Hydrogen from Next-generation Electrolyzers of Water

U.S. DEPARTMENT OF ENERGY

# H2NEW: Hydrogen (H2) from Next-generation Electrolyzers of Water Overview

Director: Bryan Pivovar, National Renewable Energy Laboratory (NREL)

Deputy Director: Richard Boardman, Idaho National Laboratory (INL)

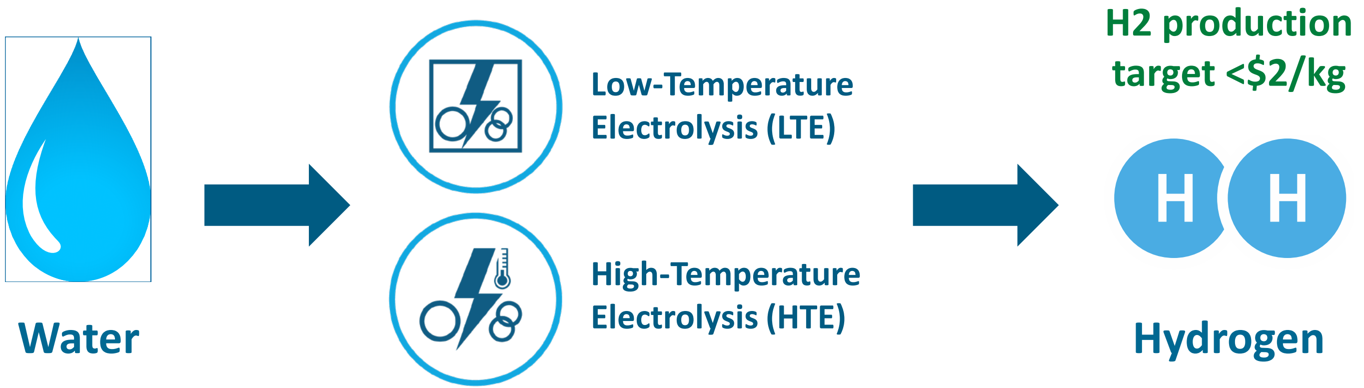
Date: 9/21/2023



NREL Transforming ENERGY · INL Idaho National Laboratory · Argonne National Laboratory · Berkeley Lab Bringing Science Solutions to the World · Lawrence Livermore National Laboratory · Los Alamos National Laboratory EST. 1943 · National Energy Technology Laboratory · Oak Ridge National Laboratory · Pacific Northwest National Laboratory

# Project Goals

Goal: H2NEW will address components, materials integration, and manufacturing R&D to enable manufacturable electrolyzers that meet required cost, durability, and performance targets, simultaneously, in order to enable \$2/kg hydrogen (by 2026 on way to H2 Shot target, \$1/kg by 2031).




H2NEW has a clear target of establishing and utilizing experimental, analytical, and modeling tools needed to provide the scientific understanding of electrolysis cell performance, cost, and durability tradeoffs of electrolysis systems under predicted future operating modes

# Overview

## Timeline and Budget

- Start date: **October 1, 2020**
- FY21 DOE funding: **$10M (75% PEM, 25% O-SOEC)**
- FY22 DOE funding: **$10M (75% PEM, 25% O-SOEC)**
- FY23 DOE funding: **$28M (45% PEM, 20% LA, 35% O-SOEC)**

## Detailed AMR posters on each task:

- https://www.hydrogen.energy.gov/amr-presentation-database.html (search H2NEW)

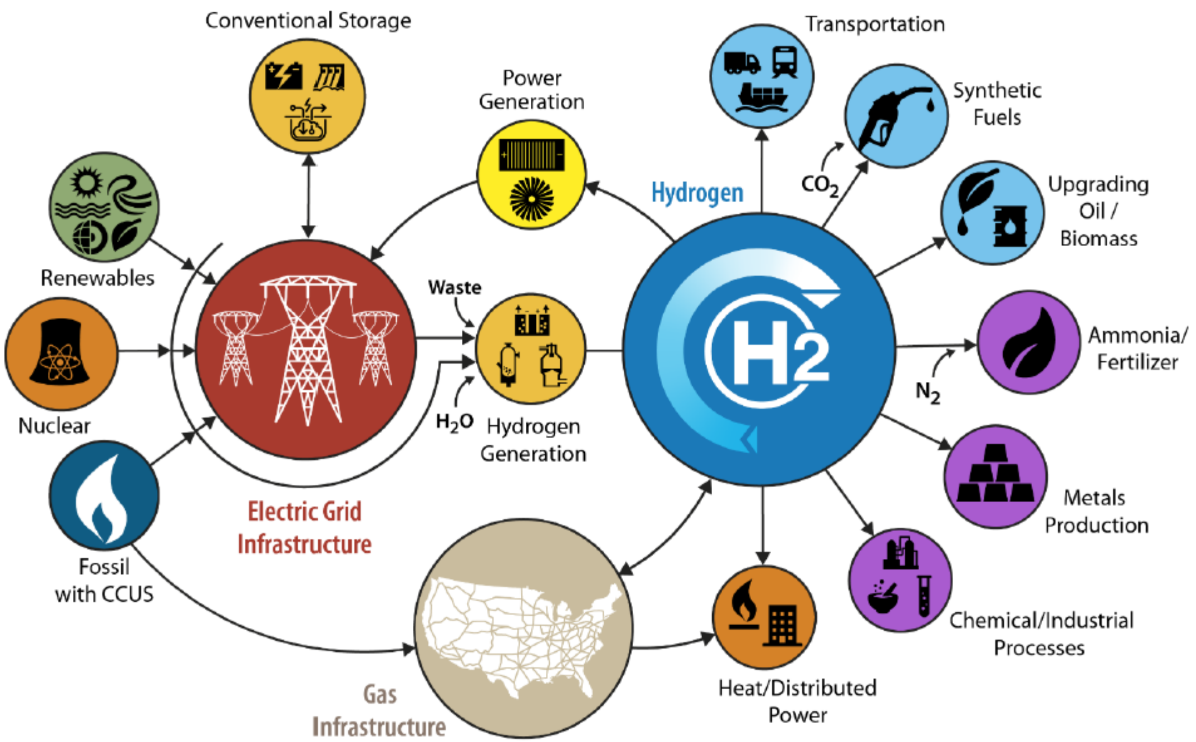
## Consortium Team*

NREL – National Renewable Energy Laboratory
Idaho National Laboratory
Argonne National Laboratory
Pacific Northwest National Laboratory
Los Alamos National Laboratory
Berkeley Lab – Bringing Science Solutions to the World
Oak Ridge National Laboratory
National Energy Technology Laboratory
Lawrence Livermore National Laboratory

- NIST, SLAC
- UC-Irvine
- Carnegie Mellon Univ
- Colorado School of Mines

* Expansion to include additional academic and industrial partners through FOA projects currently under review

# Potential Impact – H2NEW connection to H2@Scale

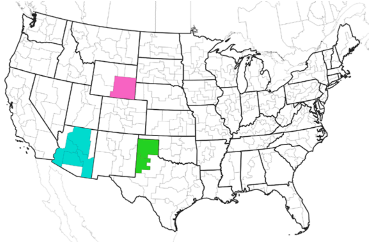



- Making, storing, moving and using H2 more efficiently are the main H2@Scale pillars and all are needed.
- Making H2 is the inherently obvious, first step to spur the wide-ranging benefits of the H2@Scale vision.
- Electrolysis has most competitive economics and balances increasing renewable generation challenges.

Illustrative example, not comprehensive

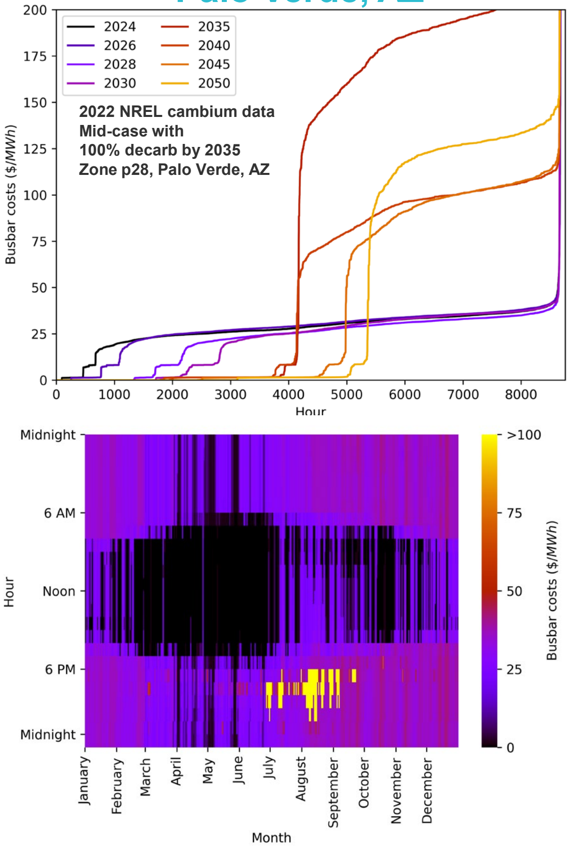
https://www.energy.gov/eere/fuelcells/h2-scale

# Accomplishment: Analysis of projected marginal electricity costs by location

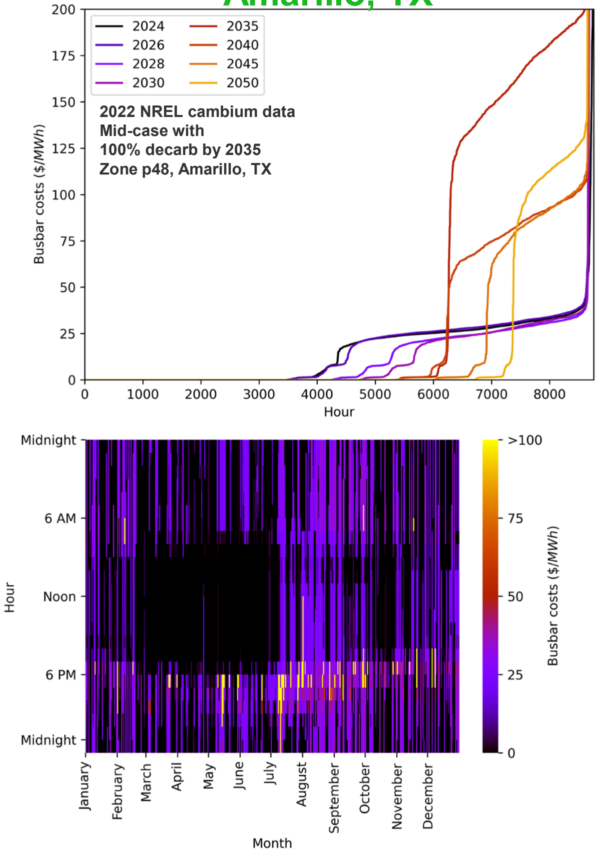


- We have expanded our analyses to explore "projected" electricity costs.
- We have chosen select locations to highlight the impact of grid mixes.
- Price structures directly influence optimal operating strategies.
- Explores the impact of "chasing" cheap electricity.
- Ignores the impact that electrolysis can have on electricity price structure.

## Palo Verde, AZ



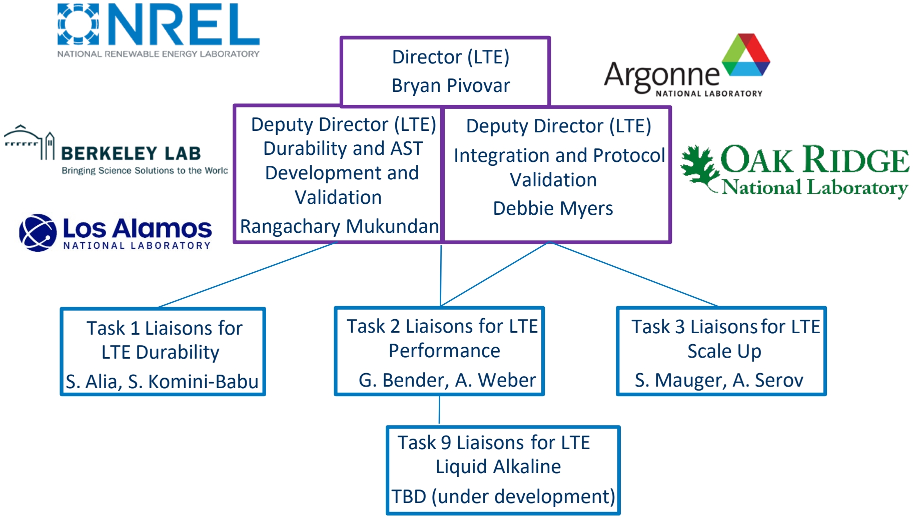

## Amarillo, TX

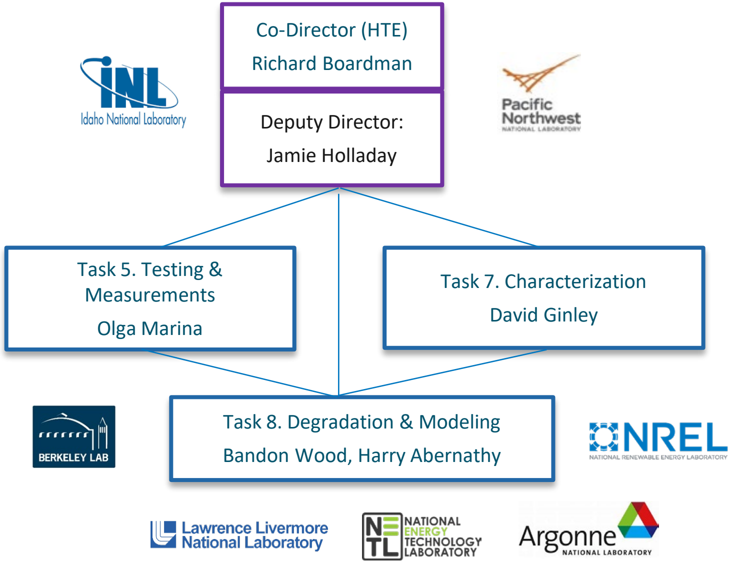





Badgett A, Saha P, Brauch J, Pivovar B. SUBMITTED: Decarbonization of the electric power sector and implications for low-cost hydrogen production from water electrolysis 2023;Advanced Sustainable Systems.

# Consortium Structure




- Well developed cross-lab structures for PEM and O-SOEC
- Liquid Alkaline efforts under development but will feed into LTE management structure

# Potential Impact: Stack Costs (PEM)

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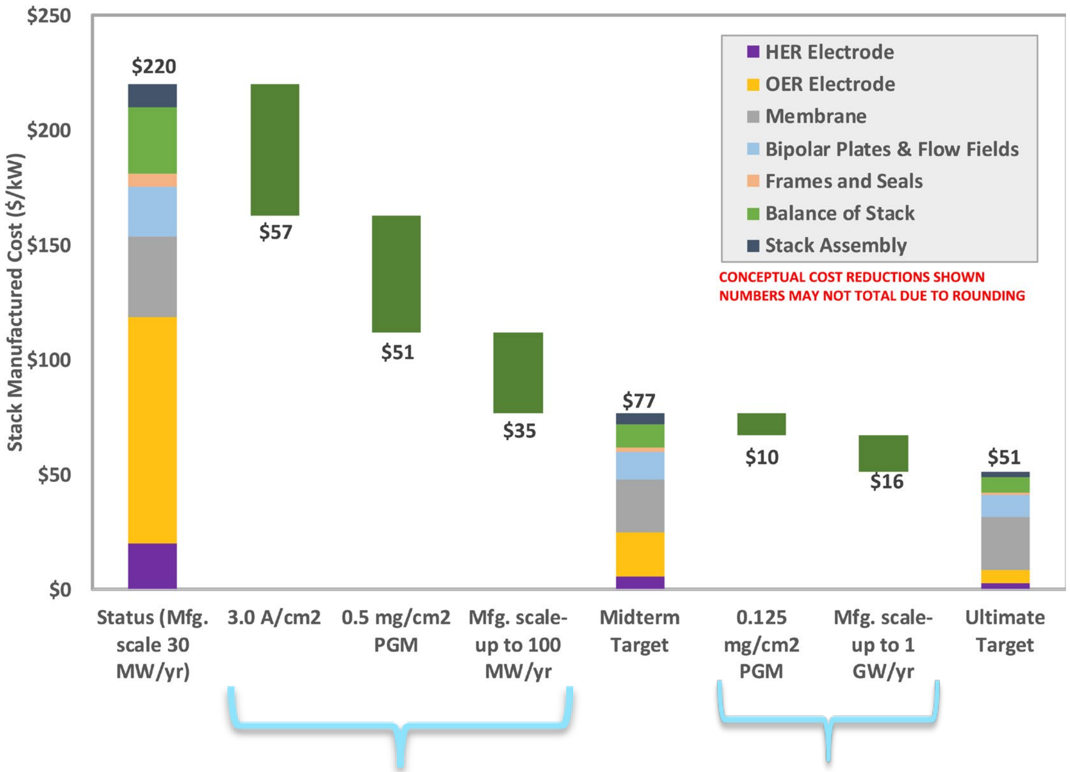



| Stack Targets | Status | 2026 | Ultimate |
|---|---|---|---|
| Cell (A/cm$^2$) | 2.0 | 3.0 | 3.0 |
| Cell voltage (V) | 1.9 | 1.8 | 1.6 |
| Lifetime (khr) | 40 | 80 | 80 |
| Degradation (mV/khr) | 4.8 | 2.3 | 2.0 |
| Capital Cost ($/kW) | 450 | 100 | 50 |
| PGM loading (mg/cm$^2$) | 3 | 0.5 | 0.125 |

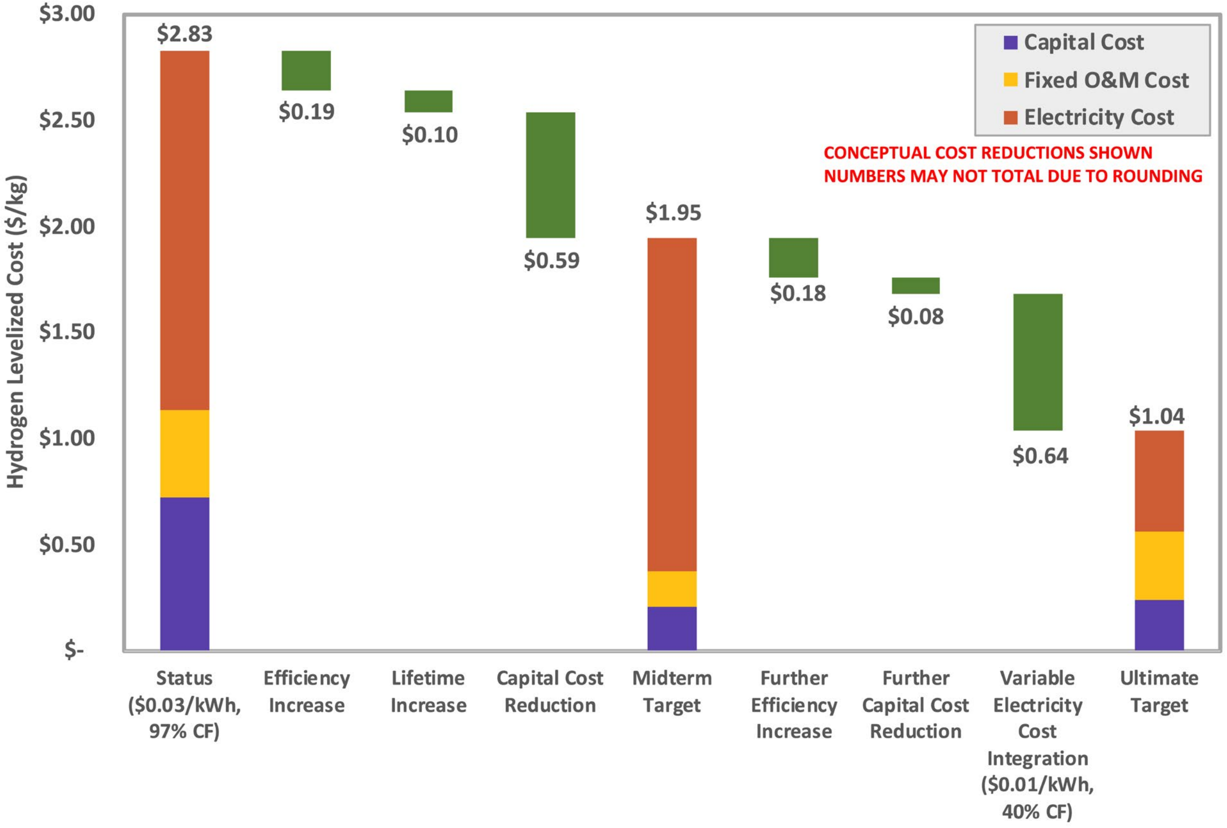
https://www.energy.gov/eere/fuelcells/technical-targets-proton-exchange-membrane-electrolysis

These 3 areas

1. Increased efficiency/current density
2. Decreased PGM loading
3. Scale-up

Are the strongest levers for addressing stack costs and primary focus of H2NEW.

# Potential Impact: Hydrogen Levelized Cost

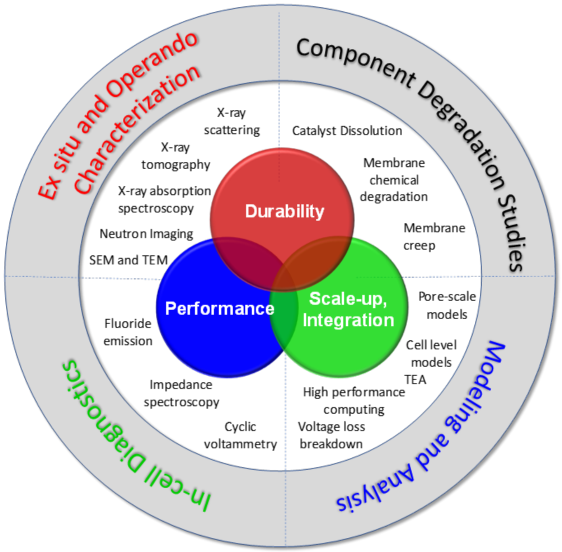



Select pathway to $2/kg and $1/kg identified.

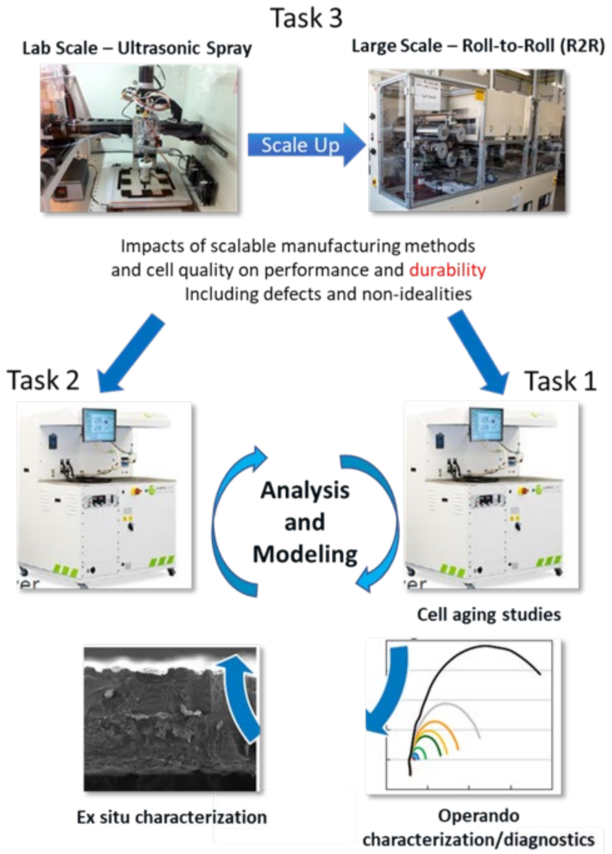
Much of HLC gains possible through greatly decreasing capital costs and enabling lower cost electricity through variable operation.

These advances can’t come with compromised durability or efficiency, so all three areas are linked.

# Approach: H2NEW Cross-technology Methodology




- Durability
  - Establish fundamental degradation mechanisms
  - Develop accelerated stress tests
  - Determine cost, performance, durability tradeoffs
  - Develop mitigation
- Performance
  - Benchmark performance
  - Novel diagnostic development and application
  - Cell level models and loss characterization
- Scale-up
  - Transition to mass manufacturing
  - Correlate processing with performance and durability
  - Guide efforts with systems and technoeconomic analysis



# H2NEW Activities: Low Temperature Electrolysis (LTE)

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# Accomplishments

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- 2023 AMR Select Highlights
  - Task 3c – Systems/Technoeconomic Analysis
    - Future electricity markets
    - Turndown ratio impact
  - Task 1 - Durability
    - Ir dissolution – Potential cycling
    - Establishing degradation baselines
    - Start/Stop – Reference Electrodes
    - AST Development
  - Task 2 - Performance
    - Benchmarking
    - Pressure effects
    - Test capability development
    - Cell modeling
  - Task 3 – Scale-up
    - Catalyst ink stability
    - R2R catalyst layer durability
  - PTL (cross task effort)
    - Novel tunable PTL/MPL development
    - PTL/CL interface optimization
    - Operando characterization of PTLs
  - Task 9 – Liquid Alkaline
    - Reference system
    - Benchmarking
    - Cell modeling
    - Initial performance testing

https://www.hydrogen.energy.gov/pdfs/review22/p196_pivovar_boardman_2022_o.pdf

# H2NEW Activities: High Temperature Electrolysis (HTE)

**Richard Boardman, H2NEW Deputy Director, and HTE Lead**

# Select HTE Highlights

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- 2023 AMR Select Highlights
  - Task 5 – Testing & Measurements
    - Established Multiple Size Cell Production
    - Achieved excellent production quality control and consistent testing
    - Established Inter-Lab Standardized Testing Protocol and Operating Procedures
    - Inter-Laboratory cell testing is closing on consistent test outcomes
    - Identified Stressors to Accelerate Degradation Mechanisms
    - Larger cell test stand with realistic interconnects, coatings, and contacts now under testing
  - Task 6b – Data Hub
    - Created Data Hub for H2NEW
    - Roll-out and demonstration, March 2023
  - Task 7 – Advanced Characterization
    - Cell characterization using standard microscopy and state-of-the-art X-ray and electron transmission microscopy.
    - Validated X-ray attenuation predictions and demonstrated XRD can be used to resolve crystal structures and defects from individual layers of intact cells (XRD, right) with simultaneous compositional analysis (XRF, below)
  - Task 8 – Degradation Modeling
    - Assessed impact of Ni/YSZ ration, operating conditions, and microstructure on Ni redistribution
    - Demonstrated multiscale framework for predicting penetration into packed GDC
    - Ab initio calculation use to parameterize multiscale models

https://www.hydrogen.energy.gov/pdfs/review22/p196_pivovar_boardman_2022_o.pdf

# Collaborations and Coordination

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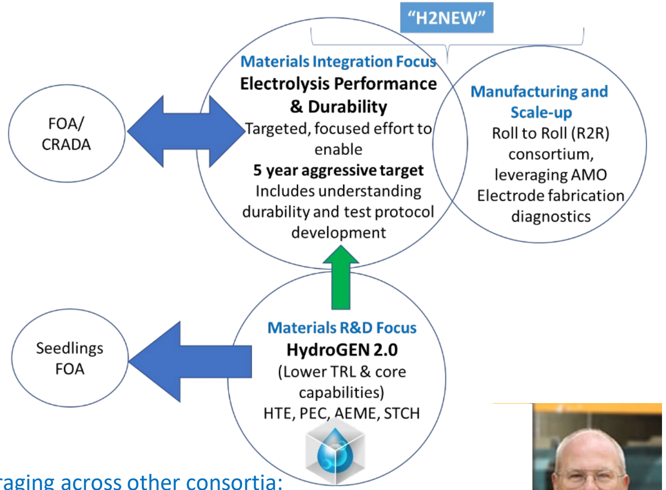



## PEM Stakeholder Advisory Board Members

Kathy Ayers
VP R&D
Nel Hydrogen

Cortney Mittelsteadt
VP Electrolyzer Technology
Plug Power

Andy Steinbach
Specialist Materials Science
3M

Jack Brouwer
Professor
U.C. Irvine

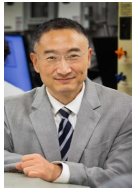
Mark Mathias
Consultant
retired (GM)

## Liquid Alkaline Stakeholder Advisory Board (under development)

Associate Lab Director Board (in place)

## HTE Stakeholder Advisory Board Members

Scott Swartz
Founder & CTO
Nexceris



Xiao-Dong Zhou
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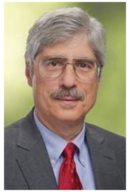
Greg Tao
Vice President
Chemtronergy

Bryan Blackburn
Chief Tech. Officer
Redox Power Systems

John Piatras
Sr. Principal Scientist, Group Leader
Saint-Gobain

Elango Elangovan
VP of Research
OxEon Energy

Joe Hartvigsen
Co-Founder & CEO
OxEon Energy



Tony Leo
Chief Tech. Officer & Exec. VP
FuelCell Energy

Scott Barnett
Prof. Materials Sci. & Engineering
Northwestern University

- Leveraging across other consortia:
- HydroGEN 2.0 (HFTO)
- ElectroCat 2.0 (HFTO)
- Million Mile Fuel Cell Truck (HFTO)
- Roll to Roll (Under development)
- Numerous industrial, academia, and international interactions: (IEA, ASTWG, materials suppliers, informal collaborations)
- Select group of advisors representing OEMs, Tier 1 suppliers, analysis and manufacturing interests.

H2IQ Webinar: https://www.energy.gov/eere/fuelcells/january-h2iq-hour-h2new-consortium-overview-electrolyzer-development-capabilities-0

NREL National Renewable Energy Laboratory · Argonne National Laboratory · Los Alamos National Laboratory · Berkeley Lab Bringing Science Solutions to the World · Oak Ridge National Laboratory · Lawrence Livermore National Laboratory · Pacific Northwest National Laboratory · INL Idaho National Laboratory · NETL National Energy Technology Laboratory · NIST Center for Neutron Research

# Lab Call Awards – Overlap w/HydroGEN

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| Subtopic | Lead Organization | PI | Project Title | Consortia Requested |
|---|---|---|---|---|
| **AEM – Membrane** | Lawrence Livermore National Laboratory | Dr. Johanna Schwartz | Studying-Polymers-On a-Chip (SPOC): Increased alkaline stability in anion exchange membranes | H2NEW, HydroGEN |
| **AEM – Electrodes** | Lawrence Berkeley National Laboratory | Dr. Xiong Peng | Hierarchical electrode design for highly efficient and stable anion exchange membrane water electrolyzers | H2NEW, HydroGEN |
| **LA – Electrodes** | Oak Ridge National Laboratory | Dr. Jun Yang | Hierarchically Structured Advanced Electrodes for Alkaline Water Electrolyzers | H2NEW, ElectroCat |
| **LA – Separators** | National Renewable Energy Laboratory | Abhishek Roy | Thin highly selective polymer membrane-separators for advanced LAW | H2NEW |
| **O-SOEC** | Pacific Northwest National Laboratory | Dr. Olga Marina | Stable High-Performing Oxygen Electrode for SOCE Operating at Lower Temperatures | H2NEW |
| **O-SOEC** | SLAC National Accelerator Laboratory | Nicholas Strange | Developing High-Entropy Materials as Superior Alternative Electrodes for Long-lasting Oxide-Conducting Solid Oxide Electrolysis Cells (O-SOECs) | H2NEW |
| **PEM – Membrane** | Sandia National Laboratory | Dr. Cy Fujimoto | Advanced Hydrocarbon Based Proton Exchange Membrane Water Electrolyzers | H2NEW, HydroGEN |
| **PEM – Catalyst** | Los Alamos National Laboratory | Jacob Spendelow | Ultralow Iridium Catalysts with Controlled Morphology and Speciation | H2NEW |
| **PEM – Catalyst** | Argonne National Laboratory | Dr. Ahmed Farghaly | Accelerated Discovery of Metallic Pyrochlores OER Catalysts for PEM Water Electrolyzers: High-Throughput Computational and Experimental Approach | H2NEW |
| **P-SOEC** | Idaho National Laboratory | Dr. Dong Ding | High Performance and Robust Proton Conducting Solid Oxide Electrolysis Cells Enabled by New Materials, Interfaces and Fabrication Methods | H2NEW, HydroGEN |
| **P-SOEC** | Lawrence Livermore National Laboratory | Dr. Joel Varley | DIRECTED SEARCH FOR STABLE AND CONDUCTIVE ELECTROLYTES FOR NEXT-GENERATION PROTON SOLID OXIDE ELECTROLYSIS CELLS | H2NEW, HydroGEN |

# Accomplishment: Establishing Relevant Durability Baselines (4000 hour test)

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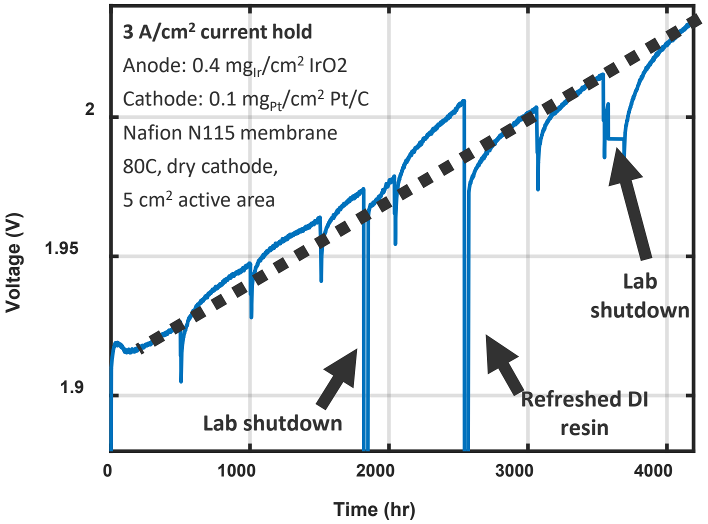
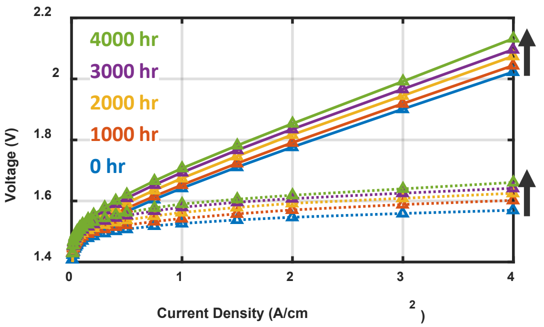
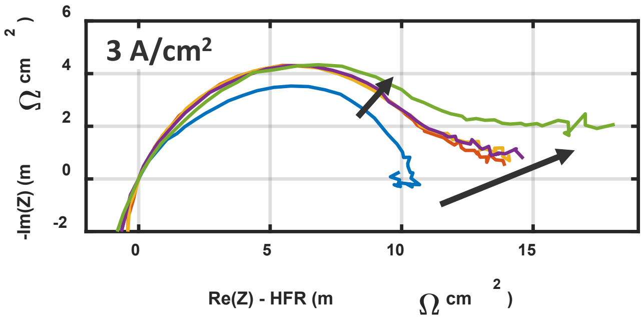
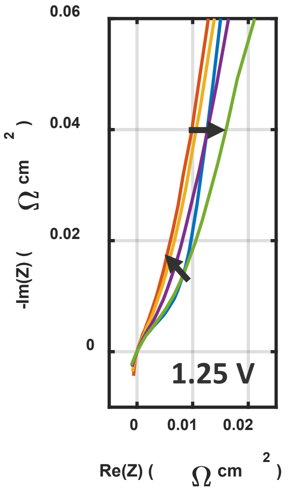



Completed 4,000 hr durability test of FuGeMEA cell:

- Benchmarking decay rates:
  - ~28 µV / hr at 3 A/cm²
    - ~ 7 µV / hr ohmic, 21 µV$_{HFR\text{-}free}$ / hr
    - Slower decay of ~ 11 µV$_{HFR\text{-}free}$ / hr at 0.1 A/cm²
- Understanding mechanisms of steady-state degradation:
  - Catalyst activity or surface area loss
  - Increasing catalyst layer resistance
  - Possible cation contamination



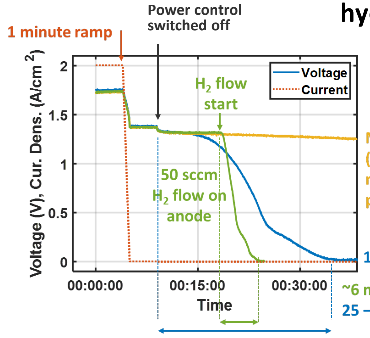

Post-mortem characterization underway to inform mechanistic understanding.

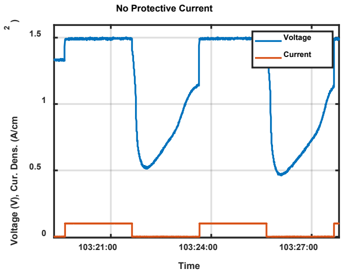
# Accomplishment: Cell Depolarization Mechanisms and Reference Electrodes for Start/Stop Durability

## Different Depolarization Behavior Depending on Shutdown Conditions

**Slow depolarization (minutes) caused by hydrogen interaction with the anode**

Important stressor to anode from hydrogen crossover during shutdown



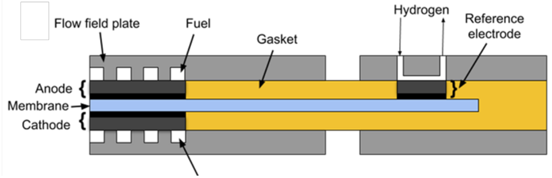




**Fast depolarization (seconds) caused by rapid current stepping (possible capacitive effect)**

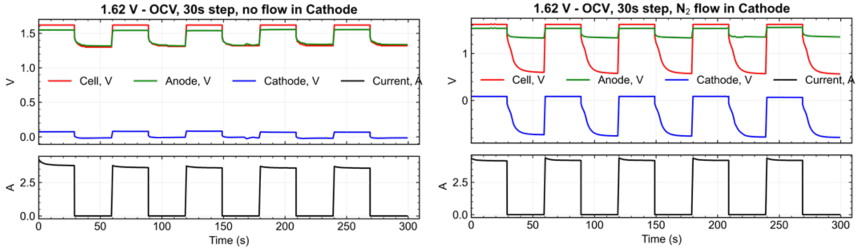
Mechanisms must be understood and controlled to design ASTs and mitigation strategies.

## Reference Electrode for Understanding Stressors on Each Electrode

Reference electrode is an essential tool for monitoring anode and cathode states




On/Off current cycling without hydrogen on cathode causes cathode potential to change.




[1] Abdelrahman, M. E. et al. Electrochimica Acta 416 (2022): 140262.

Potential on both electrodes can change during shutdown, creating different stressors depending on conditions.

Understanding and controlling different shutdown stressors is key focus for ongoing work to create targeted, reproducible durability tests

# Accomplishments: Developed Operando Characterization

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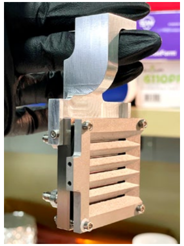
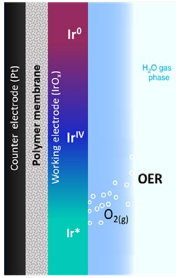
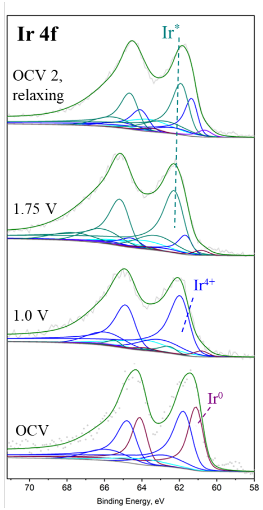
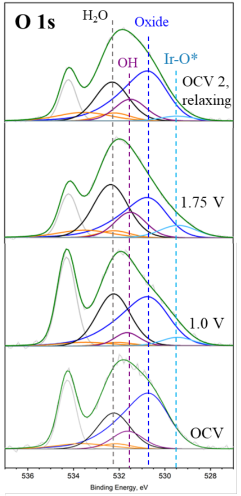
## X-ray Photoelectron Spectroscopy (XPS)



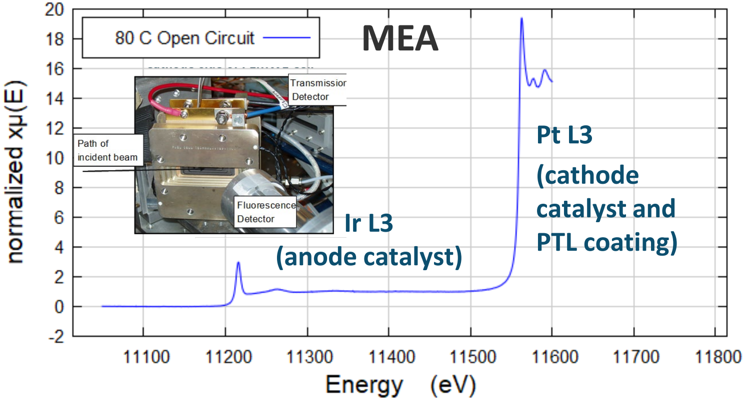


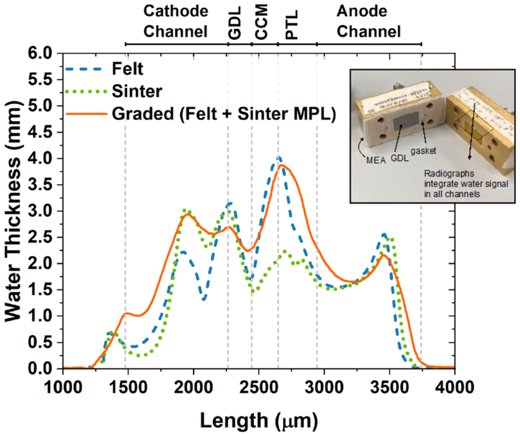




- Operando characterization provides insight into:
  - ✓ Oxidation state of anode catalyst impacting OER activity and degradation processes (XPS, XAFS)
  - ✓ Through plane water distribution impacting cell resistances and transport (Neutron imaging)
- Advanced characterization techniques enable observations of processes within operating electrolyzers and inform model development

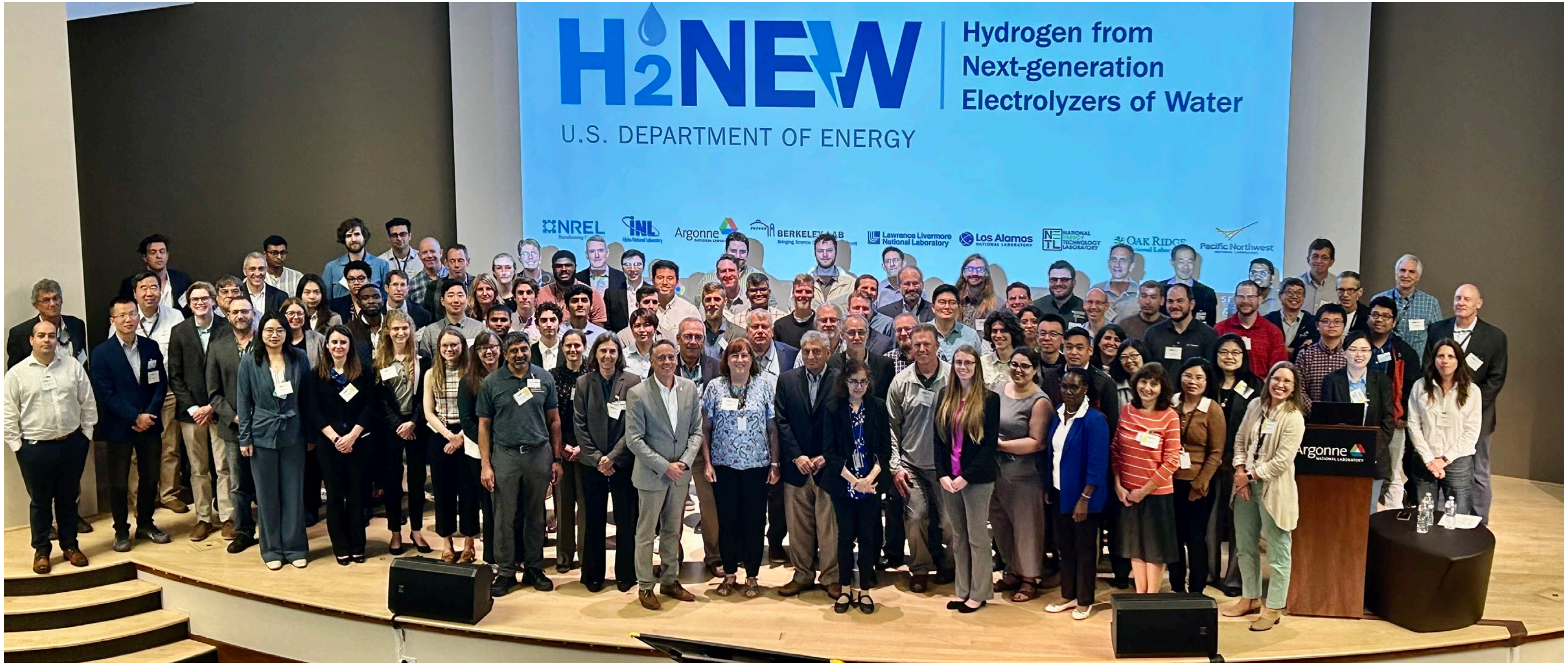
## X-ray Absorption Spectroscopy (XAFS)




## Neutron Imaging (MIT/NIST)



# Annual AOP/SAB Planning Meeting




Argonne National Lab: Sept 11-13, 2023