CLEAN
COAL
RESEARCH
PROGRAM
United States Department of Energy | Office of Fossil Energy

ADVANCED COMBUSTION SYSTEMS
TECHNOLOGY PROGRAM PLAN

JANUARY 2013

NETL

DISCLAIMER

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: OVERVIEW

1.1 INTRODUCTION

The Department of Energy's (DOE) Advanced Combustion Systems program is conducted under the Clean Coal Research Program (CCRP). DOE's overarching mission is to increase the energy independence of the United States and to advance U.S. national and economic security. To that end, the DOE Office of Fossil Energy (FE) has been charged with ensuring the availability of ultraclean (near-zero emissions), abundant, low-cost domestic energy from coal to fuel economic prosperity, strengthen energy independence, and enhance environmental quality. As a component of that effort, the CCRP—administered by the Office of Clean Coal and implemented by the National Energy Technology Laboratory (NETL)—is engaged in research, development, and demonstration (RD&D) activities to create technology and technology-based policy options for public benefit. The CCRP is designed to remove environmental concerns related to coal use by developing a portfolio of innovative technologies, including those for carbon capture and storage (CCS). The CCRP comprises two major program areas: CCS and Power Systems and CCS Demonstrations. The CCS and Power Systems program area is described in the following sections. The CCS Demonstrations program area includes three key subprograms: Clean Coal Power Initiative, FutureGen 2.0, and Industrial Carbon Capture and Storage. The technology advancements resulting from the CCS and Power Systems program area are complemented by the CCS Demonstrations program area, which provides a platform to demonstrate advanced coal-based power generation and industrial technologies at commercial scale through cost-shared partnerships between Government and industry.

While it has always been an important component of CCS research, recently DOE has increased its focus on carbon utilization to reflect the growing importance of developing beneficial uses for carbon dioxide (CO_2). At this time, the most significant utilization opportunity for CO_2 is in enhanced oil recovery (EOR) operations. The CO_2 captured from power plants or other large industrial facilities can be injected into existing oil reservoirs. The injected CO_2 helps to dramatically increase the productivity of previously depleted wells—creating jobs, reducing America's foreign oil imports, and thus increasing energy independence. Simultaneously, the CO_2 generated from power production is stored permanently and safely. The CCRP is gathering the data, building the knowledge base, and developing the advanced technology platforms needed to prove that CCS can be a viable strategy for reducing greenhouse gas emissions to the atmosphere, thus ensuring that coal remains an available option to power a sustainable economy. Program efforts have positioned the United States as the global leader in clean coal technologies.

This document serves as a program plan for NETL's Advanced Combustion Systems research and development (R&D) effort, which is conducted under the CCRP's CCS and Power Systems program area. The program plan describes the Advanced Combustion Systems R&D efforts in 2013 and beyond. Program planning is a strategic process that helps an organization envision the future; build on known needs and capabilities; create a shared understanding of program challenges, risks, and potential benefits; and develop strategies to overcome the challenges and risks, and realize the benefits. The result of this process is a technology program plan that identifies performance targets, milestones for meeting these targets, and a technology pathway to optimize R&D activities. The relationship of the Advanced Combustion Systems program[1] to the CCS and Power Systems program area is described in the next section.

---

[1] Although Advanced Combustion Systems is a Technology Area within the Advanced Energy Systems subprogram, it represents a program of research designed to help meet DOE goals. Thus, throughout this document the term Advanced Combustion Systems program is used interchangeably with Advanced Combustion Systems Technology Area.

1.2 CCS AND POWER SYSTEMS PROGRAM AREA

The CCS and Power Systems program area conducts and supports long-term, high-risk R&D to significantly reduce fossil fuel power-plant emissions (including CO_2) and substantially improve efficiency, leading to viable, near-zero-emissions fossil fuel energy systems. The success of NETL research and related program activities will enable CCS technologies to overcome economic, social, and technical challenges including cost-effective CO_2 capture, compression, transport, and storage through successful CCS integration with power-generation systems; effective CO_2 monitoring and verification; permanence of underground CO_2 storage; and public acceptance. The overall program consists of four subprograms: Advanced Energy Systems (AES), Carbon Capture, Carbon Storage, and Crosscutting Research (see Figure 1-1). These four subprograms are further divided into numerous Technology Areas. In several instances, the individual Technology Areas are further subdivided into key technologies. Advanced Combustion Systems is part of the Advanced Energy Systems subprogram.

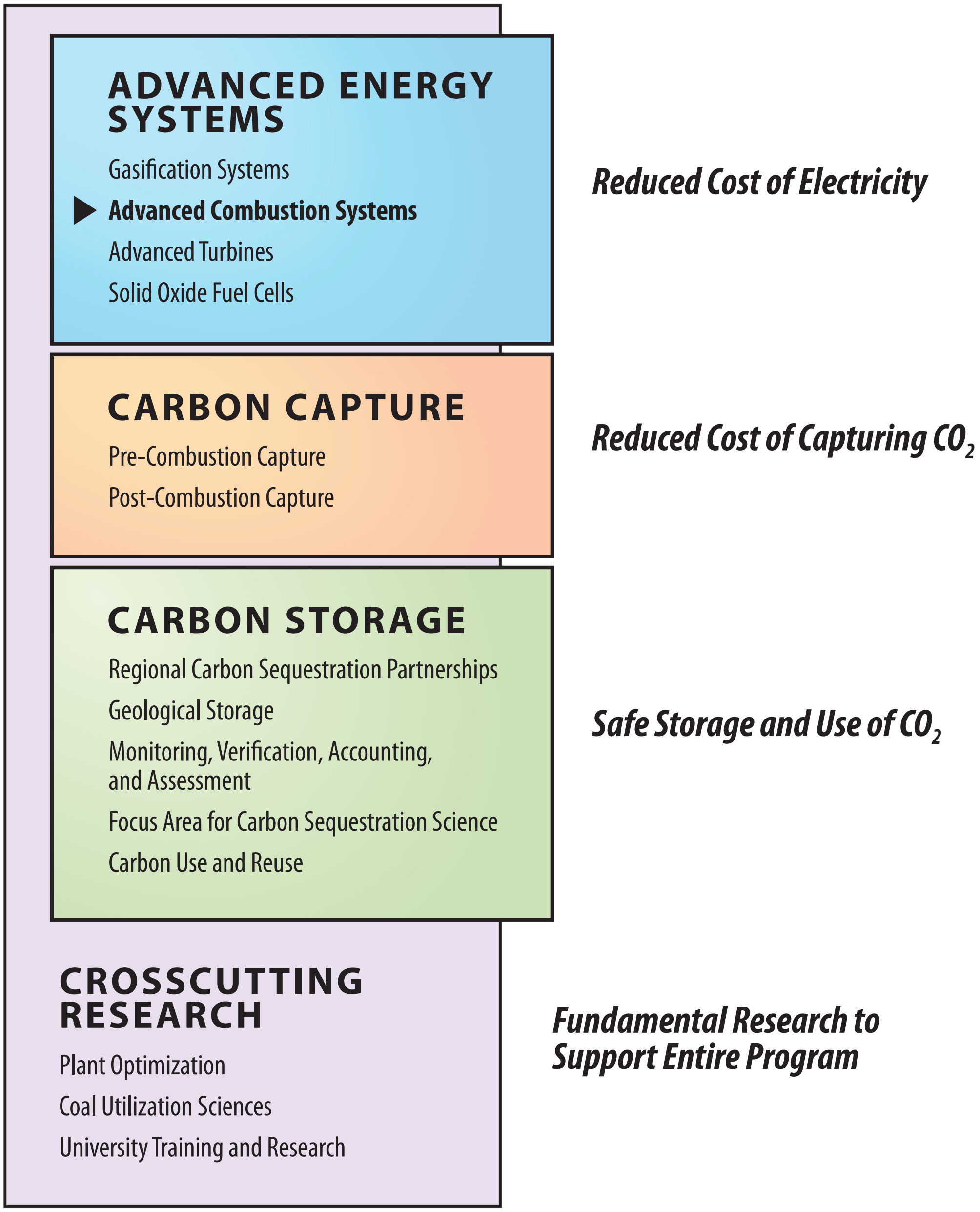


Figure 1-1. CCS and Power Systems Subprograms

The ***Advanced Energy Systems subprogram*** is developing a new generation of clean fossil fuel-based power systems capable of producing affordable electric power while significantly reducing CO_2 emissions. This new generation of technologies will essentially be able to overcome potential environmental barriers and meet any projected environmental emission standards. A key aspect of the Advanced Energy Systems subprogram is targeted at improving overall thermal efficiency, including the capture system, which will be reflected in affordable CO_2 capture and reduced cost of electricity (COE). The Advanced Energy Systems subprogram consists of four Technology Areas as described below and shown in Figure 1-2:

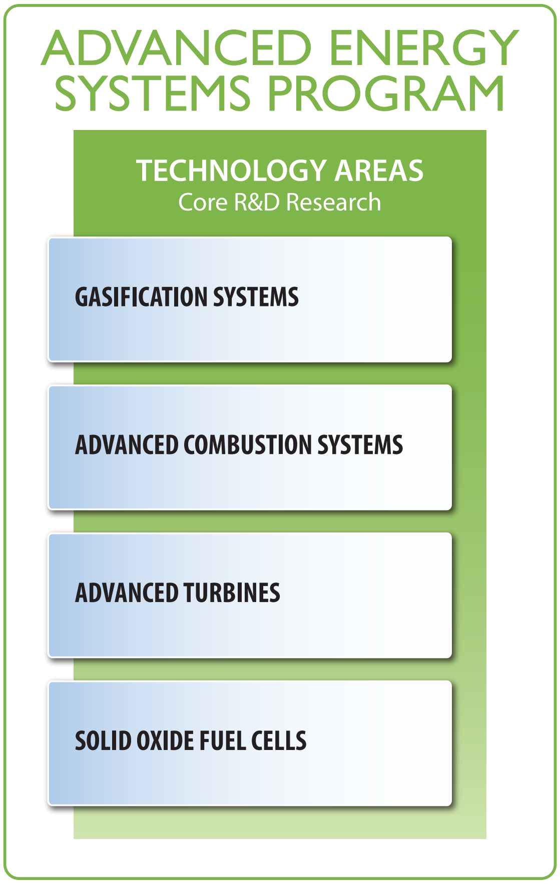


Figure 1-2. AES Subprogram Technology Areas

- ***Gasification Systems*** research to convert coal into clean high-hydrogen synthesis gas (syngas) that can in-turn be converted into electricity with over 90 percent CCS.
- ***Advanced Combustion Systems*** research that is focused on new high-temperature materials and the continued development of oxy-combustion technologies.
- ***Advanced Turbines*** research, focused on developing advanced technology for the integral electricity-generating component for both gasification and advanced combustion-based clean energy plants fueled with coal by providing advanced hydrogen-fueled turbines, supercritical CO_2-based power cycles and advanced steam turbines.
- ***Solid Oxide Fuel Cells*** research is focused on developing low-cost, highly efficient solid oxide fuel cell power systems that are capable of simultaneously producing electric power from coal with carbon capture when integrated with coal gasification.

The ***Carbon Capture subprogram*** is focused on the development of post-combustion and pre-combustion CO_2 capture technologies for new and existing power plants. Post-combustion CO_2 capture technology is applicable to conventional combustion-based power plants, while pre-combustion CO_2 capture is applicable to gasification-based systems. In both cases, R&D is underway to develop solvent-, sorbent-, and membrane-based capture technologies.

The ***Carbon Storage subprogram*** advances safe, cost-effective, permanent geologic storage of CO_2. The technologies developed and large-volume injection tests conducted through this subprogram will be used to benefit the existing and future fleet of fossil fuel power-generating facilities by developing tools to increase our understanding of geologic reservoirs appropriate for CO_2 storage and the behavior of CO_2 in the subsurface.

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 enhancing the availability and reducing the costs of advanced power systems. This subprogram also develops computation, simulation, and modeling tools focused on optimizing plant design and shortening developmental timelines, as well as other crosscutting issues, including plant optimization technologies, environmental and technical/economic analyses, coal technology export, and integrated program support.

The CCS and Power Systems program area is pursuing three categories of CCS and related technologies referred to as 1st-Generation, 2nd-Generation, and Transformational. These categories are defined in Figure 1-3.

1st-Generation Technologies—include technology components that are being demonstrated or that are commercially available.

2nd-Generation Technologies—include technology components currently in R&D that will be ready for demonstration in the 2020–2025 timeframe.

Transformational Technologies—include technology components that are in the early stage of development or are conceptual that offer the potential for improvements in cost and performance beyond those expected from 2nd-Generation technologies. The development and scaleup of these "Transformational" technologies are expected to occur in the 2016–2030 timeframe, and demonstration projects are expected to be initiated in the 2030–2035 time period.

Figure 1-3. CCS Technology Category Definitions

1.3 THE RD&D PROCESS

The research, development, and demonstration of advanced fossil fuel power-generation technologies follows a sequential progression of steps toward making the technology available for commercial deployment, from early analytic study through pre-commercial demonstration. Planning the RD&D includes estimating when funding opportunity announcements (FOAs) will be required, assessing the progress of ongoing projects, and estimating the costs to determine budget requirements.

1.3.1 TECHNOLOGY READINESS LEVELS

The Technology Readiness Level (TRL) concept was adopted by the National Aeronautics and Space Administration (NASA) to help guide the RD&D process. TRLs provide an assessment of technology development progress on the path to meet the final performance specifications. The typical technology development process spans multiple years and incrementally increases scale and system integration until final-scale testing is successfully completed. 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] Appendix A includes a table of TRLs as defined by DOE Office of Fossil Energy.

The TRL score for a technology is established based upon the scale, degree of system integration, and test environment in which the technology has been successfully demonstrated. Figure 1-4 provides a schematic outlining the relationship of those characteristics to the nine TRLs.

---

[2] Mankins, J., Technology Readiness Level White Paper, 1995, rev. 2004, Accessed September 2010. http://www.artemisinnovation.com/images/TRL_White_Paper_2004-Edited.pdf

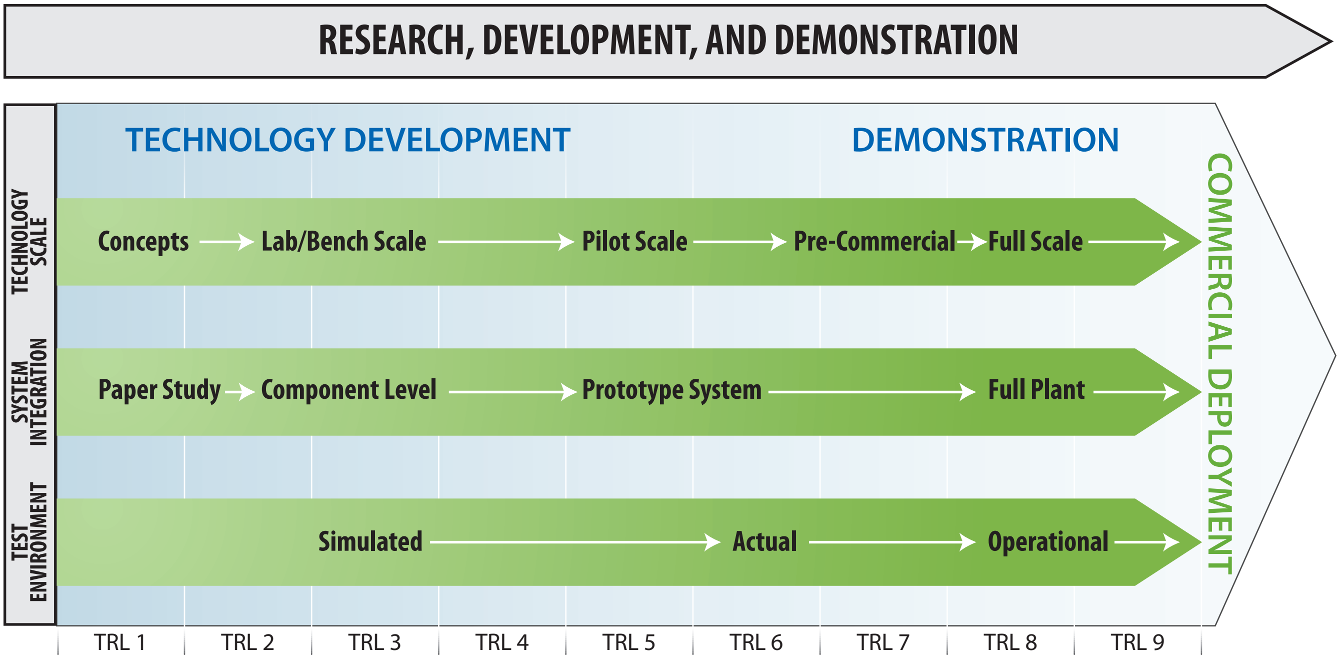


Figure 1-4. Technology Readiness Level—Relationship to Scale, Degree of Integration, and Test Environment

The scale of a technology is the size of the system relative to the final scale of the application, which in this case is a full-scale commercial power-production facility. As RD&D progresses, the scale of the tests increases incrementally from lab/bench scale, to pilot scale, to pre-commercial scale, to full-commercial scale. The degree of system integration considers the scope of the technology under development within a particular research effort. Early research is performed on components of the final system, a prototype system integrates multiple components for testing, and a demonstration test of the technology is fully integrated into a plant environment. The test environment considers the nature of the inputs and outputs to any component or system under development. At small scales in a laboratory setting it is necessary to be able to simulate a relevant test environment by using simulated heat and materials streams, such as simulated flue gas or electric heaters. As RD&D progresses in scale and system integration, it is necessary to move from simulated inputs and outputs to the actual environment (e.g., actual flue gas, actual syngas, and actual heat integration) to validate the technology. At full scale and full plant integration, the test environment must also include the full range of operational conditions (e.g., startup and turndown).

1.3.2 RD&D RISK AND COST PROGRESSION

As the test scale increases, the duration and cost of the projects increase, but the probability of technical success also tends to increase. Given the high technical risk at smaller scales, there will often be several similar projects that are simultaneously supported by the program. On the other hand, due to cost considerations, the largest projects are typically limited to one or two that are best-in-class. Figure 1-5 provides an overview of the scope of laboratory/bench-, pilot-, and demonstration-scale testing in terms of test length, cost, risk, and test conditions. In the TRL construct, “applied research” is considered to be equivalent to lab/bench-scale testing, “development” is carried out via pilot-scale field testing, and “large-scale testing” is the equivalent of demonstration-scale testing. The CCS and Power Systems program area encompasses the lab/bench-scale and pilot-scale field testing stages and readies the technologies for demonstration-scale testing.

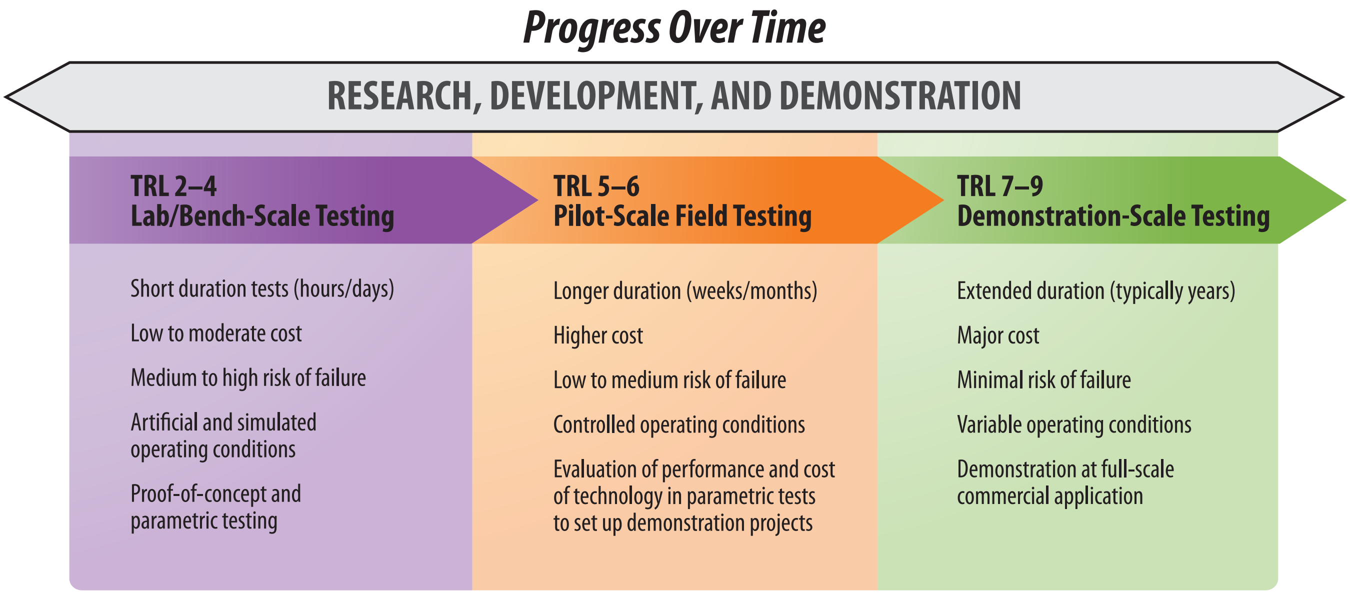


Figure 1-5. Summary of Characteristics at Different Development Scales

1.4 **BARRIERS/RISKS AND MITIGATION STRATEGIES**

The risk and mitigation strategy to achieving all performance targets by 2030 is summarized in Table 1-1. The overarching challenge to be addressed by Advanced Combustion Systems is to economically generate clean energy using fossil fuels. The same barriers, risks, and mitigation strategies apply to all research focus areas.

Table 1-1. **Issues/Barriers and Mitigation Strategies**

Issue	Barrier/Risk	Mitigation Strategy
Cost: Economically generating clean energy using fossil fuels Performance: Achieve performance targets by 2030 Environment: Meet near-zero emissions (including >90% CO_2 capture) with minimal cost impact Market: Low economic growth; low natural gas price Regulations: Uncertainties	Existing/new plants do not adopt advanced Advanced Combustion Systems technologies Lower natural gas prices Reduced Advanced Combustion Systems program budget	Near-, mid-, and long-term R&D projects to foster the commercialization of advanced technologies Multiple research focus areas

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 2: ADVANCED COMBUSTION SYSTEMS PROGRAM

2.1 INTRODUCTION

The Advanced Combustion Systems Technology Area includes three key technologies: (1) Oxy-Combustion, (2) Chemical Looping Combustion, and (3) Advanced Materials. The research focus areas for each of these technologies are depicted in Figure 2-1. 2nd-Generation research is being conducted on atmospheric pressure oxy-combustion systems and advanced materials. Transformational research is being or will be conducted on pressurized oxy-combustion systems, oxygen membrane-based oxy-combustion systems, chemical looping combustion systems, and advanced materials capable of withstanding the aggressive conditions associated with Transformational combustion systems. A brief introduction to oxy-fuel combustion systems is presented below, and additional details are provided in Chapter 4 of this plan.

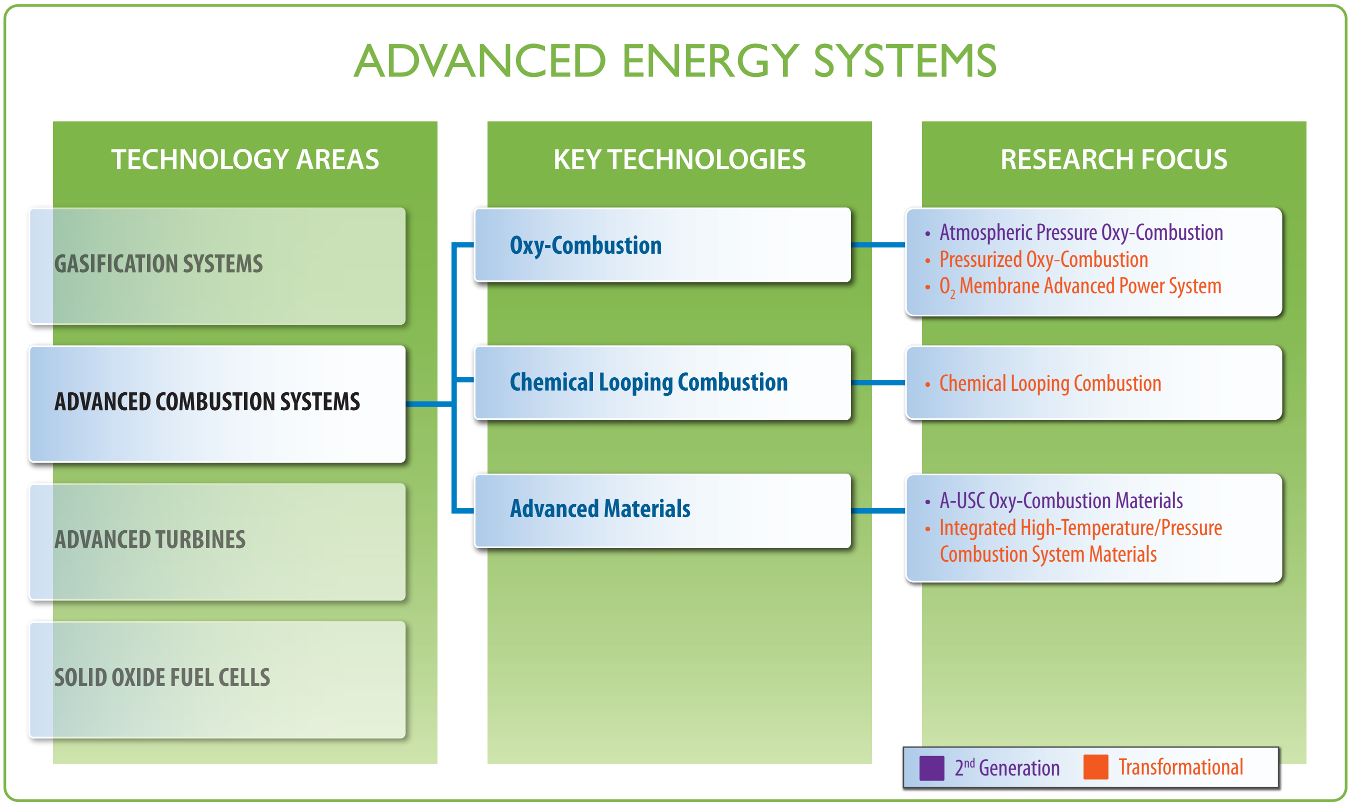


Figure 2-1. Key Technologies and Associated Research Focus in Advanced Combustion Systems

2.2 BACKGROUND

Advanced combustion power generation from fossil fuels involves combustion in a high oxygen (O_2) concentration environment rather than air, or oxy-combustion. This type of system eliminates the introduction of nitrogen (N_2) (from air) into the combustion process, generating flue gas composed of water (H_2O), 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 oxy-combustion to be a low-cost alternative for electricity generation with CCS.

Oxy-combustion is applicable to both new and existing fossil fuel-fired power plants. A simplified block diagram illustrating a typical oxy-combustion process with CO_2 capture is shown in Figure 2-2.

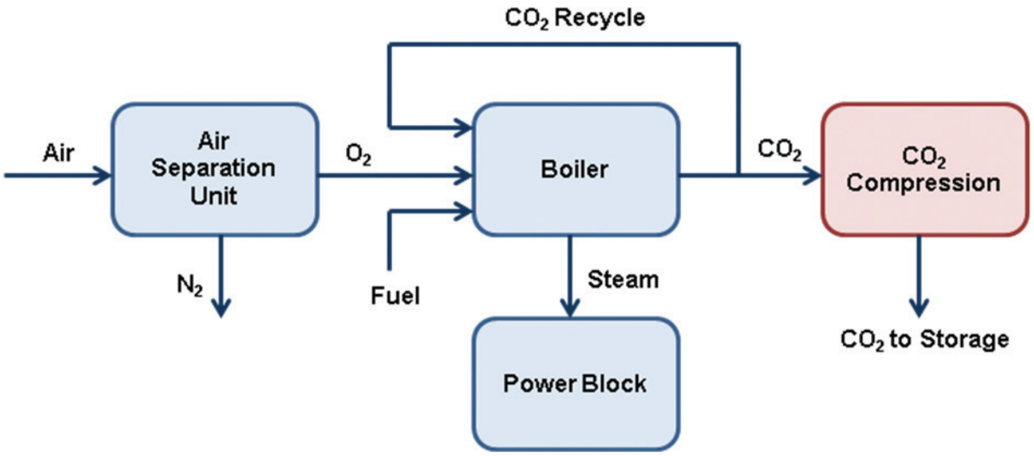


Figure 2-2. Block Diagram Illustrating an Oxy-Combustion Power Plant with CO_2 Recycle and CO_2 Capture

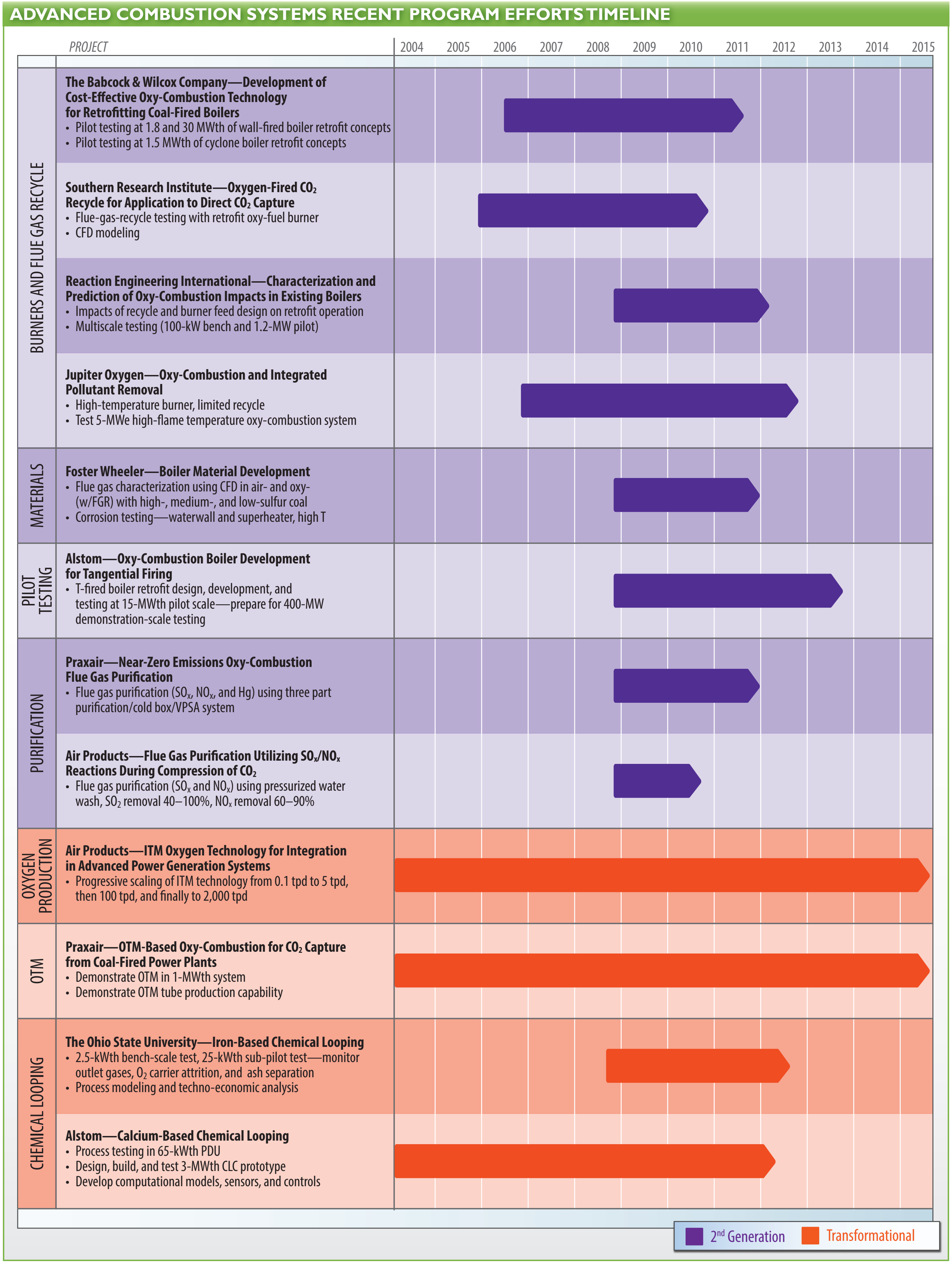
However, the appeal of oxy-combustion is tempered by a few key challenges, namely the capital cost and energy consumption for a cryogenic air separation unit (ASU), boiler air infiltration that dilutes the flue gas with N_2, and excess O_2 contained in the concentrated CO_2 stream. Due to nitrogen removal from the air, oxy-combustion produces approximately 75 percent less combustion product volume than air-fired combustion. Because of this volume reduction, flue gas recycle (≈70–80 percent) is necessary for oxy-combustion retrofit to existing air-fired boilers in order to maintain the boiler temperature, combustion, and heat transfer characteristics of combustion with air. These factors make it so that oxy-combustion systems are not cost-effective at their current level of process development.

The Advanced Combustion Systems program at NETL is focused on R&D activities that can overcome the barriers to widespread deployment of oxy-combustion technology.

2.3 RECENT R&D ACTIVITIES

R&D efforts to date within the Advanced Combustion Systems program have focused on development of advanced materials, advanced burners and boilers, flue gas purification and recycle, oxygen production, and chemical looping. Advanced materials research has involved analyses of the response of different alloys to the harsh conditions associated with oxy-combustion in terms of temperatures, pressures, and corrosion. Foster Wheeler has recently completed analyses that indicate that relatively low-cost materials can withstand the conditions that are to be expected in oxy-combustion systems. Burners and boilers required testing and analysis to determine whether oxy-combustion operation necessitated substantial alterations in retrofit applications. Work conducted by Alstom has indicated that burner and boiler retrofit challenges can be overcome. Flue gas recycle is a mechanism to allow for oxy-combustion retrofits of pulverized coal (PC) boilers. One of the challenges associated with recycle is that concentrations of corrosive constituents are amplified by the process. Efforts by Praxair and Air Products and Chemicals have shown that advanced flue gas purification processes are capable of reducing the corrosive character of oxy-combustion flue gas in order to facilitate recycle as well as CCS activities. Low-cost oxygen production is one of the most essential needs to enhance the cost-effectiveness of oxy-combustion power production. Work in this area is still at a relatively early stage of development, but Praxair's oxygen transport membrane (OTM) technology and Air Products' ion transport membrane (ITM) technology both show significant promise. Finally, chemical looping technology offers the potential to change the way in which oxygen is separated from air in order to facilitate oxy-combustion. As with oxygen production, this technology is still early in the development stage, but work by The Ohio State University and Alstom has generated encouraging results. Figure 2-3 provides an overview of the various R&D areas that have been pursued by the Advanced Combustion Systems program since 2004, along with the timing and a brief description of the scope of selected representative projects. A list of active Advanced Combustion Systems projects is presented in Appendix B.

ADVANCED COMBUSTION SYSTEMS RECENT PROGRAM EFFORTS TIMELINE



The Babcock & Wilcox Company—Development of Cost-Effective Oxy-Combustion Technology for Retrofitting Coal-Fired Boilers
- Pilot testing at 1.8 and 30 MWth of wall-fired boiler retrofit concepts
- Pilot testing at 1.5 MWth of cyclone boiler retrofit concepts

Southern Research Institute—Oxygen-Fired CO_2 Recycle for Application to Direct CO_2 Capture
- Flue-gas-recycle testing with retrofit oxy-fuel burner
- CFD modeling

Reaction Engineering International—Characterization and Prediction of Oxy-Combustion Impacts in Existing Boilers
- Impacts of recycle and burner feed design on retrofit operation
- Multiscale testing (100-kW bench and 1.2-MW pilot)

Jupiter Oxygen—Oxy-Combustion and Integrated Pollutant Removal
- High-temperature burner, limited recycle
- Test 5-MWe high-flame temperature oxy-combustion system

Foster Wheeler—Boiler Material Development
- Flue gas characterization using CFD in air- and oxy- (w/FGR) with high-, medium-, and low-sulfur coal
- Corrosion testing—waterwall and superheater, high T

Alstom—Oxy-Combustion Boiler Development for Tangential Firing
- T-fired boiler retrofit design, development, and testing at 15-MWth pilot scale—prepare for 400-MW demonstration-scale testing

Praxair—Near-Zero Emissions Oxy-Combustion Flue Gas Purification
- Flue gas purification (SO_x, NO_x, and Hg) using three part purification/cold box/VPSA system

Air Products—Flue Gas Purification Utilizing SO_x/NO_x Reactions During Compression of CO_2
- Flue gas purification (SO_x and NO_x) using pressurized water wash, SO_2 removal 40–100%, NO_x removal 60–90%

Air Products—ITM Oxygen Technology for Integration in Advanced Power Generation Systems
- Progressive scaling of ITM technology from 0.1 tpd to 5 tpd, then 100 tpd, and finally to 2,000 tpd

Praxair—OTM-Based Oxy-Combustion for CO_2 Capture from Coal-Fired Power Plants
- Demonstrate OTM in 1-MWth system
- Demonstrate OTM tube production capability

The Ohio State University—Iron-Based Chemical Looping
- 2.5-kWth bench-scale test, 25-kWth sub-pilot test—monitor outlet gases, O_2 carrier attrition, and ash separation
- Process modeling and techno-economic analysis

Alstom—Calcium-Based Chemical Looping
- Process testing in 65-kWth PDU
- Design, build, and test 3-MWth CLC prototype
- Develop computational models, sensors, and controls

Figure 2-3. Overview of Recent Advanced Combustion Systems Program R&D Efforts on 2nd-Generation and Transformational Technologies

In August 2010, DOE/NETL announced the selection of a 1st-Generation oxy-combustion technology CO_2 capture demonstration project under the American Recovery and Reinvestment Act. This effort is being conducted under the FutureGen 2.0 initiative. Ameren Energy Resources is teaming with The Babcock & Wilcox Company and Air Liquide Process & Construction to repower Unit 4 of their Meredosia Power Plant (Figure 2-4) with advanced coal oxy-combustion technology. Meredosia Unit 4 is a 202-MW, oil-fired unit approximately 20 miles west of Jacksonville, IL. Engineering and design activities are underway and operations are planned to begin in 2015.

Figure 2-4. Meredosia Power Plant, Site of FutureGen 2.0 Oxy-Combustion Demonstration Project

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 3: GOALS AND BENEFITS

3.1 GOALS

The goals of the Advanced Combustion Systems program support the energy goals established by the Administration, DOE, FE, and the CCRP. The priorities, mission, goals, and targets of each of these entities are summarized in Appendix C.

3.1.1 CCRP GOALS

Currently, the CCRP is pursuing the demonstration of 1st-Generation CCS technologies with existing and new power plants and industrial facilities using a range of capture alternatives and storing CO_2 in a variety of geologic formations. In parallel, to drive down the costs of implementing CCS, the CCRP is pursuing RD&D to decrease the COE and capture costs and increase base power-plant efficiency, thereby reducing the amount of CO_2 that has to be captured and stored per unit of electricity generated. FE is developing a portfolio of technology options to enable this country to continue to benefit from using our secure and affordable coal resources. The challenge is to help position the economy to remain competitive, while reducing carbon emissions.

There are a number of technical and economic challenges that must be overcome before cost-effective CCS technologies can be implemented. The experience gained from the sponsored demonstration projects focused on state-of-the-art (1st Generation) CCS systems and technologies will be a critical step toward advancing the technical, economic, and environmental performance of 2nd-Generation and Transformational systems and technologies for future deployment. In addition, the core RD&D projects being pursued by the CCRP leverage public and private partnerships to support the goal of broad, cost-effective CCS deployment. The following long-term performance goals have been established for the CCRP:

- Develop 2nd-Generation technologies that:
  - Are ready for demonstration in the 2020–2025 timeframe (with commercial deployment beginning in 2025)
  - Cost less than \$40/tonne of CO_2 captured
- Develop Transformational technologies that:
  - Are ready for demonstration in the 2030–2035 timeframe (with commercial deployment beginning in 2035)
  - Cost less than \$10/tonne of CO_2 captured

The planning necessary to implement the RD&D to achieve the above goals and targets is well underway and the pace of activities is increasing. The path ahead with respect to advancing CCS technologies, particularly at scale, is very challenging given today's economic risk-averse climate and that no regulatory framework is envisioned in the near term for supporting carbon management. These conditions have caused DOE/FE to explore a strategy with increased focus on carbon utilization as a means of reducing financial risk. This strategy benefits from FE's investment in the beneficial utilization of CO_2 for commercial purposes, particularly through the development of next-generation CO_2 injection/EOR technology, with the objective of creating jobs and increasing energy independence. Carbon dioxide injection/EOR is a specific market-based utilization strategy that will positively impact domestic oil production and economical CO_2 capture and storage.

3.1.2 ADVANCED ENERGY SYSTEMS STRATEGIC GOALS

The AES program supports achievement of the CCRP goals by developing and demonstrating advanced, efficient technologies that produce ultraclean (near-zero emissions, including CO_2), low-cost energy with low water use. In support of those overall goals are the specific cost and performance goals for 2025 and 2035 described in the following sections and summarized in Table 3-1.

Table 3-1. **Market-Based R&D Goals for Advanced Coal Power Systems**

	Goals (for nth-of-a-kind plants)		Performance Combinations that Meet Goals	
R&D Portfolio Pathway	*Cost of Captured CO_2, \$/tonne*[1]	*COE Reduction*[2]	*Efficiency (HHV)*	*Capital/O&M Reduction*[3]
2nd-Generation R&D Goals for Commercial Deployment of Coal Power in 2025[4]				
In 2025, EOR revenues will be required for 2nd-Generation coal power to compete with natural gas combined cycle and nuclear in absence of a regulation-based cost for carbon emissions.				
Greenfield Advanced Ultra-Supercritical (A-USC) PC with CCS	40	20%	37%	13%
Greenfield Oxy-Combustion PC with CCS	40	20%	35%	18%
Greenfield Advanced Integrated Gasification Combined Cycle (IGCC) with CCS	≤40	≥20%	40%	18%
Retrofit of Existing PC with CCS	45	n/a		
Transformational R&D Goals for Commercial Deployment of Coal Power in 2035[4]				
Beyond 2035, Transformational R&D and a regulation-based cost for carbon emissions will enable coal power to compete with natural gas combined cycle and nuclear without EOR revenues.				
New Plant with CCS—Higher Efficiency Path	<10[5]	40%	56%	0%
New Plant with CCS—Lower Cost Path	<10[5]	40%	43%	27%
Retrofit of Existing PC with CCS	30	≥40%	n/a	
Transformational pathways could feature advanced gasifiers, advanced CO_2 capture, 3,100 °F gas turbines, supercritical CO_2 cycles, pulse combustion, direct power extraction, pressurized oxy-combustion, chemical looping, and solid oxide fuel cells.				

NOTES:

(1) Assumes 90 percent carbon capture. First-year costs expressed in 2011 dollars, including compression to 2,215 pounds per square inch absolute (psia) but excluding CO_2 transport and storage (T&S) costs. The listed values do not reflect a cost for carbon emissions, which would make them lower. For greenfield (new) plants, the cost is relative to a 2nd-Generation ultra-supercritical PC plant without carbon capture. For comparison, the nth-of-a-kind cost of capturing CO_2 from today's IGCC plant, compared to today's supercritical PC without carbon capture, is about \$60/tonne. For retrofits, the cost is relative to the existing plant without capture, represented here as a 2011 state-of-the-art subcritical PC plant with flue gas desulfurization and selective catalytic reduction. The cost of capturing CO_2 via retrofits will vary widely based on the characteristics of the existing plant such as its capacity, heat rate, and emissions control equipment. The nth-of-a-kind cost of capture for retrofitting the representative PC plant described above (a favorable retrofit target) using today's CO_2 capture technology would be about \$60/tonne. (In contrast, today's first-of-a-kind cost of CO_2 capture for a new or existing coal plant is estimated to be \$100–\$140/tonne.)

(2) Relative to the first-year COE of today's state-of-the-art IGCC plant with 90 percent carbon capture operating on bituminous coal, which is currently estimated at \$133/MWh. For comparison, the first-year COE of today's supercritical PC with carbon capture is estimated to be \$137/MWh. Values are expressed in 2011 dollars. They include compression to 2,215 psia but exclude CO_2 T&S costs and CO_2 EOR revenues. However, CO_2 T&S costs were considered, as appropriate, when competing against other power-generation options in the market-based goals analysis.

(3) Cost reduction is relative to today's IGCC with carbon capture. Total reduction is comprised of reductions in capital charges, fixed operating and maintenance (O&M) and non-fuel variable O&M costs per million British thermal unit (Btu) (higher heating value [HHV]) of fuel input. Cost reductions accrue from lower equipment and operational costs, availability improvements, and a transition from high-risk to conventional financing. The ability to secure a conventional finance structure is assumed to result from lowering technical risk via commercial demonstrations.

(4) 2nd-Generation technologies will be ready for large-scale testing in 2020, leading to commercial deployment by 2025 and attainment of nth-of-a-kind performance consistent with R&D goals by 2030. Transformational technologies will be ready for large-scale testing in 2030, leading to initial commercial deployment in 2035 and attainment of nth-of-a-kind performance consistent with R&D goals by 2040.

(5) Cost of captured CO_2 ranges from \$5 to \$7/tonne for the cost reductions and efficiencies noted.

2ND-GENERATION R&D GOALS

Complete the R&D needed to prepare 2nd-Generation gasification and advanced combustion technologies—that show the ability to produce low-cost, ultraclean energy with near-zero emissions—for demonstration-scale testing (leading to commercial deployment beginning in 2025). These technologies will reduce the cost to produce energy—power with carbon capture, fuels/chemicals, or multiple products (i.e., polygeneration). Cost and performance improvements will be driven by advancements in technologies being developed in the Gasification Systems, Advanced Combustion Systems, Advanced Turbines, Crosscutting Research, and Carbon Capture R&D programs. As shown in Table 3-1, integrating the 2nd-Generation technologies has the potential to produce near-zero-emissions power with reductions in capital and O&M costs of 13–18 percent and plant efficiency of 35–40 percent. This is equivalent to a COE reduction of greater than 20 percent and a capture cost of less than \$40/tonne of CO_2.

TRANSFORMATIONAL R&D GOALS

Successfully develop Transformational technologies with CCS that produce low-cost, near-zero-emissions energy generation and are ready for demonstration-scale testing leading to commercial deployment in 2035. These technologies will reduce the cost to produce energy—power with carbon capture, fuels/chemicals, or multiple products (i.e., polygeneration). For power production, maturing technologies continue to show anticipated cost and performance improvements that will be driven by advancements in technologies being developed in the Gasification Systems, Advanced Combustion Systems, Advanced Turbines, Solid Oxide Fuel Cells, Crosscutting Research, and Carbon Capture R&D programs, which will result in near-zero-emissions power production with capital and O&M cost reductions of 0–27 percent and plant efficiency of 43–56 percent. This is equivalent to a COE reduction of greater than 40 percent and a capture cost of less than \$10/tonne of CO_2.

3.1.3 ADVANCED COMBUSTION SYSTEMS GOALS

The Advanced Combustion Systems program supports the AES goals through the development of oxy-fuel electricity-generation technologies. As noted previously, the AES goals are targeted to be achieved through the integration of technologies developed as part of the Gasification Systems, Advanced Combustion Systems, Advanced Turbines, Solid Oxide Fuel Cells, Crosscutting Research, and Carbon Capture R&D programs. R&D conducted as part of the Advanced Combustion Systems program will contribute to the achievement of the long-term AES goal through the development of high-efficiency/low-cost systems. The CCRP/AES goal is to reduce the cost of CO_2 capture from current levels of approximately \$60/tonne to \$40/tonne for 2nd-Generation technologies and less than \$10/tonne for Transformational technologies. A 2nd-Generation advanced combustion system is projected to account for approximately 85 percent of the overall contribution to the 2nd-Generation cost-reduction goal. Similarly, Transformational advanced combustion technologies are targeted to account for approximately 75 percent of the contribution to the Transformational cost-reduction goal. These contributions, as well as those of other technologies to achieving 2nd-Generation and Transformational goals, are illustrated graphically in Figure 3-1.

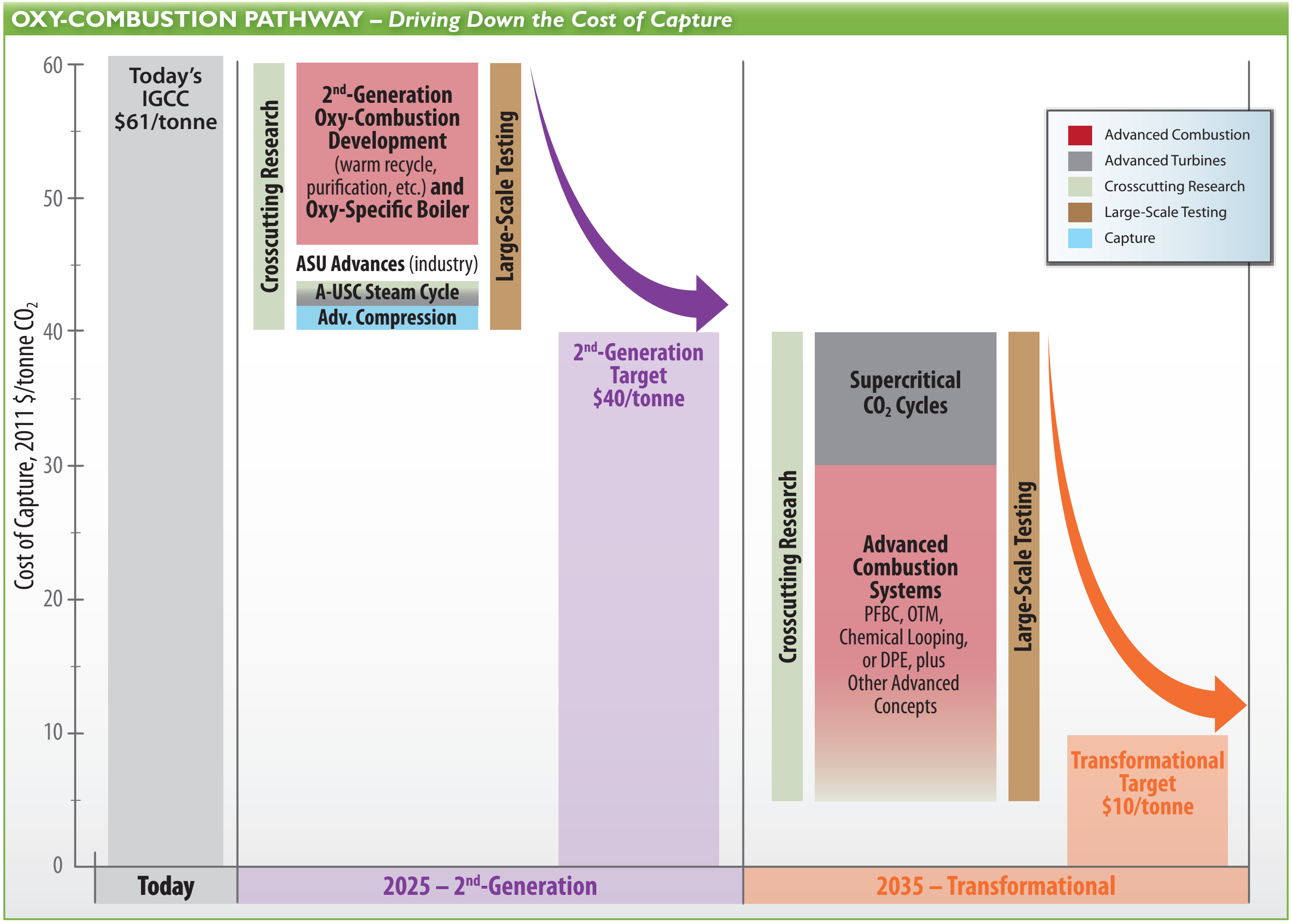


Figure 3-1. Targets for Technology Contribution of Advanced Combustion Systems to Overall CCRP Cost of Capture Goals

3.2 BENEFITS

Coal-fired electricity generation using Advanced Combustion Systems has the potential to provide significant economic, environmental, and technical benefits.

Coal is an abundant domestic fuel source with a stable price history that supports the U.S. economy, a resurgent industry, and even U.S. exports. Coal-based power-generation systems integrated with advanced technologies to improve process efficiency and reduce costs are being developed by DOE and will be able to generate power with greater than 90 percent carbon capture. Carbon captured from advanced combustion plants can be compressed, transported via pipeline, and injected into a depleted oil reservoir for EOR, thereby increasing the production of domestic oil. Alternatively, captured carbon can be used as feedstock for value-added products of commerce.

Furthermore, natural gas prices are currently low. However, historically natural gas has not had stable prices, and most predictions for natural gas prices have not been accurate. Coal is, and will remain, a key component in the U.S. electricity-generating portfolio, and for the economy to be strong there must be enough continuous low-cost fossil-based power available for the foreseeable future. Advanced combustion systems with superior environmental performance, through the development of advanced, highly efficient, low-cost technologies to convert coal into power with carbon capture, can fill this role. Industry and DOE have performed numerous techno-economic analyses demonstrating how advanced combustion systems compete with other technologies to transform coal into power, and also showing the advantages anticipated from the ongoing DOE-supported R&D program.

The development and deployment of new technologies for power production will result in the United States becoming a key leader in these technologies. This will create new, high paying domestic jobs to manufacture and oversee the deployment and operation of these next-generation advanced combustion plants.

Advanced combustion systems also have significant environmental benefits. As noted in Chapter 1, advanced combustion power plants produce flue gas that is rich in CO_2. Separation of CO_2 from this concentrated stream is much simpler than for more dilute air-fired combustion systems. A co-benefit of advanced combustion systems is the dramatic reduction in the emission of conventional pollutants (carbon monoxide, volatile organic compounds, particulate matter, sulfur dioxide [SO_2], and hazardous air pollutants) achieved through the addition of known technologies to the CO_2 purification unit. Emissions of nitrogen compounds are nearly eliminated through the exclusion of air from the boiler, negating the need for nitrogen oxide (NO_x) control technologies. Pressurized systems offer additional driving force for removal of mercury (Hg) and acid gases by shifting the temperature at which these constituents condense, allowing for their removal in the liquid phase.

In addition to the pollutant removal benefits, another benefit is that the mass and volume of the flue gas are reduced in advanced combustion systems. When the volume is reduced, the amount of heat lost in the flue gas is also reduced. This results in increased plant efficiency and reductions in the size of treatment equipment required to process the gas, decreasing capital costs. In pressurized systems, this impact is even more pronounced because the high pressure allows water vapor to be condensed at a much higher temperature than would occur under atmospheric operating conditions. As a result, the thermodynamic quality of the condensing heat is high and can be used for high value purposes such as feed-water heating to improve power-plant cycle efficiency.

The capability to produce low-cost, coal-based electricity while eliminating nearly all air pollutants and potential greenhouse gas emissions makes advanced combustion one of the most promising technologies for energy plants of the future.

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 4: TECHNICAL PLAN

4.1 INTRODUCTION

The Advanced Combustion Systems Technology Area is pursuing three key technologies:

- Oxy-Combustion
- Chemical Looping Combustion
- Advanced Materials

The following subsections describe the general characteristics of each key technology and provide details regarding different research focus areas associated with the key technologies.

4.2 OXY-COMBUSTION

The oxy-combustion key technology includes three research focus areas:

- Atmospheric Pressure Oxy-Combustion
- Pressurized Oxy-Combustion
- Oxygen Transport Membrane-Based Oxy-Combustion

The technical characteristics of each of these technologies are presented in the following sections along with the R&D approach for each research focus area and associated performance targets and measures. In addition, a technology development timeline has been prepared, and barriers/risks associated with the development process have been described along with their strategies to mitigate those barriers/risks.

4.2.1 BACKGROUND

Oxy-combustion technology is applicable to new and existing conventional PC-fired power plants. Today's oxy-combustion system (1st Generation) consists of a conventional supercritical PC boiler, a cryogenic ASU, substantial flue gas recycle, and conventional flue gas purification and CO_2 compression—equipment that 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. A simplified process schematic of an oxy-combustion system with CO_2 capture is shown in Figure 4-1.

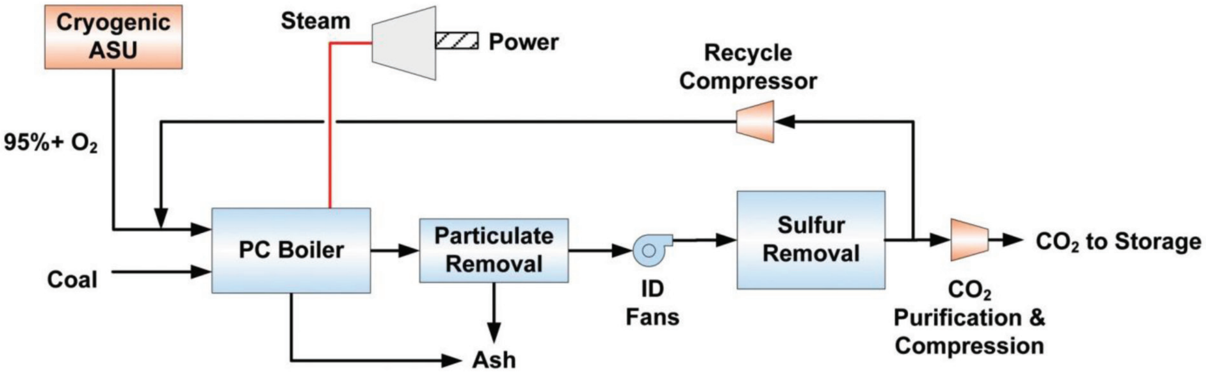


Figure 4-1. Process Schematic of Oxy-Combustion CO_2 Capture

The most significant barrier to the use of 1st-Generation oxy-combustion technology is the high cost. The Advanced Combustion Systems R&D program is developing 2nd-Generation and Transformational technologies that reduce the costs and energy requirements associated with 1st-Generation systems. This involves efforts to develop components of oxy-combustion systems that, when integrated, result in more efficient operations and lower capital costs. The components associated with 1st-Generation, 2nd-Generation, and Transformational oxy-combustion technologies are summarized in Figure 4-2. The technical discussion below describes these components and improvements that will allow for the achievement of the program goals described in Chapter 3.

OXY-COMBUSTION SYSTEM COMPONENTS

1ST-GENERATION TECHNOLOGY
Atmospheric Pressure Oxy-Combustion

- Cryogenic ASU
- Conventional Boiler
- CO_2 Recycle
- Supercritical Steam
- Conventional Purification
- Conventional Compression

2ND-GENERATION TECHNOLOGY
Atmospheric Pressure Oxy-Combustion

- Advanced Cryogenic ASU
- Advanced Oxy-Boiler
- Advanced Ultra-Supercritical Steam
- Advanced Purification
- Advanced Compression

TRANSFORMATIONAL TECHNOLOGIES

Pressurized Oxy-Combustion

- Advanced Cryogenic ASU or O_2 Membane
- High-Pressure Combustor
- Advanced Ultra-Supercritical Steam Conditions
- Supercritical CO_2 Power Cycle
- Advanced Purification
- Advanced Compression

OTM Power Cycle

- Natural Gas OTM Reformer
- OTM Partial Oxidizer
- OTM Boiler
- Advanced Ultra-Supercritical Steam Conditions
- Advanced Purification
- Advanced Compression

Figure 4-2. Components of Oxy-Combustion Systems

4.2.2 TECHNICAL DISCUSSION

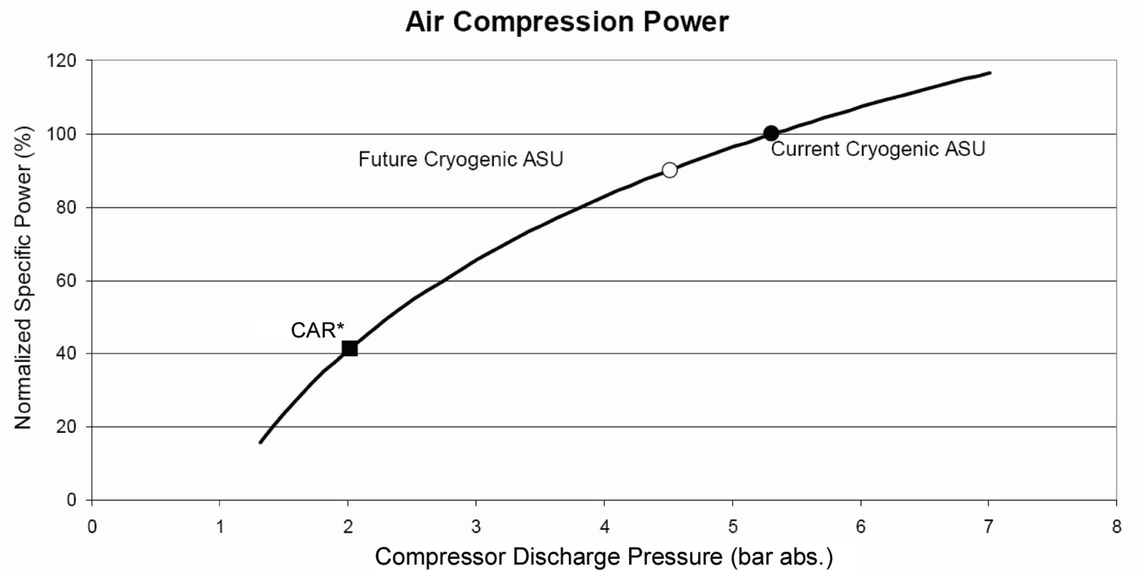
An oxy-combustion power plant with carbon capture contains several major components, including oxygen production, the oxy-combustion boiler, CO_2 purification and compression, and power cycle. This section will describe the technical aspects of each of these components.

OXYGEN PRODUCTION

Current oxygen production technology uses cryogenic separation processes that consume 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; thus, cryogenic oxygen separation represents a significant energy penalty. The energy consumption of current cryogenic technologies is four to five times the theoretical minimum energy required for the process. This indicates that there may be significant room for future improvement. However, due to the nature of the cryogenic distillation process (which involves mostly mechanical processes, such as compression/expansion for refrigeration), the potential efficiency improvement will be relatively limited. Future cryogenic processes will be able to operate around 4.5 bar, which is expected to result in a 10 percent reduction in compression work.

Oxygen production in 2nd-Generation and Transformational oxy-combustion systems will be accomplished by either advanced cryogenic separation or oxygen membrane separation. These technologies are described subsequently.

Advanced Cryogenic Oxygen Separation—The cryogenic oxygen separation process works by compressing air, cooling via expansion, followed by cryogenic distillation to separate different gases (i.e., oxygen, nitrogen, and argon). One aspect of the cryogenic oxygen separation process that shows promise in terms of cost and performance improvements is reduction of operating pressure of the cryogenic distillation column. Figure 4-3 shows how required compression work will be reduced with respect to the current state-of-the-art cryogenic process when the operating pressure of the distillation column (as indicated by compressor discharge pressure) is reduced.



*Ceramic Autothermal Recovery—a promising advanced air separation technology.

Figure 4-3. Required Compression Power vs. Operating Pressure

Oxygen Separation Membranes—The ITM process is a relatively new oxygen separation technology that has been demonstrated at the pilot scale for gasification-based systems. ITM technology is based on the transport of oxygen ions through the crystal lattice of mixed metal oxides. The ceramic materials used for this application have a high flux and selectivity to oxygen. Oxygen molecules are converted to oxygen ions at the surface of the membrane on the oxygen-rich side and transported through the membrane by an oxygen partial pressure difference. Oxygen molecules then reform on the oxygen-lean side of the membrane. An operating temperature of 800 °C is required in order to activate the ion transport process. The hot oxygen product stream is nearly 100 percent pure. The remaining gas is a pressurized, oxygen-depleted stream from which significant amounts of energy can be recovered. Figure 4-4 is a schematic diagram of an ITM separation process.

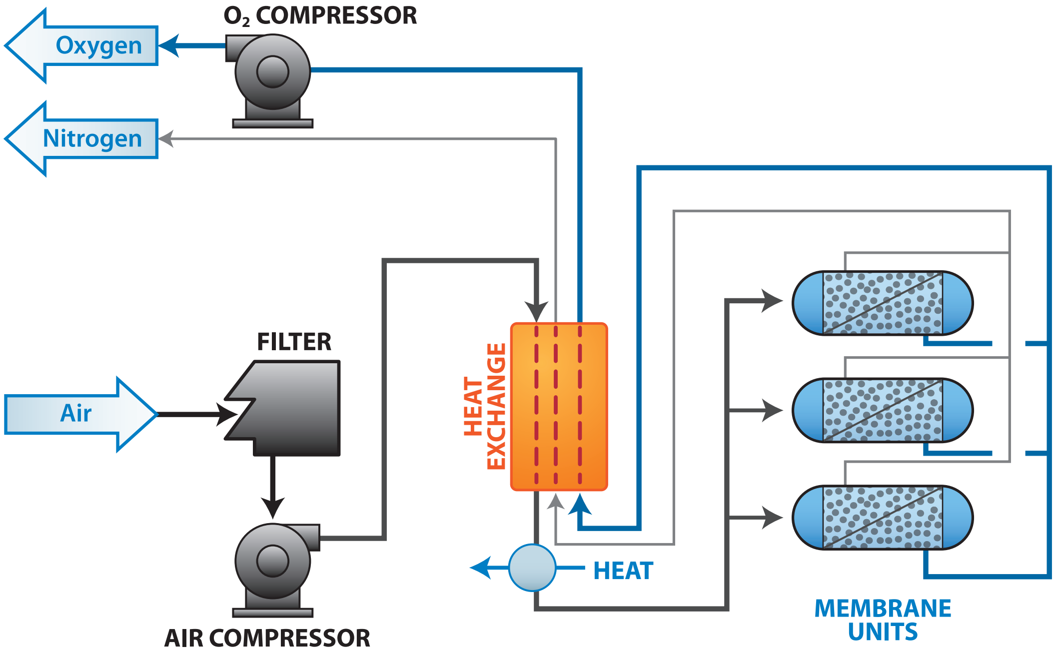


Figure 4-4. Ion Transport Membrane Air Separation Process

Although Figure 4-4 shows the ITM as a stand-alone process, in practice it will be integrated into the power-plant design to minimize energy consumption. Because ITM technology requires a high operating temperature and pressure, the main purpose of power system integration is to recover/reduce compression energy and heat loss.

BOILER DESIGN

Atmospheric Pressure Oxy-Combustion Boilers—Within the definition of 2nd-Generation oxy-combustion technologies, an advanced boiler could include reduced recycle and an advanced recycle system. An advanced recycle system eliminates the flue gas recycle superheating system used for current technology.

An advanced boiler with reduced recycle would be designed to accommodate a smaller flue gas flow and increased temperatures, which results in reduced equipment size. Because of reduced flue gas recycle, an advanced boiler would accommodate a theoretical adiabatic flame temperature of approximately 2,300 °C versus 2,000 °C for current systems. The reduced volumetric flow through the boiler system also allows for a decrease in the size of the associated equipment. Furthermore, fan loads required for flue gas recycle are reduced, increasing system efficiency.

The benefit of smaller oxy-combustion boilers may be limited due to the need for advanced materials that can handle the high temperatures that result with decreasing levels of flue gas recycle. Furthermore, as flue gas recycle is reduced, dilution of sulfur compounds by desulfurized flue gas will be reduced. This will create a demand for sulfur-tolerant materials.

Pressurized Oxy-Combustion Boilers—A number of organizations are investigating the prospect of an oxy-coal power plant in which combustion occurs under pressure. At the center of a pressurized oxy-combustion system is either a PC or circulating fluidized bed boiler operating at elevated pressure, typically in the range of 10–20 bar. Pressurized oxy-combustion has several benefits over atmospheric oxy-combustion:

- Elevated operating pressures offer the potential to reduce latent heat losses from flue gas. In atmospheric pressure oxy-combustion, latent heat can be recovered from flue gas if it is cooled below the dew point of 60–70 °C. Unfortunately, heat at this temperature is of limited value in terms of power production. However, at 10 bar pressure, the dew point rises to 120–140 °C, facilitating heat recovery in the steam cycle. This heat recovery increases boiler efficiency and thus overall plant efficiency.

- Higher pressure operations result in lower gas volumes and corresponding decreases in the volume of process units, including the boiler. This decrease in size reduces both weight and cost. Reactor wall thicknesses may need to be increased to handle the increased pressure, counterbalancing the total size decrease to some extent, but the net impact should decrease capital cost.
- Operating the boiler at elevated pressure will preclude air in-leakage that is common in atmospheric pressure boilers. This in-leakage increases the concentration of impurities in the flue gas. These impurities must either be removed, increasing costs and process complexity, or co-sequestered with the CO_2, unnecessarily occupying pore space and complicating transport.
- The cost of removing flue gas impurities is reduced at higher pressure.
- Increased gas-side pressure will significantly increase heat transfer rates. Increased gas density at pressure leads to enhanced heat transfer. With pressure increased from 1 to 10 bar, the convective heat transfer coefficient increases by a factor of four, decreasing the needed heat transfer area by a factor of four. The most significant benefit of the reduced heat transfer area will be in superheater bundles. These bundles typically require advanced materials that increase costs. If the heat transfer area is reduced by a factor of four, so too is the capital cost of the heat exchangers.
- Since the boiler operates at elevated pressure, oxygen and coal must be fed to the boiler at elevated pressure. While it requires additional power to pressurize the feed oxygen, this is more than offset by the decrease in power required to compress and purify the CO_2 leaving the plant. The oxygen feed is relatively clean, and the capital cost for the equipment to increase the pressure is much lower than the capital cost of the wet CO_2 compressor required for flue gas pressurization in an atmospheric pressure system.

While several research challenges exist, pressurized steam cycle systems have the potential to increase plant efficiencies by 5 percent or more in comparison to atmospheric steam cycle systems. Critical development needs exist to foster the understanding required to prepare the technology for demonstration-scale testing. These are grouped in two general areas: characteristics specific to the pressurized combustor, and overall system and process design. The list below identifies R&D areas that have been established at this early stage of development:

Pressurized Combustor Design	System/Process Design
Boiler configuration/type	Gas cleaning
Combustion characteristics	Thermal integration
Pressure containment	Power cycle integration
Advanced materials	Process optimization
Heat transfer	Advanced materials
Thermal integration	
Fuel feed	
Fuel conditioning	
Gas cleaning	
Flue gas recycle	

CO_2 PURIFICATION AND COMPRESSION

CO_2 Purification—Although oxy-combustion would produce a flue gas that has a high CO_2 concentration, the flue gas will also include H_2O, as well as excess O_2, N_2, SO_2, NO_x, Hg, and other contaminants. The acidic gases must be removed from the CO_2 stream prior to pipeline transportation to avoid corrosion and to comply with purity requirements for applications such as EOR and geological storage. Therefore, projects in this area focus on the development of flue gas purification technologies. While, commercially available technology exists to remove SO_2 and NO_x from oxy-combustion flue gas streams, advanced purification technologies are being developed that would take advantage of the flue gas conditions to decrease cost and improve performance.

Advanced purification technologies would take advantage of the flue gas makeup to capture SO_x, NO_x, and Hg using higher pressure (≈200–450 psia), hydrolysis, and activated carbon processes with the potential for greater than 90 percent capture and production of saleable acids. In the case of oxy-combustion retrofits with high air ingress, improvements are possible on commercially available cryogenic CO_2 separation technology to push capture rates over 95 percent by using vacuum pressure swing adsorption. Air Products and Praxair have recently completed advanced CO_2 purification research that is now ready for large pilot- or demonstration-scale testing.

CO_2 Compression—Compression is an integral part of any CO_2 capture system. Since CO_2 separation from the gas stream typically occurs at low pressure, compression is required to reduce the volume flow, making transport more practical. Furthermore, storage sites for geological sequestration and CO_2-EOR require high pressure CO_2 as well. Given the high volume flows, centrifugal compressors are typically employed, especially when the captured CO_2 is produced at near-atmospheric pressure. The physics to compress CO_2 in a centrifugal compressor is the same as that for any other gas. However, CO_2 has many unique characteristics compared to other gases that must be considered in the compressor design, such as consideration of real gas effects, high volume reduction, low speed of sound, and avoiding liquid formation. Its high molecular weight allows CO_2 to be liquefied at relatively high temperatures permitting hybrid compression and pumping options.

The CO_2 captured from a power plant will need to be compressed from near-atmospheric pressure to a pressure between 1,500 and 2,200 psia for most applications. However, the compression of CO_2 represents a potentially large auxiliary-power load on the overall power-plant system. For example, in an August 2007 study, CO_2 compression was accomplished using a six-stage centrifugal compressor with inter-stage cooling that required an auxiliary load of approximately 7.5 percent of the gross power output of a subcritical pressure, coal-fired power plant. Conventional compression technology accounts for ≈30 percent of all auxiliary loads in an oxy-combustion system. The capital cost for the compressor and associated equipment is also significant.

To reduce auxiliary power requirements and capital cost, DOE/NETL is developing novel concepts for large-scale CO_2 compression. Various compression concepts are being evaluated using computational fluid dynamics and laboratory testing, leading to prototype development and field testing. Research efforts include development of intrastage versus inter-stage cooling, fundamental thermodynamic studies to determine whether compression in a liquid or gaseous state is more cost-effective, and development of a novel method of compression based on supersonic shock wave technology. DOE/NETL is currently supporting research on two advanced CO_2 compression technologies, a supersonic shockwave compression technology, and a combined interstage cooling and liquefied CO_2 pumping technology.

Supersonic shock wave compressor design features a rotating disk that operates at high peripheral speeds to generate shock waves that compress the CO_2. Compared to conventional compressor technologies, shock compression provides high compression efficiency, high single-stage compression ratios, opportunity for waste heat recovery, and lower capital cost.

The second concept involves initial compression to 250 psia, liquefaction, and pumping. The most energy-intensive components of the process are the initial compression required to boost the CO_2 to approximately 250 psia and the refrigeration power required to liquefy the gas. The pumping power to boost the pressure to pipeline supply pressure (2,200 psia) is minimal after the CO_2 is liquefied. This concept reduces power consumption by 35 percent compared to conventional 10-stage compression.

SUPERCRITICAL CO_2 POWER CYCLE

While a supercritical CO_2 power cycle is not a part of the Advanced Combustion Systems program, its development would be an important component in helping achieve Transformational program goals. Compared to a conventional steam cycle, the supercritical CO_2 cycle has a higher efficiency at the same turbine inlet temperature. In addition, a supercritical CO_2 cycle allows for higher inlet turbine temperatures than a steam cycle using materials that are currently available. A steam cycle turbine inlet temperature limit is approximately 600 °C. A supercritical CO_2 cycle turbine inlet temperature limit is approximately 700 °C, leading to even greater improvements in efficiency. Development of advanced materials that would allow even higher inlet temperatures would lead to more efficiency improvements.

The supercritical CO_2 power cycle operates in a manner similar to other turbine cycles, but it uses CO_2 as the working fluid in the turbomachinery. The cycle is a non-condensing closed-loop Brayton cycle with heat addition and rejection on either side of the expander. Once the system is charged with CO_2, for the most part there is no addition or loss during operation. In this cycle the CO_2 is heated indirectly from a heat source through a heat exchanger—not unlike the way steam would be heated in a conventional boiler. Energy is extracted from the CO_2 as it is expanded in the turbine. Remaining heat is extracted in one or more highly efficient heat recuperators to preheat the CO_2 going back to the boiler. These recuperators help increase the overall efficiency of the cycle by limiting heat rejection from the cycle.

The cycle is operated above the critical point of CO_2 so that it does not change phases (from liquid to gas), but rather undergoes drastic density changes over small ranges of temperature and pressure. This allows a large amount of energy to be extracted from equipment that is relatively small in size. Supercritical CO_2 turbines have a gas path diameter of a few inches compared to a few feet for utility-scale combustion turbines or steam turbines. The temperature profiles of typical heat sources and the supercritical CO_2 working fluid through the recuperators and heat exchangers can be designed to better match than conventional steam heat exchangers with a phase shift, allowing lower temperature differences between the heat sources and the working fluid (CO_2). In this way irreversible entropy is minimized.

Fossil fuels, particularly coal, can provide an ideal heat source for supercritical CO_2 cycles. The open literature has shown that a supercritical CO_2 closed-loop cycle combined with a coal-fueled oxygen-blown pressurized fluidized bed combustor has the potential to increase efficiency with a lower capital cost than a comparable supercritical steam-based Rankine cycle with the same turbine inlet temperature. Studies suggest that the supercritical CO_2 oxy-fuel pressurized fluidized bed combustor system has the potential to significantly increase efficiency, as much as 9 percentage points over other PC oxy-fuel combustion configurations, with a 20 percent lower COE and the potential for near 100 percent CO_2 capture (from combustion). Water consumption and other emission profiles are also very attractive for this cycle. While benefits to other advanced combustion technologies are assumed to be similar, further analysis is necessary to fully understand the applicability and system benefit of the supercritical CO_2 power cycle to technologies other than pressurized oxy-combustion, such as OTM and chemical looping combustion.

The supercritical CO_2 cycle utilizes small turbomachinery, is fuel- and/or heat-source neutral, efficient, and can make use of lower intensity heat sources. These factors make the cycle appealing to a wide range of applications and stakeholders. For instance the supercritical CO_2 cycle can be particularly attractive as a bottoming cycle for simple-cycle gas turbines, providing an improvement of 15–20 additional percentage points, while retaining many of the desirable attributes of the simple cycle configuration. Other bottoming cycle applications will also be attractive. Due to the fuel and heat source neutrality, the cycle is also highly relevant to concentrated solar and nuclear applications, both technology components with a high level of DOE interest. The Department of Defense has also expressed a strong interest for naval propulsion and power due to the compactness and efficiency of this cycle (the

Naval Research Laboratory at Bettis Atomic Power Laboratory has one of three supercritical CO_2 test loops in the United States). In summary, this cycle has significant benefits to a number of power-based applications with multiple stakeholders. This broad range of applications makes the market-based development and deployment of this machinery highly attractive.

OTM ADVANCED POWER CYCLE

In the oxy-combustion technologies described previously, a pure stream of O_2 is separated in an ASU and then delivered to a boiler for combustion. OTM technology integrates O_2 separation and combustion in one unit.

The basic principle behind the OTM oxy-combustion system is the use of chemical potential instead of pressure as the oxygen separation driving force. Air and fuel are fed to either side of a tubular membrane. As air contacts the membrane, molecular O_2 reacts to form oxygen ions, which are transported through the membrane. Fuel species (carbon monoxide, hydrogen, methane, etc.) react with oxygen ions at the membrane surface to form oxidation products (H_2O, CO_2). The combustion reaction on the fuel side of the membrane creates a very low oxygen partial pressure compared to the air side of the membrane. This difference in chemical potential drives oxygen through the membrane without the need for additional air compression.

The advantage of the OTM oxy-combustion system is that it can provide a highly concentrated, sequestration-ready stream of CO_2 while significantly reducing the need for cryogenic oxygen production or CO_2 separation processes. The use of reactively driven OTMs is expected to reduce the power associated with oxygen production by 70–80 percent. This represents a step change in the cost and related CO_2 emissions, and will enable a variety of oxy-combustion technologies, as well as other combustion applications, where CO_2 capture may be required. Cost and performance simulations of OTM-based power cycles have shown the potential for high net efficiency (>36 percent higher heating value), a major contributing factor that allows the OTM power cycle to meet program cost and performance goals. The development of OTMs will also benefit industrial processes used to produce syngas for subsequent processing into a variety of chemical and/or petrochemical end products by dramatically reducing the power requirements.

The OTM advanced power cycle full-scale plant configuration is illustrated in Figure 4-5. The plant includes a coal gasifier with requisite oxygen production, syngas cleaning, the OTM oxy-combustion system, a conventional steam power cycle, and CO_2 purification and compression.

The OTM oxy-combustion system is composed of two primary components, the OTM boiler and the OTM partial oxidation (POx) unit, circled in red. These components are the focus of the technology R&D in this research focus area. The OTM boiler is the primary steam generator. It houses the OTM tubes that transport oxygen from air into the combustion chamber, steam tubes for the steam cycle, and the combustion chamber where fuel (syngas) is burned with oxygen to generate steam for the power cycle.

The OTM POx units are used to boost the temperature of the syngas to the operating range of the OTM boiler. Like the boiler, they also use OTM tubes to transport oxygen into the reactor for the partial oxidation of the syngas.

As shown in Figure 4-5, the OTM combustion system must be operated using a gaseous fuel. Thus, for a coal-fired OTM system, coal must first be gasified to produce syngas that drives the OTM combustor.

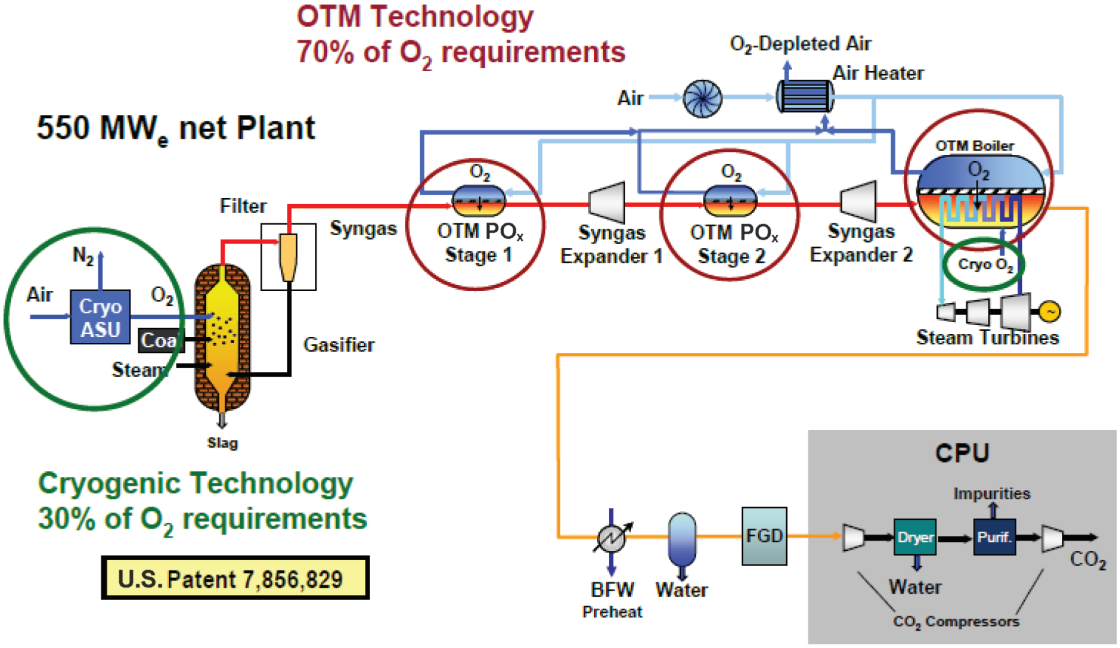


Figure 4-5. OTM Advanced Power Cycle

In addition to the development of the OTM system, another AES Technology Area, Gasification Systems, is pursuing advanced syngas production, a necessary subsystem of the OTM power system. The technical advantages and research needs for the OTM and advanced syngas production technologies are described in greater detail in the following sections.

ADVANCED SYNGAS PRODUCTION

Coal gasification is commercially available; however, in conjunction with the development of an advanced IGCC system under the Gasification Systems program, the performance of coal gasification systems is expected to improve over time, thereby improving the overall performance of the OTM advanced power cycle.

OXYGEN TRANSPORT MEMBRANE

There are several potential benefits to the use of an oxygen transport membrane. The OTM advanced power cycle is an oxy-combustion system, with many of the same advantages. However, the OTM has added benefits over 2nd-Generation oxy-combustion technologies, including:

- Oxygen is supplied to the combustion process via a boiler-integrated OTM, reducing the need for either conventional or advanced oxygen production by more than 70 percent. This significantly reduces the size of the oxygen production unit. The overall impact to a full-scale power plant using the OTM is an increase in efficiency due to lowered energy demand for oxygen production, and a decrease in capital cost due to the reduced size of the oxygen production unit.
- The CO_2 recycle that is typical of currently available oxy-combustion systems is eliminated in the OTM system. This will reduce the necessary equipment, fans, ducts, etc., thereby reducing capital cost, as well as reducing energy demand for that equipment, which boosts overall plant efficiency.

While the characteristics noted previously show the promise of the OTM system, several aspects of the technology need additional R&D to develop the understanding required to prepare the technology for demonstration-scale testing. These are grouped into three general areas: oxygen membrane characteristics, OTM boiler and POx design, and overall system and process design. The list below identifies areas for continuing R&D:

Oxygen Membrane	Boiler/POx Design	System/Process Design
Oxygen flux	Module integration	Gas cleaning
Membrane optimization	Heat transfer	Process optimization
Modularization	Fluid dynamics	Thermal integration
Seals	Thermal management	
Manufacturability	Operating conditions	
Contaminant resistance	Seals	
Operational stability	Manufacturability	
Reliability	Maintainability	

4.2.3 **R&D APPROACH—PERFORMANCE TARGETS AND MEASURES**

As noted in Chapter 1, the technology development process involves multiple stages, largely associated with the scale at which the R&D is conducted. Early stages of R&D typically involve testing and analysis at the laboratory/bench scale, and over time moves to small and then large pilot-scale testing to prepare technologies for testing at demonstration scale. Program milestones as part of the pressurized oxy-combustion system development process are expected to include the following:

- In FY 2013: Preliminary performance and economic systems analyses
- In FY 2016: Complete component development and testing
- In FY 2023: Complete component scaleup testing
- In FY 2030: Complete pilot-scale integrated system testing—ready for demonstration

Performance targets for oxy-combustion technologies have been developed based, in part, on systems analyses described in the report *Advancing Oxycombustion Technology for Bituminous Coal Power Plants: An R&D Guide*. This report describes cost and performance improvements associated principally with 2nd-Generation oxy-combustion systems, but it does not provide a timeline for achieving those improvements. It also does not provide significant insights regarding Transformational technologies. Given the relatively early stage of development of Transformational technologies, associated performance targets are more uncertain than those for 2nd-Generation technologies. The performance targets developed for non-OTM oxy-combustion systems are summarized in Table 4-1.

As noted, 2nd-Generation and Transformational CCRP and AES goals are targeted to be met for atmospheric-pressure and pressurized oxy-combustion systems through the integration of technologies being pursued in the Advanced Combustion Systems program as well as the Gasification Systems, Advanced Turbines, and Crosscutting Research programs. In addition, Table 4-1 lists the improvements in cost and performance associated with advanced ultra-supercritical steam conditions and a supercritical CO_2 power cycle that are enabled by the advanced materials research described in Section 4.4.

Table 4-1. **Performance Targets for Non-OTM Oxy-Combustion Systems**

Technology	Metric[1]	2nd-Generation	Transformational[2]
	System Type	*Atmospheric*	*Pressurized[3]*
Combustion System	COE Reduction	🟥 ↓10%	🟥 ↓14%
	Efficiency Gain	🟥 ↑<1%	🟥 ↑3–5%
	Capture Cost Reduction	🟥 ↓$14/tonne	🟥 ↓$27/tonne
Oxygen Supply	COE Reduction	🟥 ↓5%	
	Efficiency Gain	🟥 ↑2%	
	Capture Cost Reduction	🟥 ↓$3/tonne	
Advanced Compression	COE Reduction	🟦 ↓1%	
	Efficiency Gain	🟦 ↑<1%	
	Capture Cost Reduction	🟦 ↓$2/tonne	
Advanced Materials/ Advanced Power Cycle[4]	COE Reduction	🟥 ↓4%	⬛ ↓6%
	Efficiency Gain	🟥 ↑3%	⬛ ↑4%
	Capture Cost Reduction	🟥 ↓$2/tonne	⬛ ↓$9/tonne
Full System Targets	COE Reduction	↓20%	↓40%
	Capture Cost	$40/tonne	<$10/tonne

KEY:

🟥 Advanced Combustion
🟦 Carbon Capture
⬛ Turbines

NOTES:

(1) COE reduction and capture cost reductions are relative to today's IGCC with carbon capture. Efficiency gain is measured as percentage points (HHV) and is relative to a baseline oxy-combustion system.

(2) Transformational performance targets are incremental from the 2nd-Generation target of 20% reduction in COE and $40/tonne capture cost.

(3) Includes compression benefits.

(4) Advanced materials R&D supported by the Advanced Combustion program enables a 2nd-Generation A-USC power cycle. Transformational advanced materials R&D enables development of the supercritical CO_2 power cycle by the Advanced Turbines program.

A similar gradual scaleup and system integration approach will be used for OTM advanced power cycle development. The current technology development project, funded by the American Recovery and Reinvestment Act (ARRA), is anticipated to conclude in 2016. At that time, developers will have built and tested a development-scale OTM combustion system. This will be followed by OTM module scaleup development, testing, and analysis; and finally by pilot-scale integrated system testing to prepare technologies for demonstration-scale testing. Program milestones as part of the OTM advanced power cycle system development process are expected to include the following:

- In FY 2016: Complete testing development-scale system
- In FY 2023: Complete scaleup module testing
- In FY 2030: Complete pilot-scale integrated system testing—ready for demonstration

The OTM system represents a Transformational technology, and as such, will be in a fairly early stage of development by 2020. Performance targets for 2030 are noted in Table 4-2. As with pressurized oxy-combustion systems, Transformational CCRP and AES goals are targeted to be met for the OTM advanced power cycle through the integration of technologies being pursued in the Advanced Combustion program as well as the Gasification Systems, Advanced Turbines, and Crosscutting Research programs. In addition, the OTM system benefits from improvements in cost and performance associated with advanced ultra-supercritical steam conditions and a supercritical CO_2 power cycle that are enabled by the advanced materials research described in Section 4.4.

Table 4-2. **Performance Targets for the OTM Advanced Power Cycle Research Focus Area**

Technology	Metric[1]	2nd-Generation	Transformational[2]
OTM Advanced Power Cycle	COE Reduction		↓14%
	Efficiency Gain		↑3–5%
	Capture Cost Reduction		↓$27/tonne
Advanced Materials/ Advanced Power Cycle[3]	COE Reduction		↓6%
	Efficiency Gain		↑4%
	Capture Cost Reduction		↓$9/tonne
Full System Targets	COE Reduction		↓40%
	Capture Cost		<$10/tonne

KEY:

Advanced Combustion

Turbines

NOTES:

(1) COE reduction and capture cost reductions are relative to today's IGCC with carbon capture. Efficiency gain is measured as percentage points (HHV) and is relative to a baseline oxy-combustion system.

(2) Transformational performance targets are incremental from the 2nd-Generation target of 20% reduction in COE and $40/tonne capture cost.

(3) The Transformational power cycle is supercritical CO_2.

4.2.4 TECHNOLOGY TIMELINE

The timeline for oxy-combustion technology development is summarized in Figure 4-6. 2nd-Generation advanced purification projects have already been completed, and advanced compression and oxy-boiler projects are scheduled for completion in 2014–2015. Significant testing has already been conducted at pilot scale for these 2nd-Generation technologies, and as currently active projects are completed, it will be left to industry to pursue demonstration-scale testing. For pressurized oxy-combustion, short-term R&D efforts will involve techno-economic analyses followed by laboratory-/bench-scale testing of system components. This will be followed by scaleup of system components and finally by integrated testing at the pilot scale. For OTM power system development, the current module and system development effort will be followed by module scaleup and testing, and finally by integrated system testing at pilot scale.

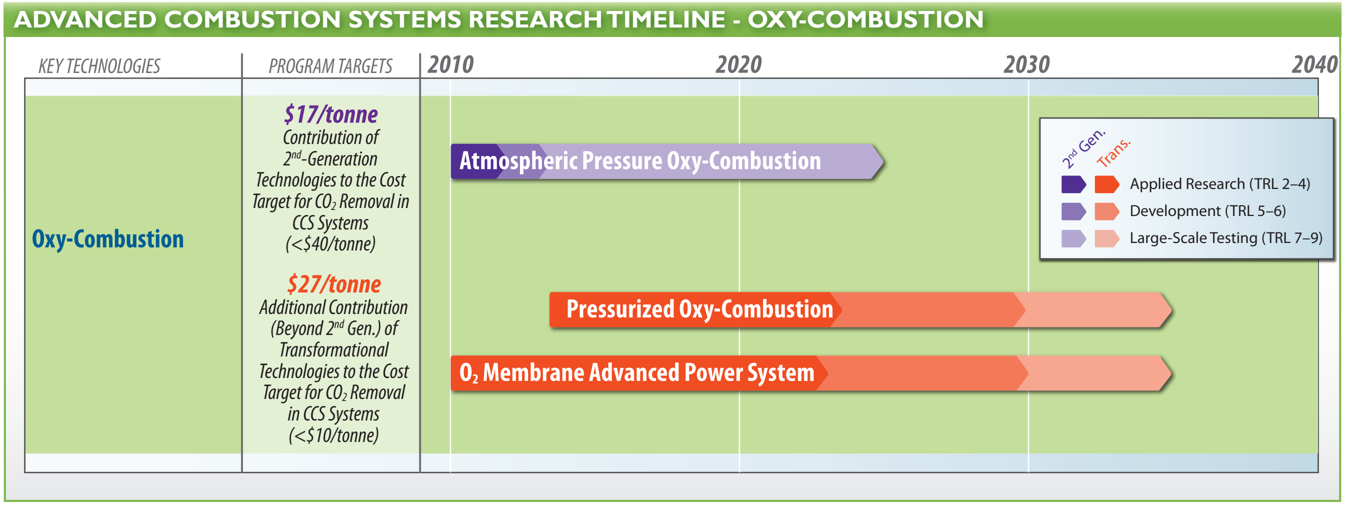


Figure 4-6. Oxy-Combustion Development Timeline

4.2.5 RESEARCH FOCUS AREA BENEFITS

The cost and performance benefits associated with achieving program targets for each of the oxy-combustion research focus areas were presented previously in Tables 4-1 and 4-2. Overall 2nd-Generation and Transformational CCRP and AES goals can be met for oxy-combustion systems through the integration of technologies being pursued in the Advanced Combustion program as well as the Gasification Systems, Advanced Turbines, and Crosscutting Research programs.

More broadly, oxy-combustion systems support the DOE/FE mission of ensuring the availability of ultraclean (near-zero emissions), abundant, low-cost domestic energy from coal to fuel economic prosperity, strengthen energy independence, and enhance environmental quality. As noted previously, separation of CO_2 from the concentrated flue gas stream generated via oxy-combustion is much simpler than for more dilute air-fired combustion systems. Oxy-combustion systems can also dramatically reduce emissions of conventional pollutants (carbon monoxide, volatile organic compounds, particulate matter, SO_2, and hazardous air pollutants) through the addition of known technologies to the CO_2 purification unit. Emissions of nitrogen compounds are nearly eliminated through the exclusion of air from the boiler, negating the need for NO_x control technologies. Pressurized systems offer additional driving force for removal of Hg and acid gases by shifting the temperature at which these constituents condense, allowing for their removal in the liquid phase.

In addition to the pollutant removal benefits, another benefit is that the mass, volume, and heat loss of the flue gas are reduced in oxy-combustion systems. This results in increased plant efficiency and reductions in the footprint of equipment required to process the gas, decreasing land costs and equipment capital costs.

Finally, development of OTM technology can result in cost reductions for other industrial processes. For example, use of an OTM system rather than a conventional steam methane reforming process can result in decreases in capital costs of 20–40 percent, reducing the costs of feedstock for production of chemicals or liquid fuels.

4.3 CHEMICAL LOOPING COMBUSTION

4.3.1 BACKGROUND

Chemical looping combustion (CLC) is a Transformational oxy-combustion 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. Figure 4-7 presents a simplified process schematic for chemical looping. 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. In one potential configuration, chemical looping is carried out in two fluidized beds. 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 the 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. For example, NETL's Office of Research and Development (ORD) is conducting laboratory R&D using nickel oxide on bentonite and copper oxide on bentonite as O_2 carriers.

The advantage of using the CLC process is that the CO_2 is concentrated once the H_2O is removed and not diluted with N_2 gas. Another advantage of the CLC process is that no separate ASU is required, and CO_2 separation takes place during combustion. CLC may also be able to take advantage of the supercritical CO_2 power cycle described previously. Elimination of the ASU and incorporation of efficiencies available from CLC provide the potential for the process to meet cost and performance goals.

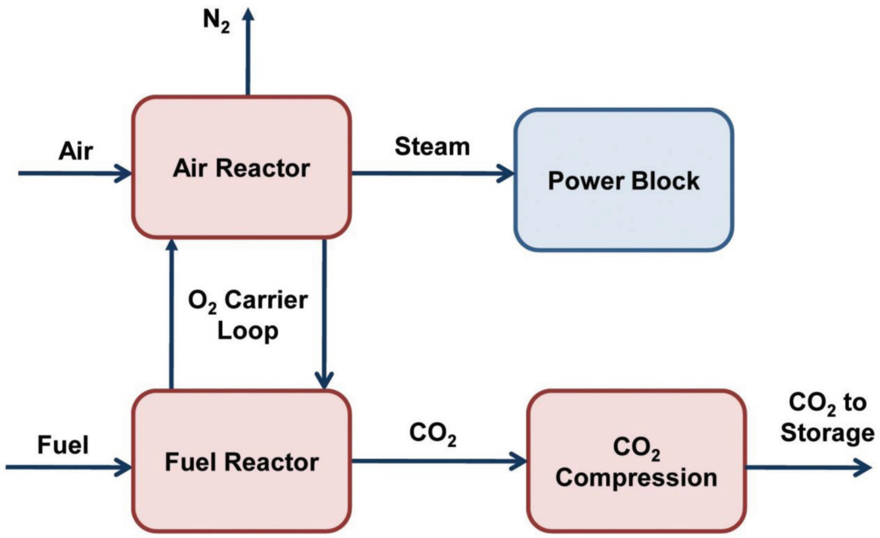


Figure 4-7. Chemical Looping Process

The eventual development of CLC offers the potential as a game-changing technology for power generation and CO_2 capture. A recent systems analysis study conducted by Alstom estimates that a power plant equipped with CLC could capture nearly all of the CO_2 generated and have a COE increase of less than 20 percent compared to a conventional coal-fired power plant without CO_2 capture. CLC offers the following advantages:

- Avoids the large investment costs and parasitic power associated with either cryogenic ASUs or ITMs used for oxy-combustion
- Captures CO_2 at high temperature without additional external energy, thus eliminating the thermodynamic penalty normally associated with CO_2 capture
- Involves small equipment and low capital cost (because of fast chemical reactions)
- Requires conventional material of construction and fabrication techniques

Key R&D issues that need to be addressed to advance the development of chemical looping systems are described in the following sections.

4.3.2 TECHNICAL DISCUSSION

NETL is conducting R&D in seven areas of technology that will improve the cost and performance of CLC:

- Oxygen carriers
- Process integration
- Solids management
- Ultra-supercritical steam
- Supercritical CO_2 power cycle
- Advanced purification
- Advanced compression

Several of the technologies being developed in these areas are applicable to a wide range of power production platforms, and thus are being pursued by NETL R&D programs outside of Advanced Combustion Systems. This section provides additional information on the technical plan for the first three areas of technology—oxygen carriers, process integration, and solids management—that are specific to chemical looping. The other four areas of technology are discussed elsewhere in this plan. However, all will contribute to achieving the goals of the Advanced Combustion Systems program.

CLC TECHNOLOGY

CLC is similar to oxy-combustion in that it relies on combustion of coal in a N_2-free environment. CLC splits combustion into separate oxidation and reduction reactions. Subsequently, the products of combustion (CO_2 and H_2O) are kept separate from the rest of the flue gases (primarily N_2). In the CLC process, oxygen is transferred from a gaseous stream (usually air) to a fuel (either gaseous or solid) through a solid chemical. The solid chemical is called the oxygen carrier. In a typical CLC process, the oxidation and reduction of the oxygen carrier are accomplished in two separate reactors. However, oxygen transport may be completed in three or more steps depending on the application and the oxygen carrier used.

Figure 4-8 is a schematic diagram of a two-reactor CLC process. The oxygen carrier is usually a solid, metal-based compound. The solid is oxidized by O_2 in the air to form an oxide of the compound and produce a hot flue gas. The hot flue gas can be used to produce steam. The metal oxide from the oxidizer enters the fuel reactor and is reduced to its initial state by the fuel. The combustion products from the fuel reactor will be a highly concentrated CO_2 and H_2O stream that can be purified, compressed, and sent to storage.

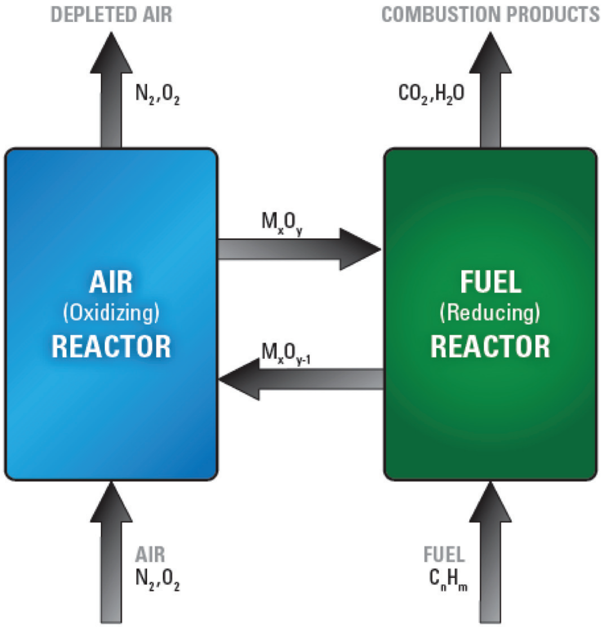


Figure 4-8. Schematic Diagram of a Two Reactor CLC Process

CURRENT CLC R&D EFFORTS

CLC is in the early stages of process development. Bench- and laboratory-scale experimentation is currently being conducted. Projects in this research focus area are advancing the development of chemical looping systems by addressing key issues, such as solids handling and oxygen carrier capacity, reactivity, and attrition. Researchers are investigating several metal oxides for use as the O_2 carrier including calcium, iron, nickel, copper, and manganese. For example, NETL's ORD is conducting laboratory-scale tests using nickel oxide on bentonite and copper oxide on bentonite as O_2 carriers. NETL is also conducting external CLC R&D projects with Alstom, The Babcock & Wilcox Company, The Ohio State University, and University of Kentucky, and has recently selected three additional projects to advance the technology.

FUTURE CLC R&D EFFORTS

While the characteristics noted previously show the promise of CLC, additional technology development is needed to foster the understanding required to prepare the technology for demonstration-scale testing. Development needs are grouped in four general areas: oxygen carrier characteristics, solids circulation strategy, reactor design, and overall system and process design. The list below identifies areas for R&D:

Oxygen Carrier	Solids Circulation	Reactor Design	System/Process Design
Composition	Dilute pneumatic	Gas cleaning	Gas cleaning
Density	Dense pneumatic	Process optimization	Process optimization
Reaction kinetics	Mechanical	Thermal integration	Thermal integration
Oxygen carrying capacity	Flow control		Heat transfer strategy
Fluidization properties	Mechanical valves		
Attrition	Non-mechanical valves		
Agglomeration	Uncontrolled		
Sintering			
Degradation—chemical, thermal, contaminants			

4.3.3 R&D APPROACH—PERFORMANCE TARGETS AND MEASURES

As with the oxy-combustion technologies, the technology development process for CLC involves multiple stages, largely associated with the scale at which the R&D is conducted. Early stages of R&D typically involve testing and analysis at the laboratory/bench scale, and over time testing moves on to small and then large pilot-scale testing to prepare technologies for testing at demonstration-scale. Program milestones as part of the CLC system development process are expected to include the following:

- In FY 2013: Complete preliminary performance and economic systems analyses
- In FY 2016: Complete component development and testing
- In FY 2023: Complete component scaleup testing
- In FY 2030: Complete pilot-scale integrated system testing—ready for demonstration

Chemical looping combustion represents a Transformational technology, and as such, will be in a fairly early stage of development by 2020. Performance targets for 2030 are noted in Table 4-3. As with the oxy-combustion systems described previously, Transformational CCRP and AES goals are targeted to be met for CLC systems through the integration of technologies being pursued in the Advanced Combustion program as well as the Gasification Systems, Advanced Turbines, and Crosscutting Research programs. In addition, the CLC system benefits from improvements in cost and performance associated with advanced ultra-supercritical steam conditions and a supercritical CO_2 power cycle that are enabled by the advanced materials research described in Section 4.4.

Table 4-3. **Performance Targets for Chemical Looping Combustion Systems**

Technology	Metric[1]	2nd-Generation	Transformational[2]
Chemical Looping Combustion	COE Reduction		↓14%
	Efficiency Gain		↑3–5%
	Capture Cost Reduction		↓$27/tonne
Advanced Materials/ Advanced Power Cycle[3]	COE Reduction		↓6%
	Efficiency Gain		↑4%
	Capture Cost Reduction		↓$9/tonne
Full System Targets	COE Reduction		↓40%
	Capture Cost		<$10/tonne

KEY:

Advanced Combustion

Turbines

NOTES:

(1) COE reduction and capture cost reductions are relative to today's IGCC with carbon capture. Efficiency gain is measured as percentage points (HHV) and is relative to a baseline oxy-combustion system.

(2) Transformational performance targets are incremental from the 2nd-Generation target of 20% reduction in COE and $40/tonne capture cost.

(3) The Transformational power cycle is supercritical CO_2.

4.3.4 TECHNOLOGY TIMELINE

The timeline for chemical looping combustion technology development is summarized in Figure 4-19. Short-term R&D efforts will involve techno-economic analyses followed by laboratory-/bench-scale testing of system components. This will be followed by scaleup of system components and finally by integrated testing at the pilot scale.

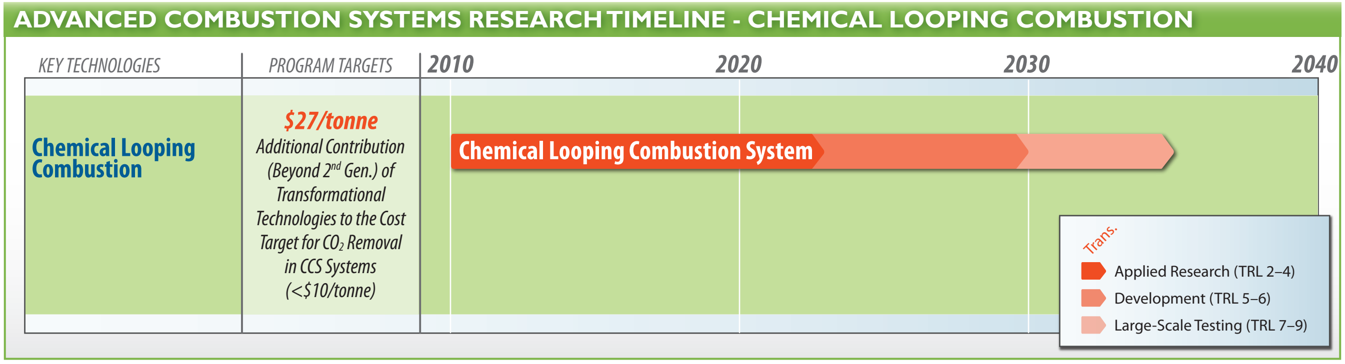


Figure 4-9. Chemical Looping Combustion Development Timeline

4.3.5 RESEARCH FOCUS AREA BENEFITS

The cost and performance benefits associated with achieving program targets for the CLC research focus area were presented in Table 4-3. As with oxy-combustion systems, overall 2nd-Generation and Transformational CCRP and AES goals can be met for CLC systems through the integration of technologies being pursued in the Advanced Combustion program as well as the Gasification Systems, Advanced Turbines, and Crosscutting Research programs.

More broadly, CLC systems support the DOE FE mission of ensuring the availability of ultraclean (near-zero emissions), abundant, low-cost domestic energy from coal to fuel economic prosperity, strengthen energy independence, and enhance environmental quality. Environmental benefits of CLC systems are similar to oxy-combustion systems in terms of CO_2, carbon monoxide, volatile organics, particulate matter, SO_2, and hazardous air pollutant removal. Emissions of nitrogen compounds are nearly eliminated through the exclusion of air from the combustion reactor, negating the need for NO_x control technologies. CLC systems also benefit from reduced footprint, reducing land costs and equipment capital costs. Finally, CLC technology development can be applied to other industrial processes similarly to OTM technology. Lessons learned from development of CLC technology can be applied to chemical looping gasification technology to produce feedstock for the production of chemicals or liquid fuels.

4.4 ADVANCED MATERIALS AND CONCEPTS

4.4.1 BACKGROUND

In combustion-based power systems, higher temperatures and pressures generally translate to higher power-plant efficiencies. However, temperatures and pressures are limited by the materials used to construct boilers and turbine systems. Development of materials that can withstand higher temperatures and pressures is the focus of advanced materials research.

In addition to advanced materials research, the Advanced Combustion Systems program plans to pursue R&D opportunities involving advanced concepts that could positively impact the cost and performance of advanced combustion systems and are outside of the scope of the research focus ares described previously. An advanced technology investigated as part of this research focus area that offers significant promise after preliminary analysis and laboratory testing could then be transitioned into its own R&D focus area, if applicable.

4.4.2 TECHNICAL DISCUSSION

ADVANCED MATERIALS

A 2nd-Generation oxy-combustion system would incorporate advanced ultra-supercritical steam conditions rather than supercritical conditions used in current designs. Today's supercritical boilers operate at steam conditions of approximately 3,500 psia (24 MPa) and 1,000 °F (540 °C). Advanced ultra-supercritical steam conditions are 5,000 psig/1,350 °F/1,400 °F (34 MPa/732 °C/760 °C). Depending on actual steam conditions, advanced ultra-supercritical plant efficiencies are generally 3–4 percentage points higher than those of comparable supercritical plant designs. Higher efficiency 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. Many of the advanced materials and coatings that support advanced ultra-supercritical conditions are still in the R&D stage of development and at varying levels of maturity.

NETL's ORD is pursuing advanced materials research in the following areas:

- Characterization of materials corrosion in oxy-combustion boilers
- Development of advanced alloys for advanced ultra-supercritical boiler and steam turbine components
- Advanced alloy design, development, and manufacturing processes for advanced ultra-supercritical boiler and steam turbine components
- Alloy optimization for ultra-supercritical (650 °C) boiler and steam turbine components
- Computational modeling of ultra-supercritical and advanced ultra-supercritical materials

This effort is planned to continue through FY 2015. The advanced materials development effort is funded out of the Advanced Combustion Systems program, but the individual projects are administered by the Crosscutting Research subprogram. More detail on advanced materials R&D is provided in the *Crosscutting Research Program Plan*.

ADVANCED CONCEPTS

An advanced concept under consideration by the Advanced Combustion Systems program is direct power extraction (DPE), formerly known as magnetohydrodynamic (MHD) power generation. DPE uses conductive, high-temperature gases as electrical conductors moving through a magnetic field. Power is generated directly from the moving gases. The high temperatures associated with oxy-combustion can be used to operate a DPE "topping" cycle. The gases that drive the DPE cycle are still at high temperature when they exit the cycle and can then be used to drive a conventional steam boiler system, or "bottoming cycle."

MHD alone was tested, and proven, for power generation in the 1970s and 1980s, but had efficiencies in the 17–22 percent range. These low efficiencies, uncontrolled arcing that damaged electrodes, and slagging issues made MHD by itself unattractive for utility power generation when compared with conventional Rankine cycle power plants (without CCS), which easily reach 40 percent efficiencies.[1] However, technology improvements have made MHD, or DPE, worth renewed consideration.

Slagging combustors available today meet slag control goals that were not achievable in the 1980s, and are likely to overcome the previously encountered issues. MHD computational fluid dynamics codes will enable DPE generator design to be optimized for reduced arcing and slag interaction. In addition, improvements in magnet technology have led to the development of devices with a magnetic field that is approximately twice as strong (10 Tesla instead of 4.5 Tesla) as magnets used in previous MHD testing. Because power output is approximately equal to the square of the magnetic field, doubling the strength of the field increases power production by a factor of four. Furthermore, oxy-combustion with modern ASU optimization significantly reduces parasitic energy demand compared to those observed in the 1980s. Preliminary analyses have shown that combining DPE with oxy-combustion and carbon capture results in overall plant efficiencies near 50 percent.

4.4.3 R&D APPROACH—PERFORMANCE TARGETS AND MEASURES

In terms of oxy-fuel combustion systems, advanced materials represent an enabling technology that facilitates the ability of combustion systems to contribute to the achievement of program goals. Given this role, separate performance targets and measures are not noted for advanced materials. Instead, their contributions to cost and performance improvements are integrated into the values shown in Tables 4-1, 4-2, and 4-3 as they apply to complete oxy-fuel power-plant systems. In addition, the R&D approach differs from those described previously in that the technologies do not necessarily advance directly from laboratory to pilot scale. Instead, as materials technologies are developed, it is anticipated that combustion system developers will incorporate them into the units that make up the system.

4.4.4 TECHNOLOGY TIMELINE

The timeline for advanced materials development is shown in Figure 4-10. This timeline calls for a consistent level of effort over time to develop materials that will enable combustion systems to withstand the aggressive conditions found in oxy-fuel environments and will provide opportunities for development of advanced concepts.

---

[1] Development of an Inductive Magnetohydrodynamic Generator, Roberto Pintus, Università degli Studi di Cagliari, Dottorato di Ricerca in Ingegneria Industriale, XXIII Ciclo, ING-IND/31 ELETTROTECNICA. http://veprints.unica.it/616/1/PhD_Roberto_Pintus.pdf.

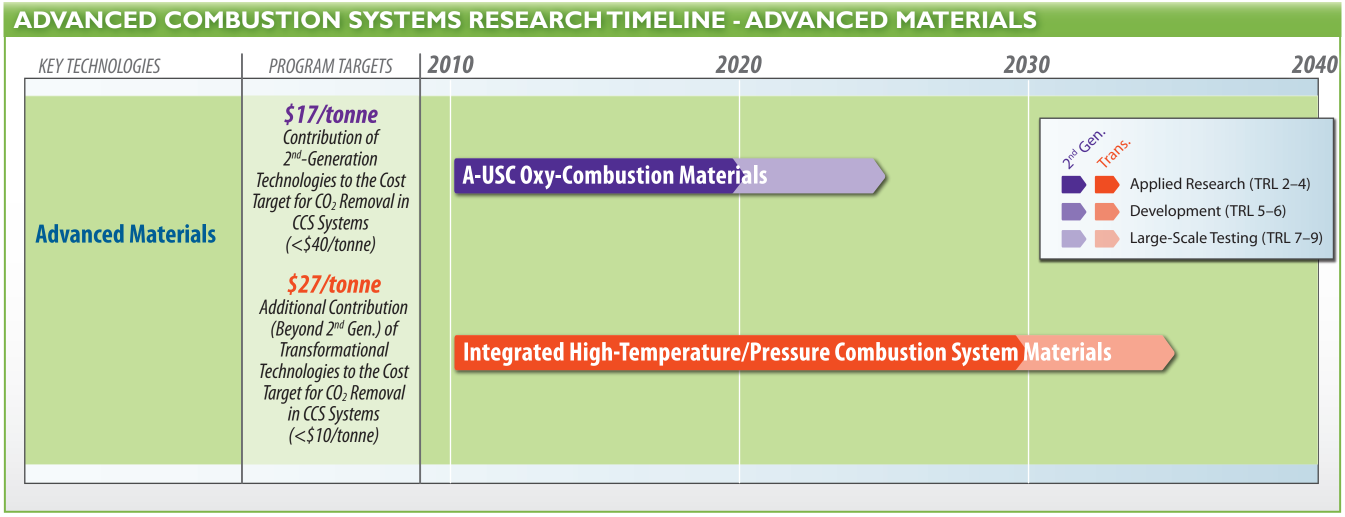


Figure 4-10. Advanced Materials and Concepts Development Timeline

4.5 SUMMARY OF TECHNOLOGY TIMELINES

The development timelines for all of the research focus areas within the Advanced Combustion Systems program are summarized in Figure 4-11. As noted previously, laboratory/bench-scale research will be conducted in multiple research focus areas leading to pilot-scale testing of the most advanced concepts to prepare them for demonstration. Demonstration of 2nd-Generation technologies is anticipated after 2020 followed by deployment after 2025. Demonstration of Transformational technologies is anticipated after 2030 with deployment after 2035. Atmospheric-pressure oxy-combustion technology is projected to contribute approximately $17/tonne captured toward the 2nd-Generation cost-of-capture goals. Transformational technologies are targeted to contribute an additional $27/tonne captured beyond the 2nd-Generation technologies. Additional detail is provided on the implementation of Advanced Combustion program R&D efforts in Chapter 5.

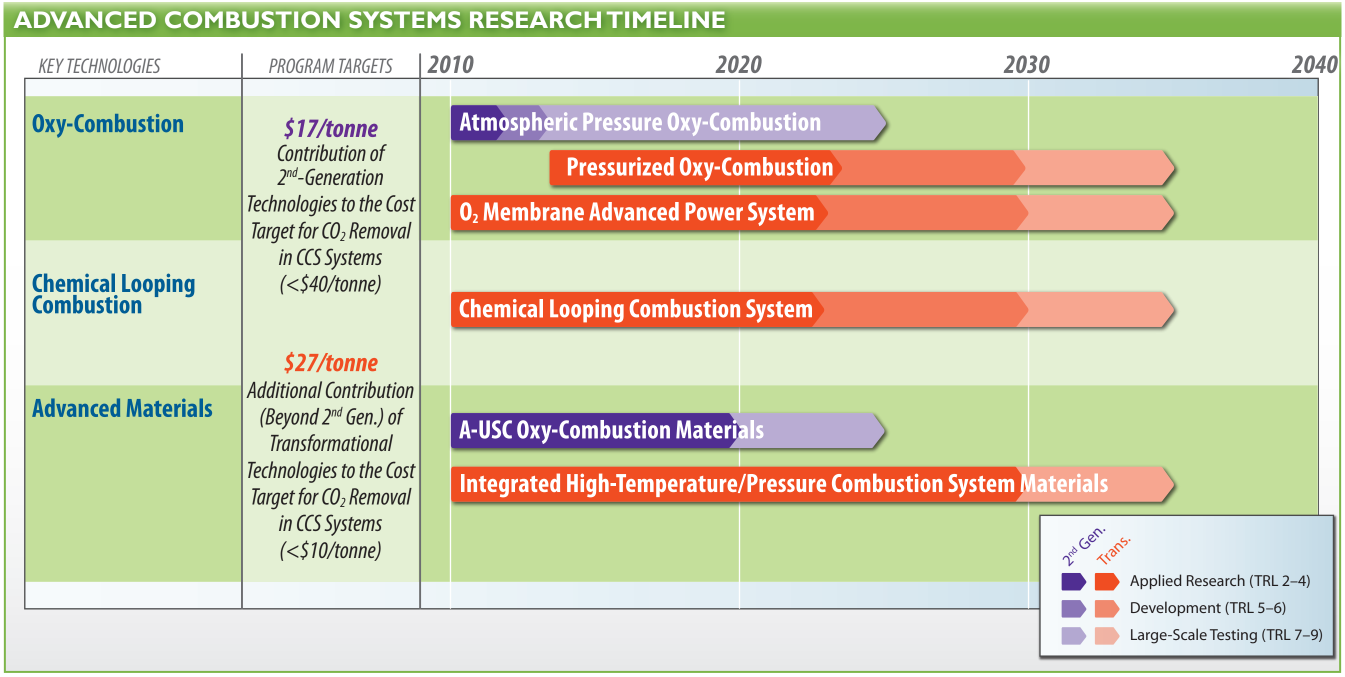


Figure 4-11. Summary of Development Timelines for the Advanced Combustion Systems Program

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 5: IMPLEMENTATION AND COORDINATION PLAN

5.1 IMPLEMENTATION PLAN

The Advanced Combustion Systems R&D program will be implemented as illustrated in Figure 5-1.

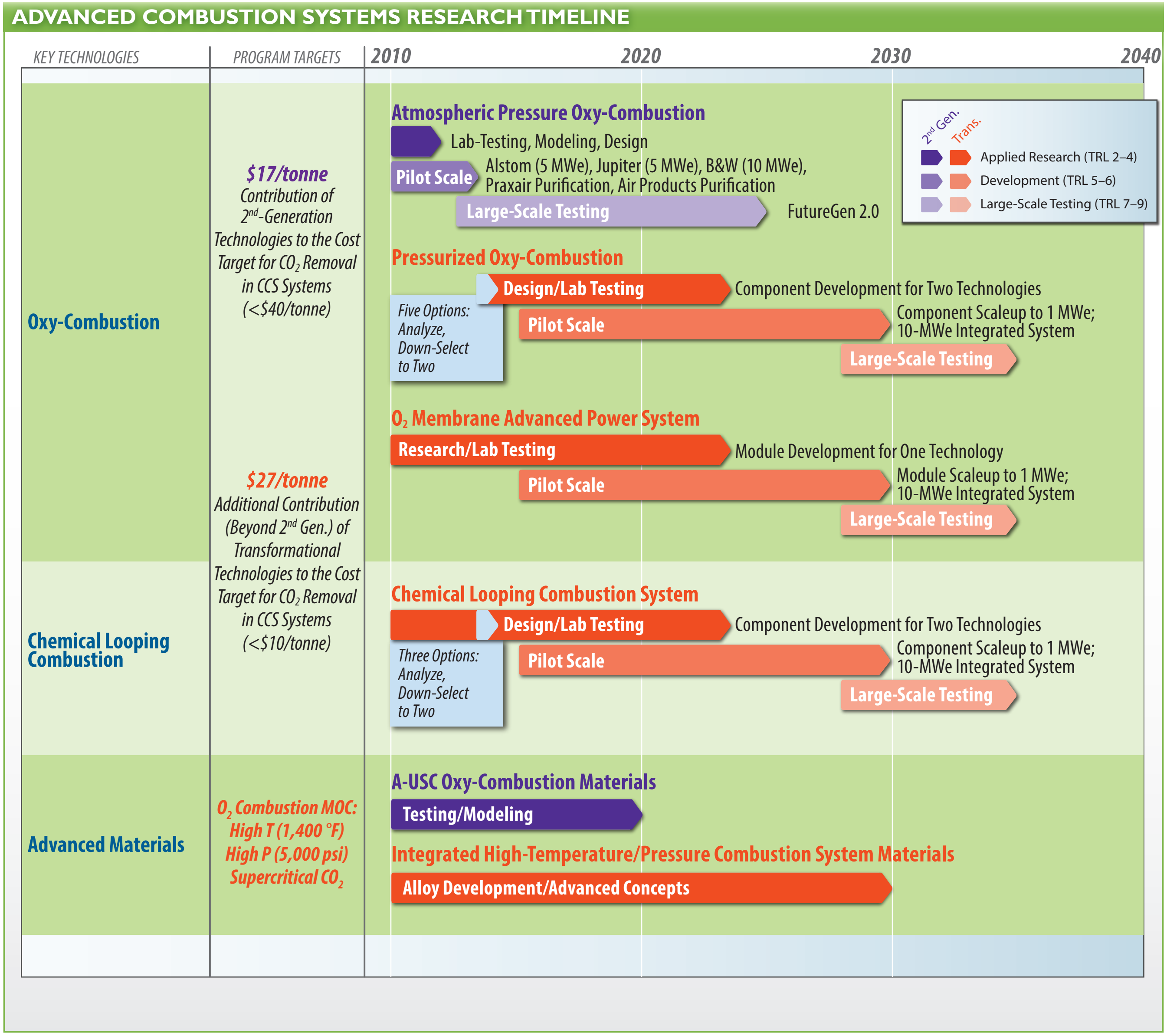


Figure 5-1. Advanced Combustion Systems RD&D Roadmap

In FY 2012, an FOA seeking proposals for research on both pressurized oxy-combustion systems and chemical looping combustion systems was released. Eight projects (five pressurized oxy-combustion and three CLC) were selected to perform 1-year detailed systems analyses of their individual technologies. These analyses will provide detailed descriptions of the potential performance and cost characteristics of each technology. At the end of that process, it is anticipated that two projects from each area (i.e., pressurized oxy-combustion and CLC) will be down-selected to move forward in the development process. The down-selected projects will spend approximately 3 years (2014–2016) developing components and testing at laboratory scale. At that point it is anticipated that DOE will seek new projects to conduct component validation and scaleup of the technology systems. This is envisioned as a 7-year (2017–2023) process during which the components will be scaled up to somewhere in the 1- to 5-MWe scale. Due to the time allotted to this phase of R&D, iterative development and testing are likely. Following that developmental stage, it is anticipated that DOE would again seek new projects to support the design, scaleup, and testing of integrated pilot-scale systems. This will likely be another 7-year phase (2024–2030). Integrated systems will be greater than 10 MWe in scale, and the 7-year phase will again allow for iterative development and testing to prepare for demonstration-scale testing (beyond 2030).

The OTM power cycle research focus area would follow a similar pattern. The current project, which is funded by ARRA, is scheduled to end by 2016. At its completion, a development-scale OTM combustion system will have been built and tested. After the completion of the current project, it is envisioned that 7 years will be spent (2017–2023) in scaleup of the development-scale unit, component validation, and scaleup to pilot scale. Design, further scaleup, and testing of integrated pilot-scale systems in preparation for demonstration will then be conducted (2024–2030). At that point the OTM would be prepared for demonstration-scale testing (beyond 2030).

As the program is currently outlined, the result of the R&D effort will be two pressurized oxy-combustion systems, an OTM advanced power system, and two CLC systems ready for demonstration-scale testing in 2030.

The Advanced Combustion Systems program described previously represents a comprehensive, three-pronged Transformational technology R&D approach. R&D on a portfolio of technologies is being pursued in three research focus areas to enhance the probability of success of research efforts that are operating at the boundaries of current scientific understanding. The R&D covers a wide scale, integrating advances and lessons learned from fundamental research, technology development, and demonstration-scale testing. The success of this effort will enable cost-effective implementation of power-generation technologies.

5.2 DESCRIPTION OF INTERRELATIONSHIPS

The Transformational technologies under development in the oxy-combustion and chemical looping combustion research focus areas are significantly different in process and equipment, with some overlap in combustor/boiler materials. As a result, interrelationships are limited to the crosscutting contributions of the advanced materials research focus area.

5.3 COORDINATION WITH OTHER TECHNOLOGY AREAS

The technologies developed within the Advanced Combustion Systems Technology Area rely upon the R&D of other DOE CCRP Technology Areas and are relied upon by other Technology Areas, as well. Figure 5-2 illustrates the interdependencies of the Advanced Combustion Systems technologies with the Gasification Systems and Advanced Turbines technologies.

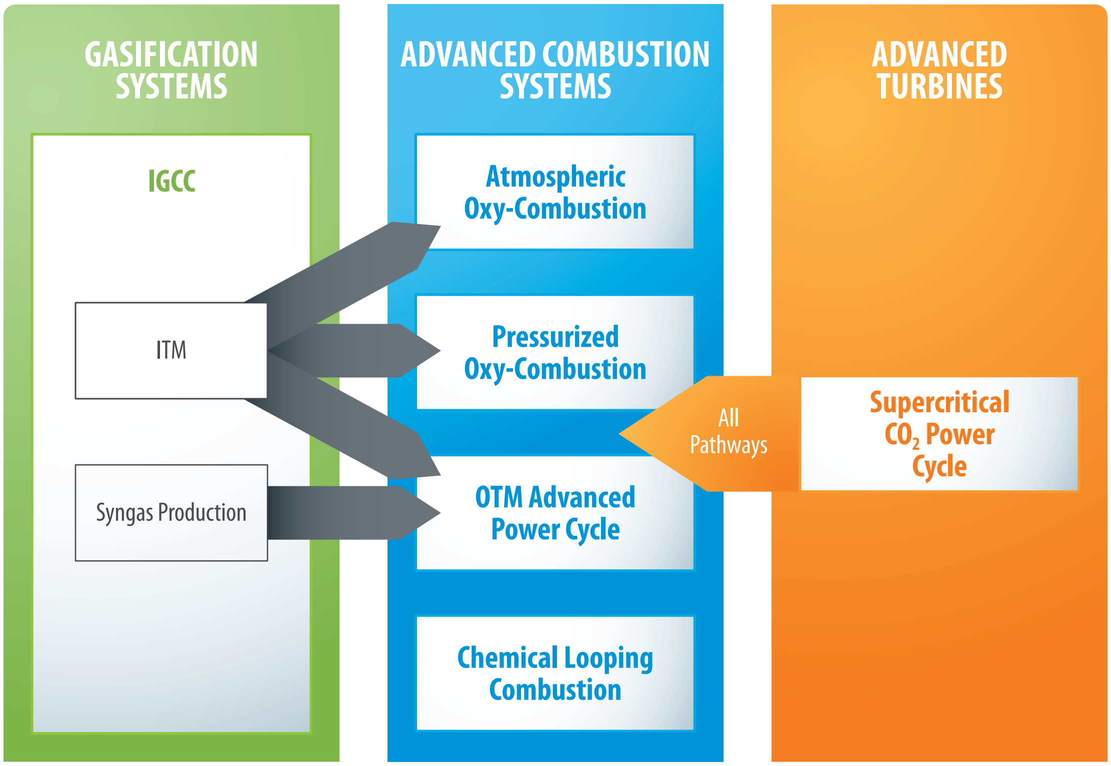


Figure 5-2. Interdependencies of Advanced Combustion Systems Technologies and Other Technology Areas

The ITM, which is being developed by Gasification Systems, represents a significant cost and performance improvement over cryogenic oxygen production. This will be important to long-term development of the oxy-combustion research focus area. Advances in syngas production, also being developed by Gasification Systems, will support the performance improvement of the OTM. The OTM boiler must be fed gasified coal, or syngas, rather than pulverized coal.

The Advanced Turbines Technology Area is developing a supercritical CO_2 power cycle, which would replace the conventional steam power cycle. This technology has the potential for significant efficiency improvements over steam, and could be integrated into any of the Advanced Combustion Systems research focus areas.

Finally, the Crosscutting Research subprogram is performing materials, sensors, and controls R&D that will support all of the Advanced Combustion Systems key technologies.

APPENDIX A: DOE-FE TECHNOLOGY READINESS LEVELS

Table A-1. **Definitions of Technology Readiness Levels**

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 might 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 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 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 relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory-scale system in a simulated environment with a range of simulants.
6	Engineering/pilot scale, similar (prototypical) system demonstrated in a relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up from a TRL 5. Examples include testing an engineering-scale prototype system with a range of simulants. TRL 6 begins true engineering development of the technology as an operational system.
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. Examples include testing full-scale prototype in the field with a range of simulants. Final design is virtually complete.
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 developmental testing and evaluation of the system within a plant/CCS operation.
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. Examples include using the actual system with the full range of plant/CCS operations.

APPENDIX B: ACTIVE ADVANCED COMBUSTION SYSTEMS PROJECTS

(AS OF OCTOBER 2012)

Table B-1. **Advanced Combustion Systems Projects**

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
		Key Technology—Oxy-Combustion		
FE0009395	Southwest Research Institute	Novel Supercritical Carbon Dioxide Power Cycle Utilizing Pressurized Oxy-Combustion in Conjunction with Cryogenic Compression	*	†
FE0009448	Pratt & Whitney Rocketdyne	Oxy-Fired Pressurized Fluidized Bed Combustor Development and Scale Up for New and Retrofit Coal-Fired Power Plants	*	†
FE0009478	Unity Power Alliance, LLC	Optimization of Pressurized Oxy-Combustion with Flameless Reactor	*	†
FE0009686	Gas Technology Institute	High-Efficiency Molten-Bed Oxy-Coal Combustion with Low Flue Gas Recirculation	*	†
FE0009702	Washington University in St. Louis	Staged, High-Pressure Oxy-Combustion Technology: Development and Scale Up	*	†
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 advanced 1st-Generation 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 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 Combustion		
FE0009469	University of Kentucky	Solid-Fueled Pressurized Chemical Looping with Flue-Gas Turbine Combined Cycle for Improved Plant Efficiency	*	†
FE0009484	Alstom Power, Inc.	Alstom's Chemical Looping Combustion Technology with CO_2 Capture for New and Retrofit Coal-Fired Power	*	†

Table B-1. **Advanced Combustion Systems Projects**

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
FE0009761	Babcock & Wilcox Power Generation Group, Inc.	Commercialization of the Iron Base Coal Direct Chemical Looping Process for Power Production with Institute Carbon Dioxide Capture	*	†
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 sub-pilot-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.
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.

Table B-1. **Advanced Combustion Systems Projects**

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
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.

NOTES:

* This project was not assessed.

† A relevancy statement was not developed for this project.

APPENDIX C: ADMINISTRATION AND DOE PRIORITIES, MISSION, GOALS, AND TARGETS

ADMINISTRATION PRIORITIES

Presidential Goal—Catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies

PRESIDENTIAL ENERGY TARGETS

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

DOE STRATEGIC PLAN—HIERARCHY OF RELEVANT MISSION, GOALS AND TARGETS

SECRETARIAL PRIORITIES

- ***Clean, Secure Energy:*** Develop and deploy clean, safe, low-carbon energy supplies.
- ***Climate Change:*** Provide science and technology inputs needed for global climate change negotiations; develop and deploy technology solutions domestically and global.

MISSION

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

GOALS

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

TARGETS

- Sustain a world leading technical work force
- Deploy the technologies we have
  - Demonstrate and deploy clean energy technologies
  - Enable prudent development of our natural resources
- Discover the new solutions the nation needs
  - Accelerate energy innovation through pre-competitive research and development
  - Facilitate technology transfer to industry
  - Establish technology test beds and demonstrations
  - Leverage partnerships to expand our impact
- Deliver new technologies to advance our mission
  - Lead computational sciences and high-performance computing

- Use Energy Frontier Research Centers where key scientific barriers to energy breakthroughs have been identified and we believe we can clear these roadblocks faster by linking together small groups of researchers across departments, schools and institutions
- Use ARPA-E, a new funding organization within the Department, to hunt for new technologies rather than the creation of new scientific knowledge or the incremental improvement of existing technologies

FOSSIL ENERGY RESEARCH AND DEVELOPMENT

MISSION

The mission of the Fossil Energy Research and Development program creates public benefits by increasing U.S. energy independence and enhancing economic and environmental security. The program carries out three primary activities: (1) managing and performing energy-related research that reduces market barriers to the environmentally sound use of fossil fuels; (2) partnering with industry and others to advance fossil energy technologies toward commercialization; and (3) supporting the development of information and policy options that benefit the public.

CLEAN COAL RESEARCH PROGRAM

MISSION

The CCRP will ensure the availability of near-zero atmospheric emissions, abundant, affordable, domestic energy to fuel economic prosperity, increase energy independence, and enhance environmental quality.

STRATEGIC GOAL

Catalyze the timely, material, and efficient transformation of the nation's energy systems and secure U.S. leadership in clean energy technologies.

STRATEGIC OBJECTIVES

- Deploy the technologies we have
- Discover the new solutions the nation needs
- Deliver new technologies to advance our mission

STRATEGY

- Accelerate energy innovation through pre-competitive research and development
- Demonstrate and deploy clean energy technologies
- Facilitate technology transfer to industry
- Establish technology test beds and demonstrations
- Leverage partnerships to expand our impact

THIS PAGE INTENTIONALLY LEFT BLANK

ABBREVIATIONS

AES	Advanced Energy Systems
ARPA-E	Advanced Research Projects Agency-Energy
ARRA	American Recovery and Reinvestment Act of 2009
ASU	air separation unit
A-USC	advanced ultra-supercritical
BFW	boiler feed water
Btu	British thermal unit
°C	degrees Celsius
CAR	ceramic autothermal recovery
CCRP	Clean Coal Research Program
CCS	carbon capture and storage
CFD	computational fluid dynamics
CLC	chemical looping combustion
CO_2	carbon dioxide
COE	cost of electricity
CPU	compression and purification unit
DOE	Department of Energy
DPE	direct power extraction
EOR	enhanced oil recovery
°F	degrees Fahrenheit
FE	Office of Fossil Energy
FGR	flue gas recycle
FOA	funding opportunity announcement
H_2O	water
Hg	mercury
HHV	higher heating value
IGCC	integrated gasification combined cycle
ITM	ion transport membrane
kWh	kilowatt hour
kWth	kilowatt thermal
MHD	magnetohydrodynamic
MPa	megapascal
MW	megawatt
MWe	megawatt electric
MWth	megawatt thermal
N_2	nitrogen
NASA	National Aeronautics and Space Administration
NETL	National Energy Technology Laboratory
Ni	nickel
NO_x	nitrogen oxides
O&M	operating and maintenance
O_2	oxygen
ORD	Office of Research and Development
OTM	oxygen transport membrane
PC	pulverized coal
PDU	process development unit
POx	partial oxidation
psia	pounds per square inch absolute
psig	pounds per square inch gauge
R&D	research and development
RD&D	research, development, and demonstration
SO_2	sulfur dioxide
SO_x	sulfur oxides
syngas	synthesis gas
T&S	transport and storage
TRL	Technology Readiness Level
USC	ultra-supercritical
VPSA	vacuum pressure swing adsorption

FOR MORE INFORMATION

National Energy Technology Laboratory
http://www.netl.doe.gov/technologies/coalpower

U.S. Department of Energy, Office of Fossil Energy
http://www.fossil.energy.gov/programs/powersystems

If you have any questions, comments, or would like more information about the DOE/NETL Advanced Combustion Systems program, please contact the following persons:

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory
Strategic Center for Coal

Scott Smouse
412-386-5725
scott.smouse@netl.doe.gov

Jared Ciferno
412-386-5862
jared.ciferno@netl.doe.gov

Sean Plasynski
412-386-4867
sean.plasynski@netl.doe.gov

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

ADVANCED COMBUSTION SYSTEMS

TECHNOLOGY PROGRAM PLAN
JANUARY 2013