Real-Time Simulation of Solid Oxide Electrolyzers (SOEC) for Dynamic Operability Improvement and Cyber-Physical System Development

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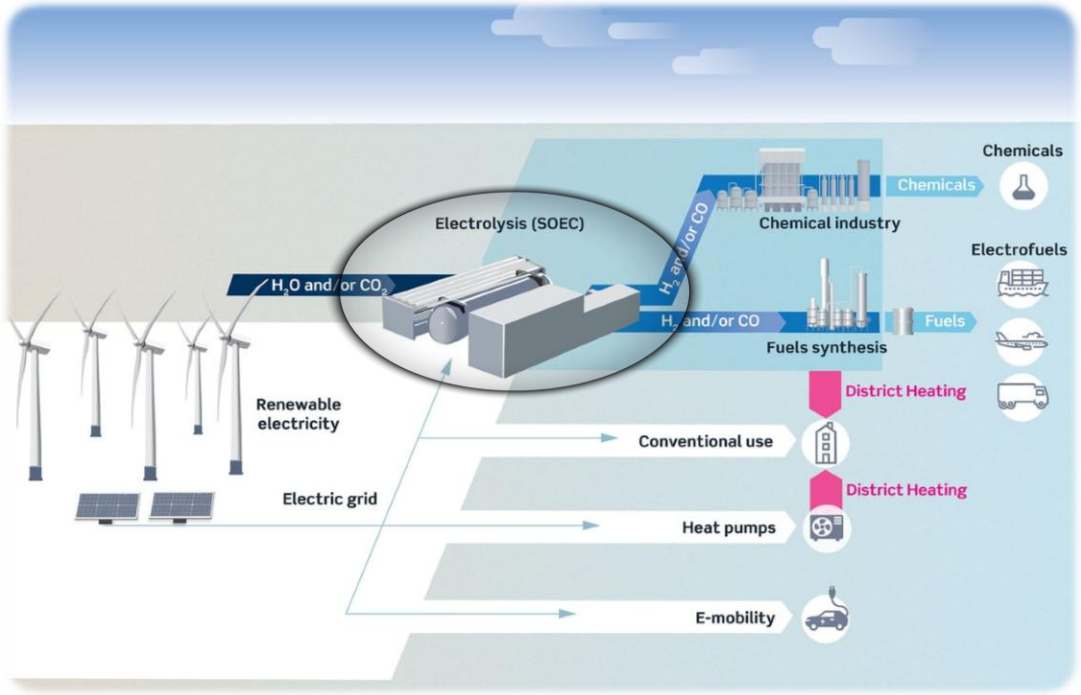
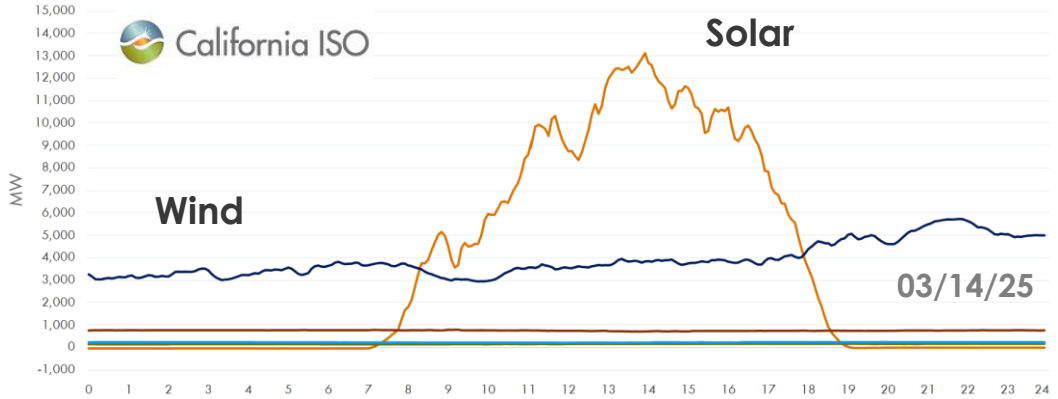
Motivation

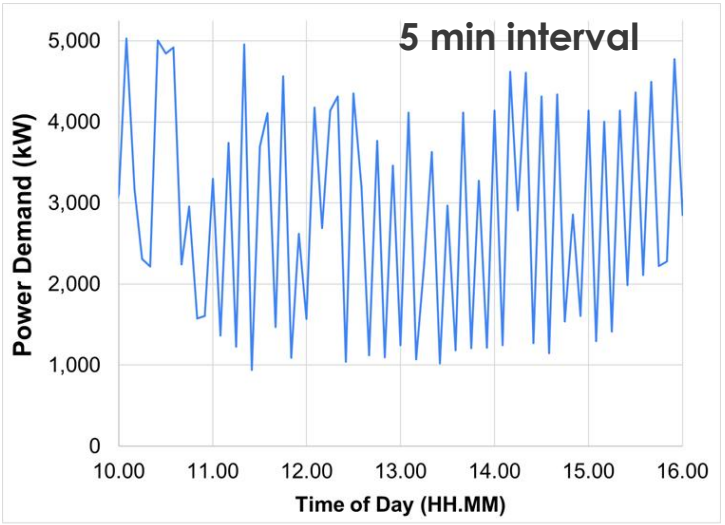
The Need for Rapid Load Transition Capability of SOEC in Renewable Energy Systems



(Source: A. Hauch et al. Science, 2020)

- **Intermittent renewable power fluctuates in diurnal cycles and shorter periods.**
- **SOEC must have rapid load transition capabilities to load follow and support grid resilience.**



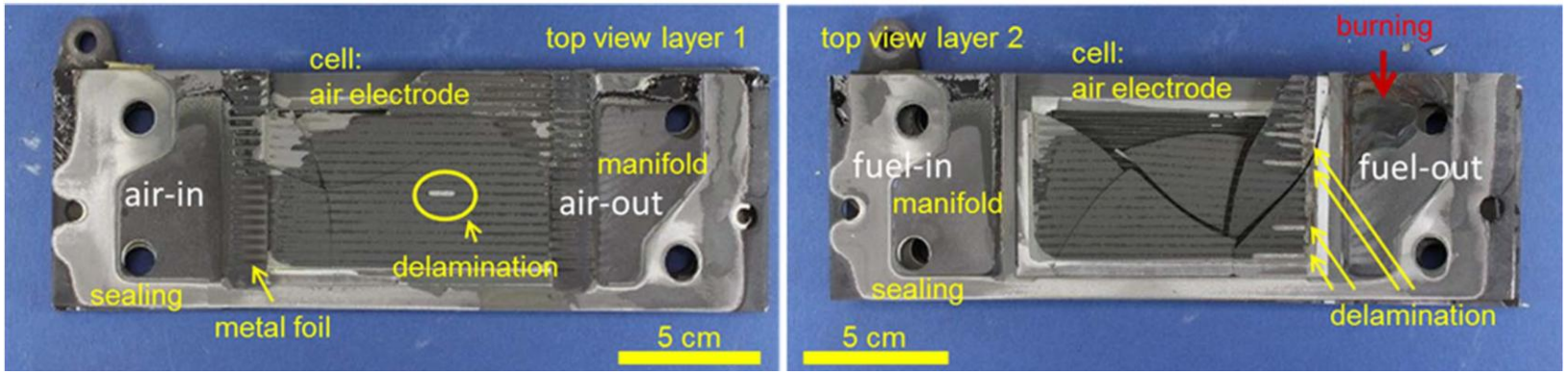


Microgrid power demand from NREL

(Source: Del A. Nagy et al. ASME Power Applied R&D 2023 Conference, POWER2023-108956.)

Dynamic SOEC System Testing is Still a Challenge

- SOEC systems are still in Research & Development (R&D) stage for pre-commercial testing.
- SOEC is expensive and fragile; its dynamic operability is limited.
- Excursion of local **temperature gradients** may lead to crack and delamination.
- **SOEC system shutdowns were mainly caused by Balance-of-Plant (BoP) components.**



(Source: Carolin E. Frey et al. Journal of The Electrochemical Society, 2018.)

Table 1 **Key performance indicators for four electrolyser technologies today and in 2050**

	2020				2050			
	Alkaline	PEM	AEM	SOEC	Alkaline	PEM	AEM	SOEC
Cell pressure [bar]	< 30	< 70	< 35	< 10	> 70	> 70	> 70	> 20
Efficiency (system) [kWh/kgH_2]	50-78	50-83	57-69	45-55	< 45	< 45	< 45	< 40
Lifetime [thousand hours]	60	50-80	> 5	< 20	100	100-120	100	80
Capital costs estimate for large stacks (stack-only, > 1 MW) [USD/kW$_{el}$]	270	400	-	> 2 000	< 100	< 100	< 100	< 200
Capital cost range estimate for the entire system, >10 MW [USD/kW$_{el}$]	500-1000	700-1400	-	-	< 200	< 200	< 200	< 300

(Source: Making the breakthrough: Green hydrogen policies and technology costs, IRENA, 2021.)

Technology Development Capital Costs

Siemens Westinghouse pilot demonstration
220 kW Solid Oxide Fuel Cell – Gas Turbine (SOFC-GT) Hybrid.

Cost: ~$16 M

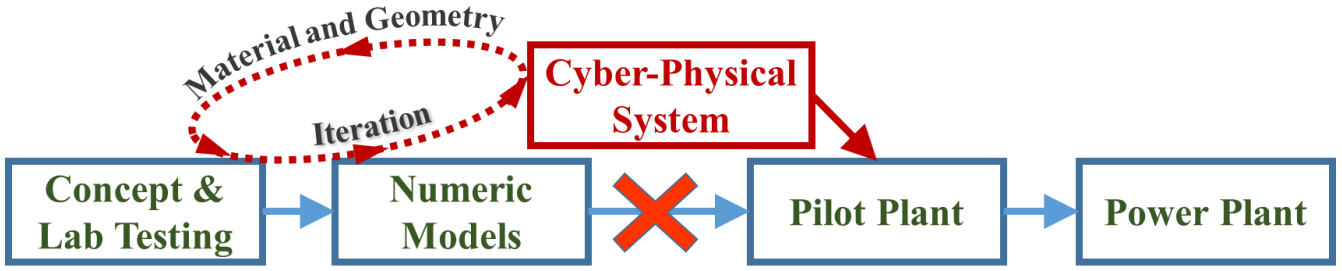
(Source: EE Power, 2000.)

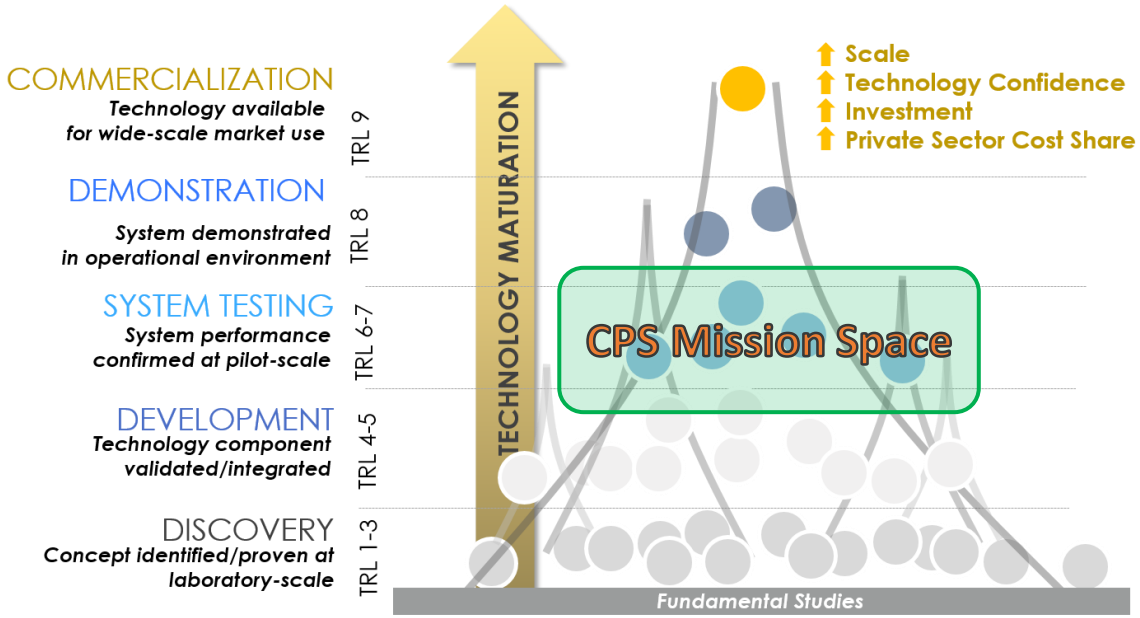
NETL cyber-physical system
400 kW SOFC-GT Hybrid.

Cost: ~$1 M

Cyber-Physical System (CPS)

A Paradigm Change in Energy Technology Development

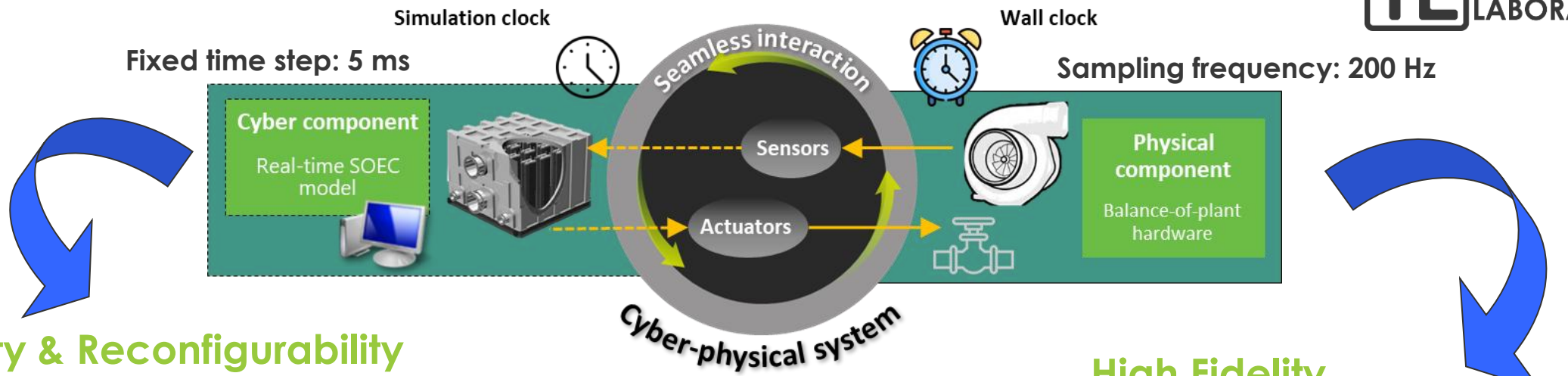




CPS approach enables:

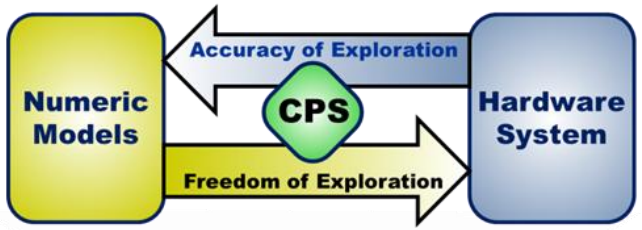
- Emulating expensive/premature components (e.g., SOEC)
- Emulating the actual hybrid system at high fidelity and low cost
  - ✓ Identifying **system integration** and **dynamic operability** issues
  - ✓ Developing **control strategies**
- **De-risking** pilot testing

Cyber-Physical System (CPS)



Flexibility & Reconfigurability

- Different components (e.g., SOFC, SOEC, nuclear, geothermal, concentrated solar…)
- Low risk, without using million-dollar hardware (e.g., SOEC stack)
- AI/ML



Emulating an actual cycle

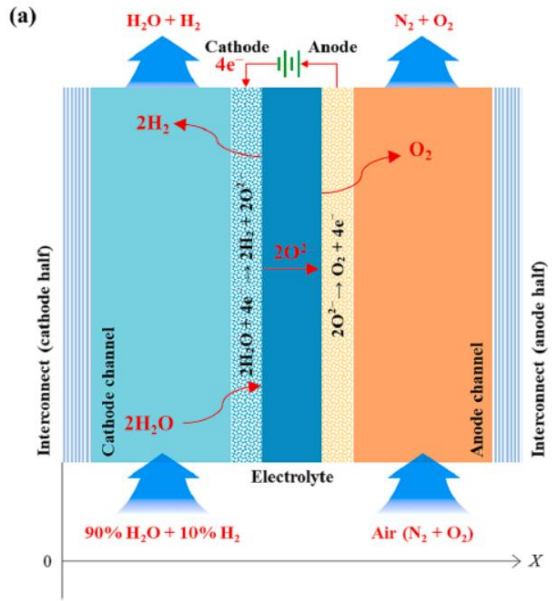
High Fidelity

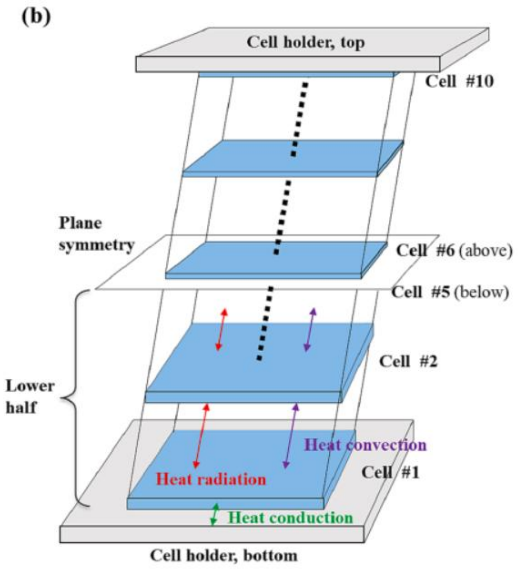
- Actual process flow (e.g., temperature & pressure)
- Real transients of turbomachinery
- Real delay of valves/ actuators
- Real noise & perturbations

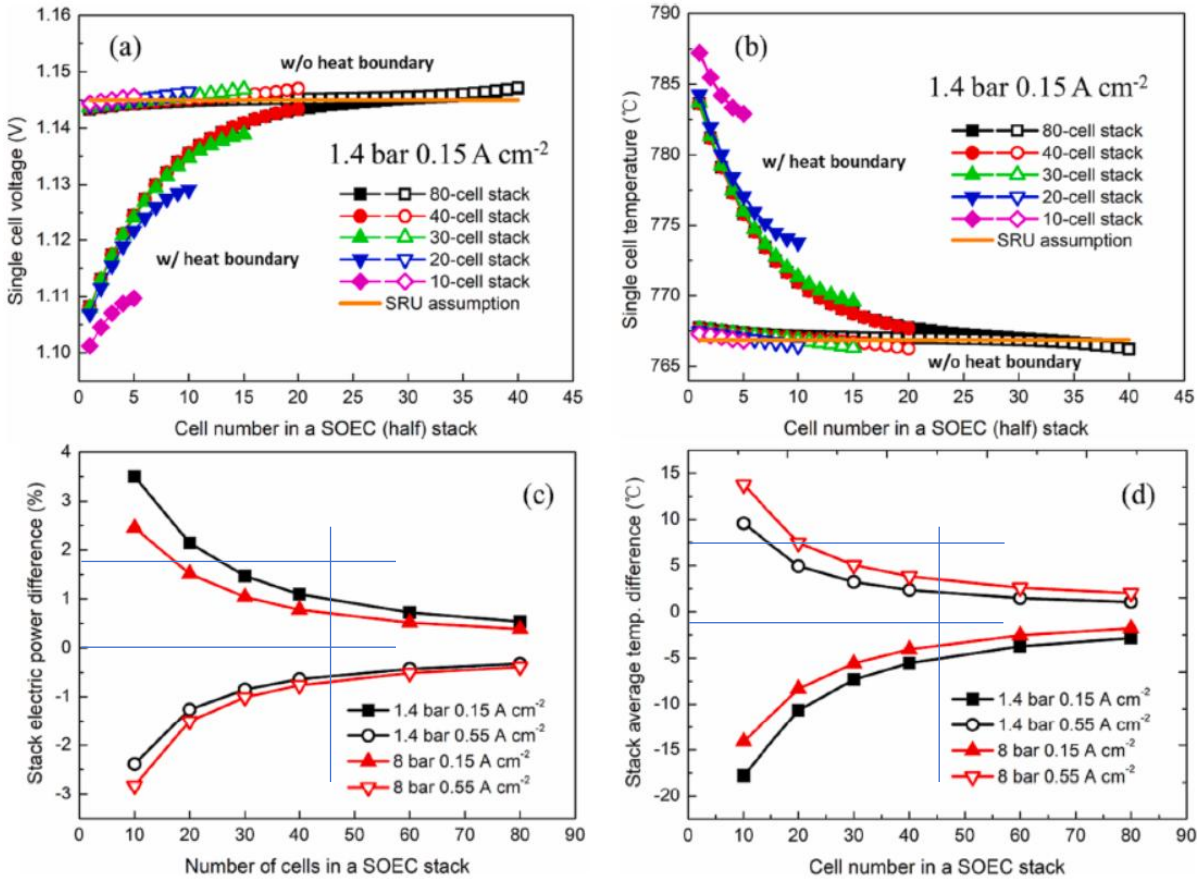
Integration – Dynamic Operability – Control

0D Real-Time SOEC Model

- **Multiphysics 0D and 1D real-time SOEC models were developed.**
- **Co-electrolysis SOEC and reversible SOFC models were also developed.**
- **0D model established a guidance** to have >45 cells in a stack to safely apply the single repeating unit (SRU) assumption.



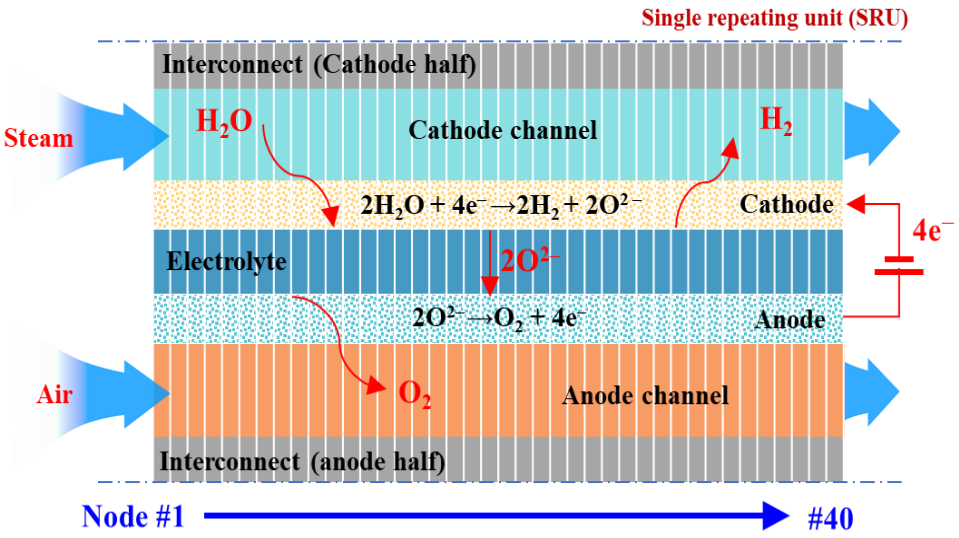




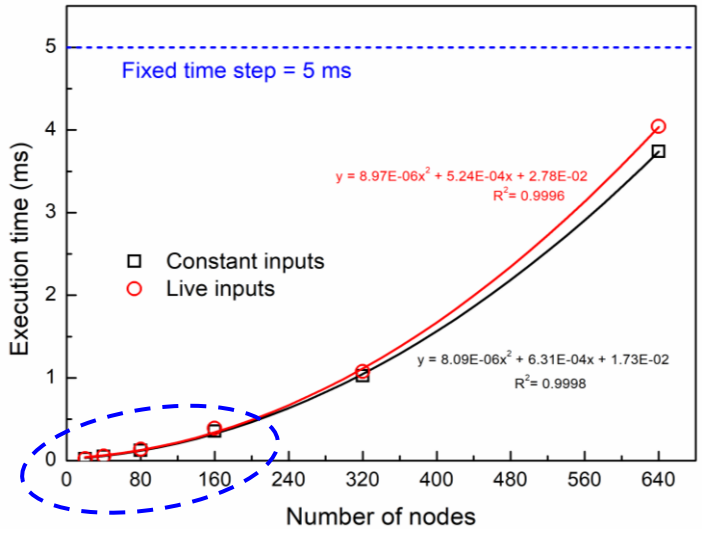
(Source: Biao Zhang et al. Energy Conversion and Management, 2023.)

1D Real-Time SOEC 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.



One-dimensional model.



Real-time simulation.

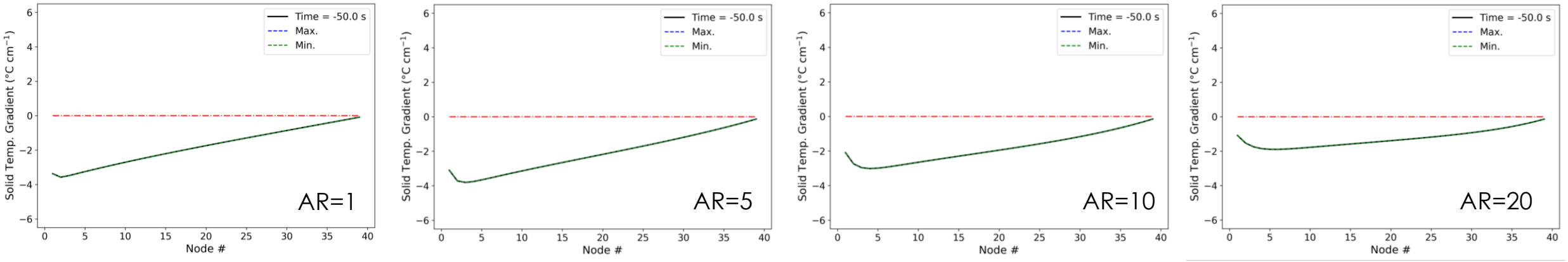
(Source: Biao Zhang et al. Applied Energy, 2025.)

Simulink model → Compiled by Simulink Coder → Processed by Opal-RT's RT-LAB software → Executable C file → Run on Opal-RT simulator

Alternative approaches for 3D real-time models:

- **Reduced order model (ROM)**
- **Wafer-scale engine**

1D Real-Time SOEC Model



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

Upon a current density step change from 0.15 to 0.55 A/cm^2:

- 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 **integration with turbomachinery.**

1D Real-Time SOEC Model (Co-Flow vs. Counter-Flow)

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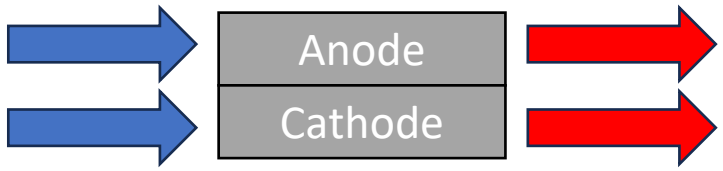
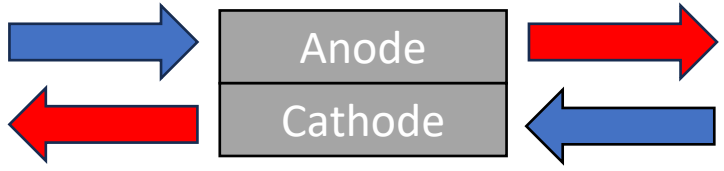
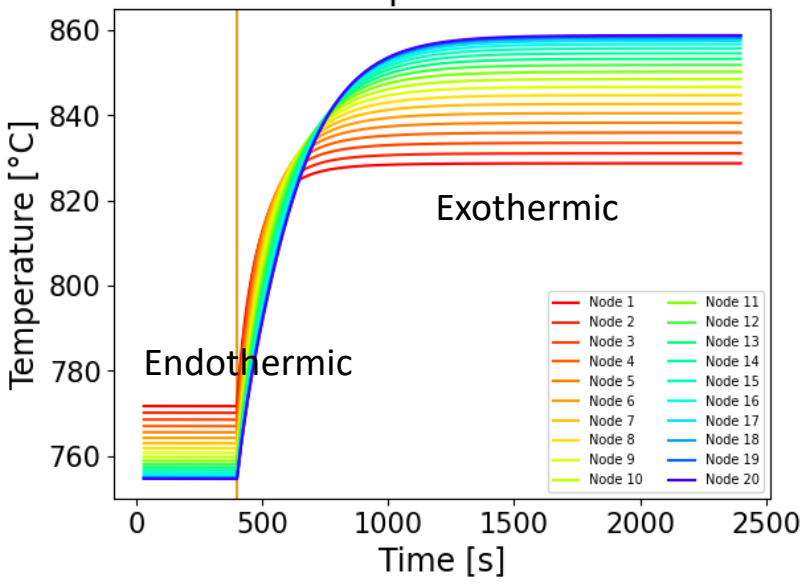
Co-Flow



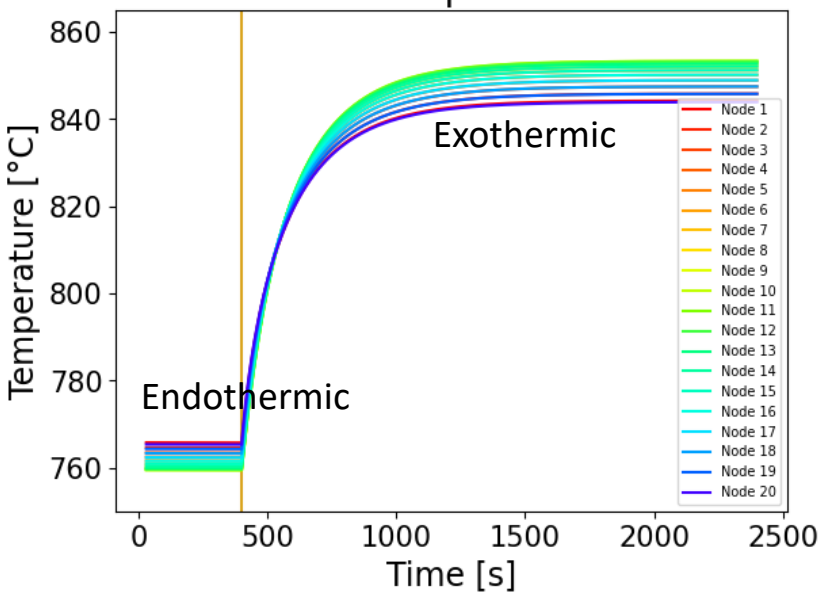
Counter-Flow



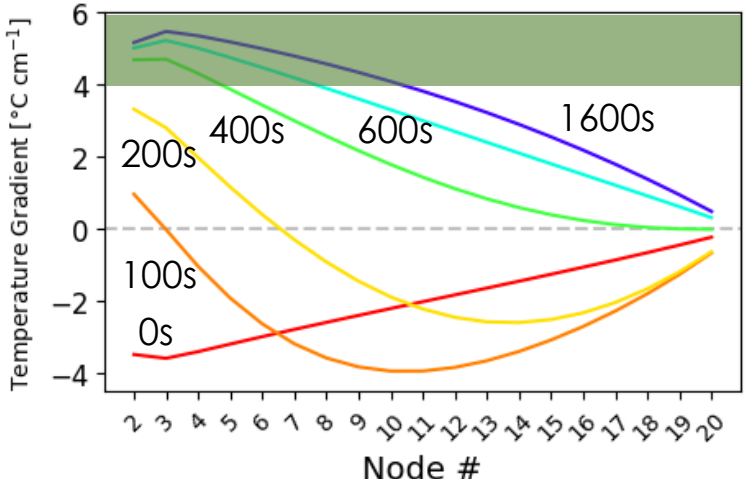
Co-Flow Temperature Evolution



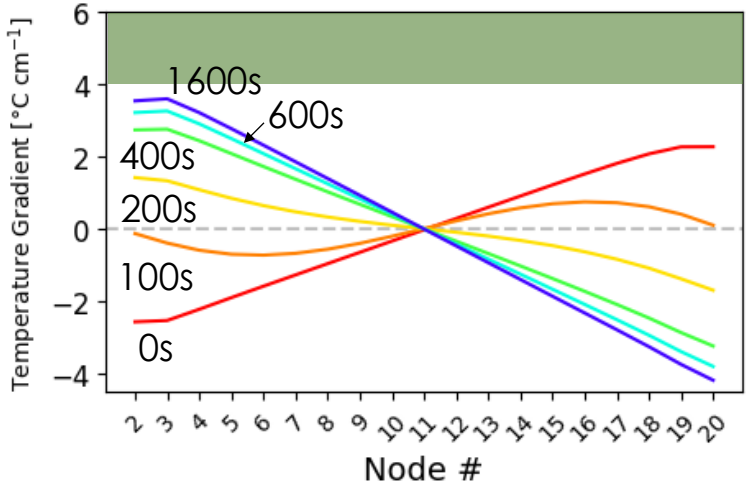
Counter-Flow Temperature Evolution



Co-Flow Temperature Gradient Across Cell



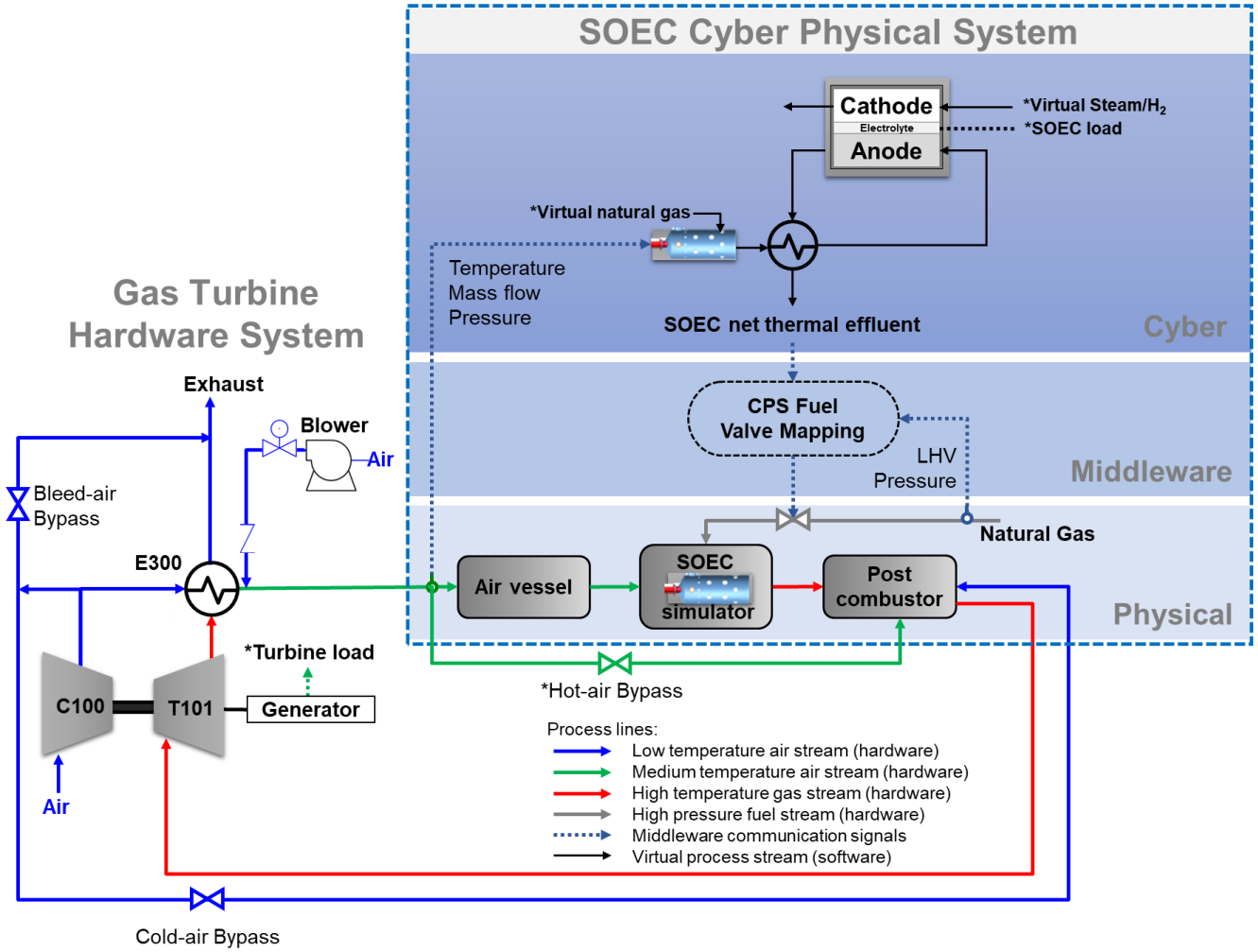
Counter-Flow Temperature Gradient Across Cell

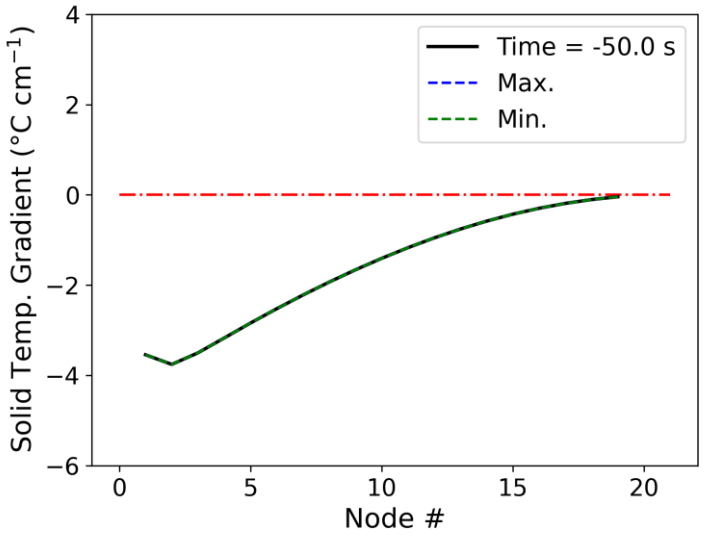


Counter-flow SOEC has a more uniform temperature distribution pattern across the flow channel.

Next Steps

Cyber-Physical Simulation of SOEC-GT Hybrid in an Integrated Energy System





- Dynamic operability research is in process.
- Use non-observable parameters (e.g., local temperature gradient) obtained by real-time models to inform advanced control development.

Acknowledgments

This work was performed in support of the U.S. Department of Energy's (DOE) Office of Fossil Energy and Carbon Management's Solid Oxide Fuel Cell Research Program & Hydrogen with Carbon Management Research Program and executed through the National Energy Technology Laboratory (NETL) Research & Innovation Center's Solid Oxide Fuel Cell Field Work Proposal & Sensors Controls and Other Novel Concepts (SCONC) Multi-Year Research Plan (MYRP).

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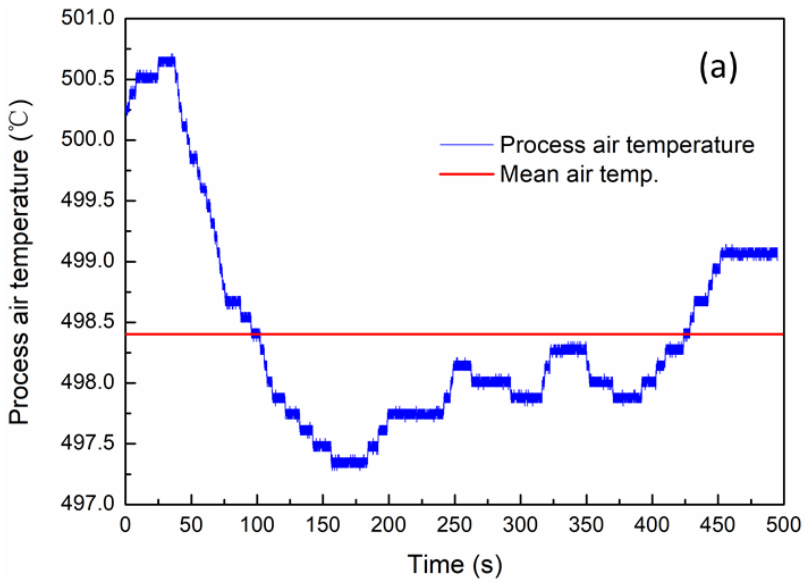
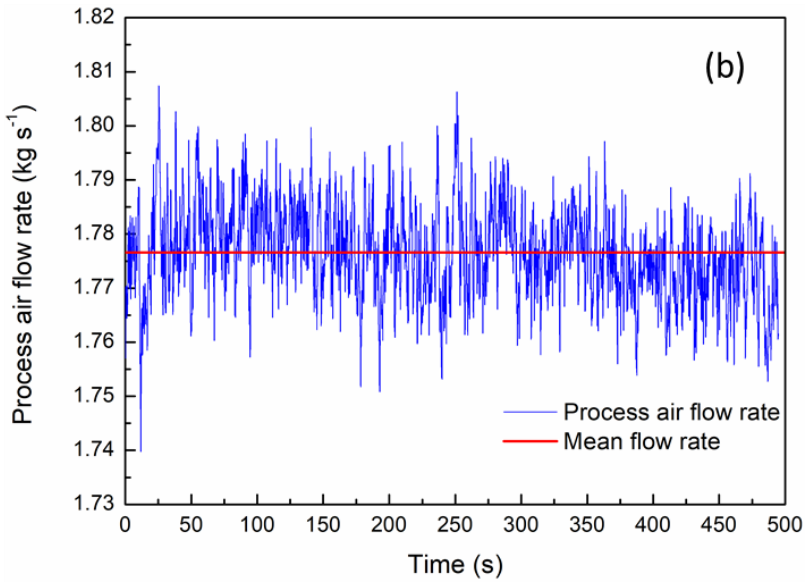
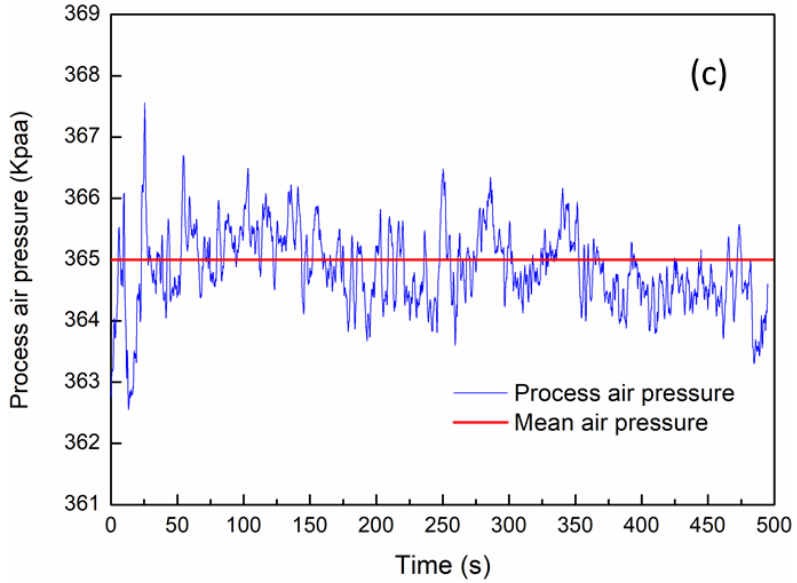
Real Process Flow Parameters

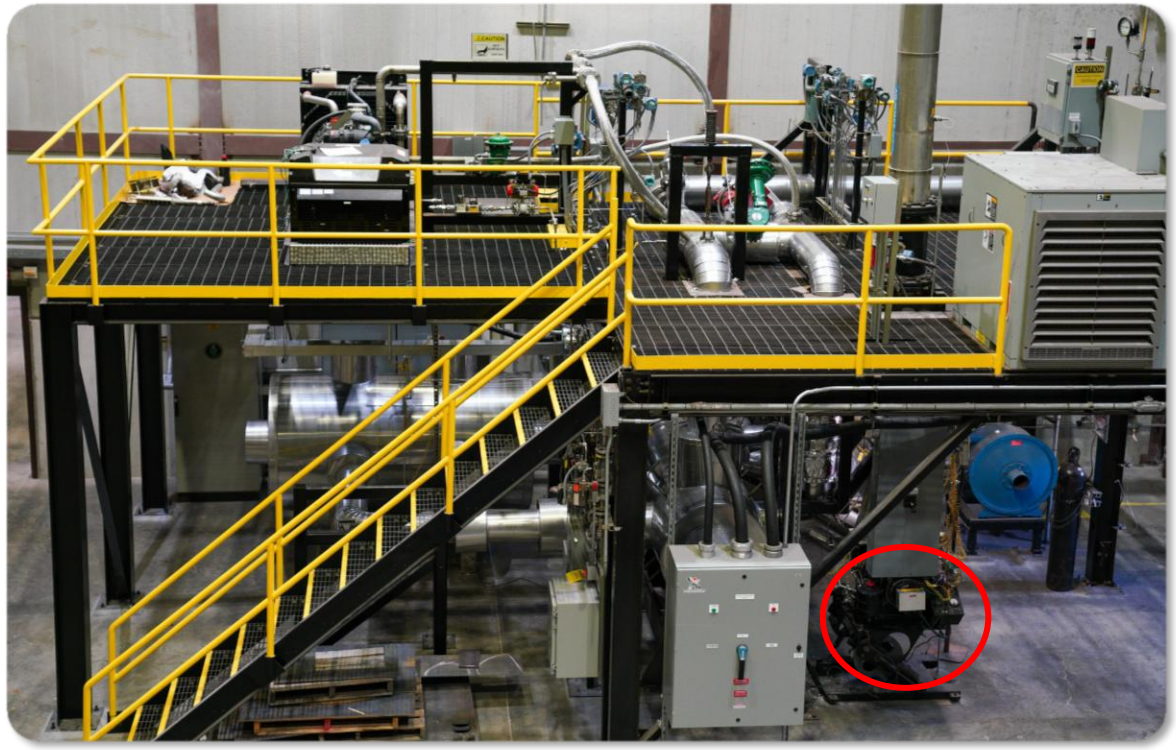
Temperature, Mass Flow Rate, and Pressure Measurements from Hardware



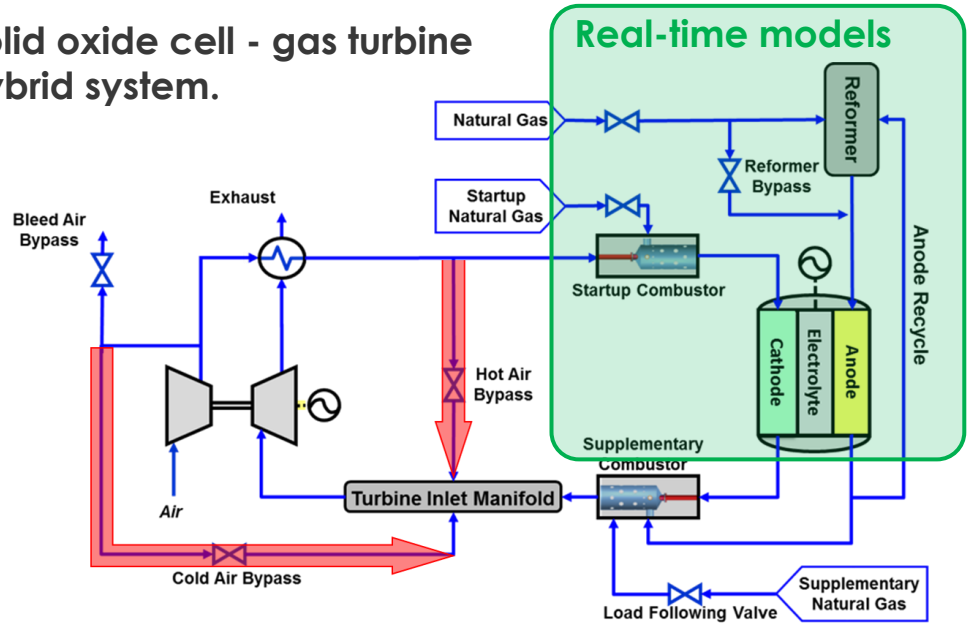




Hybrid Performance (HyPer) Facility at NETL



Solid oxide cell - gas turbine hybrid system.



Real-time models:

- SOFC
- R-SOFC
- Thermal energy storage
- Combustor
- Heat exchanger
- Gasifier