Enabling Solid Oxide Fuel Cells for Integrated Energy Systems

NATIONAL ENERGY TECHNOLOGY LABORATORY

Samuel Bayham

FWP-1022460

23rd Annual Solid Oxide Fuel Cell Program Project Review Meeting

Wednesday, October 26, 2022

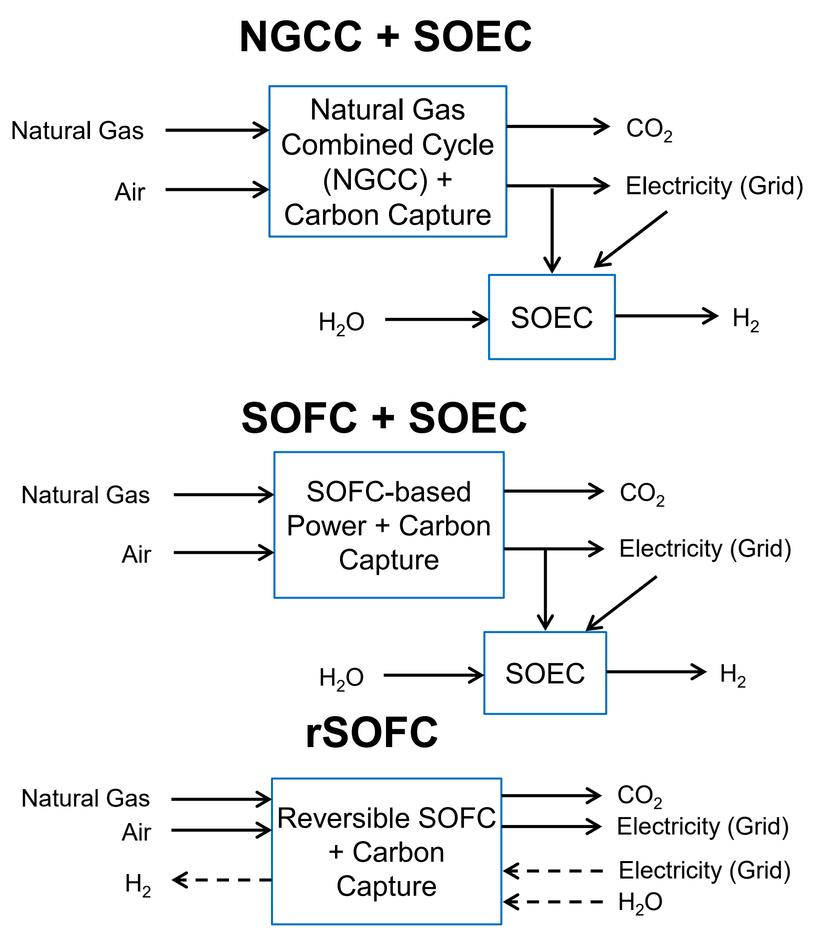
Project Overview

Enabling Solid Oxide Fuel Cells for Integrated Energy System

- Project ID: FWP-1022460
- Project Funding:
  - $2,450,000 from FECM
  - No Cost Share (Field Work Proposal)
- Period of Performance:
  - April 1st, 2021 – March 31st, 2022
- Project Participants:
  - Universities:
    - West Virginia University
    - Georgia Southern University
    - University of Notre Dame
    - Carnegie Mellon University
  - DOE National Labs:
    - Idaho National Lab
    - Sandia National Lab

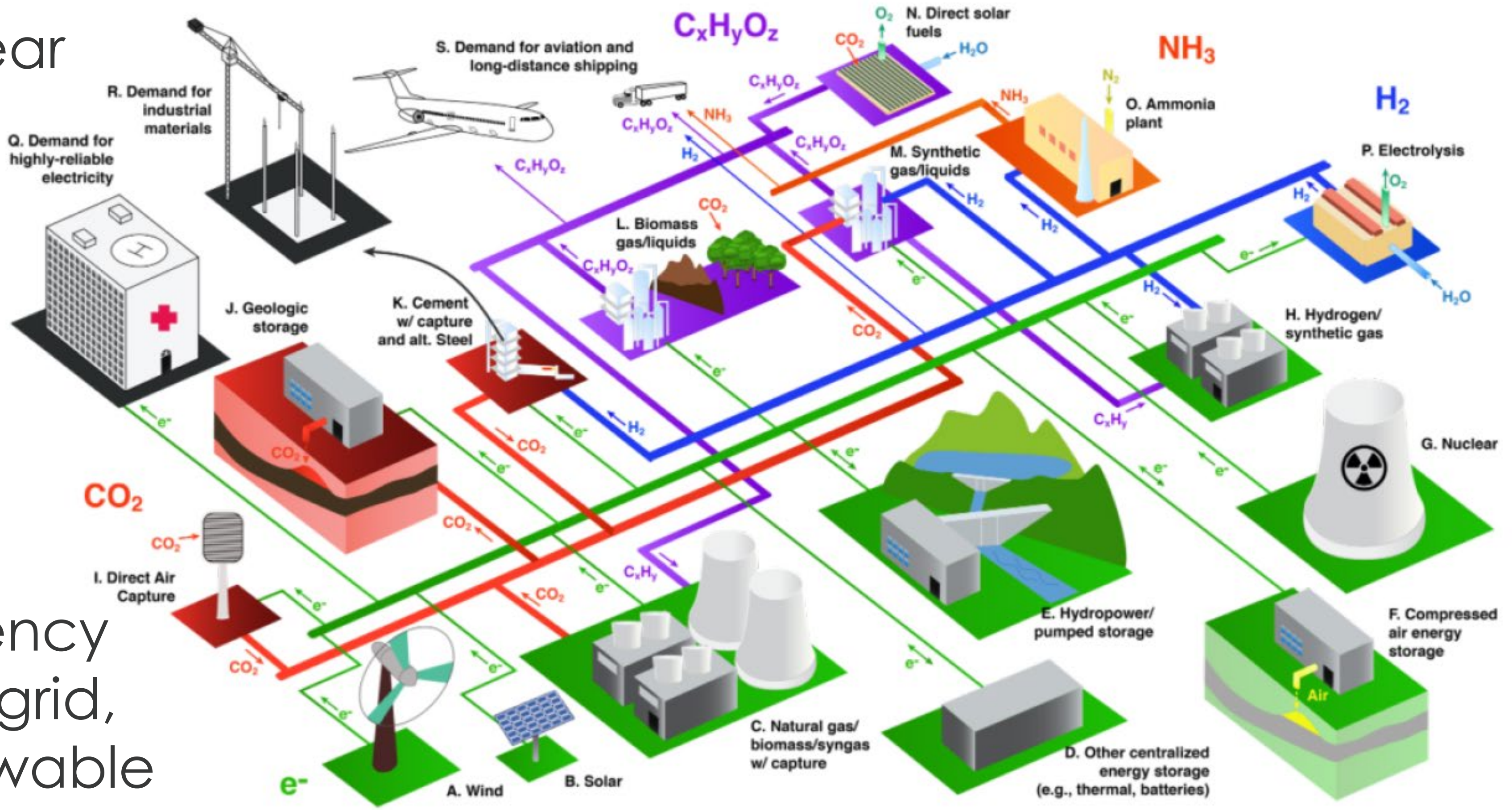
Overall Project Objectives

- Enable development of SOFCs and SOECs in <u>integrated energy systems</u>
- Combine solid oxide fuel cell/electrolyzer with other fossil technologies to achieve <u>flexibility and resilience</u> while enabling <u>carbon capture</u>
- Determine <u>operability requirements</u> and develop <u>integration</u> and <u>control strategies</u>



Integrated Energy Systems

- Multicomponent
  - Fossil
  - Nuclear
  - Renewable
- Integrated
  - Hybrids
  - Carbon Capture
  - Energy Storage
- Dynamic
  - non-dispatchable assets
  - dispatchable assets
- Fossil generation - resiliency hub for nation's power grid, enabling variable renewable generation



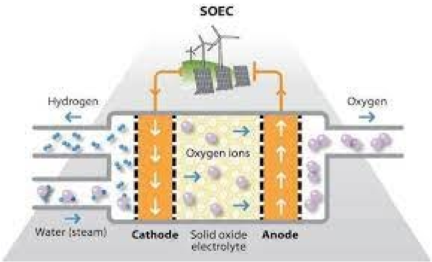
Davis et al. "Net-zero emissions energy systems." Science (2018) https://doi.org/10.1126/science.aas9793

We need to <u>develop</u> fossil energy technologies and <u>controls</u> that are able to fit into this paradigm!

Advantage of Hybrid Energy Concepts

Flexibility – Resilience - Emissions

- CCUS essential in future IES
  - 75% Reduction in CO2/MWh possible <u>before</u> CCUS
- Efficiency Critical
  - Lowers net CO2/MWh – reduces carbon pollution by eliminating emissions
  - Reduces the size of CCUS system required to achieve Net Zero – substantial cost reduction
- Dynamic operability - key to lower tons of CO_2/MWh



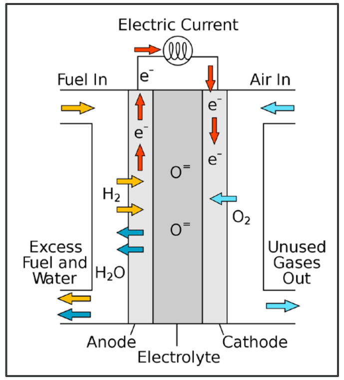
We need hybrid systems that can perform <u>efficiently at low load</u> and <u>not deteriorate</u> over many load cycles.

Technical Gaps

Overall Concept Feasibility?

Does the concept make sense from a mass/energy balance perspective? Priority of concepts?

How Much Cell Degradation?



Will the fuel cell or electrolyzer be able to handle load changes in a dynamic integrated energy system?

How can the plant turn a profit?

Is there a business case to be made for such a plant?

Can we control the plant?

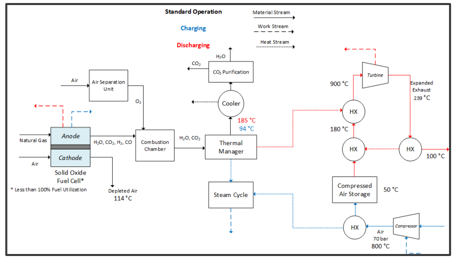
How will the plant operate? How can we control it? How will it work on the electric grid?

Addressing Technical Gaps

NATIONAL ENERGY TECHNOLOGY LABORATORY

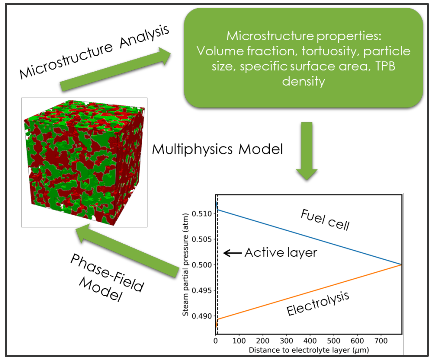
Technical Approach

Systems Analysis



Analytically evaluate hybridized carbon conversion system configurations that incorporate SOFC/SOEC.

Solid State Electrochemical Degradation



Apply knowledge of cell degradation to a wide range of operating conditions relevant to commercial systems (power and fuel production operation modes)

Design/Optimization of Hybrid Systems

$$\underset{t \in T}{\overset{Max}{\sum}} (\text{Revenues} - \text{Costs})$$

$$\text{Revenue}_{\text{Power}} = \pi_{p,t} p_t$$

$$\text{Revenue}_{\text{H2}} = \pi_h h_t$$

$$\text{Cost}_{\text{opex}} = C_{op}(p_t, h_t)$$

$$\text{Cost}_{\text{fixed}} = C_{cap+fixedO\,M}(P_{max}, H_{max})$$

Use IDAES* platform to evaluate and strengthen value proposition for integrated energy systems that leverage hybrid carbon conversion technologies to produce electricity and hydrogen

Grid Impact on Hybrid SOFC System

Characterize operability and develop integration and control strategies to achieve the flexibility and resilience that SOFC-HCC systems must meet to be fully compatible with a dynamic power grid

U.S. DEPARTMENT OF ENERGY

*IDAES: Institute for the Design of Advanced Energy Systems framework

Systems Analysis

Analytically evaluate hybridized carbon conversion system configurations that incorporate SOFC/SOEC.

NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY

Accomplishments and Challenges Resolved

Systems Analysis

- NETL and INL collaboration to assess eight hybrid process concepts
  - SOC + Compressed Air Energy Storage (CAES)
  - SOC + Reciprocating Engine
  - SOC + Gas Turbine
- SOC + CAES chosen for additional study due to general applicability to utility-scale fossil fueled systems with large-scale energy storage capabilities

Criteria	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7	Concept 8
	SOFC + Renewables	SOFC + Renewables + CO_2 Source + Products	SOFC + NE	SOFC + NE + Renewables	SOFC + NE + Renewables + CO_2 + Products	SOFC + Reciprocating Engine	SOFC + Gas Turbine	SOFC + CAES
Reliability	5	7	7	7	10	7	7	7
Resiliency	7	7	10	10	10	7	7	10
Flexibility	7	5	5	5	7	10	10	10
Low Carbon Emissions	7	7	7	7	7	5	7	7
Fossil Fuel Efficiency	7	5	7	7	5	7	10	7
System Complexity	7	3	5	5	3	10	7	10
Carbon Utilization	1	10	1	1	10	1	1	1
Non-Power-Sector Markets	5	10	5	5	10	1	1	1
Water Use	5	1	3	3	1	10	10	10
State of Development	7	5	3	5	3	7	7	7
Geographic Limitations	7	5	3	3	3	10	10	1
Modularity	10	3	5	5	3	10	5	5
System Life	5	5	5	5	5	7	7	7
Decommission/End of Life	3	3	1	1	1	5	5	5

Worst 1 3 5 7 10 Best

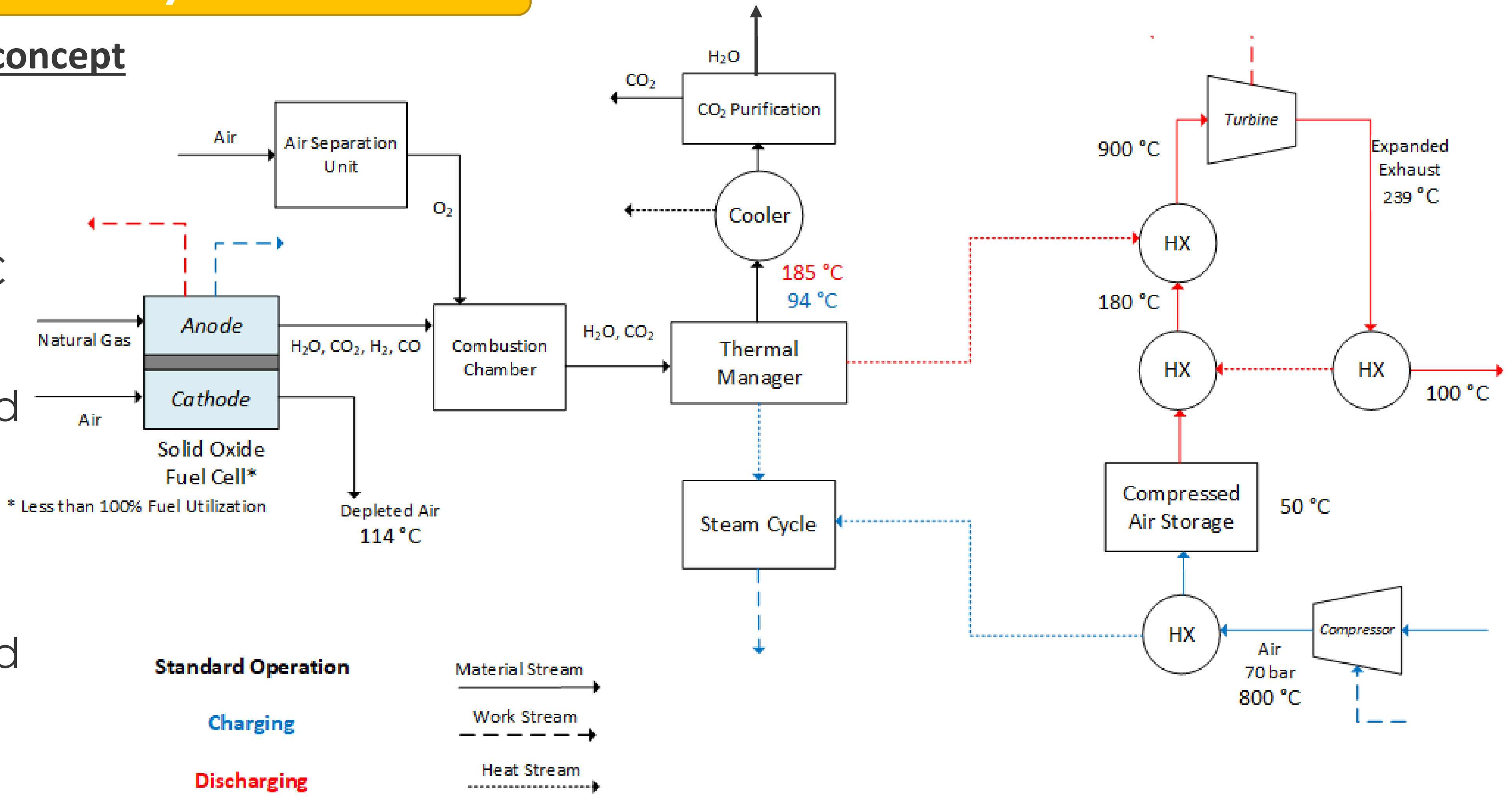
Results are available as an NETL internal technical report

Accomplishments and Challenges Resolved

Systems Analysis

SOC + CAES hybridized concept

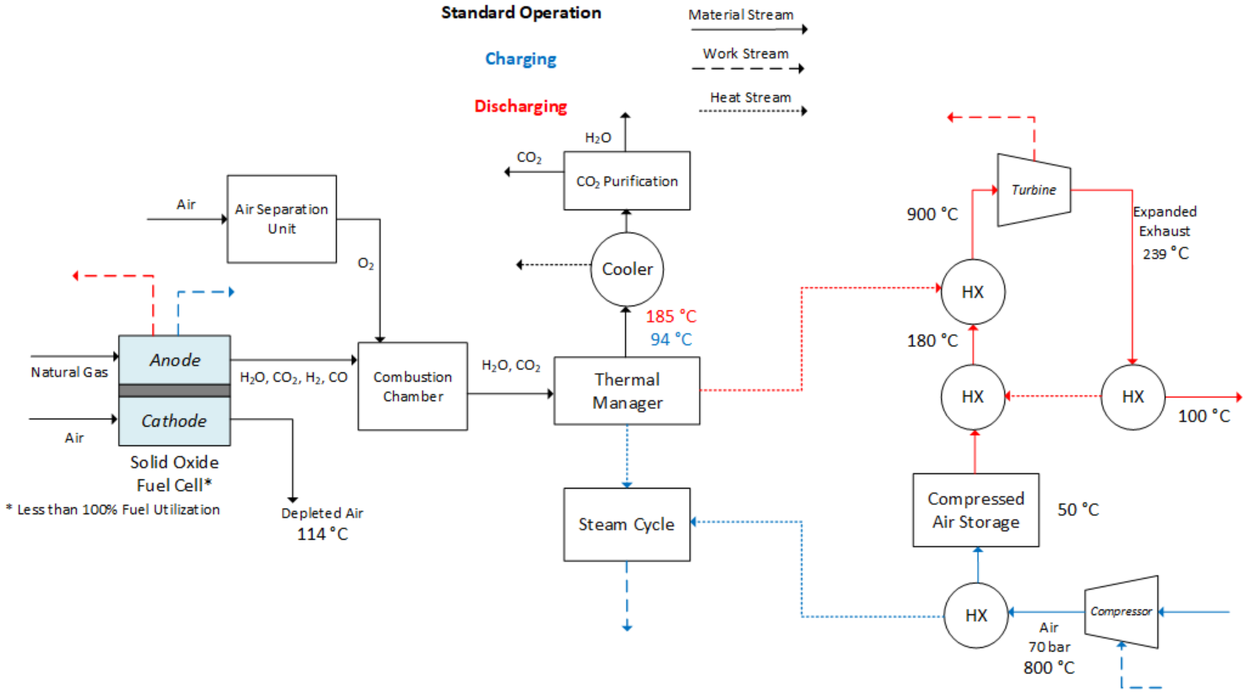
- Electricity runs air compressor when low demand
- Air released, SOFC power increased during high electricity demand
- Multiple ramping options provide flexibility for adapting to electricity demand

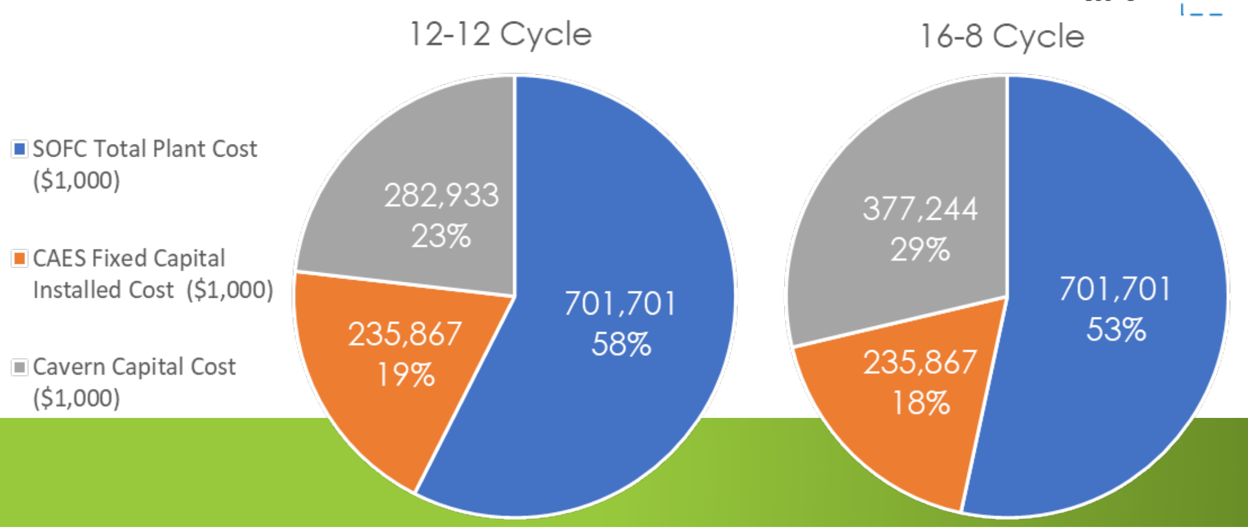


Accomplishments and Challenges Resolved

Systems Analysis

- **<u>SOC + CAES hybridized concept</u>**
- Meets system heat requirements at power ratio of ≈ 3.1 SOC:CAES
- Cost ratio of 1.4 SOC:CAES shows how high cost of energy storage is relative to power output ratio
- Screening analysis provides guidance on aspects to focus on in the follow-on techno-economic assessment
- Results are available as an NETL internal technical report





Design/ Optimization of Hybrid Systems

Use IDAES* platform to evaluate and strengthen value proposition for integrated energy systems that leverage hybrid carbon conversion technologies to produce electricity and hydrogen

NATIONAL ENERGY TECHNOLOGY LABORATORY

Goal / Technical Gaps

Design/Optimization of Hybrid Systems

SOC systems that produce electricity and H_2

- Evaluate value proposition for producing electricity/H2
- Generate targets for cost reduction and performance improvement
- Analyze transient responses under rapid load change and low-load operation
- Metrics:
- Max achievable net profit over specific time horizons
- Traditional metrics LCOE, $LCOH_2$, NPV

Process Concepts	Power MW_e	H2 Capacity (kg/s)
NGCC	650	-
SOFC	650	-
NGCC + SOEC	650	5
rSOC	650	5
SOFC + SOEC	710	5
SOEC	-	5

Assumptions:

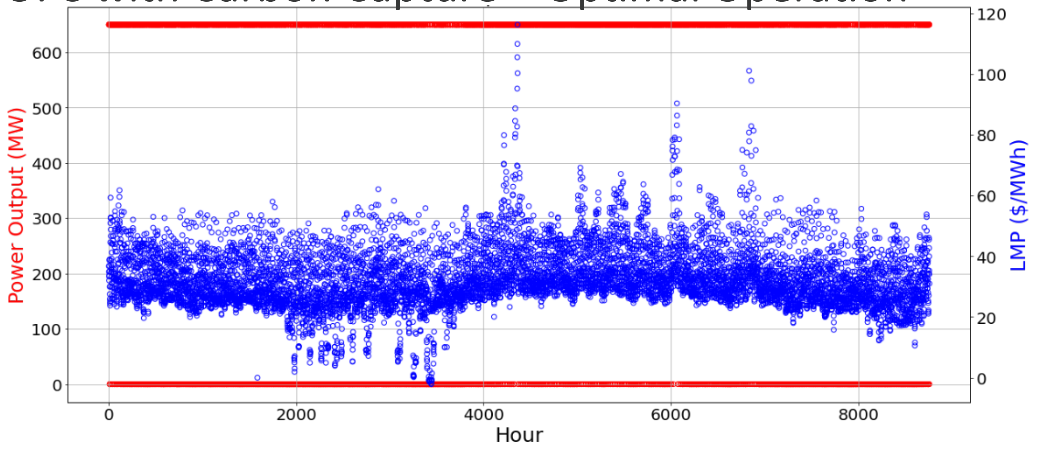
- SOFC: $225/kW stack cost
- SOEC: $105/kW stack cost
- Stack degradation rate: 0.2% / 1000 hr
- Hydrogen: 6.479 MPa, < 10 ppm H_2O
- Captures > 97% CO_2
- CO_2 transport and storage costs not included

Accomplishments and Challenges Resolved

Design/Optimization of Hybrid Systems

rSOFC with Carbon Capture – Optimal Operation

Full year:



2015 CAISO, Power capacity factor = 0.48; H_2 capacity factor = 0.52

Maximize

$$\sum_{t\in T} CF_{H_2} \cdot \pi_{H_2} + CF_{elec} \cdot \pi_{elec} - \text{Costs}\left(CF_{H_2}, CF_{elec}\right)$$

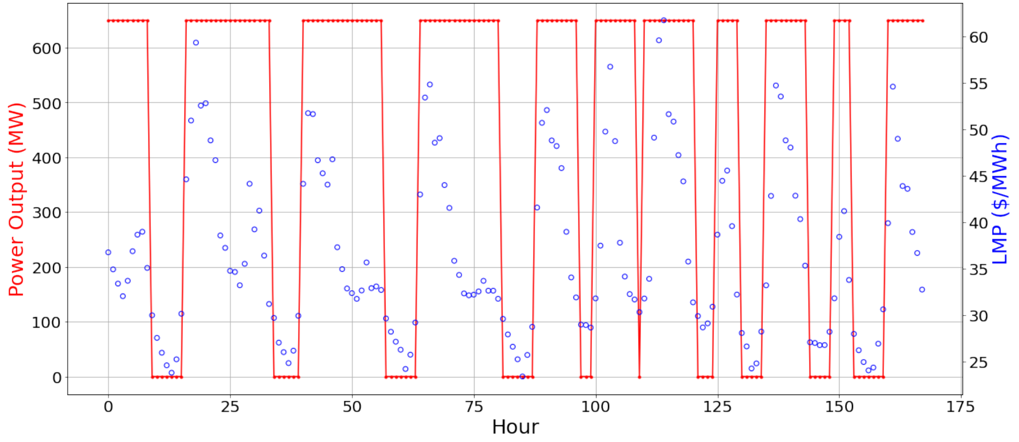
$$CF_{H_2} = \text{Capacity Factor for Hydrogen}$$

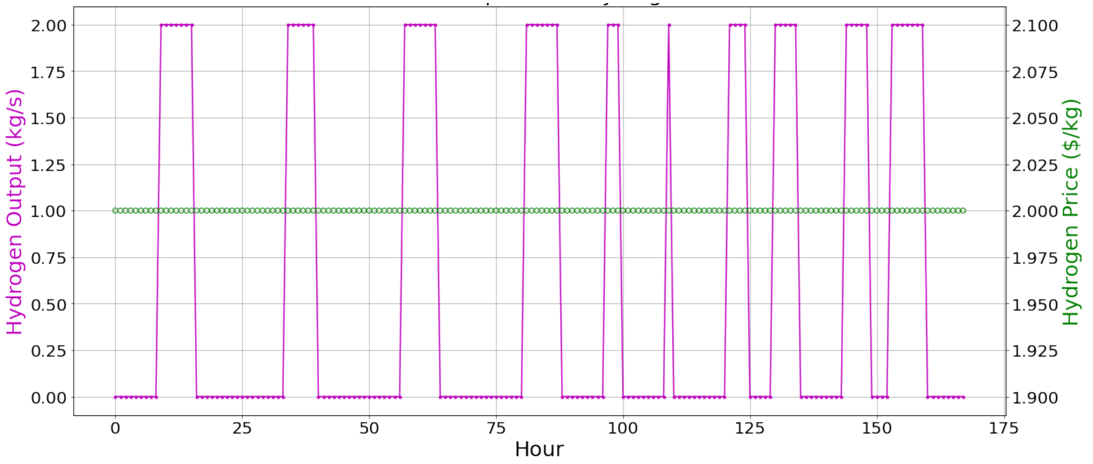
$$\pi_{H_2} = \text{Hydrogen Price}$$

$$CF_{elec} = \text{Capacity Factor for Electricity Production}$$

$$\pi_{elec} = \text{Electricity Price}$$

Week 1:

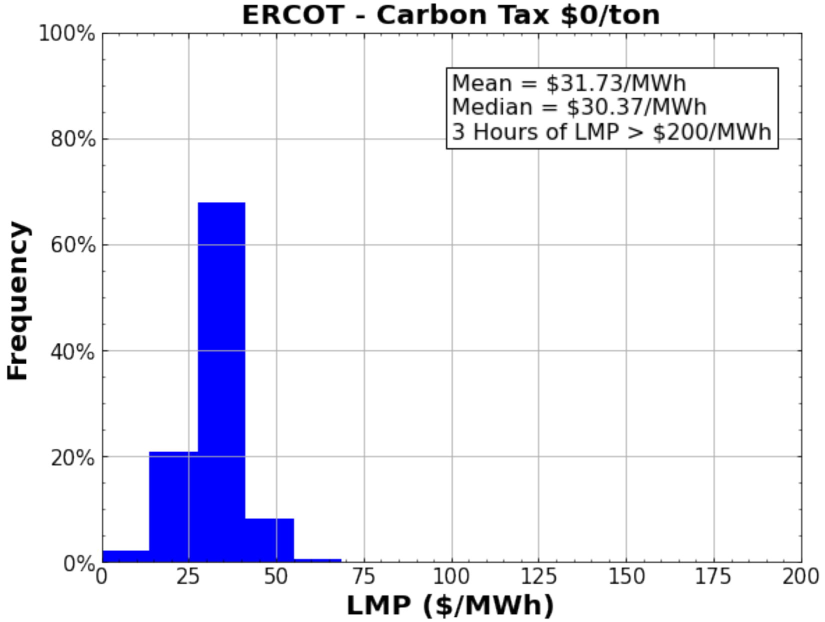




Process/Market Analysis

Selling Price of H_2 = $2/kg, Natural Gas = $4.42/mmBTU

Low Electricity Prices	ERCOT $0/ton Carbon Tax Low Prices Mean: $32/MWh
NGCC	M$ -163.5/yr Capacity Factor Power: 0.19
SOFC	M$ -71.5/yr Capacity Factor Power: 0.92
SOEC	M$ 33.6/yr Capacity Factor H_2: 0.97 ★
NGCC + SOEC	M$ -128.1/yr Capacity Factor Power: 0.02 Capacity Factor H_2: 0.98
SOFC + SOEC	M$ 19.2/yr Capacity Factor Power: 0.03 Capacity Factor H_2: 0.97
rSOC	M$ -3.7/yr Capacity Factor Power: 0.20 Capacity Factor H_2: 0.80



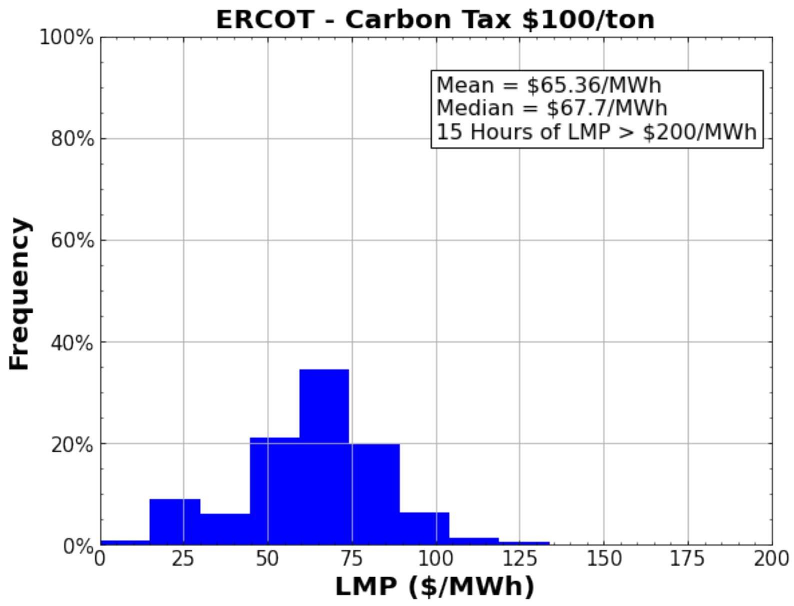
- **Standalone power generation cases are highly unprofitable.**
  - Electricity prices are too low to offset carbon capture costs.
- **H_2-only systems are most profitable.**

Standalone SMR+capture = ~M$ 80/yr ★

Process/Market Analysis

Selling Price of H_2 = \$2/kg, Natural Gas = \$4.42/mmBTU

High Electricity Prices	ERCOT \$100/ton Carbon Tax High Prices Mean: \$65/MWh
NGCC	M\$ -4.1/yr Capacity Factor Power: 0.87
SOFC	M\$ 116.9/yr Capacity Factor Power: 0.98 ★
SOEC	M\$ -58.2/yr Capacity Factor H_2: 0.19
NGCC + SOEC	M\$ -35.4/yr Capacity Factor Power: 0.78 Capacity Factor H_2: 0.22
SOFC + SOEC	M\$ 132.1/yr Capacity Factor Power: 0.81 Capacity Factor H_2: 0.19 ★
rSOC	M\$ 126.6/yr Capacity Factor Power: 0.87 Capacity Factor H_2: 0.13 ★



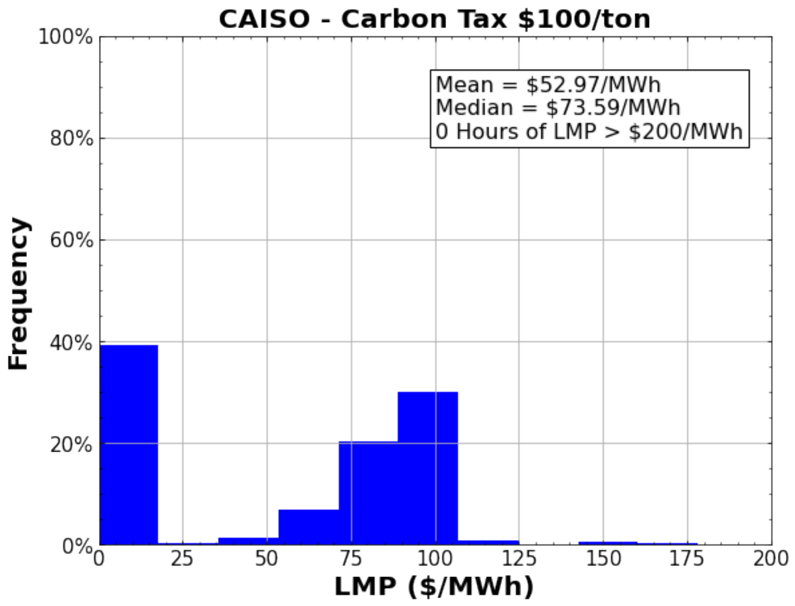
- Efficiency of power generation is king
- Systems using SOFC technology for power are highly profitable
- Motivation for power/H_2 systems is rather low

Standalone SMR+capture = ~M\$ 80/yr ★

Process/Market Analysis

Selling Price of H_2 = \$2/kg, Natural Gas = \$4.42/mmBTU

Bimodal Electricity Prices	CAISO \$100 Carbon/ton Tax Bimodal Mean: \$53/MWh
NGCC	M\$ -1.5/yr Capacity Factor Power: 0.61
SOFC	M\$ 96.8/yr Capacity Factor Power: 0.61
SOEC	M\$ 42.6/yr Capacity Factor H_2: 0.40
NGCC + SOEC	M\$ -9.2/yr Capacity Factor Power: 0.60 Capacity Factor H_2: 0.40
SOFC + SOEC	M\$ 171.8/yr Capacity Factor Power: 0.60 Capacity Factor H_2: 0.40
rSOC	M\$ 202.1/yr Capacity Factor Power: 0.61 Capacity Factor H_2: 0.39



- rSOC and SOFC+SOEC achieve ~2X the profit of standalone SOFC
- Business case for power and H_2 systems is strongest when electricity prices are bimodal.

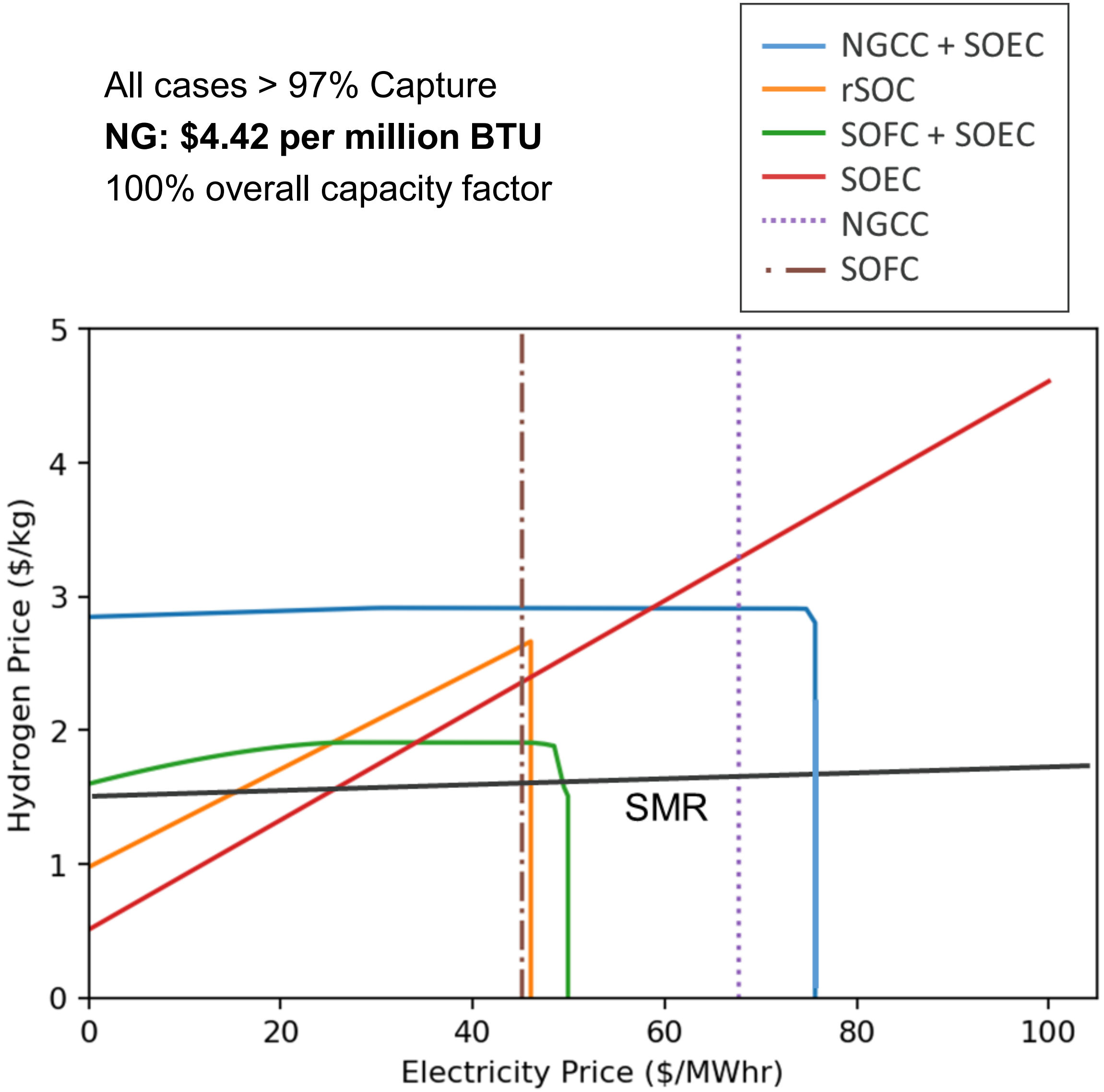
Standalone SMR+capture = ~M\$ 80/yr

Breakeven Curves for Process Concepts

All cases > 97% Capture

NG: $4.42 per million BTU

100% overall capacity factor



Takeaways:

- NGCC+SOEC is highest cost
- SOFC is far lower cost than NGCC
- SOEC preferred over SMR at low electricity prices
- rSOC preferred over SOFC+SOEC at low and high electricity prices.
- SOFC+SOEC is lower cost than rSOC between ~$22-45/MWh.

Solid State Electrochemical Degradation

Apply knowledge of cell degradation to a wide range of operating conditions relevant to commercial systems (power and fuel production operation modes)

NATIONAL ENERGY TECHNOLOGY LABORATORY

Goal / Technical Gaps

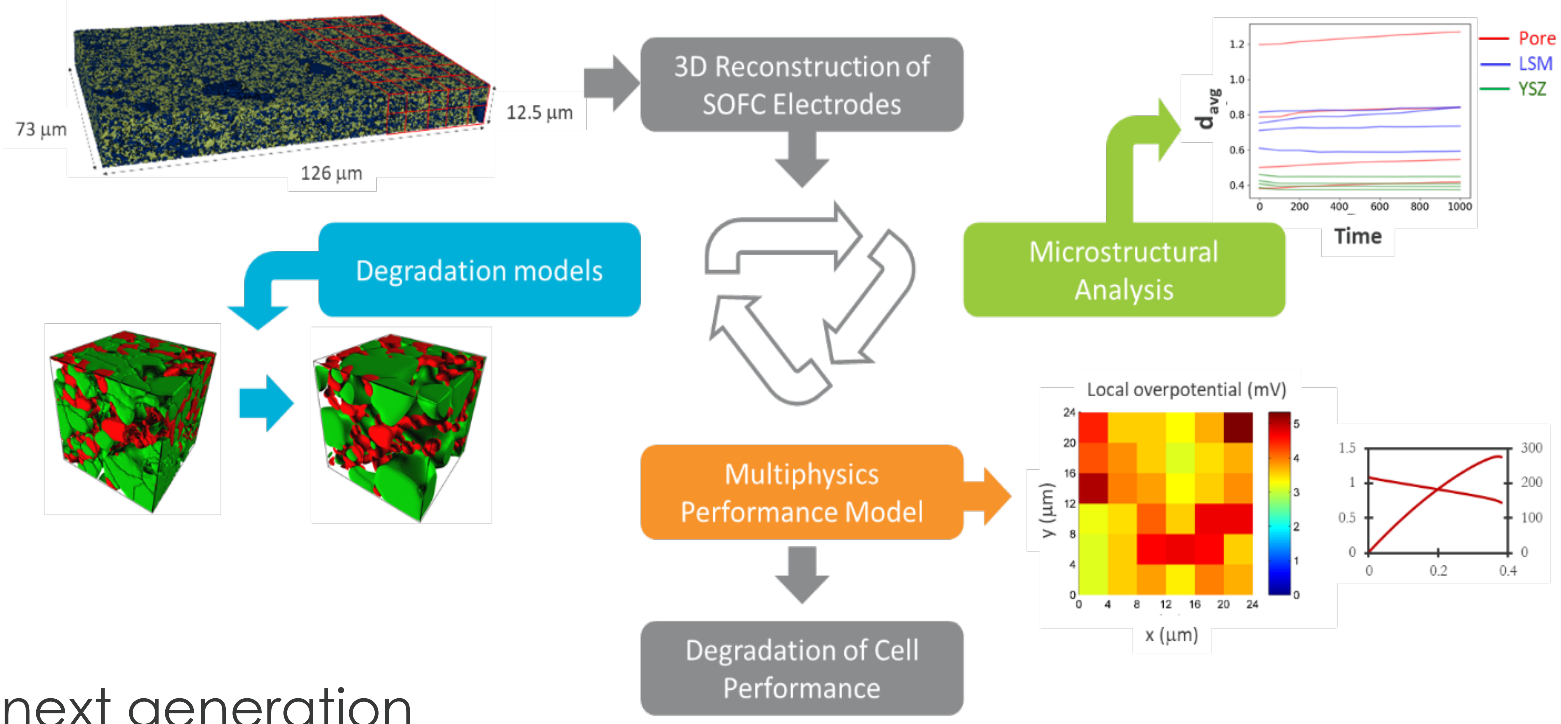
Solid State Electrochemical Degradation

Goal:

- Develop predictive tools to understand electrolyzer degradation under load changes

Approach:

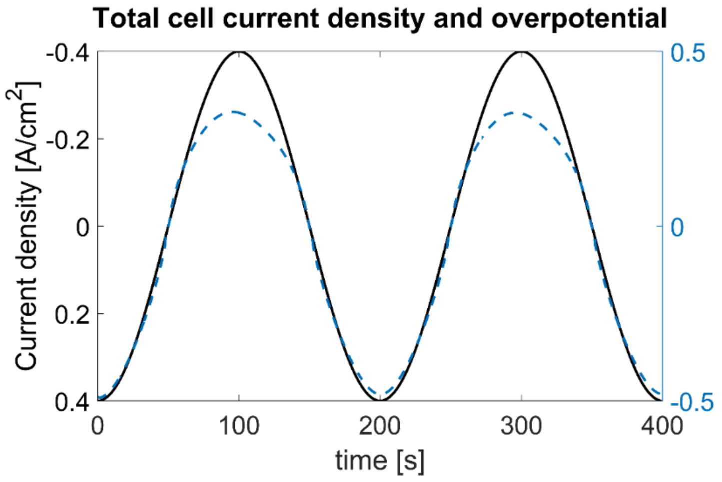
- Adjust in-house Multiphysics and degradation models to accommodate reversible operation
- Adapt performance models for next generation materials sets
- Develop optical fiber sensors for distributed temperature and gas composition measurements

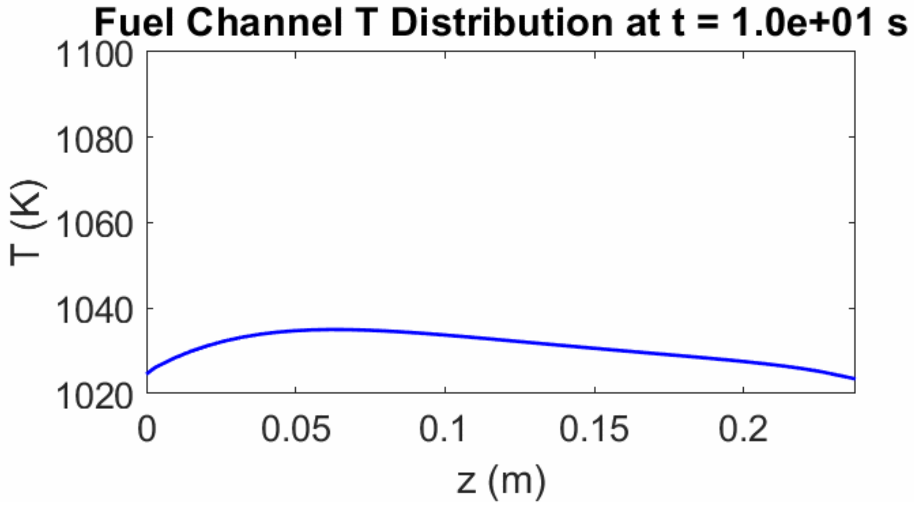


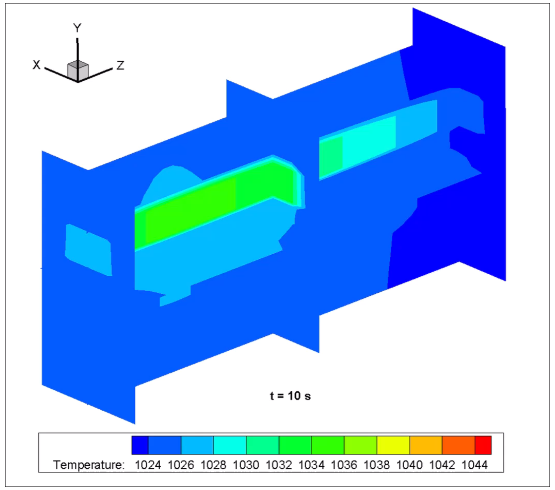
Accomplishments and Challenges Resolved

Solid State Electrochemical Degradation

- Planar cell model adjusted to include electrolysis/reversible operation
  - Adjusted gas diffusion models to accommodate wider range of gas compositions
- Impedance simulation capability added for subsections and for whole cell
  - Effect of overpotential and current fluctuation on the temperature distribution with a channel
  - Cross-flow versus counter-flow





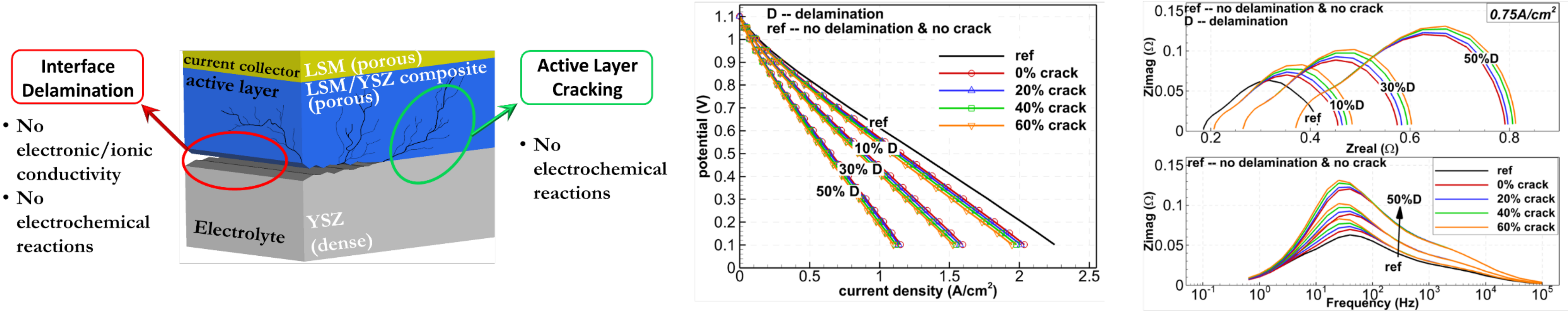


Temperature transients along anode fuel channel when a ±0.4 A/cm^2 sinusoidal signal (200 s period) applied (750°C, 50%H_2/50%H_2O)

Accomplishments and Challenges Resolved

Solid State Electrochemical Degradation

- Modified button cell model to include reaction pathways with proton-conducting electrolyte
- Completed button cell study differentiating impedance response due to electrode delamination from electrolyte vs. intergranular cracking within the electrode
  - Delamination affects ohmic, polarization resistances
  - Cracking affects only effects polarization resistance

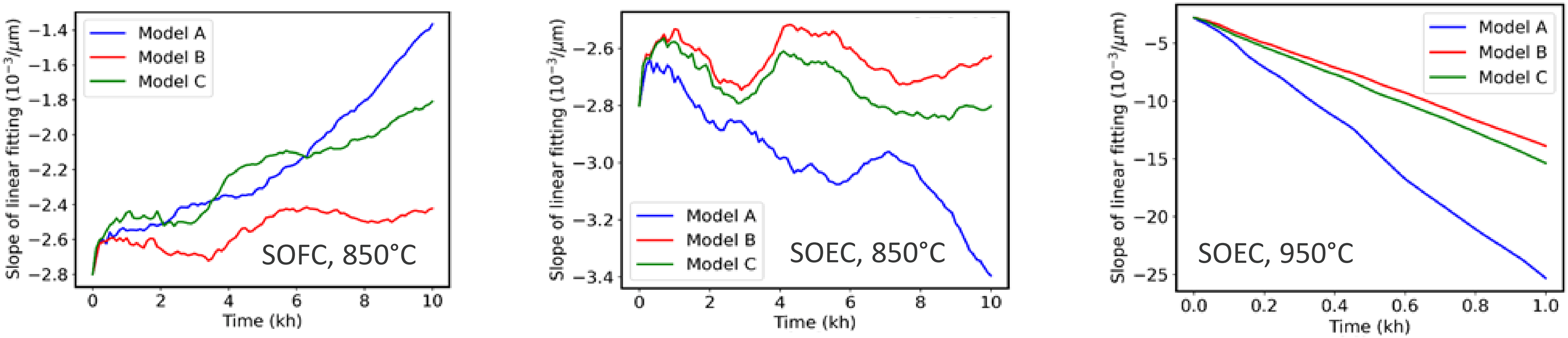


Performance degradation of LSM/YSZ-based cell experiencing different levels of delamination or cracking

Accomplishments and Challenges Resolved

Solid State Electrochemical Degradation

- Ni redistribution simulations trend with literature
  - Time, temperature, steam content, and overpotential
  - Need to explain driving forces behind absolute values of observed changes
- Reduced atmosphere reaction chamber designed, constructed for testing anode symmetrical cells
  - Cells fabricated for measuring Ni redistribution under SOC conditions



Slope of Ni volume fraction moving away from the electrolyte when comparing different Ni/YSZ wetting angle models under different operating conditions as a function of time

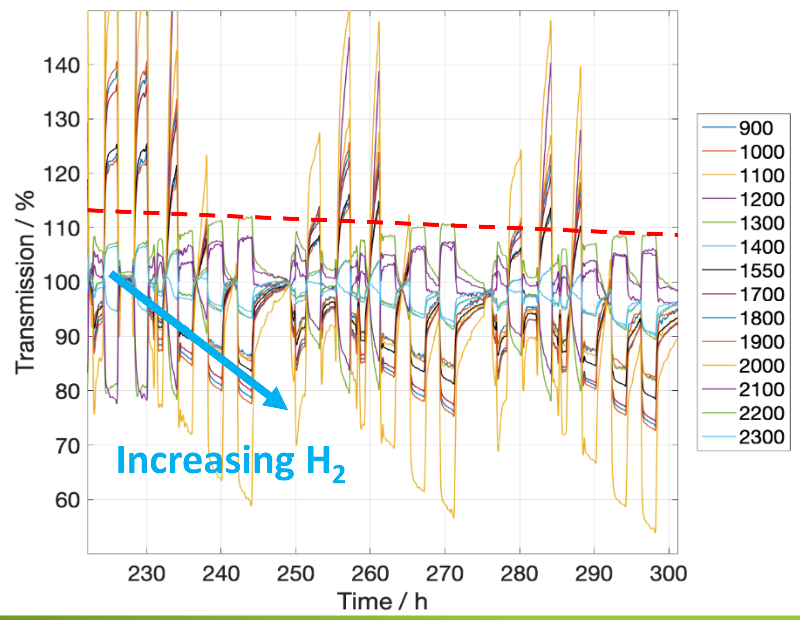
Accomplishments and Challenges Resolved

Solid State Electrochemical Degradation

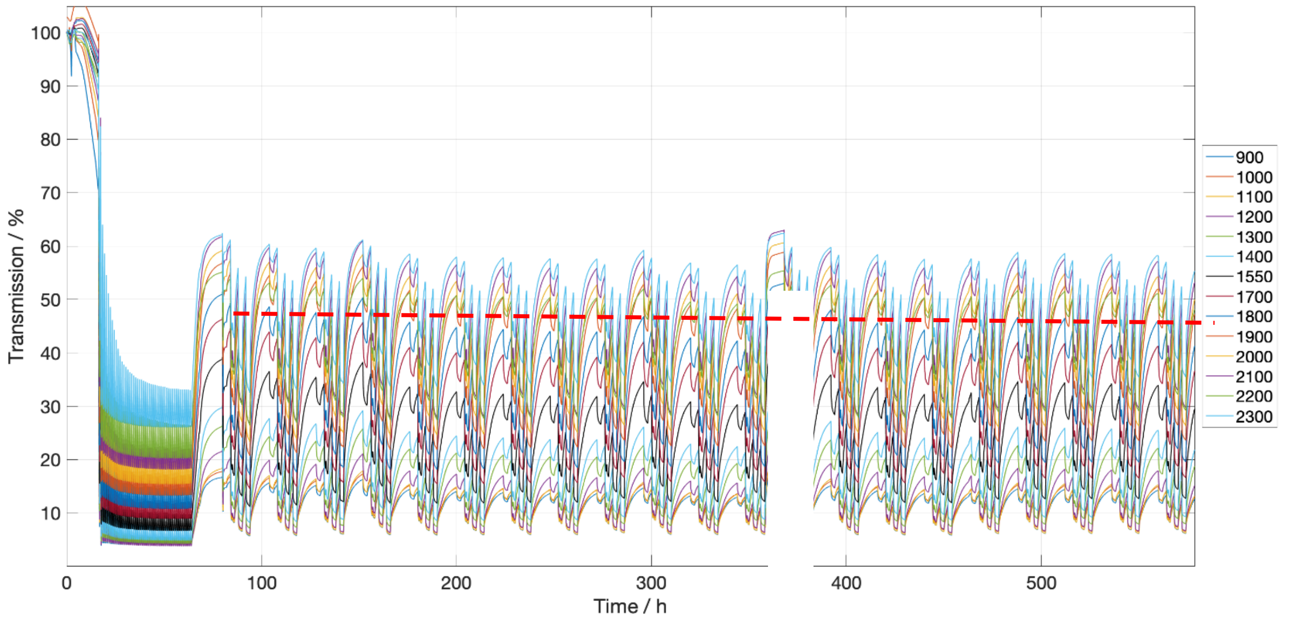
Hydrogen Optical Fiber Sensor Probe:

- Response increased 5-10 times by sputtered PCO instead of dip coated
- LSTO-coated sensor lifetime increased by covering with a 5 nm SiO_2 capping layer

Bare 70nm LSTO, 3 H_2 cycles



70nmLSTO + 5nmSiO$_2$, >20 H_2 cycles



H_2 sensing response as a function of wavelength for LSTO-coated optical fiber at 700°C

Grid Impact on Hybrid SOFC System

Characterize operability and develop integration and control strategies to achieve the flexibility and resilience that SOFC-HCC systems must meet to be fully compatible with a dynamic power grid

NATIONAL ENERGY TECHNOLOGY LABORATORY

Goal / Technical Gaps

Grid Impact on Hybrid SOFC System

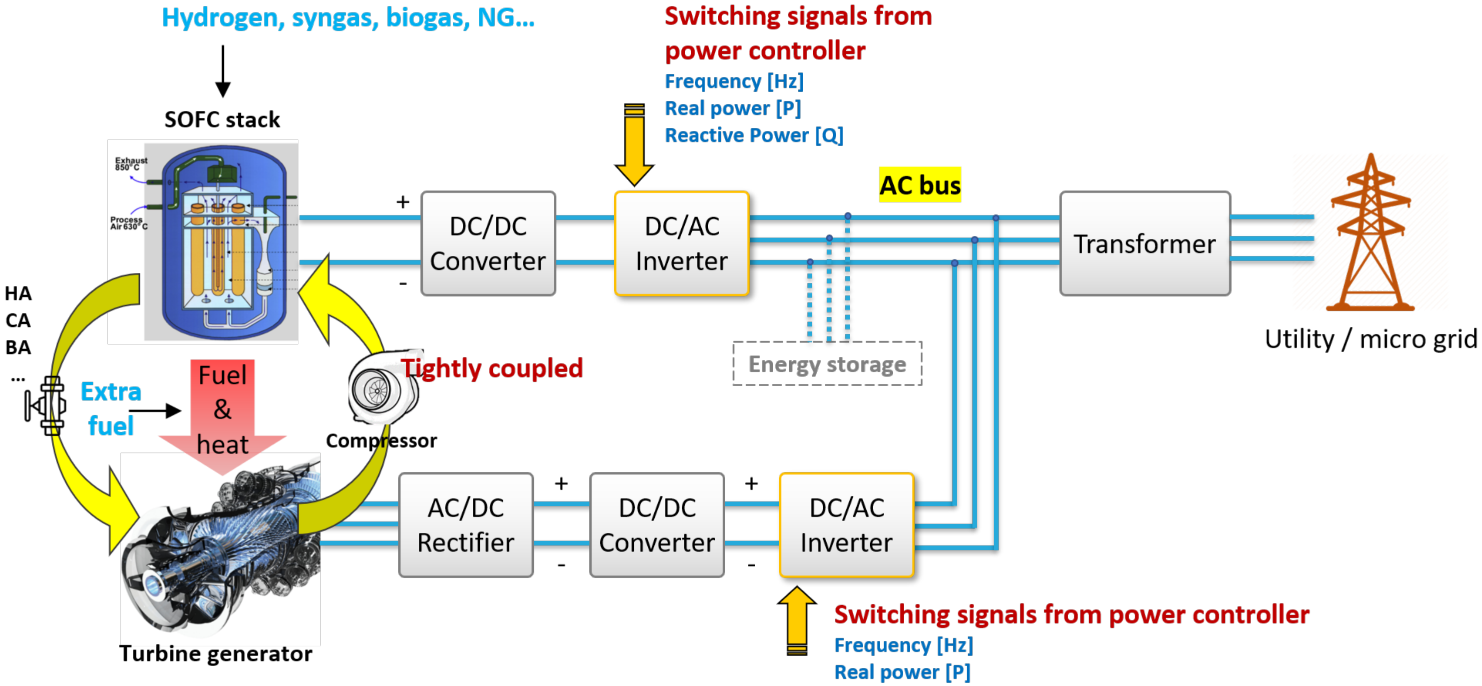
Goal:

- Show the feasibility of highly-coupled IES to load follow and respond to a rapidly changing grid.

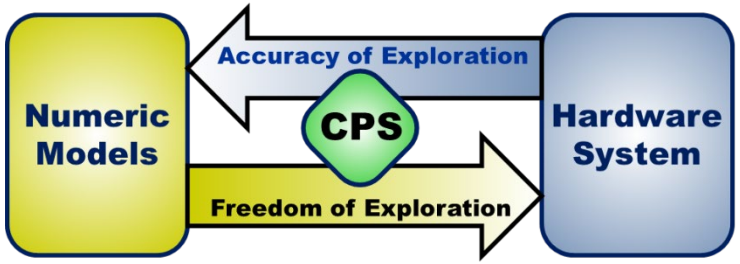
Approach:

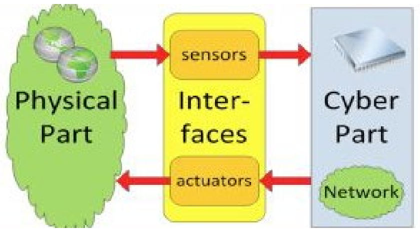
- Develop adaptive control strategies for load following
- Develop real-time SOEC model to couple with the HYPER cyber-physical system
- HYPER = Hybrid Performance facility at NETL Morgantown

Real-time execution (within 5 milliseconds) needed to ensure real-time control



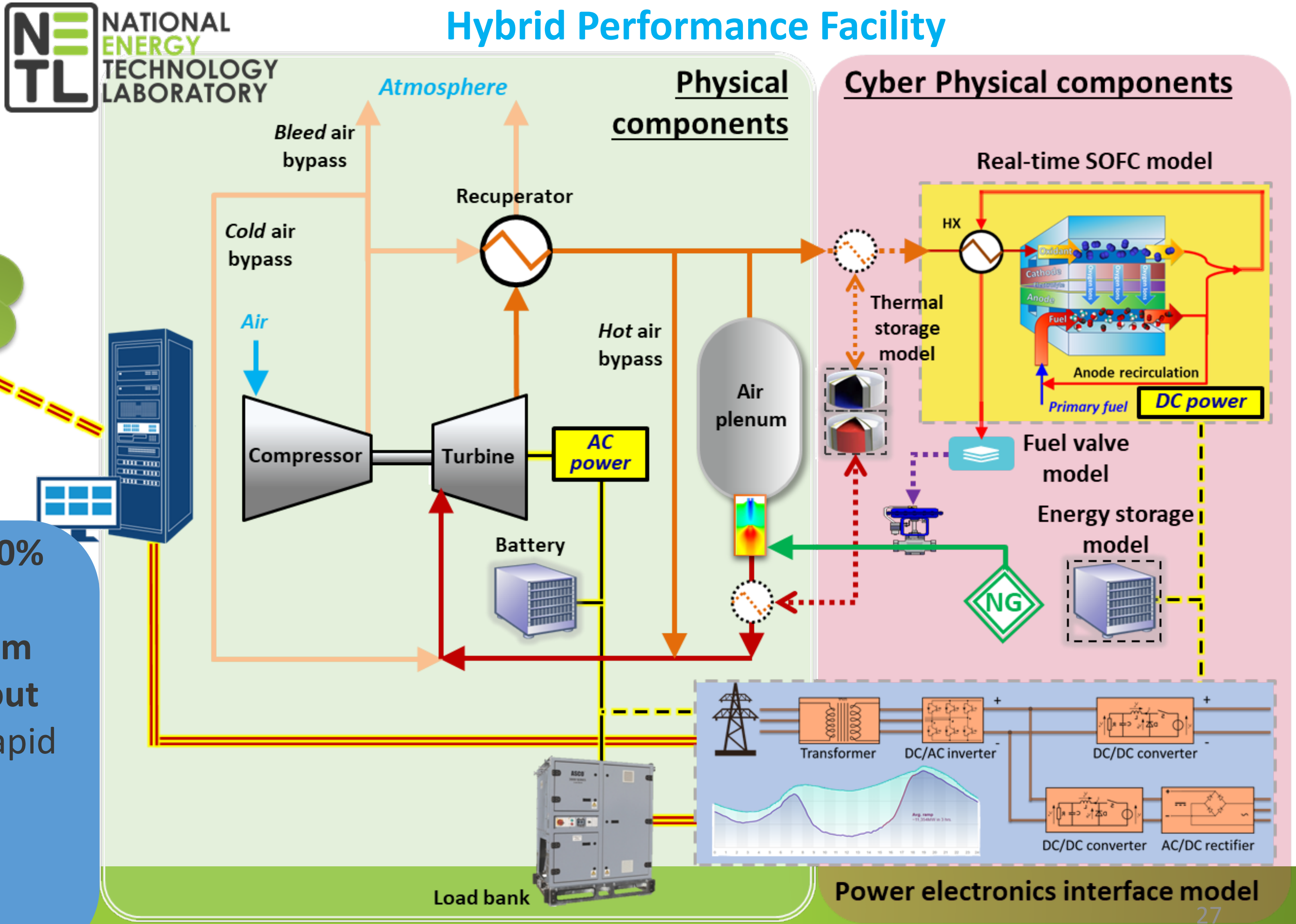
(Images from Huang et al. 2013 and Internet)





Accomplishments and Challenges Resolved

Grid Impact on Hybrid SOFC System

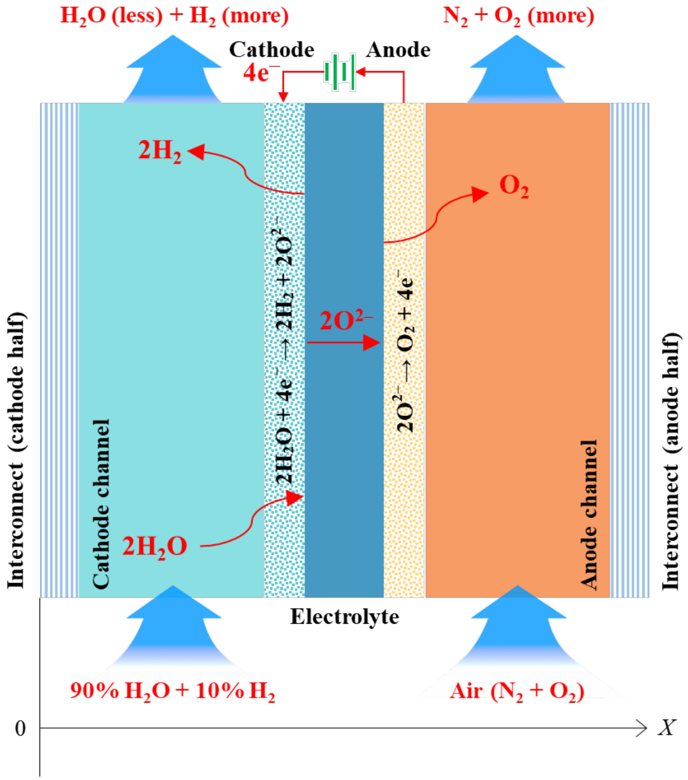


NETL successfully demonstrated that **a 50% load change for a solid oxide fuel cells (SOFC) - Gas Turbine hybrid power system in less than 10 seconds is possible without violating operability constrains.** These rapid load transitions were accomplished by controlling cathode inlet air flow and temperature to manage temperature gradients in the SOFC.

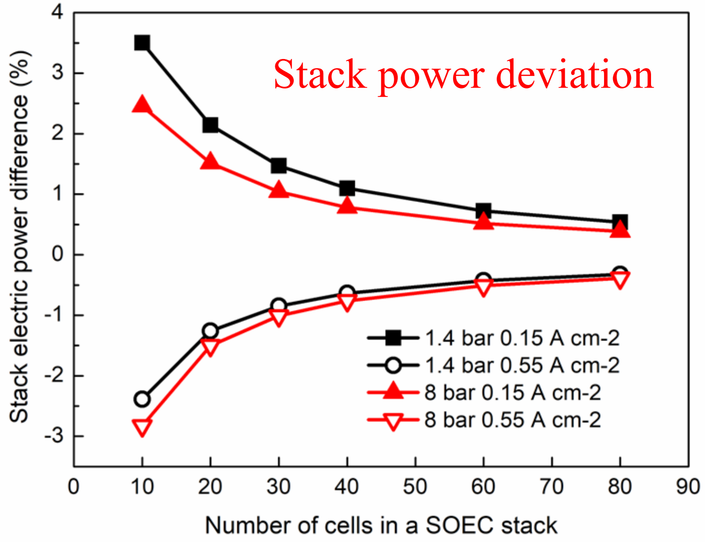
Accomplishments and Challenges Resolved

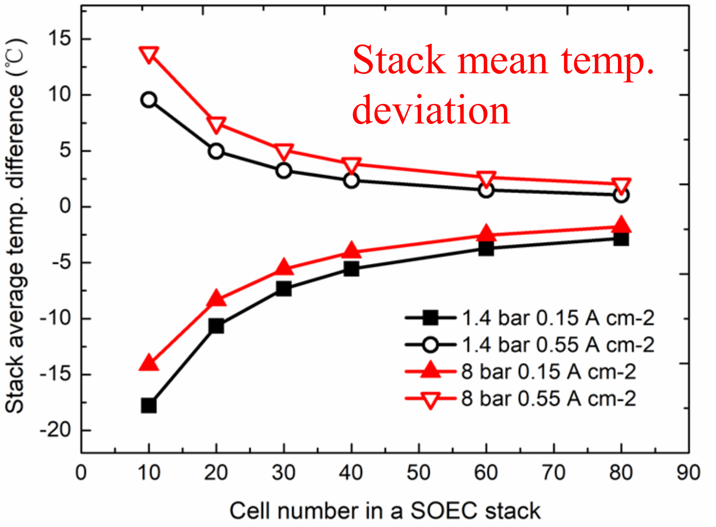
Real-time SOEC model for dynamic operability

- Multiphysics 0-D (lumped) SOEC model developed and validated against experimental data
- Non-isothermal model enables dynamic system analysis over a broad operating envelope
- Quantified effect of thermal conduction boundary on SOEC stack performance predictions
- Real-time execution has been demonstrated



Single repeating unit (SRU) assumption overestimated stack power consumption in endothermic mode.



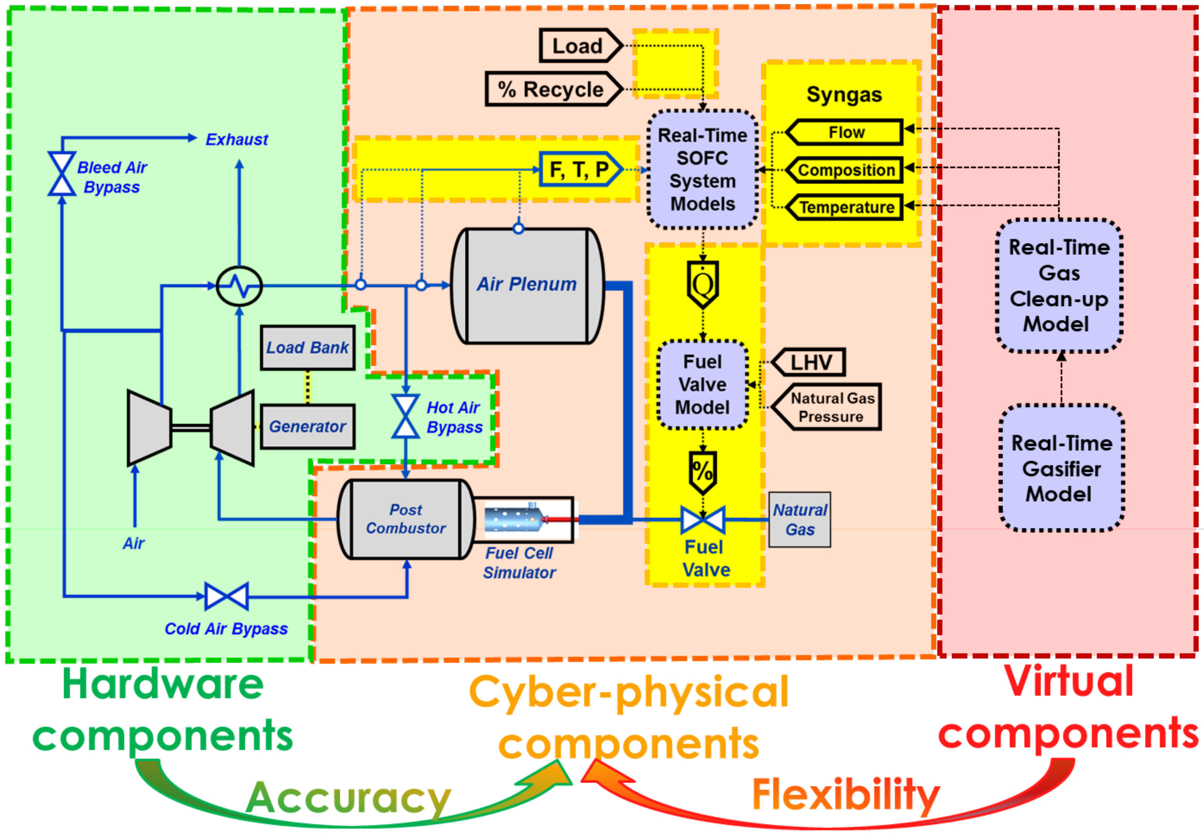


Accomplishments and Challenges Resolved

Grid Impact on Hybrid SOFC System

- Test plan developed to characterize six control actuators
- Ramp system by 25% and 50% load turndowns
- 100% total hybrid power and progressively stepping down to 75% and to 50% of total hybrid power
- Fixed power split between GT and SOFC
- Fixed hybrid component sizes, which are based on the existing configuration of a cyber-physical SOFC/GT system in the Hyper.
- A fixed fuel type using humidified hydrogen.
- Similar type of work for new SOEC model in future years

80% SOFC:20% GT or 85% SOFC:15% GT



	Actuators	Control variables
1.	Auxiliary fuel valve	Gas turbine speed
2.	Pre-combustor fuel flow	Cathode inlet temperature
3.	Anode fuel flow	SOFC fuel utilization
4.	Hot air bypass valve	Cathode inlet air mass flow
5.	Bleed air bypass valve	Gas turbine speed
6.	Cold air bypass valve	Surge margin

Project Wrapup

NATIONAL ENERGY TECHNOLOGY LABORATORY

Solid Oxide Fuel Cell – Integrated Energy Systems

Systems Analysis

- Completion and results dissemination of a TEA of a down-selected IES concept as identified in efforts completed in previous years

Solid State Electrochemical Degradation

- Planar SOC code created to simulate reversible cell load
- ID'd local physical, chemical, and/or electrochemical driving forces that cause varying degrees of nickel redistribution reported in the literature.
- Modify existing Ni-coarsening code under cyclical reversible operation.
- Demonstrate increased lifetime of the fuel gas optical fiber

Design/Optimization of Hybrid Systems

- Completed preliminary analysis and ranking of optimized process options using refined costing assumptions
- Completed development of dynamic models for high-priority IES components

Grid Impact on Hybrid SOFC System

- Successful demonstration of a 50% load change for SOFC-GT hybrid power system in 10 seconds possible without violating operability constrains.
- SOEC 0D model completed, 1D model in progress

Thanks for your attention

VISIT US AT: **www.NETL.DOE.gov**

@NETL_DOE

@NETL_DOE

@NationalEnergyTechnologyLaboratory

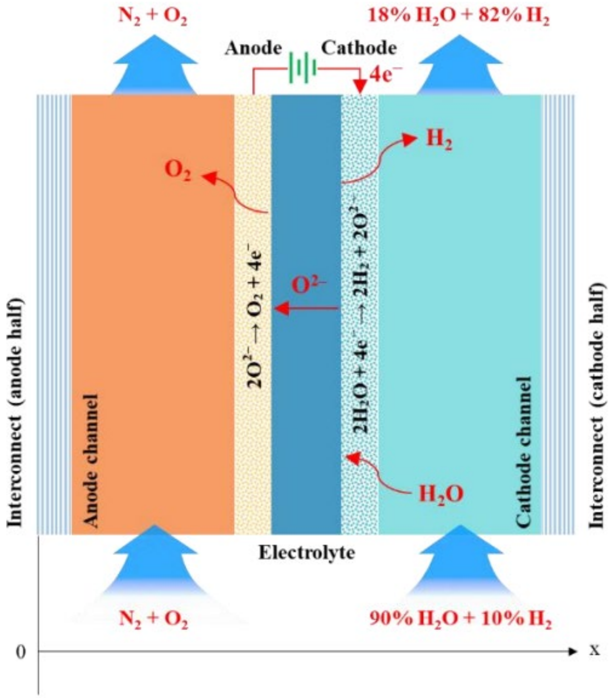
CONTACT:
Samuel Bayham, Technical Portfolio Lead, SOFC-IES
Samuel.Bayham@netl.doe.gov
O: (304)285-4178

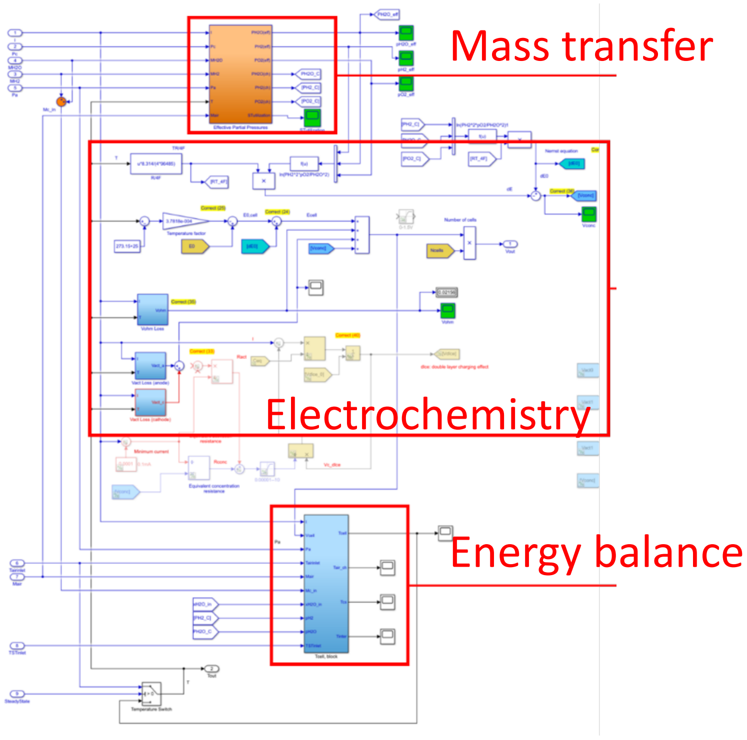
Supplemental Slides

Accomplishments and Challenges Resolved

Grid Impact on Hybrid SOFC System

- Dynamic 0D (lumped) SOEC model developed based on literature and technical resources from INL
- Model validation: geometry and electrochemical/thermal parameters from experimental data from actual SOEC stack testing at INL and the German Aerospace Center (DLR)
- Model able to predict experimental polarization trend and temperature variation





Code written in MATLAB/Simulink, programmed into OPAL-RT platform

Accomplishments and Challenges Resolved

Design/Optimization of Hybrid Systems

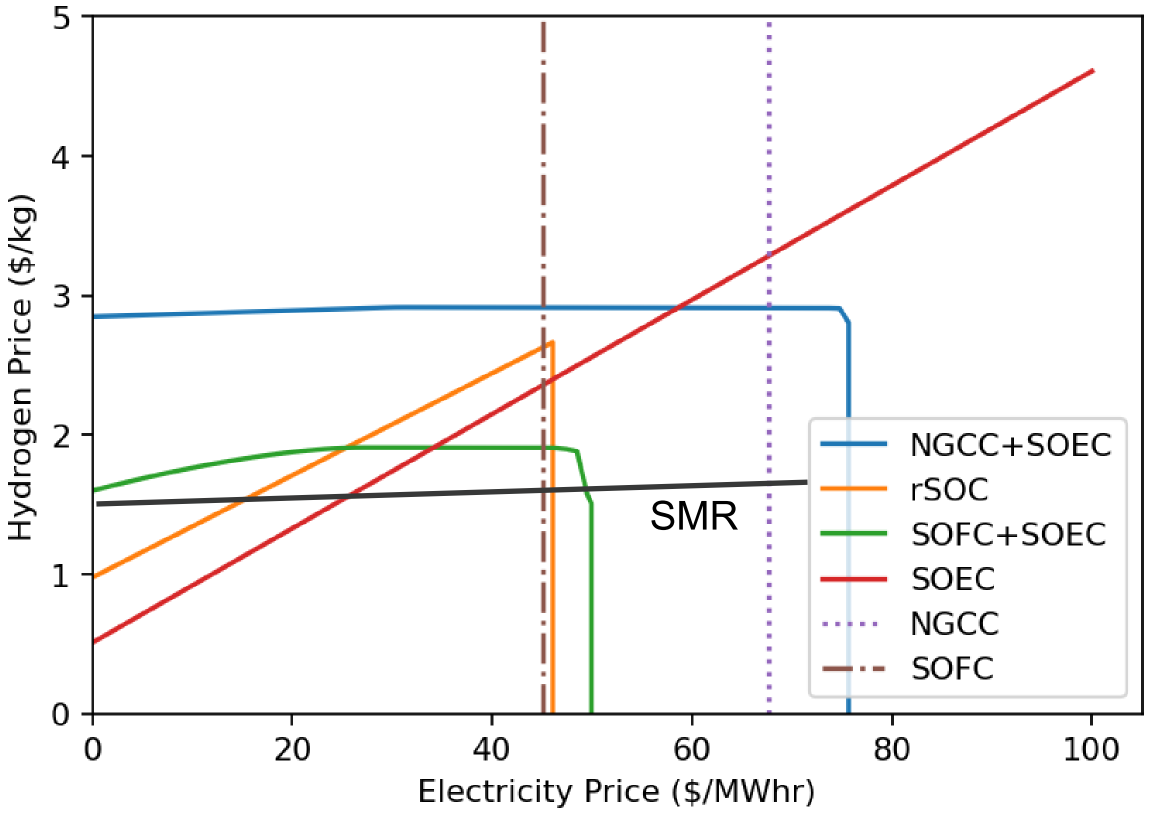
- Several IES process models were generated using the IDAES platform and a consistent costing approach.
- An optimization-based analysis framework was developed and demonstrated to obtain a preliminary ranking of initial process concepts under a base set of assumptions.

Assumptions: 2018 $'s, $4.42/MMBtu NG, $70.3/MWh, $2/kg H_2, 100% system availability, > 97% capture

System	Electricity Nameplate Capacity	Hydrogen Nameplate Capacity	Net Profit with Base Assumptions ($/hr)	Electricity Cost ($/MWh)	H_2 Selling Price ($/kg H2) Needed to Outperform Power Only Baseline at $70.3/MWh	Electricity Price ($/MWh) Needed to Turn Profit at $2/kg H2
NGCC	650 MW	-	5008	61	-	-
NGCC + SOEC	650 MW	2.0 kg/s	(6511)	-	> 3.6	Negative
SOFC	650 MW	-	17879	43	-	-
SOFC + SOEC	650 MW	2.0 kg/s	(2113)	-	> 4.8	Negative
rSOFC	650 MW	5.0 kg/s	17291	-	> 4.6	< 29

- A Localized Marginal Price (LMP) dataset was identified for the combined process-market analysis that spans broad range of future scenarios – 2035 ERCOT, carbon taxes $0-$250/ton CO_2.
- A 1st-principles planar, anode-supported, pressurized, air-fed, H_2-fed, non-isothermal SOFC/SOEC dynamic model was developed and exercised over a range of voltages and hydrogen production rates.

Breakeven Curves for Process Concepts

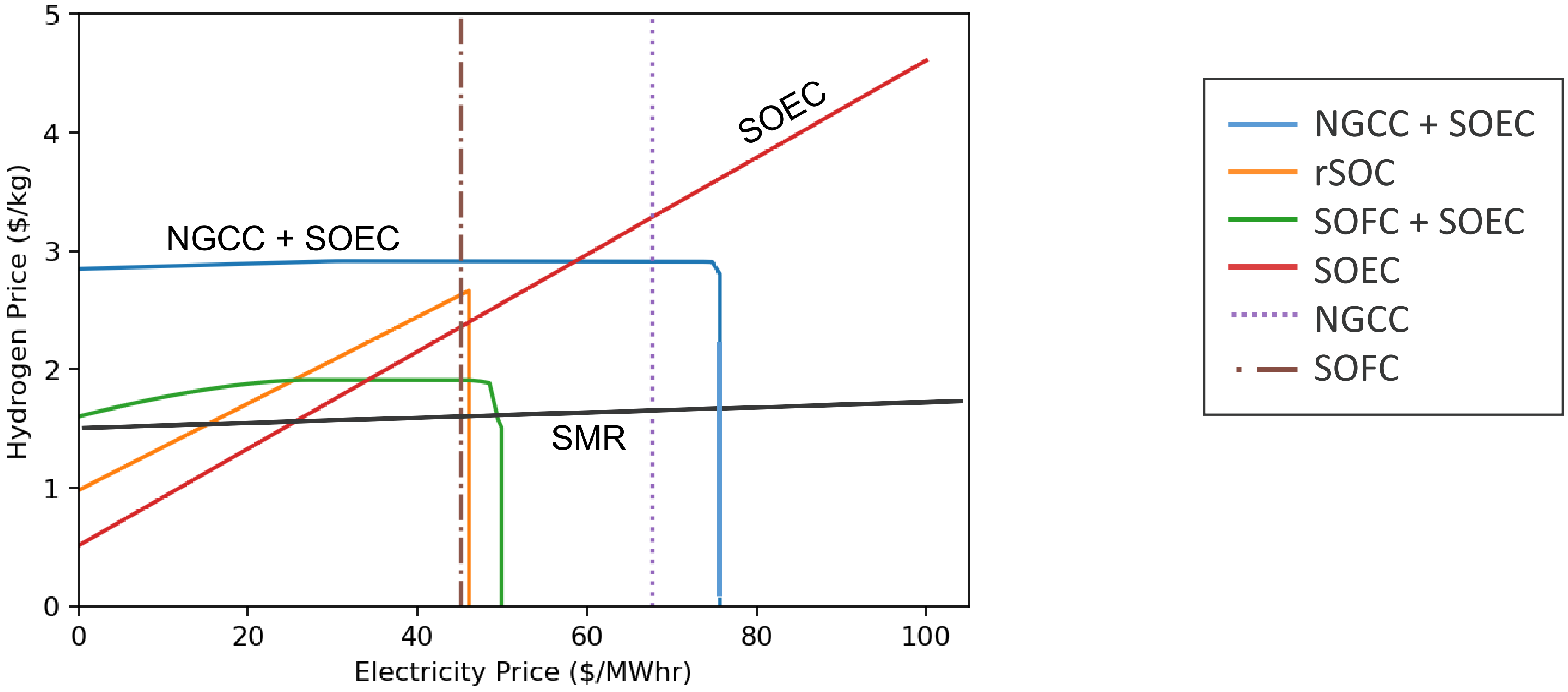


- Power only systems:
  - SOFC & NGCC are vertical lines.
  - SOFC is far lower cost than NGCC.
- Hydrogen only systems:
  - SMR & SOEC are lines with +ive slopes.
  - SOEC preferred over SMR at low electricity prices but can be much higher cost at high electricity prices.
- Integrated power and H_2 systems:
  - Breakeven curves are box-like.
  - NGCC+SOEC is highest cost.
  - rSOC preferred over SOFC+SOEC at low and high electricity prices.
  - SOFC+SOEC is lower cost than rSOC between ~$22-45/MWh.

All cases > 97% Capture

NG: $4.42 per million BTU

100% overall capacity factor


NGCC + SOEC
SOEC
SMR
Hydrogen Price ($/kg)
Electricity Price ($/MWhr)
0
1
2
3
4
5
0
20
40
60
80
100
NGCC + SOEC
rSOC
SOFC + SOEC
SOEC
NGCC
SOFC

Design and Costing Basis*

- Greenfield Plants, Midwestern US
- Hydrogen: 6.479 MPa, < 10 ppm H_2O
- All systems designed to capture > 97% CO_2
- CO_2 transport and storage costs not included

- 2018 $'s
- 100% capacity factor+
- SOFC: $225/kW stack cost
- SOEC: $105/kW stack cost
- Stack degradation rate: 0.2% / 1000 hr (~7 yrs stack life)

Process Concepts	Power Capacity ($MW_{e,net}$)	Hydrogen Capacity (kg/s)
NGCC	650	-
SOFC	650	-
NGCC + SOEC	650	5
rSOC	650	5
SOFC + SOEC	710	5
SOEC	-	5

* Theis, Quality Guidelines for Energy System Studies – Cost Estimation Methodology for NETL Assessments of Power Plant Performance, February 2021, (NETL-PUB-22580)

+ Major assumption that process-market optimization allows us to relax.

Accomplishments and Challenges Resolved

NATIONAL ENERGY TECHNOLOGY LABORATORY

Real-time SOEC model for dynamic operability

- Lumped model was extended to 1-D by considering 20 nodes along the length direction
- Current density distribution profile require iterations for convergence in one time step (5 ms)
- Preliminary results confirmed that the model can be executed in real-time
- Model validation using distributed temperature measurements and code optimization are in process
- Cyber-physical SOEC hybrid systems are in planning using the developed model and NETL's Hyper facility