Analysis of Solid Oxide Fuel Cell Plant Configurations with CCS

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• Collaborators
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  – DOE National Energy Technology Laboratory
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    • Travis Shultz
    • William Summers
    • Kristin Gerdes
    • Walter Shelton
Objectives

- Develop technology pathways that project plant performance and cost of electricity for Integrated Gasification Fuel Cell (IGFC) and Natural Gas Fuel Cell (NGFC) Plant Configurations with carbon capture and storage (CCS)
- Select pathways that
  - Focus on SOFC power block technology advances and
  - Alternate pathway to include gasifier advances for high methane syngas for IGFC systems
- Utilize site, fuel and economic assumptions consistent with the NETL Bituminous Coal Baseline report
- Compare pathway results to ‘Today’s fossil plants’ with and w/o CCS
  - Supercritical PC
  - IGCC
  - NGCC
Design Basis Common to All Cases

• Consistent with NETL Bituminous Coal Baseline Report
• Site: mid-western U.S.; ISO conditions
• Plant Boundary: total plant facility
  – COE includes transport, storage and monitoring of CO$_2$
• Fuels: IL #6 Coal and Natural Gas
• Plant Capacity: 550 MWe with carbon capture & storage
• Conventional Cryogenic Air Separation
• Gas Cleaning for IGFC Plants: Dry Gas Cleaning
Design Basis: SOFC Power Island

- Planar SOFC technology
- Separate cathode and anode off-gas
- Cathode and anode gas recycle
IGFC Gasification Process

coal

Gasifier
steam
oxygen
air
N₂
oxy-comp O₂

Coal Treatment

Heat Recovery

Particulate and Scrubbing
Low-temp Cooling
Trace Removal
Selexol and Polishing

Dry Gas Cleaning
condensate
sulfur sorbents

Clean Syngas

NATIONAL ENERGY TECHNOLOGY LABORATORY
NGFC Natural Gas Supply

Diagram:
- ASU producing oxidant
- Air and oxidant go to the Reformer
- Steam enters the Reformer
- NG Expander
- Natural gas and Syngas outputs
SOFC Plant Concepts
Pathways consider alternate fuel supply and SOFC operating pressure (NGFC with external and internal reforming; IGFC with conventional and catalytic gasifiers)
Design Basis: SOFC

- Carbon deposition control: (atomic O / atomic C) > 2.0
- Operating voltage = stack inlet Nernst potential – overpotential
- Baseline Conditions (consistent with current test data and cost)
  - 140 mV overpotential
  - 1.5%/1000 hrs degradation
  - 5.9% gasifier methane content
  - 97% inverter efficiency
  - $296/kW Atm. Pressure SOFC stack unit installed cost
  - 80% plant capacity factor

- Advancements
  - 70 mV overpotential
  - 0.2%/1000 hrs degradation
  - 10.2% conventional gasifier methane content
  - 30% catalytic gasifier methane content
  - 98% inverter efficiency
  - $268/kW Atm. Pressure SOFC stack unit installed cost
  - 85% and 90% plant capacity factors
  - 285 psia pressurized SOFC
  - Internal catalytic SOFC reforming (applicable for NGFC plants)
Pathway Study Process Cases

- Conventional Gasifier Pathway
- Catalytic Gasifier Pathway
- Natural Gas Pathway

- Each pathway begins with the atm. pressure SOFC baseline conditions
- 30 cases used to show results from improvements in baseline conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base</th>
<th>Improved</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOFC Degradation (%/1000 hrs)</td>
<td>1.5</td>
<td>0.2</td>
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<td>Cell Overpotential (mv)</td>
<td>140</td>
<td>70</td>
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<td>Gasifier CH₄ (conventional)</td>
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<td>30%</td>
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<td>SOFC Stack Cost (Atm.) ($/kW)</td>
<td>296</td>
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<tr>
<td>SOFC Stack Cost (Pressure) ($/kW)</td>
<td>442</td>
<td>414</td>
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<td>Inverter Efficiency</td>
<td>97%</td>
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Results: Data Reported

- Process Block Flow Diagram and Stream Table
- Power Summary
- Mass Flow Diagram
- Energy Flow Diagram
- HP and LP-Steam Balances
- Water Balance
- Carbon Balance
- Sulfur Balance
- Air Emissions
- Capital Cost Breakdown
- Owner’s Cost Breakdown
- First-year COE Breakdown
IGFC Mass Flow Balance Example

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Coal feed: ILL #5 as received

- Main fuel stream mass flows (% of plant coal feed rate)
- Non-fuel stream mass flows
IGFC Energy Flow Diagram Example

**Design Basis (Case 1)**

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<td>SOFC</td>
<td>Planar, Atm Press.</td>
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<td>Gasifier</td>
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**Diagram Elements**

- **Plant fuel stream flow (% plant coal HHV)**
- **Non-energy streams**
- **Auxiliary power streams (% plant coal HHV)**
- **Steamwater flows (% of plant coal HHV)**
- **Power outputs (% of plant coal HHV)**
- **Heat exchanger duty (% of plant coal HHV)**
Cost Estimation

- Consistent with Bituminous Coal Baseline Study: June 2007 $

- Capital Costs (total overnight cost): equipment, materials, labor, indirect construction costs, engineering, owner’s costs, and contingencies

- Operating Costs: operating, maintenance, administrative labor; consumables; fuel; waste disposal; stack replacement cost

- Contingencies and Capital Charge Factor
  - Consistent with Baseline Study

- SOFC Stack Module Cost (Stack, enclosure, inverter)
  - Assumes NETL Cost Target (consistent with technology developers cost estimates)
  - Cost reduction consistent with 20% reduction in stack cost

- CO₂ transport, storage and monitoring consistent with Baseline study

- Natural Gas Price, $/MMBtu: 4.0, 6.55, 12.0
Conventional Gasifier Pathway: Efficiency and Capital Cost

Comparison with Today’s IGCC and PC

- IGCC (CoP gasifier) CCS: 31.0 %, $3466/kW
- SCPC CCS: 28.4 %, $3570/kW
- SCPC w/o CCS: 39.3 %, $2024/kW

Parameter | Baseline | With R&D
--- | --- | ---
SOFC Degradation (%/1000 hrs) | 1.5 | 0.2
Cell Overpotential (mv) | 140 | 70
Gasifier CH₄ | 5.9% | 10.2%
SOFC Stack Cost (Atm.) ($/kW) | 296 | 268
SOFC Stack Cost (Pressure) ($/kW) | 442 | 414
Inverter Efficiency | 97% | 98%

SCPC = Supercritical PC
Conventional Gasifier Pathway: FY COE

**Cost of Electricity, $/MWh**

- Today’s SCPC or IGCC w/ CCS
- Today’s SCPC or NGCC w/o CCS

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**Notes:**
- SCPC = Supercritical PC
- Natural Gas Price = $6.55/MMBtu
IGFC Catalytic Gasifier Pathway: FY COE

Cost of Electricity, $/MWh

- Conventional Gasifier
- Catalytic Gasifier

Today’s SCPC or IGCC w/ CCS

Today’s SCPC or NGCC w/o CCS

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NGFC Pathway FY COE
Atmospheric Pressure SOFC

Today’s SCPC or IGCC w/ CCS
Today’s NGCC w/ CCS
Today’s SCPC or NGCC w/o CCS

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<tr>
<td>Fuel Utilization</td>
<td>75%</td>
<td>90%</td>
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Note: prior pathway cases use external reforming

SCPC = Supercritical PC
Natural Gas Price = $6.55/MMBtu
Water Consumption (with CCS)

Consumption range from pathway studies.
Conclusions

• IGFC and NGFC have significant environmental advantage over all other fossil fuel power plants
  – Near-zero emissions including > 99% carbon capture (97% for pressurized SOFC)

• IGFC with commercial gasifier and enhanced-commercial gasifier technology
  – Significant performance and cost advantage over today’s IGCC and PC with CCS
  – Cost comparable to today’s IGCC without CCS

• IGFC with catalytic coal gasifier and atmospheric-pressure SOFC
  – Greatest cost benefit
  – Costs comparable to today’s PC and NGCC without CCS

• IGFC with catalytic coal gasifier and pressurized-SOFC
  – Performance benefits over IGFC with atmospheric-pressure SOFC, but no COE benefit
Conclusions

• **Systems analysis shows benefit of**
  – Reducing cell overpotential (capital and efficiency benefit)
  – Reducing degradation (capital benefit)
  – Improving system reliability (COE benefit)
  – Internal catalytic SOFC reforming: beneficial if achieved w/o significant stack cost increase

• **Pathway study informs technology development**
  – Basis for prioritizing technology development
  – Basis for selecting test conditions (e.g. syngas composition)

• **Additional integrated system opportunities**
  – Humid gas cleaning with atmospheric-pressure SOFC
  – Advance CO$_2$ compression