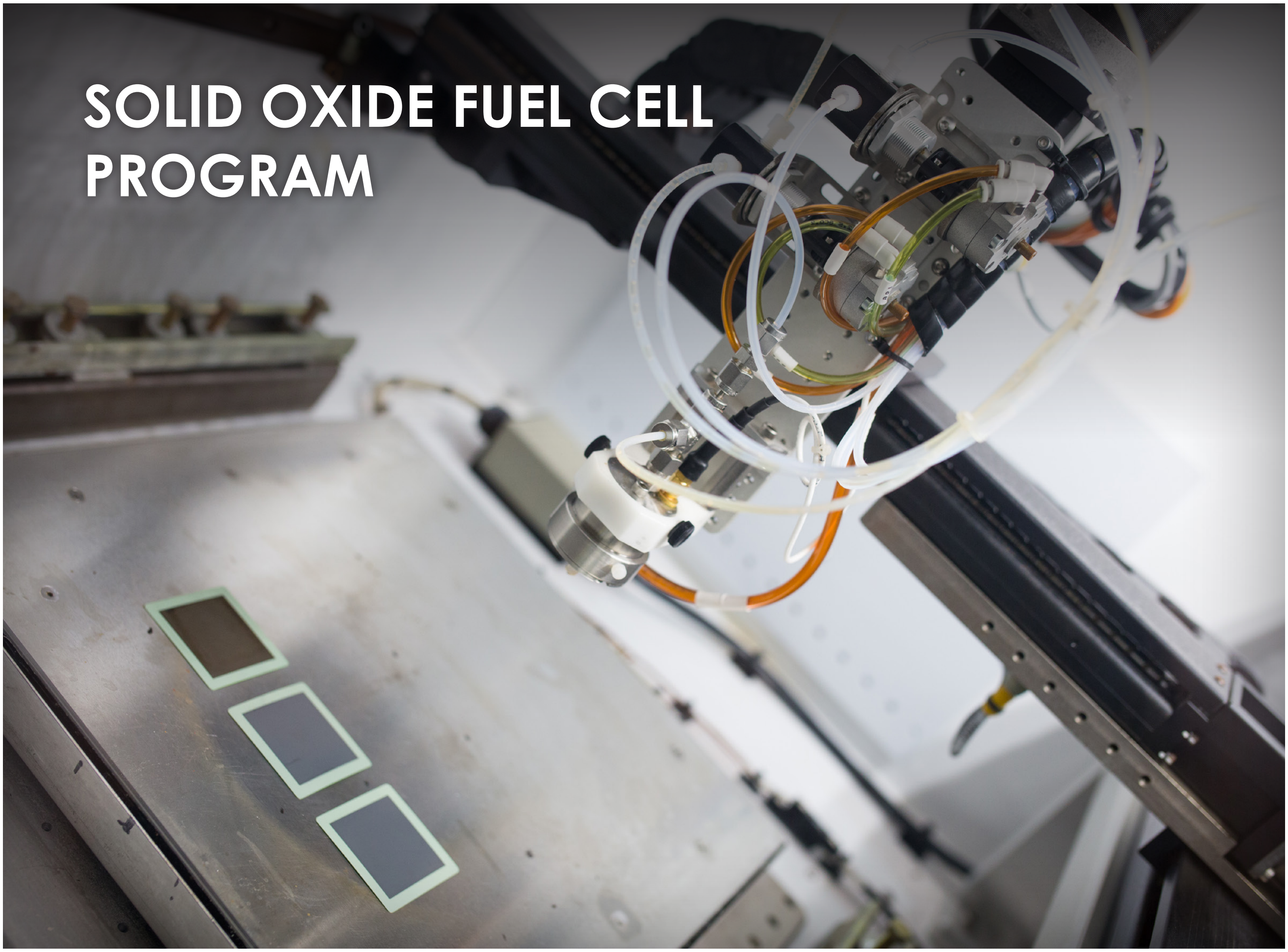
# SOLID OXIDE FUEL CELL PROGRAM



NETL

NATIONAL ENERGY TECHNOLOGY LABORATORY

## OVERVIEW

The primary mission of the U.S. Department of Energy's Office of Fossil Energy (FE) is to ensure the nation can continue to rely on its indigenous fossil fuel resources for clean, secure, and affordable energy. Contributing to that mission is the Solid Oxide Fuel Cell (SOFC) Program, administered by FE's National Energy Technology Laboratory (NETL). The SOFC Program focuses on the research, development, and demonstration (RD&D) to enable the generation of highly efficient, cost-effective electricity from coal and natural gas with near-zero atmospheric emissions of carbon dioxide ($CO_2$) and criteria pollutants and minimal water consumption.

# SOLID OXIDE FUEL CELL PROGRAM



## BACKGROUND

The Department of Energy's (DOE) SOFC program is conducted under the Clean Coal and Carbon Management Research Program (CCCMRP). Ensuring that the nation can continue to rely on clean, affordable energy from ample domestic fossil fuel resources is the principal mission of DOE FE's research programs. As a component of that effort, the CCCMRP - administered by FE and implemented by the National Energy Technology Laboratory (NETL) - is engaged in RD&D activities with a goal to develop and deploy innovative energy technologies and inform data driven policies that enhance U.S. economic growth, energy security, and environmental quality.

## SOFC PROGRAM

The SOFC program is developing low-cost SOFC power generation systems that produce electric power from coal or natural gas with intrinsic carbon capture capabilities. SOFC power systems have the potential to achieve greater than 60 percent efficiency and more than 97 percent carbon capture at a cost-of-electricity projected to be 40 percent below presently available integrated gasification combined cycle systems (IGCC) equipped with carbon capture (CCS). The SOFC's operating temperature is lower than combustion-based processes which precludes NOx formation, and there are near-zero emissions of $CO_2$, criteria pollutants, and particulates. Furthermore, SOFC power systems require approximately one-third the amount of water relative to conventional combustion-based power systems.

The SOFC Program is committed to: developing efficient, low-cost electricity from natural gas or coal with carbon capture capabilities for distributed generation (DG) and central power generation applications; maintaining cell development and core technology research to increase the reliability, robustness, and durability of cell, stack, and system technology; and providing the technology base to permit cost-competitive DG applications and utility-scale systems with carbon capture capabilities. Additionally, the SOFC Program is pursuing the synergistic solid oxide electrolysis cell (SOEC) technology. SOECs produce hydrogen from water splitting. Thermal energy can be used as a source of part of the energy required for hydrogen production by SOECs, thus increasing electrical efficiency due to more efficient thermodynamics. High temperature SOEC operation yields fast kinetics and avoids noble metal catalysts. SOECs can possess the same materials sets as the more widely researched SOFCs. SOFCs produce power and water from the oxidation of hydrogen, the reverse of SOECs.

SOFC technology is inherently modular and fuel flexible. Thus, cell and stack designs demonstrated at kW-MW scale can directly be scaled and aggregated into modules that serve as the building blocks for utility-scale SOFC power systems. The SOFC's ability to internally reform methane allows for a common module design for use with either natural gas or coal-derived synthesis gas (syngas). Capitalizing on these inherent capabilities, an attractive pathway to the deployment of central station SOFC systems (fueled by either natural gas or syngas) is through the development of natural-gas-fueled DG SOFC power systems.

A natural-gas-fueled DG SOFC system will employ essentially the same cell and module technology as that intended for use with syngas. Because the DG system will be smaller in size and have a simpler front-end fuel supply, it will most likely be first to the marketplace. Its development is synergistic with the development of syngas-fueled utility scale applications. Thus, the performance, reliability, and durability targets and cost reductions pursued by the SOFC program for utility-scale applications are closely aligned with the near-term DG goals of industry—without compromising the goals of the coal-based program.

## KEY TECHNOLOGIES

The SOFC Program consists of three key technologies (shown in Figure 1): (1) Cell Development, (2) Core Technology, and (3) Systems Development. Activities within these three key technologies include efforts to develop solid oxide fuel cells and solid oxide electrolysis cells.

**Cell Development –** The electrochemical performance, durability, and reliability of the solid oxide fuel cell are the key determinants in establishing the technical and economic viability of SOFC power systems. The components of the SOFC, the anode, electrolyte, and cathode are the primary research emphasis of Cell Development. Based on feedback from SOFC developers, who identified chromium contamination as a major contributor to cell degradation and reduced reliability, NETL launched an initiative to address and mitigate chromium poisoning. Additional research efforts include evaluation of anode contaminants, materials development, advanced manufacturing, materials characterization, and failure analysis.

**Core Technology –** This key technology conducts applied research and development on technologies – exclusive of the cell components - that are critical to the commercialization of SOFC technology. Efforts are focused on: developing and implementing advanced technologies to improve the reliability, durability, and robustness of the SOFC stack; identifying and mitigating stack-related degradation issues; cost reduction; and computational tools and modeling.

**Systems Development –** This key technology maintains a portfolio of projects that focus on the research, development, and demonstration (RD&D) of SOFC power systems. Project participants (systems developers) are independently developing unique and proprietary SOFC technology suitable for either syngas- or natural gas fueled applications. The systems developers are responsible for the design and manufacture of the fuel cells, integration of cells hardware development, manufacturing process development, commercialization of the technology, and market penetration. These developers also focus on the scale up of cells and stacks for aggregation into fuel cell modules and the validation of technology. This key technology also supports laboratory-scale stack tests, proof-of-concept systems, and pilot-scale tests. The multi-developer approach not only provides technology diversification but also offers insurance against business environment risk, reducing program dependency on a single developer. The systems developers 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.

Within the Systems Development key technology is an Innovative Concepts initiative that supports the research, development, and demonstration of SOFC technology that has the potential to surpass current anode-supported planar SOFC technology in terms of cost and reliability. Program participants are developing novel cell and stack architectures and/or material sets. This next generation SOFC technology in the near-term includes nominally 5-10 kWe-scale stack tests using cells envisioned in the developer's future commercial systems. These strategically oriented research projects may offer significant future cost reductions.

FIGURE 1. SOFC Program Key Technologies

| TECHNOLOGY AREA | KEY TECHNOLOGIES | |
|---|---|---|
| SOLID OXIDE FUEL CELLS | Cell Development | • Increased power density<br>• Reduced degradation<br>• Reduced costs |
| | Core Technology | • Improved reliability & robustness<br>• Reduced degradation<br>• Enhanced durability<br>• Reduced costs |
| | Systems Development | • Cell fabrication & testing<br>• Cell/stack integration & scale-up<br>• Stack/balance-of-plant integration & testing<br>• Innovative cell & stack technologies |

## PROGRAM DEVELOPMENT TIMELINE

In 2019, the Office of Fossil Energy prepared a report in response to a request from the United States Congress to provide a summary of the status of the Office of Fossil Energy's Solid Oxide Fuel Cell (SOFC) Program (Program). The Report on the Status of the Solid Oxide Fuel Cell Program included a new program timeline based on recommendations in the report. This timeline is shown below.

The state-of-the-art (SOA) anode-supported planar SOFC technology, under development for more than 15 years, has matured to the point that cell performance, degradation, and reliability are acceptable for entry-into-service. SOA developers have validated their respective technology through progressively larger stack tests and are acquiring system integration and operational experience via larger scale, fully integrated system tests. Two proof-of-concept (POC) SOFC power systems, fueled by pipeline natural gas, were successfully demonstrated by FuelCell Energy (FCE) and LG Fuel Cell Systems (LG), respectively. FCE built and tested a 50 kWe SOFC power system integrated into the electrical grid, producing ~50 kWe of AC power at 55% electrical efficiency (HHV) with a degradation rate of 0.9% per 1,000 hrs over 1,500 hours of operation. LG built and tested a pressurized SOFC power system integrated into the grid, delivering ~200 kWe of AC power at 57% efficiency (HHV).

A 200 kWe SOFC prototype system (FuelCell Energy, Figure 2) was designed, built and field-tested on pipeline natural gas. The system incorporated current technologies and operated for over 5,000 hours under a range of conditions, assessing system durability, performance, and operating costs toward commercial readiness. The satisfactory operation of these systems is necessary to validate the technology at large-scale prior to embarking on larger-scale demonstration. In a separate project, Cummins/Ceres Power are testing an integrated 10 kWe SOFC system with an innovative fuel cell concept to show long-term performance over 1,000 hours of operation.

In addition to a portfolio of cell, stack, and systems-level projects, the SOFC Program has recently awarded three projects to develop small-scale distributed power generation SOFC systems, eight projects to develop hybrid systems using solid oxide systems for hydrogen and electricity production, and one project to develop a cleaning process for coal-derived syngas to be used as SOFC fuel and testing of single and multiple cells on syngas.

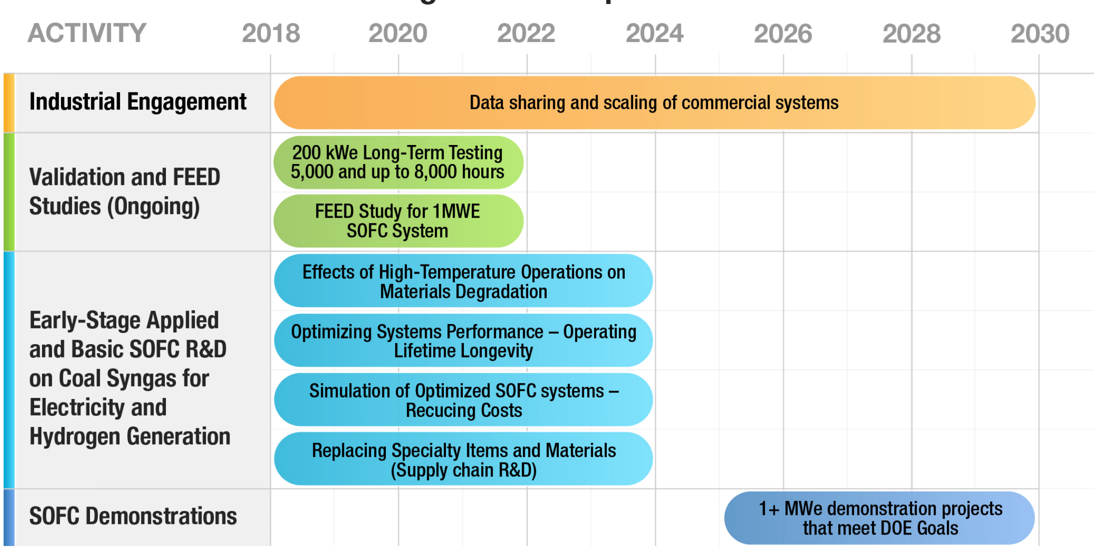
In parallel, the SOFC Program will continue RD&D, through the Innovative Concepts initiative, into the next generation of SOFC technology and conduct progressively larger stack tests.

Additional information may be found on NETL's Solid Oxide Fuel Cell web page.


FIGURE 2. FuelCell Energy 200 kWe Prototype System. Photo courtesy of FuelCell Energy

FIGURE 3. Cummins/Ceres Power 10 kWe SOFC System. Photo courtesy of Cummins/Ceres Power

## SOFC Program Development Timeline




Adapted from **"Report on the Status of the Solid Oxide Fuel Cell Program – Report to Congress (April 2019)."**
https://www.energy.gov/fe/report-congress-status-solid-oxide-fuel-cell-program

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