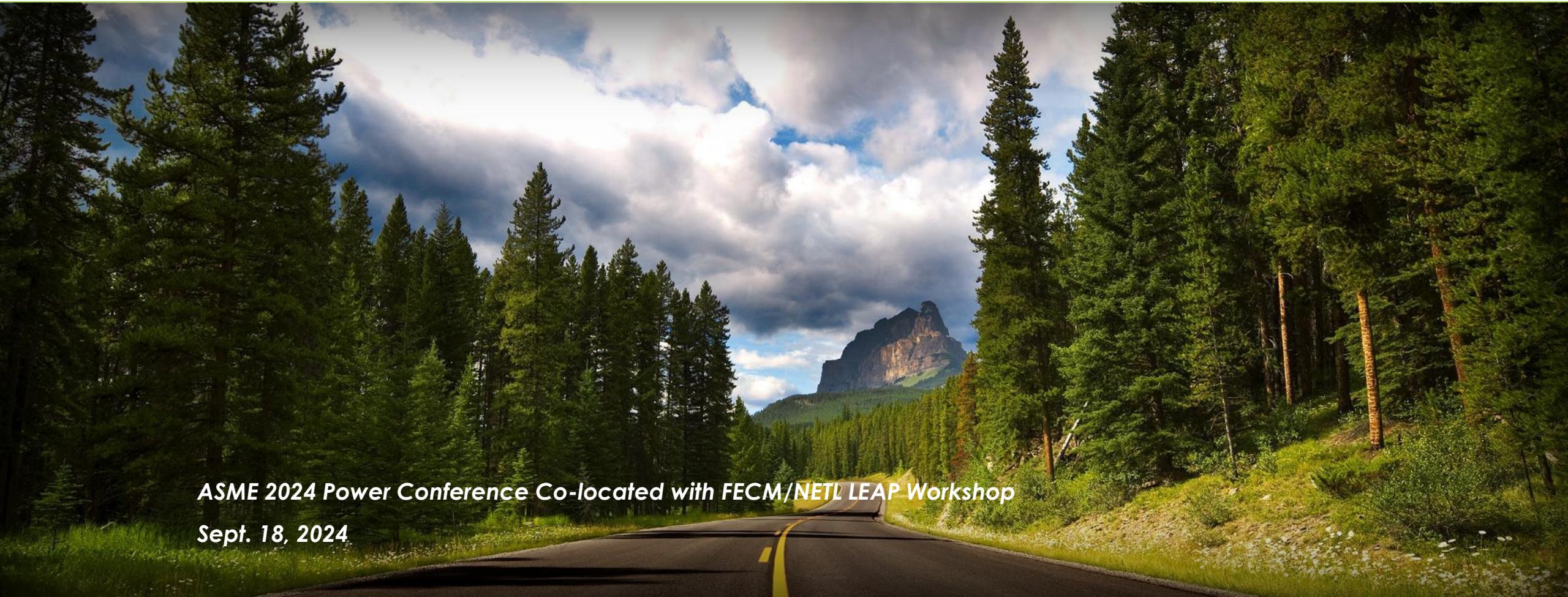


Cyber-Physical Simulation of an Innovative Solid Oxide Electrolysis Cell – Gas Turbine (SOEC-GT) Hybrid Energy System



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Authors and Contact Information



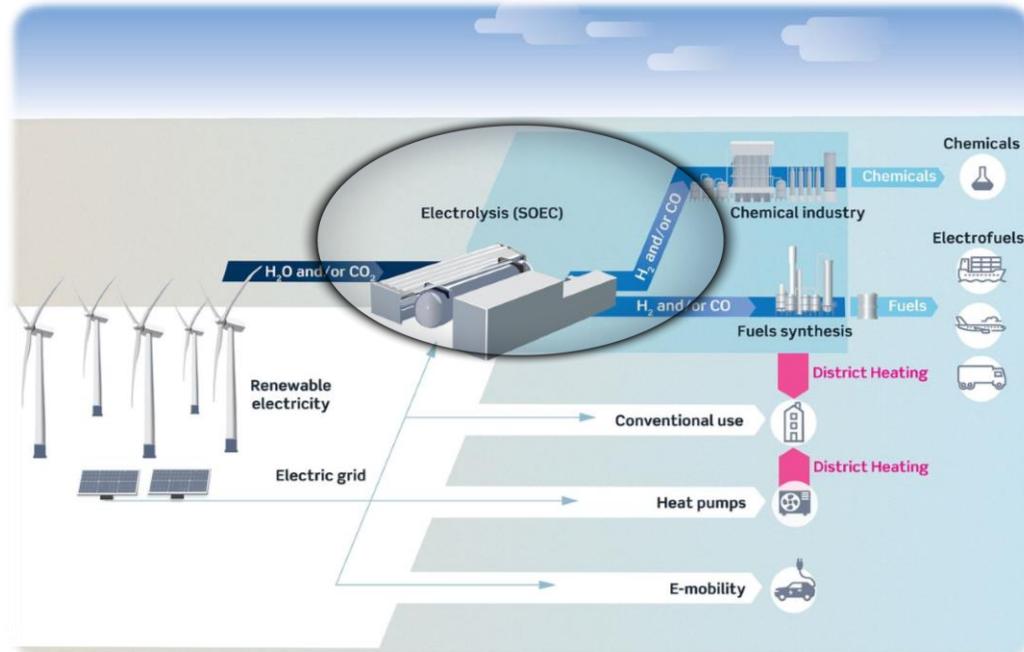
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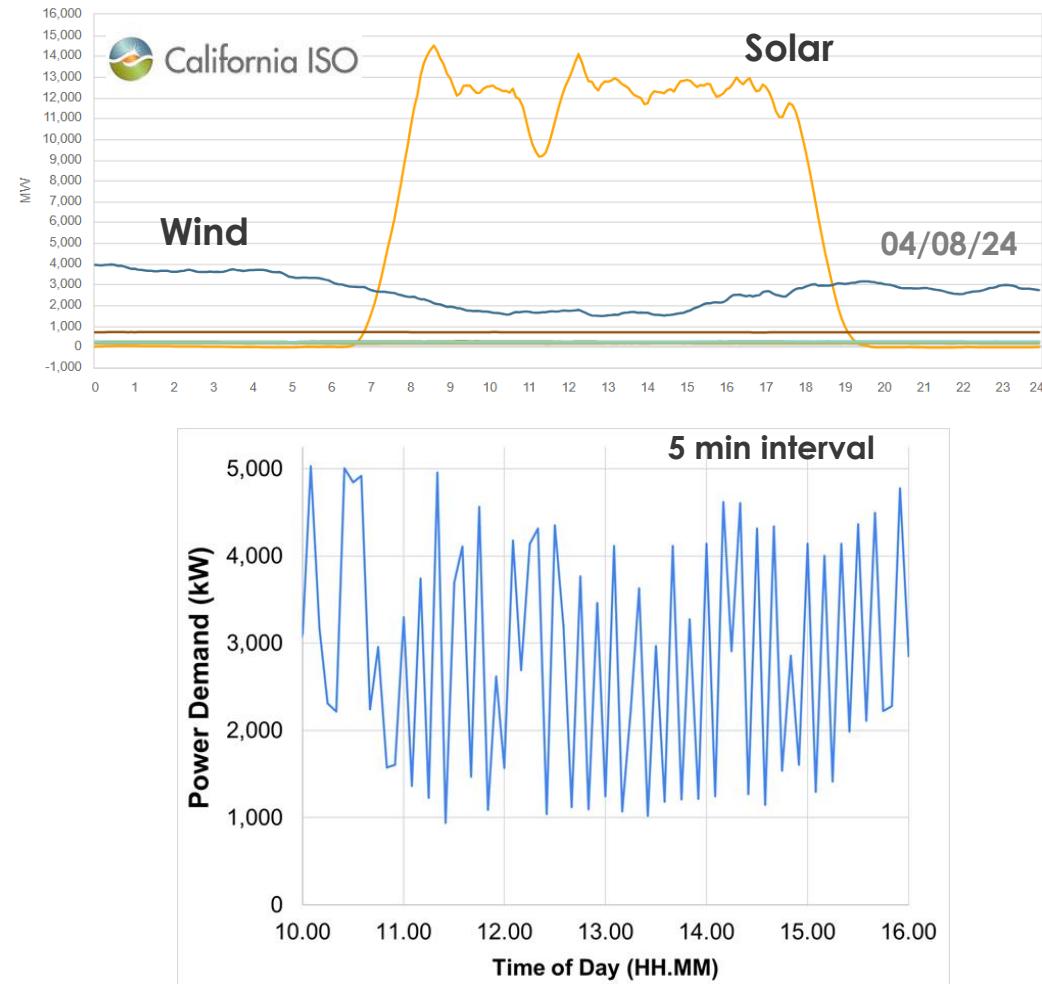
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Rapid Load Transition of SOEC in Renewable Energy Systems



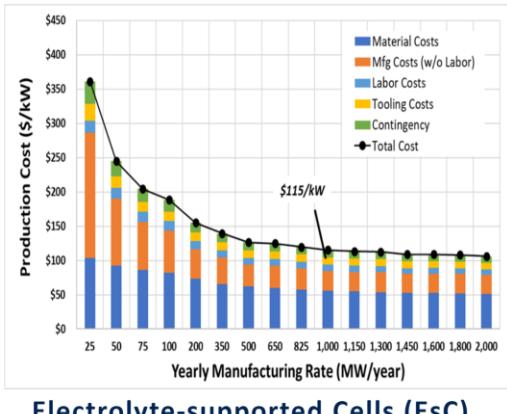
- Intermittent renewable power fluctuates **in diurnal cycles and shorter periods**.
- SOEC must have **rapid load transition** capabilities to load follow and support grid resilience.



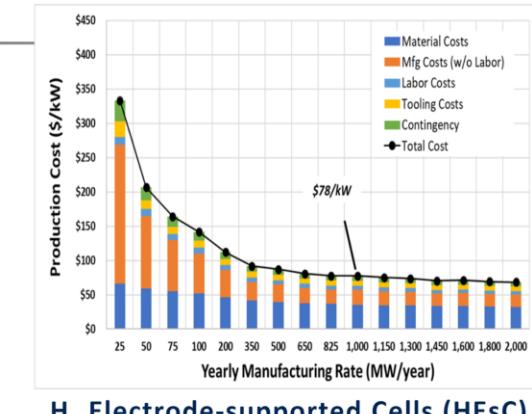
Experimental SOEC System Testing is Still a Challenge

- SOEC is expensive!
- SOEC's fragile electrode/electrolyte materials cannot withstand big thermal shock.
- Excursion of **local temperature gradients** may lead to crack and delamination.

(Source: Brian D. James et al. Strategic Analysis Inc., 2022)



Electrolyte-supported Cells (EscC)



H₂ Electrode-supported Cells (HEsC)

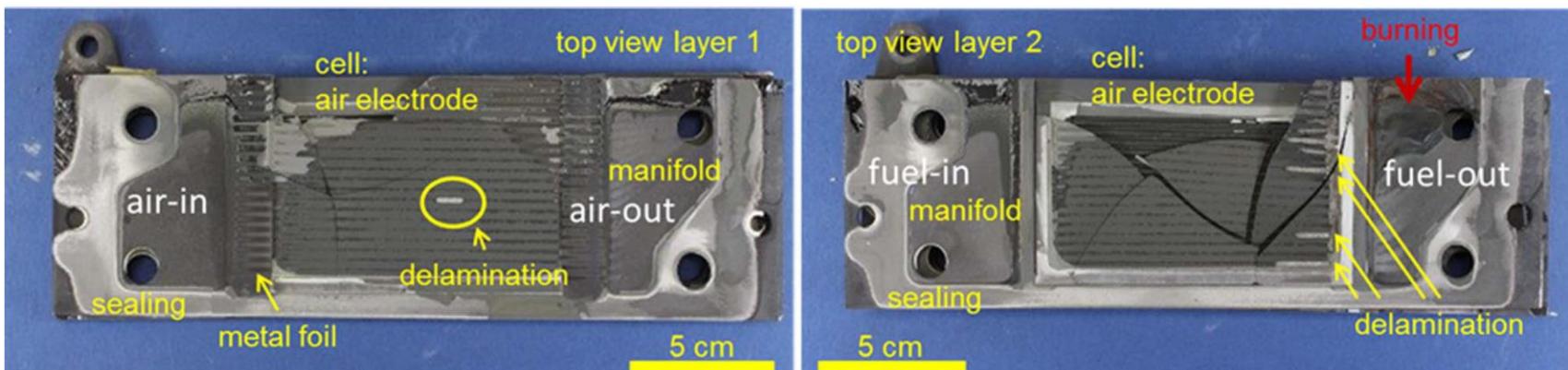


Table 1 Key performance indicators for four electrolyser technologies today and in 2050

	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	-	> 2000	< 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

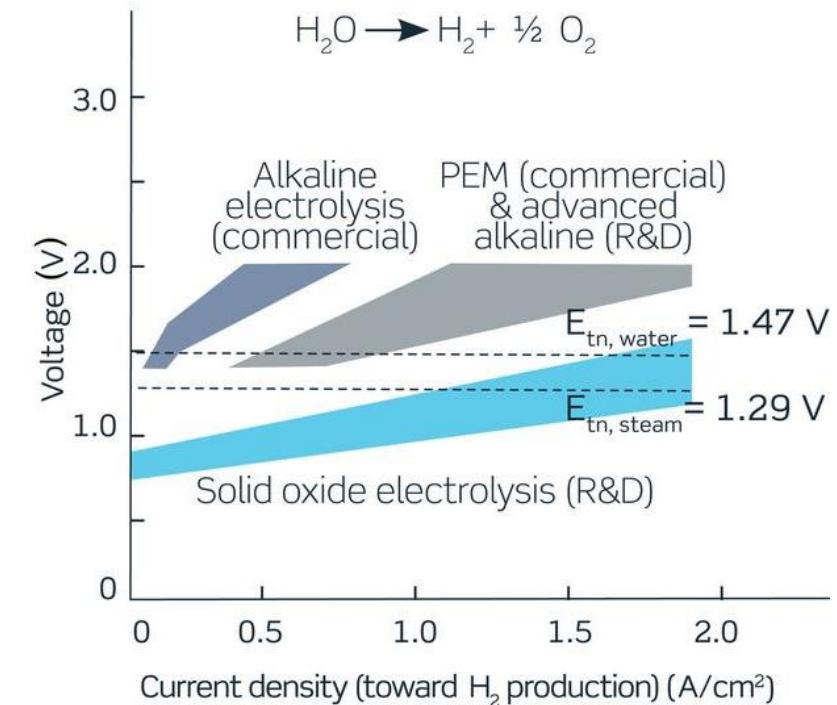
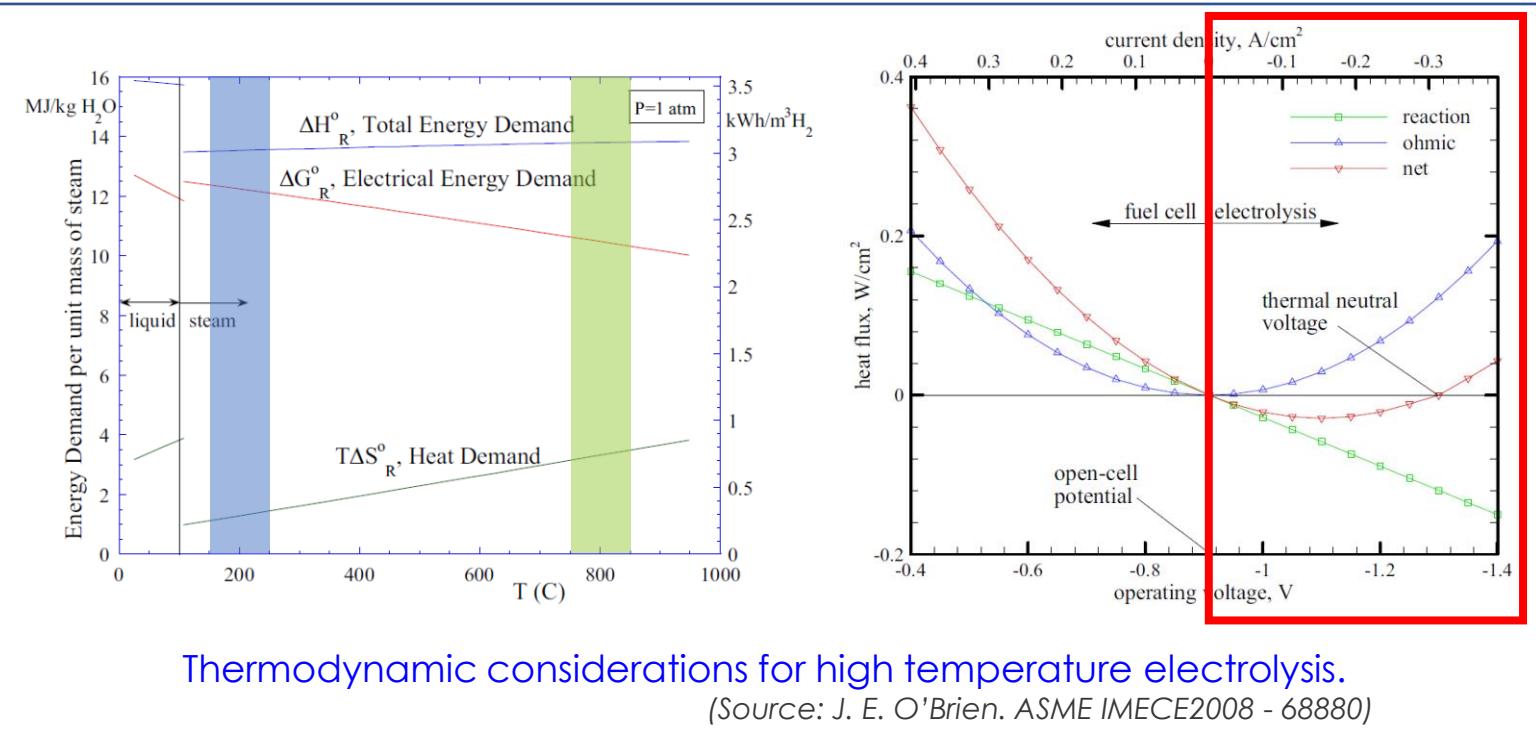
(Source: Making the breakthrough: Green hydrogen policies and technology costs, IRENA, 2021)

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

SOEC's Favorable Thermodynamics for H₂ Production



A Unique Opportunity for Thermal Integration



- SOEC can utilize thermal energy to partially compensate for electric power consumption.
- SOEC can be operated in endothermic, exothermic, or thermoneutral modes.

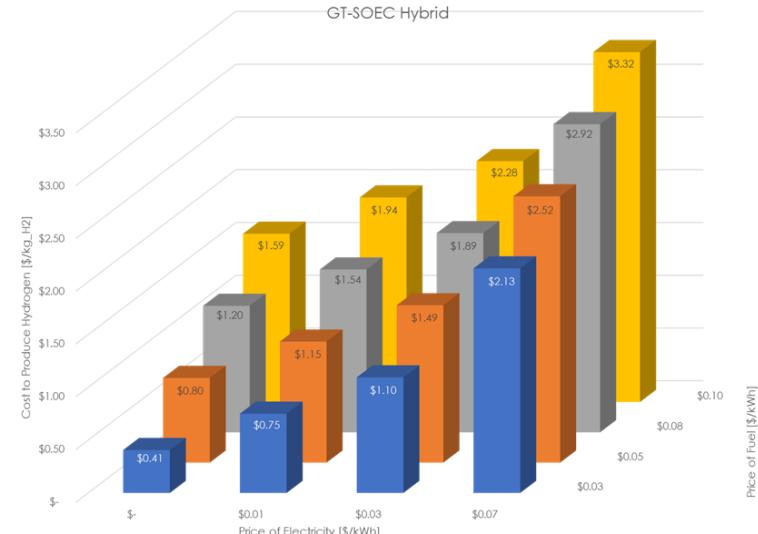
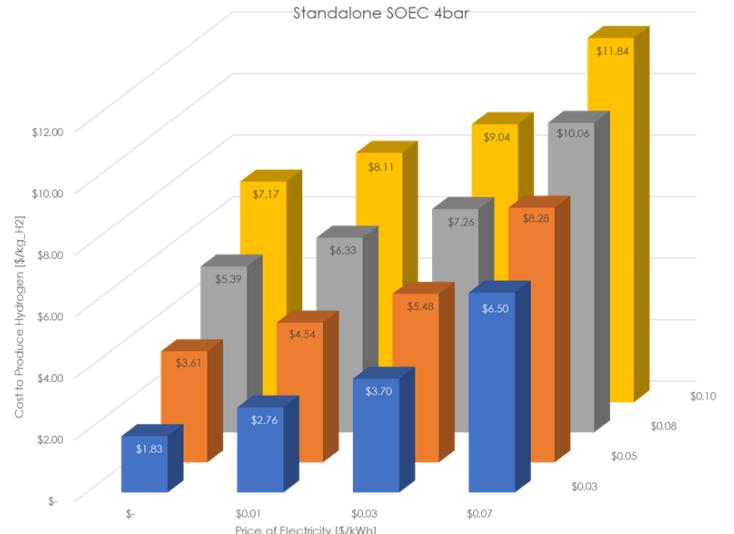
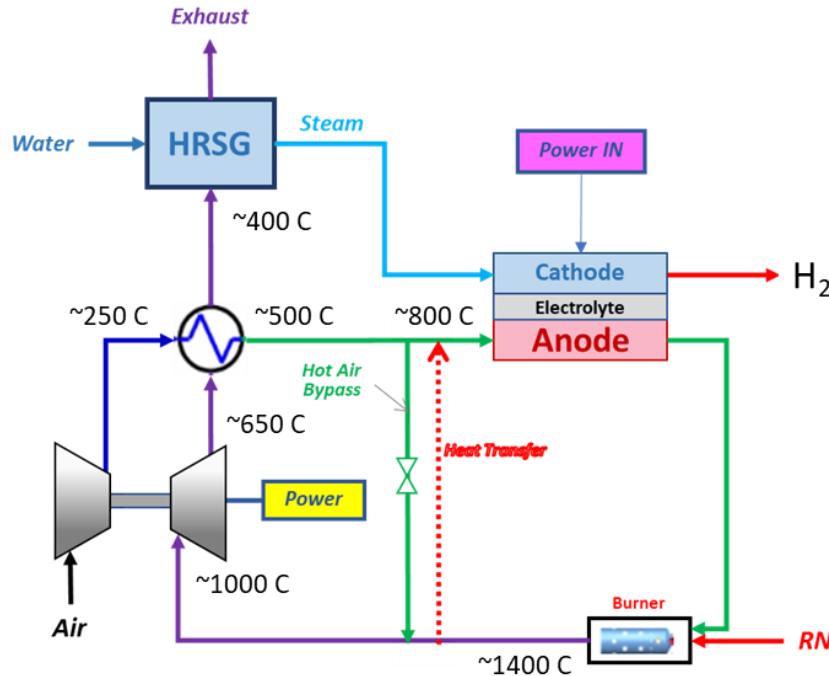
Typical performance ranges of competing electrolysis technologies for H₂O splitting.

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



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SOEC-Gas Turbine Hybrid Energy System



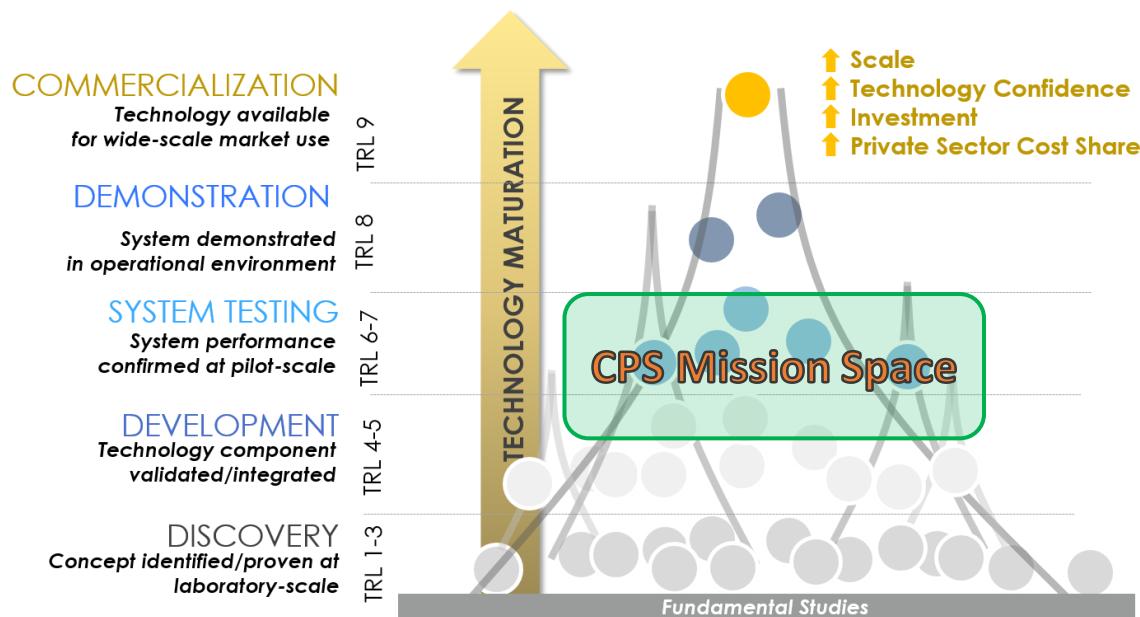
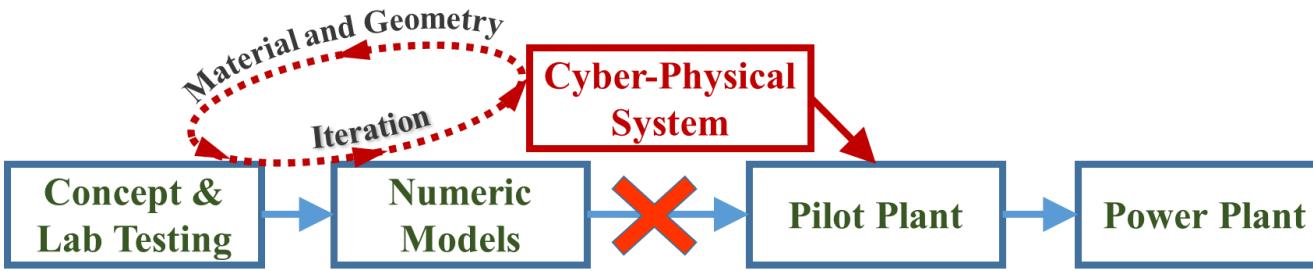
H₂ unit price (\$/kg) at different electricity price and fuel price.

- Can produce hydrogen or power or both.
- Possible load turndown (SOEC) –100% - 0% - 100% (GT).
- SOEC is kept hot all the time.
- Rapid mode switching.
- Have great potential to meet U.S. DOE's Hydrogen Shot cost target of \$1 per kg.



Cyber-Physical Simulation (CPS)

A Paradigm Change in Energy Technology Development

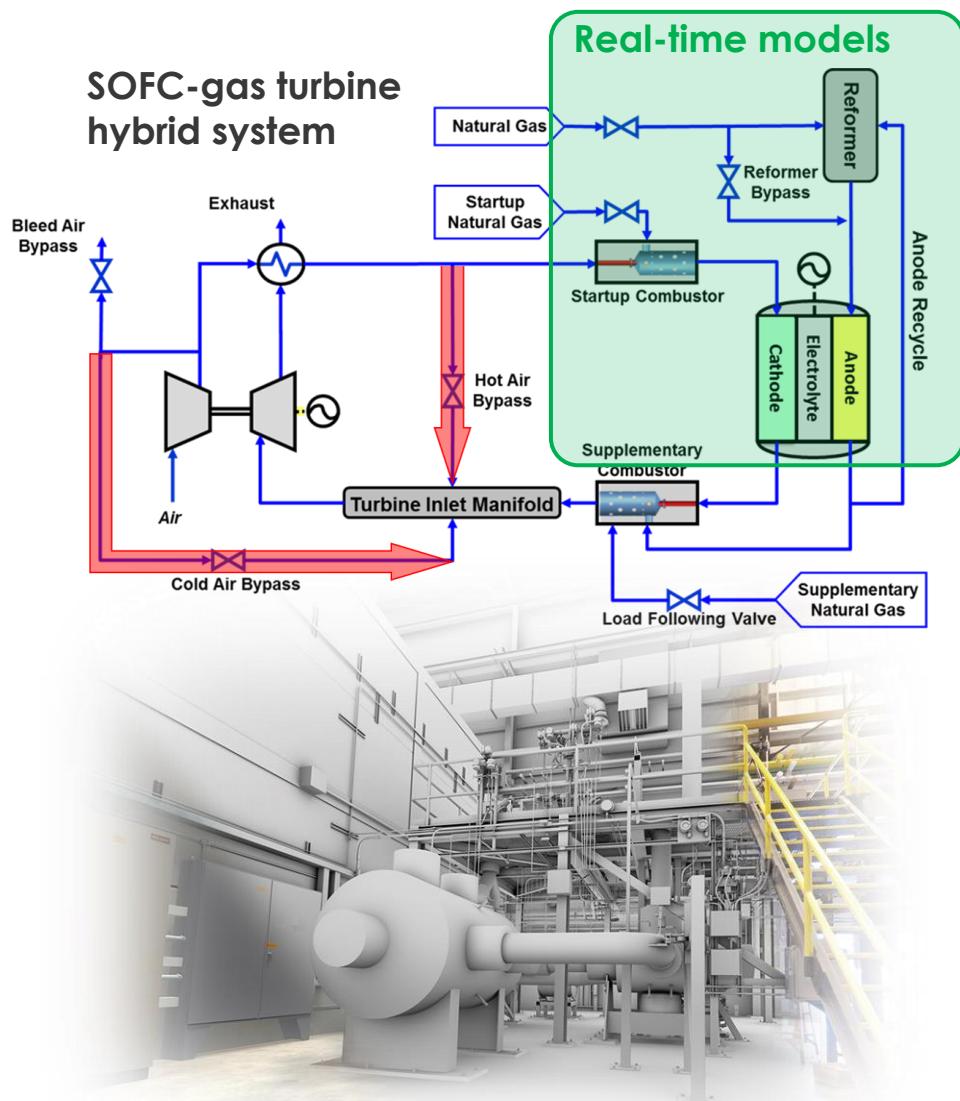


CPS approach enables:

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

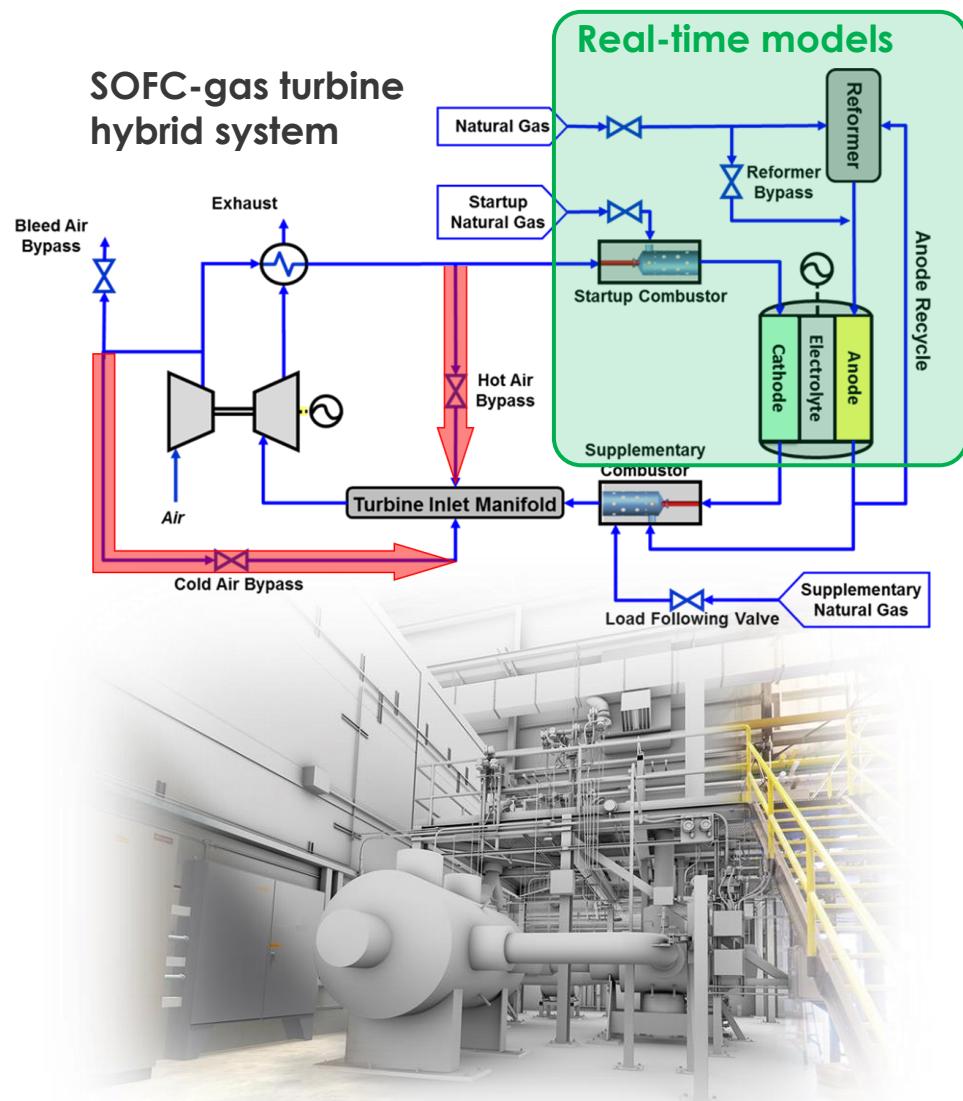


Hybrid Performance Project (HyPer) at NETL



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Hybrid Performance Project (HyPer) at NETL



Goal:

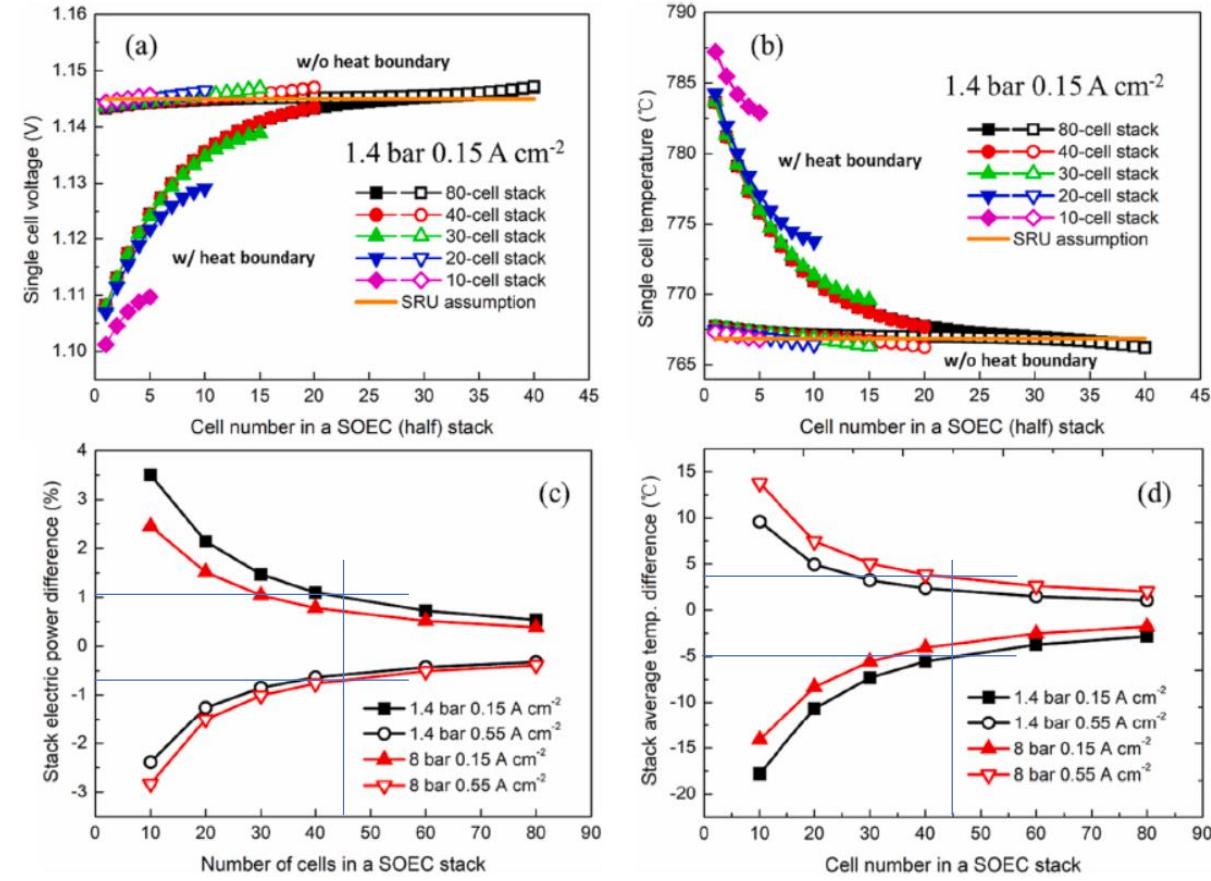
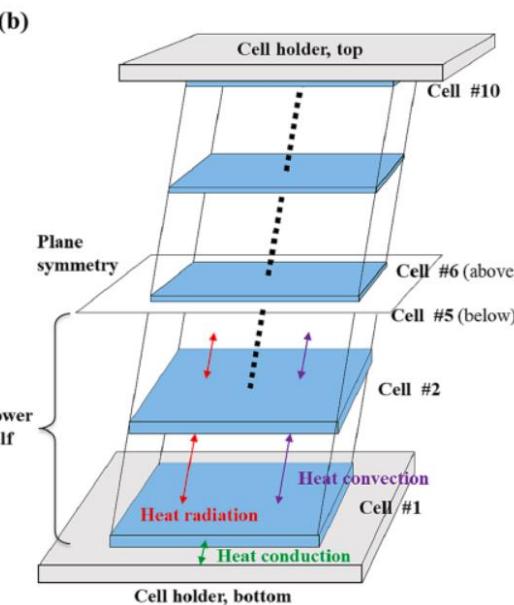
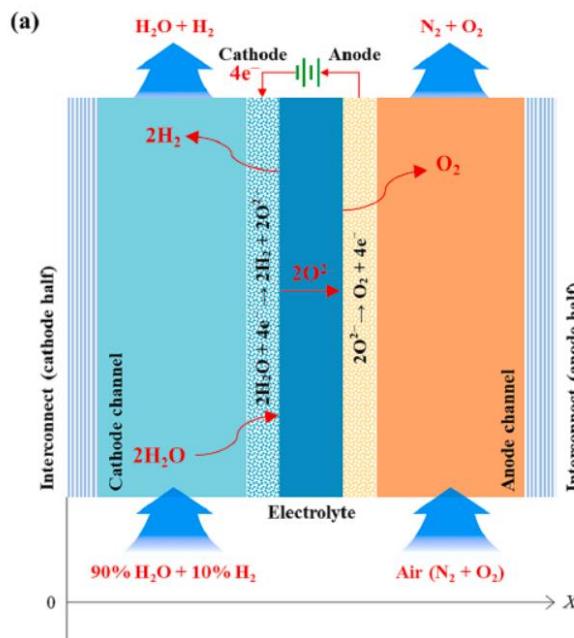
- ✓ **Derisk** the adoption of SOC systems for **hydrogen production** by demonstrating concepts using a cyber-physical approach.
- ✓ Show the feasibility of highly-coupled SOC systems to load follow and respond to a rapidly changing grid.



Development of Real-Time SOEC Models for Cyber-Physical Simulation



- ✓ Multiphysics **0D** and **1D** real-time SOEC models were 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)

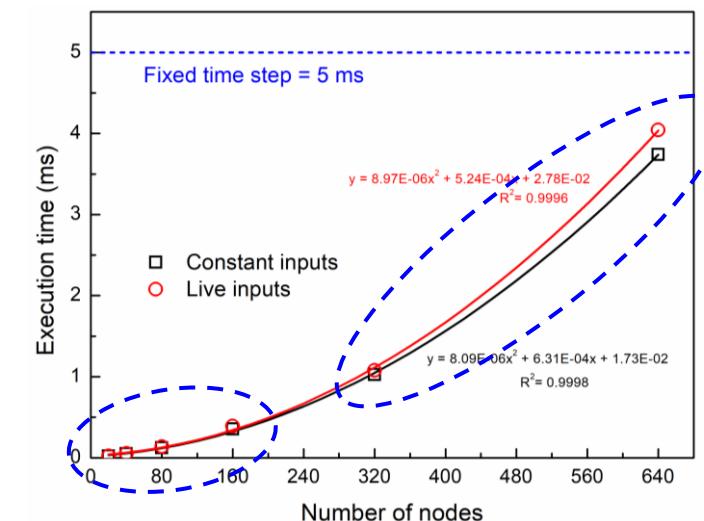
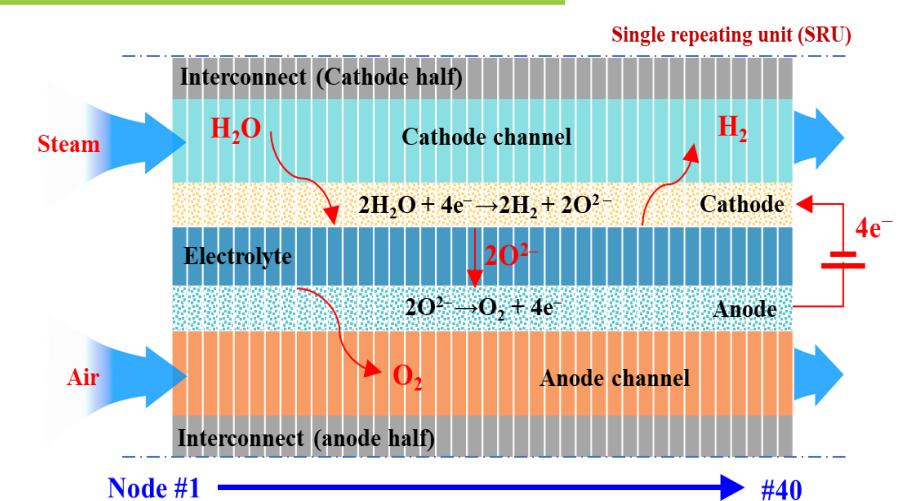
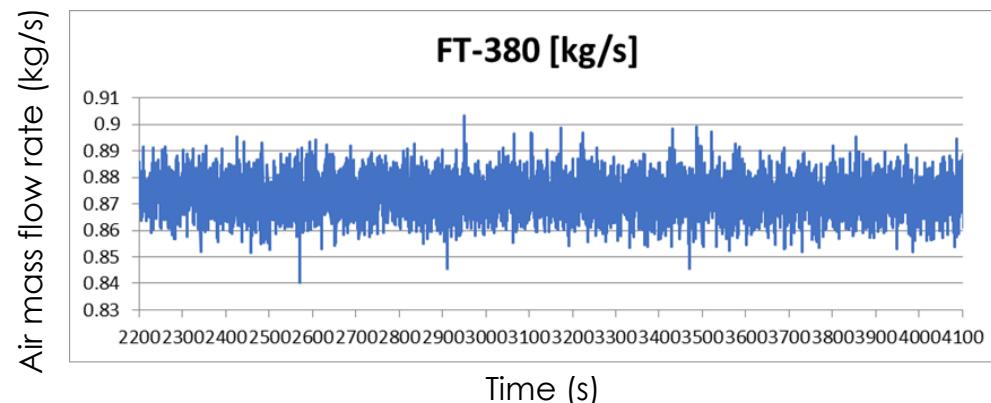


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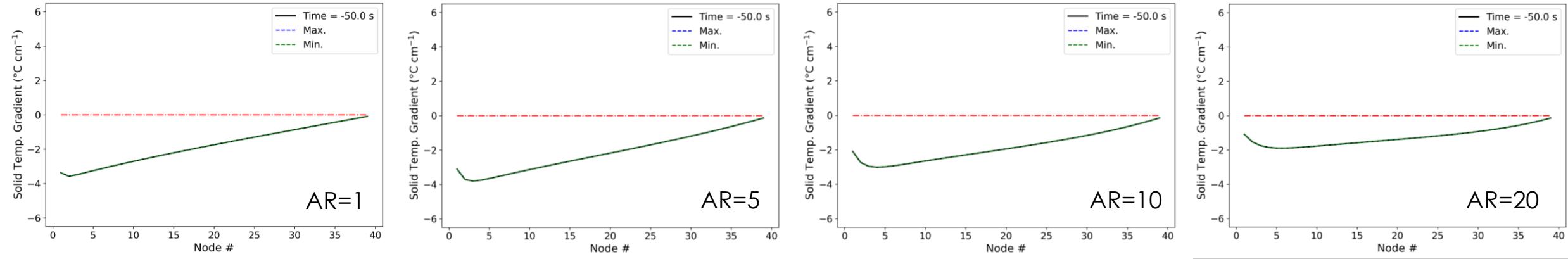
Development of Real-Time SOEC Models for Cyber-Physical Simulation



- ✓ [1D 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 constraints, and vice versa.
- ✓ **Versatile applications** – from **ultrafine** multiphysics distribution at micrometers intervals to **ultrafast** transients at microseconds.



Development of Real-Time SOEC Models for Cyber-Physical Simulation

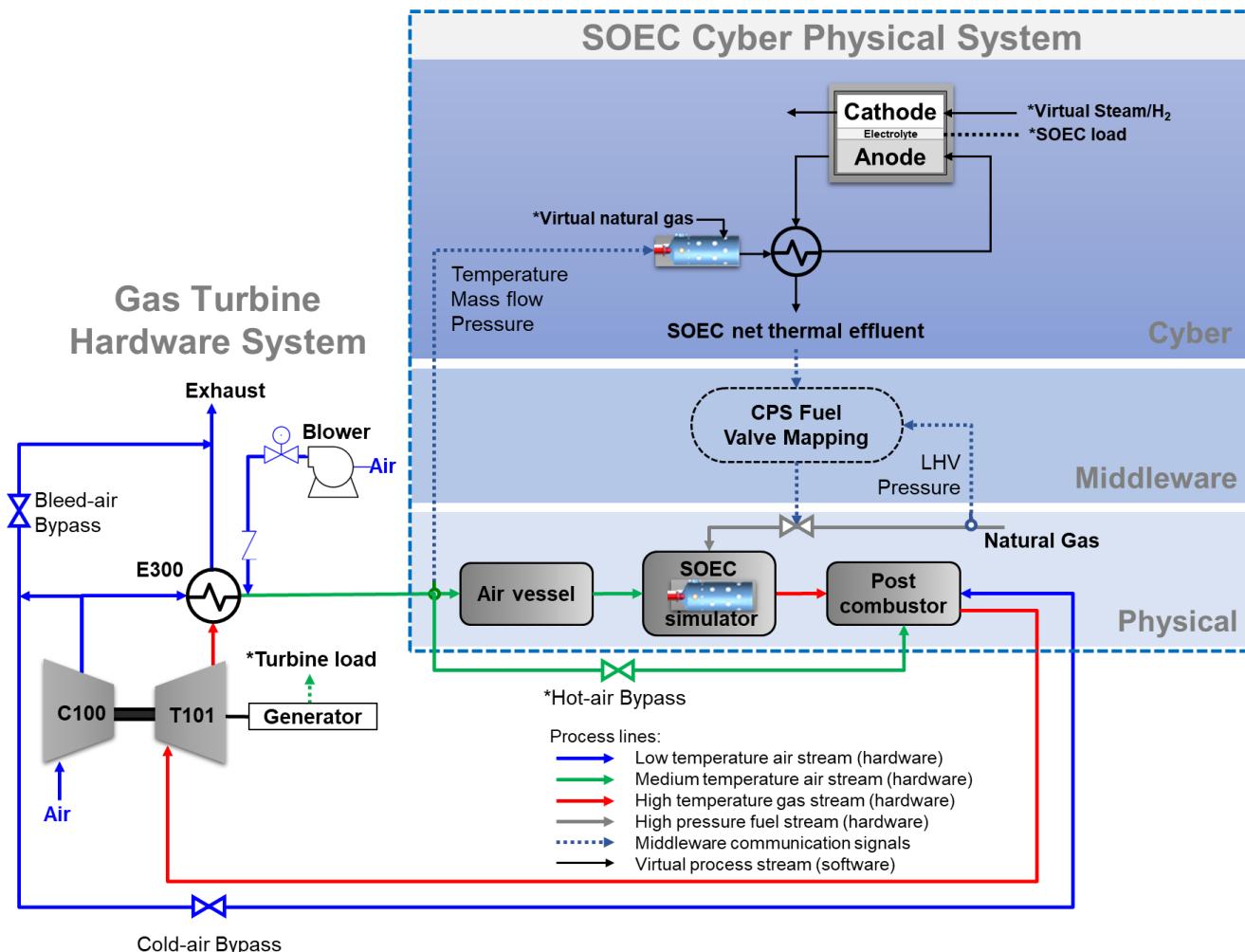


Effect of excess air ratio (AR) on local solid temperature gradient.

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 **system integration**.

Cyber-Physical Simulation of SOEC-GT Hybrid Energy System



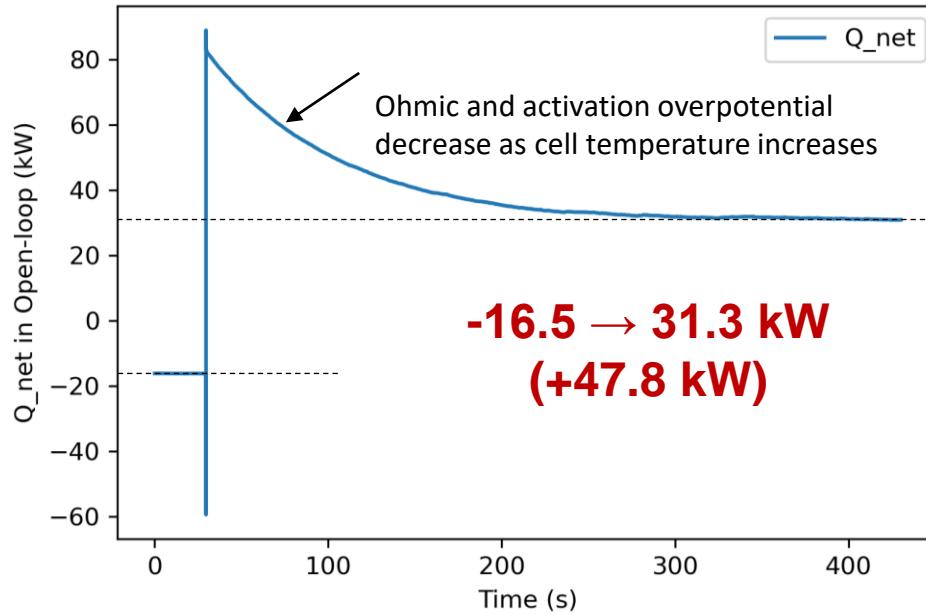
- Cyber-physical SOEC was established and coupled with NETL's Hyper facility.
- A pre-combustor model was integrated for higher operational flexibility.
- SOEC's **net thermal effluent** (i.e., **sensible heat difference**) was used to control a fuel value, which regulates the amount of fuel to be burned in the physical system.



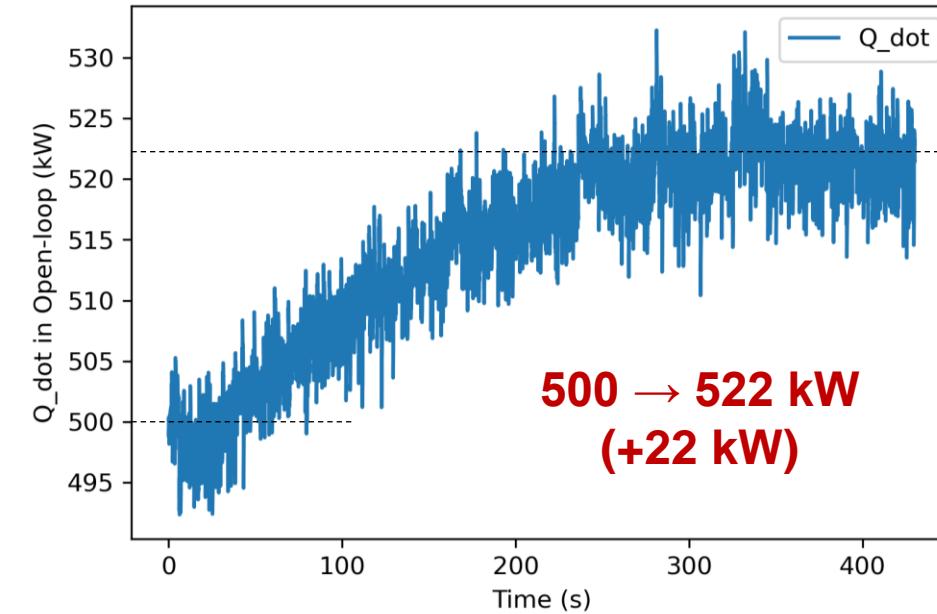
Cyber-Physical Simulation of SOEC-GT Hybrid Energy System



Upon a Step Change from 0.15 (Endothermic Mode) to 0.55 A/cm² (Exothermic Mode)



Q_{net} is the **difference** between electric power and electrolysis reaction energy.

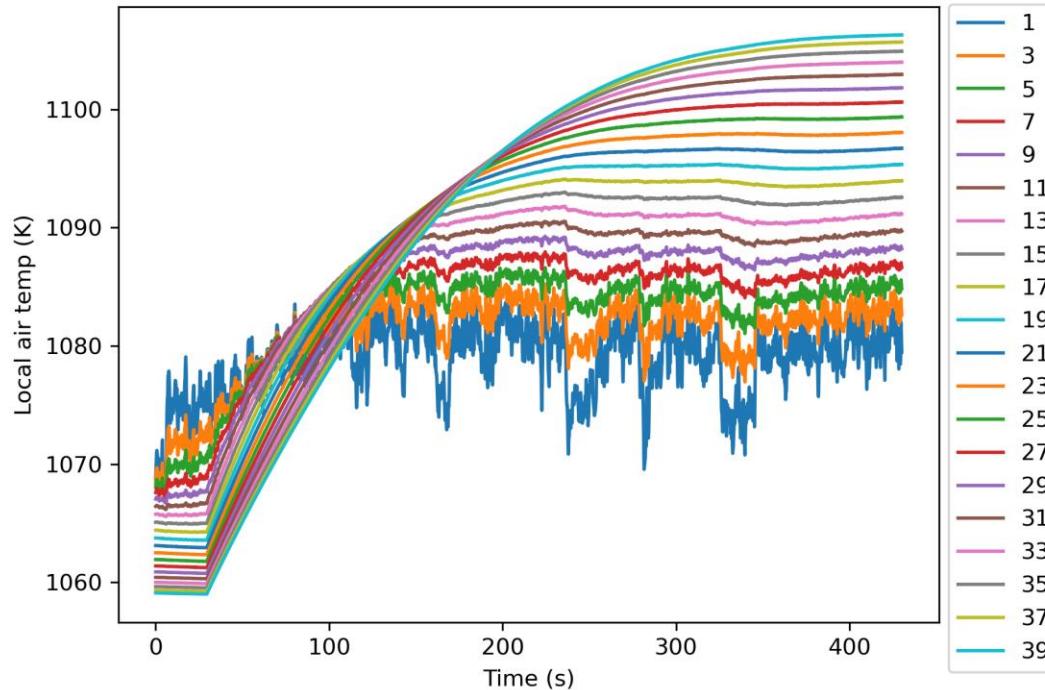


Q_{dot} is the **sensible heat difference** across the model closure.

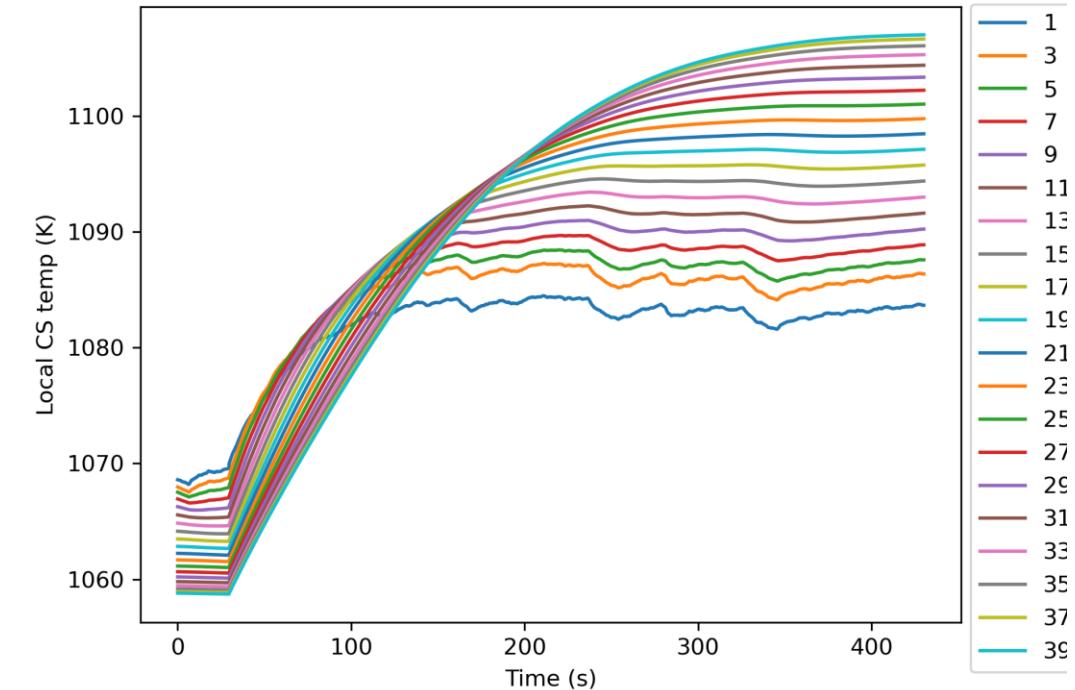
Cyber-Physical Simulation of SOEC-GT Hybrid Energy System



Upon a Step Change from 0.15 (Endothermic Mode) to 0.55 A/cm² (Exothermic Mode)



Air temperature **on the first few nodes** were affected by inlet air flow variation.

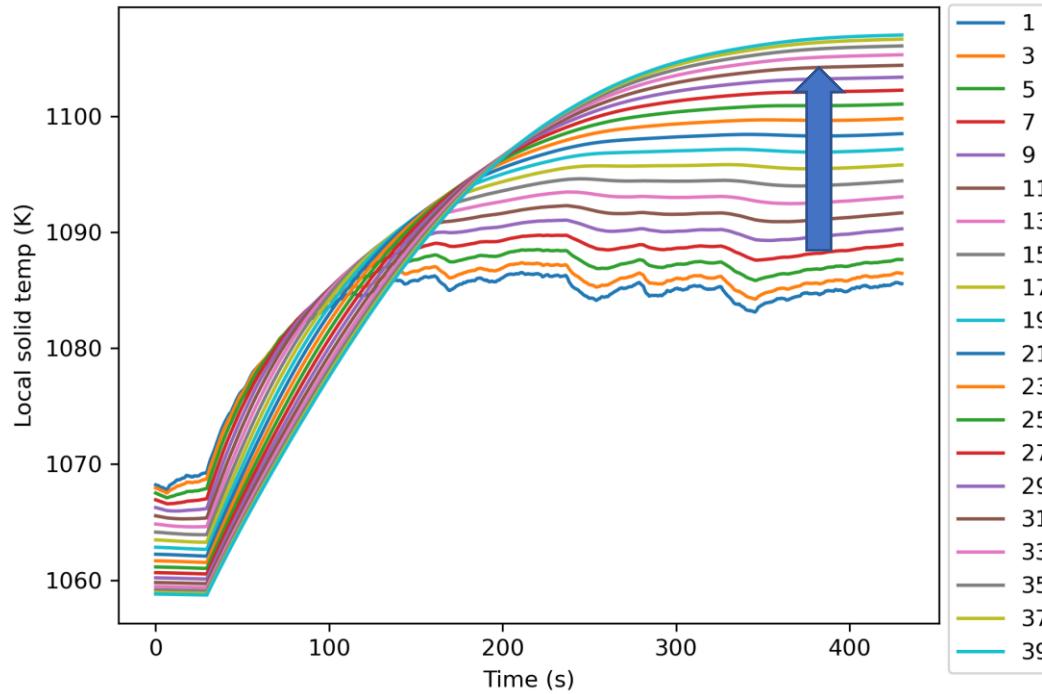


Cathode stream temperature was more stable as the inlet steam process flow was constant.

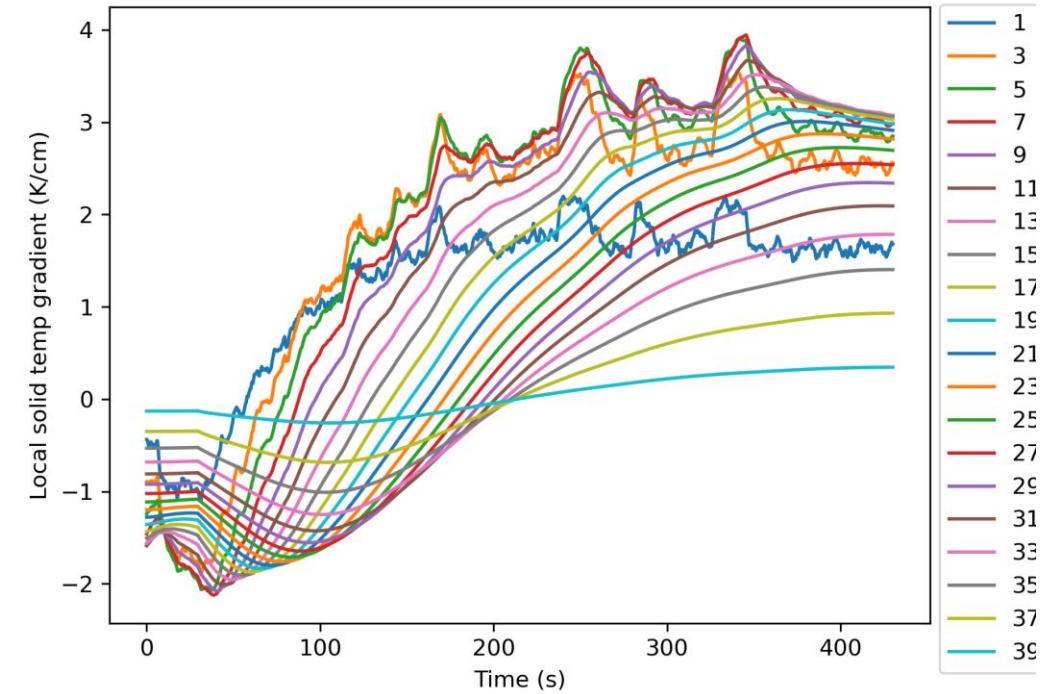
Cyber-Physical Simulation of SOEC-GT Hybrid Energy System



Upon a Step Change from 0.15 (Endothermic Mode) to 0.55 A/cm² (Exothermic Mode)



Solid temperature **on the first few nodes** were affected by inlet air flow variation.



The first few nodes showed the highest solid temperature gradient during transients.

Conclusions



1. A cyber-physical SOEC-GT hybrid energy system has been developed.
2. Seamless coupling of hardware and real-time SOEC model has been demonstrated.
3. At high air excess ratio (i.e., high air flow rate), a **rapid load transition** on SOEC has been demonstrated without violating the constraint on SOEC local temperature gradient.

Next steps:

1. Cycle analyses to identify the system integration issue at design/off-design conditions.
2. Develop controls to improve the dynamic operability of this hybrid system.

Acknowledgments



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