CLEAN COAL RESEARCH PROGRAM

United States Department of Energy | Office of Fossil Energy

SOLID OXIDE FUEL CELLS
TECHNOLOGY PROGRAM PLAN

JANUARY 2013

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CHAPTER 1: OVERVIEW

1.1 INTRODUCTION

The Department of Energy's (DOE) Solid Oxide Fuel Cells 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 more detail below. 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 the Government and industry.

While it has always been an influential 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 available 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 Solid Oxide Fuel Cells research and development (R&D) effort, which is conducted under the CCRP's CCS and Power Systems program area. The program plan describes the Solid Oxide Fuel Cells 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 Solid Oxide Fuel Cells program[1] to the CCS and Power Systems program area is described in the next section.

1 Although Solid Oxide Fuel Cells 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 Solid Oxide Fuel Cells program is used interchangeably with Solid Oxide Fuel Cells 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. Solid Oxide Fuel Cells is part of the Advanced Energy Systems subprogram.

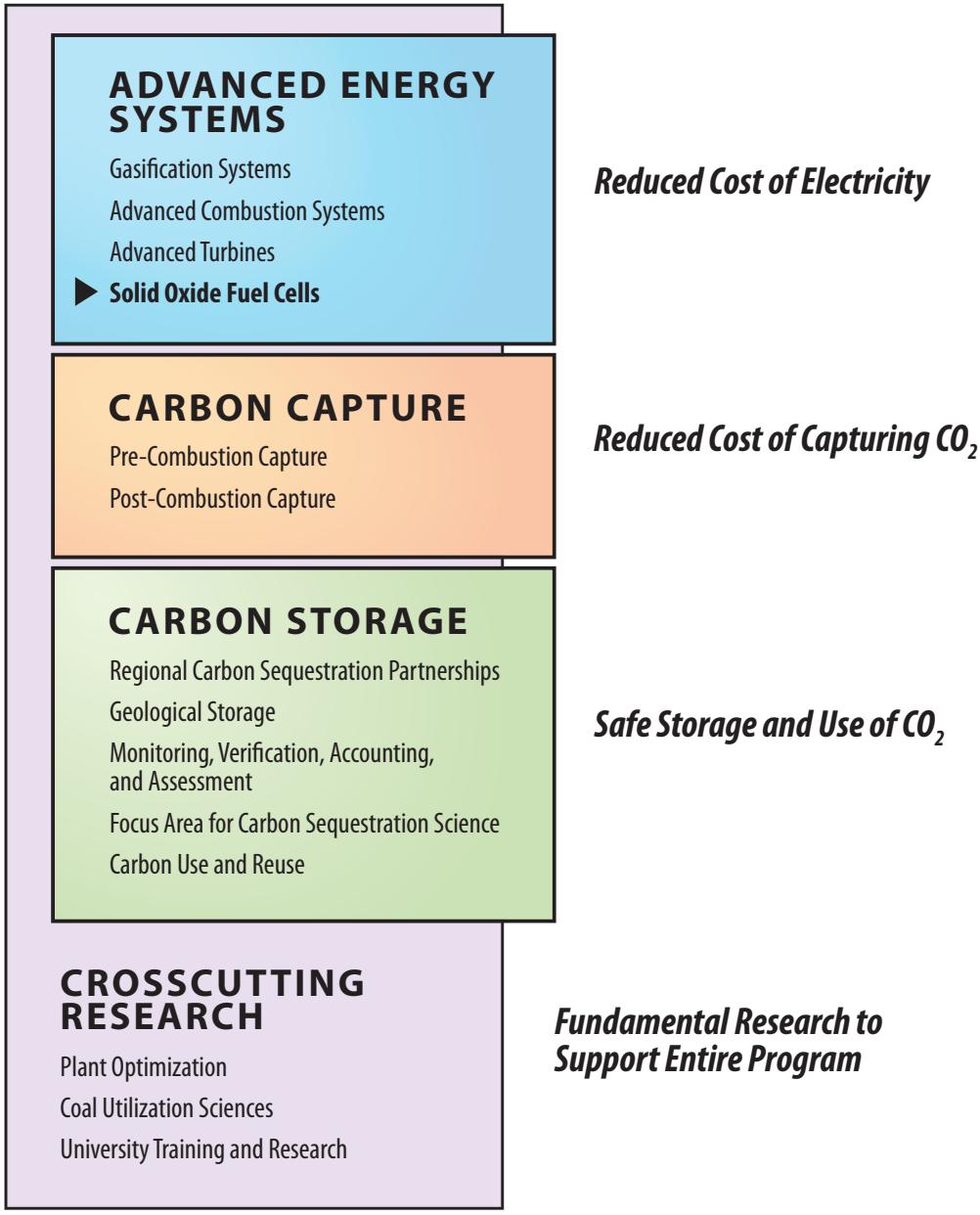


Figure 1-1. CCS and Power Systems Subprograms

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:

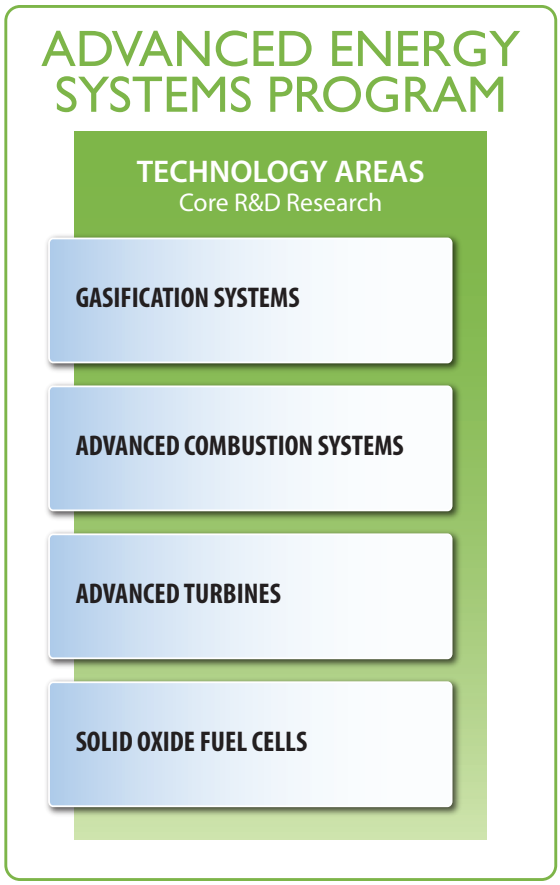


Figure 1-2. AES Subprogram Technology Areas

- ***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 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

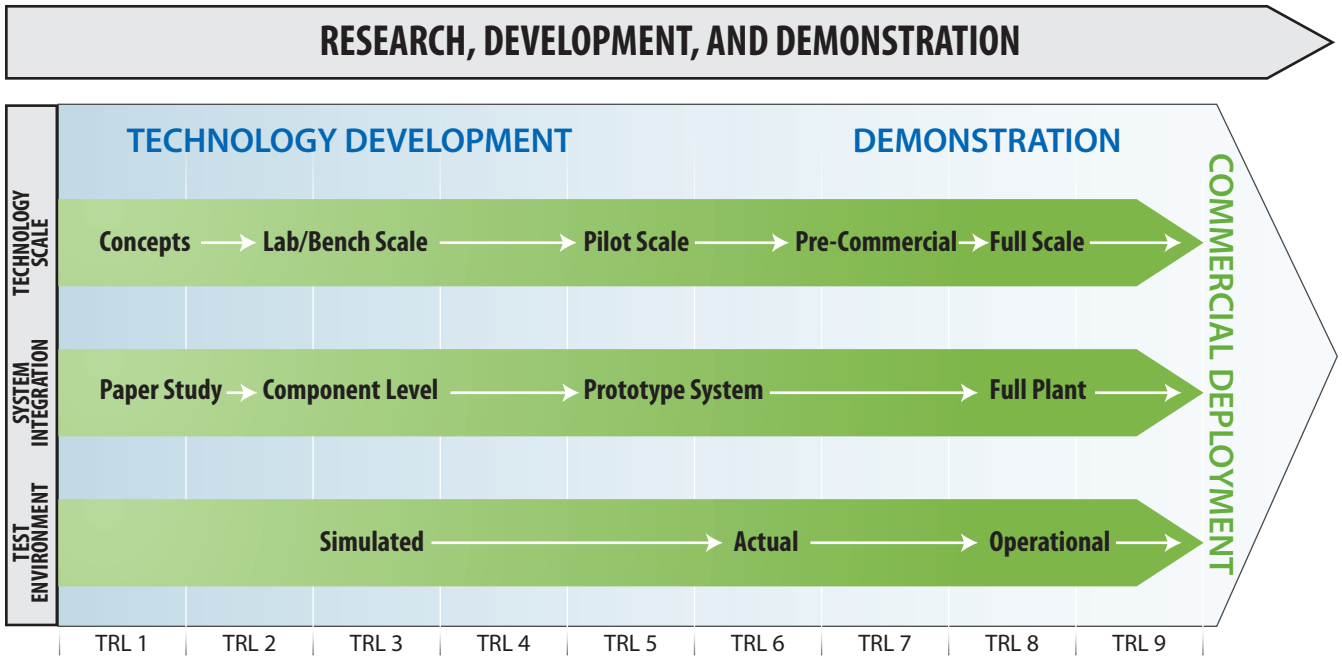


Figure 1-4. Technology Readiness Level—Relationship to Scale, Degree of Integration, and Test Environment

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.

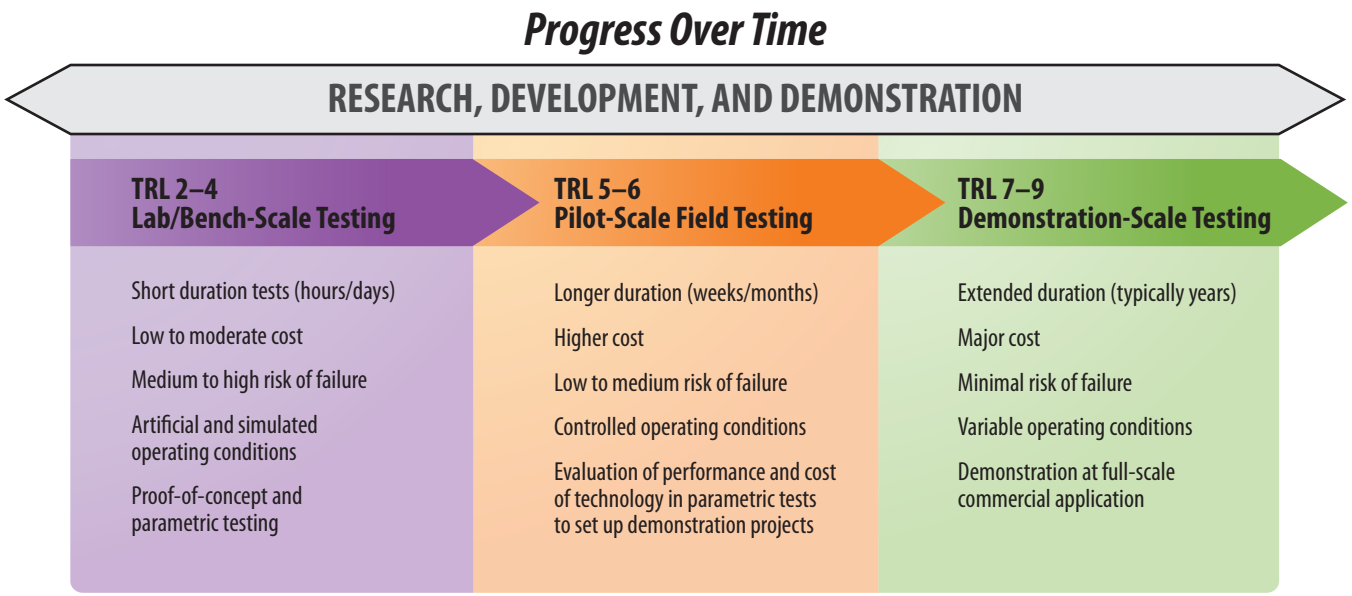


Figure 1-5. Summary of Characteristics at Different Development Scales

1.4 BARRIERS/RISKS AND MITIGATION STRATEGIES

Technical risks facing the Solid Oxide Fuel Cells program range from understanding the fundamental reaction kinetics of the cathode oxygen (O_2) reduction mechanism to the development of high-temperature components. The overall mitigation strategy employed by the Solid Oxide Fuel Cells program is to develop a diversified portfolio of R&D projects to address the technical challenges and ensure a high probability of achieving the desired cost and performance targets. The strategy includes a mix of near-, mid-, and long-term R&D projects as well as laboratory, proof-of-concept, and pilot-scale projects to foster the advancement of solid oxide fuel cell (SOFC) technologies for deployment in a integrated gasification fuel cell (IGFC) power system that meets or exceeds the stated targets for efficiency, cost, and carbon capture.

TECHNICAL BARRIERS AND RISKS

Cells—Cell performance is one of the key factors in determining the efficiency of the fuel cell stack (module) and overall system. Within the cell, the performance of the cathode has a significant impact on stack and system performance and cost. However, the least understood area within the cell is the cathode oxygen reduction mechanism. Due to its high ionic and electronic conductivities, the electrochemical performance of the cathode is limited by surface kinetics. A more electrochemically active cathode will result in the cell having a lower area specific resistance (ASR) and higher power density, resulting in a performance increase and reduced cost. Additional technical challenges associated with the cathode include reducing the long-term degradation rate (loss of voltage over time), improved mechanical integrity, and lower material costs.

The SOFC system is expected to operate at 700–900 °C on coal syngas. Contaminants in gasified coal vary considerably with the coal feedstock. The sensitivity of the anode to high levels of contaminants is known; however, the mechanisms by which the contaminants contribute to the loss of performance, accelerated degradation rates, and mechanical failure are not fully quantified. Furthermore, the impact of long-term exposure to low-level contaminants on anode performance, mechanical integrity, and service life is unknown.

Cell performance and reliability are affected by the lot-to-lot consistency of raw materials and fabrication processes. Lack of sufficient knowledge with respect to critical raw material and fabrication process parameters may result in substandard cells, inconsistent performance, reduced service life, and increased costs.

Module—The technical risks associated with the SOFC stack include effective reactant flow distribution, seals, thermal management, mechanical integrity, and low cost. Flow maldistributions may restrict fuel utilization and—along with inadequate thermal management—increase the cathode air requirements; both of which contribute to performance reductions, increased degradation, and increased operating and maintenance (O&M) costs. Seals between the cathode (oxidant side) and anode (fuel side) are necessary to prevent the mixing of fuel and oxidant within the stack, to prevent fuel and oxidant from leaving the stack, and to electrically isolate cells in the stack. Seals must be structurally stable, chemically compatible with other stack materials, and inexpensive. Understanding stack failure mechanisms, defining a safe operating strategy, and developing low-cost module materials are present-day challenges.

Pressurization[3]—Pressurizing the SOFC increases the Nernst potential, allowing for more efficient cell and system operation. This enhanced performance may be offset by increased costs, particularly those associated with the fuel cell stack enclosure, additional operational risks, and a more complex integration with associated subsystems. A deeper understanding is needed on the behavior of the state-of-the-art SOFC material set under pressurized operation and the effect of pressure on cell performance, reliability, and degradation.

Scaleup—The present state-of-the-art modules are typically first-of-a-kind and are nominally rated at <100 kW. Modules on order of 250 kWe to 1 MWe are generally considered to be required for cost-effective integration with central station-scale power generation, gas cleanup, and heat recovery technologies. Acquiring significant and broad-based operating experience through proof-of-concept systems, pilot-scale projects, and early adopters will be vital to demonstrate technology readiness and garner stakeholder support.

Balance of Plant—Fuel cell modules require that various high-temperature components have reliable long-term operation and be cost-effective. These components are outside the focus of the fuel cell module and also outside the scope of the enabling and supporting technologies, systems, and components such as the gasifier, gas cleanup system, etc. Typically the balance-of-plant components that support the fuel cell system include high-temperature heat exchangers, high-temperature recycle blowers, etc.

MITIGATION STRATEGIES

Cells—Establish a portfolio of R&D projects to pursue multiple paths with respect to the critical technological hurdles. A fundamental understanding of the cathode oxygen reduction and transport phenomena is critical in order to direct future efforts. Concepts for optimizing cathode surfaces by correlating surface property/electronic structure data with electrochemical performance are to be developed, optimized, and validated. A coal contamination study to quantify the effects of coal syngas contaminants and the coal syngas purity required to avoid mechanical failure and accelerated performance degradation, determine the mechanisms by which contaminants damage and degrade anodes will be conducted. Interconnection components for both atmospheric and pressurized operation will be developed. A number of projects will focus on the development, testing, and analyses of seals, interconnect alloys and coatings, and cathode contact aids. Additionally, focus will be on statistical process control and the use of established manufacturing processes for cell manufacture to reduce performance variation and improve production yields.

Module—Fuel cell developers, each of whom is developing unique proprietary SOFC technologies suitable for IGFC applications and have developed in-house design and analysis packages, have access to a complete fuel cell thermal-flow-electrochemistry-structural analytical package developed to facilitate failure and design analysis. These tools facilitate effective design and reduce the length of the design cycle. The thermochemical properties of materials under typical operating conditions will be characterized and used to produce high-fidelity models to predict stack behavior and identify degradation mechanisms. Component-level modeling is employed to predict long-term performance and reliability. Performance metrics have been established and must be demonstrated via a series of increasingly larger stack tests. Developers are required to validate their proprietary modeling packages against stack-test data. Stack and module design must adhere to the American Society of Mechanical Engineers

3 The pressurization technical barrier/risk is applicable only to the Pressurized Systems key technology.

SOFC design basis. In addition, alternative cell and stack designs are being explored to provide improved robustness, reduced degradation, and improved performance.

Pressurization[4]—At the cell level, the majority of technical barriers and their respective mitigation strategies are similar for both atmospheric and pressurized operation. Cell-related issues unique to pressurized operation are addressed in a portfolio of R&D projects that include development of interconnect materials and seals, respectively, that are appropriate for pressurized operation. At the module and system level, a Solid Oxide Fuel Cells program Industrial Team member is dedicated to and solely focused on the development of pressurized SOFC technology and is addressing issues such as: evaluating the behavior of the state-of-the-art SOFC material set under pressure; quantifying the effect of pressurization on cell performance, reliability, and degradation; resolving operational issues associated with pressurized operation; and long-term testing at pressure to evaluate reliability and durability.

Scaleup—SOFC technology is inherently modular. Cell and stack designs may be mass-produced and aggregated like batteries to satisfy a broad range of nearer term market opportunities such as auxiliary power units, unmanned undersea vehicles for the military, and distributed-generation applications in the multi-hundred kWe to MWe-class. Upon satisfactory demonstration, it is expected that a fleet of SOFC power systems will be deployed by private equity/early adopters that will not only provide a vast collection of lessons learned, but also allow the program to take advantage of the cost-benefits of high-volume production.

Balance of Plant—Although SOFC power systems represent first-of-a–kind applications, many balance-of-plant components are commercially available, albeit in limited quantities, requiring some design modifications. Advanced heat exchangers and further advances for high-temperature blowers would significantly improve cost and performance. Additional mitigation strategies include work on balance-of-plant coatings for reducing chrome volatility; chrome gettering materials; new, lost-cost alloys; and robust electrodes. The Solid Oxide Fuel Cells program is utilizing the Small Business Innovation Research program to yield desired improvements in balance-of-plant components. In addition, other Federal agency programs are/may be leveraged.

ENABLING TECHNOLOGIES

The optimal use of SOFC technology in a coal-based, central power station requires an integrated system that minimizes energy losses and maximizes the inherent characteristics of an SOFC to achieve high efficiency and facilitate carbon capture. Thus, in addition to the fuel cell system, there are other advanced technologies needed for ultra-efficient low-cost IGFC systems that are not commercially available and are also in need of development. The development of these enabling technologies is beyond the scope of the Solid Oxide Fuel Cells program.

Advanced Gasifiers—An IGFC power system with conventional gasification technology can achieve efficiencies near or exceeding 50 percent (net AC/coal higher heating value [HHV]). However, the SOFC can directly reform methane (an endothermic reaction that reduces the stack cooling requirement and therefore cathode air blower parasitic loads) and also serves as a water-gas-shift reactor. Catalytic gasifiers, which offer high cold-gas efficiencies and produce higher amounts of methane than conventional gasifiers, will more effectively utilize the SOFC's waste heat. An IGFC with an advanced catalytic gasifier may achieve efficiencies greater than 60 percent.

Gas Cleanup—Contaminants typically associated with coal-derived syngas that have deleterious effects on SOFC performance. Commercially available cold gas cleaning technologies are capable of removing the contaminants to the necessary levels but are neither cost effective nor ideally suited for integration with the high-temperature SOFCs. Less expensive, warm gas cleaning technologies that achieve specified levels of contaminants with reduced parasitics are needed.

4 The pressurization mitigation strategy is applicable only to the Pressurized Systems key technology.

Oxy-Combustion—IGFC systems presently under consideration include SOFC configurations that maintain separate anode and cathode effluent streams. The anode effluent is primarily CO_2 and water (H_2O) (as >85 percent of the fuel is electrochemically consumed) with a small amount of residual fuel, hydrogen (H_2), and carbon monoxide. Oxy-combustion of this stream and condensation of the product water will yield a highly concentrated CO_2 stream ready for EOR or sequestration with little or no additional processing.

CHAPTER 2: SOLID OXIDE FUEL CELLS PROGRAM

2.1 INTRODUCTION

The Solid Oxide Fuel Cells Technology Area consists of four key technologies:

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

Two of the key technologies, AEC Development and Alternative AEC Development, are R&D in nature—whereas the other two, Atmospheric Pressure Systems and Pressurized Systems, are focused on the development, demonstration, and deployment of SOFC power systems. The research focus areas for each of these key technologies are depicted in Figure 2-1. The program's two research key technologies will contribute to the development of SOFC power systems on an ongoing basis. Transformational technologies associated with SOFC power systems are expected to be available for deployment in the 2030–2040 time period.

A discussion on the SOFC technology is presented in the following section. A comprehensive discussion on the Solid Oxide Fuel Cells program technical plan is provided in *Chapter 4: Technical Plan*.

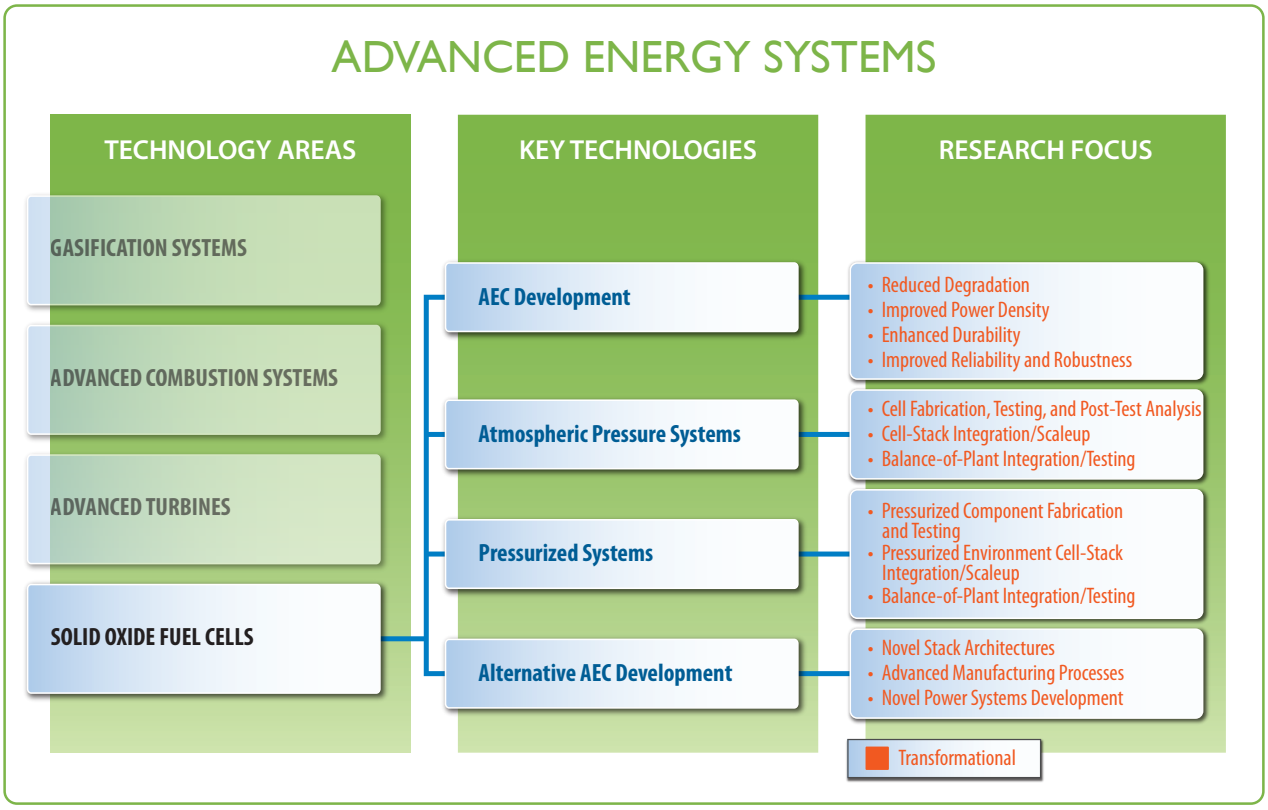


Figure 2-1. Key Technologies and Associated Research Focus in the Solid Oxide Fuel Cells Program

2.2 BACKGROUND

Presented in the following sections are an introduction and discussions on the operating principles of SOFCs and SOFC power systems, respectively.

SOFC OPERATING PRINCIPLES

Fuel cells are electrochemical devices similar to batteries that convert chemical energy of a fuel and oxidant directly into electrical energy. Since fuel cells produce electricity through an electrochemical reaction and not through a combustion process, they are inherently much more efficient and environmentally benign than conventional electric power-generation processes. For example, maximum efficiency is not constrained by typical Carnot-cycle limitations for heat engines (e.g., Brayton and Rankine cycles) and lower temperature operation compared to that of combustion-based processes does not form nitrogen oxides (NO_x). While the operating principles of a fuel cell and battery are similar, they differ in some respects. A battery is an energy storage device in which a finite amount of energy is stored within the battery. Once the available energy is consumed, the battery must either be recharged or replaced. In contrast, a fuel cell is an energy conversion device that—in theory—will produce power as long as fuel and oxidant are supplied.

The basic structure of a fuel cell consists of an electrolyte positioned between an anode (the negative electrode) and the cathode (positive electrode). Fuel is delivered to the anode and oxidant (typically air) to the cathode, while the electrolyte conducts ions to the electrodes where the electrochemical reaction takes place.

Fuel cells are a family of technologies classified by the type of electrolyte—which, in turn, determines the electrochemical reactions and the type of ions that pass through the electrolyte. Solid oxide fuel cells have an electrolyte that is a solid, nonporous metal oxide, usually yttria-stabilized zirconia (YSZ) and operate at temperatures in the range of 650–900 °C. The anode is typically a porous nickel YSZ cermet and the cathode is commonly a porous strontium-doped lanthanum manganite (LSM). Individual cells are linked with an interconnect (typically a ferritic stainless steel) in electrical series to increase voltage and power, forming a stack. As shown in Figure 2-2 the interconnect electrically connects the anode (negative side) of one cell (the lower cell in Figure 2-2) in series with the cathode (positive side) of the adjacent, or upper cell in this illustration. This stacking arrangement forms the fuel channel for the lower cell and the air channels for the upper cell. Cells can be stacked in this manner until an optimal stack size is achieved. A number of stacks can then be arrayed in series and/or parallel to form an SOFC module.

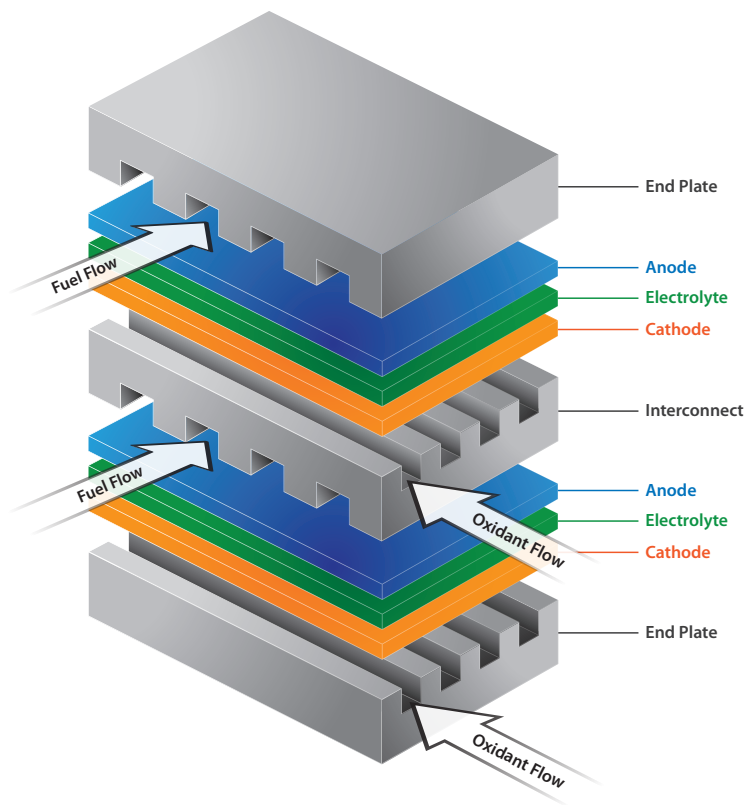


Figure 2-2. Planar SOFC (Two Cell Array)

The buildup from cells to stacks to a module is shown in Figure 2-3.

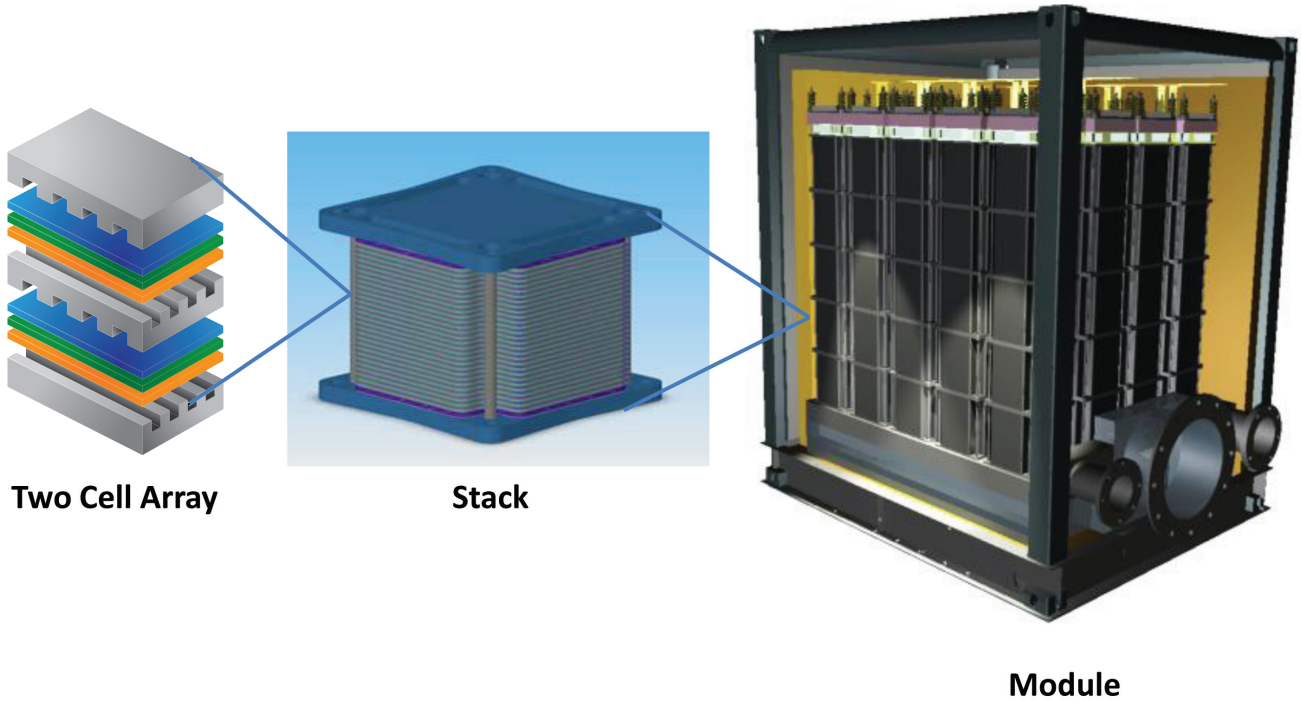


Figure 2-3. Cell to Stack to Module Buildup

As shown in Figure 2-4, air flows along the cathode. Oxygen atoms are adsorbed and reduced to $O^{=}$ ions on the active cathode surface and diffuse to the cathode/electrolyte interface. At the operating range of 650–900 °C, the YSZ electrolyte, which is impervious to molecular gas flow, is a good ionic conductor, allowing the $O^{=}$ ions to pass through to the anode side of the SOFC.

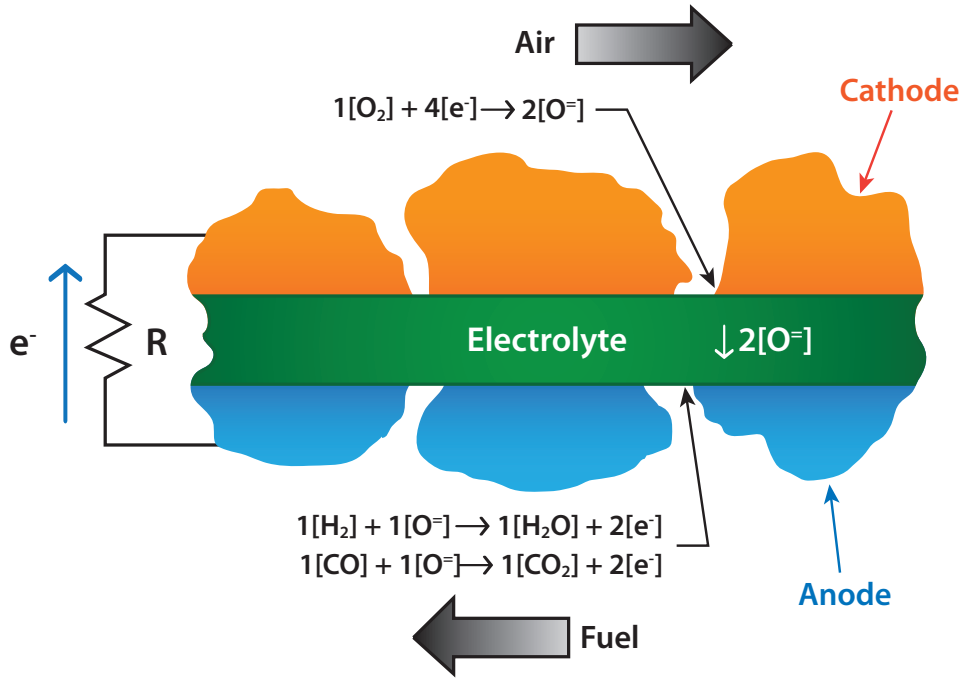


Figure 2-4. SOFC Components and Electrochemical Reactions

Fuel is delivered to the anode where hydrogen molecules diffuse through the anode to the anode/electrolyte interface. Here they react catalytically with the oxygen ions, releasing electrons and producing water and heat. The electrons are transported through an external circuit, producing electricity. Thus, the electrochemical reactions occurring in the cell are:

Cathode: $\frac{1}{2} O_2 + 2e^- \rightarrow \frac{1}{2} O_2^=$

Anode: $H_2 + \frac{1}{2} O_2^= \rightarrow H_2O + 2e^-$

Overall: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$

The high operating temperature of SOFCs enables the direct oxidation of methane, CH_4, (the primary constituent of natural gas) and carbon monoxide, CO, where the anode reactions are:

$$CH_4 + 4O^= \rightarrow 2H_2O + CO_2 + 8e^-$$

$$CO + O^= \rightarrow CO_2 + 2e^-$$

The SOFC has inherent characteristics and attributes that can be leveraged to meet and exceed the CCRP goals (described in *Chapter 3: Goals and Benefits*) for cost, efficiency, environmental impact, and carbon capture. Specific advantages include:

- ***High Efficiency:*** SOFCs produce electricity through an electrochemical reaction; consequently, their thermal efficiency is not constrained by Carnot-cycle limitations for heat engines (e.g., Brayton and Rankine cycles). SOFCs also produce high-quality byproduct heat for utilization in a bottoming cycle to further enhance efficiency. A system efficiency of 60 percent (HHV), including >97 percent CO_2 capture, may be achieved with an advanced catalytic gasifier and pressurized SOFC.
- ***Low Emissions:*** SOFCs operate at lower temperatures (≤900 °C) than those of combustion-based processes and therefore do not form NO_x.
- ***Ease of CO_2 Capture:*** Carbon capture is facilitated since the anode (fuel) and cathode (air) streams are separated by the electrolyte. All carbon enters the SOFC with the fuel on the anode side and exits in the anode off-gas as CO_2. The residual fuel in the anode off-gas (approximately 10–15 percent) is combusted in oxygen, producing a stream that contains only H_2O and CO_2. Condensing out the H_2O leaves an exhaust stream that contains >97 percent CO_2 and is ready for compression and reuse or storage.
- ***Low Water Consumption:*** Water in the anode effluent is easily captured and reused in the system. SOFC systems use approximately one-third the amount of water relative to conventional combustion-based power systems (1.5–3 gallons per minute/MW).
- ***Fuel Flexibility:*** SOFCs operate on H_2, carbon monoxide, and methane—making them suitable for a broad spectrum of hydrocarbon fuels, including coal-derived syngas and natural gas.
- ***Modularity:*** Like all fuel cell systems, SOFC systems consist of one or more modules that, in turn, consist of numerous SOFC stacks. Multiple modules may be connected to provide the desired power rating. For example, current commercial fuel cell systems (not SOFCs) range from the kilowatt-scale to greater than 10 MW.

SOFC POWER SYSTEMS

In tandem, fuel flexibility and modularity enable fuel cell technology to be applied in a variety of applications. SOFC technology, due its relatively high operating temperature compared to that of other fuel cell technologies, is uniquely suitable for direct use with conventional fossil fuels such as coal-derived syngas and natural gas. In support of the CCRP's mission to develop a new generation of clean fossil fuel-based power systems capable of producing affordable electric power while significantly reducing CO_2 emissions and minimizing water consumption, the primary focus of the Solid Oxide Fuel Cells program is the development SOFC power systems utilizing coal-derived syngas produced via gasification. However, with the SOFC's ability to internally reform methane (the primary component of natural gas), a common module design can be employed for use with either fuel (syngas or natural gas). Figure 2-5 illustrates the use of a common SOFC module in either the IGFC configuration or a natural gas fuel cell (NGFC) power-system configuration.

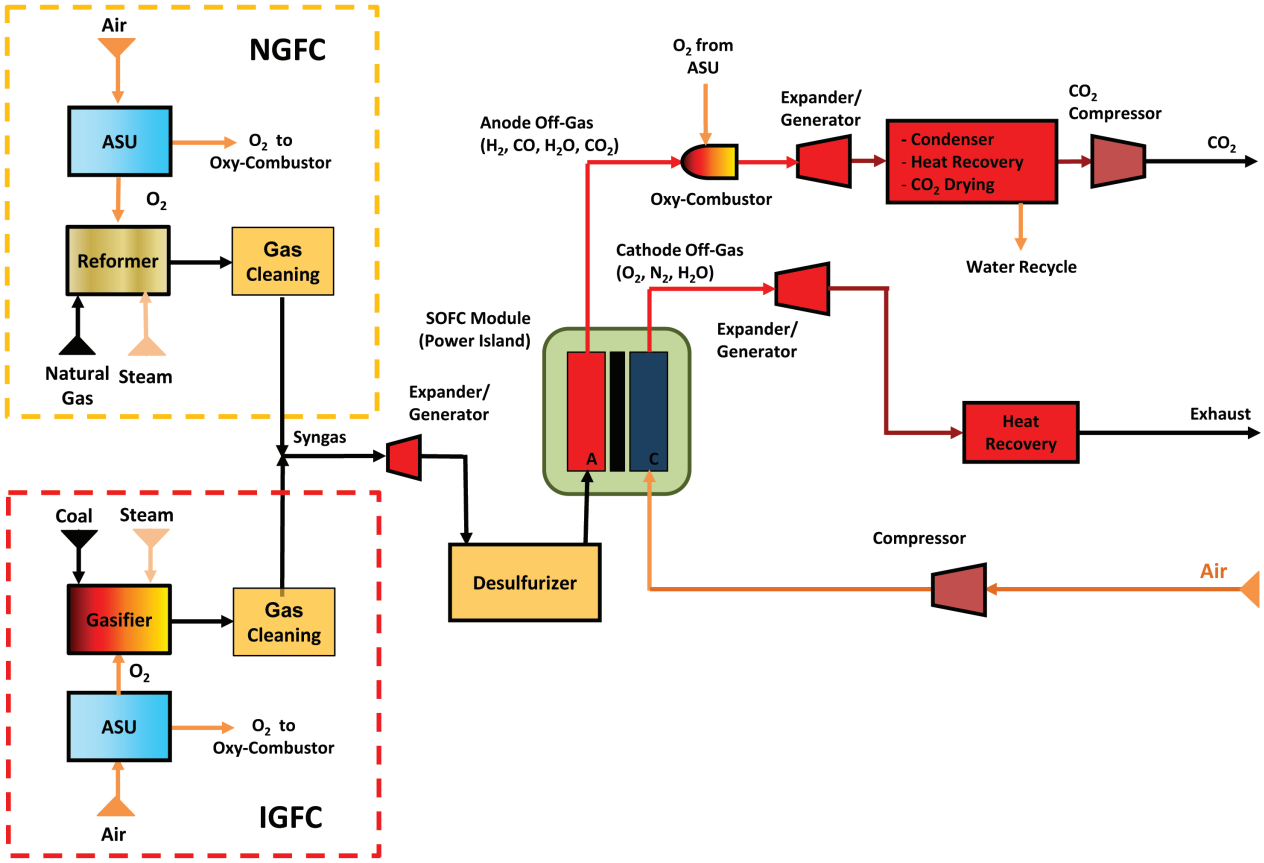


Figure 2-5. IGFC/NGFC Power System Diagram

IGFC POWER SYSTEMS

Integrated gasification combined cycle (IGCC) power systems are among the most efficient and cleanest of the state-of-the-art coal-based power-generation technologies. In an IGCC a solid feedstock, generally coal, is delivered to the gasifier where it is converted into syngas consisting primarily of H_2 and carbon monoxide. Typically, the carbon monoxide is shifted to CO_2 and H_2 in a water-gas-shift reactor. The hydrogen is used for power generation in a Brayton cycle and the CO_2 is captured for reuse or storage.

The SOFC is a unique energy conversion technology that produces electricity from chemical energy without the need for an intermediate heat-to-power cycle (either a Brayton or Rankine cycle or a combination thereof).

Thus, the integration of IGCC and SOFC technology represents a Transformational shift in gasification-based power generation—the IGFC power system, shown in Figure 2-6.

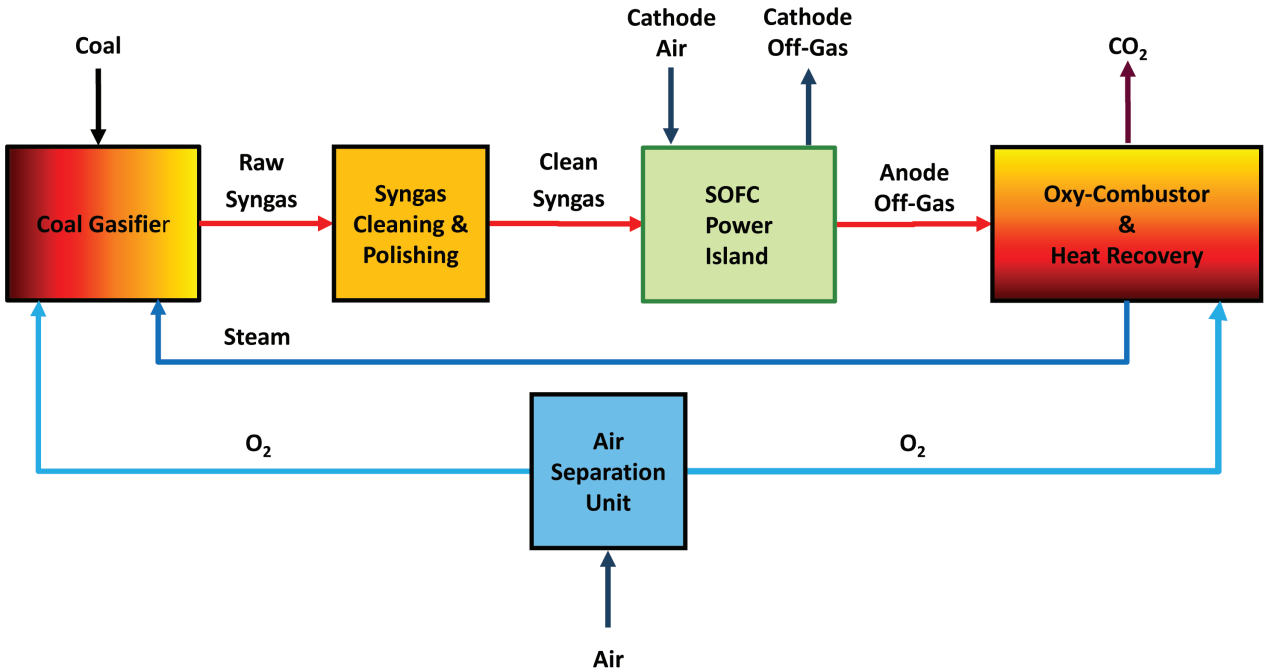


Figure 2-6. IGFC Power System

In the IGFC power system, the SOFC power island (and associated ancillary subsystems) replaces the gas turbine power island found in a conventional IGCC. The gasifier-produced syngas has its contaminants removed in a gas cleanup system and—after a final polishing to reduce the sulfur content to acceptable levels—is delivered to the SOFC power island. The SOFC electrochemically reacts approximately 85–90 percent of the clean syngas, producing electric power. The SOFC anode off-gas (depleted fuel) is delivered to an oxy-combustor where the remaining 10–15 percent of the fuel is combusted in oxygen, producing an exhaust gas stream containing only H_2O and CO_2. A heat recovery system condenses out the H_2O and recycles it back to the gasifier in the form of steam, capturing >97 percent of the CO_2 for reuse or storage. The only other plant exhaust stream is the cathode off-gas consisting of vitiated air. This stream may also contain sufficient high-quality heat that can be used for steam generation. Waste heat may then be used in a Rankine bottoming cycle.

The development and deployment of SOFC power systems is the research focus of two of the four key technologies that constitute the Solid Oxide Fuel Cells program. The SOFC technology is common to both; however, the two system configurations—atmospheric and pressurized—are sufficiently unique that each configuration merits its own research focus. The two configurations are discussed in the following sections.

ATMOSPHERIC PRESSURE IGFC

In the atmospheric pressure IGFC configuration, Figure 2-7, the SOFC modules are operated at near-ambient pressure. Major systems/subsystems/components are identified therein.

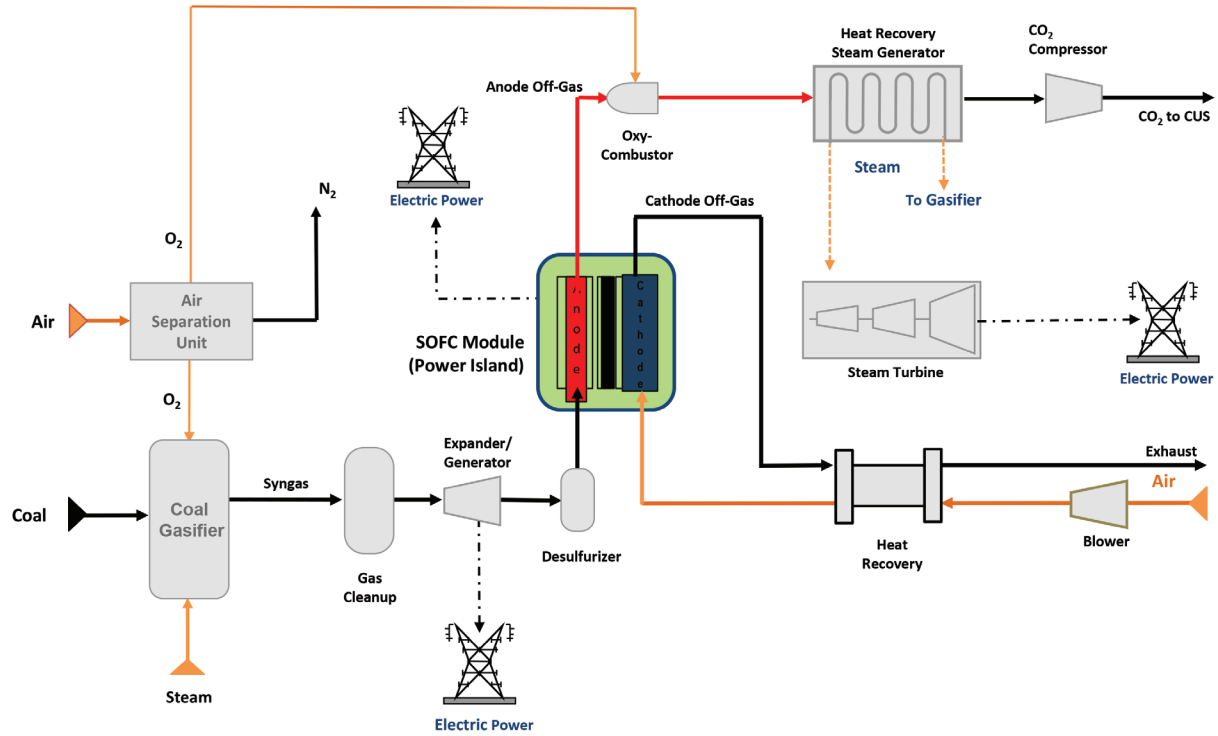


Figure 2-7. Atmospheric Pressure IGFC

Coal is fed to the gasifier where it is converted to syngas. Contaminants are removed from the syngas via conventional gas cleanup technology (e.g., Selexol™ or Rectisol®). The clean syngas, initially at elevated pressure, is then expanded to near-atmospheric pressure, producing alternating current (AC) power, processed to reduce sulfur to acceptable levels, and subsequently delivered to the SOFC power island. Oxygen needed by the gasification system is supplied by a conventional cryogenic air separation unit. Steam for the gasification process is raised in the cycle using power-system heat and recycled water, minimizing raw water consumption.

The SOFC electrochemically utilizes 85–90 percent of the incoming fuel to produce electric power. The anode off-gas (depleted fuel) is combusted in oxygen. Heat is recovered from this process and used to generate steam for use in a bottoming cycle and for the gasification process.

Process air for the electrochemical reaction and for module cooling is delivered by an air blower. Heat is recovered from the cathode off-gas and—similar to the anode off-gas—may be used to generate steam for use in a bottoming cycle (not shown in Figure 2-6).

The SOFC module is designed to maintain separate anode and cathode streams. Keeping these two streams isolated restricts atmospheric nitrogen to the cathode stream and simplifies the CO_2 capture process to one involving anode off-gas cooling, water vapor condensation, CO_2 drying, and CO_2 compression.

PRESSURIZED IGFC

Solid oxide fuel cells demonstrate enhanced performance by increasing the cell operating pressure. The increase in cell voltage is described by:

$$\Delta V\ (\text{mV}) = 59 \log \frac{P_2}{P_1}$$

where P_1 and P_2 represent cell pressure

The increase in cell voltage as a function of pressure is shown in Figure 2-8.

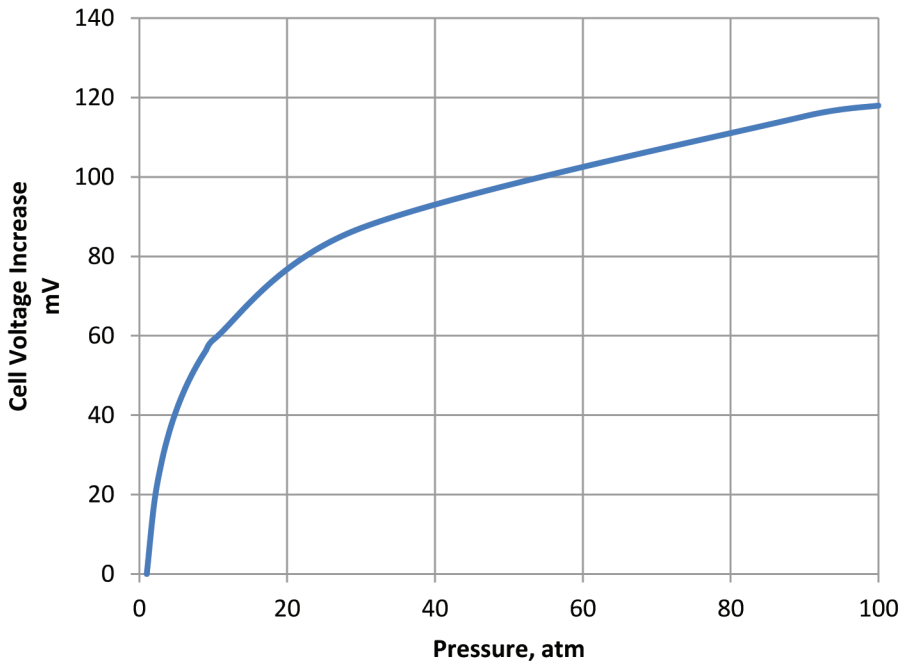


Figure 2-8. Cell Voltage as a Function of Pressure

While the pressurized IGFC enjoys an efficiency advantage due to the increase in cell voltage, it has a more complex system configuration, as shown in Figure 2-9.

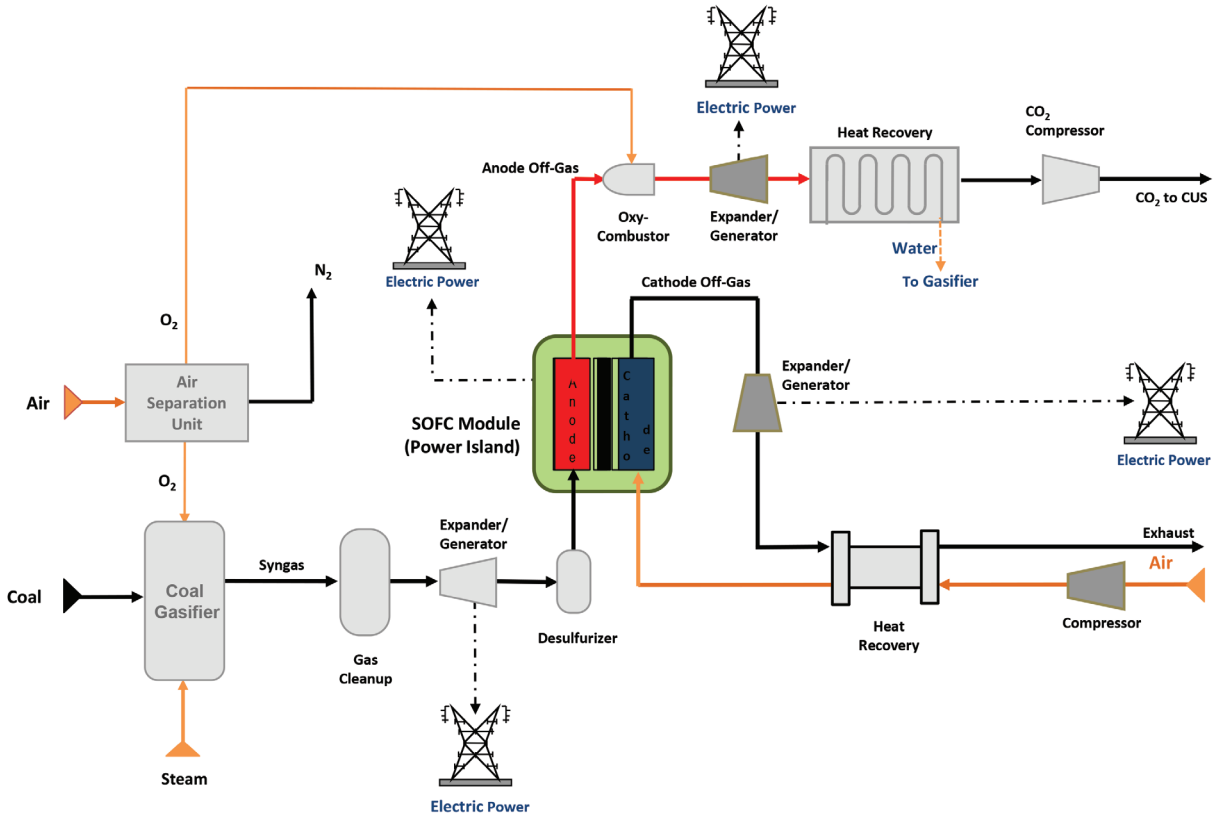


Figure 2-9. Pressurized IGFC

The pressurized system configuration differs from the atmospheric configuration in that the air blower is replaced with a compressor, and the expander and generator components are employed in both the anode off-gas and cathode off-gas streams to reduce the pressure—generating AC power in the process. Along with increased system complexity pressurization also presents operational challenges, particularly during startup, shutdown, and during transients. A less subtle, but significant issue brought on by pressurization involves maintaining the separate anode and cathode streams. High-integrity seals, relative to atmospheric pressure operation, are required to keep the streams separated. It is also important to note that in the pressurized configuration the steam bottoming cycle is eliminated as there is insufficient heat remaining in the off-gas streams to raise steam. In addition to reducing system complexity and cost, eliminating the steam bottoming cycle also reduces the pressurized IGFC power-system water requirements.

COAL GASIFIER EFFECTS

Syngas fuel for either IGFC power-system configuration could be supplied by any of the current commercially available (i.e., 1st Generation) coal gasifiers. Those gasifiers, offered by various suppliers, differ in configuration and performance characteristics, but typically the syngas they produce is rich in H_2 and carbon monoxide, and there may be a small methane component that will usually be no larger than 4–5 percent, by volume. Power system analyses performed by NETL and others indicate that IGFC power systems fueled by these gasifiers will operate with electric efficiencies in the 45–50 percent range (net AC/coal HHV).

For highest electric efficiencies, studies indicate a catalytic gasifier is preferred for an advanced IGFC power system. Relative to conventional coal gasification, a catalytic gasifier would run at a lower process temperature, require less oxygen input, and produce a syngas stream with a significantly higher methane concentration (15–30 percent by volume), in addition to hydrogen and carbon monoxide. With its lower temperature and relatively high cold-gas efficiency (coal energy conversion to syngas energy), and with the SOFC module designed to take cooling advantage of internal methane reformation, analyses show that application of this gasification technology can be expected to raise the pressurized IGFC efficiency by 5–10 percentage points, achieving a power-system efficiency nearing or exceeding 60 percent. In lieu of a catalytic gasifier, similar efficiencies can be achieved by enriching the syngas produced by a conventional gasifier (typically 4–5 percent by volume methane) with natural gas.

SOFC PROGRAM STRUCTURE

The research key technologies of the Solid Oxide Fuel Cells program and the development of the respective power systems are coordinated through the Solid State Energy Conversion Alliance (SECA). SECA—which is dedicated to the development of low-cost, modular, fuel-flexible SOFC technology—consists of three groups: the Industry Teams, the Core Technology Program, and Federal Government management, as shown in Figure 2-10. Industry Teams are focused on the development and commercialization of SOFC technology. The Core Technology Program, the R&D element, is focused on the critical crosscutting technology hurdles and on the development and assessment of the viability of advanced concepts and technologies. The Federal Government management facilitates interaction between Industry Teams and the Core Technology Program, as well as establishes technical priorities and approaches.

The Industry Teams are independently developing unique and proprietary SOFC technology suitable for IGFC applications. They are responsible for the design and manufacture of the fuel cells, hardware development, manufacturing process development, commercialization of the technology, and market penetration. These teams also focus on the scaleup of cells and stacks for aggregation into fuel cell modules and the validation of technology that evolves from the Core Technology Program. Stack tests (laboratory scale), proof-of-concept systems, pilot-scale demonstrations, and deployment of full-scale commercial power systems are the responsibility of the Industry Teams. The multi-Industry Team approach not only provides technology diversification, but also offers insurance against business environment risk, reducing program dependency on a single developer. The Industry Teams have the opportunity to determine relevant R&D topics based on their design-specific experience and needs and are held to a common set of performance and cost metrics.

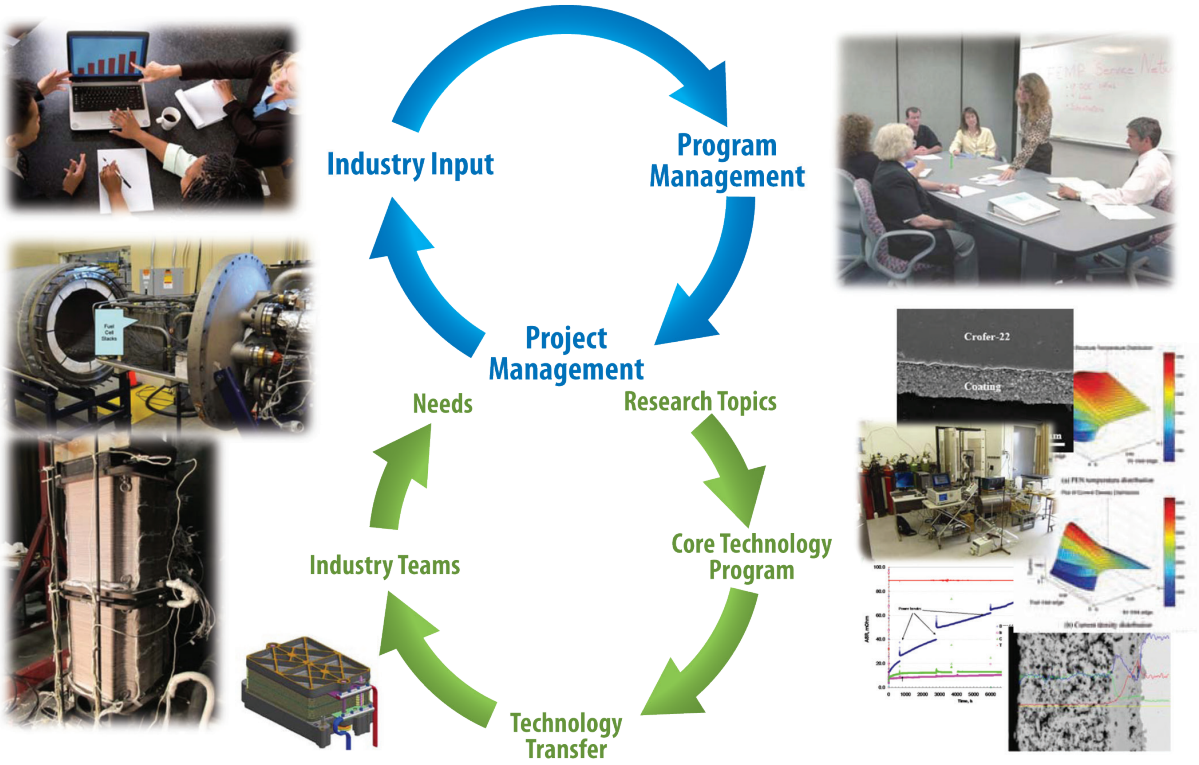


Figure 2-10. SECA Program Structure

The Core Technology Program—which comprises universities, national laboratories, small businesses, and other R&D organizations—addresses applied technological issues common to all Industry Teams and provides vital R&D and laboratory-scale testing. Multiple paths to solving the technical hurdles are pursued by the R&D teams, and their findings and inventions under the Core Technology Program are made available to all Industry Teams under unique intellectual property provisions that serve to reduce R&D redundancy and accelerate development as illustrated in Figure 2-11.

In addition to the development of SOFC technology, the CCRP's Advanced Energy Systems program also supports a broader portfolio of IGCC-related research in its companion Gasification Systems Technology Area that is critical to the IGFC—gasification, air separation, gas cleaning, and oxy-combustion. The fully integrated, Transformational IGFC power system will be deployed consistent with the CCRP's Transformational technologies timeline and is expected to meet or exceed the Transformational R&D goals defined in *Chapter 3: Goals and Benefits*.

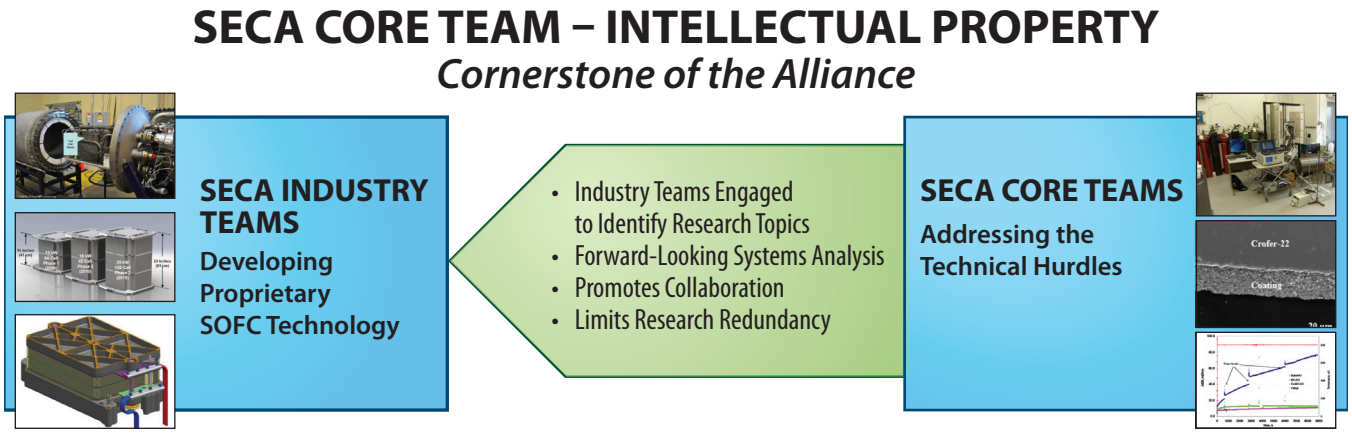


Figure 2-11. SECA Core and Industry Teams Collaboration

2.3 RECENT R&D ACTIVITIES

HISTORIC

Since its inception in 2001, SECA has made remarkable progress in clearing one of the greatest hurdles facing fuel cells—cost. Fuel cell technology, in general, and SOFCs, in particular, have traditionally been too expensive for broad penetration into commercial markets. To be practical for widespread use in the marketplace, fuel cell systems need to reach economic viability through mass production and they need to generate cost-effective power. As shown in Figure 2-12 the SECA program has reduced the SOFC stack cost by nearly an order of magnitude from that at the time of the program's onset. A number of factors contributed to this, including cell performance improvements, increased power density, enhanced reliability, and advanced manufacturing techniques. Fiscal year 2010 goals for mass production costs were $175/kWe for the SOFC stack and $700/kWe for the SOFC power island (2007$), as shown in Table 2-1. Achieving these goals represents an 8-fold improvement in cell cost, a 5-fold increase in cell size, and a 25-fold increase in stack size over the course of the program. Figures 2-13 and 2-14 show the successful scaleup in cell size and stack size achieved by the Industry Teams.

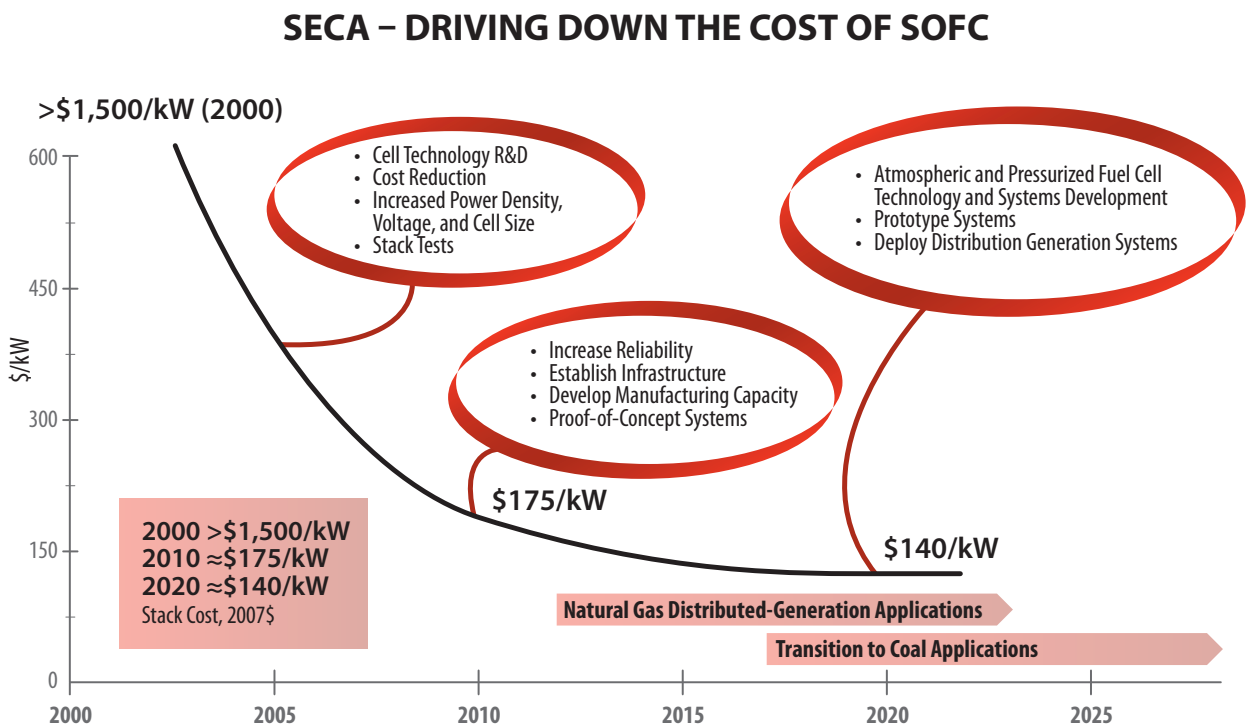
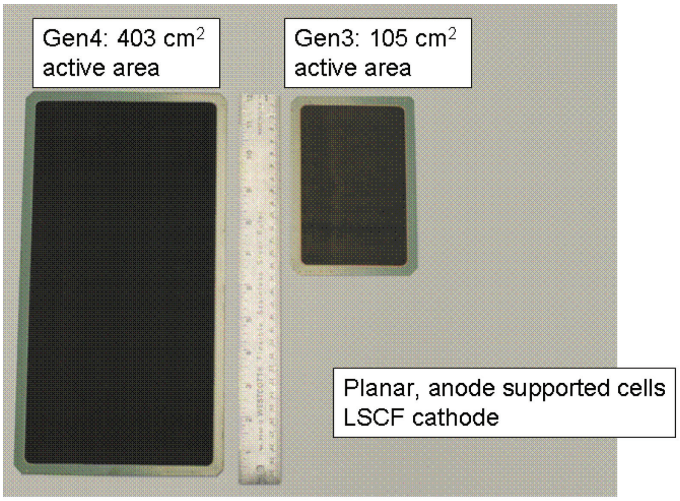


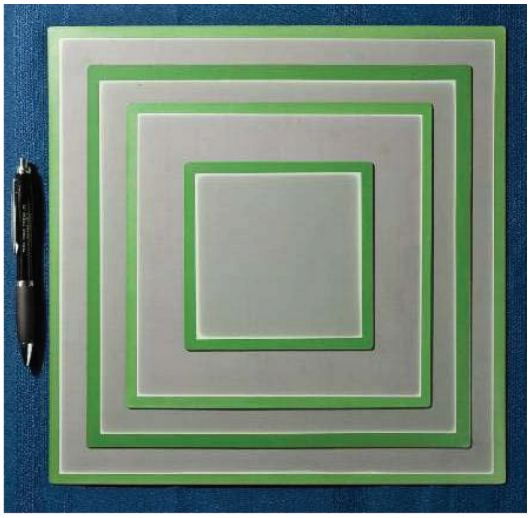
Figure 2-12. SOFC Stack Cost Reduction

Table 2-1. **SECA Program Milestones—FY 2010**

Performance Measure	Target	Actual
Stack Cost (2007$)	175	150
Power Island Cost (2007$)	$700/kW	$685/kW
Maintain Power Density	≈300 MW/cm^2	Achieved

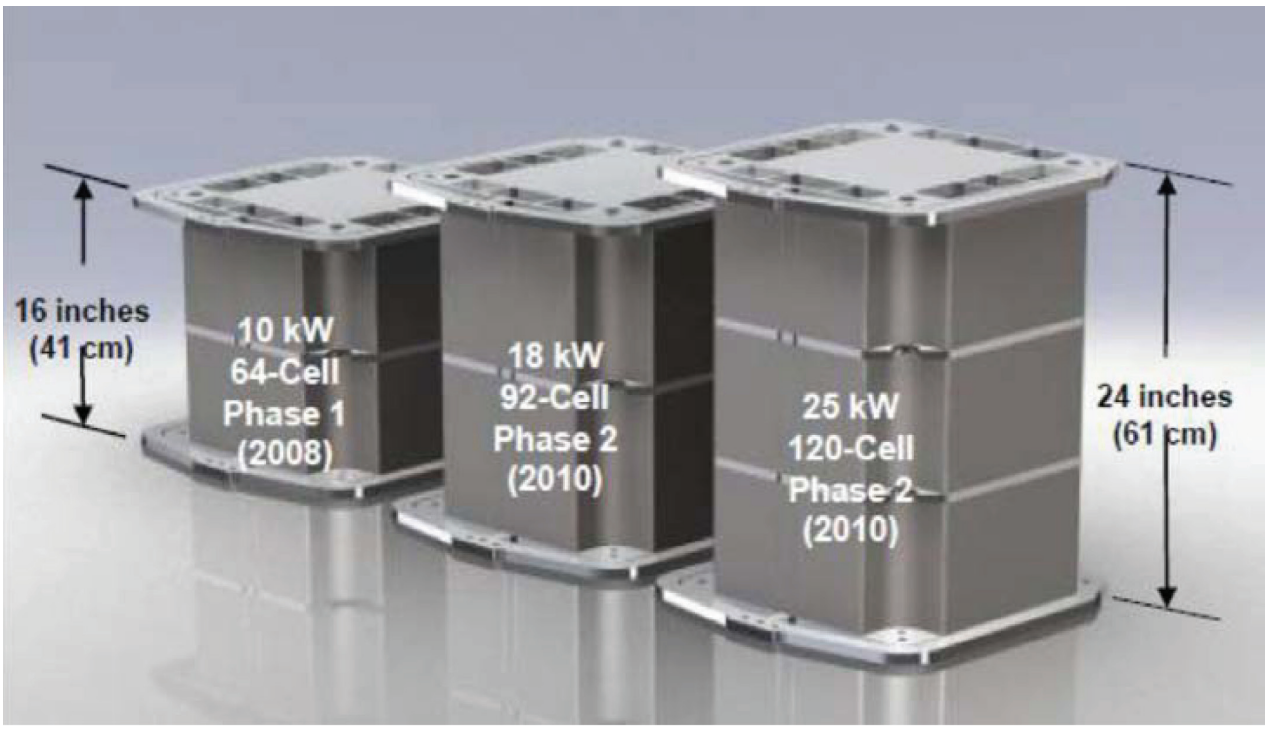


Courtesy Delphi



Courtesy FuelCell Energy/Versa Power Systems

Figure 2-13. Increase in Cell Size (Active Area)



Courtesy FuelCell Energy/Versa Power Systems

Figure 2-14. Increase in Stack Size

PRESENT

The primary objective of SECA program is central-station power generation with a coal feedstock that generates cost-effective electricity, with near-zero levels of air pollutants, facilitates >97 percent CO_2 capture, and has an efficiency of ≥60 percent (HHV), with minimal raw water consumption. A supporting objective is to provide the technology base for natural-gas-fueled SOFC power systems. Natural-gas-fueled SOFC systems may be deployed as central stations, as grid-independent distributed-generation systems, or in a grid-support application. A distributed-generation SOFC power system fueled with natural gas will use essentially the same SOFC module technology

as an IGFC, possibly with a bottoming cycle; and with its smaller size and simpler front-end fuel-supply system, it will likely be first to the marketplace. Thus, operation of distributed-generation systems, in both the demonstration context as well as commercial, will occur relatively early, and is expected to provide useful information in the central-station system development. The distributed-generation development is therefore viewed as being synergistic with coal-fueled central-station work. Thus, the cost reduction and performance/reliability enhancement pursued by the Solid Oxide Fuel Cells program for central-station generation are closely aligned with the near-term distributed-generation goals of industry—without compromising the goals of the coal-based program. Industry success in pursuing near-term market opportunities, utilizing substantial private funding, will establish the manufacturing and operational experience necessary to validate and advance the technology.

The analyses of coal-fueled power-system concepts developed by the Industry Teams and by NETL generally project that the 60 percent efficiency objective is achievable, particularly with the implementation of advanced catalytic coal gasifier technology or with natural gas enrichment of conventionally derived syngas. A comparison of current IGFC efficiency estimates with values for conventional coal-fueled power-plant technologies is provided in Table 2-2, and the IGFC efficiency advantage is apparent.

Table 2-2. **Performance Estimates for IGFC and Conventional PC and IGCC Power Systems**

Power System Type	Efficiency Estimate (Net AC/Coal HHV), %
Pulverized Coal (PC)	28
IGCC	33
IGFC, with Conventional Coal Gasification	
Atmospheric Pressure SOFC	47
Pressurized SOFC	50
IGFC, with Catalytic Coal Gasification	
Atmospheric Pressure SOFC	56
Pressurized SOFC	60

Industry Teams continue to demonstrate progress toward the cost and performance targets, as shown in Table 2-3. Designs for the basic repeatable SOFC module configuration are also being developed by the Industry Teams, and prototypes are being fabricated and tested at team-member facilities. Tests are intended to evaluate performance (power output and voltage degradation rate at steady-state current output) and to enable the projection of commercial module capital costs. Modules rated at ≈25 kWe have been tested for over 1,500 hours and voltage degradation of less 1 percent/1,000 hours has been observed. Both results—high elapsed operating time and low-degradation rate—meet requirements for this stage of module development. The module designs have also met FY 2010 projected cost metrics, <$700/kW for power block and <$175/kW for module (2007$).

Table 2-3. **SECA Program Milestones—FY 2011**

Performance Measure	Target	Actual
Operating hours	1,500	>1,500
Degradation Rate (%/1,000 hours)	2	<1
Stack Cost (2007$)	175	150
Power Island Cost (2007$)	$700/kW	$685/kW

Industry Team cell design development efforts are pushing to increase the active power-generating area of individual cells, and also—via material improvements—to increase the cell power density. The larger cell is desired because it will reduce cell-stack part count, and the ability to design for higher cell power densities is attractive since it will translate to the need for fewer cells and cell stacks to produce the required power output. Via improvements in electrolyte and cathode designs, Industry Teams have succeeded in achieving a power density increase of 36 percent, and cell active area increases by over a factor of five have been achieved in recent years. A 30 kWe-class SOFC module is shown in Figure 2-15.

Figure 2-15. 30-kWe Stack Tower (2012)

Ways to minimize cell material content by reducing planar cell layer thicknesses, while still maintaining a robust cell design, are being developed by SECA Core Team participants; these are responsible in large part for success in reducing cell stack costs and meeting cost targets. Reductions in cell material thicknesses also tend to improve cell electric performance by reducing cell electric resistance. In addition, work is underway to evaluate alternative cell materials that would support more efficient cell operation at reduced temperature levels (650–800 °C). Current program efforts have resulted in an 18 percent increase in cell voltage at 650 °C. This reduced cell temperature initiative is targeted at providing the cell with an operating environment that is less harsh, which should make the cell more tolerant of operating temperature swings, thereby producing a more robust product design.

In the Core Technology Program, work is continuing in several areas. Technologies involved in cell interconnect fabrication are being developed, with work proceeding on the electrodeposition and aerosol spray interconnect fabrication processes. Low, stable values of interconnect area specific resistance represent a design requirement that will increase cell-stack voltage and power output. Stable cell performance over periods of sustained operation as long as 40,000 hours is necessary.

The development of viscous glass-based seal materials and seal designs is of key importance to maintain in-stack gas segregation. Seal materials that self-heal and seal designs that use the materials most effective in accommodating stresses within the cell stack are sought. Program participants currently have several glasses in various stages of development, and glass characterization and tests are underway.

For potential use by fuel cell system developers, two- and three-dimensional cell and cell stack analysis models continue in the development process. The models are intended for the prediction of electrochemical and thermo-

dynamic conditions within the cell and stack, and their development places emphasis on being optionally able to interface with system analysis tools that are commonly used by fuel cell and fuel cell system developers.

Cathode research and development is an important area of work since significant in-cell voltage loss occurs across the cathode, and a body of evidence is beginning to link operating voltage to performance degradation rate. Thus, fundamental work to understand cathode science has been underway as part of the SECA program for several years. In particular, basic theoretical and experimental work has focused on characterizing the surface properties under in situ conditions. New tools are being utilized, such as synchrotron-based X-ray techniques, to assess the chemical, crystallographic, and electronic structures of Industry Team-relevant cathode materials such as lanthanum strontium manganite and lanthanum strontium cobalt ferrite. This knowledge is being correlated with electrochemical performance and stability trends to identify cathode surfaces with the best performance. In parallel, techniques for manufacturing surface-functionalized cathodes, such as infiltration of metal salts, is being optimized. Ultimately, Industry Teams will have the manufacturing techniques and fundamental knowledge necessary to achieve improved cathode voltages that can be maintained for 40,000 hours.

FUTURE

Going forward, emphasis will be placed on improved material and structural stability at component scales suitable for megawatt-class deployment, while maintaining low cost. The Industry Teams will continue to concentrate on the development and commercialization of SOFC technology. The participants in the Core Technology Program will continue to address the engineering solutions to the technical challenges and barriers facing the Industry Teams—with specific emphasis on enhancing the reliability, robustness, and endurance of SOFC stacks to commercially viable levels, all while maintaining the program's cost, performance, and durability goals. Collectively, these efforts will develop the performance, reliability, and robustness demanded for commercial service.

The research portion of the program becomes more critical in the outyears, because of the increasingly difficult technical challenges as more stringent goals are approached.

Cell performance is one of the key factors in determining the electrical efficiency of the SOFC stack and the overall power system. The actual performance, as measured by cell voltage, is decreased from its theoretical voltage because of several types of irreversible losses (resistances):

- ***Activation Polarization:*** These losses stem from the activation energy of the electrochemical reactions at the electrodes. These losses depend on the specific reactions, the electrocatalyst material and microstructure, reactant activities (i.e., air and fuel utilizations), and weakly on current density.
- ***Ohmic Polarization:*** Losses that are caused by ionic resistance in the electrolyte and electrodes, electronic resistance in the electrodes, current collectors and interconnects, and contact resistances. Ohmic losses are proportional to the current density, depend on the materials and stack geometry, and on temperature. Ohmic resistance is typically normalized by the active cell area and referred to as area specific resistance (ASR).
- ***Concentration Polarization:*** Mass-transport-related losses are a result of finite mass-transport limitations and rates of the reactants, and depend strongly on current density, reactant activity, and electrode structure.

Theoretical cell voltage as a function of temperature is shown in Figure 2-16. The effect of the polarization losses on theoretical cell voltage is shown in Figure 2-17.

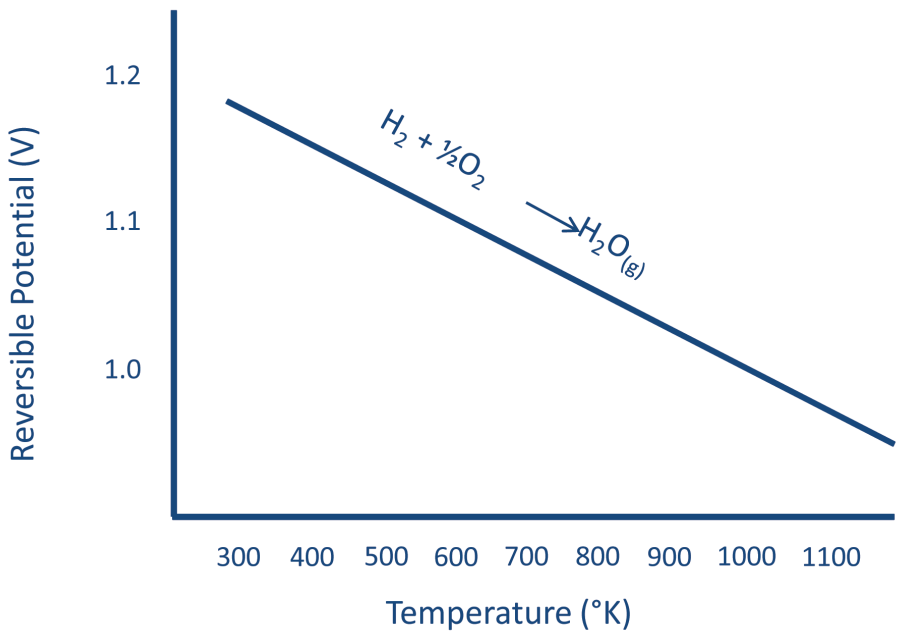


Figure 2-16. Theoretical Cell Voltage as a Function of Temperature

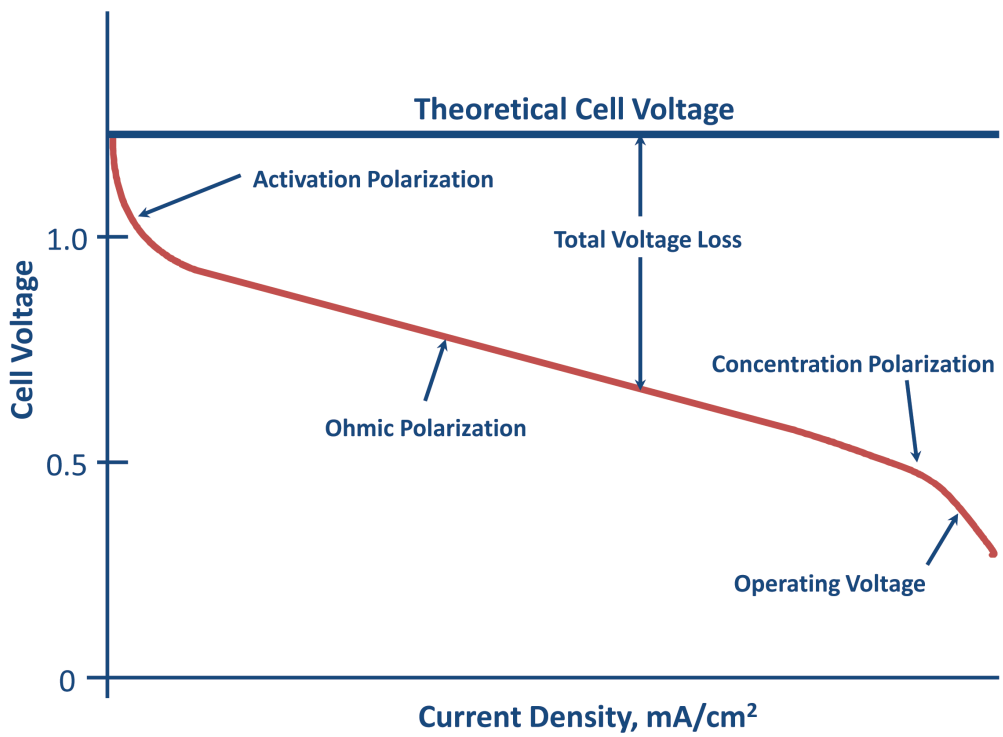


Figure 2-17. Cell Polarization Losses

Within the SOFC, the cathode has a greater impact on cell performance than does the anode, as shown in Figure 2-18, and yet is the least understood area.

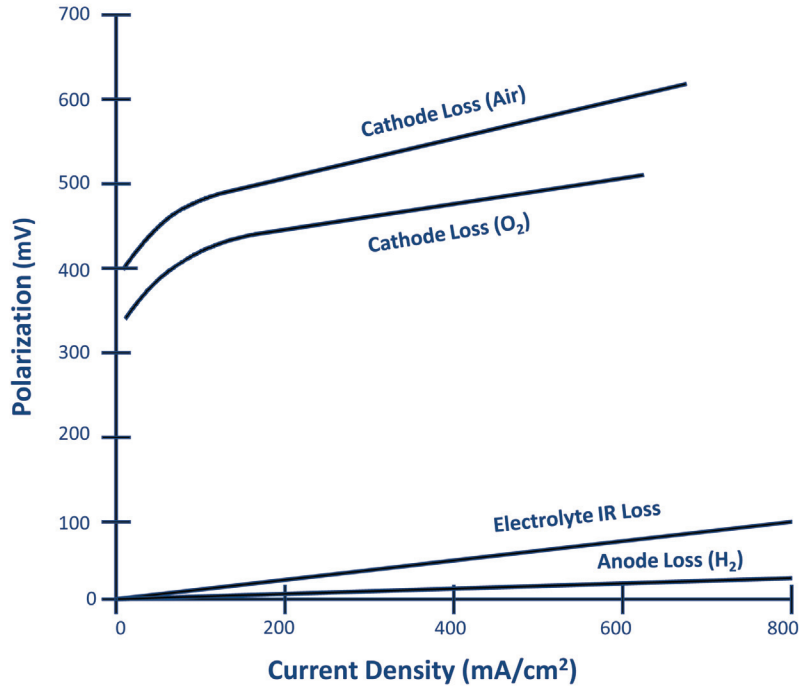


Figure 2-18. Polarization Losses

Thus, in FY12 the Core Technology Program initiated projects for:

- R&D in electrochemical performance enhancement
- R&D focused on studying the durability of cathode materials

The goal of the electrochemical performance enhancement projects are to acquire the fundamental knowledge and understanding of cell interfaces to facilitate R&D in electrochemical performance enhancement while meeting program cost, stability, and lifetime targets. An improved understanding of cell interfaces along with verified concepts of how to integrate potential modifications to improve electrochemical performance would provide valuable guidance to the SECA Industry Team members in enhancing the reliability, robustness, and endurance of their SOFC stacks while maintaining cost reduction goals.

The durability of cathode materials projects will study the durability of cathode materials in terms of stability and performance when they are exposed to real-world air conditions with varying levels of humidity and minor constituents such as chrome, CO_2, and particulate materials.

In both instances, R&D will be focused on the current material sets and operating conditions used by the Industry Team members and modifications should be amenable to their respective cell technology. The results of the R&D will be made available to all Industry Teams.

It is anticipated that successful progression from the present status of laboratory-scale tests to commercial-scale demonstration will result in SOFC technology being available for full-scale commercial deployment sometime between 2020 and 2030.

To successfully complete the maturation of the SOFC technology from its present state to the point of commercial readiness, the program's efforts are channeled through four key technologies, each of which has its respective research focus (Figure 2-1): (1) AEC Development, (2) Atmospheric Pressure Systems, (3) Pressurized Systems, and (4) Alternative AEC Development.

AEC DEVELOPMENT—This key technology, comprising research at universities, national laboratories, small businesses, and other R&D organizations, consists of projects that will lead to substantially improved power density, enhanced performance, reduced degradation rate, and more reliable and robust systems. Research is focused on the technologies critical to the commercialization of SOFC technology, such as cathode performance, gas seals, interconnects, failure analysis, coal contaminants, fuel processing, and balance-of-plant components. The data and results are available to all Industry Teams, ensuring broad technology development and avoiding the duplication of R&D activities.

ATMOSPHERIC PRESSURE SYSTEMS (INDUSTRY TEAMS)—This key technology focuses on the design, scaleup, and integration of the SECA fuel cell technology, ultimately resulting in atmospheric-pressure modules suitable to serve as the building blocks for distributed-generation, commercial, and utility-scale power systems. Activities include fabrication, testing, post-test analysis of cells; integrating cells into stacks; and the development and validation testing of progressively larger stacks (>10 kWe) to meet performance, reliability, endurance, and cost goals.

PRESSURIZED SYSTEMS (INDUSTRY TEAMS)—SOFCs demonstrate enhanced performance by increasing the cell pressure. Thus, IGFC systems with pressurized SOFC technology have the potential to achieve efficiencies greater than 60 percent (HHV) with greater than 97 percent carbon capture, near-zero emissions, and low water usage. In addition to executing activities similar to those described in the Atmospheric Pressure Systems key technology, the Pressurized Systems key technology is developing a deeper understanding on the behavior of the state-of-the-art SOFC material set under pressurized operation; quantifying the effects of pressure on cell performance, reliability, and degradation; and indentifying and resolving the operational issues associated with pressurizing the SOFC stack.

ALTERNATIVE AEC DEVELOPMENT—This key technology evaluates, develops, and implements advanced technologies to reduce costs and enhance performance, robustness, reliability, and endurance of SOFCs. It supports activities that will contribute critical information to assess the viability and benefits of new novel cell and stack architectures (including alternative anodes, cathodes, electrolytes, materials, and configurations), advanced processing techniques, and novel SOFC power systems.

The research timeline for the Solid Oxide Fuel Cells program is shown in Figure 2-19. The two research key technologies of the program, AEC Development and Alternative AEC Development, will contribute to the development of SOFC power systems on an ongoing basis. R&D concepts will be identified, developed, and validated in a laboratory environment before being transferred to the systems developers (Industry Teams). Transformational SOFC power-system technologies are expected to be available for deployment by 2030.

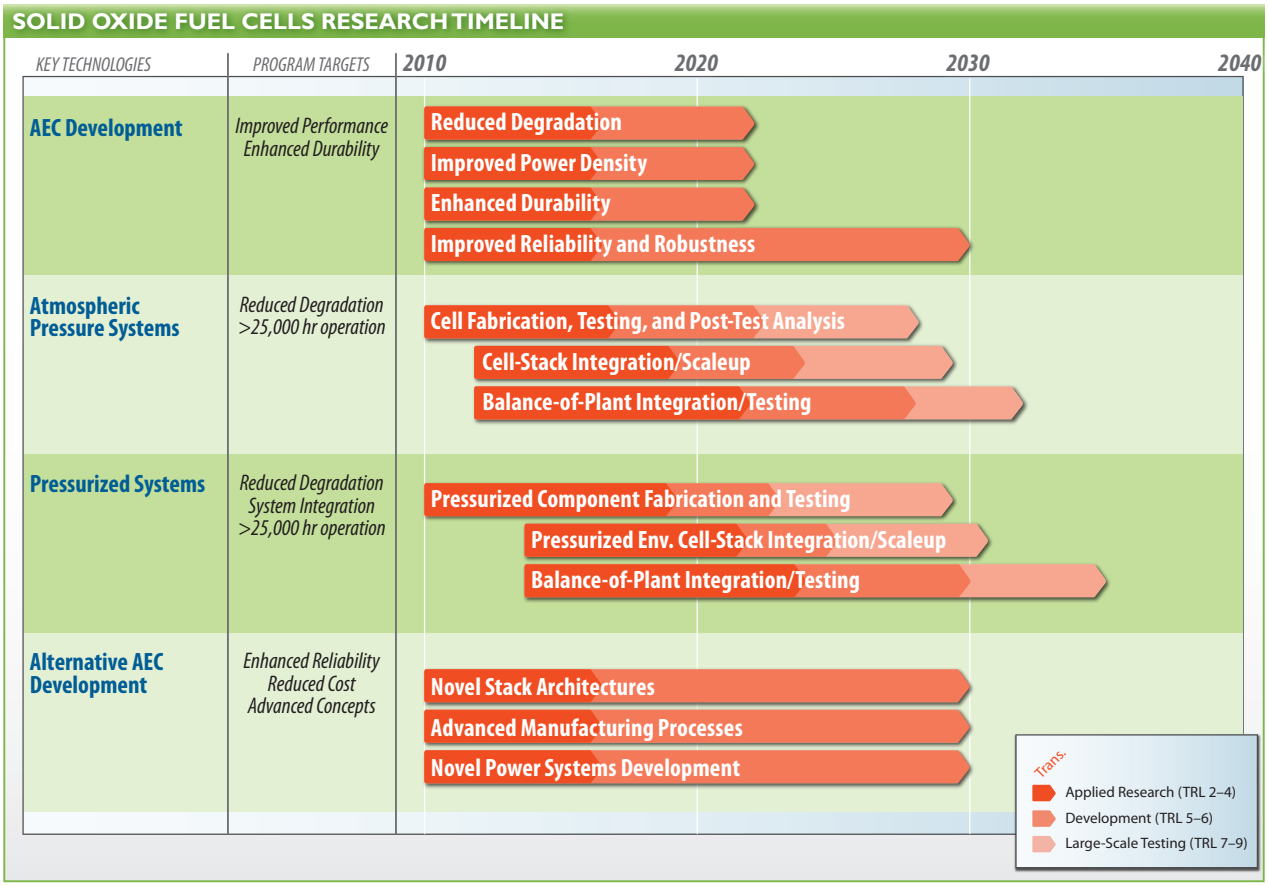


Figure 2-19. Solid Oxide Fuel Cells Program Research Timeline

A list of active (as of October 2012) Solid Oxide Fuel Cells projects, associated TRL scores, and project descriptions is provided in Appendix B.

CHAPTER 3: GOALS AND BENEFITS

3.1 GOALS

The goals of the Solid Oxide Fuel Cells program support the energy goals established by the Administration, DOE, FE, and the CCRP. The priorities, mission, goals, and targets 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 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-Geneneration 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 PC with CCS	40	20%	37%	13%
Greenfield Oxy-Combustion PC with CCS	40	20%	35%	18%
Greenfield Advanced 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 O&M and non-fuel variable O&M costs per million British thermal unit (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 per-

formance 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 SOLID OXIDE FUEL CELLS GOALS

The Solid Oxide Fuel Cells program supports the AES goals through the development of SOFC power systems and the R&D that addresses the technical hurdles and barriers to deployment of those power systems. The CCRP/AES long-term goal is to develop Transformational technologies with CCS that produce low-cost, near-zero emissions energy production that will be available for deployment in the 2030–2040 timeframe. Specifically, these goals are to reduce the cost of CO_2 capture from \$60/tonne to less than \$10/tonne while reducing the COE by more than 40 percent (see Table 3-1). The Solid Oxide Fuel Cells program will contribute to the achievement of the AES Transformational goals through the deployment of SOFC power systems with efficiencies greater than 56 percent (HHV) and capture more than 97 percent of the CO_2 at a cost that is projected to be approximately 40 percent below presently available IGCC systems with carbon capture. To meet these performance and cost metrics, the Solid Oxide Fuel Cells program has established the following goals:

- 20 percent cost reduction in cells and stacks (cumulative)
- 50 percent reduction in overpotential
- >85 percent reduction in degradation rate

The individual and collective contribution of these goals to the overall AES Transformational R&D goals for commercial deployment in 2040 is discussed in the following section, *Section 3.2—Benefits*. The technical approach to achieving the strategic goals of the Solid Oxide Fuel Cells program is presented in *Chapter 4—Technical Plan*.

3.2 BENEFITS

The AES goal is to develop Transformational technologies with CCS that produce low-cost, near-zero-emissions energy generation that will be available for deployment in the 2030–2040 timeframe. For the higher efficiency path (see Table 3-1) this results in a plant efficiency of 56 percent (HHV). This equates to a reduction in the COE of approximately 40 percent and a capture cost of approximately \$10/tonne of CO_2 captured. If the R&D program is successful, the Solid Oxide Fuel Cells program will contribute a 14 percent reduction in the COE and a decrease of \$18/tonne in the cost of CO_2 captured. Collectively, these values represent 35 percent of the COE reduction goal and 36 percent of the targeted reduction in the cost of CO_2 captured. The individual contributions of the aforementioned Solid Oxide Fuel Cells program goals toward the overall AES goals are summarized in Table 3-2.

Table 3-2. **Solid Oxide Fuel Cells Program Contribution to the AES Goals**

Solid Oxide Fuel Cells program Goal	Contribution to AES Goal	
	Cost of Electricity	*Cost of CO_2 Captured*
20% Cost Reduction	1% decrease	\$2/tonne decrease
50% Reduction in Overpotential	6% decrease	\$5/tonne decrease
>85% Reduction in Degradation Rate	7% decrease	\$11/tonne decrease
Total	14% decrease	\$18/tonne decrease

Figure 3-1 illustrates the contribution of the IGFC pathway in reducing the cost of CO_2 captured. Similarly, the benefits of the IGFC pathway in reducing the COE are depicted in Figure 3-2. It is important to note that the IGFC pathway can achieve the CCRP/AES goals by either developing an advanced catalytic gasifier or by enriching the syngas from a conventional gasifier with natural gas.

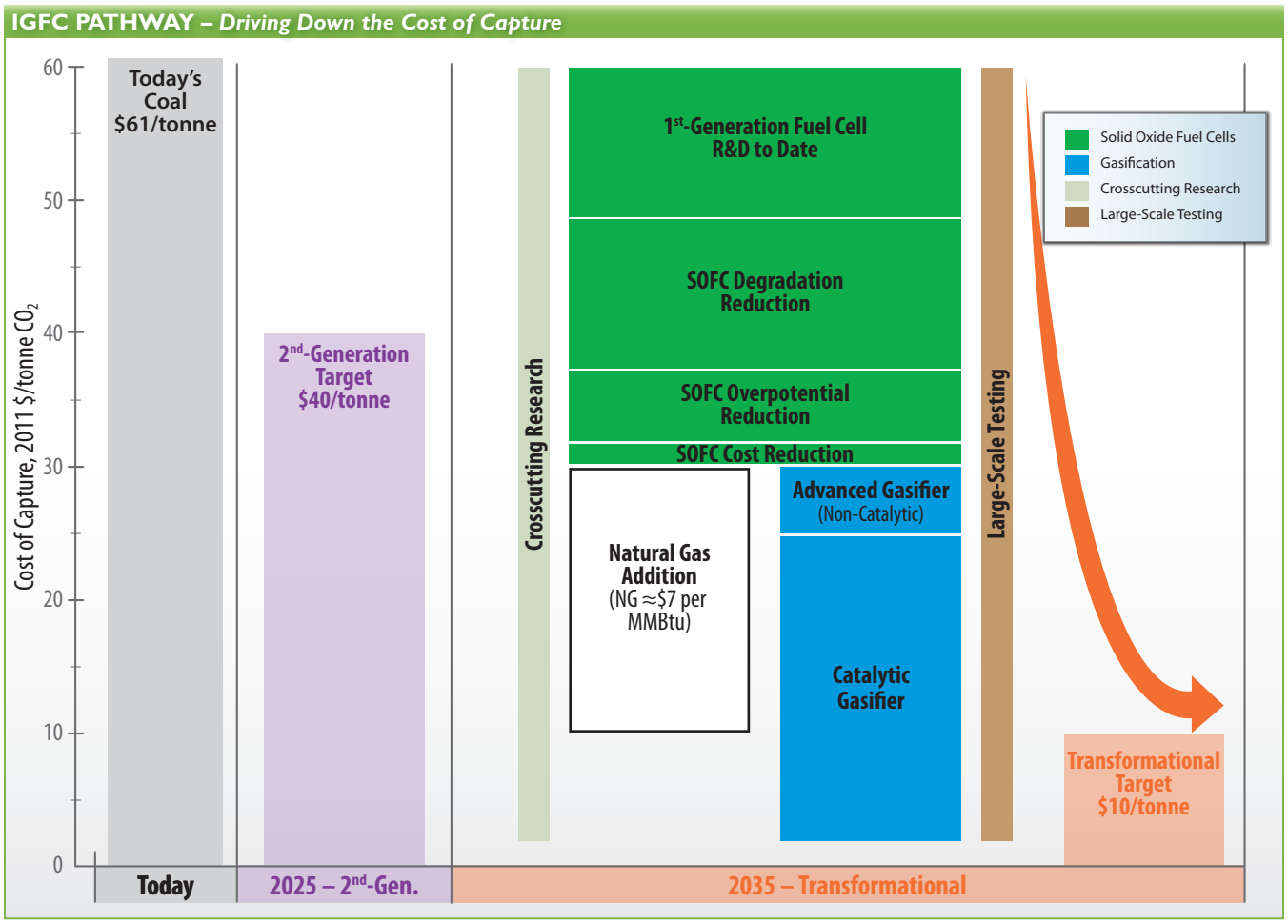


Figure 3-1. Targets for Technology Contributions to Overall CCRP Cost-of-Capture Goals—IGFC Pathway

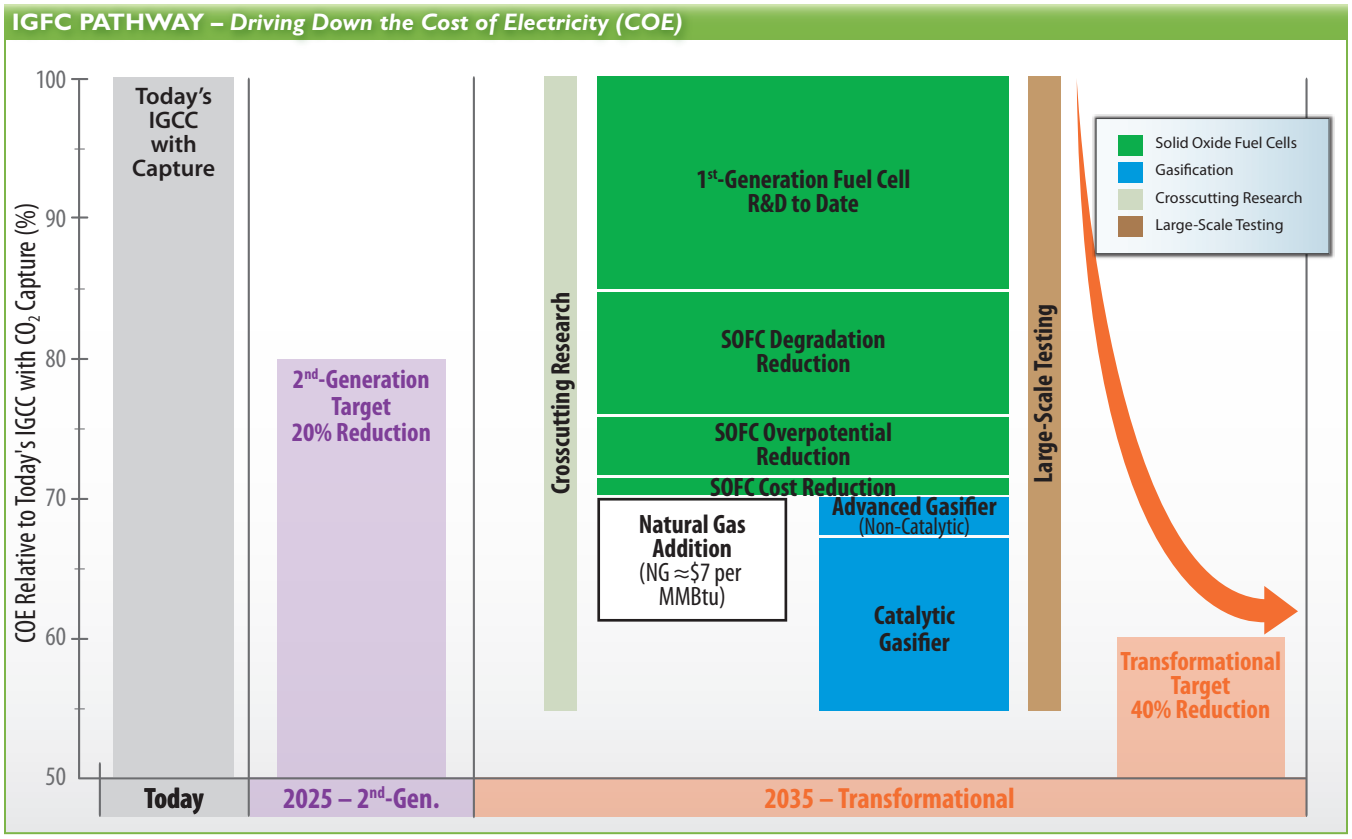


Figure 3-2. Targets for Technology Contributions to Overall CCRP COE Goals—IGFC Pathway

CHAPTER 4: TECHNICAL PLAN

4.1 INTRODUCTION

The AES R&D goals support CCRP goals through the development of advanced energy production systems to produce ultraclean, low-cost energy with near-zero emissions, including CO_2 and low water use. The AES goals contribute to the achievement of the higher-level CCRP goals. In turn, the Solid Oxide Fuel Cells program goals directly support the goals of the AES and implicitly the priorities, mission, goals, and targets of the Administration, DOE, FE, and the CCRP. The SOFC technical plan discusses how the Solid Oxide Fuel Cells program will achieve its respective goals. In support of the AES goals, the Solid Oxide Fuel Cells program is structured to pursue the following major objectives:

- Improve the robustness, reliability, and endurance of atmospheric pressure SOFC stacks to commercially viable levels while reducing the SOFC stack cost by 20 percent.
- Improve the robustness, reliability, and endurance of pressurized SOFC stacks to commercially viable levels, while reducing the SOFC stack cost by 20 percent.
- Incrementally scale up and test atmospheric and pressurized SOFC modules to the size required (≥1 MWe) for aggregation in central-generation systems, while maintaining the corresponding IGFC power block cost at ≤$700/kWe (2007$).
- Achieve an overall IGFC power-plant efficiency of >56 percent (net AC/coal HHV)—inclusive of the coal gasification and carbon separation processes, as required—while maintaining the SOFC power block cost at ≤$700/kWe (2007$), with near-zero emissions, low water consumption, and greater than 97 percent CO_2 capture.

These objectives are being addressed through the four key technologies (Figure 2-1):

- AEC Development
- Atmospheric Pressure Systems
- Pressurized Systems
- Alternative AEC Development

Two of the key technologies, AEC Development and Alternative AEC Development, are R&D in nature and the efforts therein will support the development, demonstration, and deployment of the SOFC power systems developed under the other two key technologies. The technical plans that will culminate in the deployment of an atmospheric pressure and a pressurized IGFC power system, respectively, are discussed in the following sections.

4.2 ATMOSPHERIC PRESSURE SYSTEMS

This key technology focuses on the design, scaleup, and integration of the SOFC technology, ultimately resulting in atmospheric pressure modules suitable to serve as the building blocks for distributed-generation, commercial, and utility-scale power systems. Activities include fabrication, testing, post-test analysis of cells; integrating cells into stacks; and the development and validation testing of progressively larger stacks (>10 kWe) to meet performance, reliability, endurance, and cost.

4.2.1 BACKGROUND

A discussion on the background of the Solid Oxide Fuel Cells program is provided in Chapter 2.

4.2.2 TECHNICAL DISCUSSION

A detailed discussion of an atmospheric pressure IGFC power system is provided in Chapter 2.

4.2.3 R&D APPROACH—PERFORMANCE TARGETS AND MEASURES

FY 2012 MILESTONES

- 1Q FY 2012: Complete test of non-repeat hardware for proof-of-concept module.
- 2Q FY 2012: Develop cell fabrication technology for cell manufacturing for proof-of-concept module stacks.
- 3Q FY 2012: Complete preliminary proof-of-concept module system design.
- 4Q FY 2012: Complete test of proof-of-concept module.

FY 2013 MILESTONES

- 1Q FY 2013: Complete development of proof-of-concept module power-plant control philosophy.
- 2Q FY 2013: Demonstrate degradation rate of <1 percent/1,000 hours.
- 3Q FY 2013: Demonstrate cell materials and component design improvement that reduces degradation rate by 25 percent.
- 4Q FY 2013: Complete detail design of the proof-of-concept module power plant.

OUT-YEAR MILESTONES

By 2015

- Demonstrate building block atmospheric pressure stack module (>30 kWe).
- Maintain SOFC power block cost at <$700/kWe (2007$).
- Identify and prioritize degradation and failure mechanisms in state-of-the-art SOFC cells and stacks, to serve as the basis for R&D to achieve commercially viable reliability and endurance.
- Complete the design of the >125 kWe-class atmospheric-pressure proof-of-concept SOFC system.
- Begin operation of >125 kWe-class atmospheric-pressure proof-of-concept SOFC system.

By 2020

- Achieve 5,000 hours of operation for >125 kWe-class atmospheric-pressure proof-of-concept SOFC system, demonstrating an overall degradation rate of ≤2 percent per 1,000 hours, system availability of ≥80 percent, and central-generation system power block cost at <$700/kWe (2007$).
- Achieve ≤0.2 percent per 1,000 hours degradation over ≥5,000 hours for atmospheric pressure SOFC stacks under representative system conditions (laboratory scale) in preparation for MWe-class system.
- Complete the design and construction of the MWe-class (pilot scale) atmospheric pressure SOFC system.
- Begin operation of MWe-class atmospheric pressure SOFC system (>25,000-hour test).

By 2025

- Achieve 25,000 hours of operation for MWe-class atmospheric-pressure SOFC system, demonstrating a degradation rate of ≤0.5 percent per 1,000 hours, system availability of ≥80 percent, and central-generation system power block cost at <$700/kWe (2007$).

By 2030

- Initiate operation of commercial-scale atmospheric pressure IGFC system.
- Achieve 10,000 hours of operation for commercial-scale atmospheric pressure IGFC system.

4.2.4 TECHNOLOGY TIMELINE

The timeline leading to the development and deployment of an atmospheric pressure IGFC power system is presented in Figure 4-1.

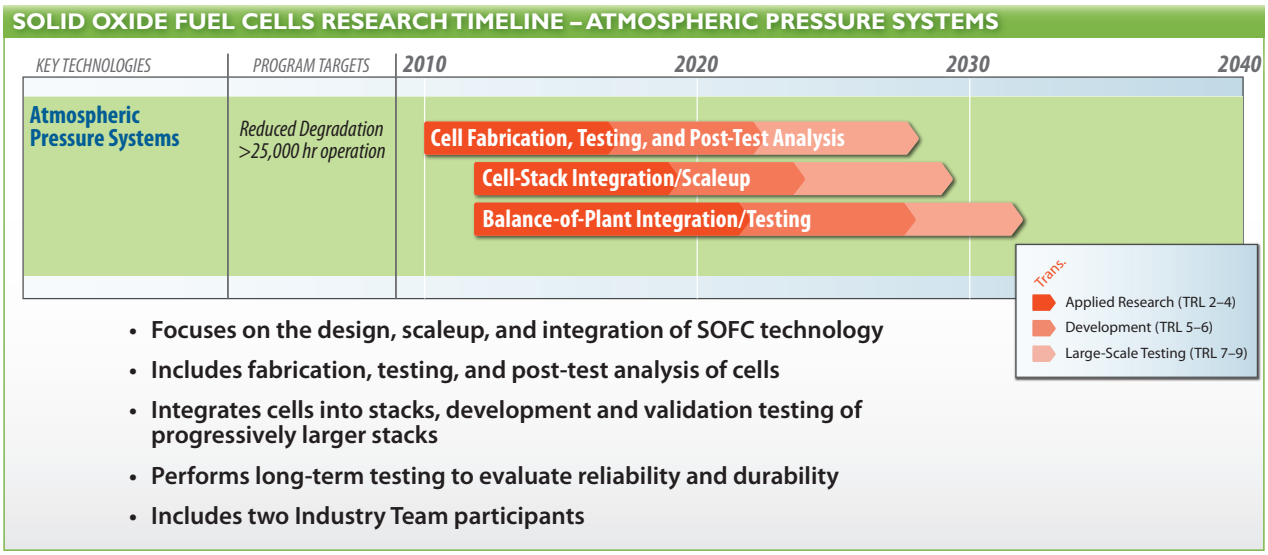


Figure 4-1. Atmospheric Pressure Systems Research Timeline

4.2.5 RESEARCH AREA FOCUS BENEFITS

The AES goal is to develop Transformational technologies with CCS that produce low-cost, near-zero-emissions energy generation that will be available for deployment in the 2030–2040 timeframe. For the higher efficiency path (see Table 3-1), this results in a plant efficiency of 56 percent (HHV). This is equivalent to a reduction in the COE of approximately 40 percent and a capture cost of approximately \$10/tonne of CO_2 captured. If the R&D program is successful, the Solid Oxide Fuel Cells program will contribute a 14 percent reduction in the COE and a decrease of \$18/tonne in the cost of CO_2 captured. Collectively, these values represent 35 percent of the COE reduction goal and 36 percent of the targeted reduction in the cost of CO_2 captured. The individual contributions of the Solid Oxide Fuel Cells program goals toward the overall AES goals are summarized in Table 4-1.

Table 4-1. **Atmospheric Pressure Systems Benefits**

Solid Oxide Fuel Cells program Goal	Contribution to AES Goal	
	Cost of Electricity	*Cost of CO_2 Captured*
20% Cost Reduction	1% decrease	\$2/tonne decrease
50% Reduction in Overpotential	6% decrease	\$5/tonne decrease
>85% Reduction in Degradation Rate	7% decrease	\$11/tonne decrease
Total	14% decrease	\$18/tonne decrease

4.3 PRESSURIZED SYSTEMS

This key technology is developing a deeper understanding on the behavior of the state-of-the-art SOFC material set under pressurized operation; quantifying the effects of pressure on cell performance, reliability, and degradation; and identifying and resolving the operational issues associated with pressurizing the SOFC stack. In addition, this key technology focuses on the design, scaleup, and integration of the SECA fuel cell technology operating at elevated pressure to serve as the building blocks for distributed-generation, commercial, and utility-scale power systems. Activities include fabrication, testing, post-test analysis of cells, integrating cells into stacks, and the development and validation testing of progressively larger stacks (>10 kWe) to meet performance, reliability, endurance, and cost.

4.3.1 BACKGROUND

A discussion on the background of the Solid Oxide Fuel Cells program is provided in Chapter 2.

4.3.2 TECHNICAL DISCUSSION

A detailed discussion of an atmospheric pressure IGFC power system is provided in Chapter 2.

4.3.3 R&D APPROACH—PERFORMANCE TARGETS AND MEASURES

FY 2012 MILESTONES

- 1Q FY 2012: Complete test of non-repeat hardware for proof-of-concept module.
- 2Q FY 2012: Develop cell fabrication technology for cell manufacturing for proof-of-concept module stacks.
- 3Q FY 2012: Complete preliminary proof-of-concept module system design.
- 4Q FY 2012: Complete test of proof-of-concept module.

FY 2013 MILESTONES

- 2Q FY 2013: Complete 5,000-hour Phase I test.
- 2Q FY 2013: Complete 3,000-hour Phase II test.
- 3Q FY 2013: Verify pressurized IGFC cost.

OUT-YEAR MILESTONES

By 2015

- Maintain SOFC power block cost at <$700/kWe (2007$).
- Identify and prioritize degradation and failure mechanisms in state-of-the-art SOFC cells and stacks, to serve as the basis for R&D to achieve commercially viable reliability and endurance.
- Demonstrate building-block pressurized stack module (>20 kWe).

By 2020

- Achieve ≤0.2 percent per 1,000 hours degradation over ≥5,000 hours for pressurized SOFC stacks under representative system conditions (laboratory scale) in preparation for MWe-class system.
- Achieve 5,000 hours of operation for >125 kWe-class proof-of-concept SOFC system, demonstrating an overall degradation rate of ≤2 percent per 1,000 hours, system availability of ≥80 percent, and central-generation system power block cost at <$700/kWe (2007$).

By 2025

- Begin operation of MWe-class (pilot-scale) pressurized SOFC system.
- Achieve 10,000 hours of operation for MWe-class pressurized SOFC system.

By 2030

- Achieve 25,000 hours of operation for MWe-class pressurized SOFC system, demonstrating a degradation rate of ≤0.5 percent per 1,000 hours, system availability of ≥80 percent, and central-generation system power block cost at <$700/kWe (2007$).
- Complete design and construction of commercial-scale pressurized IGFC system.

By 2035

- Initiate operation of commercial-scale pressurized IGFC system.
- Achieve 25,000 hours of operation for commercial-scale pressurized IGFC system.

4.3.4 TECHNOLOGY TIMELINE

The timeline leading to the development and deployment of a pressurized IGFC power system is presented in Figure 4-2.

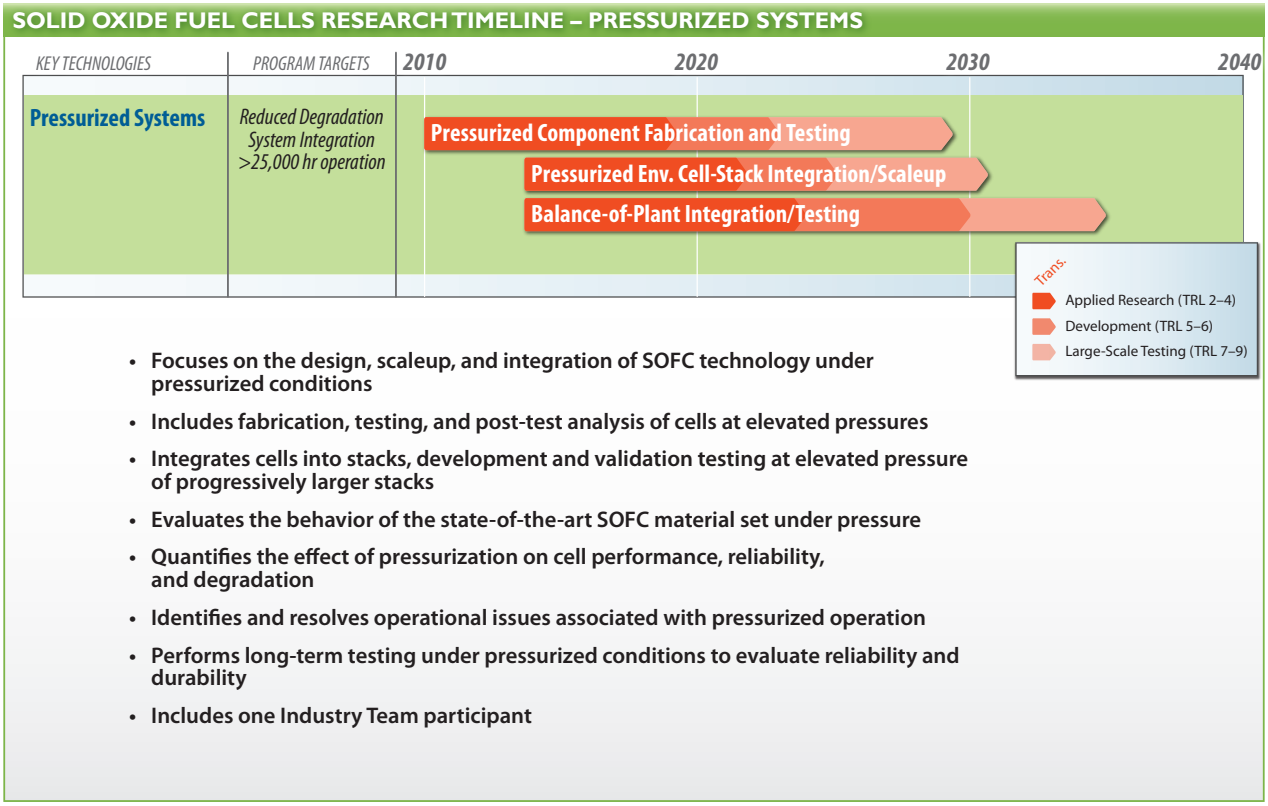


Figure 4-2. Pressurized Systems Research Timeline

4.3.5 RESEARCH AREA FOCUS BENEFITS

The AES goal is to develop Transformational technologies with CCS that produce low-cost, near-zero-emissions energy generation that will be available for deployment in the 2030–2040 timeframe. For the higher efficiency path (see Table 3-1) this results in a plant efficiency of 56 percent (HHV). This is equivalent to a reduction in the COE of approximately 40 percent and a capture cost of approximately $10/tonne of CO_2 captured. Given a successful R&D program, the Solid Oxide Fuel Cells program will contribute a 14 percent reduction in the COE and a decrease of $18/tonne in the cost of CO_2 captured. Collectively, these values represent 35 percent of the COE reduction goal and 36 percent of the targeted reduction in the cost of CO_2 captured. The individual contributions of the Solid Oxide Fuel Cells program goals toward the overall AES goals are summarized in Table 4-2.

Table 4-2. **Pressurized Systems Benefits**

Solid Oxide Fuel Cells program Goal	Contribution to AES Goal	
	Cost of Electricity	*Cost of CO_2 Captured*
20% Cost Reduction	1% decrease	$2/tonne decrease
50% Reduction in Overpotential	6% decrease	$5/tonne decrease
>85% Reduction in Degradation Rate	7% decrease	$11/tonne decrease
Total	14% decrease	$18/tonne decrease

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CHAPTER 5: IMPLEMENTATION AND COORDINATION PLAN

5.1 IMPLEMENTATION PLAN

The Solid Oxide Fuel Cells program is presently funded (FY 2012) at $25 million. As shown in Figure 5-1, the historical average program funding over the past decade was ≈$50 million per year.

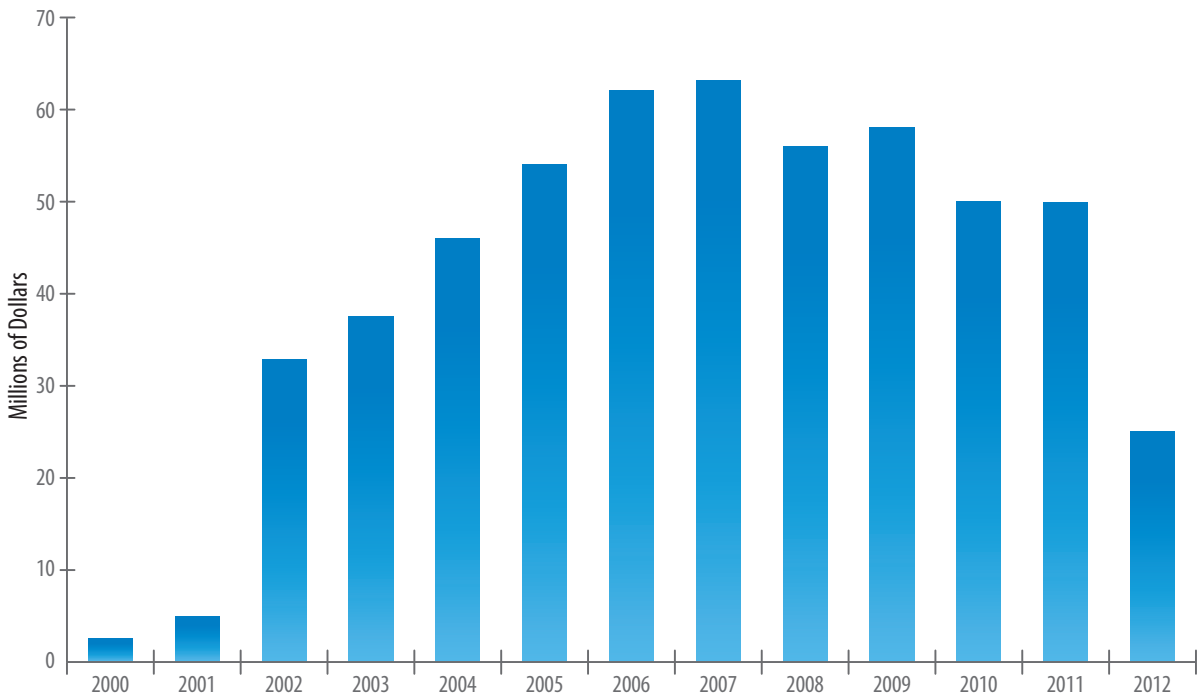

Figure 5-1. Solid Oxide Fuel Cells Program Budget History

5.2 COORDINATION WITH OTHER TECHNOLOGY AREAS

The successful deployment of the two system-based key technologies being developed by the Solid Oxide Fuel Cells program, Atmospheric Pressure Systems and Pressurized Systems, relies on the successful development of enabling technologies that will evolve out of the Gasification Systems and Advanced Combustion Systems Technology Areas, and the Crosscutting Research program, respectively. The interrelationship of the Solid Oxide Fuel Cells program with the Gasification Systems, Advanced Combustion Systems, and Crosscutting Research programs is illustrated in Figure 5-2.

Highlights of the Solid Oxide Fuel Cells program's coordination with other Technology Areas are described below.

- ***Gasification Systems***—The Gasification Systems program supports the Solid Oxide Fuel Cells program through the development of advanced technologies that both lower the cost of producing ultraclean syngas and increase the efficiency of coal conversion systems. This enables IGFC systems to produce cost-effective electricity in an environmentally benign manner consistent with the long-term AES goals.

- ***Advanced Combustion Systems***—IGFC systems presently under consideration include SOFC configurations that maintain separate anode and cathode effluent streams. The anode effluent is primarily CO_2 and water with a small amount of residual fuel, hydrogen, and carbon monoxide. Oxy-combustion of this stream and condensation of the product water will yield a highly concentrated CO_2 stream ready for EOR or sequestration with little or no additional processing. The Advanced Combustion Systems program is developing components of oxy-combustion systems that, when integrated, result in more efficient operations and lower capital costs.

- ***Crosscutting Research***—Support is directly provided by the Crosscutting Research program to the Solid Oxide Fuel Cells program through the development of high-temperature sensors, novel control architectures, and high-performance materials and modeling.

The synergy between these respective Technology Areas and the Solid Oxide Fuel Cells program will culminate in the development of the technologies necessary for the deployment of highly efficient SOFC power systems that simultaneously produce low-cost electricity from coal or natural gas with carbon capture.

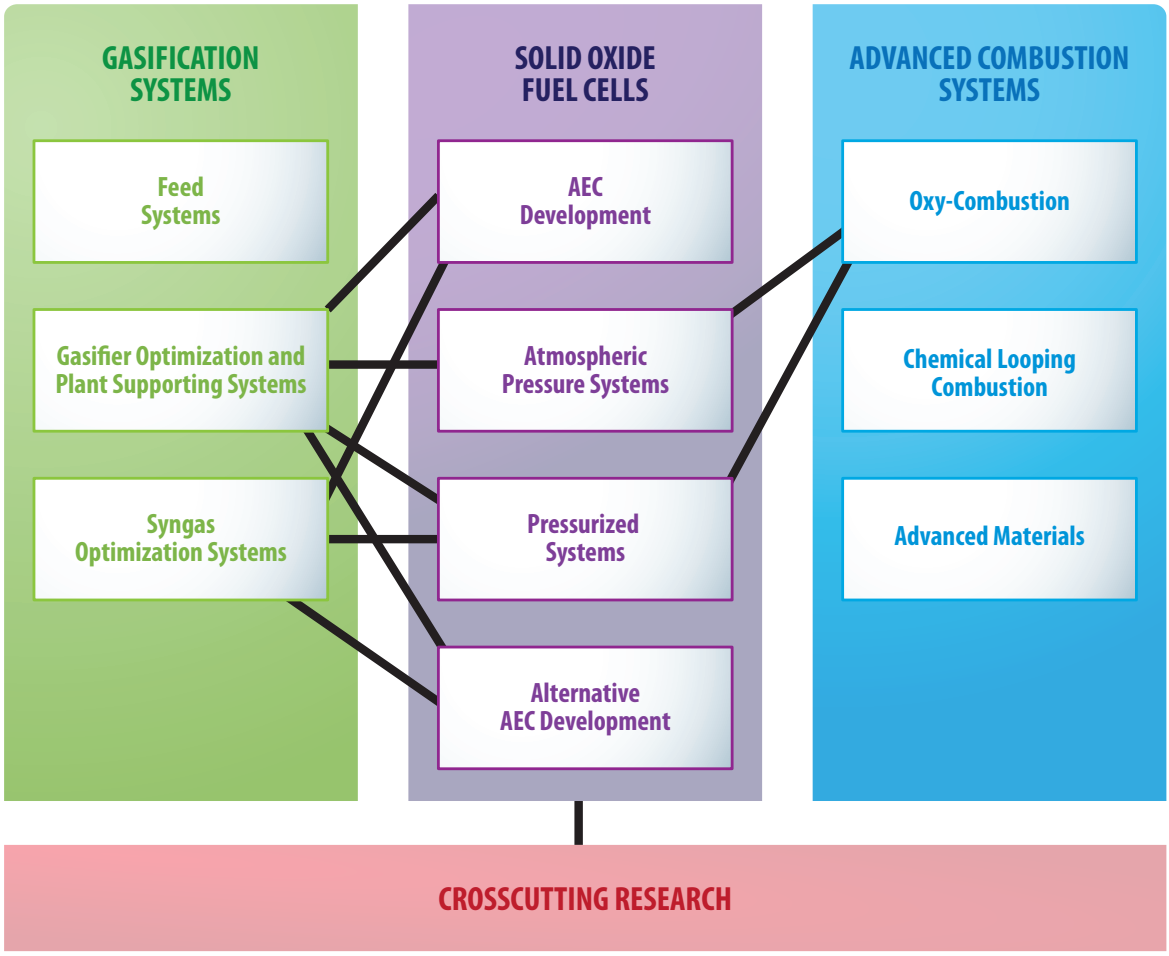

Figure 5-2. Solid Oxide Fuel Cells Program Integration with Other Technology Areas

5.3 NEXT STEPS

The success of the Solid Oxide Fuel Cells program, along with the success of the companion programs, is essential to successfully develop and demonstrate Transformational technologies with CCS that produce low-cost, near-zero-emissions energy generation. These technologies will result in near-zero-emission power production with a 40 percent reduction in the COE and a capture cost of approximately \$10/tonne of CO_2 captured.

Successful implementation of the two systems-based SOFC key technologies requires a budget near its historical average of \$50 million per year. This would allow the two key technologies to culminate in the deployment of an atmospheric pressure IGFC followed by a pressurized IGFC that fully integrates all the Transformational technologies and achieves the performance, cost, and capture requirements. The implementation plan includes a mix of short-, mid-, and long-term R&D projects as well as laboratory (stack) tests, proof-of-concept, and pilot-scale projects.

The two system-based key technologies would proceed in parallel as fundamental technology focused on SOFCs (anodes, electrolytes, cathodes, etc.) is common to both. As appropriate, system-specific projects would be established to solve issues solely related to the respective power system. However, the two power systems are on separate development timelines with respect to stack testing, proof-of-concept system tests, pilot-scale MWe-class demonstration projects, and the commissioning of commercial-scale IGFC power systems. If the program is fully funded, the Atmospheric Pressure Systems key technology will lead the Pressurized Systems key technology by approximately 2–3 years.

In the short term (<5 years), the present portfolio of Core Technology Program R&D projects would be expanded to include projects critical to addressing the technologies essential in the commercialization of SOFCs. Examples include technologies (models and methods) for reducing cell degradation, stack models, compliant seals, and interconnect surface treatments. Testing of kilowatt-class (laboratory scale) stacks would continue—implementing and validating technologies emanating from the R&D key technologies as they became available. Atmospheric pressure proof-of-concept systems would be designed, built, and tested. A 1-to-2-year lag is expected for similar-sized pressurized systems.

Based on successful atmospheric pressure proof-of-concept and pilot-scale testing, DOE expects that private industry will have sufficient experience with and confidence in the technology to pursue commercial opportunities in the natural gas distributed-generation market. Operational experience, lessons learned, and the cost benefits accrued via the commercialization of distributed-generation systems will contribute to the long-term success of the Solid Oxide Fuel Cells program.

The mid-term strategy (5–10 years) will enable the Pressurized Systems key technology to validate its technology through stack testing and proof-of-concept tests, then initiate the design of a pilot-scale (MWe-class) demonstration. Within this timeframe it is expected that a commercial offering of pressurized systems for distributed-generation markets will be made by industry stakeholders. Pilot-scale testing (MWe-class) of the SOFC building block for the atmospheric pressure IGFC will have accumulated a significant period of operation. Advanced technologies that address cost reduction, robustness, reliability, and endurance streaming from the R&D key technologies will be implemented as appropriate.

Consistent with AES program goals for Transformational technology, the design, construction, and operation of the atmospheric pressure IGFC will occur circa mid-2020s with the successful operation of the pilot-scale system providing the trigger for the design of the commercial-scale IGFC. Operation of the atmospheric pressure IGFC at commercial scale would follow in the latter 2020s. The Pressurized Systems will follow the Atmospheric Pressure Systems by approximately 2–3 years, culminating with operation of a commercial-scale pressurized IGFC post-2030.

Figure 5-3 illustrates the interaction of the respective key technologies and the ultimate deployment of the respective power systems.

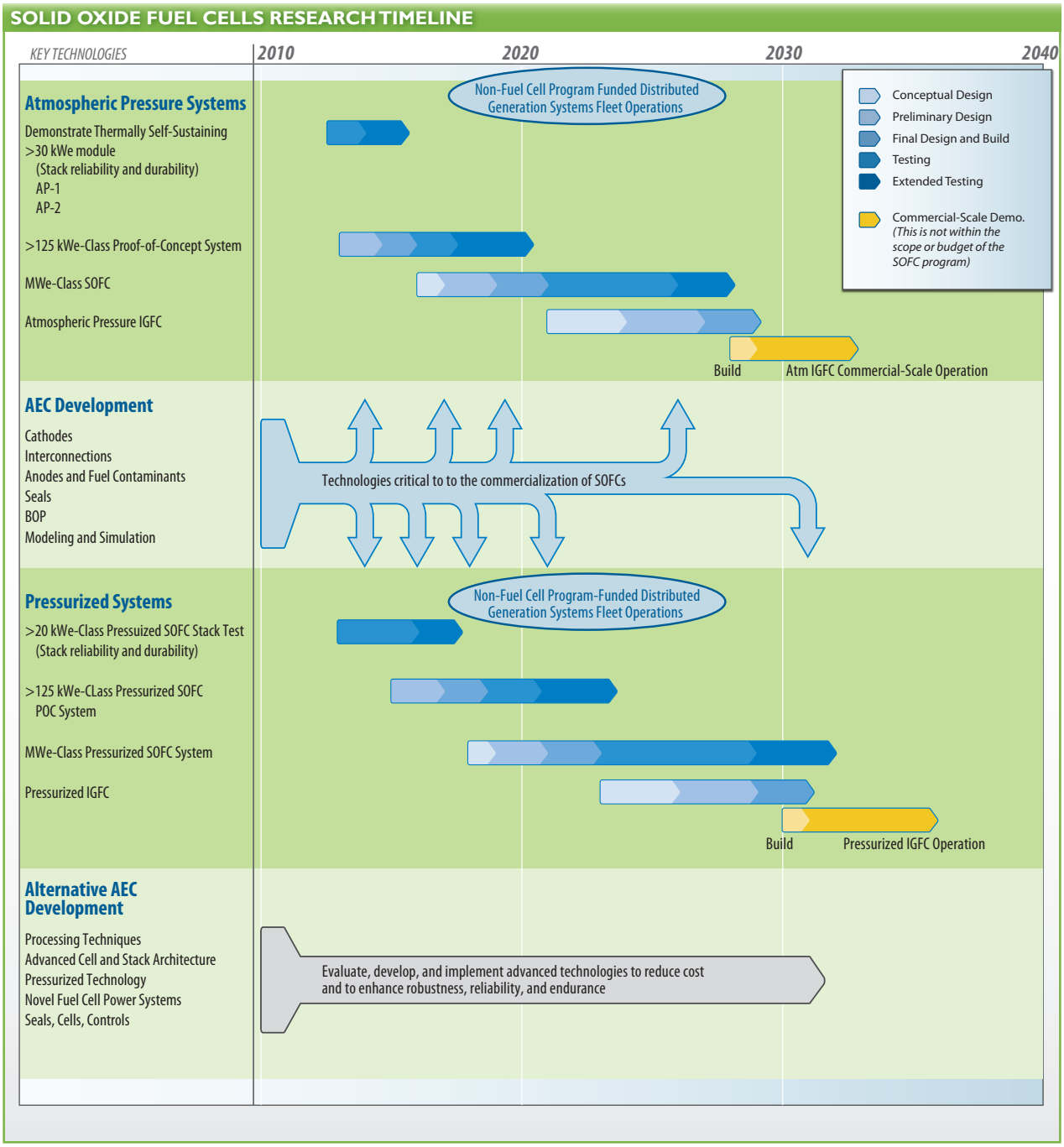

Figure 5-3. Solid Oxide Fuel Cells Program Research Timeline

As described herein, the *Solid Oxide Fuel Cells Program Plan* encompasses a comprehensive R&D plan to address the technical issues facing the commercialization of SOFC technology and a series of increasingly larger demonstration projects intended to validate the solutions to those issues.

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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 SOLID OXIDE FUEL CELLS PROJECTS

(AS OF OCTOBER 2012)

Table B-1. **Solid Oxide Fuel Cells Projects**

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—AEC Development				
49071	Argonne National Laboratory	SOFC Materials Research/ Synchotron	3	Develop an understanding of cathode surface phenomena to improve cell performance by measuring the atomic and chemical state of cathode materials under typical operating conditions to enable models for the design of high-performance cathode materials.
NT0004105	Carnegie Mellon University	Investigation of Cathode Electrocatalytic Activity Using Surfaced Engineered Thin-Film Samples and High-Temperature Property Measurements	3	Understand the role of atomic-scale surface chemistry and microstructure on cathodes to improve cathode performance by specifically targeting the O_2 uptake process by changing the base component material or adding a catalyst to the existing material set.
FE0006165	Faraday Technology, Inc.	Phase III Xlerator Program: Electrodeposited Mn-Co Alloy for Solid Oxide Fuel Cell Interconnects	*	†
FE0009652	Georgia Tech Research Corporation	Fundamental Investigators and Rational Design of Durable, High-Performance Cathode Materials	*	†
FE0009620	Leland Stanford Junior University	Surface-Modified Electrodes: Enhancing Performance Guided by In Situ Spectroscopy and Microscopy	*	†
FE0000773	LG Fuel Cell Systems, Inc.	LG Fuel Cell Systems SOFC Model Development	*	†
NT0004117	Massachusetts Institute of Technology	Chemistry of SOFC Cathode Surfaces: Fundamental Investigation and Tailoring of Electronic Behavior	3	Understand how physical, chemical, and electronic structures relate to cathode performance to propose improved cathode surfaces with enhanced electrochemical performance and low degradation by characterizing the surface properties of catalytic cathode materials.
SC0006374	Materials and Systems Research, Inc.	Solid Oxide Fuel Cell Cathode Enhancement Through a Vacuum-Assisted Infiltration	*	†
NT0004115	Montana State University	Synchrotron Investigations of LSCF Cathode Degradation	3	Identify degradation mechanisms in cathode materials to improve cell performance and durability by modifying and characterizing the cathode/ electrolyte interface and correlating the modifications to the effects of overpotential, current, and gaseous environment.
SC0002491	Mo-Sci Corporation	High-Temperature Viscous Sealing Glasses for Solid Oxide Fuel Cells	*	†
2012.03.04	National Energy Technology Laboratory	Task 2: Cell and Stack Degradation	3	Compile knowledge of degradation modes in anode/cathode/electrolyte and quantify relative importance to generate a predictive model describing modes of degradation applicable to cells and stacks by conducting direct cell testing in the laboratory.
2012.03.04	National Energy Technology Laboratory	Task 3: Cathode Engineering	3	Complete the development and performance evaluation of cathode materials and structure to improve cell power output by 30%, while maintaining cost and durability, by lab-scale cell tests and subsequent scaleup and testing in a complete cell stack
SC0008203	NexTech Materials, Ltd.	SOFC Protection Coatings Based on a Cost-Effective Aluminization Process	*	†
SC0008267	nGimat Company	Low-Cost Spray-On Coatings for Protection of SOFC Interconnects and Balance-of-Plant Components	*	†
FEAA066	Oak Ridge National Laboratory	Reliability of Materials and Components for Solid Oxide Fuel Cells	3	Characterize the thermomechanical properties of materials under typical operating to produce high-fidelity models to predict and assess cell and stack behavior and identify degradation mechanisms through lab-scale tests and analysis of experimental data.

Table B-1. **Solid Oxide Fuel Cells Projects**

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
FWP-40552	Pacific Northwest National Laboratory	SECA Core Technology Program	3–4	Develop advanced cell and stack component materials and computational tools to increase performance, improve robustness, reduce degradation, and lower cost of SOFC cells and stacks, through lab-scale tests and benchmarking results against industry data.
NT0004396	Pennsylvania State University	Solid Oxide Fuel Cells Operating on Alternative and Renewable Fuels	*	†
SC0008236	QuesTek Innovations LLC	Low-Cost Alloys for High-Temperature SOFC Systems Components	*	†
SC0007608	SEM-COM Company, Inc.	Stable Glass-Ceramic Nanocomposites as Compliant Seals for SOFCs	*	†
FE0009656	Trustees of Boston University	Unraveling the Role of Transport, Electrocatalysis, and Surface Science in the Solid Oxide Fuel Cell Cathode Oxygen Reduction Reaction	*	†
NT0004104	Trustees of Boston University	Unraveling the Relationship Between Structure, Surface Chemistry and Oxygen Reduction	3	Understand the role of surface atomic and electronic structure in the oxygen-reduction reaction to provide guidance in improving cathode performance by acquiring surface-specific chemical and structural data using advanced analytical techniques.
FE0009682	University of Connecticut	Study of the Durability of Doped Lanthanum Manganite- and Cobaltite-Based Cathode Materials Under "Real World" Air Exposure Atmosphere	*	†
FE0009084	University of Maryland	Mechanistic Enhancement of SOFC Cathode Durability	*	†
FE0009435	University of Wisconsin System	Enhancement of Solid Oxide Fuel Cell Cathode Electrochemical Performance Using Multiphase Interfaces	*	†
FE0005652	US Department of the Navy	Understanding of Solid Oxide Fuel Cell Stack in Pressurized Conditions	*	†
FG02-06ER46299	West Virginia University	Direct Utilization of Coal Syngas in High-Temperature Fuel Cells	3	Identify the fundamental mechanisms of carbon deposition and coal-contaminant poisoning to establish the tolerance limits for the impurities for SOFCs operating on coal syngas by using experimental, theoretical, and modeling techniques.
FE0009675	West Virginia University Research Corporation	Understanding of Oxygen Reduction and Reaction Behavior and Developing High-Performance and Stable Heterostructured Cathode with Heterostructured Surface	*	†
Key Technology—Atmospheric Pressure Systems				
FC26-04NT41837	FuelCell Energy, Inc.	SECA Coal-Based Systems	4	Develop cell and stack technology with emphasis on performance, reliability, and cost to show progress toward demonstrating a proof-of-concept module through design and materials development and fabrication, testing, and post-test analysis of cells and stacks.
NT-0003894	UTC Power Corporation	Coal-Based IGFC Project—Phase I	4	Integrate smaller stacks into larger systems focusing on durability, reliability, cost, and manufacturability to validate scaled up operability and system performance by (1) building and testing a thermally self-sustaining stack and (2) system modeling and analysis.
Key Technology—Pressurized Systems				
FE-0000303	LG Fuel Cell Systems, Inc.	SECA Coal-Based Systems	4	Develop cell and stack technology with a focus on performance enhancement to deliver a stack technically and economically suitable for aggregation into the proof-of-concept module by validating technology developments through system-level block testing.

Table B-1. **Solid Oxide Fuel Cells Projects**

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—Alternative AEC Development				
NT-0004109	General Electric Company	Performance Degradation of LSCF Cathodes	4	Develop mitigation strategies for degradation mechanisms and investigate alternate manufacturing techniques to improve cell performance and durability and reduce costs through electrochemical tests and micro-analytical techniques.
FE0000982	NuVant Systems, Inc.	Improved Flow Field Structures for Direct Methanol Fuel Cells	*	†
FE0000528	University of Akron	Techno-Economic Analysis of Scalable Coal-Based Fuel Cells	*	†

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

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ABBREVIATIONS

AC	alternating current
AEC	anode electrolyte cathode
AES	Advanced Energy Systems
ASR	area specific resistance
°C	degrees Celsius
CCRP	Clean Coal Research Program
CCS	carbon capture and storage
CO_2	carbon dioxide
COE	cost of electricity
DOE	Department of Energy
EOR	enhanced oil recovery
FE	Office of Fossil Energy
FY	fiscal year
H_2	hydrogen
H_2O	water
HHV	higher heating value
IGCC	integrated gasification combined cycle
IGFC	integrated gasification fuel cell
kWe	kilowatt electric
MW	megawatt
MWe	megawatt electric
NASA	National Aeronautics and Space Administration
NETL	National Energy Technology Laboratory
NGFC	natural gas fuel cell
NO_x	nitrogen oxides
O&M	operating and maintenance
O_2	oxygen
PC	pulverized coal
psia	pounds per square inch absolute
R&D	research and development
RD&D	research, development, and demonstration
SECA	Solid State Energy Conversion Alliance
SOFC	solid oxide fuel cell
syngas	synthesis gas
T&S	transport and storage
TRL	Technology Readiness Level
YSZ	yttria-stabilized zirconia

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 Solid Oxide Fuel Cells program, please contact the following persons:

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