This presentation provides an overview of a Fossil Energy and Carbon Management (FECM) R&D Program that is implemented based on both Administration priorities and Congressional direction. Plans for future technology development reflect expected trajectories of current R&D, but these plans are subject to change. Furthermore, some stages of future technology development, although necessary for commercialization, may not be financially supported by the government.
Conduct R&D to mature SOFC and SOEC technologies and make progress towards low cost, high efficiency hydrogen production and power generation

SOFC Program: Near-Term Objectives

Validate small-scale SOFC systems for distributed generation applications

Develop efficient and cost-effective electrolyzers (SOEC) for hydrogen production
SOFC Program Structure

TECHNOLOGY AREA

SOLID OXIDE FUEL CELLS

KEY TECHNOLOGIES

Cell Development

Core Technology

Systems Development

Figure courtesy NETL

Figure courtesy LG Fuel Cell Systems

Figure courtesy FuelCell Energy
## SOFC Program Metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Current</th>
<th>2025/2030 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Cost (100 kW-1 MW)</td>
<td>&gt;$12,000/kWe</td>
<td>$900/kWe</td>
</tr>
<tr>
<td>System Degradation</td>
<td>1 – 1.5% per 1,000 hrs</td>
<td>&lt;0.2% per 1,000 hrs</td>
</tr>
<tr>
<td>Demonstration Scale</td>
<td>5 kWe – 200 kWe</td>
<td>DG: MWe-class</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Utility-scale: 10 – 50 MWe</td>
</tr>
</tbody>
</table>

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

Funding History

Annual, $M

Fiscal Year

SOFC Program Project Portfolio
FY21 Participants

[Map showing project portfolio and participants across the United States]
SOFC R&D at NETL Research and Inovation Center (RIC)

**Cell and Stack Degradation Modeling**
- Development of comprehensive predictive modeling tool
- Atoms to system scale bridging
- Validated through experiment

**Electrode Engineering**
- Mitigation of prominent degradation modes
- Successful transfer of technology to industry

**Systems Engineering and Analysis**
- Public dissemination of SOFC market potential, performance, and cost advantages
- Hybrid configuration assessment
- Tie to R&D goals and objectives

**High Temp Optical Sensors**
- Multi-application technology under development for high temperature sensing
- Demonstrated in SOFC
- In-situ sensing of temperature distribution and gas composition
<table>
<thead>
<tr>
<th>NETL RIC - Accomplishments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cell and Stack Degradation Modeling</strong></td>
</tr>
<tr>
<td>• Formalized partnership with developer to integrate high temperature fiber optic sensors into SOFC stack</td>
</tr>
<tr>
<td>• Demonstrated ability to predict SOFC performance degradation from multiple modes</td>
</tr>
</tbody>
</table>
  • Progress toward public release of predictive toolsets in 2021 |
| • Added to simulations:  |
  • Infiltrated materials  |
  • Reversible SOFC operation  |
  • Delamination |
| **Electrode Engineering** |
| • Tested commercial SOFC in reversible mode for 2400 h, cycling between fuel cell and electrolysis mode every 100 h  |
  • Infiltrated commercial SOFC showed significant reduction in degradation when operating under electrolysis mode |
| • Novel materials discovery and fabrication |
| **Systems Engineering and Analysis** |
| • Robust cell and stack production cost model completed  |
  • Intended for public release March 2021 |
| • IGFC and NGFC techno-economic analyses under final NETL review  |
  • Intended for public release March 2021 |
| • Scoping study completed on hybrid carbon conversion technologies with SOFC component  |
  • Collaboration with INL |
SOFC Program
The Role of other National Laboratories

- **Pacific Northwest National Laboratory**
  - Modeling & Simulation
  - Materials Development
  - SOFC Component Development

- **Argonne National Laboratory**
  - Cell Materials characterization and statistical analysis to improve batch-to-batch variability
  - Develop low-cost high-throughput diagnostic techniques

- **Oak Ridge National Laboratory**
  - Materials characterization
  - Mechanical testing of cell and stack materials

- **Idaho National Laboratory**
  - Partnership on hybrid fuel cell systems.
SOFC Prototype System Field Tests

FuelCell Energy
- 200 kWe integrated SOFC Power System
- Fabrication of ~2,000 full-scale cells
- ~5,800 hours operation - Full power for one of the two modules
- System power degradation < 1.5% per 1,000 hrs

Cummins-Ceres Power
- 10 kWe integrated SOFC Power System
- ~1,000 hours operation
- System power degradation < 0.5% per 1,000 hrs

Photo courtesy Ceres Power
Small-Scale Solid Oxide Fuel Cell Systems and Hybrid Electrolyzer Technology Development

- **Issue date:** 5/28/2020
- **$34M DOE, 20% cost share**
- **AOI 1** – Small-scale distributed power generation SOFC systems.
- **AOI 2** – Hybrid systems using solid oxide systems for hydrogen and electricity production including the validation and development of materials and systems required for improving the cost, performance and reliability.
- **AOI 3** – Cleaning of coal-derived syngas for use as SOFC fuel and testing of single and multiple cells on syngas.

“Per the FY 2020 Energy and Water Appropriations Act Report (H.R. 1865 / Public Law 116–94) , “The Department is directed to issue a funding opportunity announcement for $30,000,000 for Solid Oxide Fuel Cells that includes all topic areas as outlined in the recommendations of the Department's August 2019 Report on the Status of the Solid Oxide Fuel Cell Program”
<table>
<thead>
<tr>
<th>AOI</th>
<th>Awardee (Prime)</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cummins Inc.</td>
<td>Improving Cost and Efficiency of the Scalable SOFC Power System</td>
</tr>
<tr>
<td>1</td>
<td>Redox Power Systems, LLC</td>
<td>Small-Scale Solid Oxide Fuel Cell Systems and Hybrid Electrolyzer Technology Development</td>
</tr>
<tr>
<td>1</td>
<td>Aris Energy Solutions LLC</td>
<td>Modular Fuel Cells Providing Resiliency to Data Centers and Other Critical Power Users</td>
</tr>
<tr>
<td>2</td>
<td>The Regents of the Univ. of Calif., U.C. San Diego.</td>
<td>Efficient, Reliable and Cost-Effective Reversible Solid Oxide Cell Technology for Hydrogen and Electricity Production</td>
</tr>
<tr>
<td>2</td>
<td>Cummins Inc.</td>
<td>Cummins R-SOFC System Development</td>
</tr>
<tr>
<td>2</td>
<td>Phillips 66</td>
<td>A Highly Efficient and Affordable Hybrid System for Hydrogen and Electricity Production</td>
</tr>
<tr>
<td>2</td>
<td>Pacific Northwest National Laboratory</td>
<td>Low Cost, Large Area SOEC Stack for H2 &amp; Chemicals</td>
</tr>
<tr>
<td>2</td>
<td>NexTech Materials, Ltd. dba Nexceris, LLC</td>
<td>Reversible Solid Oxide Fuel Cell System</td>
</tr>
<tr>
<td>2</td>
<td>Saint-Gobain Ceramics and Plastics</td>
<td>Reversible SOFC-SOEC Stacks Based on Stable Rare-Earth Nickelate Oxygen Electrodes</td>
</tr>
<tr>
<td>2</td>
<td>Battelle Energy Alliance, LLC (Idaho National Laboratory)</td>
<td>Performance Validation of a Thermally Integrated 50 kW High Temperature Electrolyzer System</td>
</tr>
<tr>
<td>3</td>
<td>University of North Dakota</td>
<td>Solid Oxide Fuel Cell Technology Development</td>
</tr>
</tbody>
</table>
FOSSIL ENERGY BASED PRODUCTION, STORAGE, TRANSPORT AND UTILIZATION OF HYDROGEN APPROACHING NET-ZERO OR NET-NEGATIVE CARBON EMISSIONS

Develop technologies to reinvigorate the use of the United States' vast fossil-fuel resources and power infrastructure for net-zero carbon energy and commodity production through the production, transport, storage, and utilization of fossil-based hydrogen with zero or negative carbon emissions.

• Issue date: 1/15/2021
• Close date: 3/8/2021
• AOI 5: Solid Oxide Electrolysis Cell (SOEC) Technology Development for Hydrogen Production
• Total DOE Funds: $8M
• Number of awards: 8
<table>
<thead>
<tr>
<th>Awardee</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Georgia Institute of Technology</td>
<td>Durable and High-Performance SOECs Based on Proton Conductors for Hydrogen Production</td>
</tr>
<tr>
<td>Massachusetts Institute of Technology</td>
<td>Improving Durability and Performance of Solid Oxide Electrolyzers by Controlling Surface Composition on Oxygen Electrodes</td>
</tr>
<tr>
<td>OxEon Energy LLC</td>
<td>Development of Stable Solid Oxide Electrolysis Cell for Low-Cost Hydrogen Production</td>
</tr>
<tr>
<td>The Regents of the Univ. of Calif., U.C. San Diego.</td>
<td>Development of Novel 3D Cell Structure and Manufacturing Processes for Highly Efficient, Durable and Redox Resistant Solid Oxide Electrolysis Cells</td>
</tr>
<tr>
<td>University of Louisiana at Lafayette</td>
<td>Development of High-Performance Metal-Supported SOECs and Innovative Diagnostic Methodologies</td>
</tr>
<tr>
<td>University of South Carolina</td>
<td>Developing Stable Critical Materials and Microstructure for High-Flux and Efficient H₂ production through Reversible Solid Oxide Cells</td>
</tr>
<tr>
<td>West Virginia University Research Corporation</td>
<td>Designing Internal Surfaces of Porous Electrodes in Solid Oxide Electrolysis Cells for Highly Efficient and Durable Hydrogen Production</td>
</tr>
<tr>
<td>Worcester Polytechnic Institute</td>
<td>Heterostructured Cr Resistant Oxygen Electrode for SOECs</td>
</tr>
</tbody>
</table>
Conducting additional basic R&D to address critical needs and mature technology – SOFC and SOEC

Acquiring fabricating and operational experience on integrated, prototype field tests

Potential for hybrid systems to produce hydrogen in SOEC mode and electricity in SOFC mode

Prior and on-going SOFC R&D supported by FE will provide the technology basis for SOEC development going forward

SOFC power systems offer a pathway to the highest efficiency and lowest cost electric power generation with CCS
Questions?

VISIT US AT:  www.NETL.DOE.gov

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@NationalEnergyTechnologyLaboratory

https://netl.doe.gov/coal/research/energy-systems/fuel-cells

CONTACT:
Shailesh D. Vora, Technology Manger, Fuel Cells
Shailesh.Vora@netl.doe.gov
412-386-7515

REFERENCE SHELF:
- SOFC Program Project Portfolio
- Workshop Proceedings
- Systems Analysis