Co-Electrolysis of Water and CO₂ for synthetic fuels

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Co-Electrolysis of Water and CO$_2$ for synthetic fuels

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Outline

1. Solid Oxide Electrolyser Cell (SOEC)

2. SOEC Electrode Potentials, Thermodynamic

3. Gas Diffusion and Conversion
The Solid Oxide Cell

Ni-YSZ support & current collector

Ni-YSZ electrode

YSZ electrolyte

LSM-YSZ electrode

LSM current collector

\[
\text{LSM} = \left(\text{La}_{0.75}\text{Sr}_{0.25}\right)_{0.95}\text{MnO}_3 \\
\text{YSZ} = \text{Zr}_{0.84}\text{Y}_{0.16}\text{O}_{1.92}
\]
The Solid Oxide Cell

Solid Oxide Electrolysis Cell

+ \[ \rightarrow \text{H}_2 \text{O (and CO)} \]

H_2O (and CO_2) \[ \rightarrow \text{O}_2 \]

1.3 V

Solid Oxide Fuel Cell

+ \[ \rightarrow \text{H}_2 \text{ (and CO)} \]

H_2 (and CO) \[ \rightarrow \text{O}_2 \]

0.8 V

H_2O (and CO_2) \[ \rightarrow \text{H}_2 \text{ (and CO)} \]

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Thermodynamics

$\text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2$

Total energy demand ($\Delta H_f$)

Electrical energy demand ($\Delta G_f$)

Heat demand ($\Delta S_f$)

$\eta = 100 \% \text{ at } E = E_{tn} \text{ (no heat loss)}$

$E_{cell} = E_{tn}$
Thermodynamics

\[ \text{CO}_2 \rightarrow \text{CO} + \frac{1}{2}\text{O}_2 \]

Energy demand (KJ/mol)

0 100 200 300 400 500 600 700 800 900 1000

Temperature (°C)

0 0.26 0.52 0.78 1.04 1.30 1.55

Energy demand (Volt)

Electrical energy demand ($\Delta G_f$)

Heat demand ($T\Delta S_f$)

Total energy demand ($\Delta H_f$)
Thermodynamics

Electrical energy demand ($\Delta G_f$)

$\text{CO}_2 \rightarrow \text{CO} + \frac{1}{2}\text{O}_2$

$\text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2$

$750^\circ\text{C} - 900^\circ\text{C}$

$\Delta G_{\text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2} = \Delta G_{\text{CO}_2 \rightarrow \text{CO} + \frac{1}{2}\text{O}_2}$
Co-electrolysis of H$_2$O and CO$_2$

1 kW - 10-cell stack – 12 × 12 cm$^2$
850 °C, -0.50 (-0.75) A/cm$^2$, 45 % CO$_2$ / 45% H$_2$O / 10 % H$_2$
Electrolyte degradation at high current

Cell with $R_s$ constant (-1 A/cm$^2$)

Cell with $R_s$ increase (-2 A/cm$^2$)

TEM study of the YSZ grain boundaries.... →

Ref. Knibbe et al., J. Electrochem. Soc., 157(8), B1209, 2010

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Electrolyte degradation at high current

TEM of YSZ grain boundary near oxygen electrode from cell tested at -2 A/cm² (Rs increase)

Pore / gaps inbetween YSZ grains in the YSZ close to the electrolyte – oxygen electrode interface observed.
The Pressure Test Setup

850 °C, 50% H₂ + 50% H₂O, Air

Cell voltage / V

Current density / A/cm²

1 bar
10 bar
Synthetic Fuel Production

CO₂ → Purification → 300 °C → Catalyst → H₂O(g) + CO₂ + H₂ + CO → 900 °C → SOEC stack → O₂

H₂O(l) → Recycling → 300 °C → CO + H₂ + H₂O(g) + CO₂

synth. fuel(l) → O₂

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Synthetic Fuel Production Economy

S. D. Ebbesen, S. H. Jensen, A. Hauch and M. Mogensen, to be submitted

9.6 €¢/kWh
Synthetic Fuel Production Economy

1.15 €/L Diesel, EU average excluding taxes


S. D. Ebbesen, S. H. Jensen, A. Hauch and M. Mogensen, to be submitted
SOEC Economy

Søren Højgaard Jensen, Unpublished work

DTU Energy Conversion, Technical University of Denmark
WTI and BRENT Crude Oil price
Conclusions

1. Stable co-electrolysis operation below -1 A/cm²

2. Operation at high pressure makes internal catalysis possible which enables high production efficiency

3. Using Only Cheap Electricity Doesn’t change the synthetic fuel production costs significantly
I wish to thank Colleagues at DTU Energy Conversion for contributions to this presentation
Vision

\[ \text{CO}_2 + 2\text{H}_2\text{O} \leftrightarrow \text{CH}_4 + 2\text{O}_2 \]

\[ \Delta H^o \] / 8F = 1.15 V

\[ \Delta G^{1000\text{C}} / 8F = 1.04 \text{ V} \]
At 15 Mpa and 650 C, a mixture of 85% methane and 15% hydrogen dry gas with small concentrations of CO and CO$_2$ can be produced without producing equilibrium carbon, at V= 1.08 V vs. air.

S. H. Jensen and M. Mogensen, 19th World Energy Congress, Sydney, Australia 2004

\[
\begin{align*}
\text{CO}_2 + 2\text{H}_2\text{O} & \leftrightarrow \text{CH}_4 + 2\text{O}_2 \\
\frac{\Delta H^0}{8F} &= 1.15 \text{ V} \\
\frac{\Delta G^{1000C}}{8F} &= 1.04 \text{ V}
\end{align*}
\]
Vision

LI. Thorup Salt caverns

- 150-200 bar
- 500 mill Nm$^3$ storage
- 5000 mill kWh stored
- 200 M€ CAPEX
## Operating cost and conditions

<p>| | |</p>
<table>
<thead>
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<tbody>
<tr>
<td>Operating pressure</td>
<td>150-200 bar</td>
</tr>
<tr>
<td>Storage capacity (volume)</td>
<td>500 Mio Nm³</td>
</tr>
<tr>
<td>Storage capacity (Energy (CH₄))</td>
<td>5000 GWh</td>
</tr>
<tr>
<td>Cavern CAPEX (CH₄)</td>
<td>200 M€</td>
</tr>
<tr>
<td>Cavern CAPEX (CO₂ + CH₄)</td>
<td>0.08 €/kWh</td>
</tr>
<tr>
<td>Electrolysis/Fuel-cell operation/year</td>
<td>4000 hours</td>
</tr>
<tr>
<td>SOC cost</td>
<td>150 €/kW</td>
</tr>
<tr>
<td>Total SOC CAPEX</td>
<td>200 M€</td>
</tr>
<tr>
<td>Total system CAPEX</td>
<td>600 M€ (0.12 €/kWh)</td>
</tr>
</tbody>
</table>

Assume the return of investment on the storage facility is 5 years, the round trip efficiency is 70% and that the storage facility buys electricity during the summer (4000 h) at a cost of 9.6 €¢/kWh. Then the storage facility will be able to sell electricity during the winter periods (4000 h) for 14 €¢/kWh.