Reversible Solid Oxide Cells for Energy Storage

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Presentation Outline

I. Overview of Reversible Solid Oxide Cell (ReSOC) concept

II. Thermodynamics & Thermal Management of Reversible Systems

III. Process Systems Engineering of ReSOC ‘Flow Batteries’
   - 100 kW / 800 kWh

IV. Techno-Economic Outlook
   - Distributed systems
   - Power–to–gas
A reversible solid oxide cell (ReSOC) has similarities to a flow battery where reactants are tanked

- **Flow battery advantage:**
  - Power scales with size of stack
  - Energy scales with size of storage tanks

- **The reversible solid oxide cell (ReSOC) advantage**
  - High efficiency and energy dense fuels

![Diagram of ReSOC](image)

*Figure (right): Jensen, Graves, Wendel, Braun, et al., Energy & Env Sci (2015)
High temperature fuel cell systems are comprised of cell-stack hardware and balance-of-plant equipment.

Ni-YSZ | YSZ | LSCF (~800°C)

Figure: Kee et al., Proc. Combustion Institute 30 (2005)
High temperature reversible SOCs are more suitable for energy storage than PEM cells

- The fuel cell stack is not the whole picture
  - Storage (tanks)
  - Delivery (pipes and pumps)
  - Thermal integration (Heat exchangers and cell conditions)

\[ \eta_{RT} = \frac{V_{FC}}{V_{EC}} \]

@ 0.5 A/cm²,
SOC: \( \eta_{RT} = 81\% \)
PEM: \( \eta_{RT} = 39\% \)

Cell performance is important, but the balance-of-plant is also critical to roundtrip system efficiency

\[
V_{\text{cell}} = E_N(T, p, x_i) - (\eta_{\text{ohmic}} - \eta_{\text{act}} - \eta_{\text{conc}})_{j, r, p, x_i}
\]

\[
\eta_{RT, \text{stack}} = \frac{\text{power generated (SOFC)}}{\text{power consumed (SOEC)}} = \frac{i_{FC} V_{FC}}{i_{EC} V_{EC}} = \frac{V_{FC}}{V_{EC}}
\]

\[
\eta_{RT, \text{sys}} = \frac{\text{SOFC mode net power}}{\text{SOEC mode total power}} = \frac{V_{SOFC} * i_{SOFC} - P_{SOFC,BOP}}{V_{SOEC} * i_{SOEC} + P_{SOEC,BOP}}
\]

**DOE target: 80%**

**Roundtrip Stack Efficiency:** 
\(i_{FC} = i_{EC}\) for continuous operation

**Roundtrip System Efficiency:**

- **How can we improve system efficiency?**
  1. Reduce overpotential (cell/stack performance - ASR)
  2. Reduce balance of plant power (system design & operation)
Thermodynamics suggest maximum roundtrip efficiencies are higher with CH$_4$ / H$_2$O than H$_2$ / H$_2$O systems.

- Maximum roundtrip efficiency < 80% at 625°C and above.
- When considering evaporative load, $\eta_{RT,max}$ < 70%.
- Maximum roundtrip efficiency ~100% at all temperatures.
- ~10% efficiency reduction when considering liquid H$_2$O.

Ideal efficiency: $\eta_{RT,max} = \frac{\Delta G}{\Delta H} = 1 - \frac{T \Delta S}{\Delta H}$

Methane

Direct CH$_4$ red-ox cannot be executed, thus practical gas compositions and utilization reduce maximum efficiency

- With utilization < 100% and equilibrium considerations, $\eta_{RT,max}$ decreases
- Maximum roundtrip efficiency lowered to 97% at 570°C

- When considering evaporative load, $\eta_{RT,max} \approx 85\%$ at 1 atm ($\approx 87\%$ at 20 atm)

Operation - stack thermal management is crucial and improves with internal reforming/generation of methane

- Fuel cell requires heat rejection (air-cooled)
- Electrolysis requires heat supply (overpotential)
- Thermoneutral voltage is lowered by methanation

**SOEC mode reactions**

- **Fuel channel**
  - Reverse water gas shift: $H_2 + CO_2 \rightarrow H_2O + CO$
  - Methanation: $3H_2 + CO \rightarrow CH_4 + H_2O$

- **Oxygen channel**
  - $H_2O \rightarrow \frac{1}{2}O_2 + H_2$ at 600°C

- **Power source**

Methanation promoted by:
- Low temperature
- High pressure

**Highly exothermic!**

**Highly endothermic!**
Quantify stack thermal management with the thermoneutral voltage

- **Thermoneutral voltage**: $V_{TN} \sim \Delta H / nF$ (not as straightforward for HC mixtures)
  - Net heat generated by irreversible loss balanced by net reaction heat (stack operates both isothermally and adiabatically)

- >200 mV voltage reduction in electrolysis mode with CH$_4$ systems

$$\dot{Q}_{gen} = i(V_{cell} - V_{TN})$$

For H$_2$/O$_2$

- $V_{TN} = 1.29$ V
- $E_N = 0.98$ V

For CH$_4$/O$_2$

- $V_{TN} = 1.04$ V
- $E_N = 1.04$ V
Cell-stack electrochemical model is calibrated to next-gen ReSOC performance data and extrapolated

Electrochemical parameters derived from button-cell calibration are applied to a 1D channel level model

\[ V_{\text{cell}} = E_N(T, p, x_i) - (\eta_{\text{ohmic}} - \eta_{\text{act}} - \eta_{\text{conc}}) j, T, p, x_i \]

- Ohm’s law
- Bulte-Volmer equation
- Fickian diffusion

Test data and cell performance in collaboration with S. Barnett (Northwestern)

*see Wendel et al., J. Power Sources, 283:329-42, (2015).*
Cell-stack electrochemical model is calibrated to next-gen ReSOC performance data and extrapolated

Electrochemical parameters derived from button-cell calibration are applied to a 1D channel level model

\[
V_{\text{cell}} = E_N(T, p, x_i) - (\eta_{\text{ohm}} + \eta_{\text{elec}} + \eta_{\text{cov}})
\]

Ohm’s law

ASR @ 650°C (Ωcm²)

<table>
<thead>
<tr>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Button</td>
<td>0.18</td>
</tr>
<tr>
<td>Cell</td>
<td>0.20-0.25</td>
</tr>
<tr>
<td>Stack</td>
<td>0.30-0.40</td>
</tr>
</tbody>
</table>

*see Wendel et al., J. Power Sources, 283:329-42, (2015).*
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Distributed-scale ReSOC systems are nearer-term, but require careful design integration

Stand-alone System Features (8-hour storage):
- High temp., pressurized vapor storage (~200°C, 20 bar)
- Minimal BOP: two-stage compression w/ intercooling

Baseline Results:
- Roundtrip efficiency: 65 - 70% (expander)
- Energy density ($\epsilon_{st}$): 19 - 40 kWh/m³ (tank pressure)

Trade-space Variables:
1. Reactant utilization
2. Stack vs. Tank pressure
3. Water management

Baseline stack conditions: 600°C, 1 atm, and $U_F$=60%

The preliminary outlook for 100 kW (800 kWh) ReSOC based energy storage system is competitive with batteries

- Pressurized stack, 155-bar H₂ tanks
- Design enables dual-mode operation
  - Levelized cost and efficiency still challenged to meet DOE long-term targets
  - Cost compares well vs other technologies
  - Tank cost is 25% of capital in this analysis

<table>
<thead>
<tr>
<th>Technology Comparison²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
</tr>
<tr>
<td>ReSOC</td>
</tr>
<tr>
<td>Na-Ni-Cl</td>
</tr>
<tr>
<td>Li-Ion</td>
</tr>
<tr>
<td>Na-S</td>
</tr>
<tr>
<td>Va-Redox</td>
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</tbody>
</table>

100 kW / 800 kWh ReSOC Energy Storage Cost Distributions

LCOS Breakdown
22.4 ¢/kWh

- O&M: 9%
- Electricity: 26%
- PCS: 6%
- Capital: 59%

Capital Cost Breakdown
(414 $/kWh)

- Stack: 21.8%
- Turbo-mach: 15.7%
- HXs: 21.1%
- Tanks: 25.0%
- PCS: 10.2%
- Misc: 6.2%

Hydrogen-tanks = $10,100/m³
Electricity cost = 3.5 ¢/kWh
65% capacity factor
Pressurization, tank cost reduction, improve economics

How to get capital cost reduction?

Levelized Cost of Storage

<table>
<thead>
<tr>
<th>Method</th>
<th>LCOS (cents/kWh)</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric ReSOC</td>
<td>31.5</td>
<td>29%</td>
</tr>
<tr>
<td>Pressurized ReSOC</td>
<td>22.4</td>
<td>37%</td>
</tr>
<tr>
<td>Press. ReSOC, CNG tanks</td>
<td>19.9</td>
<td>53%</td>
</tr>
<tr>
<td>Press. ReSOC, 50% cap red</td>
<td>14.8</td>
<td></td>
</tr>
</tbody>
</table>

\[
LCOS = \frac{\sum_j TIC_j \left( \frac{d}{1-(1+d)^{-N_j}} \right)}{E_{cyc} n_{cyc,ann}} + \frac{P_{elec}}{\eta_{RT,AC}} + C_{O&M}
\]
Summary

- Cost and performance outlook:
  100 kW / 800 kWh: ~60-65% RT efficiency, 20 ¢/kWh, 250-400 $/kWh TIC
  P2G-to-Power: ~61% RT efficiency, 15 ¢/kWh, ~1500 $/kW CAP

- No depth of discharge limitations
- “Battery” cycling desirable (provided stack thermal cycling controlled)
- In P2G: LCOS can be manipulated on-the-fly by variable op mode

Technology Development (Low-TRL: far behind low-T electrolysis)

- **Cell:** Advanced cell development towards 600°C and pressurization
  - Scale-up, Long-term stability and durability testing

- **System:** Upscale, integration, & pilot demo incl. extensive mode-switching
  - Dynamic operation & control (part-load, ramping dynamics)
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