Cyber-Physical Simulation of Solid Oxide Cell Hybrid Systems

SOFC Task 5 (FWP-1022411)

NATIONAL ENERGY TECHNOLOGY LABORATORY

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2024 FECM/NETL Spring R&D Project Review Meeting

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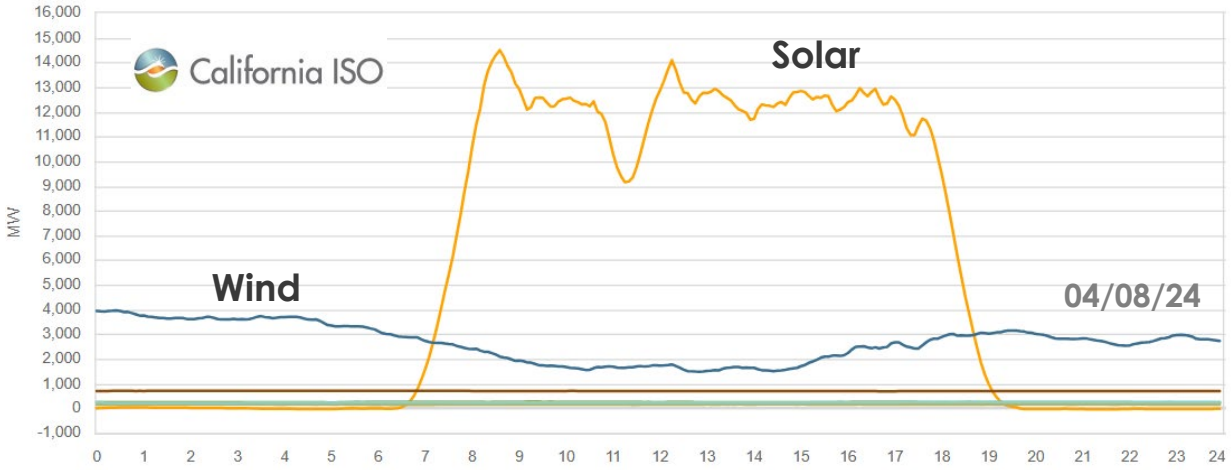
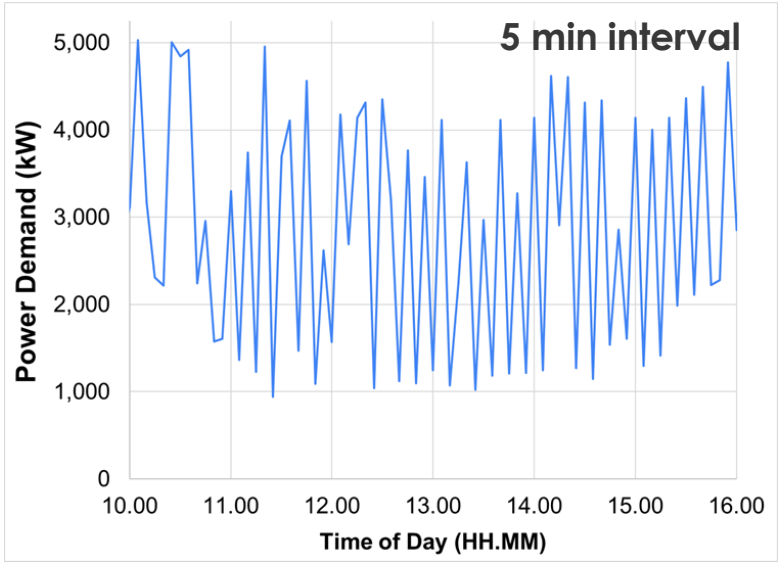
SOFC Task 5: Cyber Physical Modeling





Microgrid power demand from NREL

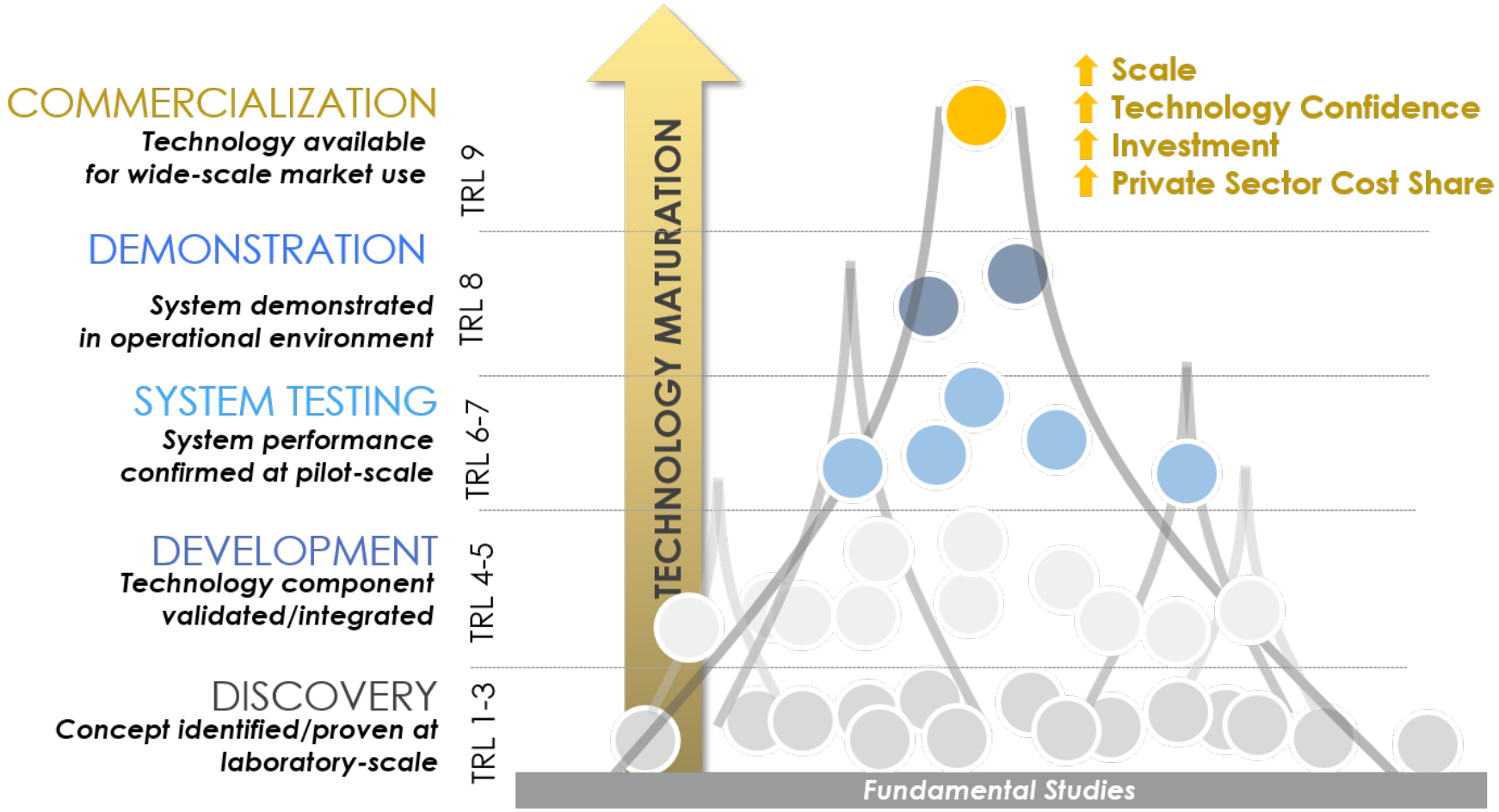
- Intermittent renewable power fluctuates **in diurnal cycles & shorter period**
- SOCs must have **rapid load transition** capability to load follow & support grid resilience

Goal:

- ✓ **Derisk** the adoption of SOC systems for hydrogen production by demonstrating concepts using a **cyber-physical approach**
- ✓ Show the feasibility of highly-coupled SOC systems to **load follow** and respond to a rapidly changing grid

Technology Development Pathway

An Active Portfolio from Concept to Market Readiness



Lessons Learned in the First-of-a-Kind Kemper Project

Source: IEEE Spectrum 2017

Source: POLITICO 2015

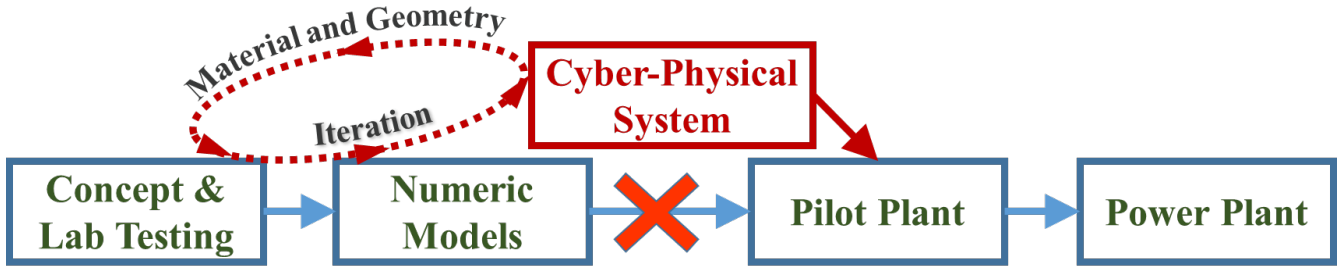
From Final Project Report (2019):

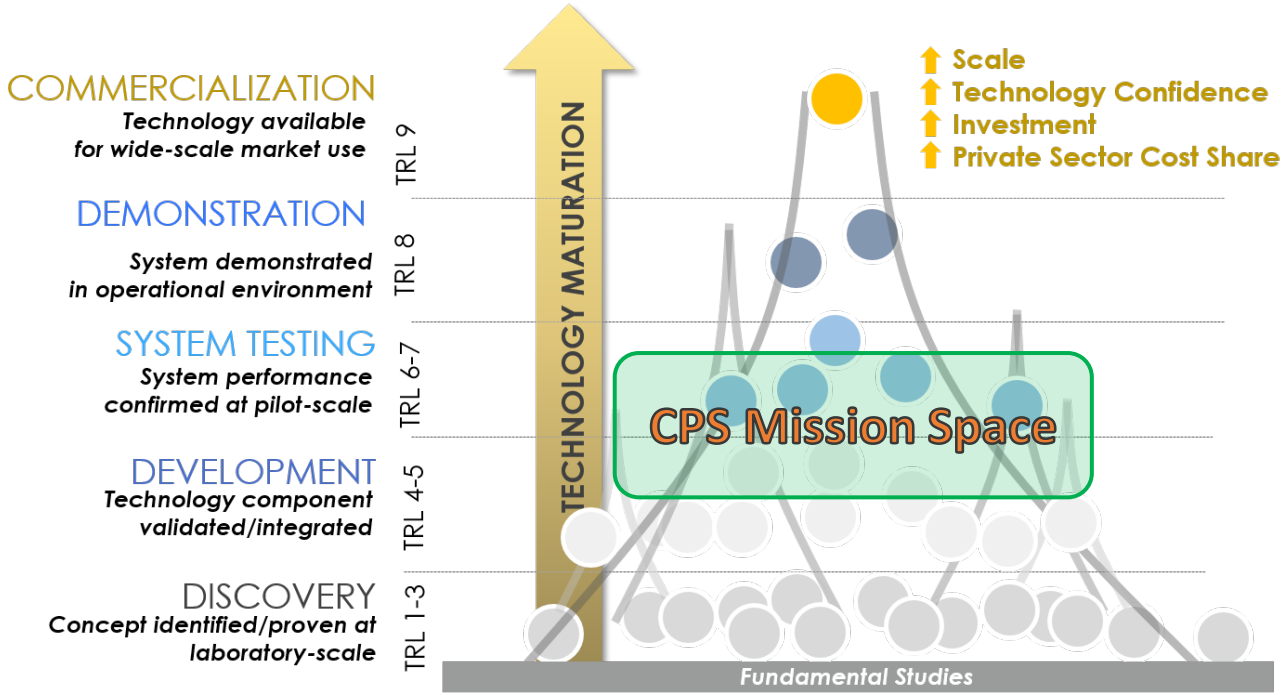
- *"Ensure time is allotted during the **design phase** to evaluate the effect of startup, shutdown, and other transient operating scenarios …on process design, equipment design, and controls design."*
- *"Allow time to develop commissioning, startup, shutdown, and transient scenarios for consideration during design."*
- *"Control logic changes for individual equipment should be reviewed…to ensure they will not cause unwanted system or unit trips."*

System integration & dynamic operability issues should be addressed to derisk design & operation.

Cyber-Physical Simulation (CPS)

A paradigm change…

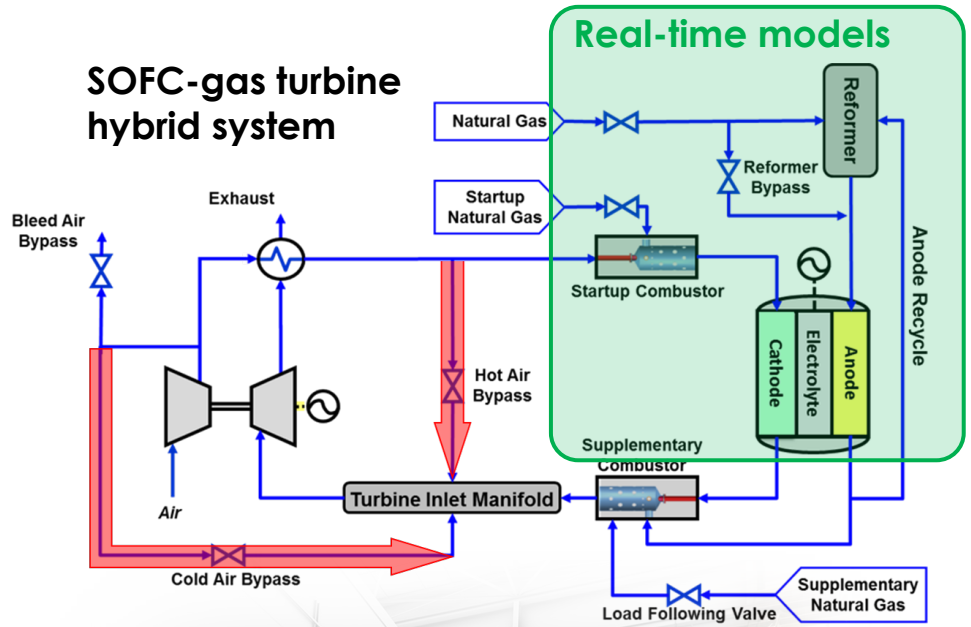


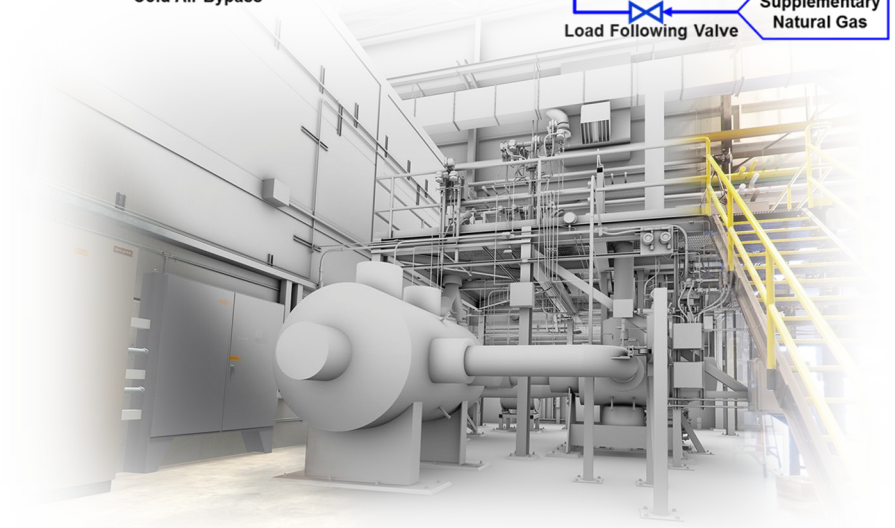


CPS approach enables:

- ✓ Emulating expensive/pre-mature components
- ✓ Emulating the actual system at high fidelity and lower cost
- ✓ Identifying **system integration** and **dynamic operability** issues
- ✓ Developing **control strategies**
- ✓ **De-risking** pilot testing

Hybrid Performance Project (HyPer) at NETL



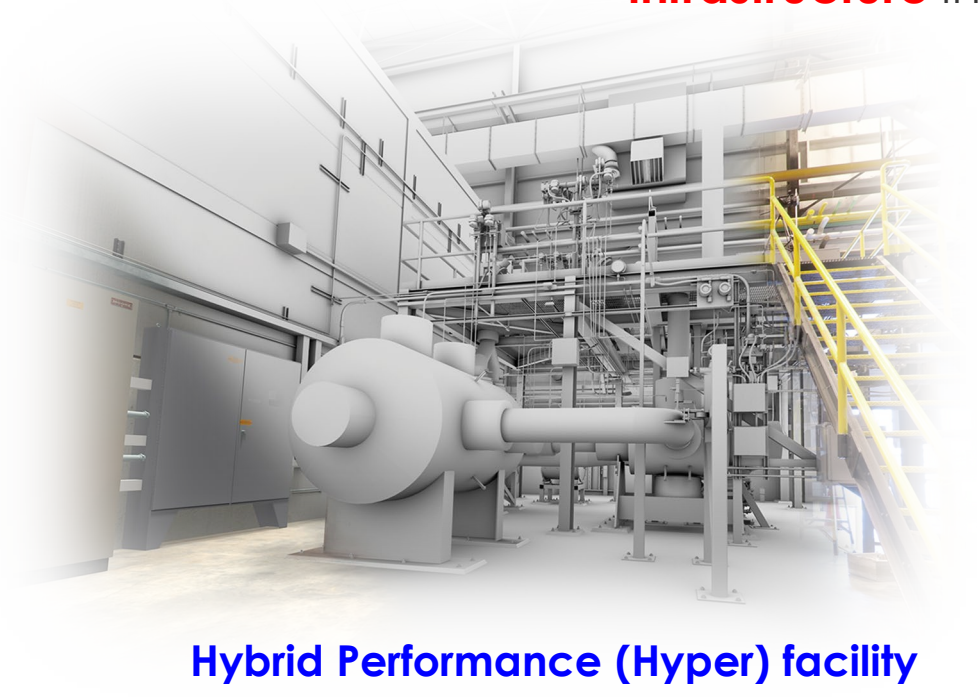


Goal:

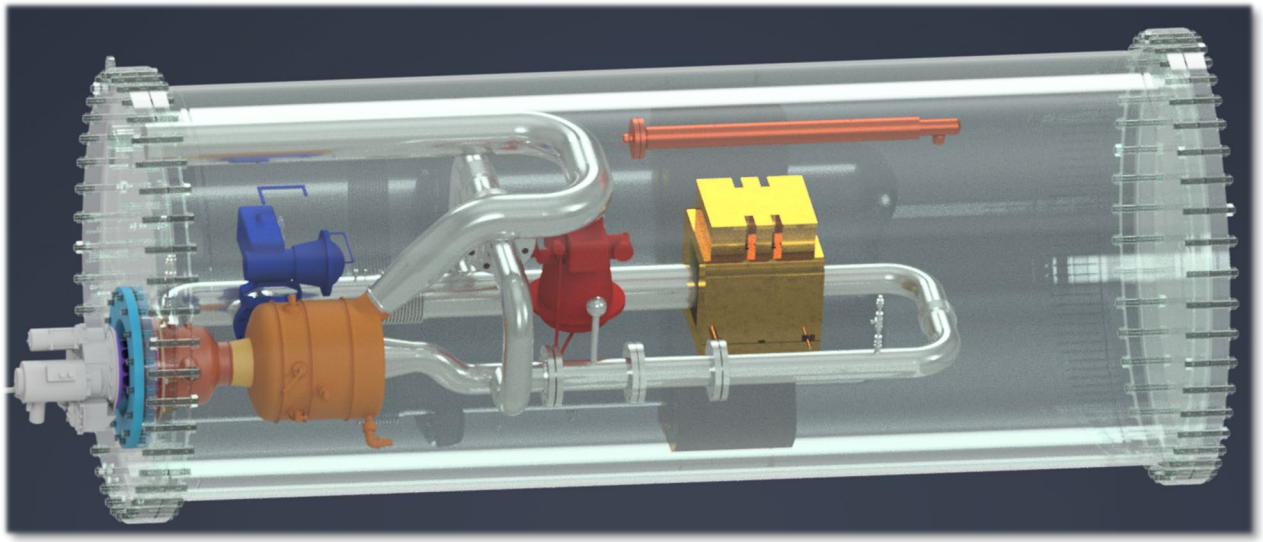
- ✓ Derisk the operation of SOFC systems in hydrogen production by demonstrating the concept of using a cyber-physical approach
- ✓ Showing the ability of highly-coupled SOFC systems to load follow and respond to a rapidly changing grid

Subtask 1 – Develop Real-Time SOEC Model to Couple with NETL's Hyper Facility

- ✓ **Multiple operational & control scenarios** can be performed without using / destroying a real cell
- ✓ Work under this subtask also prepares the **Hyper/mini-Hyper** capability for **infrastructure** in Multi-Year Research Plan (MYRP) involving a **real SOEC/SOFC**



Hybrid Performance (Hyper) facility



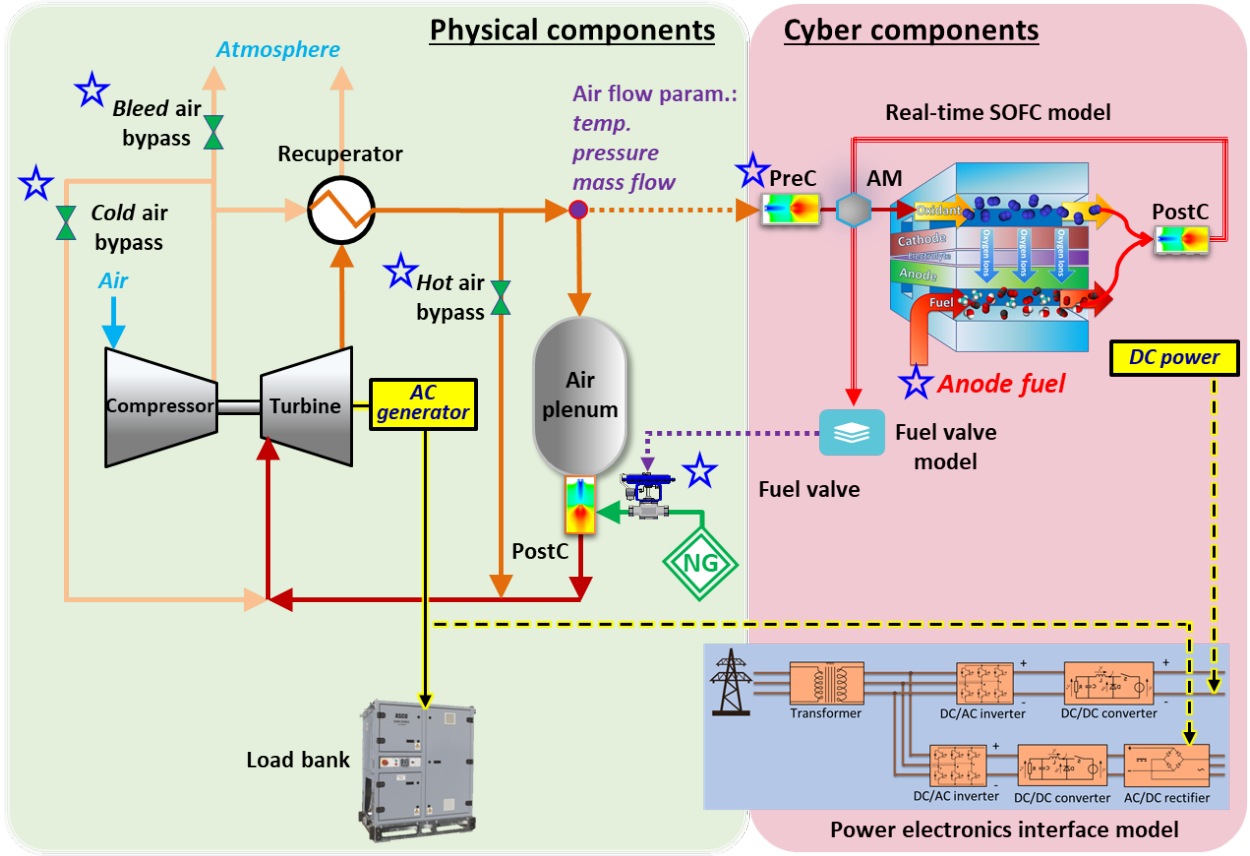
ARPA-E Cyber-Physical Reformer (a.k.a., Mini-Hyper)

The first-of-a-kind automated CPS SOFC/SOEC test facility

Subtask 2 – Perform system characterization & develop adaptive control strategies for load following

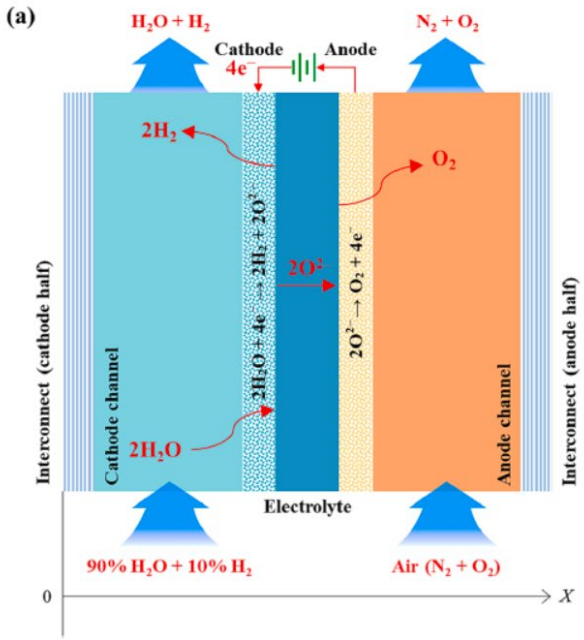
- Experimentally **characterize dynamic response** of the Hyper facility with the SOFC model and the new 1D SOEC model
- Characterize **control states** and control valve response
- Develop **an adaptive control strategy** suitable for attaining greater than 50% turn-down in closed-loop

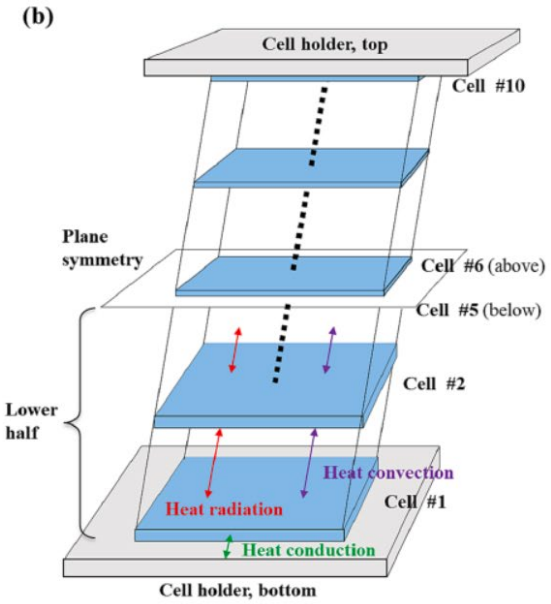
	Actuators	Control Variables
1	Auxiliary fuel valve	Gas turbine speed
2	Pre-combustor fuel flow	Cathode inlet temperature
3	Anode fuel flow	SOFC fuel utilization
4	Hot air bypass valve	Cathode inlet air mass flow
5	Bleed air bypass valve	Gas turbine speed
6	Cold air bypass valve	Surge margin

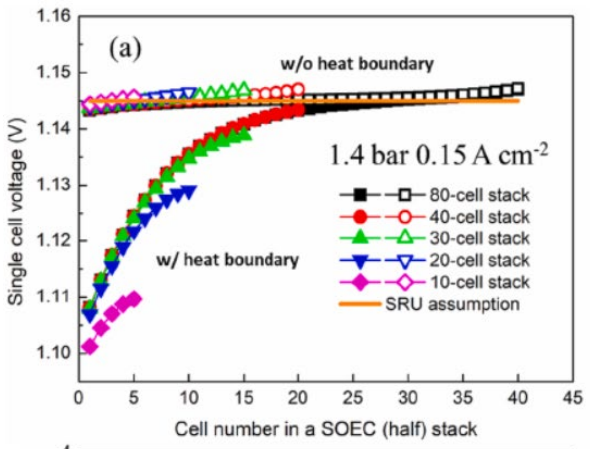


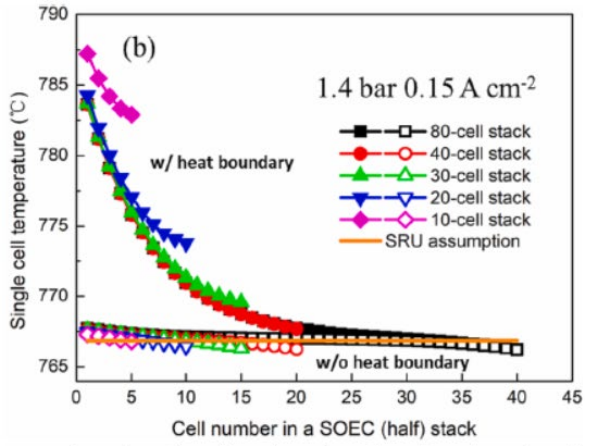
Accomplishment 1 – Real-Time SOEC Model for Dynamic Operability & CPS

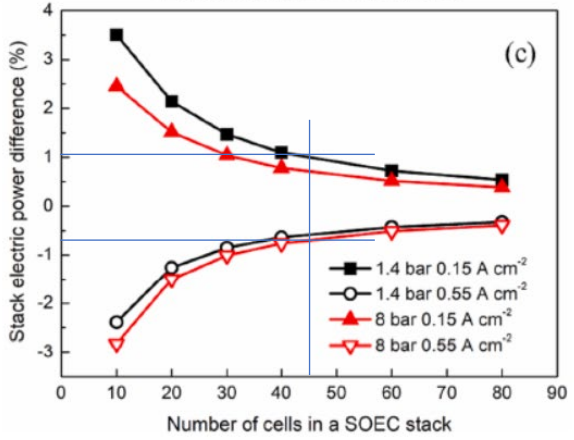
- ✓ Multiphysics **0-D (lumped)** and **1-D real-time SOEC models** were developed
- ✓ **[0-D model] Established a guidance** to have >45 cells in a stack to safely apply the SRU assumption

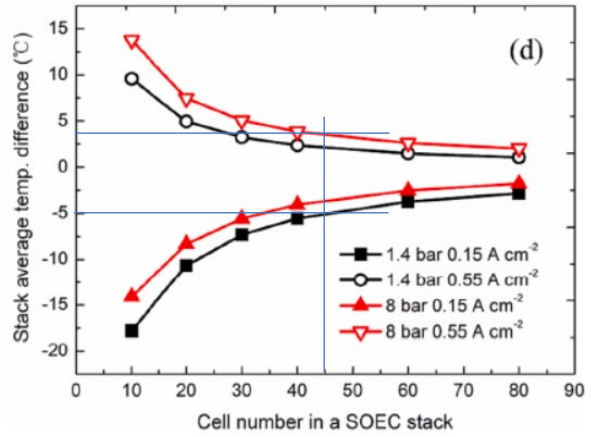












Accomplishment 1 – Real-Time SOEC Model for Dynamic Operability & CPS

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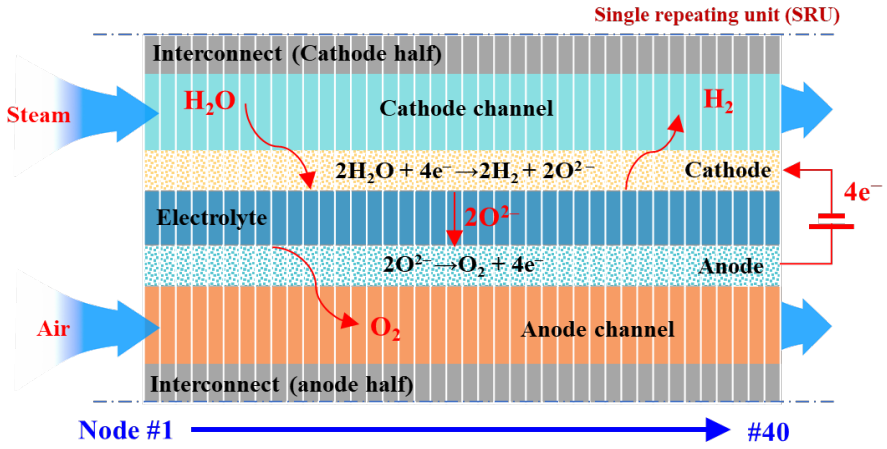
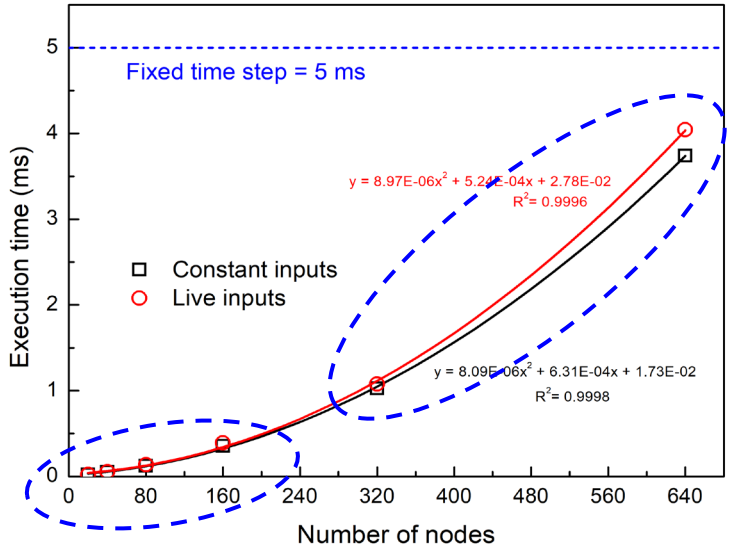
- ✓ **[0-D model] Established a guidance** to have >45 cells in a stack to safely apply the SRU assumption
- ✓ **[1-D model] Real-time execution capability** was verified, local temperature gradient was obtained
- ✓ **Great flexibility** – one can trade spatial resolution for better temporal resolution by tightening time step constrains, and vice versa
- ✓ **Versatile applications** – from **ultrafine** multiphysics distribution at micrometers intervals to **ultrafast** transients at microseconds





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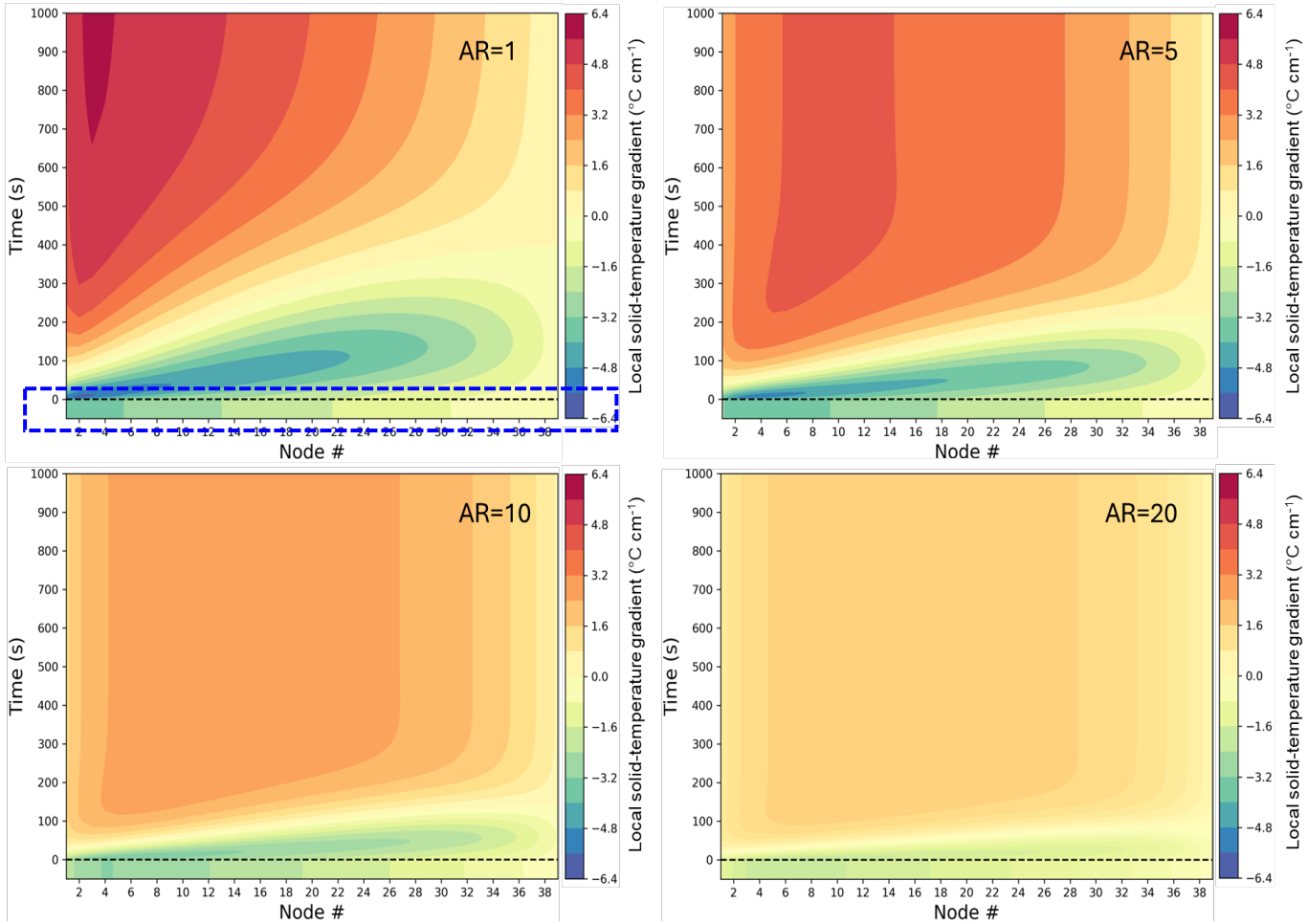
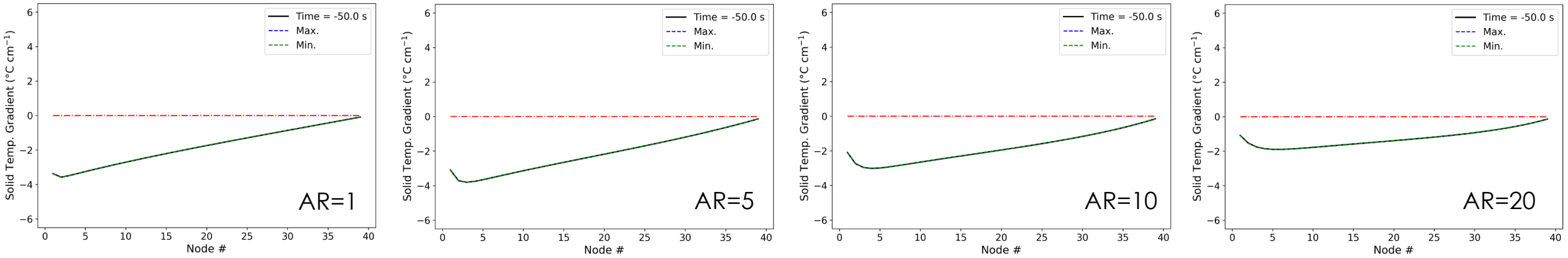


Effect of excess air ratio (AR) on local solid temperature gradient.

Upon a current density step change from 0.15 to 0.55 A/cm²:

- Identified **direction change of local temperature gradient** on SOEC solid materials during transients
- This could induce **alternating stresses** on SOEC solid materials to (possibly) **accelerate degradation**
- Higher air flow is beneficial for SOEC **thermal management**, thus highlighting the opportunity for **system integration**

Accomplishment 1 – Real-Time SOEC Model for Dynamic Operability & CPS



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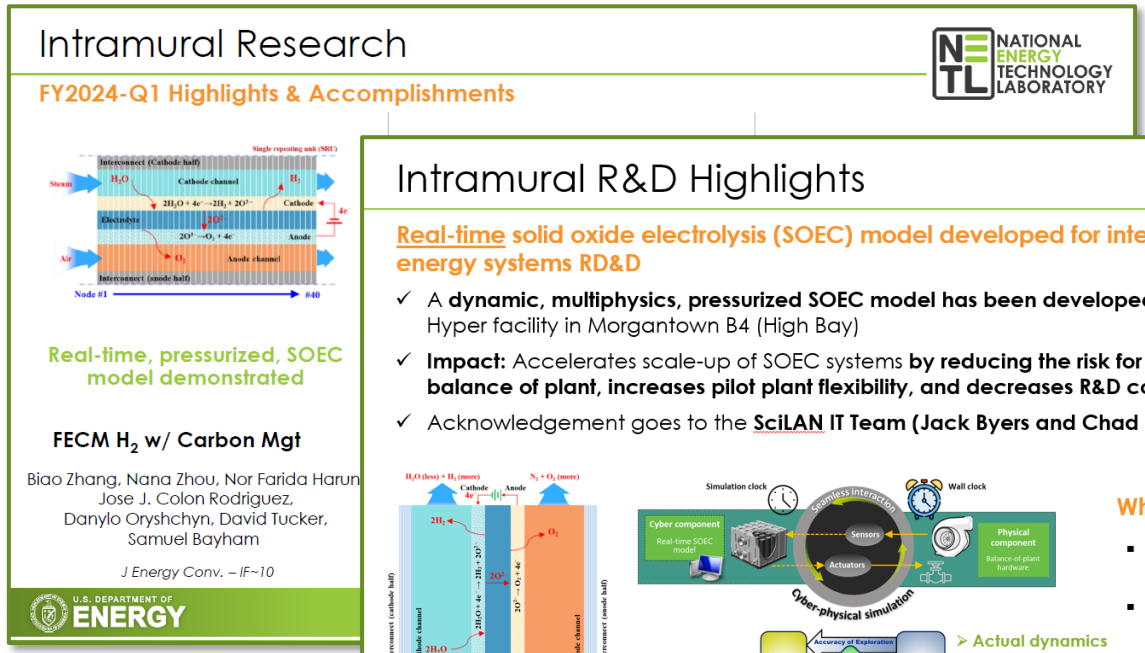
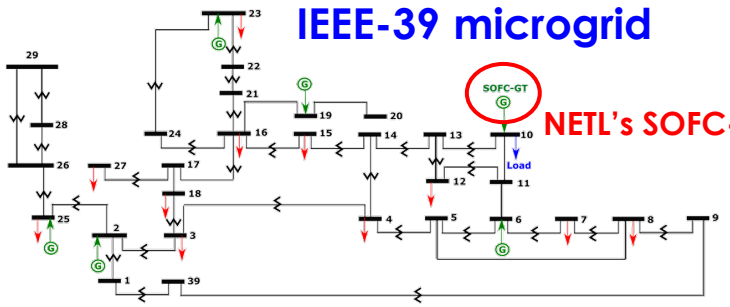


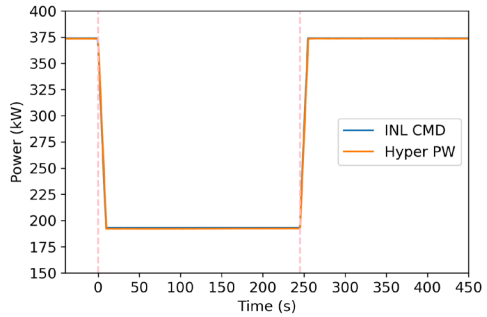
- Highlighted by NETL's former acting Director **Dr. Sean I. Plasynski** in the NETL Town Hall Meeting (January 2024) as the **#1 achievement in FY24-Q1**.
- Also highlighted by NETL RIC's Assoc. Lab Director for Research & Innovation **Dr. Bryan Morreale** in the NETL Intramural R&D Town Hall (February 2024).

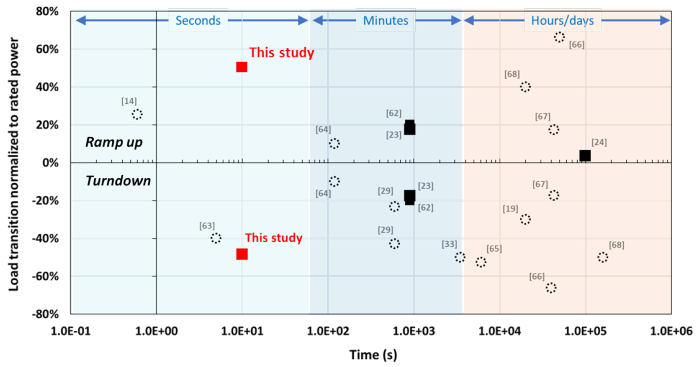
Next steps:

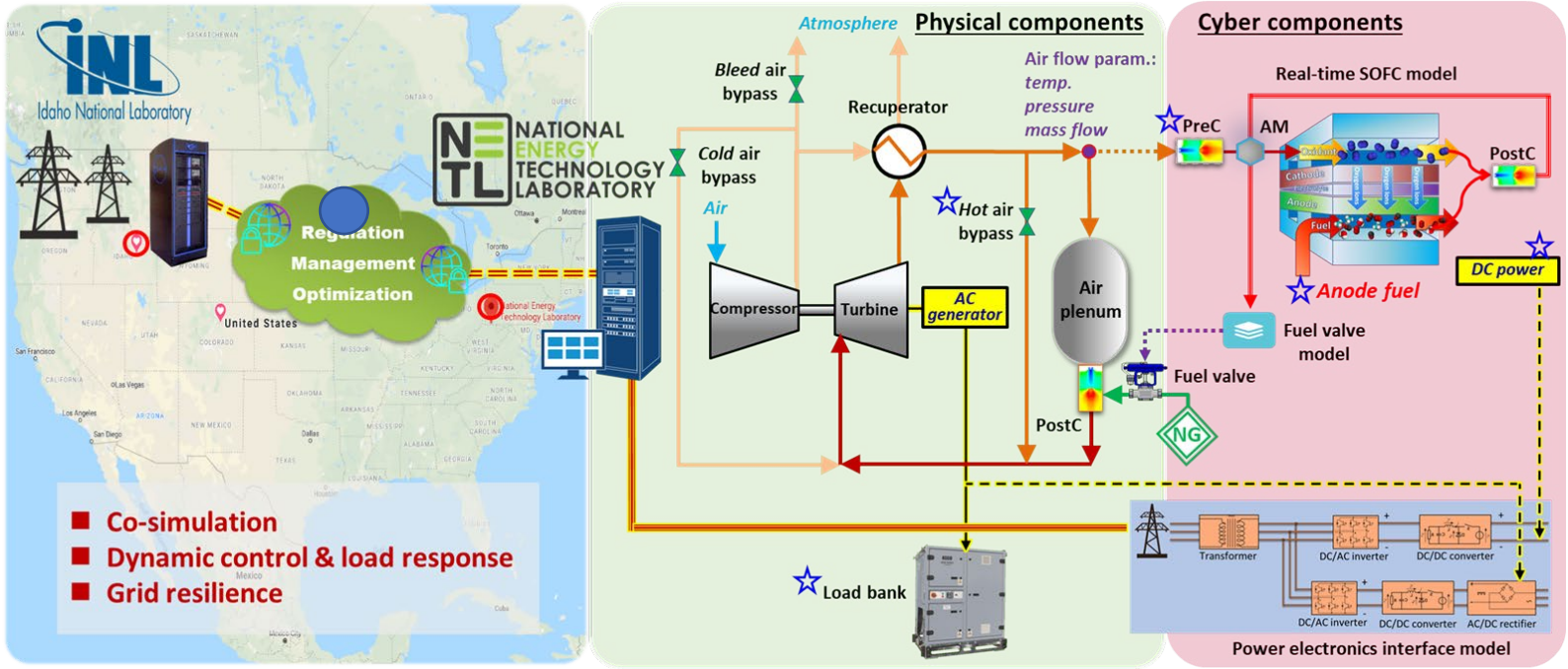
- R-SOFC hybrid systems research in **MYRP**
- Real-time co-electrolysis SOEC model in a Laboratory Directed Research & Development (**LDRD**) project

Accomplishment 2 – Grid Impact on Hybrid SOFC System





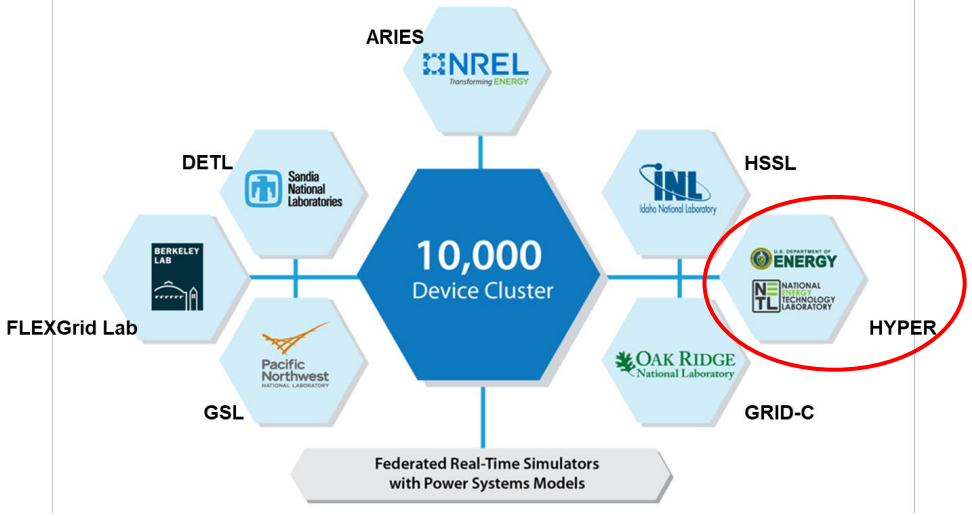




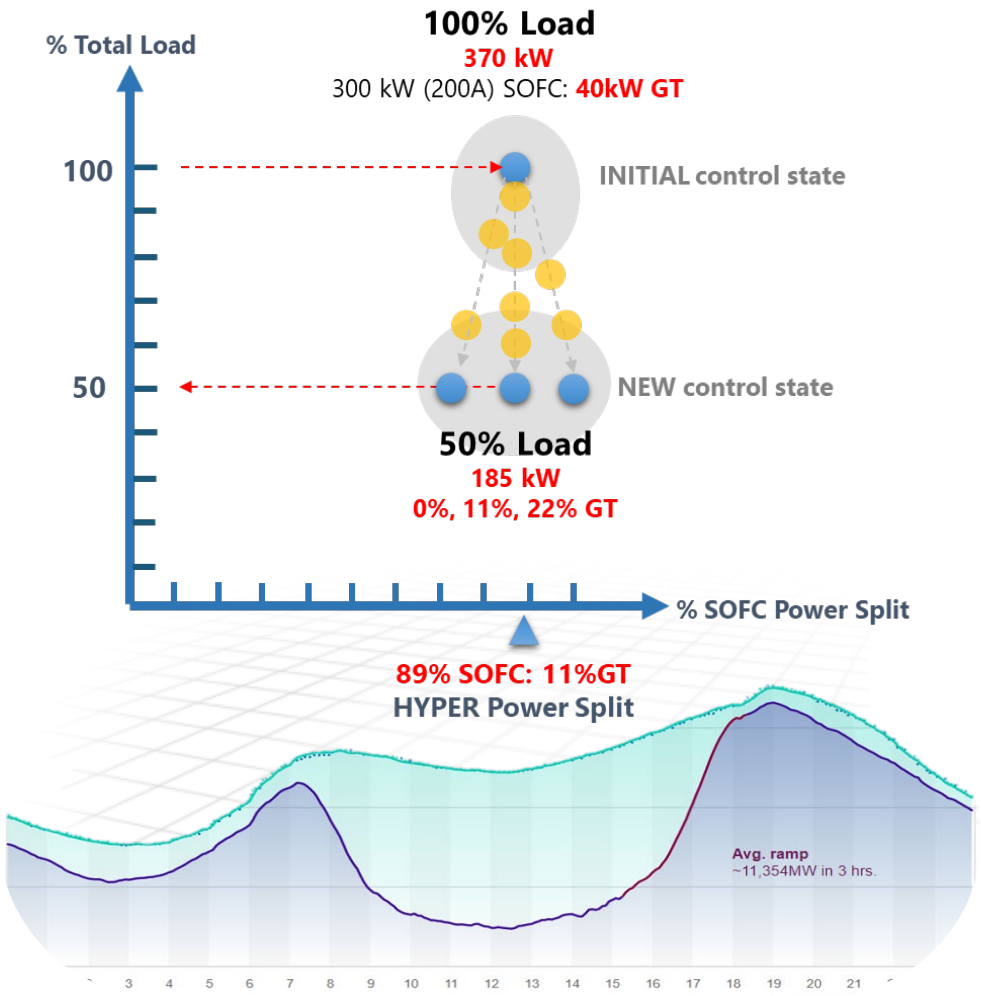
- ✓ **Co-simulation** of SOFC-GT hybrid system with INL's grid simulator
- ✓ **1st demonstration** and **a record** of 50% load turndown in <10 s
- ✓ Identified the needs of **advanced controls** for SOFC-GT hybrids
- ✓ Identified the **value** of improved flexibility of SOFC-GT hybrids.

Accomplishment 2 – Grid Impact on Hybrid SOFC System

- Highlighted as one of the **top achievements of NETL** during 2021
- Highlighted by NETL's former Director **Dr. Brian J. Anderson** in his keynote at the **ASME Power 2022 Conference**
- Highlighted by NETL's former Acting Deputy Director & Chief Technology Officer **Dr. Sydni Credle** in her keynote at the **ASME Power Applied R&D 2023 Conference**
- NETL has been invited to the **SuperLab 2.0 consortium** as the **ONLY** lab that has dispatchable power capability to improve grid resilience
- NETL led a consortium with **8** partners from **4** countries (USA, Italy, Austria, Sweden) in the Clean Energy Transition Partnership Program



Accomplishment 3 – Control Strategy Development for 50% Load Turndown



- In **system identification**, **32** open-loop dynamic experiments were conducted for 50% load turndown scenarios to develop controls for:
  - ✓ Turbine speed control
  - ✓ Thermal management
  - ✓ Air flow management
- Identified **control state transitions** and **operational constraints** during 50% load turndown
- Quantified **nonlinear coupling behavior** of the integrated components using transfer function models
- Developed controllers' gains at each system state, the adaptive control strategy is realized using a **gain scheduling approach**

Work Plan for EY24

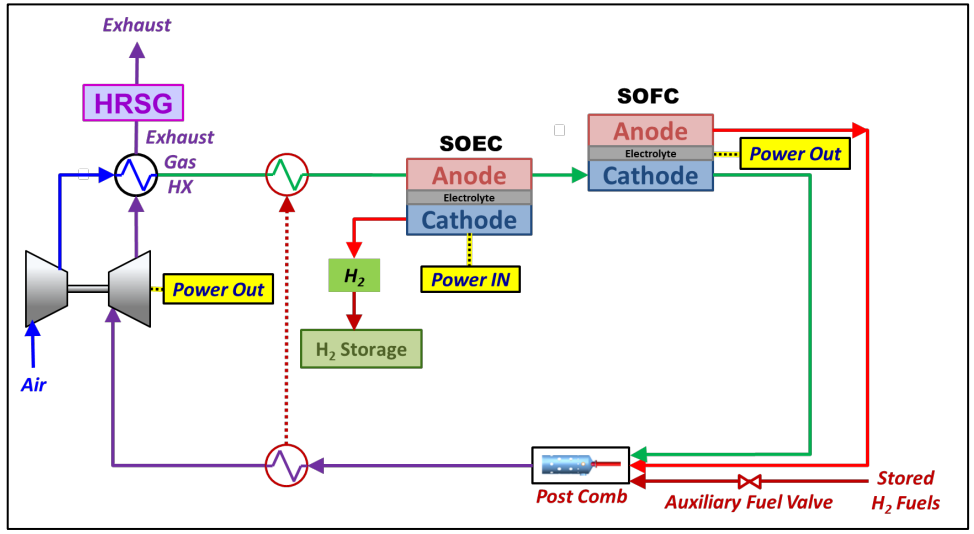
Goal – **Derisk and accelerate** hardware testing and demonstration

Outcomes –

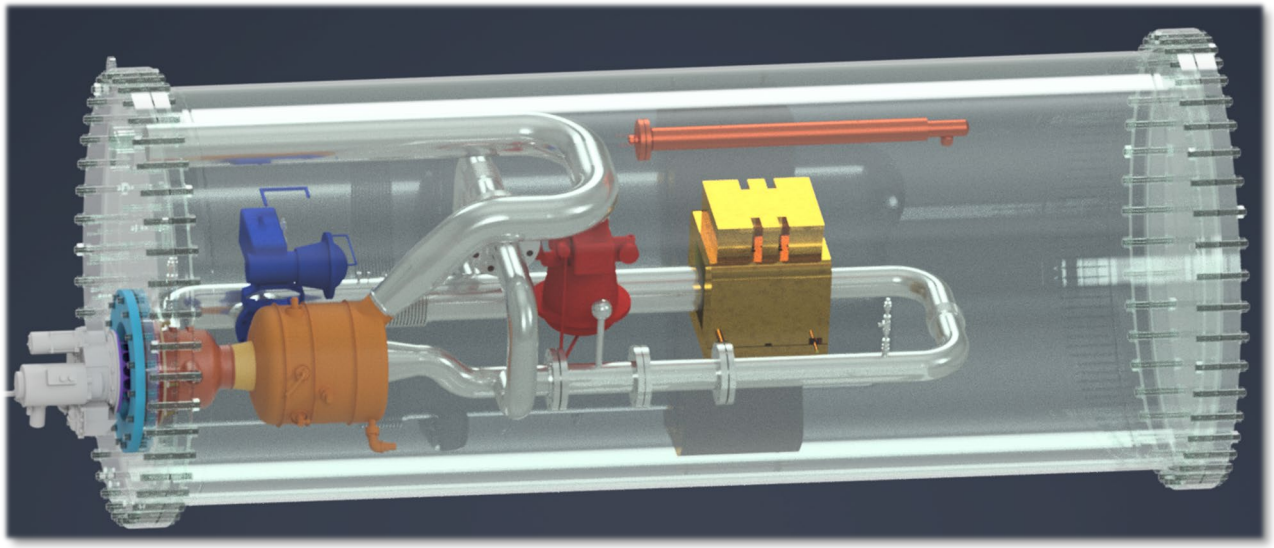
- Reveal system integration and interoperability issues
- Identify dynamic operability and control **challenges/opportunities**

Overall Approach –

Real-time system model → Controller Hardware in the Loop → Cyber-physical Systems → Hardware testing



SOFC-SOEC hybrid systems



RSOFC hybrid systems

List of Work Products

Published Journal Papers

- Biao Zhang, Nor Farida Harun, Nana Zhou, Jose J. Colon-Rodriguez, Danylo Oryshchyn, Lawrence Shadle, David Tucker, Samuel Bayham. A real-time multiphysics model of a pressurized solid oxide electrolysis cell (SOEC) for cyber-physical simulation. ***Energy Conversion and Management*** (2023) 298, 117778.
- Biao Zhang, Daniel Maloney, Nor Farida Harun, Nana Zhou, Paolo Pezzini, Anudeep Medam, Rob Hovsapian, Samuel Bayham, David Tucker. Rapid load transition for integrated solid oxide fuel cell – Gas turbine (SOFC-GT) energy systems: A demonstration of the potential for grid response. ***Energy Conversion and Management*** (2022) 258, 115544.
- Rupen Panday, Nor Farida Harun, Biao Zhang, Daniel Maloney, David Tucker and Samuel Bayham. Analyzing Gas Turbine-Generator Performance of the Hybrid Power System. ***IEEE Transactions on Power Systems*** (2022) 37, 543-550.

Delivered Presentation

- Biao Zhang, Nana Zhou, Nor Farida Harun, Jose Colon-Rodriguez, Danylo Oryshchyn, David Tucker, Samuel Bayham. Development of Multiphysics Dynamic Solid Oxide Electrolysis Cell (SOEC) Models for Hybrid Energy Systems. ***Presentation at the ASME Power Applied R&D 2023 Conference***, Long Beach, CA, August 6-8, 2023.

List of Work Products

Manuscript in preparation

- Biao Zhang, Nor Farida Harun, Nana Zhou, Danylo Oryshchyn, Jose J. Colon-Rodriguez, Lawrence Shadle, David Tucker, Samuel Bayham. A Distributed One-Dimensional Real-Time Solid Oxide Electrolysis Cell (SOEC) Model for Cyber-Physical Systems.

Scheduled Presentations

- Samuel Bayham et al. Hybrid Power Systems and Cyber-Physical Systems Modeling at NETL. ***Presentation at INL's Digital Engineering Conference 2024***, Idaho Falls, ID, April 29 – May 1, 2024.
- Biao Zhang et al., Cyber-physical simulation of an innovative solid oxide electrolysis cell – gas turbine (SOEC-GT) hybrid energy system. ***Presentation at the ASME Power 2024 Conference***, Washington, D.C., September 15–18, 2024.
- Nor Farida Harun et al. Analysis of 50% Power Turndown in SOFC/GT Hybrid Systems: Dynamic Characterization of Operational Control States Through Transfer Functions. ***Presentation at the ASME Power 2024 Conference***, Washington, D.C., September 15–18, 2024.
- Samuel Bayham et al. Potential Cost Reductions by Combining a Gas Turbine to a Solid Oxide Fuel Cell. ***Presentation at the ASME Power 2024 Conference***, Washington, D.C., September 15–18, 2024.

Acknowledgments

This work was performed in support of the U.S. Department of Energy's (DOE) Fossil Energy and Carbon Management's **Solid Oxide Fuel Cell Research Program** and executed through the National Energy Technology Laboratory (NETL) Research & Innovation Center's **Solid Oxide Fuel Cell Field Work Proposal**.

Acknowledgement also goes to **Dr. Harry Abernathy** as Technical Portfolio Lead of the Solid Oxide Fuel Cell Field Work Proposal and **Dr. Ben Chorpening** as Team Supervisor.

ASME Power 2024 Conference Co-located with the 8th Low Emission Advanced Power (LEAP) Workshop

For those who are interested in integrated energy system & CPS approaches…

- Keynote speakers:
- ✓ **Mr. Mark Ackiewicz**, Director, Office of Carbon Management Technologies, DOE FECM
- ✓ **Mr. Scott Parent**, Ansys Energy CTO
- Washington, D.C.
- September 15–19, 2024
- More information will be released soon

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