Progress in SOFC Technology Development at FuelCell Energy

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2022 SOFC Project Review Meeting
Pittsburgh, PA
Our Technologies Will Provide Optionality as Energy Transition Evolves

**Large Scale Grid Support**
- Bridgeport Fuel Cell Park, a 14.9 MW project located in Bridgeport, CT, is a utility-scale distributed power solution that revitalized a 1½ acre brownfield site and contributes to the economic redevelopment in the area.

**Micro-Grid**
- FuelCell Energy has built several utility microgrid applications, including a microgrid fuel cell at the University of California – San Diego, that supports critical building loads with independent capabilities.

**Distributed Hydrogen**
- Building hydrogen distribution platform in Long Beach to support Toyota’s operations to fuel zero emission FCEVs and provide clean water.
- Will enable hydrogen transportation
- No pipeline infrastructure needed

**Carbon Capture / Carbon Separation**
- Fuel cells can separate carbon dioxide from an external exhaust stream, making the carbon dioxide easier to capture and sequester (approximately 90% CO₂ capture, 70% NOx elimination).
- CO₂ can be either sequestered or used in applications such as food and beverage and agriculture.

Image: Bridgeport Fuel Cell Park
Image: UC San Diego microgrid enabled fuel cell platform
Image: Rendering of Tri-Generation Fuel Cell Project at the Toyota Facility at the Port of Long Beach, California
Image: The Scotford Upgrader, a Canadian oil sands bitumen processor, is the site of a recently announced carbon capture project with FuelCell Energy
Pathways to development of a low-cost, efficient, and reliable MWe-class SOFC power system towards commercial deployment in distributed generation applications:

- Complete manufacturing analysis and planning to support efficient capacity expansion of 2nd generation cell and stack production processes to enable MW-class production rates at competitive cost
- Design a multi-stack module to house low-cost Compact SOFC Architecture (CSA) stacks and serving as a building block for integration into MWe-class systems
- Develop the conceptual process, electrical, and mechanical designs for a low-cost, high-efficiency, and reliable MWe-class SOFC pilot system
- Complete a Techno-Economic Analysis to forecast the system cost
SOFC Technology
Solid Oxide Fuel Cell Technology Overview

Anode-Supported Solid Oxide Fuel Cell

Scale up of cells up to 1000 cm² active area

<table>
<thead>
<tr>
<th>Component</th>
<th>Materials</th>
<th>Thickness</th>
<th>Porosity</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode</td>
<td>Conducting ceramic</td>
<td>~50 µm</td>
<td>~30%</td>
<td>Screen printing</td>
</tr>
<tr>
<td>Barrier</td>
<td>CGO</td>
<td>~4 µm</td>
<td>&lt;10%</td>
<td>Screen printing</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>YSZ</td>
<td>5 µm</td>
<td>&lt;5%</td>
<td>Screen printing</td>
</tr>
<tr>
<td>AFL</td>
<td>Ni/YSZ</td>
<td>~8 µm</td>
<td>~40%</td>
<td>Screen printing</td>
</tr>
<tr>
<td>Anode</td>
<td>Ni/YSZ</td>
<td>~0.3 mm</td>
<td>~40%</td>
<td>Tape casting</td>
</tr>
</tbody>
</table>
SOFC Cell fabrication process has evolved from laboratory to pilot-production in 2001. "TSC" SOFC fabrication process is flexible & scalable to high volume and low-cost production.
Typical 0.3 mm Thin Cell Performance

- Performance of cell at high fuel utilization is strongly dependent on anode thickness

Reduction of anode thickness has further improved cell performance (2.34 W/cm² at 4.7 A/cm²)
**1 Cell Stack - 81 cm² Active Area**

- Furnace Temperature: 750°C
- Fuel: 55 H₂:45 N₂, uf = 50%
- Oxidant: Air + 3% H₂O, Ua = 25%
- Current: 40.1 A (0.5 A/cm²)

**Overall Degradation:**
- 31 mV over last 13,704 h
- 2.25 mV or 0.26% / 1000 h

**3% water concentration in cathode throughout testing period**

**Verified long-term cell endurance test >1.5 years of operation with a 0.26%/1000h performance degradation with 3% cathode humidity throughout**
SOFC Stack Development
Compact Solid Oxide Architecture (CSA) Stack

Solid Oxide Stack Design Progression

- Thinned components (cell + interconnect) to minimize stack material content (~0.5 kW/kg)
- Simplified unit cells with fewer components
- Designed for automated assembly

Comparison of Large Area Stack (LAS) stacks tower versus CSA stacks assembly

**Solid Oxide Stack Design Progression**

<table>
<thead>
<tr>
<th></th>
<th>Baseline PCI 390 mA/cm²</th>
<th>96 cell Wartsila 300 mA/cm²</th>
<th>120 cell coal based 200 mA/cm²</th>
<th>350 cell CSA Stack At 290 mA/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross Power (W)</td>
<td>1100</td>
<td>14900</td>
<td>16200</td>
<td>7000</td>
</tr>
<tr>
<td>Stack Voltage (Vdc)</td>
<td>24</td>
<td>75</td>
<td>101</td>
<td>295</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>17.3</td>
<td>185</td>
<td>213</td>
<td>15</td>
</tr>
<tr>
<td>Power to Weight Ratio (W/kg)</td>
<td>64</td>
<td>80</td>
<td>76</td>
<td>467</td>
</tr>
<tr>
<td>Approx. Envelope (L)</td>
<td>5.3</td>
<td>69</td>
<td>88</td>
<td>9</td>
</tr>
<tr>
<td>Power to Volume Ratio (W/L)</td>
<td>207</td>
<td>215</td>
<td>185</td>
<td>778</td>
</tr>
</tbody>
</table>

 CSA stack design offers low material content for reduction in cost and superior thermal characteristics
Integrated compression

Oxidant outlet manifold

350 cells - 17” tall

Flexible structure offers compliance and robustness

Flow Geometry

Modeling and tests indicate that CSA stacks allow for flexible operation regarding fuels including Natural Gas with in-stack reforming as well as hydrogen
## Compact SOFC Architecture (CSA) Stack Platform

### Property

<table>
<thead>
<tr>
<th>Property</th>
<th>CSA Stack Scale</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Short</td>
<td>Mid</td>
</tr>
<tr>
<td>Cell count</td>
<td>50</td>
<td>150</td>
</tr>
<tr>
<td>Fuel cell voltage, V</td>
<td>42</td>
<td>128</td>
</tr>
<tr>
<td>Stack power, kW</td>
<td>1.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Height, cm</td>
<td>9.1</td>
<td>21.1</td>
</tr>
</tbody>
</table>

New generation stack utilizes advanced thin and lightweight cell structure.
Completed over 1800 hours of fuel cell operation on system gas compositions with good voltage stability and tight voltage spread (35 mV)
Solid Oxide Applications

- **Power Generation Stack Module** – Runs in power generation mode on a wide range of fuels, including natural gas, biofuels and hydrogen.
- **Electrolysis Stack Module** – Produces hydrogen from steam with power input.
- **Energy Storage Stack Module** – Alternates between power generation and electrolysis producing hydrogen from water.

**Versatile platform with multiple commercialization pathways**

- **200 kW Power Generation System**
- **Electrolysis**
  - 600 kg/day H2 from 1.1MW
- **Energy Storage System**
  - 1MW, 8MWh
Cell And Stack Manufacturing
• Utilize established baseline TSC3 cell design and manufacturing, (120 mm Ø) and anode-supported cell (0.3 mm thick)
  – Design for high-throughput manufacturing technologies for thin components taking cues from CD / DVD manufacture
• Manufacture high quality cells and stacks based on controlled documentation:
  – Drawing and Material Specifications
  – Work Instructions, and Incoming Inspection Plans
  – Continued emphasis on quality and Gage R&R for QC tools
• Identify and plan for resolving process gaps, equipment throughput bottlenecks, as well cost saving and efficiency improvements
Cell Quality Control and Multiple Steps

- Dimensional – Inner Diameter, Outer Diameter (via Machine Vision)
- Dimensional - thickness
- Electrolyte Integrity via leak check
- Visual for various cell defect types
- Cells individually serialized with QR coded tied to: cell history, input materials and QC data

### Visual Defects

<table>
<thead>
<tr>
<th>Visual Defect</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole</td>
<td>![Hole Image]</td>
</tr>
<tr>
<td>Air Bubble</td>
<td>![Air Bubble Image]</td>
</tr>
<tr>
<td>Debris / Contamination</td>
<td>![Debris Image]</td>
</tr>
</tbody>
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**Cell Quality Control**

- **Hole**
- **Air Bubble**
- **Debris / Contamination**
Robotic work cell for:

(a) Cell QC - measure / leak test (Demonstrated >3 MW/shift/year throughput)
(b) Interconnect sub-assembly / QC (Demonstrated > 3 MW/shift/year throughput)
(c) Stack build (Demonstrated > 10 MW/shift/year throughput)

Stack Manufacturing Approach

- Utilize high speed pick and place robot for efficient sub-assembly build, cell and component QC and precise cell / stack assembly
- 50 minutes to assemble a 350-cell stack
Manufacturing Expansion to Enable Sub-MW & MW-scale Systems

- Cell and stack fabrication yield improvements
- Automated screen printing on half-cells
- Multi stack conditioning
- Development of standardized work instructions
- Streamlined and efficient inventory management

Focused on new technology and automation
SOFC Stack Module Design
• Stack modules of various power ratings under development using stack arrays as building blocks:
  • 6-Stack SOFC Test Module
    • $40kW_{DC}$ Rated Power
    • Status: Receiving final components to build and test
  • 16-Stack Solid Oxide Module
    • $100 \ kW_{DC}$ Rated SOFC Power
    • Minimum 150 kg/day SOEC H₂ Production
    • Status: Being built for an electrolysis demonstration at Idaho National Laboratory (INL)
  • 48-Stack Solid Oxide Module
    • $318kW_{DC}$ Rated SOFC Power
    • Leverage design work completed from 16-Stack Module
    • Status: Being developed as a basis for the future

• Lessons from fabrication and testing of smaller SOFC modules will feed into the design of the MW Plant 48-Stack module
Module Design and Component Development

- Developments from NextGen SOFC Module
  - Process gases distributed to 6 stacks via multi-layered Stack Distribution Base connected to plumbing passing through sides of steel enclosure
  - CFD was used to achieve excellent flow and thermal distribution between stacks

Temperature Plot

<table>
<thead>
<tr>
<th>Results</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode In Mass Flow Rate Deviation</td>
<td>-1.7% to 1.7%</td>
</tr>
<tr>
<td>Anode In Maximum Outlet Temperature Variation</td>
<td>7.0°C</td>
</tr>
<tr>
<td>Total Anode Press Drop (In to Out of Module)</td>
<td>25.5 IWC</td>
</tr>
</tbody>
</table>

Vessel received in Danbury
Cut-away of lower-half of the module
**Air Distribution**

- **Developments from NextGen SOFC Module**
  - **Air Distribution Tubes (ADT)** protrude vertically from the *Stack Distribution Base*.
  - Dead-ended perforated tubing modeled in CFD software to evaluate flow distribution along height of tube.
  - Performance of the ADT meets basic requirements of:
    - Mass flow distribution
    - Maximum allowable pressure drop

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[Simulated Inlet Mass Flow Rate Variation]

- **Percent Variation From Average**
  - Absolute Pressure: [412.73, 410.07, 409.94, 408.01, 409.07, 407.14, 405.30, 413.07]
  - Hole Position Group: [1 - Hole closest to bottom, 23 Hole closest to top]
40 kW Stack Module Build Status

Upper Enclosure Insulated

Stacks Base Plate

Power Take Off Bus Bar Hardware

Two Stacks in Shipping Container

Components are fabricated for final assembly of 6-stack stack module

Lower Enclosure
• 16-Stack Solid Oxide Module
  - Pre-assembled Stack Base Assembly maximizes access by production floor assemblers
  - Houses Stacks, Stack Distribution Base and accompanying I/O & power take-off hardware
  - Includes fitted insulation panels held together and secured by easily handled bolted sheet metal
  - Base Build Plate FEA determined appropriate material for low cost welded fabrication
  - Stack Base Assembly unit inserted into Module Enclosure shell via dolly and rails
• 48-Stack Solid Oxide Module for Large Scale Applications
  – Incorporate lessons learned from fabrication, assembly, and testing of the 40-kW stack module
  – Lifting access via standard ISO container corner blocks while providing option for forklift access
  – Process gas header channels that run underneath the multi-layered base designed for adequate gas flow to the entire length of the base
  – Designed for ease of factory assembly and future commercialization
System Design
FuelCell Energy

SubMW SOFC System Development

- 50 kW (2014-2016)
- 1st Gen Stack
- Fuel: NG

- 200 kW (2017-2020)
- 1st Gen Stack
- Fuel: NG

- 250 kW Commercial Products
- CSA Stacks
- Muti-Fuel: NG, ADG, H2
SubMW SOFC system design is used as the foundation for larger systems.
Simulation Performance

CHEMCAD modeling used to create design and performance parameters for equipment among several different operational modes for the plant.

### MW Class System Simulation Performance
Alternate Fuels

<table>
<thead>
<tr>
<th></th>
<th>NG</th>
<th>ADG</th>
<th>H₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross DC Power, kWdc</td>
<td>1101</td>
<td>1143</td>
<td>1161</td>
</tr>
<tr>
<td>Net AC Power, kWac</td>
<td>1000</td>
<td>983</td>
<td>1000</td>
</tr>
<tr>
<td>Electrical Efficiency, [LHV / LHV with CHP]</td>
<td>62 / 86</td>
<td>55 / 82</td>
<td>65/77</td>
</tr>
<tr>
<td>CO₂ Emissions, kgCO₂/MWₜ</td>
<td>331</td>
<td>597</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>
Repeating Core BOP/Stack Module Block

Natural Gas Desulfurizer & Water Treatment

Core Mechanical BOP/Stack Module Block

48 x Stack Module

Power Conditioning Units: (DC-to-AC) Inverter, Switchgear

250 kW SubMW Power System
Dimensions: 35’ x 8’ x 10’

250 kW SubMW Power System
(Enclosure Removed)

Repeating Core BOP/Module Blocks for MW-Class System Based on Design of SubMW Systems
High Power Plant Availability Achievable Utilizing Repeatable Core Blocks

MW SOFC System Layout

Plant (57.75’ x 36.75’) 2,122sf
Plant plus maintenance (57.75’ x 49.25’) 2,844sf
Techno-economic Analysis
CSA Stack Cost Update @1 GWe/yr Production

Cost Contributions Included:
- Procured Parts
- Commodity Materials
- Direct Fabrication Labor
- Direct Assembly Labor
- Indirect Labor
- Utilities
- Capital Recovery
- Equipment Maintenance
- Consumables
- Equipment Commission and Test
- Overhead & Building

Excluded:
- R&D, sales and marketing, G&A, warranty expenses and taxes

CSA Stack Factory Cost updated from 2019 estimate (DE-FE0026093) including the following modifications:

- Cost sensitivity analysis of different parts containing nickel (part thickness and porosity) for high volume costing
- Updated re-designed non-repeat parts (NRP) cost including top and bottom end plates and air manifolds
- Advances in manufacturing automation
- Cost trade-off analysis for protective Manganese-Cobalt Oxide (MCO) coating processes
- Update of cost parameters subject to Inflation

Costing following DOE Methodology and Recommended Inputs
Yr2019 CSA-SOFC Stack Factory Cost Estimate for 1 GW stacks per Year

$ 863 / stack at 160,000 stacks/year

Stack cost per unit power produced:

- $122 /kWe DC (gross)
- 133 $/kWe AC (Net)
- < $225 / kWe AC DOE cost target

58% of the estimated cost is due to material
Top 3 cost contributors by **Functional Area** are:

1) Cell Materials
2) Cell Fabrications
3) Repeat Components
Volume Impact / Previous Work

**CSA-SOFC Stack Factory Cost Estimate vs Stack Volume**

- **Reference to Yr 2018 TEA CSA Stack Cost Analysis on DOE Report [DE-EE0006961]**
- **1 GW/Year CSA Stack Cost Analysis Yr2019**
- **Updated 1 GW/Year CSA Stack Cost Analysis Yr2019**

- **FCE In-house Methodology**
  - Annual Production: 7040 Stacks/Year, Cost: $1,962

- **DOE Methodology**
  - Annual Production: 14000 Stacks/Year, Cost: $1,332
  - Updated Cost: $863

- **Note:** Updated 1 GW/Year CSA Stack Cost Analysis Yr2019.
Wrap-Up
• 48-stack module design has been developed utilizing key components derived from configuration of existing smaller modules (6 and 16 stacks):

• 1 MW SOFC system design development is being matured from conceptualization to the next level of detailed engineering:
  — System concept was developed achieving efficiency >60% on Natural Gas fuel and incorporating capability for utilizing hydrogen fuel
  — Balance-of-Plant (BoP) key equipment were identified, and design data sheets were prepared
  — Preliminary 3-dimentional CAD model and system layout were developed to ensure reduced installation cost and ease of maintenance
  — Technoeconomic analysis has shown that at low annual volume production of one MW, a plant cost of <$6000/kW is feasible meeting the DOE cost target for the first-of-a-kind 1MW SOFC system demonstration

• Factory cost of stacks at 1GW/year production is estimated to be $122/kWdc.
Thank You

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Dr. Shailesh Vora
Dr. Patcharin (Rin) Burke

Our purpose:
Enable the world to be empowered by clean energy