Oxy-FC Concept

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Electrochemistry is fundamentally different from combustion.

What if we treated fuel cells differently from a heat engines?

What if carbon-capture was an integral part of a power cycle?

Oxy-FC is a novel system integration with the potential for combined (i.e. power + H₂) efficiency greater than 80% (LHV) including the cost of carbon capture and liquefaction.
» What is Oxy-SOFC?
  > Pressurized SOFC polygeneration with pure O₂ cathode

» What are the benefits of Oxy-FC?
  > Higher FC operating voltage
  > Nearly 100% H₂ recovery
  > No high temperature air heat exchangers
  > Integrated carbon capture & liquefaction

» What needs to occur for Oxy-FC to happen?
  > Validation of commercial SOFC cells at high pressure with pure O₂
  > Internal temperature control development & validation
  > Purge cycle validation

» What else can Oxy-SOFC do?
  > Food/Energy nexus: efficient (carbon neutral) ammonia production
  > De-coupled FC-GT: Highly efficient parallel stream power generation

» A vision for Oxy-SOFC development:
  > Phase 1: lab bench validation up to 1kW
  > Phase 2: Module development (500kW) & system integration
  > Phase 3: Scale up and demonstration
Differences from standard SOFC:
- Pressurized, pure $O_2$ cathode increases FC efficiency
- Higher anode $H_2$ concentration increases FC efficiency
- Waste heat captured in chemical potential of $H_2$
- Cryogenic air separation synergistically produces $O_2$ for FC and liquid $N_2$ for the carbon liquefaction and $H_2$ recovery
Performance differences from standard SOFC:
This chart details the voltage & power improvement to a SOFC meeting SECA target performance from
a) pure O\textsubscript{2} cathode, b) pressurization to 10 atm, c) higher anode H\textsubscript{2} concentration

<table>
<thead>
<tr>
<th>Variable</th>
<th>SECA</th>
<th>Pure O\textsubscript{2}</th>
<th>Pure O\textsubscript{2} @10atm</th>
<th>Reform Cooling</th>
<th>Reform Cooling @10atm</th>
<th>Anode Recirculation</th>
<th>Anode Recirculation @ 10atm</th>
<th>Higher Power @10atm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (mW·cm\textsuperscript{-2})</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>750</td>
</tr>
<tr>
<td>Voltage</td>
<td>0.70</td>
<td>0.817</td>
<td>0.956</td>
<td>0.829</td>
<td>0.954</td>
<td>0.826</td>
<td>0.943</td>
<td>0.9018</td>
</tr>
<tr>
<td>Utilization</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
<td>63.9%</td>
<td>85.3%</td>
<td>70.0%</td>
<td>89.6%</td>
<td>80%</td>
</tr>
<tr>
<td>Single Pass Utilization</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
<td>63.9%</td>
<td>85.3%</td>
<td>39.7%</td>
<td>79.3%</td>
<td>61.11%</td>
</tr>
<tr>
<td>Current (A·cm\textsuperscript{-2})</td>
<td>0.715</td>
<td>0.612</td>
<td>0.523</td>
<td>0.603</td>
<td>0.524</td>
<td>0.606</td>
<td>0.530</td>
<td>0.8317</td>
</tr>
<tr>
<td>Oxygen (kg\textsubscript{O\textsubscript{2}}·kWh\textsuperscript{-1})</td>
<td>0.427</td>
<td>0.365</td>
<td>0.312</td>
<td>0.360</td>
<td>0.312</td>
<td>0.362</td>
<td>0.316</td>
<td>0.331</td>
</tr>
</tbody>
</table>

- Thermally unbalanced
- Requires steam production
- Recirculation provides steam
Energy Flow: 1.43kJ (LHV)

Oxy-FC system concept

Electric Power: 1kJ

Net Electric Power:

ASU Parasitic: 0.1kJ

Hydrogen Recovery

HSU Parasitic (condensing H₂O)

0.33 kJ

0.05 kJ HSU parasitic

0.85kJ

Net Recirculation: 0.82kJ

Thermal Energy: 0.23kJ

Hydrogen Energy: 0.59kJ

Gas Input: 1.43kJ (LHV)

Energy outputs and parasitics for Oxy-FC at 10atm & 750mW·cm⁻²

<table>
<thead>
<tr>
<th>Energy Flow</th>
<th>% of Fuel Input Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Output</td>
<td>69.83</td>
</tr>
<tr>
<td>H₂ Recovery</td>
<td>23.12</td>
</tr>
<tr>
<td>HSU Parasitic (condensing H₂O)</td>
<td>-1.1</td>
</tr>
<tr>
<td>ASU Parasitic</td>
<td>-7 to -21</td>
</tr>
<tr>
<td></td>
<td>depending on scale of ASU</td>
</tr>
<tr>
<td>Net Efficiency (LHV)</td>
<td>84.9 (@500MW) to 70.9 (@1MW)</td>
</tr>
</tbody>
</table>
How big is the penalty for producing $O_2$?
This chart illustrates the energy penalty of producing the oxygen.
Oxygen production is more efficient at large scale (*note log-axis of size).
At 1 MW, the penalty is ~21%, but above 50MW the penalty is <10%.

\[ y = 1086x^{-0.202} \]
\[ R^2 = 0.9596 \]
\[ \% \text{ Parasitic} = 85.83x^{-0.202} \]
Cost of Electricity Estimation

Oxy-FC competes with $0.07/kW electricity at a scale of 10MW with co-production of $2/kg H₂.

**Assumptions:**
- Only the electricity and hydrogen considered
- Hydrogen production is valued at $2 per kg (consistent with U.S. DOE production cost targets)
- ASU parasitic scales with system capacity (see previous slide)
- SOFC system cost assumed to be $3000/kW
- The ASU cost scaled to a current 40 ton/day system with an installed cost of $10M
- Capital financing is assumed to be 4% over the lifetime of the system, 20 years
- Natural gas is assumed to be $4 per mmBTU for an industrial customer
- Annual operations and maintenance costs are assumed to be a fixed value of $200 per kW of installed electric capacity
Without a pass through cathode flow, controlling temperature is more complicated. The anode gas flow must control both temperature and power. A novel controller has been hypothesized and tested on simulated Oxy-FC using current and fuel flow to control power, voltage and temperature while maintaining electrochemical stability.

\[ CH_4 + H_2O \xrightarrow{R_{rf}} CO + 3H_2 \]

\[ CO + H_2O \xrightarrow{R_{sf}} CO_2 + H_2 \]

\[ V \cdot i = \frac{i}{2F} \cdot h_{rxn1} - (\hat{n}_c p \Delta T)_{Anode} - \frac{i \cdot \hat{n}_{CH_4}}{i^* \cdot Cells} \cdot (h_{rxn2} + h_{rxn3}) \]
De-coupled FC–GT

New De-Coupled FC-GT

Differences from standard FC-GT
• Potential for retrofit to existing systems
• Eliminates costly high temperature heat exchangers
• FC not directly in working flow risking surge/stall
• Independent control of GT flow and FC flow
• Higher efficiency operating condition for fuel cell
• Potential for low emission combustion
Oxy-FC can provide ultra-efficient, carbon free, fertilizer production!
- The Oxy-FC concept is readily integrated with the standard Haber-Bosch process of ammonia synthesis by passing the exhaust $N_2$ and $H_2$ streams over a catalyst bed to form $NH_3$
- Ammonia production consumes 2% of the world's fossil fuel at less than 50% thermal efficiency
- Eliminates steam reforming, partial oxidation, shift reactors, and gas refining from ammonia plant
Phase I: Lab-bench validation (2 years)
- Single cell to short stacks ~1kW
- Performance validation with pressurization & pure O₂ cathode
- Oxygen contaminant sensitivity, purge tests

Phase II: Module development (2 years)
- Full stack testing (0.5-1MW)
- Thermal control validation
- Purge cycle validation
- CO₂ liquefaction & hydrogen recovery validation

Phase III: Demonstration scale (2 years)
- Installation at site with existing cryogenic air separation
- Test multiple modules comparing stacks from different manufactures
- Combine with ammonia synthesis

Year 1: Steady-state validation
Year 2: Dynamic performance characterization

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Summary

» Oxy-FC completely rethinks how electrochemistry is incorporated in a cycle
  > No high temperature air heat exchangers
  > CO₂ separation and liquefaction incorporated in design
  > 100% H₂ recovery from anode stream

» Thermodynamic synergies between SOFC and cryogenic air separation increases net system efficiency:
  > Higher cathode O₂ concentration increases voltage
  > Cooling with fuel reforming increases anode H₂ concentration and voltage
  > Cathode flow at 4% of standard FC allows pressurization benefit to exceed work

» Oxy-FC can integrate with other energy systems
  > De-coupled FC-GT
  > Oxy-FC-Haber for co-production of ammonia

» Validation of the Oxy-FC concept is essential
  > Test facilities are under construction at WSU
  > Commercial manufacturer involvement is essential
  > Scale-up to established balance-of-plant components is long-term goal (>100MW)