Natural Gas-Fueled Distributed Generation SOFC Systems

Performance and Cost of Electricity

Prepared for:
10th Annual SECA Meeting
Pittsburgh, PA, USA

Date: July 14th, 2009
1. Background, Objective, and Approach
2. System Definition
3. Heat & Material Balances
4. Cost Analysis
5. Conclusions
Interest in fuel cells for distributed generation has waxed and waned.

• Around 2000, interest in DG peaked:
  – Low natural gas cost (Henry Hub ~$2/MMBTU)
  – Prospect of suitable new generation technologies

• Fuel cells were thought to be a good fit:
  – Low emissions
  – High efficiency
  – Small scale

• But:
  – Fuel cells were not ready
  – Natural gas cost rose (Henry Hub >$4/MMBTU)
Objective

DOE wanted to understand the performance & cost state-of-the-art SOFC in DG applications.

• Basis for analysis:
  – 5 MW\textsubscript{e} grid-connected system
  – SOFC stack technology available commercially 2020
  – Relevant energy cost (EIA projections)
  – Appropriate operating strategies (incl. CHP)
  – Consider cost implications of DG operation

• Based on detailed performance & cost analysis

• Allow comparison with central generation options such as IGCC and IGFC

• Consider potential impact of CCS requirements
We used our established fuel cell system model to project NG DG SOFC system performance and cost.

- Define System
- Analyze Stack Performance
- Compute System Heat & Material Balances
- Obtain Sizing Parameters
- Estimate System CAPEX & OPEX

System Efficiency, Emissions
LCOE

Consider Impact of Carbon Capture Separately in Sensitivity Analysis
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The application and scale dictates a simple and efficient flowsheet.

- Stack technology: atmospheric w/ separated flows
- Relatively small system:
  - Simple maintenance
  - Easy siting / permitting
  - Low cost
- This means:
  - Avoid wet scrubbing / adsorption processes
  - Minimize # of unit operations
  - Minimize water consumption
  - Avoid noisy components (compressors)
The SOFC stack assumptions used are consistent state-of-the-art stacks and with other recent studies.

- Performance consistent with state-of-the-art planar technology:
  - Polarization similar to current performance
  - Durability and temperature range consistent with DOE program targets for 2015
  - Case with small (125 cm²) and large (2000 cm²) cells

### Key Stack Performance Characteristics

<table>
<thead>
<tr>
<th>Stack Temperature</th>
<th>Fuel Utilization (single pass / overall)</th>
<th>Anode Recycle</th>
<th>Cathode Stoichiometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>650 – 800°C</td>
<td>70% / 86%</td>
<td>60%</td>
<td>2.86</td>
</tr>
<tr>
<td>Cell Voltage</td>
<td>0.83V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell Current Density</td>
<td>0.50 A/cm²</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Several carbon capture options are technically possible.

- Sorbent capture from exhaust
- Water gas shift + capture from syngas
- Oxyfuel combustion of anode exhaust + whole gas capture
Agenda

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To achieve high efficiency, significant recuperation is necessary.
Syngas recycle is critical to the system water balance: it provides steam for the reformer.

**Water Management (5 MW System)**

- **Make-Up Water:** 0.03 kg/s
- **Net Water:** 0.52 kg/s in Syngas Recycle
- **Moisture to Exhaust:** 0.4 kg/s
- **Net Water Consumption:** ~800 gal/day (or 7 gal/MWh_{net})
~58% efficiency (HHV) is achievable in simple-cycle configuration.

<table>
<thead>
<tr>
<th><strong>System Performance</strong> (5 MW DG System)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel Cell Stack</strong></td>
</tr>
<tr>
<td>Fuel Utilization (single pass, overall)</td>
</tr>
<tr>
<td>Anode Recycle</td>
</tr>
<tr>
<td>Cathode Stoichiometry</td>
</tr>
<tr>
<td>Stack Temperature</td>
</tr>
<tr>
<td>Cell Voltage</td>
</tr>
<tr>
<td>Fuel Cell Gross Power</td>
</tr>
<tr>
<td><strong>Reformer</strong></td>
</tr>
<tr>
<td>Steam / Carbon Ratio</td>
</tr>
<tr>
<td>Methane Slip</td>
</tr>
<tr>
<td>Water Use</td>
</tr>
<tr>
<td><strong>BoP</strong></td>
</tr>
<tr>
<td>Blower Power</td>
</tr>
<tr>
<td>Other Parasitic Loads</td>
</tr>
<tr>
<td><strong>System</strong></td>
</tr>
<tr>
<td>Exhaust Temperature</td>
</tr>
<tr>
<td>System Efficiency (HHV Basis)</td>
</tr>
</tbody>
</table>
Cell voltage and stack temperature rise have the greatest impact on efficiency.

### Sensitivity of System Efficiency (5 MW DG System)

<table>
<thead>
<tr>
<th>Component</th>
<th>Sensitivity Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel Cell Stack</strong></td>
<td></td>
</tr>
<tr>
<td>Cell Voltage</td>
<td>0.77 V - 0.85 V</td>
</tr>
<tr>
<td>Stack ΔT</td>
<td>75°C - 200°C</td>
</tr>
<tr>
<td>Anode Recycle</td>
<td>40% - 75%</td>
</tr>
<tr>
<td>Fuel Utilization</td>
<td>60% - 85%</td>
</tr>
<tr>
<td>Stack Heat Loss</td>
<td>50% - 200%</td>
</tr>
<tr>
<td><strong>Reformer</strong></td>
<td></td>
</tr>
<tr>
<td>Steam / Carbon Ratio</td>
<td>2 - 3.5</td>
</tr>
<tr>
<td><strong>BoP</strong></td>
<td></td>
</tr>
<tr>
<td>Other Parasitic Loads</td>
<td>25 kW - 250 kW</td>
</tr>
<tr>
<td>Blower Efficiency</td>
<td>50% - 85%</td>
</tr>
</tbody>
</table>

Performance Analysis  Sensitivity Analysis

![Graph showing sensitivity analysis]
Oxyfuel combustion & whole anode gas capture likely presents the most realistic CCS option.

### Impact of CCS on Efficiency
(Maximum 30 gCO₂/kWh Emissions)

<table>
<thead>
<tr>
<th>Net System Efficiency (% HHV)</th>
<th>Baseline</th>
<th>Shift &amp; Absorb</th>
<th>End-of-Pipe</th>
<th>Oxy-Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>With CSS 60%</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>With CSS 50%</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>With CSS 40%</td>
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<tr>
<td>With CSS 30%</td>
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<tr>
<td>With CSS 20%</td>
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<tr>
<td>With CSS 10%</td>
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<td></td>
</tr>
<tr>
<td>With CSS 0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No CSS -10%</td>
<td></td>
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</tbody>
</table>

J. Thijassen, LLC
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The cost analysis followed a well-established methodology, building on several previous studies.

- Bottom-up activity-based stack cost analysis
- BoP equipment costs via scaling from quotes
- Costs were escalated to 2007 based on DoC’s PPI
- A uniform 42.5% installation factor was used
The cost analysis indicates that installed CAPEX would be around $870/kW

Capital Cost Estimates (5 MW DG System, 2007$)

- QC, Assembly, Installation
- Controls, Inverter, Interconnection
- Rotating Equipment
- Thermal Management
- Reformer
- Stack Infrastructure
- SOFC Stack
The LCOE from NGDG SOFC systems ranges from 7 to 9.5 cents/kWh.
Gas price, carbon capture, and stack degradation most strongly impact LCOE for DG systems.

**Sensitivity of LCOE (5 MW DG System)**

- Gas Price (2.5 - 12 $/MMBTU)
- Carbon Capture (0 - 90%)
- Stack Degradation (0, 1.5%)
- Avoided Distr. Cost (0 - 2 ¢/kWh)
- CAPEX (660 - 1220 $/kW)
- Capacity Factor (60 - 95%)
- System Efficiency (52 - 61%)
Conclusions

Technically spectacular NGDG SOFC systems appear feasible...

• State-of-the-art SOFC enable highly efficient, simple-cycle, systems:
  – ~58% efficiency (HHV basis)
  – Water use ~7 gal/MWh
  – CO₂ emissions 340 g/kWh (CCS technically possible)
  – Very low noise, local air emissions

• But degradation should be reduced to ~0.5%/1,000 hrs or less
Conclusions

... and in some selected market segments their cost could be attractive.

- In high-volume production:
  - CAPEX ~$870/kW (2007$)
  - LCOE 7.2 – 9.3 ¢/kWh
  - Strong function of gas price, capacity factor

- This range is likely competitive in selected market segments (CHP, incentives, local conditions)

- It is not broadly competitive with central generation

- If deep carbon reductions are required(>60%):
  - CCS would be required
  - NG DG would likely be uncompetitive
Acknowledgement

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Thank You!