Energy
FG 2.0	FutureGen 2.0
Fluor EFG+	Fluor Econoamine FG Plus
FPM	Federal Project Manager
FY	fiscal year

GHG	greenhouse gas
GPRA	Government Performance and Results Act
H_2	hydrogen
H_2O	water
H_2S	hydrogen sulfide
HBCU/OMI	Historically Black Colleges and Universities and Other Minority Institutions
HECA	Hydrogen Energy California, LLC
HHC	high-hydrogen content
HRSG	heat recovery steam generator
HTM	hydrogen-transport membrane
ICCS	Industrial Carbon Capture and Storage
ICTL	integrated carbon-to-liquids
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IGFC	integrated gasification fuel cell
InSAR	interferometric synthetic aperture radar
ITM	ion-transport membrane
kW	kilowatt
kWe	kilowatt electric
LIDAR	laser-induced differential absorption radar
MBS	molecular basket sorbents
MFIX	Multiphase Flow with Interphase eXchanges
$MgCO_3$	magnesium carbonate
MHI	Mitsubishi Heavy Industries
Mo	molybdenum
MVA	monitoring, verification, accounting, and assessment
MW	megawatt
MWh	megawatt hours
NASA	National Aeronautics and Space Administration
Nb	niobium
NETL	National Energy Technology Laboratory
Ni	nickel
NO_x	nitrogen oxide
NRAP	National Risk Assessment Partnership
NRG	NRG Energy, Inc.
O_2	oxygen
ORD	Office of Research and Development

PC	pulverized coal
PDAC	pressure decoupled advanced coal
POT	Plant Optimization Technologies
PPA	Post Project Assessment
PRB	Powder River Basin
PSA	pressure swing absorption
R&D	research and development
RCSP	Regional Carbon Sequestration Partnerships
RD&D	research, development, and demonstration
SCC	Strategic Center for Coal
SCS	Southern Company Services, Inc.
SECA	Solid State Energy Conversion Alliance
SECARB	Southeast Regional Carbon Sequestration Partnership
Si	silicon
SOFC	solid oxide fuel cell
TBC	thermal barrier coating
TRA	Technology Readiness Assessment
TRIG™	Transport Reactor Integrated Gasification
TRL	Technology Readiness Level
TSA	temperature swing adsorption
UAN	urea ammonium nitrate
UCR	University Coal Research
USC	ultra-supercritical
UTR	University Training and Research
VSA	vacuum swing adsorption
W	tungsten
WO_3	tungsten trioxide
ZIF	zeolitic imidazolate frameworks

National Energy Technology
Laboratory (NETL)
U.S. Department of Energy

Albany Location:
1450 Queen Avenue SW
Albany, OR 97321-2198
541.967.5892

Fairbanks Location:
2175 University Avenue South
Suite 201
Fairbanks, AK 99709
907.452.2559

Morgantown Location:
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304.285.4764

Pittsburgh Location:
626 Cochrans Mill Road
Pittsburgh, PA 15236-0940
412.386.4687

Sugar Land Location:
13131 Dairy Ashford Road
Suite 225
Sugar Land, TX 77478
281.494.2516

Customer Service
1.800.553.7681

Website
www.netl.doe.gov

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