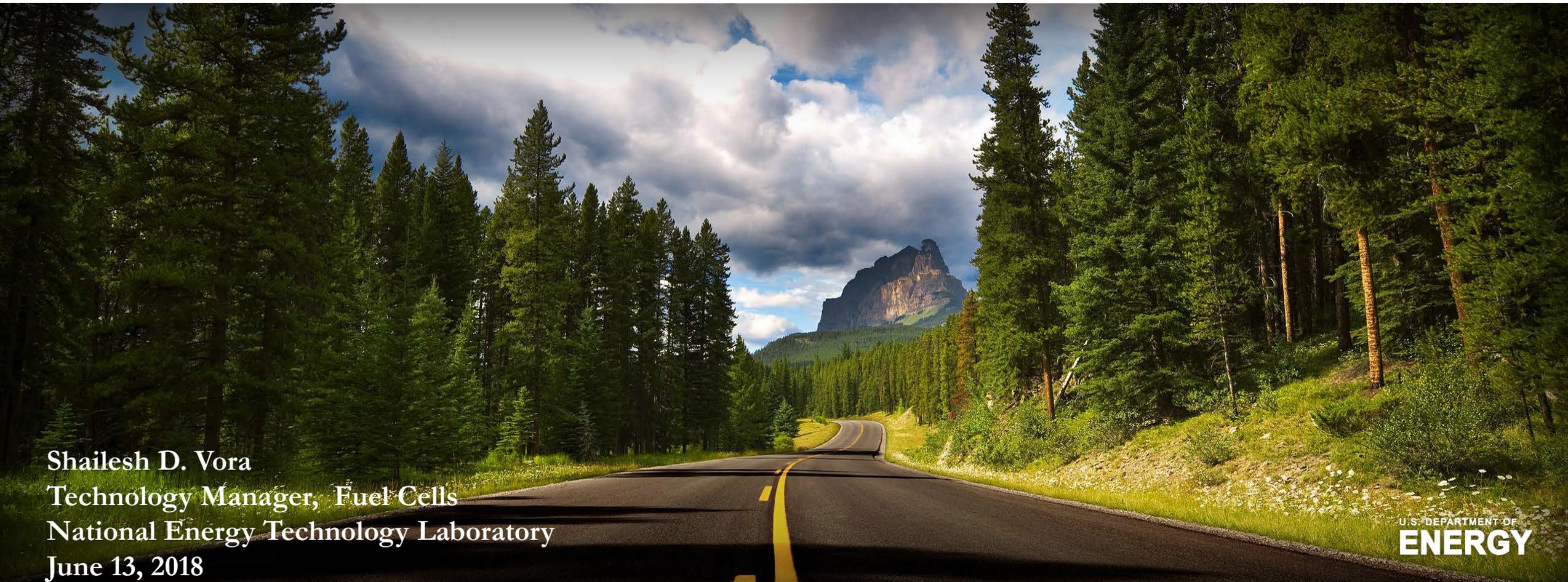


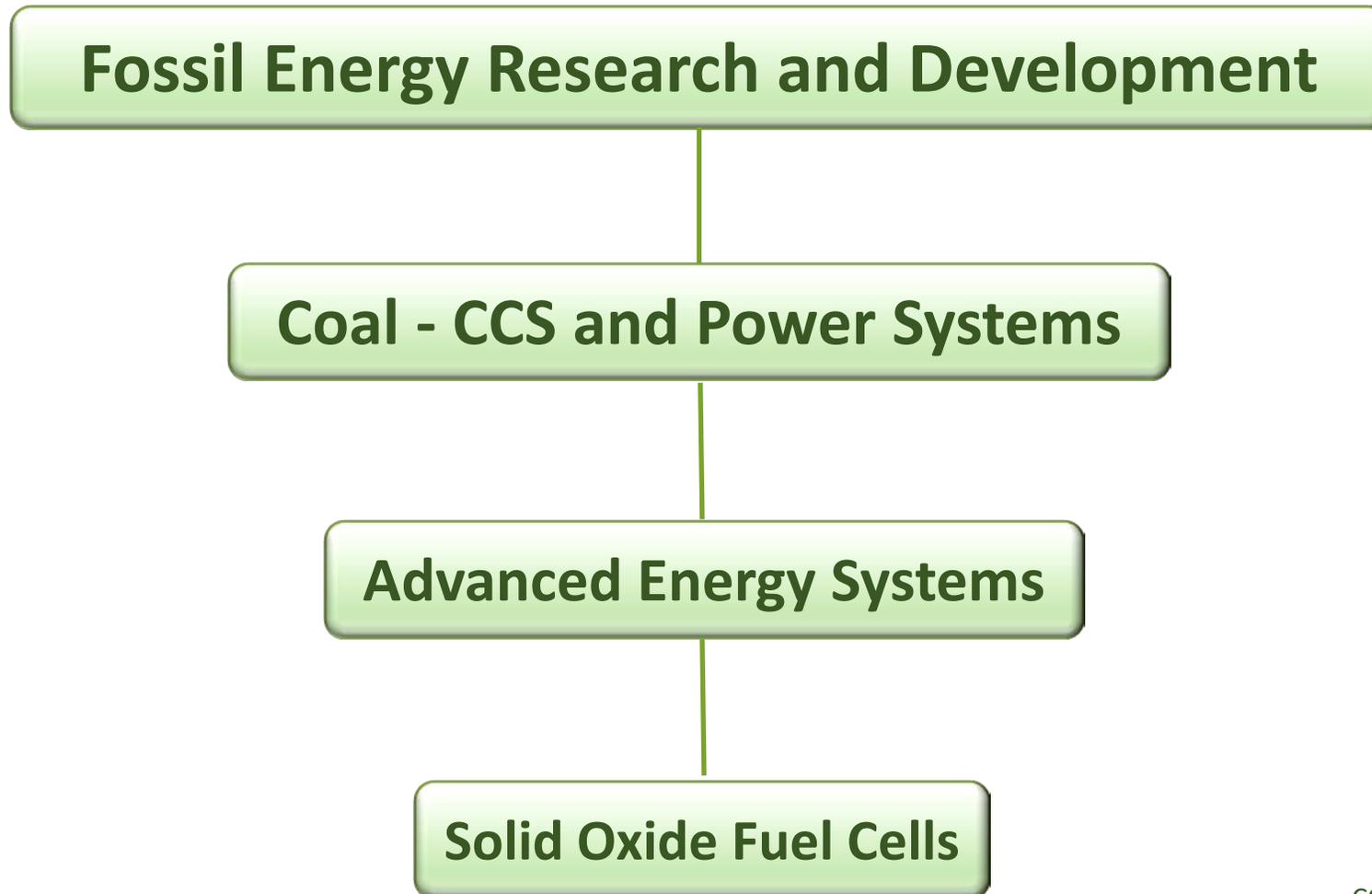
U.S. DOE Office of Fossil Energy Solid Oxide Fuel Cell Program



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DOE Office of Fossil Energy (FE)

Solid Oxide Fuel Cell (SOFC) Program



CCS: Carbon Capture and Storage

SOFC Program

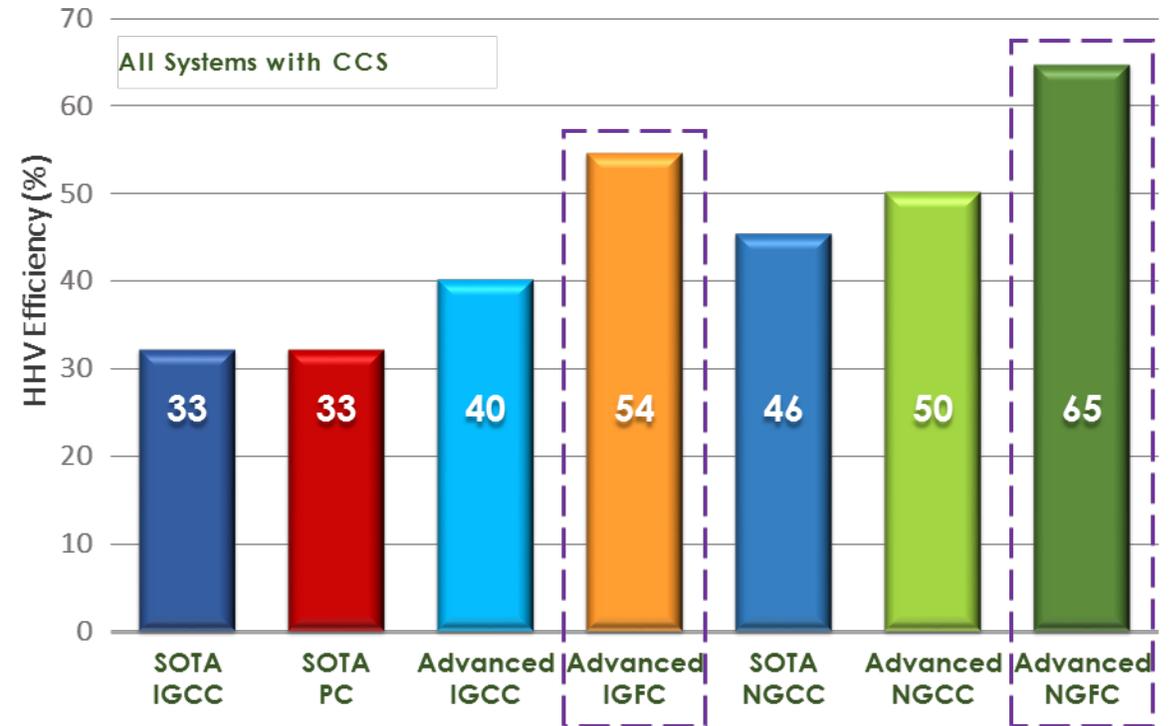
Mission and Drivers

➤ Program Mission

- To enable the generation of efficient, low-cost electricity with intrinsic carbon capture capabilities for:
 - Near-term natural gas-fueled distributed generation (DG) systems and modular coal-fueled systems
 - Long-term coal and/or natural gas-fueled central power systems with CCS

➤ Drivers

- Cost and efficiency benefits to coal and natural gas power systems
- Near-term natural gas DG applications



SOFC power systems offer a pathway to the lowest cost, highest efficiency electric power generation from fossil fuels with CCS

SOFC Program Structure

Key Technologies

TECHNOLOGY AREA	KEY TECHNOLOGIES	
SOLID OXIDE FUEL CELLS	Cell Development	<ul style="list-style-type: none">• R&D on individual cell components<ul style="list-style-type: none">– Anode, cathode, electrolyte– TRL 2-5
	Core Technology	<ul style="list-style-type: none">• R&D on cell & stack components• Purpose-specific BOP development<ul style="list-style-type: none">– TRL 2-5
	Systems Development	<ul style="list-style-type: none">• Systems Integration<ul style="list-style-type: none">– State-of-the-Art<ul style="list-style-type: none">• Anode-supported planar and integrated planar– TRL 5-6• Innovative Concepts<ul style="list-style-type: none">– R&D on advanced cells & stacks<ul style="list-style-type: none">• Lower cost and/or higher performance– TRL 4-6

SOFC Program

R&D Approach



➤ Applied Research

- Cell and Core Technologies
- TRL 2 – 5
- Technical priorities established with key stakeholders (NETL, National Labs, academia, industry)
- Collaboration with an SOFC Developer (industry) encouraged

➤ Development

- State-of-the-Art systems development
- Innovative Concepts
- TRL 5 – 6
- Multiple developers - with unique and proprietary technology - provide technology diversification and reduces program dependency on a single developer
- Stacks through fully-integrated power systems

The SOFC Program is focused on the design, scale-up, and integration of the SOFC technology into modules and systems, and the development and testing of progressively larger stacks/systems

SOFC Program

Partners and their roles



➤ **Cell Technology**

- National Labs, academia, small businesses, research institutions
- Applied research on individual cell components

➤ **Core Technology**

- National Labs, government agencies, academia, small businesses, research institutions, industry
- Applied research on stack technology issues

➤ **Systems Development**

- Industry
- Develop unique and proprietary technology
- Identify Cell and Core Technology R&D focus
- Bring the technology to market

SOFC Program

Outreach Activities



➤ **NETL “Roadshow”**

- NETL facilitated one-on-one interaction between National Labs and Industry
- Twice per year

➤ **SOFC Program Workshop**

- Annual meeting for SOFC Program participants and the fuel cell community
- Active participation by ARPA-E

➤ **SOFC Program Roundtable**

- NETL facilitated meeting with select program participants (10-15 on rotating basis) to identify crosscutting issues (e.g. cathode, chromium poisoning, reliability)

➤ **Participation in the EERE Annual Merit Review**

➤ **Monthly teleconferences with all DOE offices working on fuel cells**

SOFC Program Project Portfolio

FY18 Participants



➤ Cell Development

- Argonne National Lab
- Boston University*
- Case Western Reserve*
- Glacigen
- Georgia Tech*
- HAMR
- Kettering University
- Massachusetts Institute of Tech.
- Michigan State Univ
- Montana St. University*
- NETL – RIC
- Oak Ridge National Lab
- Pacific Northwest Natl Lab
- Pneumaticcoat
- PolarOnyx
- Saint-Gobian
- Sonata
- SMI
- Stanford
- Tennessee Tech. Univ.*
- University of Connecticut*
- University of Maryland
- University of Pennsylvania*
- University of South Carolina*
- West Virginia University*

➤ Core Technology

- Atrex*
- Auburn University
- General Electric
- HifFunda
- Michigan State Univ.
- Mohawk*
- National Renewable Energy Lab
- NexTech
- Oak Ridge National Lab
- Pacific Northwest National Lab
- Redox Power
- Sonata
- University of Pittsburgh
- U.S. Department of the Navy
- West Virginia University

➤ Systems Development

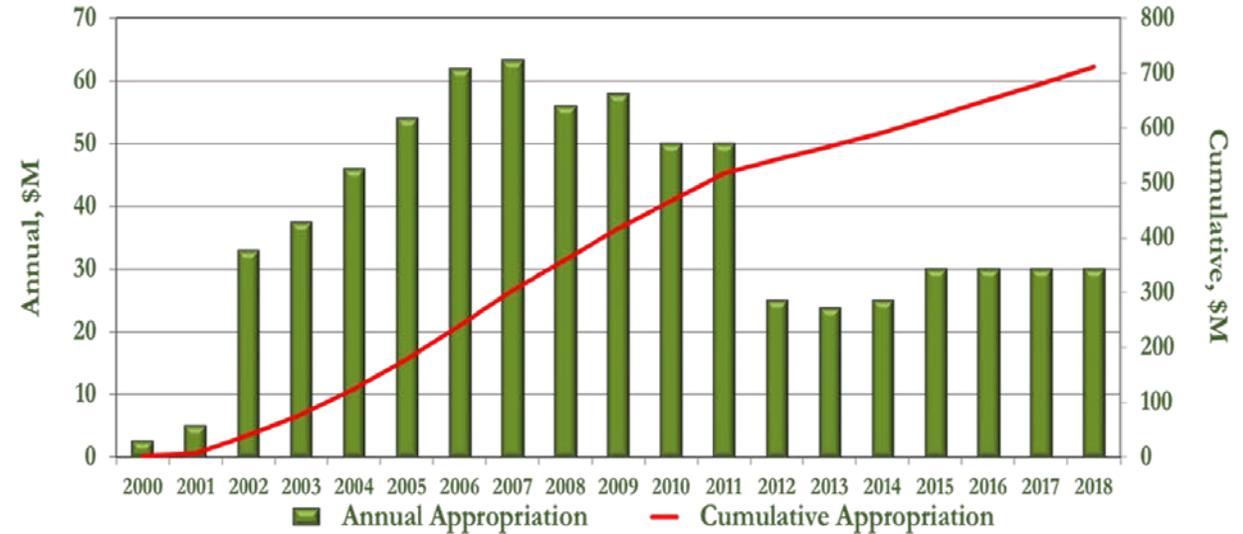
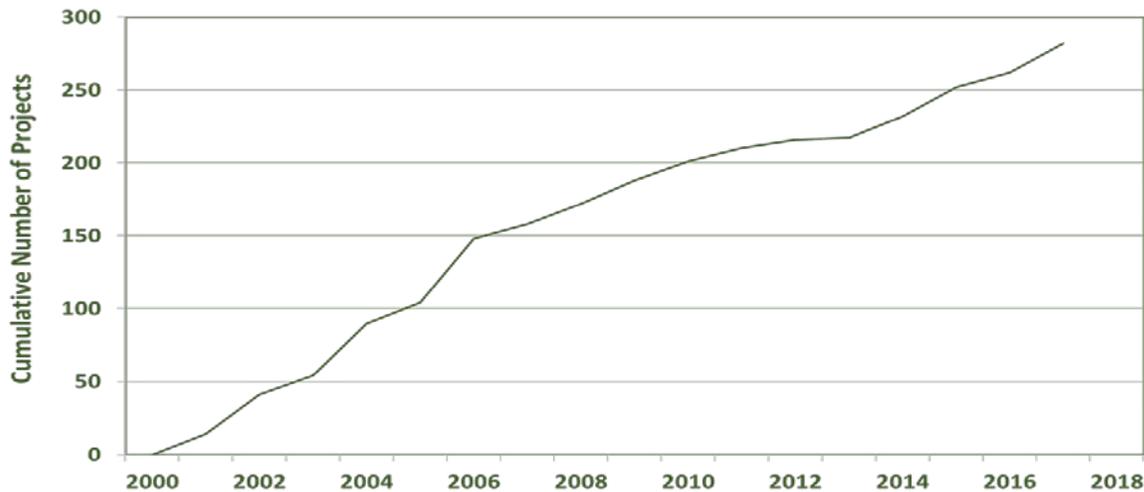
- Atrex
- Cummins
- FuelCell Energy*
- General Electric
- LG Fuel Cell Systems*
- Redox Power*
- University of California San Diego



SOFC Program

Funding History

- FY18 DOE Appropriation: **\$30M**
- Cumulative Funding (FY00 – FY18)
 - DOE ~\$712M
 - Participant Cost Share ~\$265M



- Total Number of Awards **>290**
- Total Number of Participants **116**
 - Industry **66**
 - Academia **40**
 - National Labs/Agencies **10**

SOFC Program

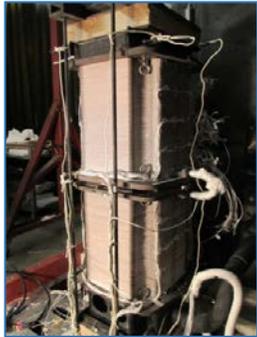
How the technology has evolved

SYSTEMS

MODULES

STACKS

CELLS



10 kWe-Class Stack Tests

- Improved efficiency, 35 – 41%
- Reduced degradation, <2%/1000 hr
- Cost target at high volume achieved (extrapolated)



200 kWe Prototype Field Test
(two in-progress)

10 MWe Pilot
(planned)

50 MWe Utility-Scale Demo
(planned)

Cell and Stack Performance Improvements

- Increased cell area by 5x
- Increased cell power by 10x
- Degradation reduced to 0.2 - 0.5%/1,000 hrs



Cell Development

- increased power
- Established material set
- Improved reliability
- Reduced cost

MWe-Class Pilot

Proof-of-Concept Systems

- Two POC systems, 50kW & 200 kW
- Efficiency improvements to >55%



50 kWe POC
(courtesy FuelCell Energy)



200 kWe POC
(courtesy LG Fuel Cell Systems)

Technology Validation

2000

2010

2020

2030

From Concept to Market Readiness

A Recent Example

COMMERCIALIZATION

Technology available for implementation in SOFC production line

DEMONSTRATION

Technology implemented and tested at SOFC stack (kW) scale

SYSTEM TESTING

Evaluate technology on several commercial developer cells

DEVELOPMENT

Patents obtained

DISCOVERY

Proof of Concept

2019

Licensing to SOFC commercial developer

TRL 7-8

Atrex Cells

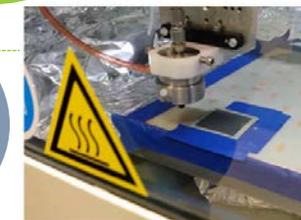


2017-18

Direct collaboration with Atrex Energy to scale up technology

TRL 6

Demonstration at Lab Scale



2012-16

Demonstration on commercially relevant scale

TRL 4-5

Sonotek Sonic Spray Coater used for technology scale-up

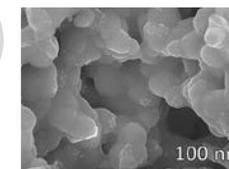


2009-12

Technology validated on SOFC button cells (several W) scale

TRL 2-3

Electrode infiltration technique evaluated



Infiltrated Cathode

2009

SOFC Power System

FCE 50 kW Proof-of-Concept System

- Fully integrated SOFC Power System
- Testing completed FY2016
- ~50 kWe AC to grid
- Efficiency: 55% (HHV)
- Degradation rate: 0.9%/1,000 hrs
- 1,500 hrs of operation
- TRL 6



SOFC Power System

FCE 200 kW Prototype Field-Test

- Fully integrated SOFC Power System
- Test site: NRG Energy Center, Pittsburgh, PA
- Rating: ~200 kW_e
- Natural gas fueled
- Grid connected
- Factory Test underway
- Target operating time: 5,000 hrs
- TRL 6



Figure courtesy FuelCell Energy

SOFC Program Metrics

Metric	Current	2020 Target	2025/2030 Target
System Cost (100 kW- 1MW)	>\$12,000/kWe	\$6,000/kWe	\$900/kWe
Single Cell Degradation	0.2 - 0.5% per 1,000 hrs		
Cell Manufacturing Approach	Batch	Semi- Continuous	Continuous
System Degradation	1 – 1.5% per 1,000 hrs	0.5 - 1.0% per 1,000 hrs	<0.2% per 1,000 hrs
Fuel Reformation	Primarily external natural gas conditioning/reforming	100% integrated natural gas reformation inside cell stack	
Durability	<2,000 hrs	5,000 hrs	5 years
Platform	Proof-of-Concept	Prototype/Pilot	DG: Commercial Utility-scale: Pilot
Configuration	Breadboard/Integrated systems	Fully packaged	Fully packaged
Fuel	Natural gas	Natural gas Simulated syngas	Natural gas Coal-derived syngas
Demonstration Scale	50 kWe – 200 kWe	200 kWe – 1 MWe	DG: MWe-class Utility-scale: 10 – 50 MWe

Single-cell performance and degradation are acceptable; stack and system performance, reliability and endurance need to be demonstrated

SOFC Program

Technology Development Status



➤ Progress:

- Significant progress in increasing cell active area and power density, leading to lower cost
- Well-established first generation cell and interconnect materials
- Advanced cell manufacturing facilities with well established processes.
- Adequate testing experience at single cell and small stack (≤ 5 kWe) levels.
- Single cell degradation rates $<0.5\%/1,000$ hrs
- Cell Development and Core Technology research are well aligned with industry need

➤ Stack and System Challenges:

- Stack/system degradation rates are 2-4X higher than cell degradation rates
- Initiated fabrication and testing of integrated SOFC prototype field tests

Based on progressively larger natural gas-fueled validation tests, MWe-class DG SOFC Power Systems that are cost-competitive with existing DG technologies are envisioned circa 2020

SOFC Program

FY18 Funding Opportunity Announcements



➤ **DE-FOA-0001850 – Preliminary Design and Techno-Economic Evaluation of MWe-Class Solid Oxide Fuel Cell Systems**

- Two-phased program
 - Phase I: Preliminary Design and TEA - \$4.5M, 18 months
 - Phase II: Build and Test - \$TBD, 24 months
- Moves the technology from proof-of-concept and prototype test to pilot-scale

➤ **DE-FOA-0001853 –Solid Oxide Fuel Cell Core Technology Research**

- Area Of Interest 1: Core Technology R&D to support manufacturers in addressing issues related to cost reduction and reliability of systems - \$3.5M, 24 months
- Area Of Interest 2: Core Technology R&D in support of Near-Term SOFC Power System Prototype Tests - \$6M, 24 months

➤ **Both FOAs are closed, proposals under review**

FY18 SOFC Program Peer Review

- Convened an independent panel of four leading academic and industry subject matter experts
- Panel was chartered to assess the Program's relevance, mission, goals and objectives, technology development timeline, project portfolio, program management, resources, and strategic plans
- Panel's findings were documented in the "FY18 Solid Oxide Fuel Cells Program Peer Review Report"

FY18 SOFC Program Peer Review

Meeting Summary



” ... The panel concluded the program is well aligned with relevant Congressional appropriations language and its goals and objectives are well-defined. The panelists discussed at length the program’s strategy to test progressively larger stack and systems and unanimously endorsed the approach to achieve its mission, goals, and objectives. ... ”

FY18 Solid Oxide Fuel Cells Program Peer Review Report

SOFC Program

Key Takeaways



- Program now emphasizing the resolution of design, operation, and performance considerations at the system level
- Acquiring fabricating and operational experience on integrated, prototype field tests based on state-of-the-art cell and stack technology
- Cell Development and Core Technology research continues and is well aligned with industry need
- FY18 awards planned for the preliminary design and techno-economic analysis of a natural gas-fueled, MWe-class pilot-scale system for DG application

For Additional Information

Office of Fossil Energy: www.energy.gov/fe/office-fossil-energy

NETL Website: www.netl.doe.gov/

SOFC Program website: www.netl.doe.gov/coal/research/energy-systems/fuel-cells

Reference Shelf:

- SOFC Program Project Portfolio
- SOFC Technology Program Plan
- Technology Readiness Assessment
- Past Workshop Proceedings
- Systems Analysis
- Fuel Cell Handbook

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