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Reversible Solid Oxide Cells for Energy Storage

Prof. Rob Braun, Evan Reznicek
Department of Mechanical Engineering
College of Engineering & Computational Sciences
Colorado School of Mines
Golden, CO USA
(http://aes.mines.edu)

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GCEP
Global Climate & Energy Project
STANFORD UNIVERSITY

AESG
Advanced Energy Systems Group

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’

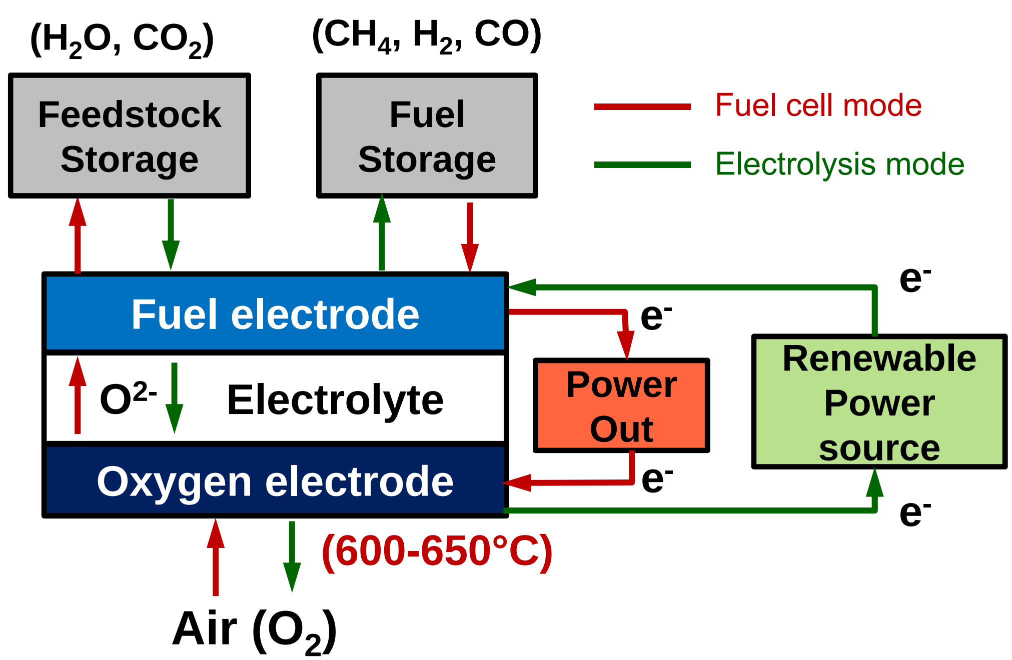
- 100 kW / 800 kWh

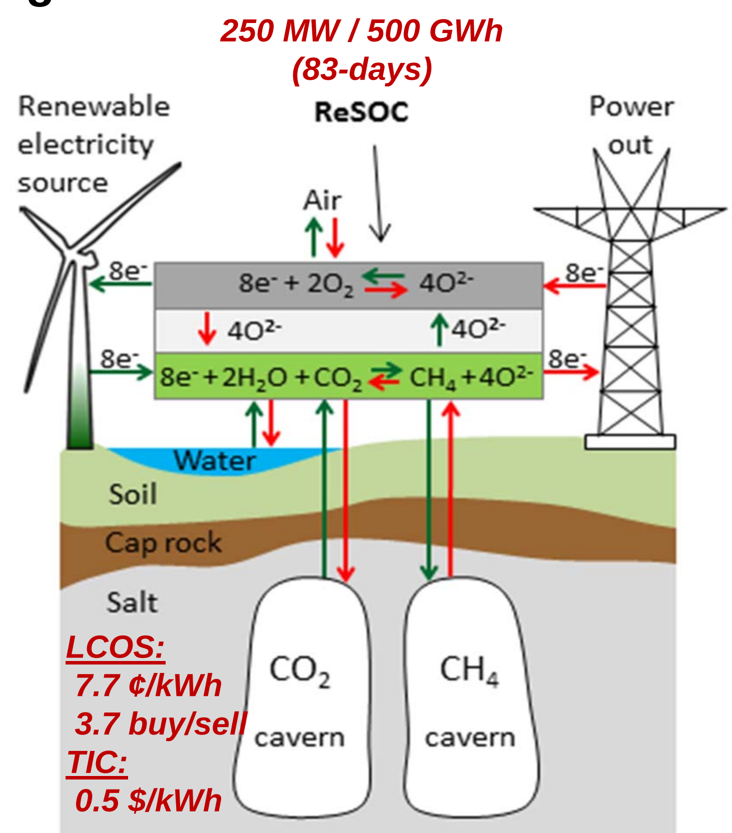
IV. Techno-Economic Outlook

- 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 <u>and</u> energy dense fuels



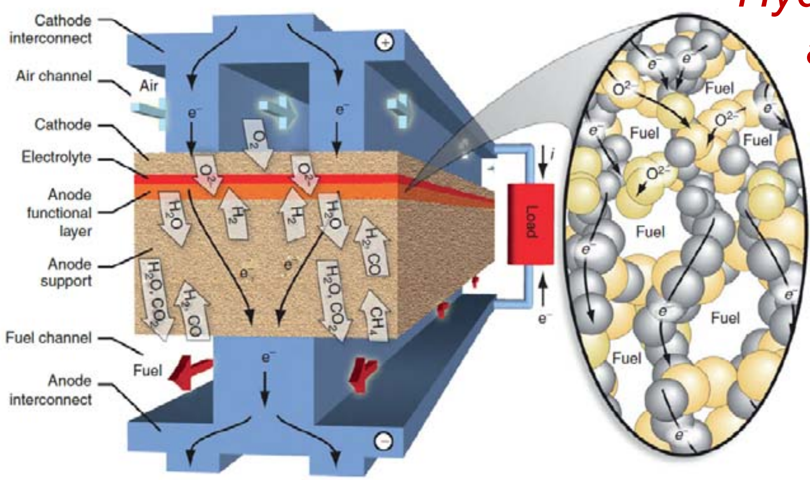


Grid-scale ReSOC Concept*

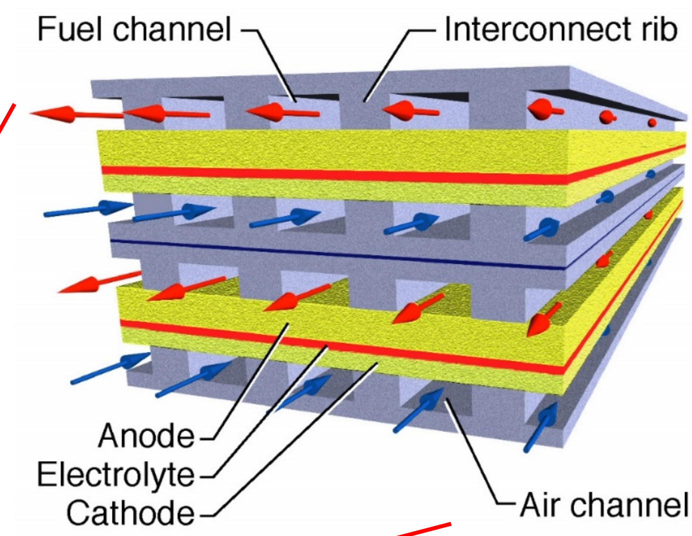
**Figure (right):* Jensen, Graves, Wendel, Braun, et al., *Energy & Env Sci (2015)*

High temperature fuel cell systems are comprised of cell-stack hardware and balance-of-plant equipment

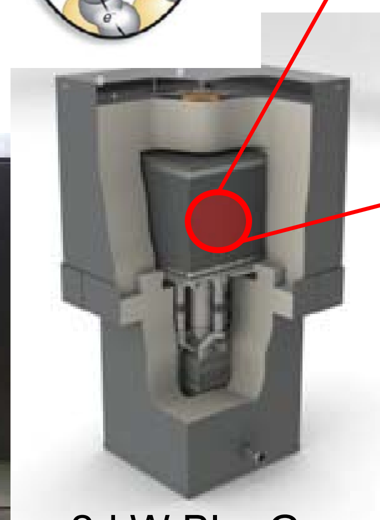
Ni-YSZ | YSZ | LSCF (~800°C)



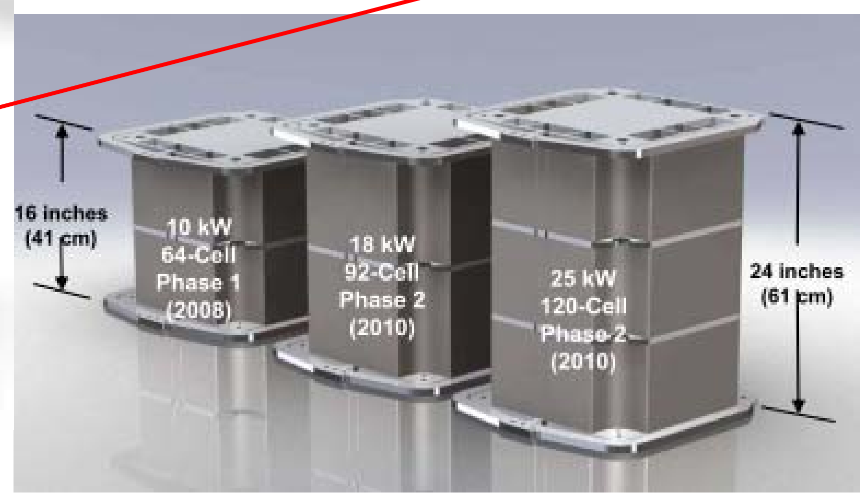
Hydrocarbons allowed



100-kW Bloom Box (SOFC)



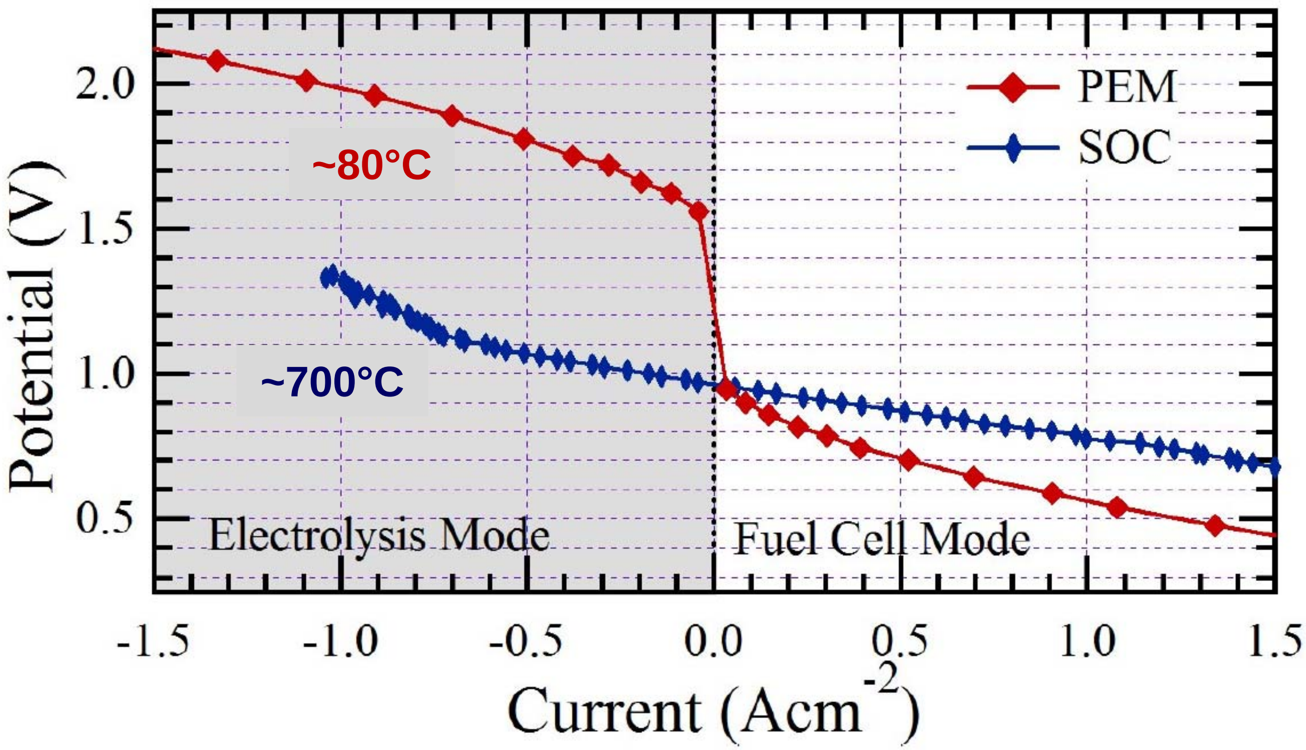
2-kW BlueGen CFL (SOFC)



10-25 kW stacks Fuel Cell Energy (SOFC)

*Figure: Kee et al., Proc. Combustion Institute **30** (2005)*

High temperature reversible SOCs are more suitable for energy storage than PEM cells



H2 – H2O system

$$\eta_{RT} = \frac{V_{FC}}{V_{EC}}$$

@ 0.5 A/cm^2,

SOC : $\eta_{RT} = 81\%$

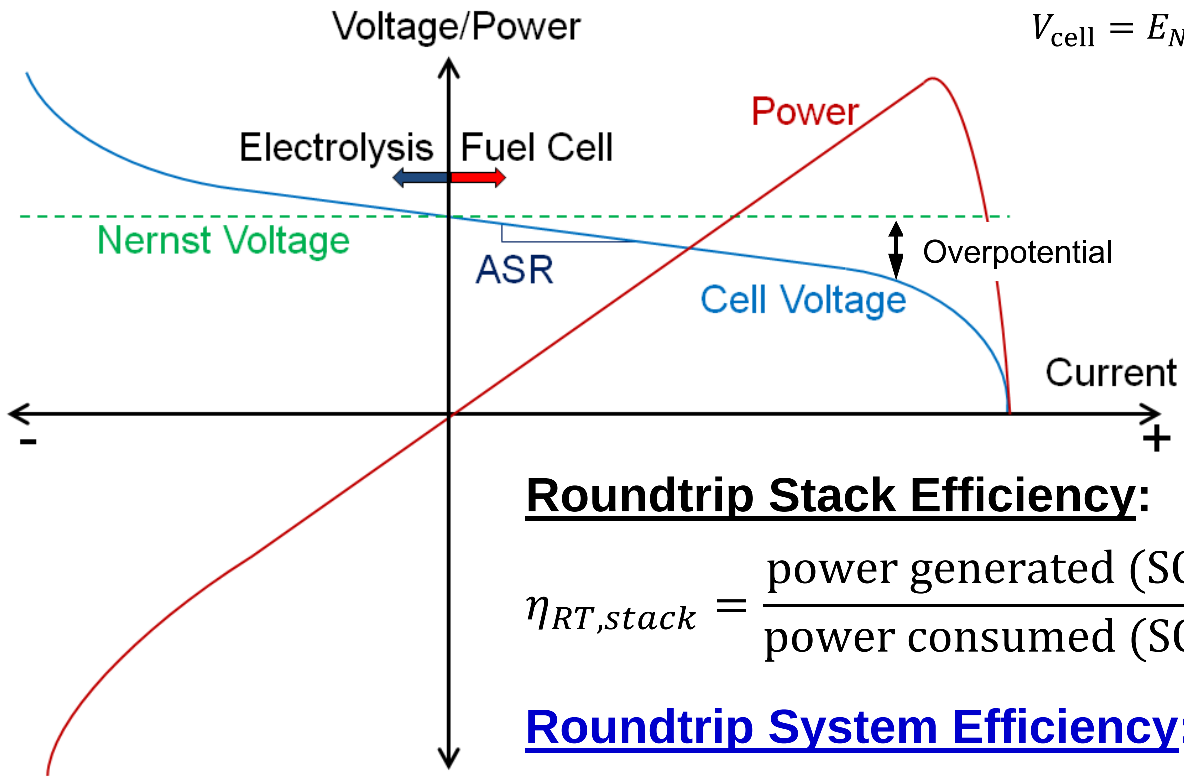
PEM : $\eta_{RT} = 39\%$

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

G.Chen, et al., *Electrochem. Comm.*, **10**(9):1373–1376 (2008).

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

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



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

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

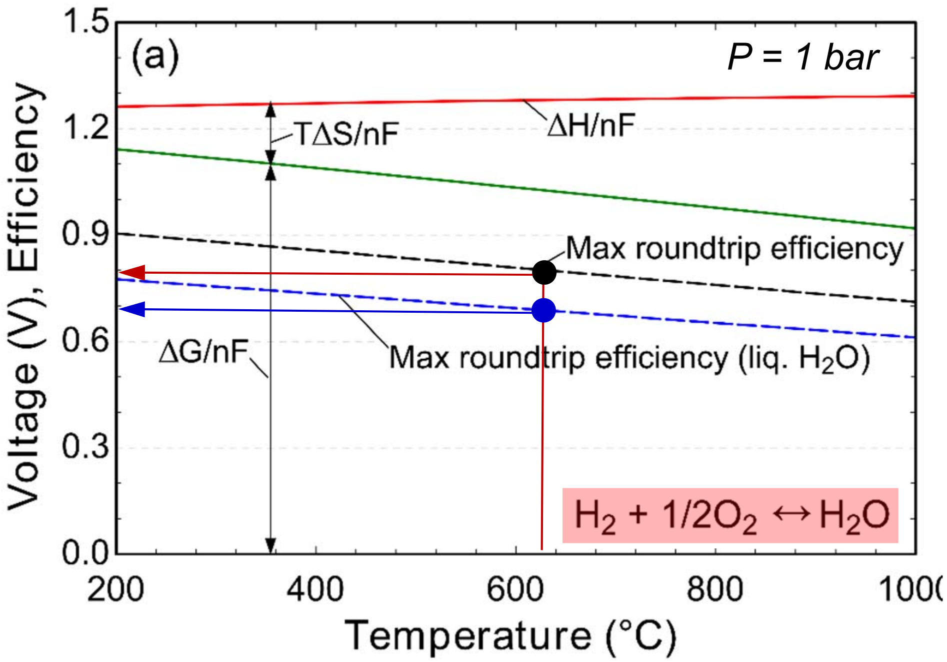
Roundtrip System Efficiency:

DOE target: 80%

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

- **How can we improve system efficiency?**
  1. Reduce overpotential (cell/stack performance - ASR)
  2. Reduce balance of plant power (system design & operation)

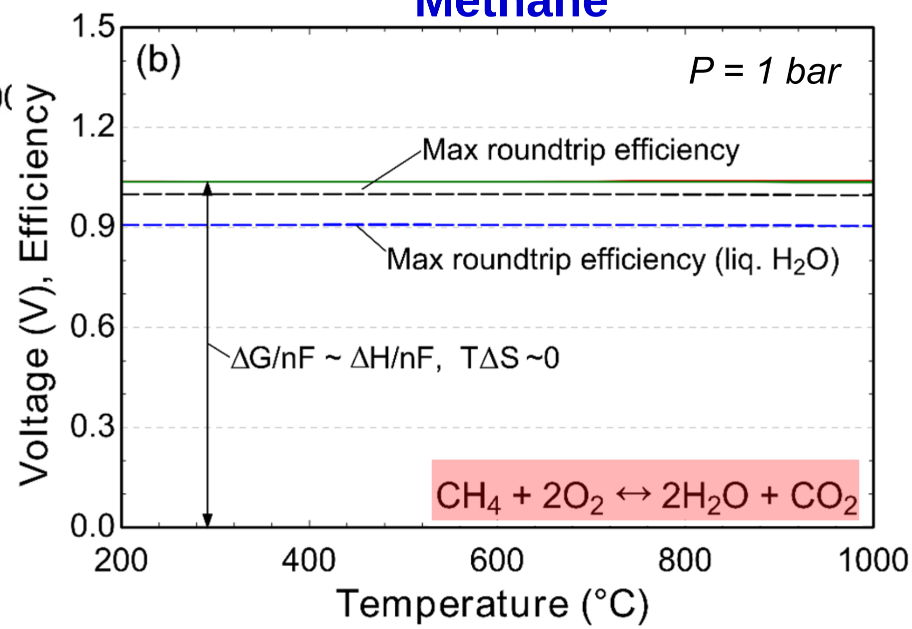
Thermodynamics suggest maximum roundtrip efficiencies are higher with CH_4 / H_2O than H_2 / H_2O systems



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

- Maximum roundtrip efficiency < 80% at 625°C and above
- When considering evaporative load, $\eta_{\mathrm{RT,max}}$ < 70%

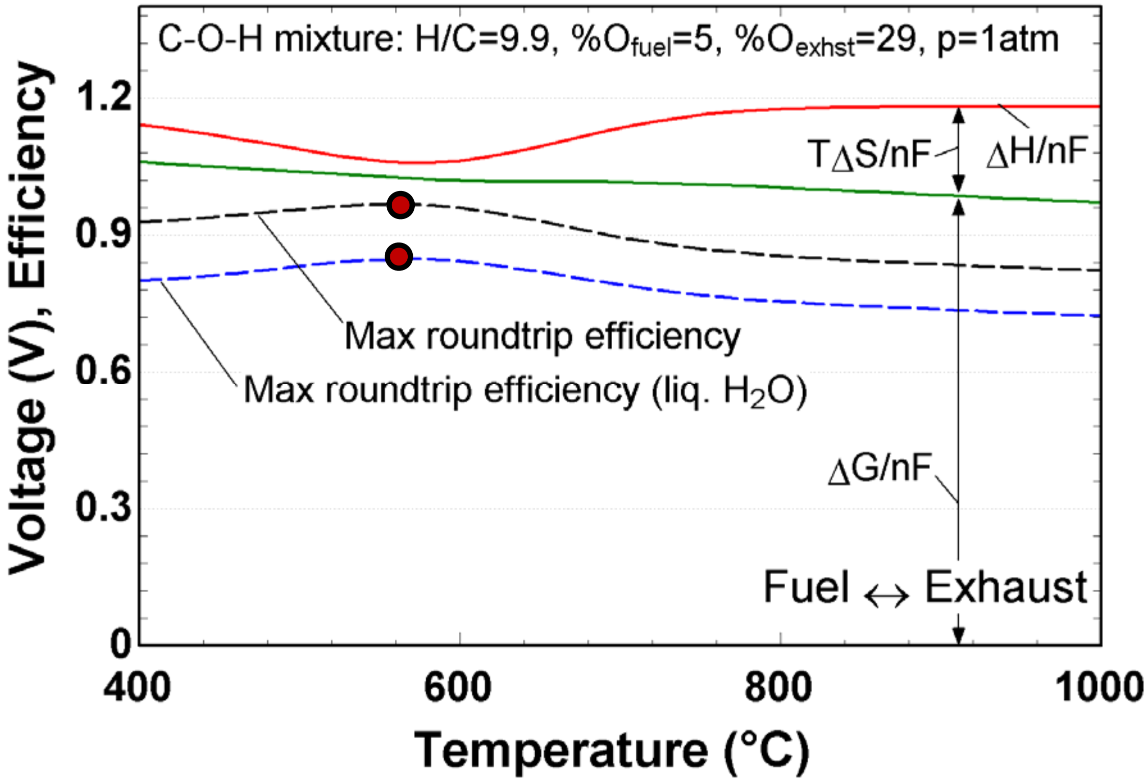
Methane



- Maximum roundtrip efficiency ~100% at all temperatures
- ~10% efficiency reduction when considering liquid H_2O

Wendel and Braun, *Applied Energy* **172** (2016)

Direct CH_4 red-ox cannot be executed, thus practical gas compositions and utilization reduce maximum efficiency



	SOEC	%	SOFC
H_2	35.0		65.0
CO	2.9		1.5
CH_4	1.6		22.0
H_2O	47.7		10.9
CO_2	12.8		0.6

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

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

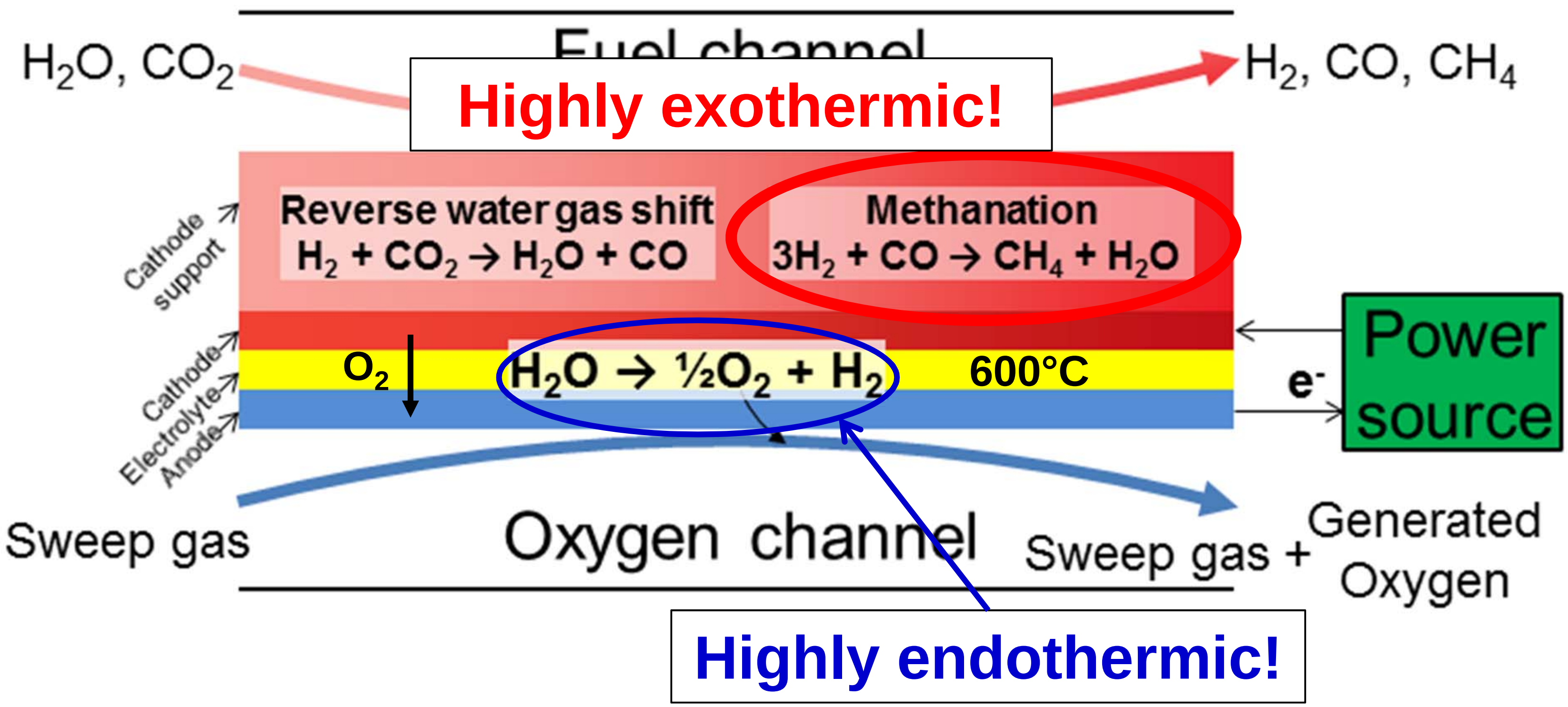
Wendel and Braun, *Applied Energy* **172** (2016)

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

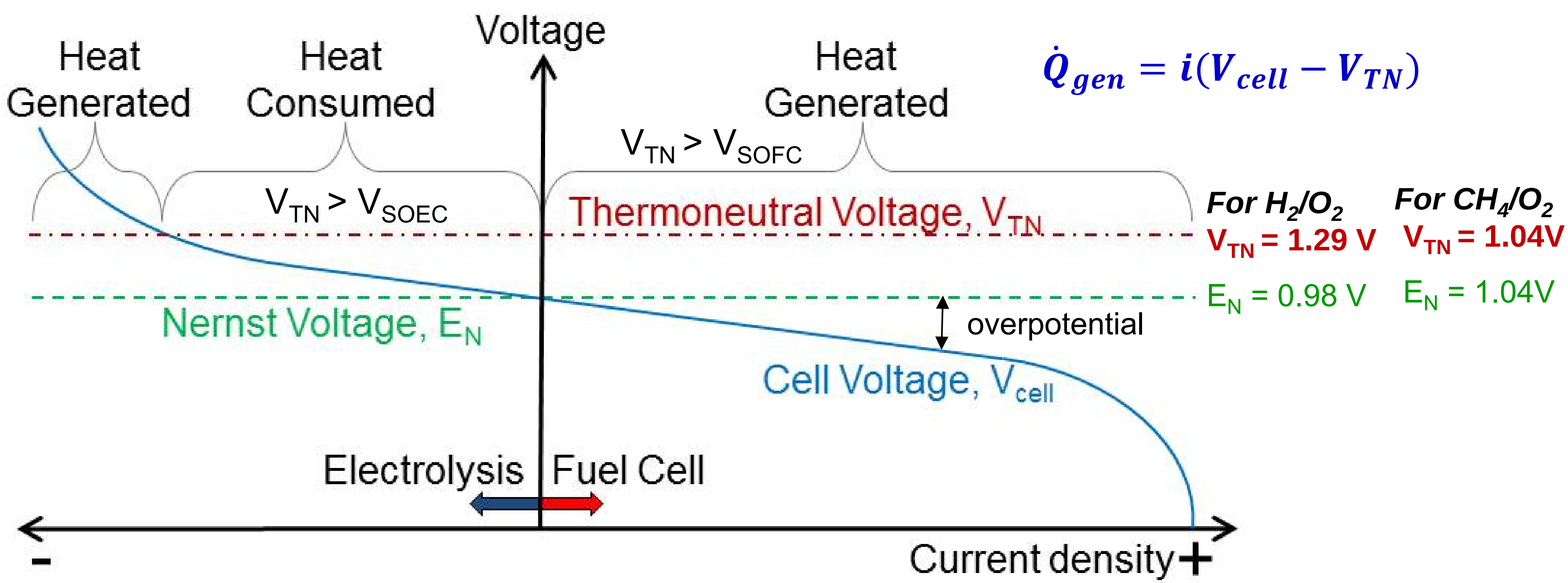
Methanation promoted by:
- Low temperature
- High pressure

SOEC mode reactions



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



Cell-stack electrochemical model is calibrated to next-gen ReSOC performance data and extrapolated

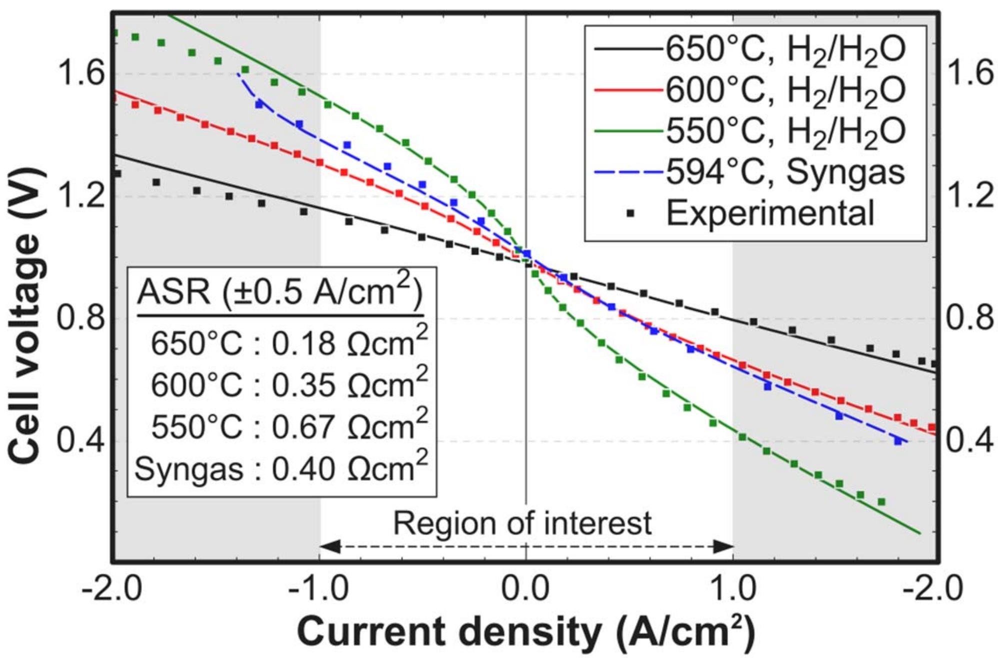
Electrochemical parameters derived from button-cell calibration are applied to a 1D channel level model

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

Ohm's law → η_{ohmic}

Bulter-Volmer equation → η_{act}

Fickian diffusion → η_{conc}



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

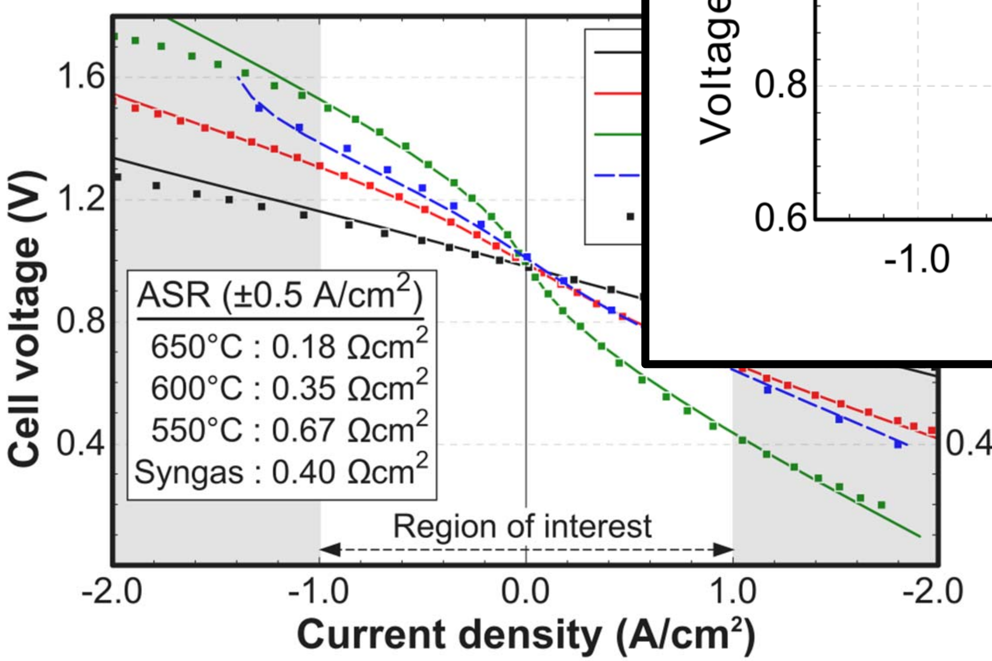
*see Wendel et al., *J. Power Sources*, **283**:329-42, (2015).

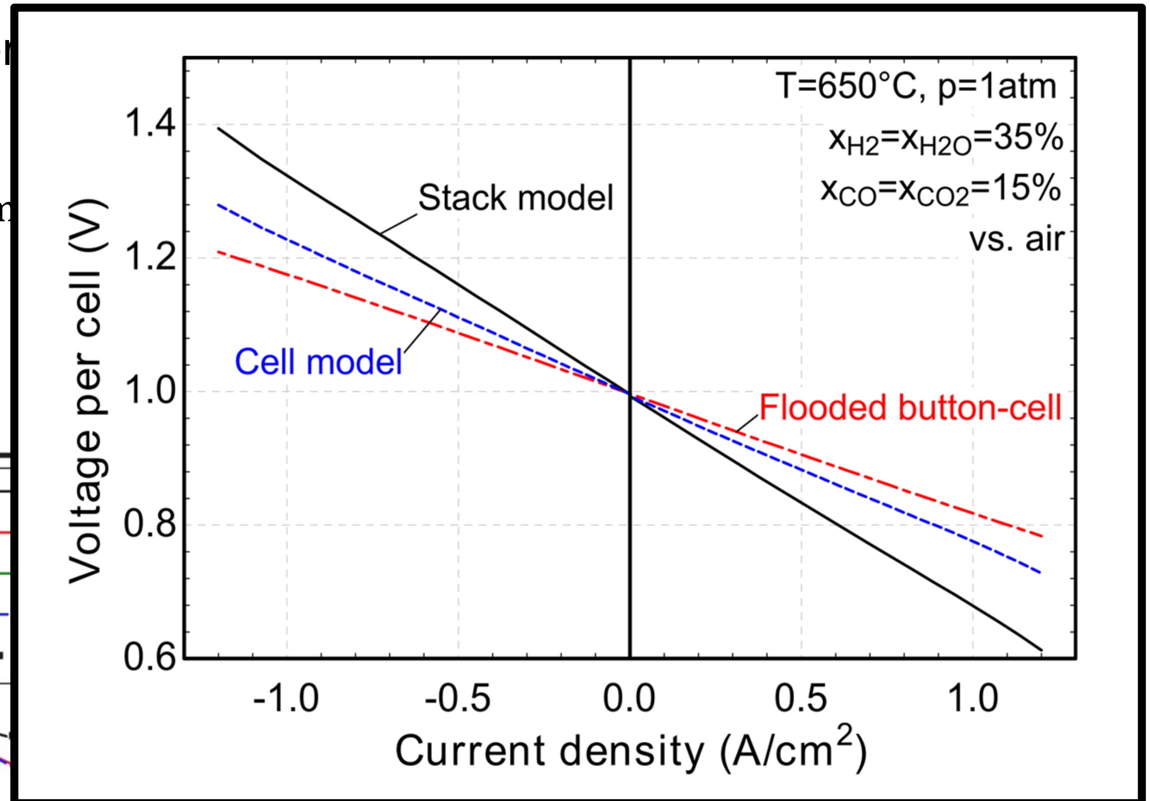
Cell-stack electrochemical model is calibrated to next-gen ReSOC performance data and extrapolated

Electrochemical parameters der
channel level model

$$V_{\text{cell}} = E_N(T, p, x_i) - (\eta_{\text{ohm}}$$

Ohm's law





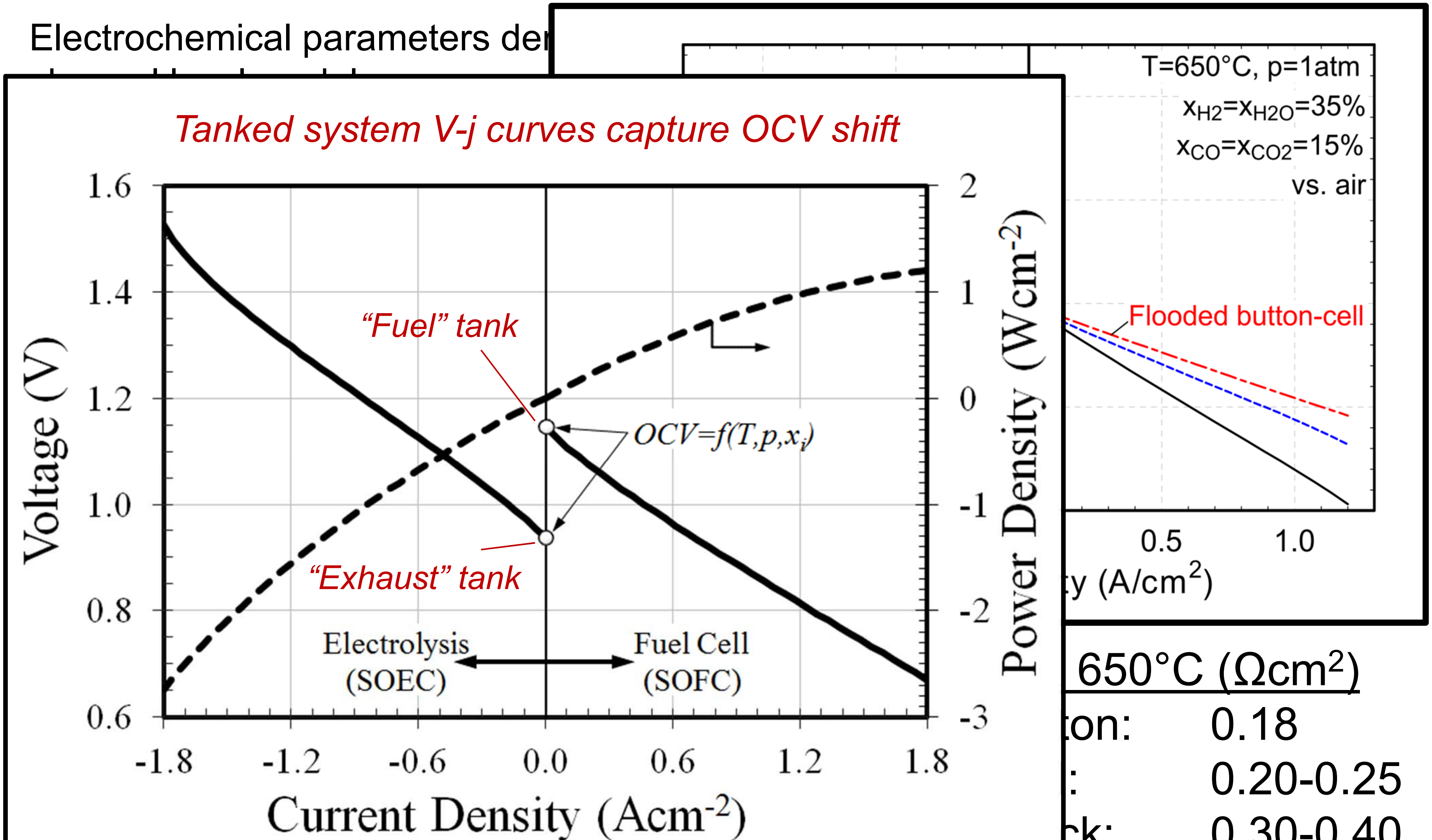
ASR @ 650°C (Ωcm^2)

Button:	0.18
Cell:	0.20-0.25
Stack:	0.30-0.40

*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 de



650°C (Ωcm²)

ton:	0.18
:	0.20-0.25
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*see Wendel et al., *J. Power Sources*, **283**:329-42, (2015).

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

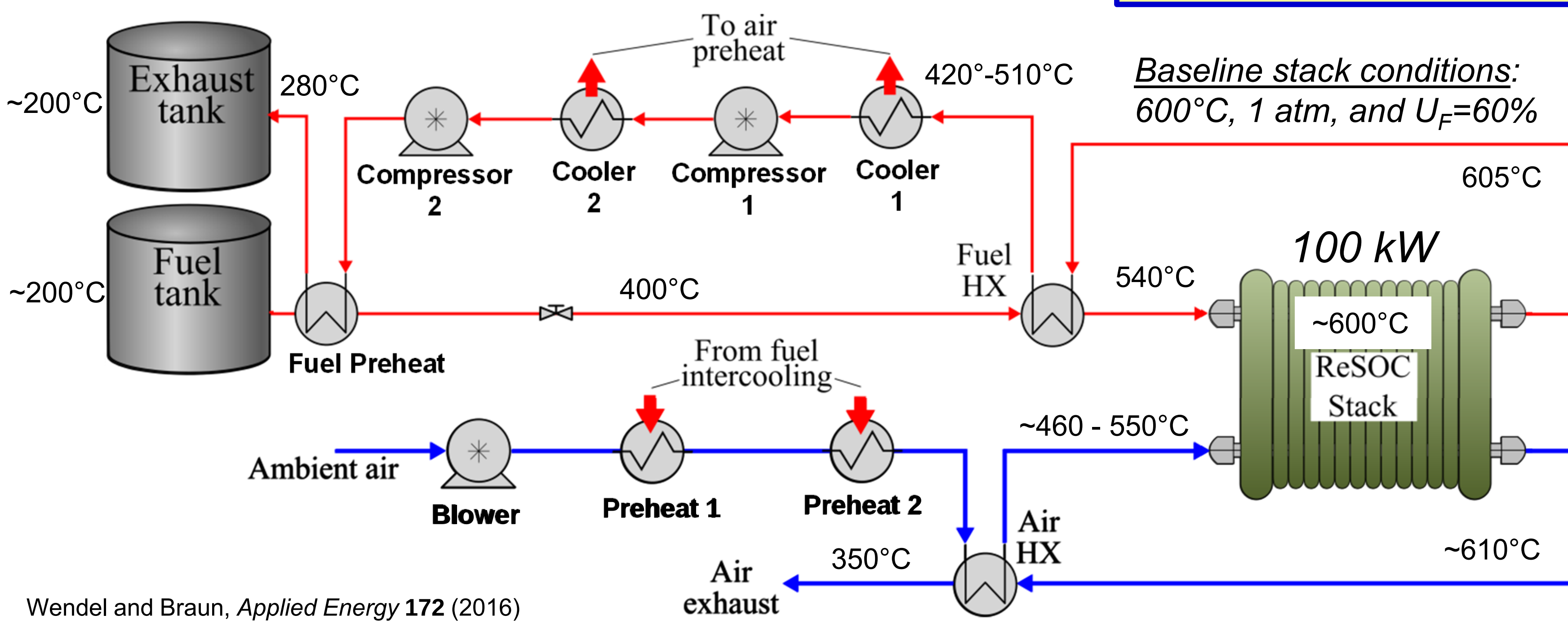
Baseline Results:

– Roundtrip efficiency: 65 - 70% (expander)

– Energy density (ϵ_{st}): 19 - 40 kWh/m³ (tank pressure)

Trade-space Variables:

1. Reactant utilization
2. Stack vs. Tank pressure
3. Water management



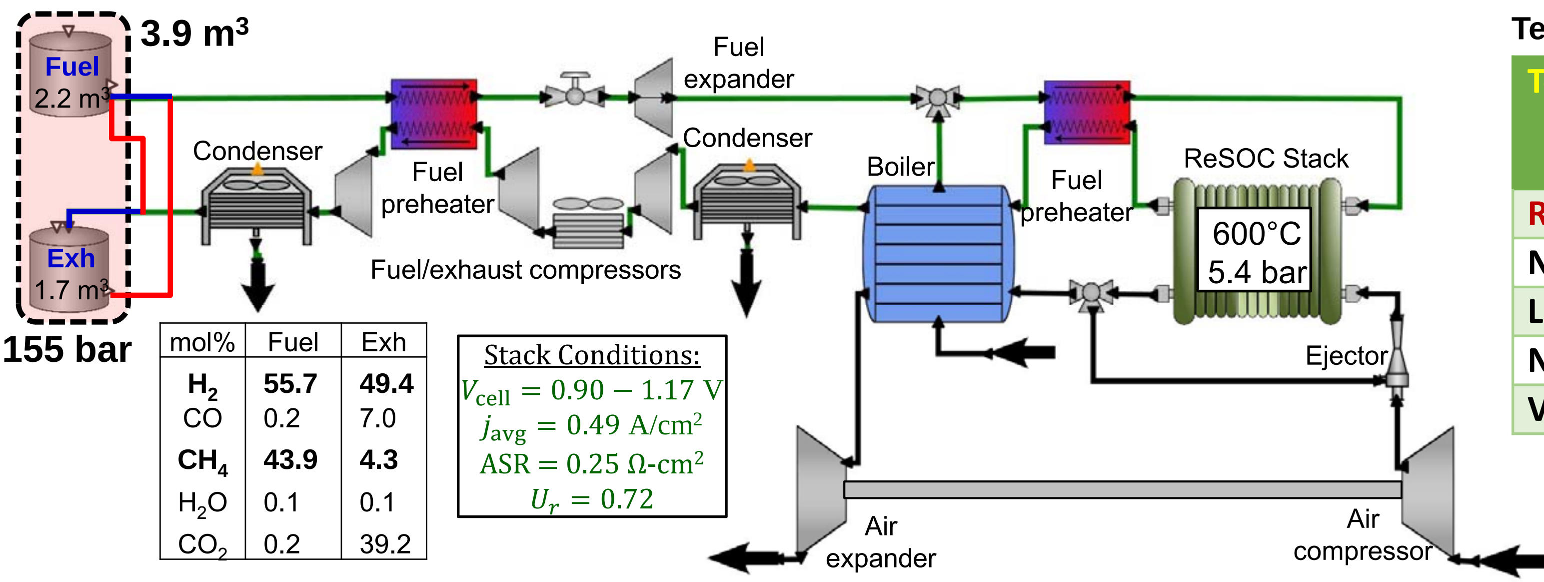
Wendel and Braun, *Applied Energy* **172** (2016)

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

- Pressurized stack, 155-bar H_2 tanks
- Design enables dual-mode operation
- Levelized cost and efficiency still challenged to meet DOE long-term targets
- Cost compares well vs other technologies

Metric	ReSOC value	DOE target
Stack roundtrip efficiency (%)	75.2	
System roundtrip efficiency (DC-DC) - %	66.2	
System roundtrip efficiency (AC-AC) - %	59.8	80
Energy density (kWh/m³)	205	
Total capital cost ($/kWh)	197	
Total installed capital cost ($/kWh)	414	150
Levelized cost of storage (LCOS – ¢/kWh)	22.4	10

- Tank cost is 25% of capital in this analysis



mol%	Fuel	Exh
H_2	55.7	49.4
CO	0.2	7.0
CH_4	43.9	4.3
H_2O	0.1	0.1
CO_2	0.2	39.2

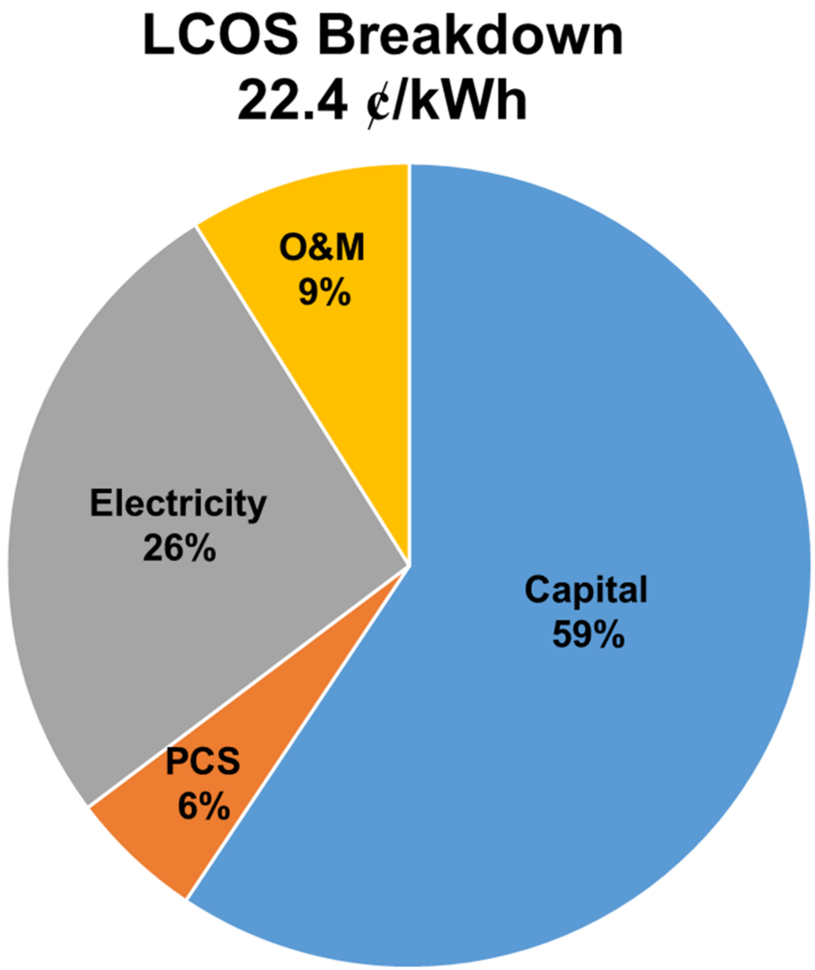
Stack Conditions:
$V_{cell} = 0.90 - 1.17$ V
$j_{avg} = 0.49$ A/cm²
ASR $= 0.25$ Ω-cm²
$U_r = 0.72$

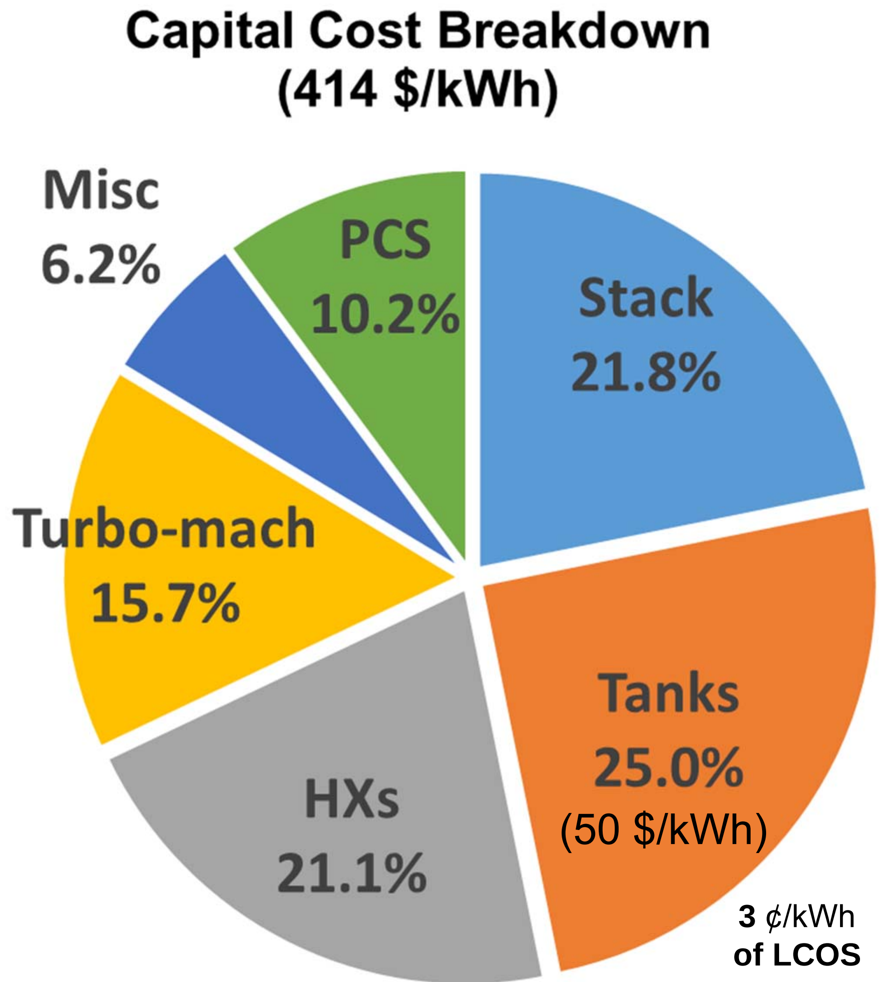
Technology Comparison[2]

Technology	LCOS (¢/kWh)
ReSOC	21-60
Na-Ni-Cl	31-62
Li-Ion	70-180
Na-S	20-36
Va-Redox	41-56

[1]U.S.Dept. of Energy, Grid Energy Storage Report, Dec. (2013).
[2]A.A. Akhil et al (2013). DOE/EPRI 2013 Electricity Storage Handbook, SAND2013-5131

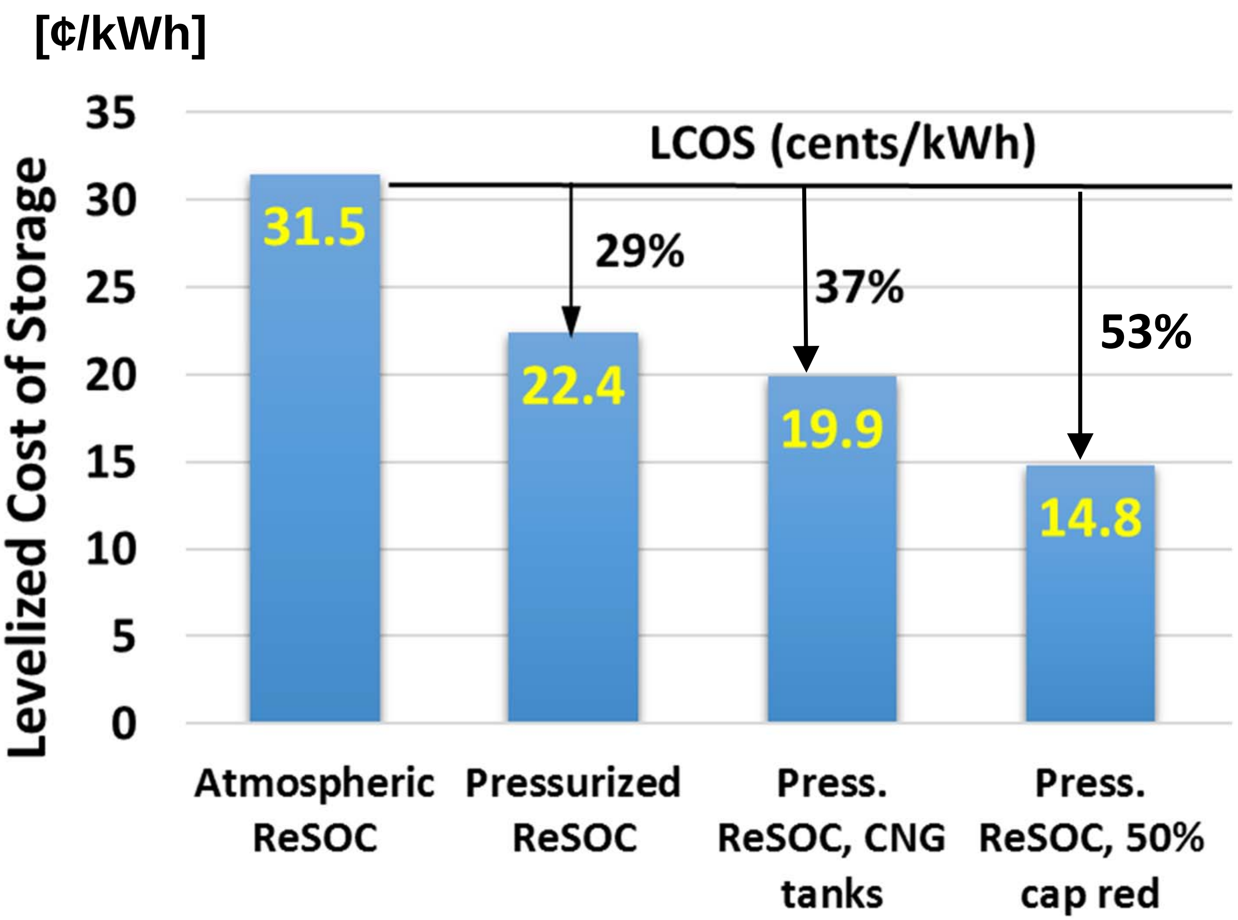
100 kW / 800 kWh ReSOC Energy Storage Cost Distributions





Hydrogen-tanks = $10,100/m^3$
Electricity cost = 3.5 ¢/kWh
65% capacity factor

Pressurization, tank cost reduction, improve economics



How to get capital cost reduction?

$$\mathrm{LCOS} = \frac{\Sigma_j \mathrm{TIC}_j \left(\frac{d}{1-(1+d)^{-N_j}}\right)}{E_{\mathrm{cyc}} n_{\mathrm{cyc,ann}}} + \frac{P_{\mathrm{elec}}}{\eta_{\mathrm{RT,AC}}} + C_{\mathrm{O\&M}}$$

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)

Acknowledgements

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Dr. Robert Kee (CSM)

Dr. Scott Barnett (Northwestern University)

Braun Advanced Energy Systems Research Group (http://aes.mines.edu)