Versatile Reversible Solid Oxide Cell System for Hydrogen and Electricity Production

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Nexceris Mission

Our vision is to create a better world through energy innovations.

We collaborate with leading global customers and partners to transform powerful ideas into solutions that make energy production safer, more efficient, and environmentally responsible.

The Value of Nexceris

Nexceris is Vertically Integrated for SOC Development

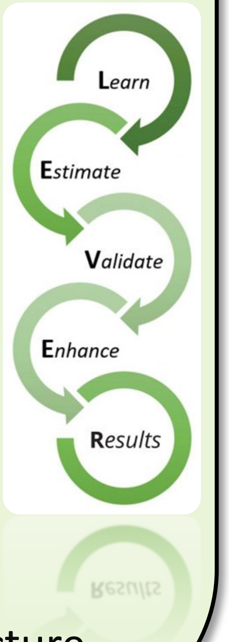
Products

- ***Fuel Cell Materials*** provides standard and custom SOC materials and components
    - Powders
    - Inks
    - Substrates
    - Cells

- We work with customers to provide materials and components from lab-scale to industrial-scale
- Quickly and accurately tailor powders and components to fit the needs and processes of our customers

Services

- Joint development and contract R&D services
- Leveraging our expertise and 25+ years of know-how in the SOC industry
- Accelerate customer development timelines on material, cell, and stack levels
- Our facilities accommodate a variety of synthesis and testing methods
- Fast-paced, versatile development structure



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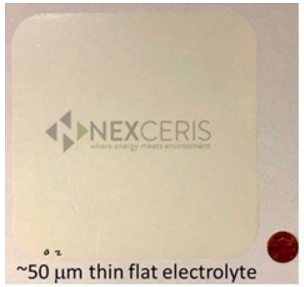
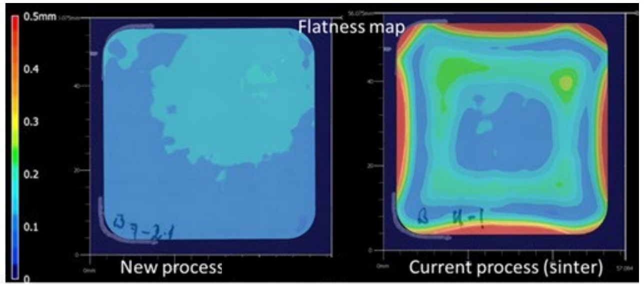
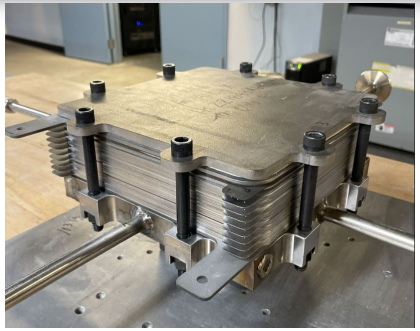
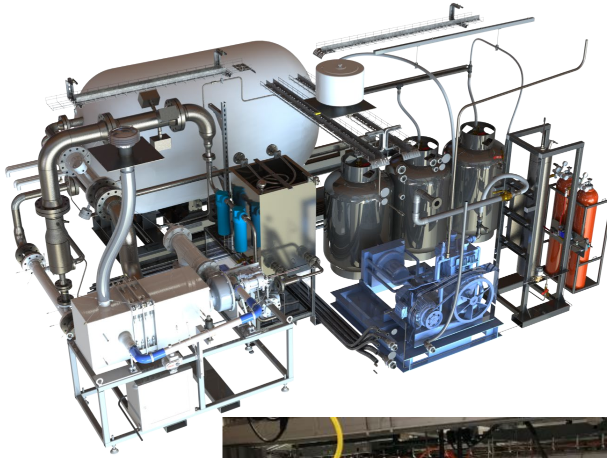
Nexceris Active Projects





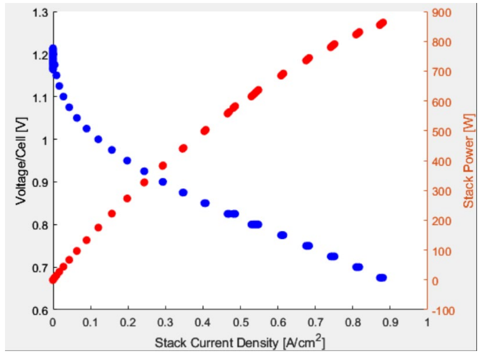


Low-Cost Manufacture of SOEC Stacks
[DE-EE0009621]

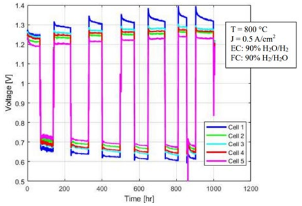


SOFC/Turbine Hybrid Power System
[DE-AR0000956]

High Power Density Anode Supported Cells
[DE-AR0001774]



Reversible Solid Oxide Cell for H_2 and Electricity
[DE-FE0031986]



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Versatile Reversible Solid Oxide Cell System for Hydrogen and Electricity Production (DEFE0031986)

Project Objectives

≥ 1kW_e power generation in fuel cell mode with roundtrip stack efficiency (RTE) of ≥ 60%.

Achieve dynamic switching between modes in response to grid demands (6-hr cycles).

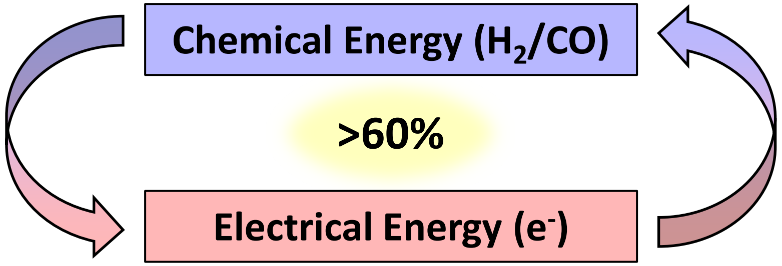
Achieve long-term electrolysis and define a path to produce H_2 at ≤ $2/kg (at scale).

Demonstrate versatile fuel composition in electrolysis mode (H_2O + CO_2).

System Design

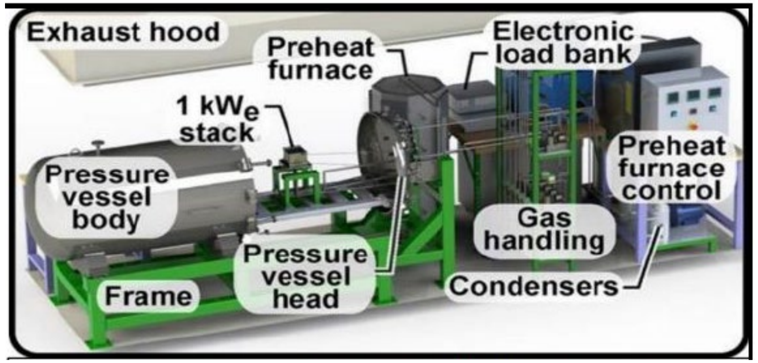
Pressurized System to Increase RSOC Stack Efficiency

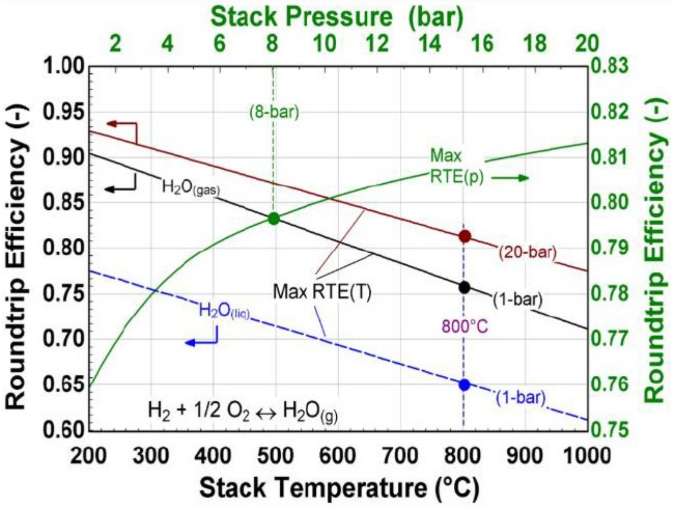
- Theoretical round-trip-efficiency (RTE) of the stack is a function of **temperature** and **pressure**

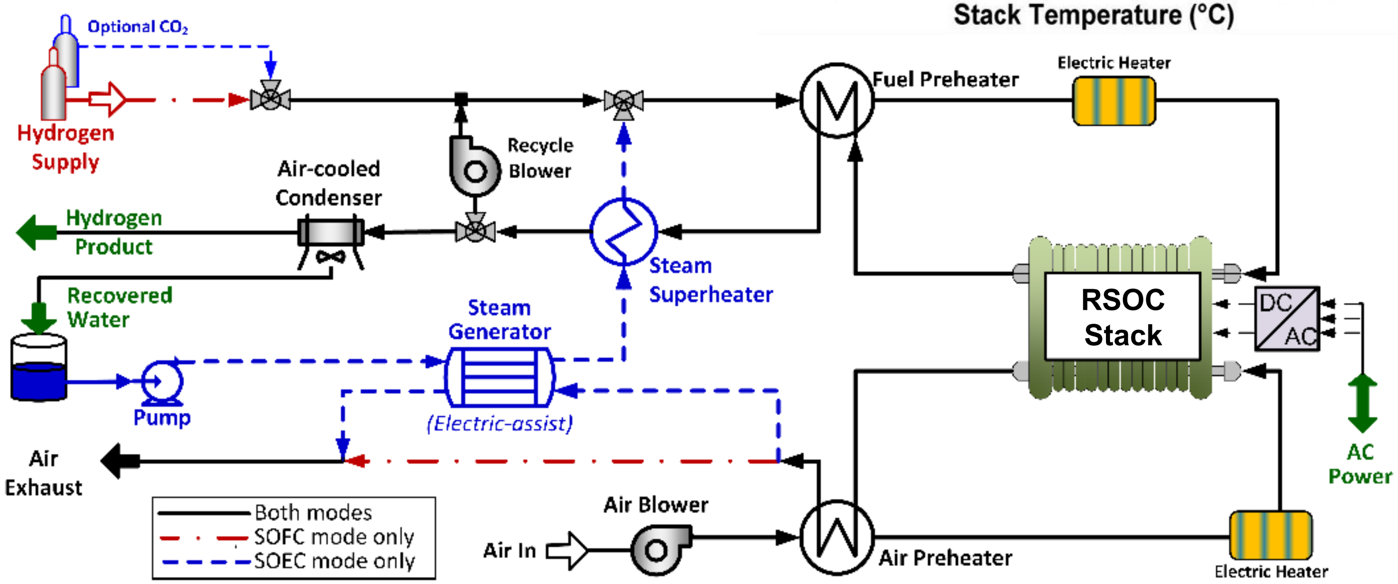


- RTE *increases* with **pressure**
  - Stack performance (kinetics, mass transport) also expected to increase with pressure

- Majority of RTE increase is gained up to ~8bar







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System Design

Major Challenges and Goals for Proposed System

Electrode Performance & Stability

Cell performance → >1Acm^{-2}

Cell durability → 0.5%/1000hrs

Dynamic switching

Stack Validation & Co-Electrolysis

Dynamic (6hr) stack cycling

Stack RTE > 60%

Co-electrolysis exhaust analysis with GC

System Demonstration

Pressurized BOP construction at CSM

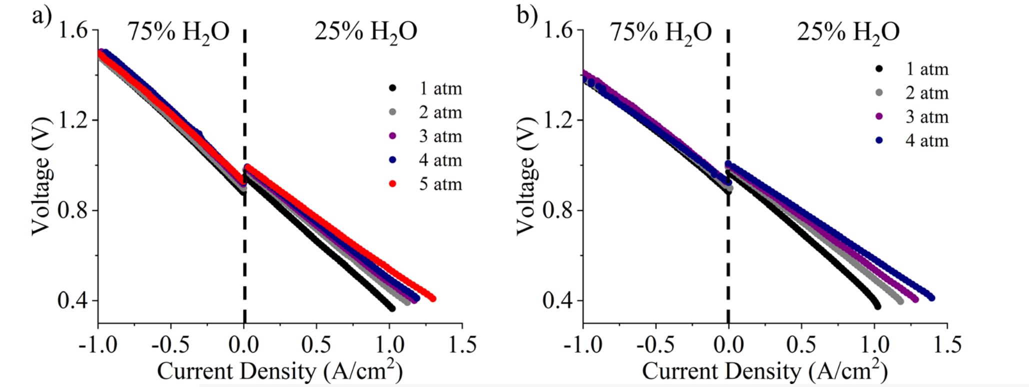
Ambient BOP construction at Nexceris

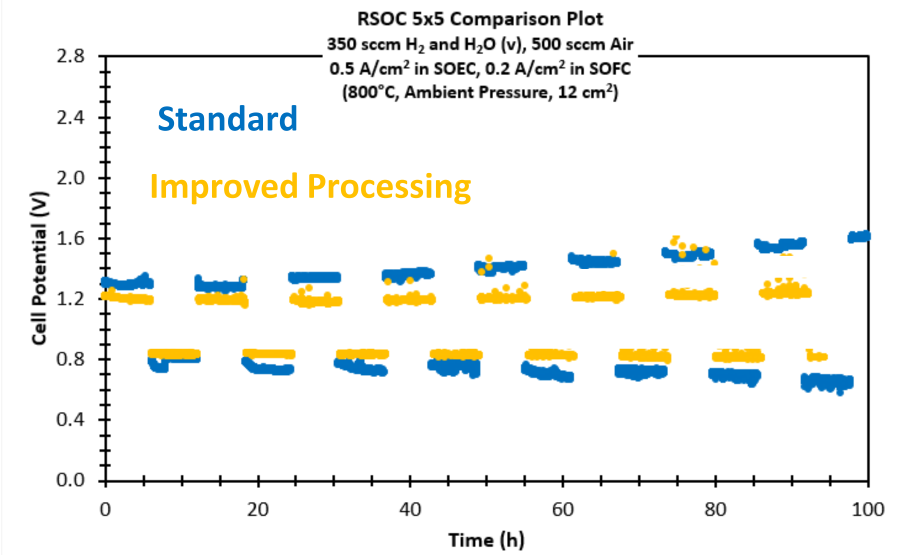
1kW$_e$ with 60% stack RTE at 0.7 Acm^{-2}

Electrode Performance & Stability

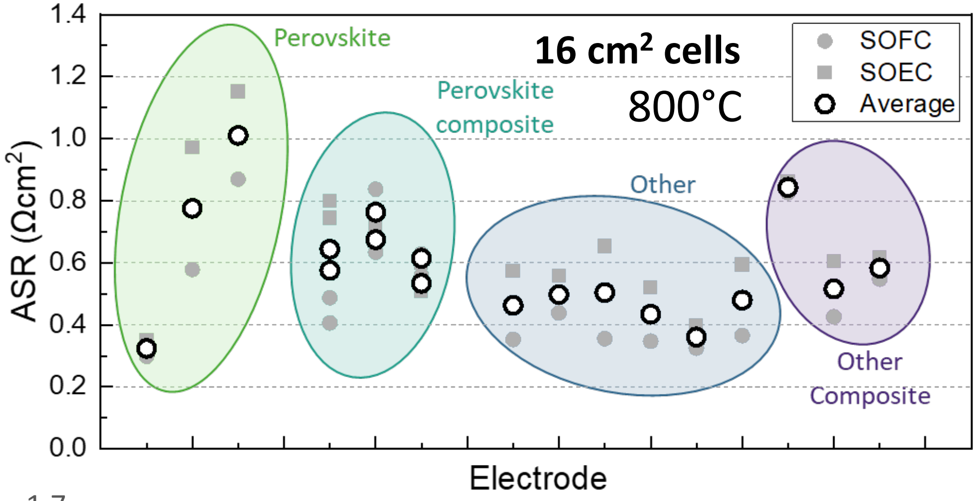
Electrode Evaluation for SOEC/SOFC

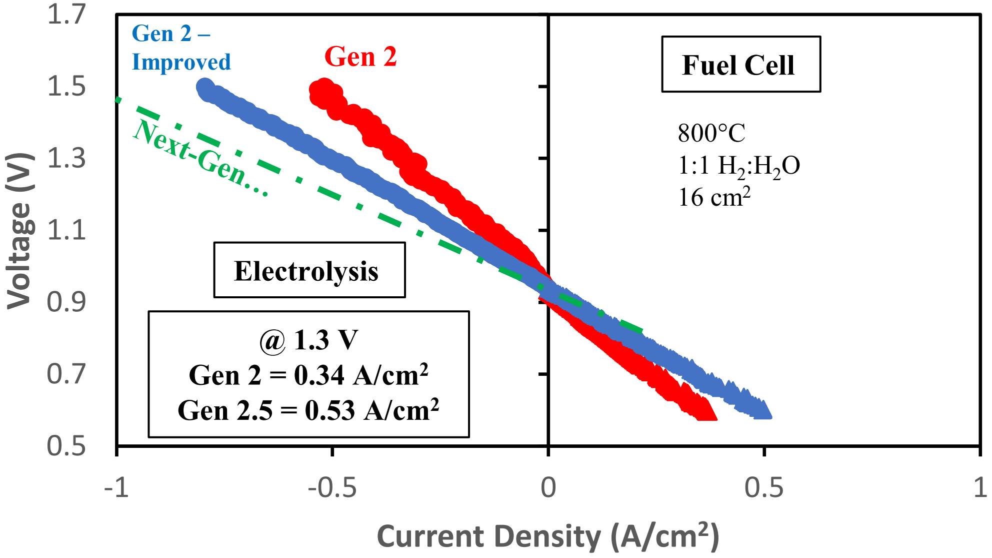
Developing & Understanding Pressurization





Screening & Scaling High Performance





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Stack Level Performance & Stability

RSOC 1000 hr durability 5-cell Stack

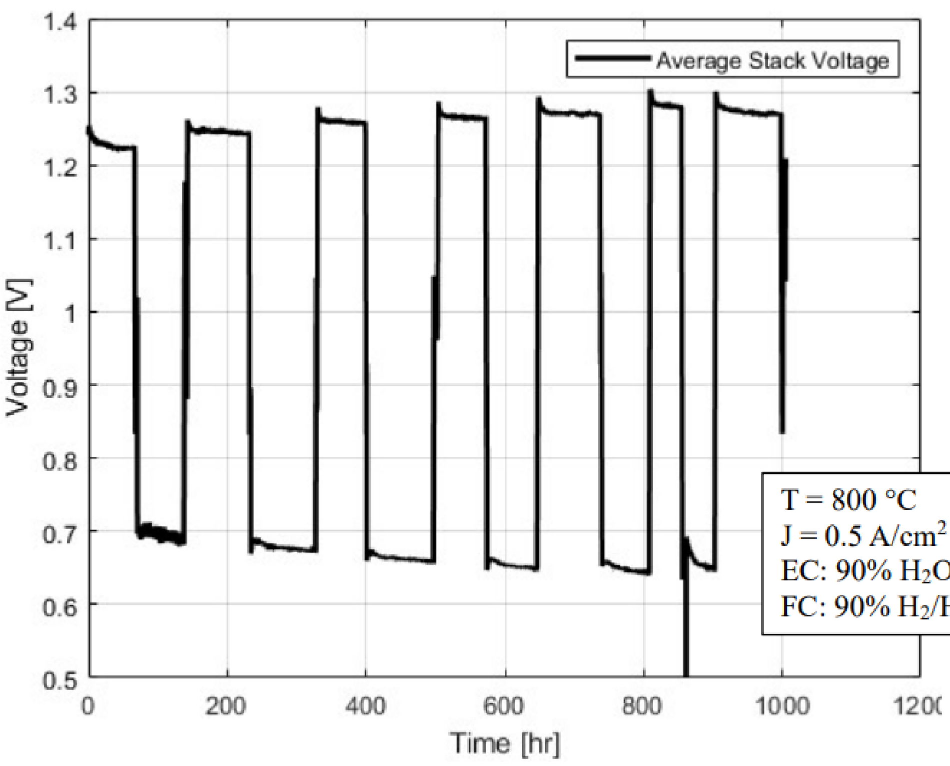
RSOC Durability testing on ESC cells is underway at Nexceris

At 50 hr/cycle rate the average stack RTE decreased ~9% after 1,000 hrs of testing

Co-electrolysis collected after durability

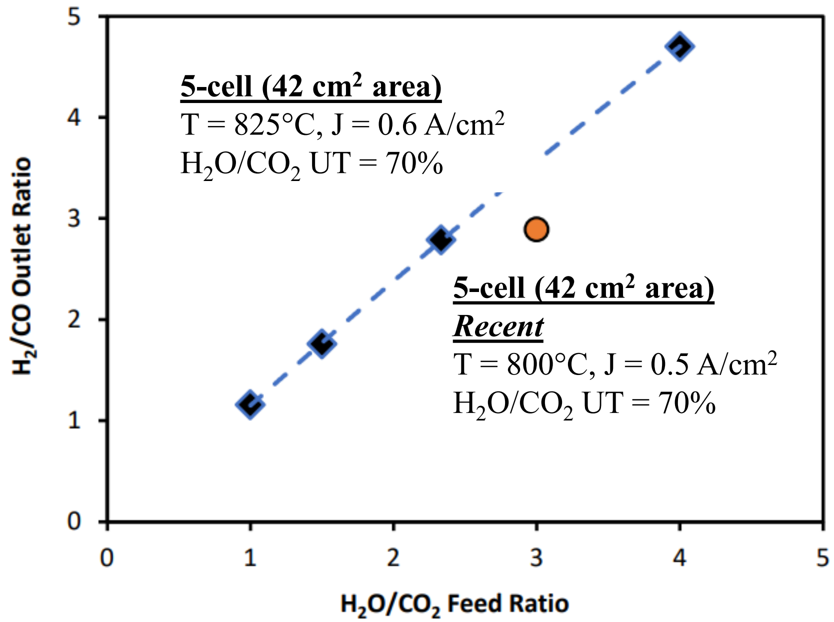
Highlights utility of small-scale stacks for durability data

Temperature	Current Density (both modes)	Fuel: Product	Cycle Rate
800°C	0.5 A/cm^2	9:1	50 hr/cycle



Cell ID	Initial RTE	Final RTE
Stack Avg	56.4%	51.3%

Co-Electrolysis Testing



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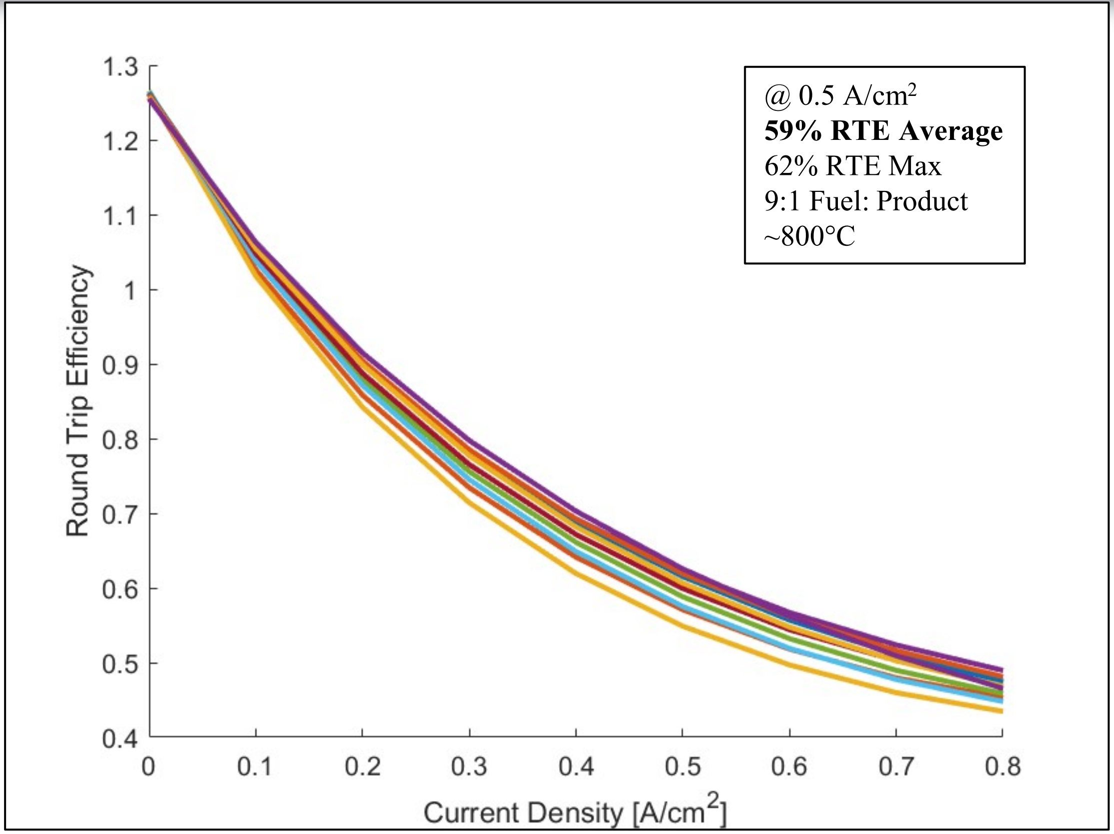
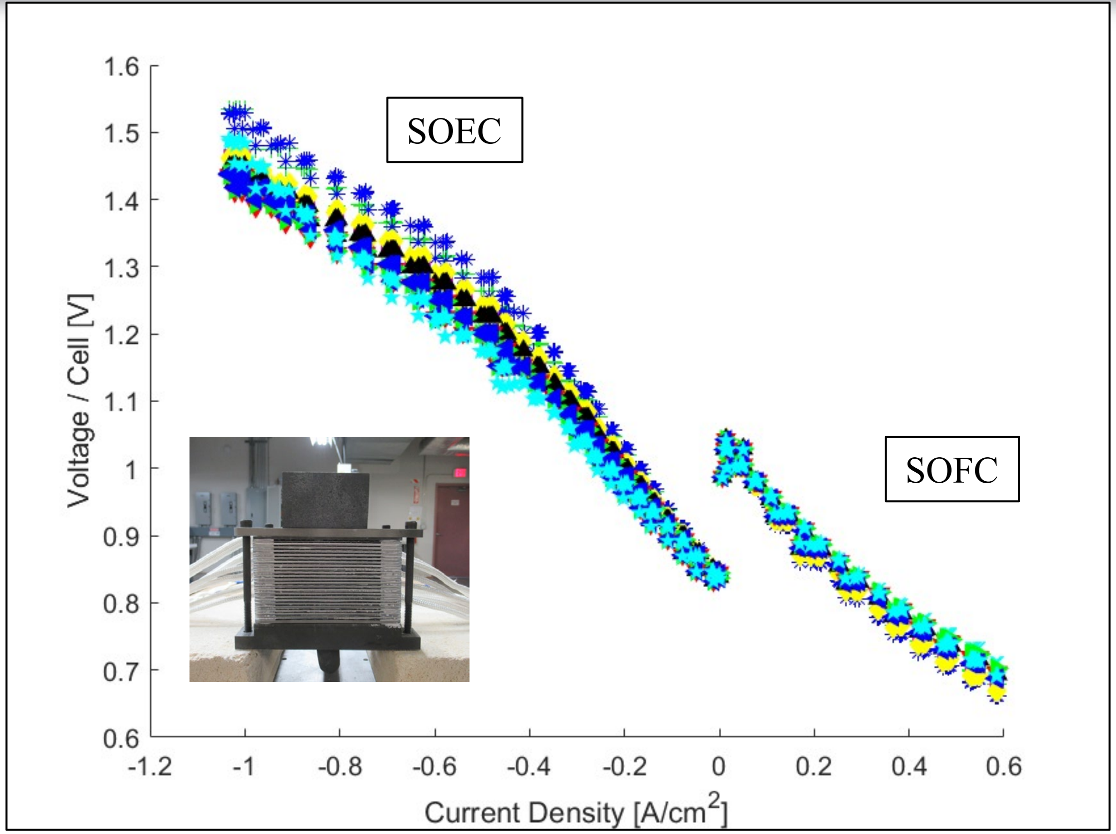
Stack Level Performance

RSOC Performance 24-cell Stack (1 kW scale)

9:1 Fuel: Product
~800°C





24-cell ESC-based, 91 cm² active area.

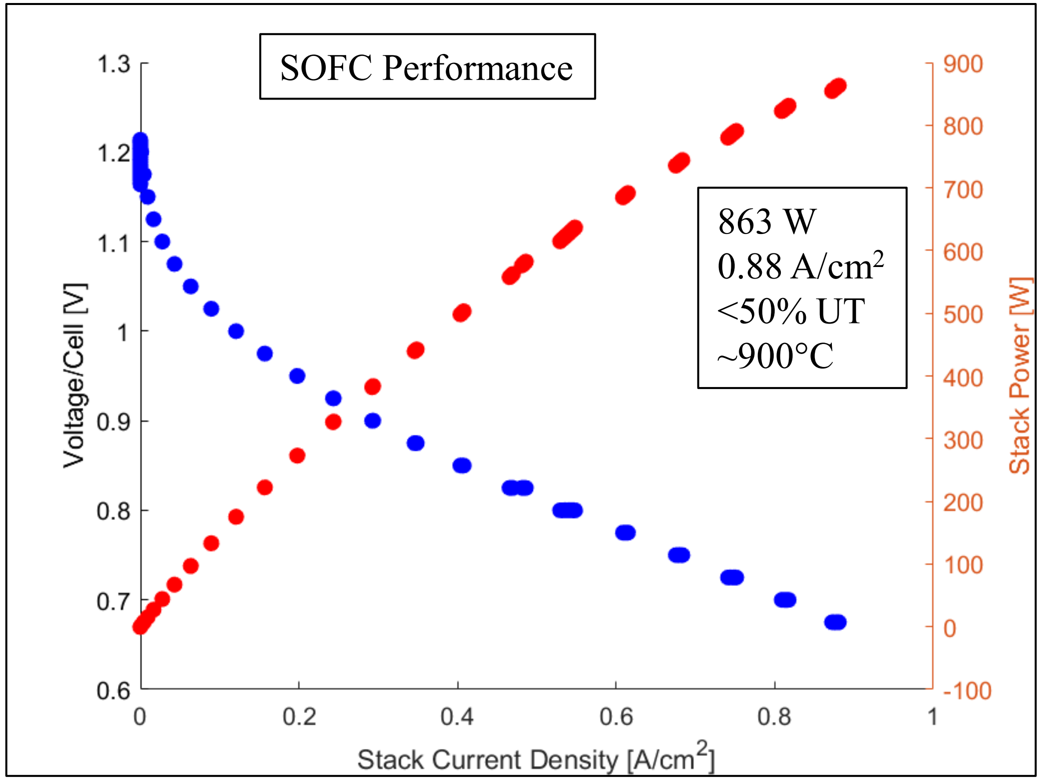
Stack design and cells to be used for demonstration system

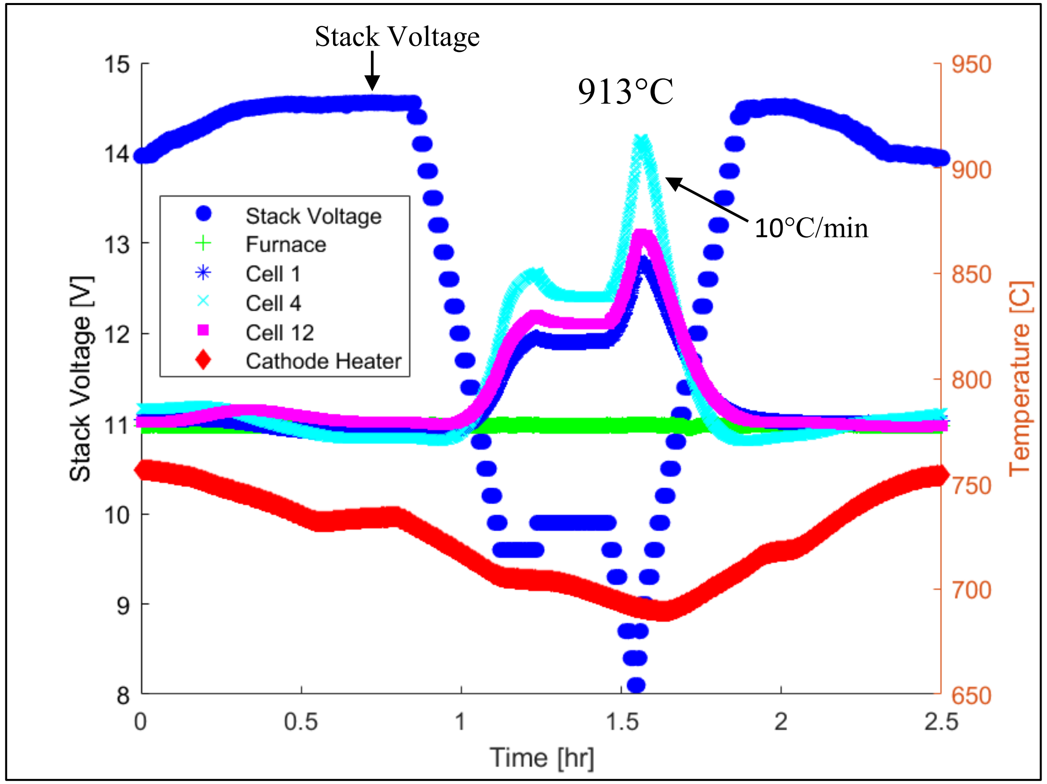
Stack Level Performance & Stability

RSOC Initial Testing Anode-Supported Stack

In preparation for high-current density RSOC stack platforms a 12-cell trial was completed using Elcogen ASCs with active area of 121 cm^2 (related project at Nexceris)

Stack was shown to be mechanically robust with components surviving multiple high temperature swings





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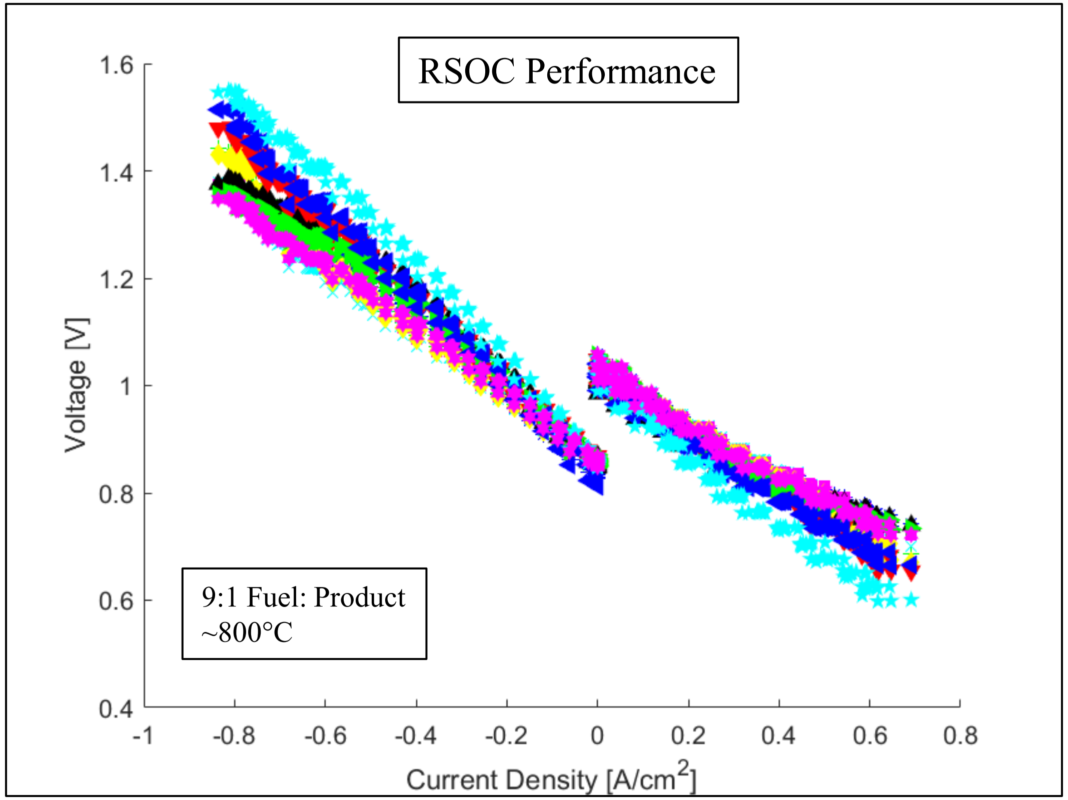
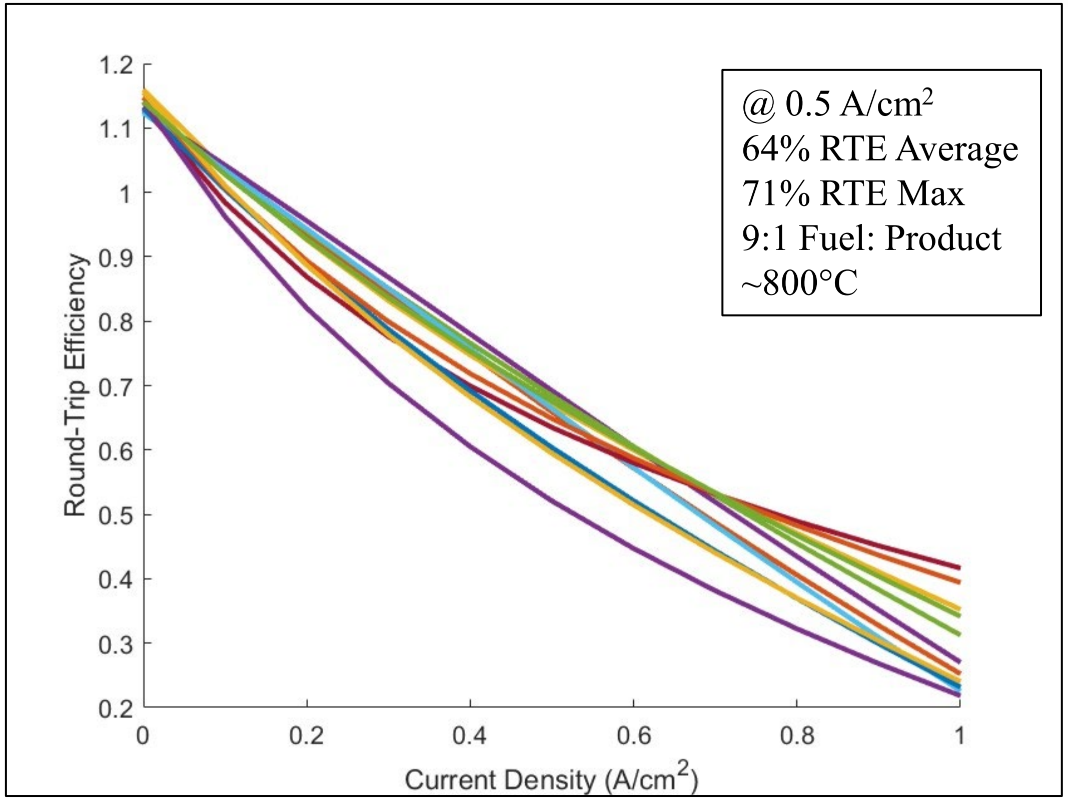
Stack Level Performance & Stability

RSOC Initial Testing Anode-Supported Stack





Stack was able to ***maintain >60% RTE at 0.5 A/cm²***

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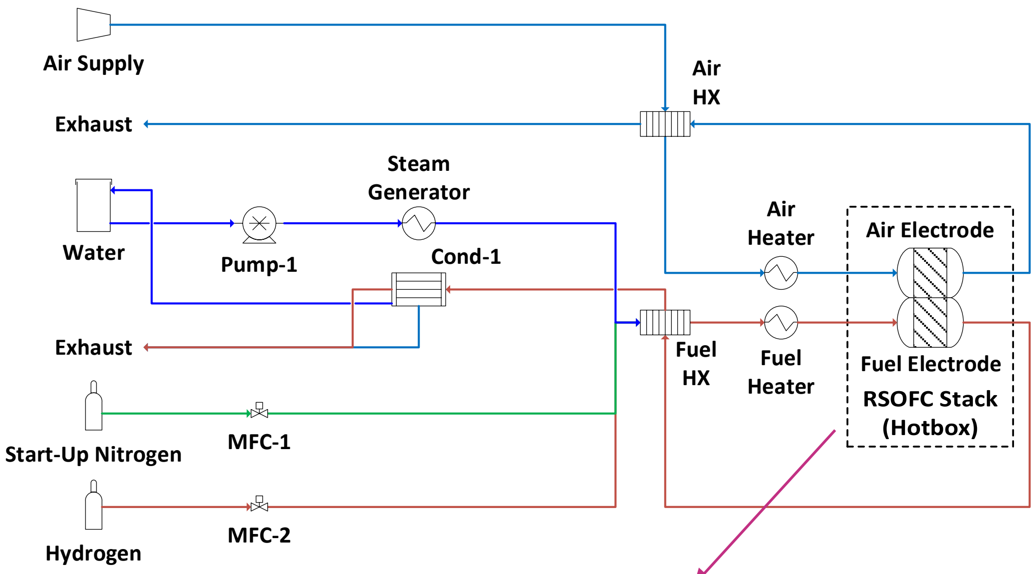
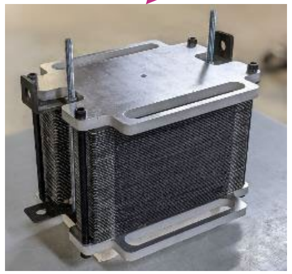
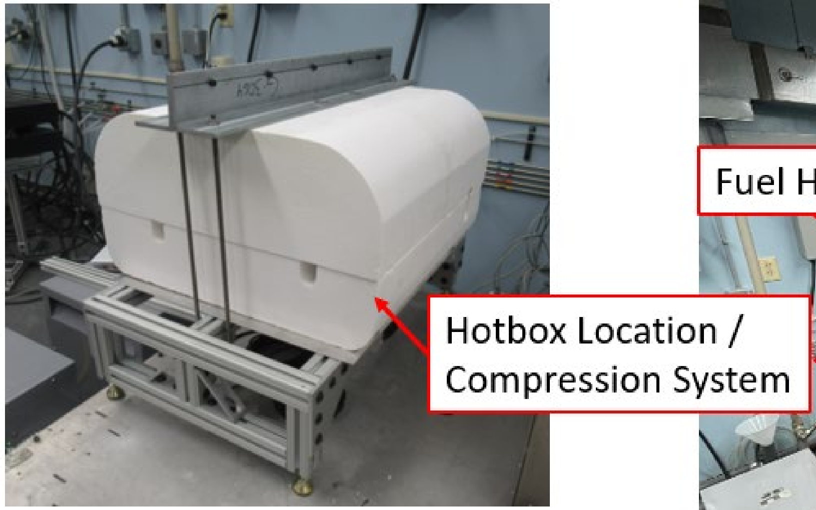
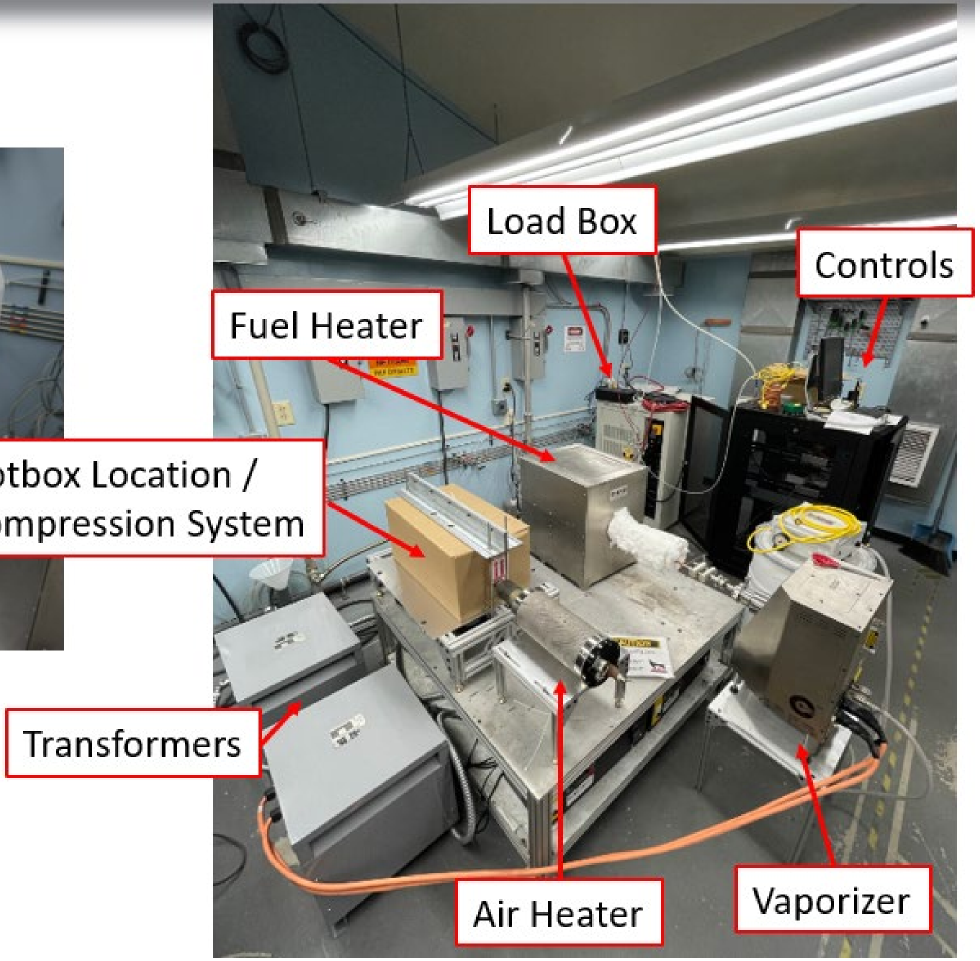
RSOC Stack Demonstration System

Planned to accommodate 1 kW RSOC ESC stacks









Mines is focused on pressurized stack testing and system-level design and TEA

Remaining Project Goals:

- ➢ Electrochemical durability tests (500 hours) completed on RSOC pressurized stacks (3-6 bar) at 750 – 800 °C with reversible operation demonstrated for 10-hour cycles

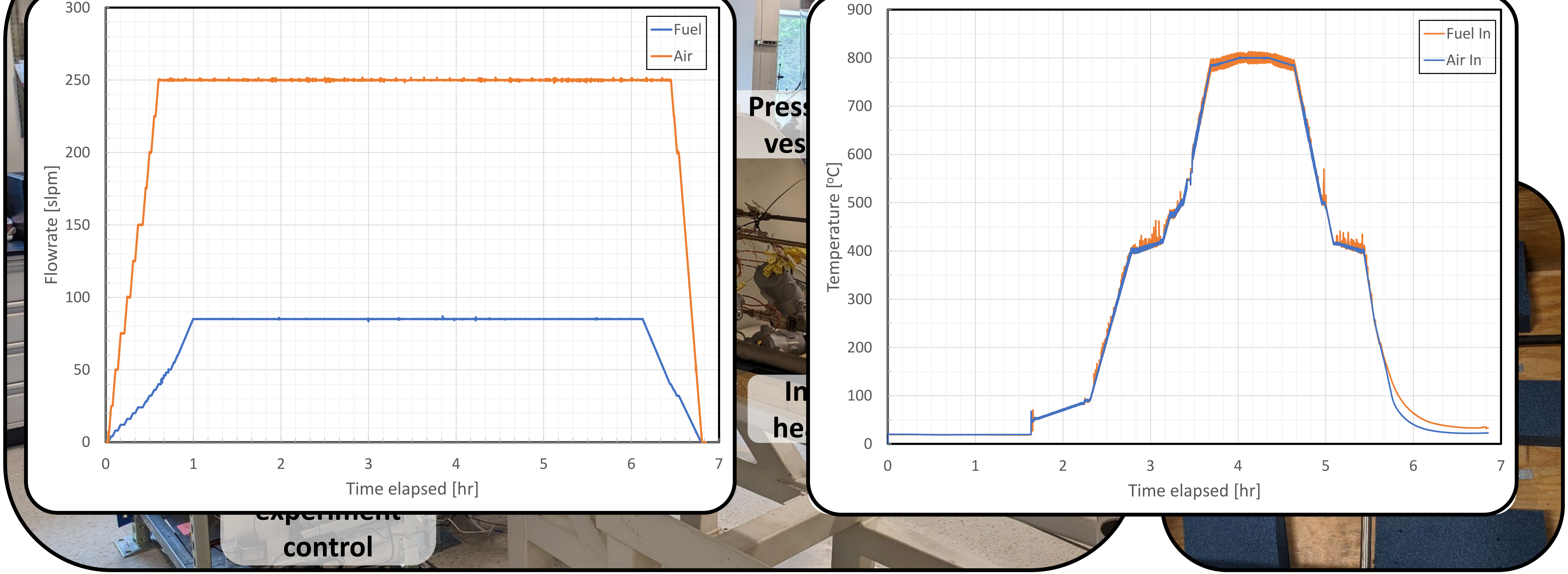
- ➢ Finalize techno-economic assessment based on experimental results and **describe a clear path** to $2/kg hydrogen production (at scale)
  - 100 kW
  - 1 MW

Advanced Energy Systems Group

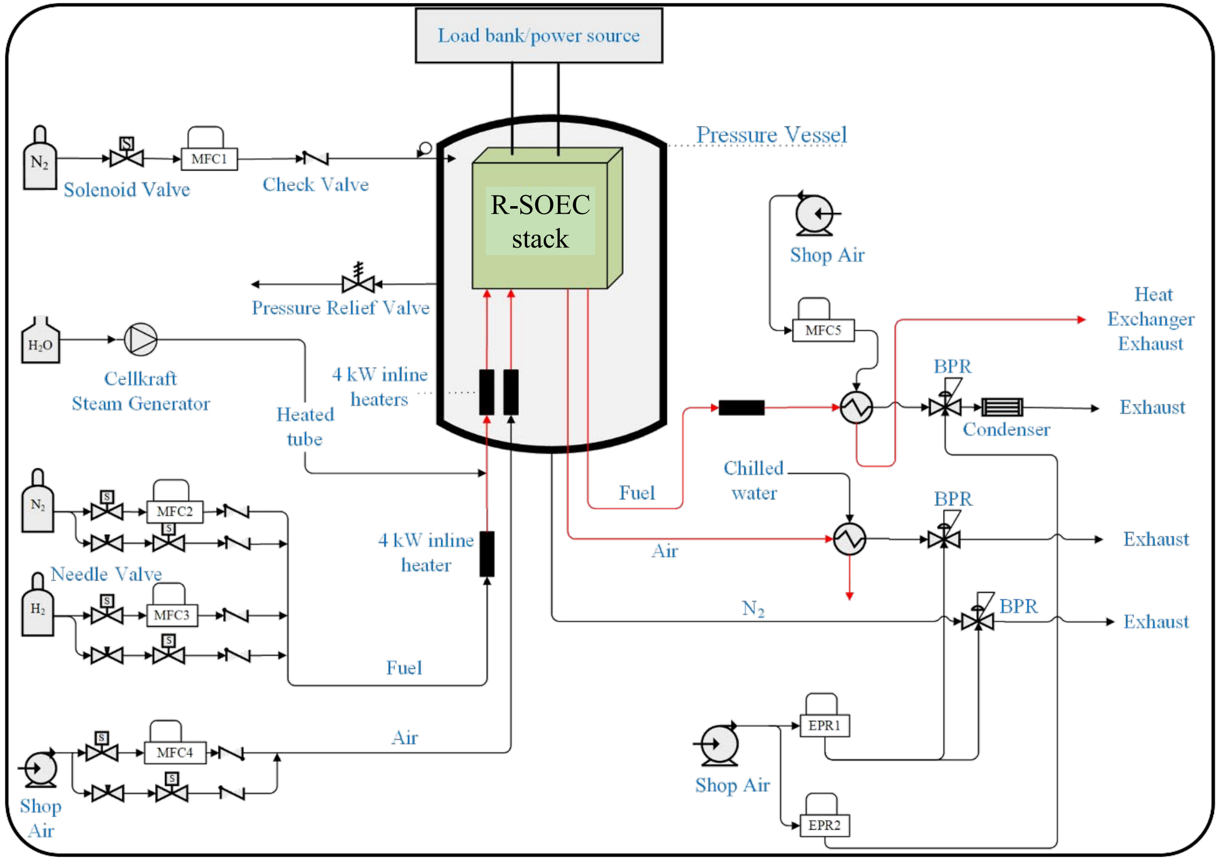
- Stack and system modeling
- Pressurized stack testing
- Techno-economic analysis

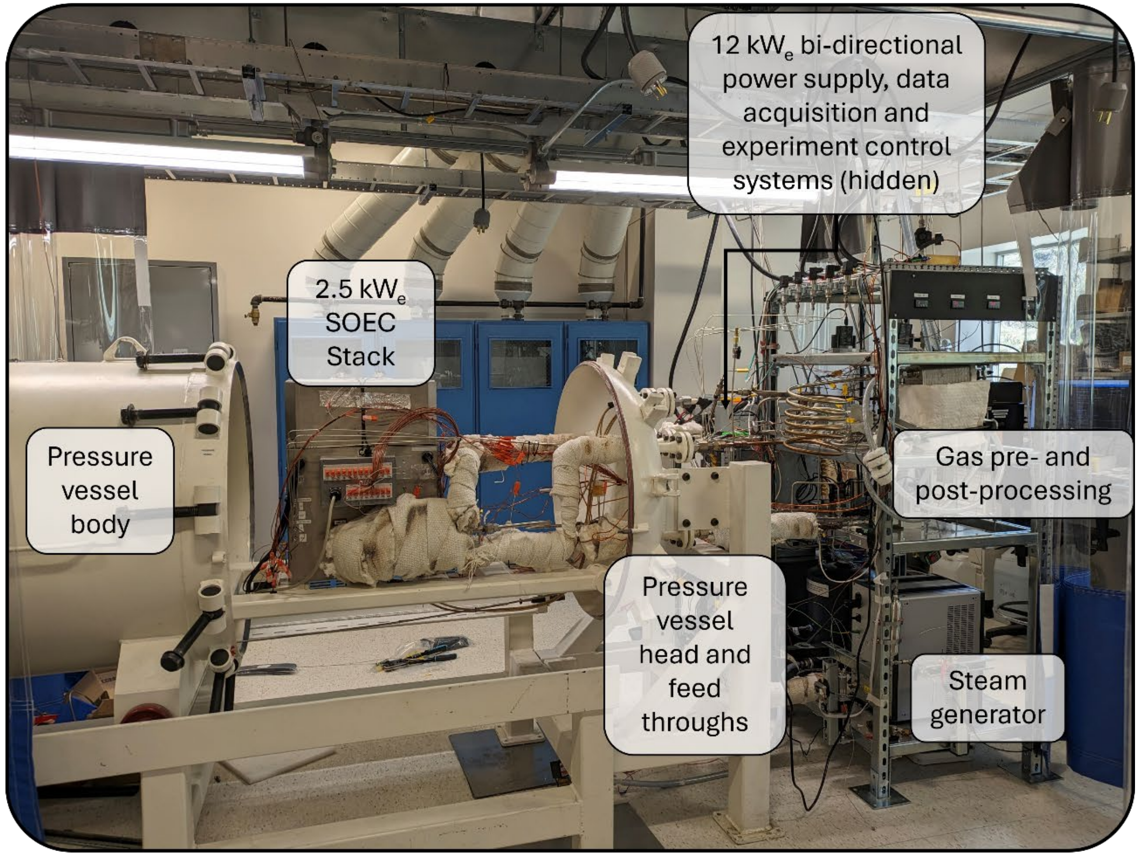
Development of rig for pressurized testing of 1-3 kW Nexceris stack at 800°C at Mines and up to 6.5-bar testing

Next steps:



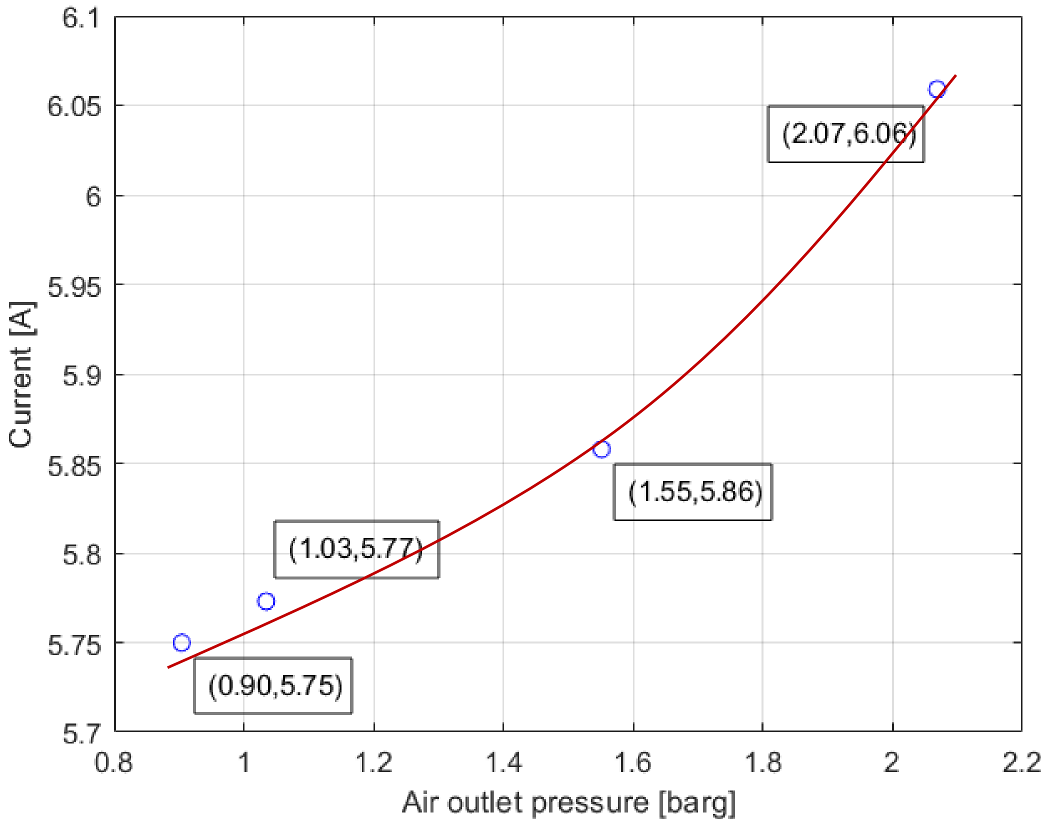
Rig was designed for tight cross-MEA pressure control and to accommodate both SOEC/SOFC stacks from 600 to 850°C





- Electric heater gas supply temperatures to 880°C
- Upgraded steam generation capacity using Cellkraft E-3000 steam generator
- ➢ Commissioning nearly completed – implement unattended operation underway

Test rig commissioning has been completed with preliminary results on substitute ~1 kW SOFC stack run in SOEC mode

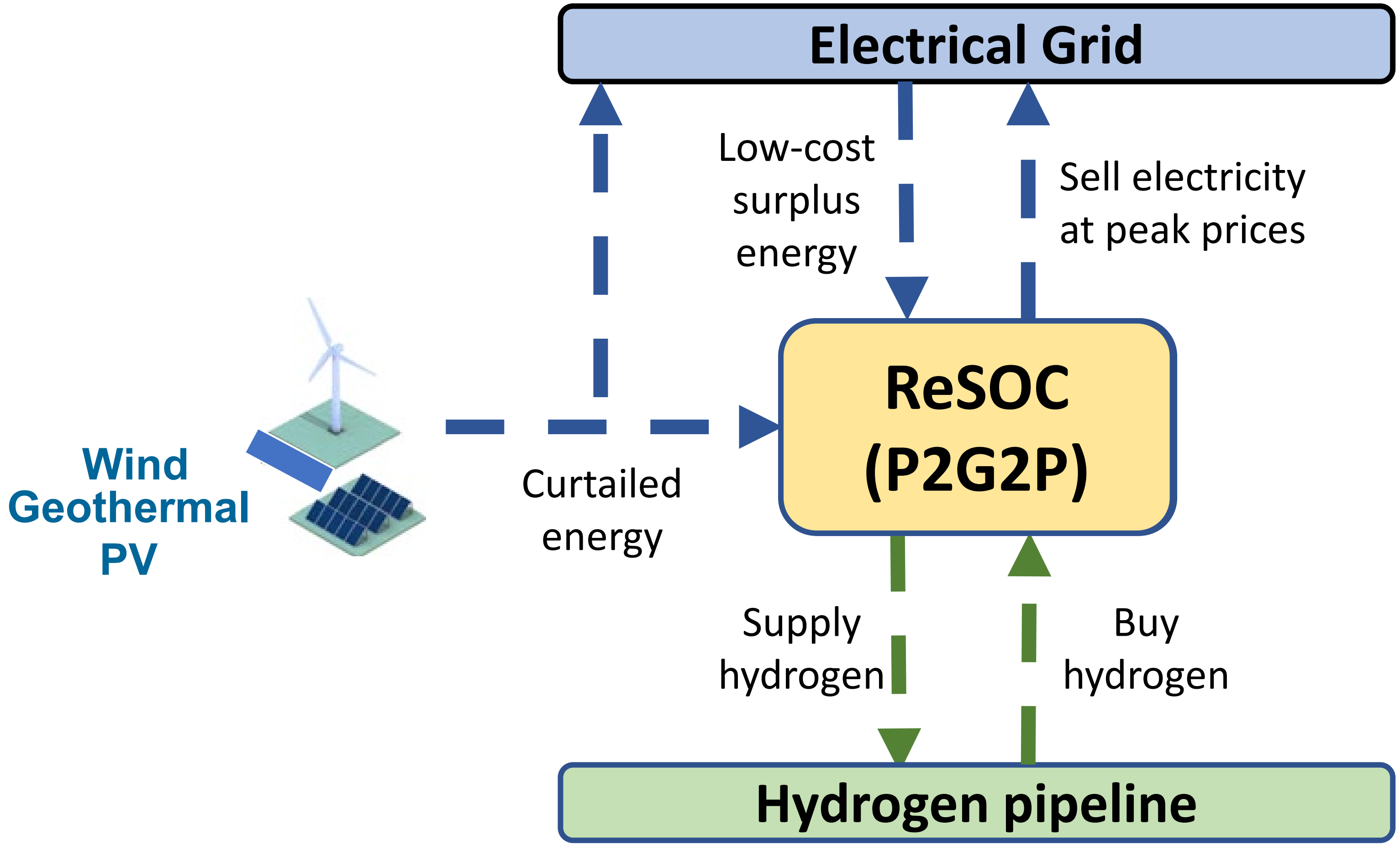


Observations:

- At constant thermal-neutral voltage, the current density increases by ~6% when moving from 0.9 to 2.1 bar_g
- The performance improvement trend appears to be slightly non-linear with increasing pressure.
- Mode-switch accomplished, but need to automate for unattended operation

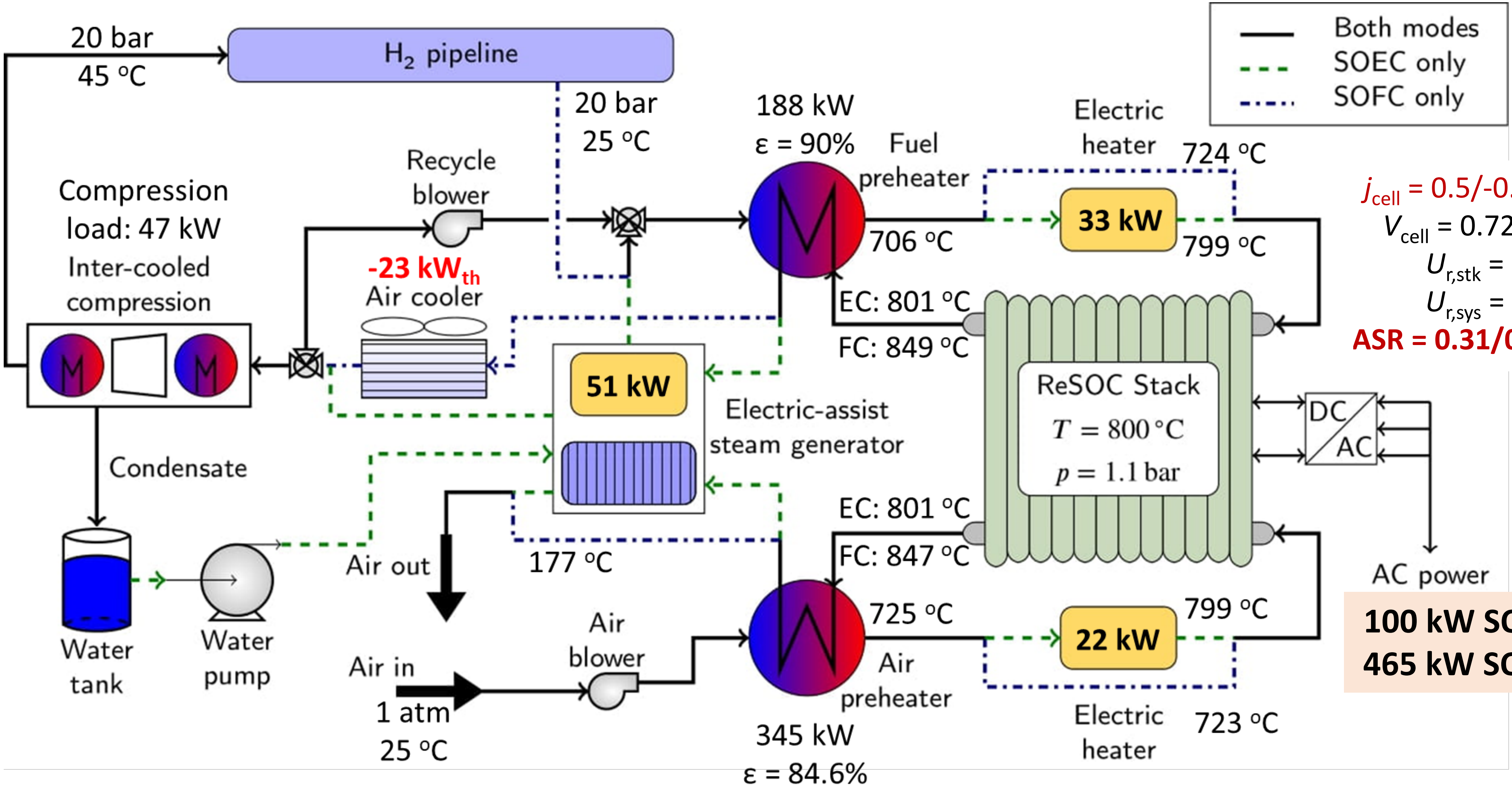
N_2 flow – 26 slpm
H_2 flow – 2 slpm
Air flow – 100 slpm
Steam flow – 25 slpm

System-level activities focused on R-SOEC systems (ReSOC) without onsite storage for flexible *H2* or *Power* production



- Lower hydrogen production cost
- Boost capacity factor

Both 100 kW & 1 MW conceptual systems under design and evaluation (100-kW, 1-atm shown here)



j_{cell} = 0.5/-0.68 A/cm²

V_{cell} = 0.72/ 1.29 V

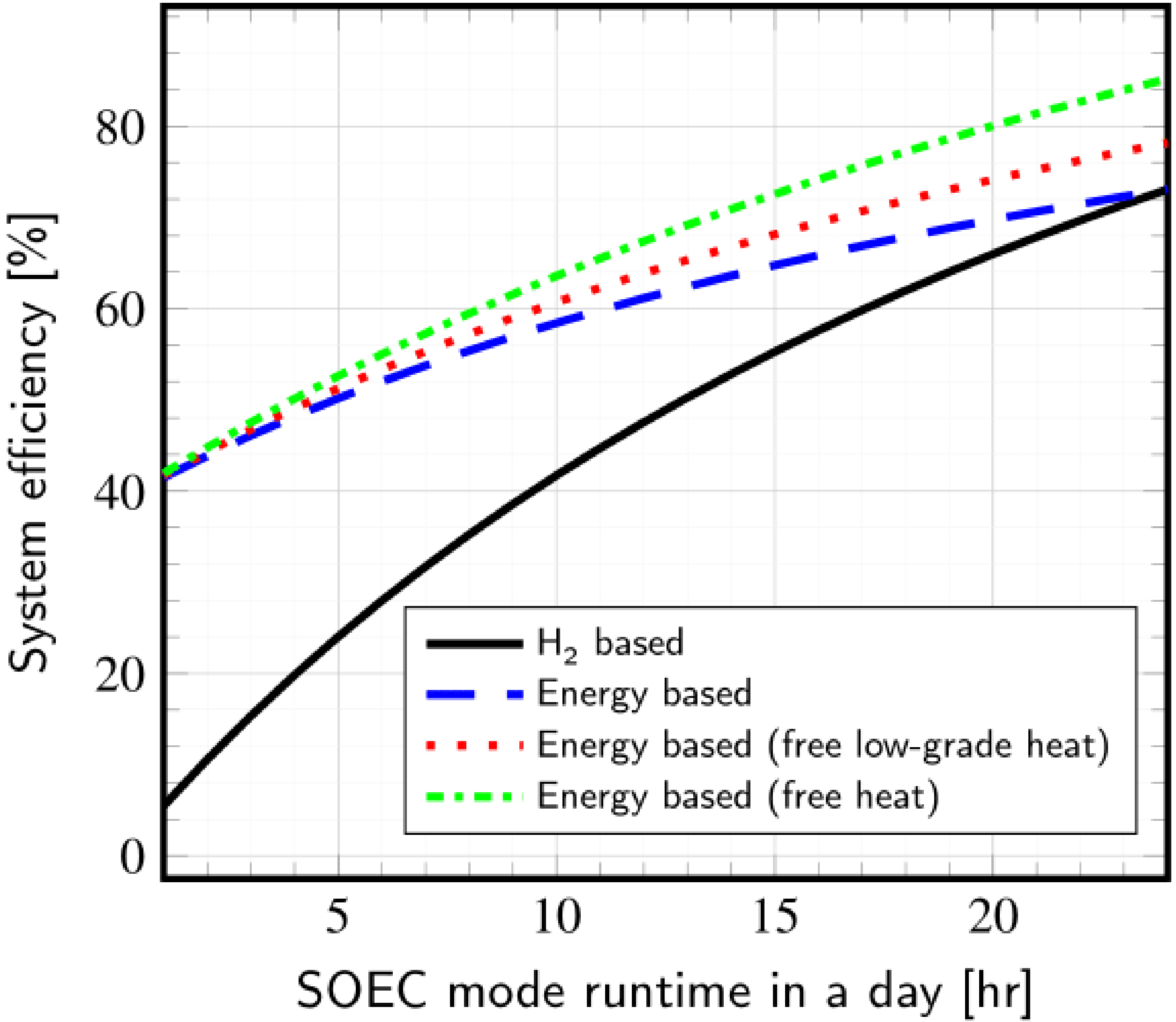
$U_{r,stk}$ = 70 %

$U_{r,sys}$ = 90 %

ASR = 0.31/0.41 Ω cm²

100 kW SOFC
465 kW SOEC

System efficiency based on input and output energy a better measure



- Energy based efficiency bound by LHV efficiencies of both modes
- Energy-based efficiency considers electricity as output; hence higher

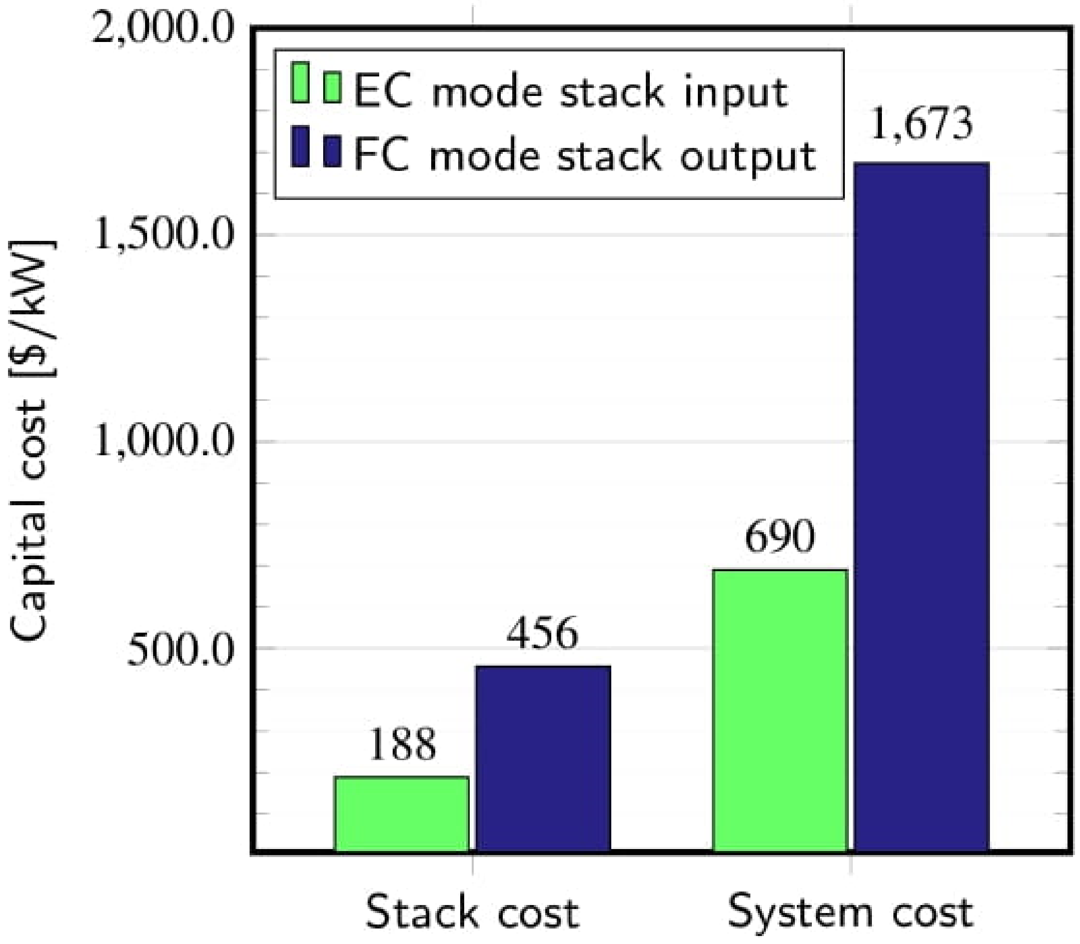
$$\eta_{H_2} = \frac{E_{H_2,\text{LHV,SOEC}}}{E_{H_2,\text{LHV,SOFC}} + E_{\text{elec,SOEC}}}$$

$$\eta_{\text{En}} = \frac{E_{H_2,\text{LHV,SOEC}} + E_{\text{elec,SOFC}}}{E_{H_2,\text{LHV,SOFC}} + E_{\text{elec,SOEC}}}$$

~44 kWhe/kg

No charge conservation between modes

Economic parameters (100 kW SOFC AC output system)



- System life: 20 years
- Stack life: 5 years
- Installation factor: 1.4
- Indirect factor: 1.5
- Capacity factor: 90%
- Variable O&M cost
  - 5 ¢/kWh
  - Converted from kg H_2 to kWh using LHV of hydrogen

The value proposition of a flexible H2 production system relies on arbitrage, efficiency, and off-taker agreements

$$\mathrm{LCOH} = \frac{C_{\mathrm{ins,a}} + C_{\mathrm{O\&M,fix,a}} + C_{\mathrm{O\&M,var,a}}}{m_{\mathrm{H_2,a}}}$$

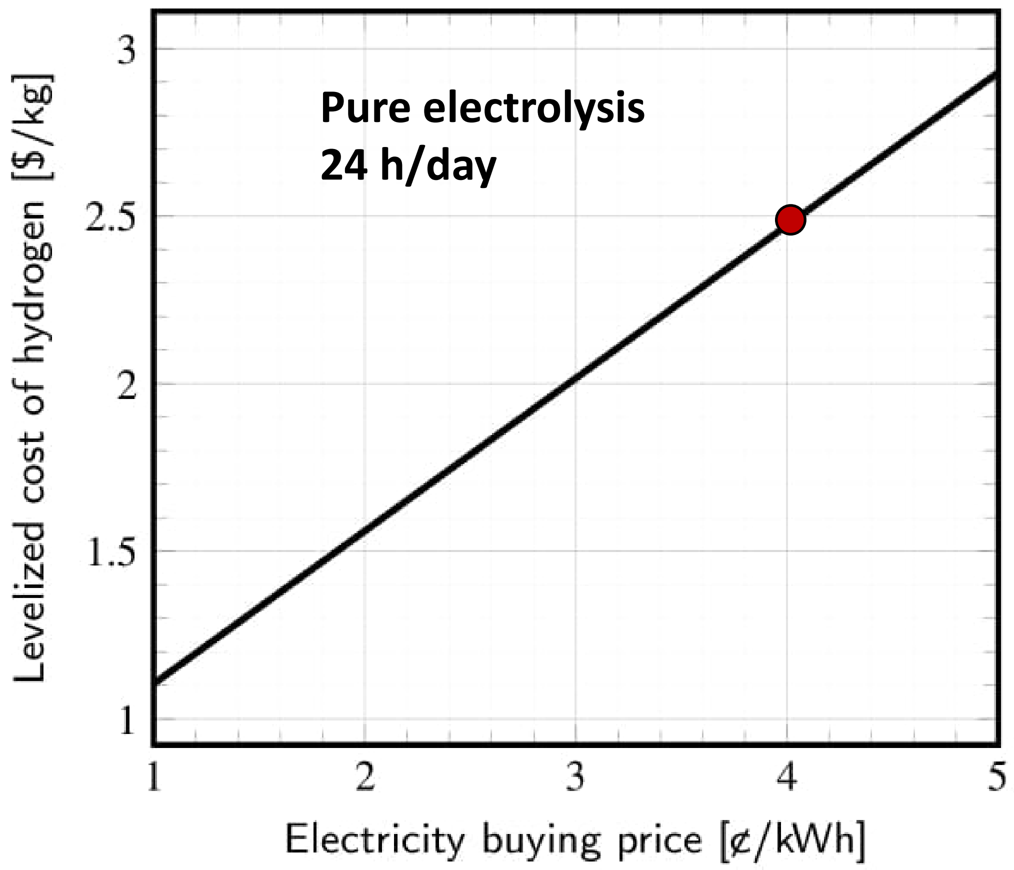
Traditional LCOH

$$\mathrm{LCOH} = \frac{C_{\mathrm{ins,a}} + C_{\mathrm{O\&M,fix,a}} + C_{\mathrm{buy}} \dot{W}_{\mathrm{SOEC}} t_{\mathrm{SOEC,a}} - C_{\mathrm{sell}} \dot{W}_{\mathrm{SOEC}} t_{\mathrm{SOEC,a}}}{\dot{m}_{\mathrm{H_2,SOEC}} t_{\mathrm{SOEC,a}} - \dot{m}_{\mathrm{H_2,SOFC}} t_{\mathrm{SOFC,a}}}$$

Modified LCOH

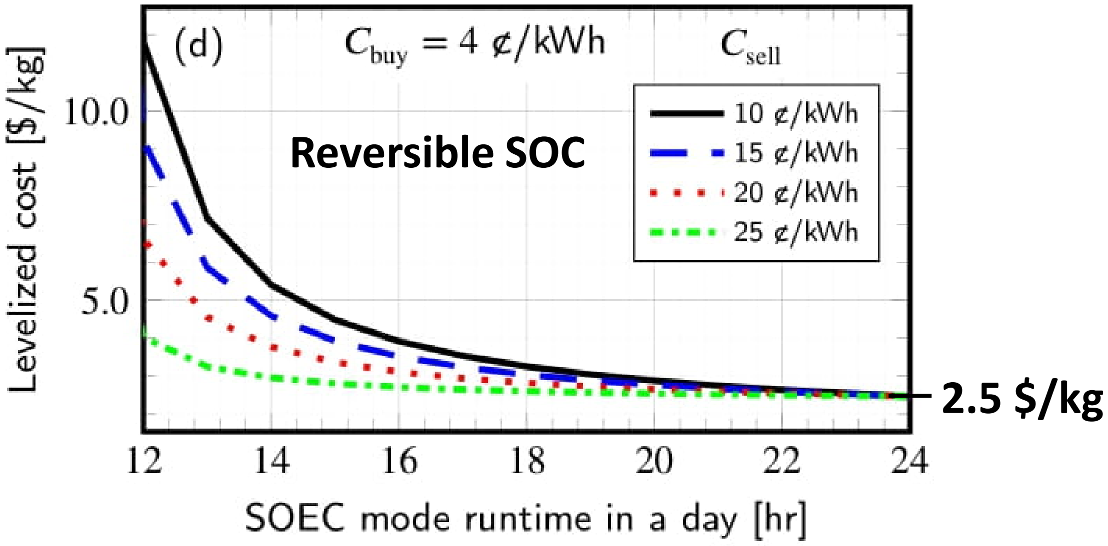
Net hydrogen produced

Levelized cost of hydrogen at different electricity purchase prices

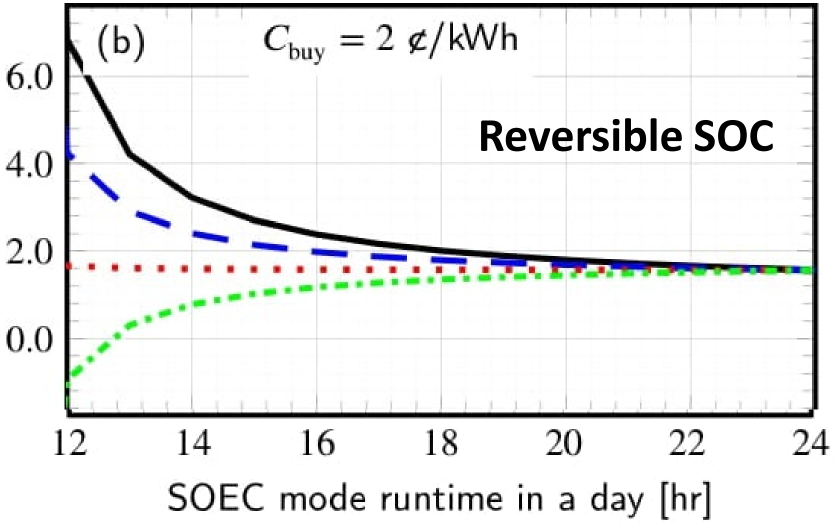


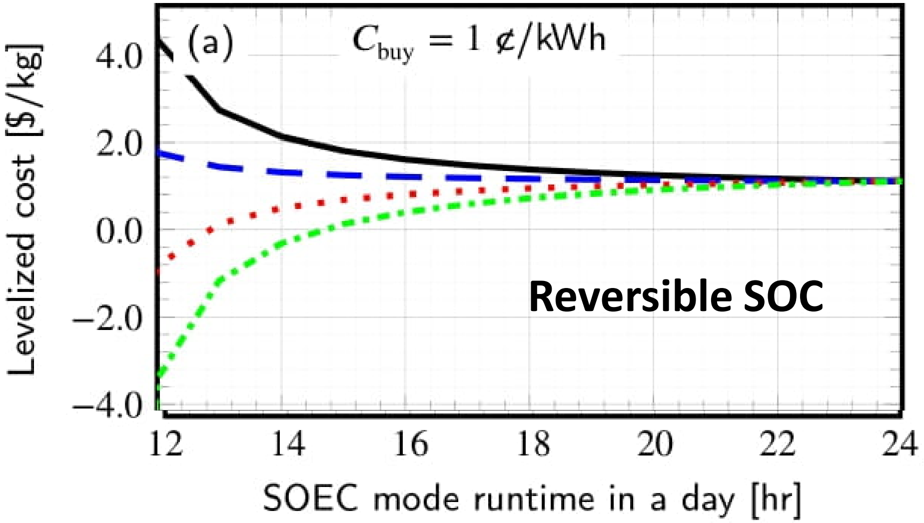
- Pure SOEC: Influence of electricity purchase price on LCOH is ~1-to-½ impact.
- But what is the “advantage” (if any) of RSOCs?

Levelized cost of hydrogen at different electricity buying and selling prices influences the potential LCOH



- The cheaper the buy price of electricity, the greater the potential to lower LCOH using RSOC
- More variability/volatility in electricity prices preferred for arbitrage
- At very high variability, trade-off between desired H_2 production volume and profit margin

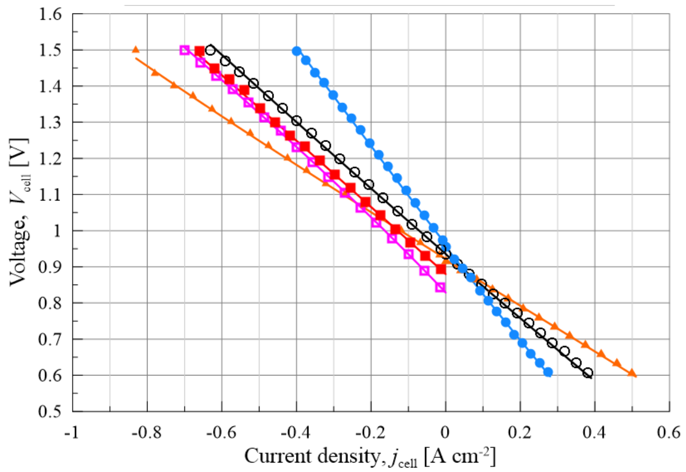


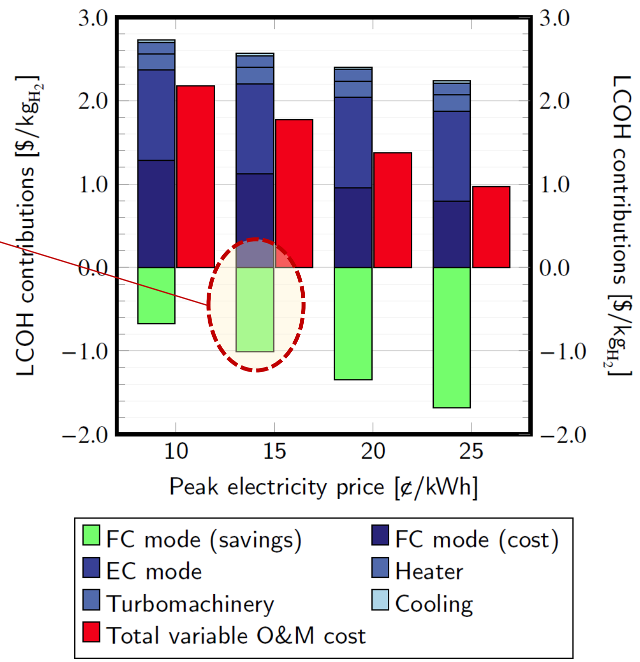


Next Steps

- Install Nexceris R-SOEC stack and run pressurized test cases with 10-h mode switch cycles.
- Complete Nexceris-based R-SOEC stack model validation and incorporate into system models for 1 MW system analysis
- Finalize techno-economic assessment based on experimental results and describe a *clear path* to $2/kg hydrogen
    - Preliminary results illustrate impact of SOFC mode savings

ASR: 0.79 - 0.90 Ω-cm²





Acknowledgements

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