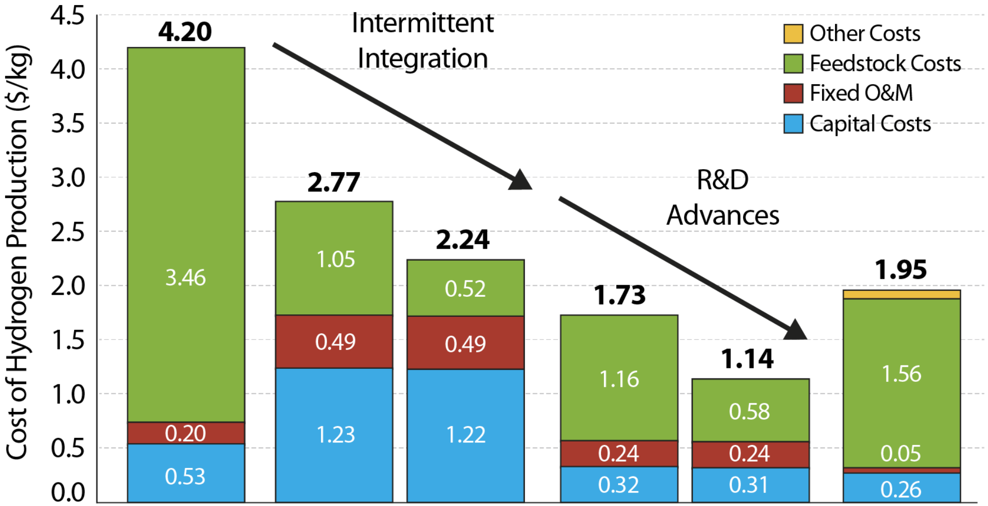
H2NEW Overview

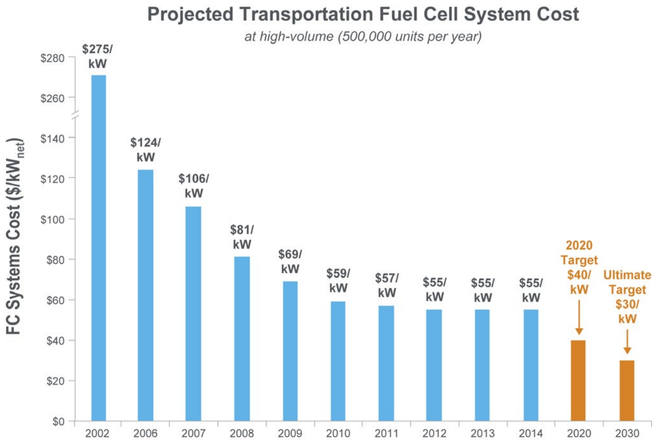
HydroGEN Topic 2B meeting

March 1, 2021

LTE Advances/Economics

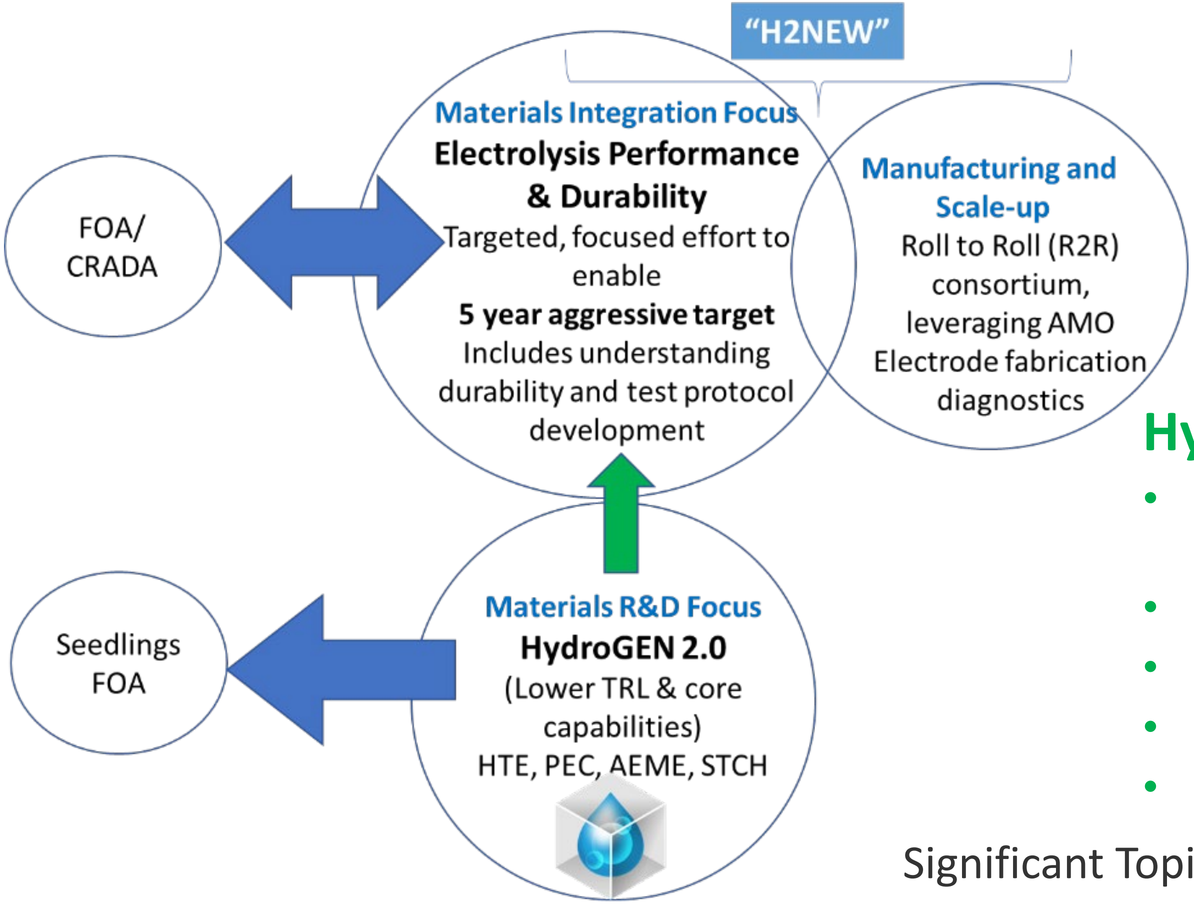


Capacity Factor	97%	40%		40%		0.9
Cost of Electricity	¢6.6/kWh	¢2/kWh	¢1/kWh	¢2/kWh	¢1/kWh	
Capital Cost	$400/kW	$400/kW		$100/kW		
Efficiency (LHV)	66%	66%		60%		
	Electrolyzer					**SMR**



H2NEW will build upon these analyses and advance cell technology

HydroGEN Materials R&D Feeds to H2NEW Materials Integration



H2NEW:

- Polymer electrolyte membrane (PEM) Electrolysis
- Oxygen-conducting solid oxide electrolysis (SOEC)

HydroGEN:

- Alkaline exchange membrane (AEM) Electrolysis
- Metal-supported SOEC (MS-SOEC)
- Proton-conducting SOEC (p-SOEC)
- Photoelectrochemical (PEC)
- Solar thermochemical (STCH)

Significant Topic 2B Overlap

Consortium Goals/Approach

- 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**.
- 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
- Leverage other HFTO Consortia (primarily M2FCT – methodologies; and HydroGEN – electrolyzer materials development)
- Cells, PTLs in scope, materials development (catalysts, electrolytes) out of scope.

H2NEW Consortium: H2 from Next-generation Electrolyzers of Water

A comprehensive, concerted effort focused on overcoming technical barriers to enable affordable, reliable & efficient electrolyzers to achieve <$2/kg H_2

- Launching in Q1 FY21
- Both low- and high-temperature electrolyzers
- $50M over 5 years

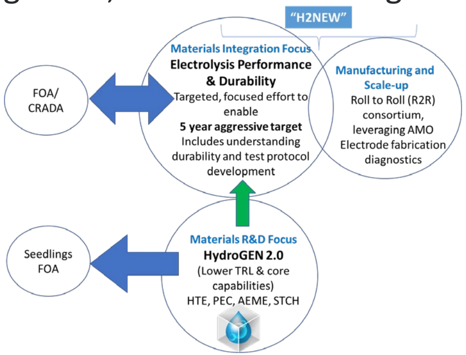
National Lab Consortium Team

NREL (National Renewable Energy Laboratory), INL (Idaho National Laboratory), Argonne National Laboratory, Berkeley Lab, Pacific Northwest National Laboratory, Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, National Energy Technology Laboratory (NETL)

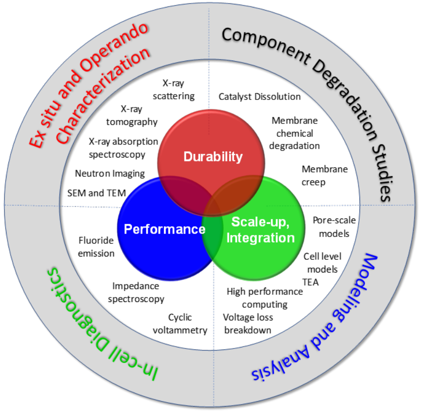
Clear, well-defined stack metrics to guide efforts.

Draft Electrolyzer Stack Goals by 2025		
	LTE PEM	HTE
Capital Cost	$100/kW	$100/kW
Elect. Efficiency (LHV)	70% at 3 A/cm²	98% at 1.5 A/cm²
Lifetime	80,000 hr	60,000 hr

The focus is not new materials but addressing components, materials integration, and manufacturing R&D



Utilize combination of world-class experimental, analytical, and modeling tools



Durability/lifetime is most critical, initial, primary focus of H2NEW

- Limited fundamental knowledge of degradation mechanisms.
- Lack of understanding on how to effectively accelerate degradation processes.
- Develop and validate methods and tests to accelerate identified degradation processes to be able to evaluate durability in a matter of weeks or months instead of years.
- National labs are ideal for this critical work due to existing capabilities and expertise combined with the ability to freely share research findings.

H2NEW Consortium (LTE) Leadership

Stakeholder Advisory Board (SAB)

H2NEW Co-Director (HTE)
Richard Boardman

Director (LTE)
Bryan Pivovar

Deputy Director (LTE)
Durability and AST Development and Validation
Debbie Myers

Deputy Director (LTE)
Integration and Protocol Validation
Nem Danilovic

FOA Projects

Outreach

Data

Task 1 Liasons for LTE Durability
S. Alia, R. Mukundan

Task 2 Liaisons for LTE Performance
G. Bender, A. Weber

Task 3 Liasons for LTE Scale Up
M. Ulsh, D. Wood

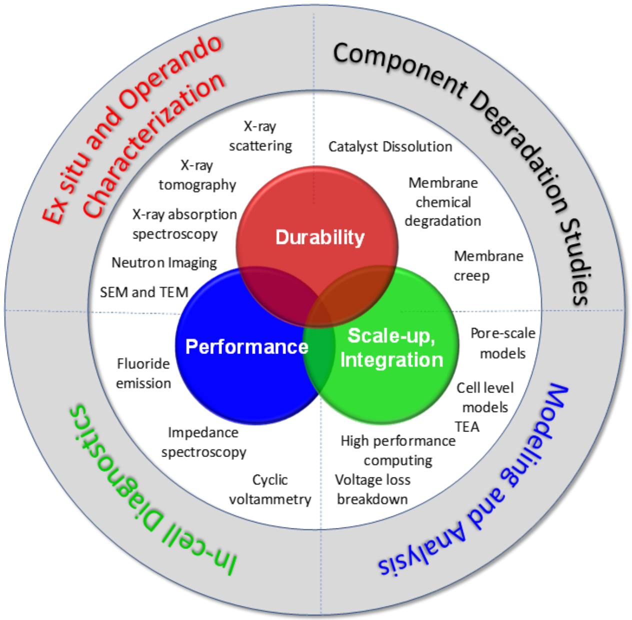
Stakeholder Advisory Board

Kathy Ayers (Nel hydrogen)
Corky Mittelsteadt (Plug Power)
Chris Thomas (3M)
Jack Brouwer (UC-Irvine)
Mark Mathias (retired GM)

FOA projects expected to add into H2NEW in near future, pending budgets and advancing priorities.

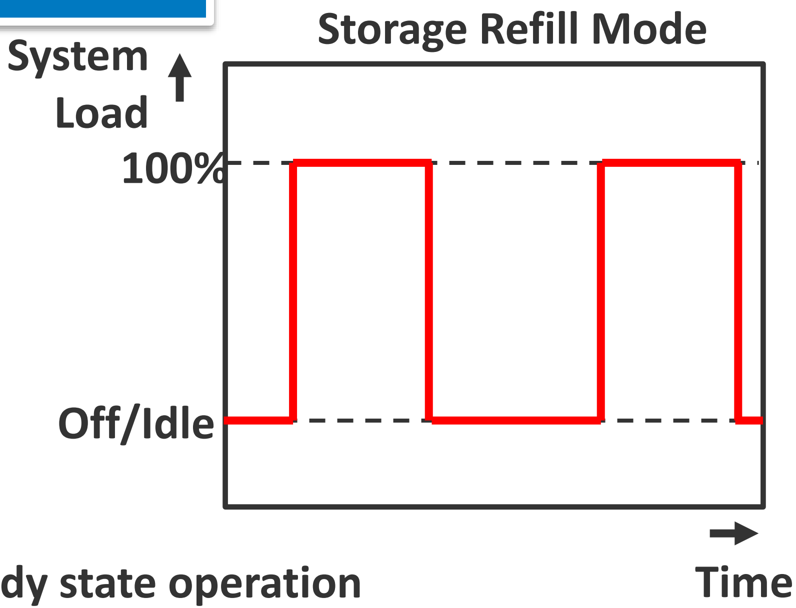
LTE Task Breakdown

- LTE, H2NEW is structured to broadly address barriers related to:
  - ✓ **Durability** (Task 1, ~45%)
  - ✓ **Performance** (Task 2, ~20%)
  - ✓ **Scale-up/Integration** (Task 3, ~35%)



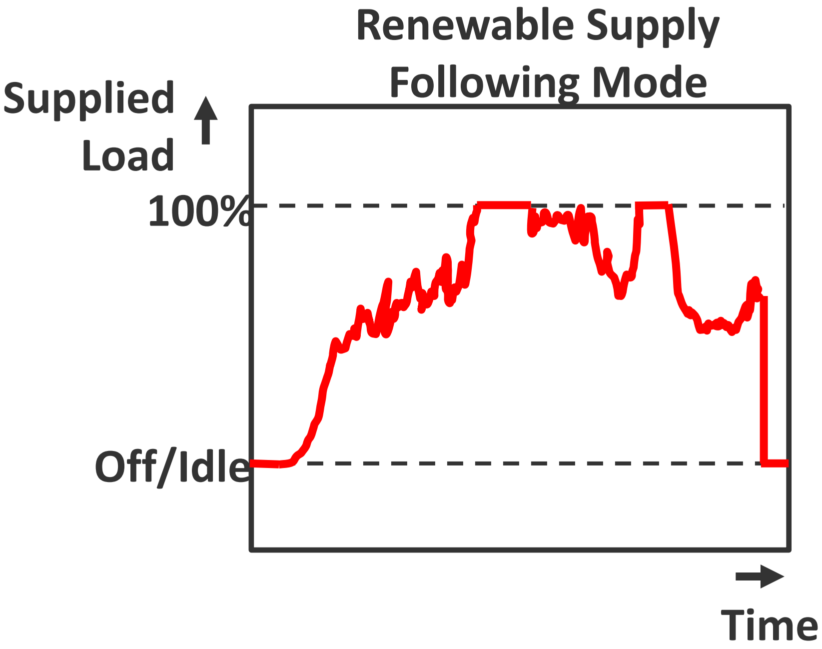
Operating Strategies

Existing Systems



- Steady state operation
- Turn system on at certain vessel pressure
- Refill system at 100% system power
- Switch system to off or idle

Future Systems



- Follow renewable energy supply
- Maybe cap high and low performance to minimize degradation

LTE State-of-the-Art

Existing Systems

- **2V @ 2A/cm^2**
- **2-3 mg/cm^2 PGM catalyst loading on anode & cathode**
- **60k – 80k hours in commercial units**
- **Niche applications**
  - Life support
  - Industrial H_2
  - Power plants for cooling
- **\$3.7/kg H_2 production***

Future Systems

- **2V @ $\geq$ 2A/cm^2**
- **Thinner membranes**
- **Lower loadings**
- **$\geq$ 80k hours**
- **Supply following**
- **Renewable & Grid integrated applications**
  - Wind
  - Solar
  - Nuclear
- **\$2/kg H_2 production***

*High volume projection of hydrogen production for electrolysis: https://www.energy.gov/sites/prod/files/2017/10/f37/fcto-progress-fact-sheet-august-2017.pdf

** K.Ayers, AMR Presentation PD094, 06/2014

H2NEW LTE Task Goals

- Durability (Task 1)
  - Establish fundamental degradation mechanisms
  - Develop accelerated stress tests
  - Determine cost, performance, durability tradeoffs
  - Develop mitigation
- Performance (Task 2)
  - Benchmark performance
  - Novel diagnostic development and application
  - Cell level models and loss characterization
- Scale-up (Task 3)
  - Transition to mass manufacturing
  - Correlate processing with performance and durability
  - Guide efforts with systems and technoeconomic analysis

Task 3c Analysis Rationale

- Ultimate target it is to enable \$2/kg H_2, but stack costs are only one piece of puzzle
- Electricity prices have historically been primary cost driver
- Evolving energy system (increasing renewables) leading to lower cost, intermittently available resources – need to understand window of potential operating strategies
- Complex tradeoffs in duty cycle vs durability will impact materials and design choices
- The ideal system, optimized integration, and operating strategy is unknown
- These activities critical for establishing stack/cell level targets and quantifying tradeoffs
- By integrating analysis and R&D efforts (which typically isn't done in this context) we can increase success.

H2NEW's Approach to Addressing LTE Durability

Operando cell studies

- ✓ Determine key stressors accelerating degradation
- ✓ Identify relevant degradation mechanisms at the component level

Ex situ component studies

Membrane

- ✓ Limits of durability and the impact of different membrane chemistry
- ✓ Variables: Side chain, equivalent weight, pre-aging, reinforcements, recombination layers and/or radical scavenging
- ✓ Impact of seal area/edges, pressure

Accelerated Stress Tests

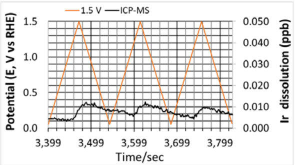
- ✓ Orders of magnitude acceleration of component degradation rates
- ✓ Assess cost and durability trade-offs, accelerate materials development, MEA integration, and optimal operating strategies for LTEs

Understanding → Understanding and Evaluation → Solutions

2025
80,000 h
2.24 μV/h
0.5 mg_{PGM}/cm^2

- ✓ Quantify losses associated with different operating conditions
- ✓ Propose and demonstrate degradation mitigation measures

Catalyst



- ✓ Aqueous electrochemical cell coupled with ICP-MS
- ✓ Potential and potential profile dependence of the dissolution of anode catalysts
- ✓ Correlation with oxidation state

Mitigation Strategies

- ✓ Develop and implement operational, materials, and cell design-based degradation mitigation strategies
- ✓ Coordinate with AST development, technoeconomic analysis, and cell fabrication tasks

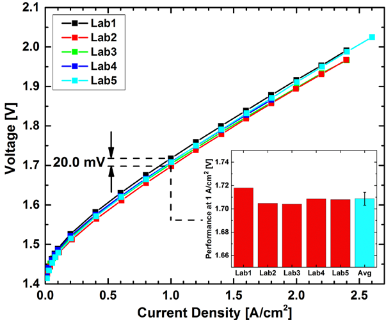
In-cell Diagnostics:
I-V curves, impedance spectroscopy, cyclic voltammetry, fluoride emission

→ Voltage loss breakdown/modeling →

***Ex situ* component characterization:**
SEM, TEM, X-ray spectroscopy, scattering, tomography

H2NEW’s Approach to Addressing Performance

Benchmarking and Protocols

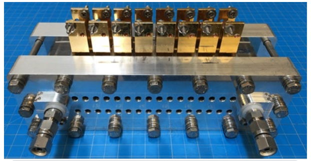


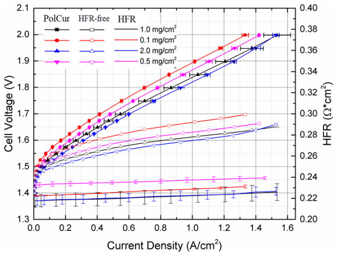
- Baseline MEA
- 0.4 mg_{Ir}/cm^2 anode catalyst layer
  - Alfa Aesar IrO_2
  - Evaluate new materials
- Porous Transport Layers
  - Critical component
  - Ti sinter (Mott) vs Ti fiber (Bekaert)
  - Coatings (sputtered) vs e-plated (commercial)
  - Evaluate structure functionality
- Membrane
  - Nafion 1135
  - Evaluate new materials

Bender et al, IJHE 44 (2019) 9174-9187

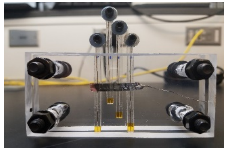
Novel Diagnostic Development

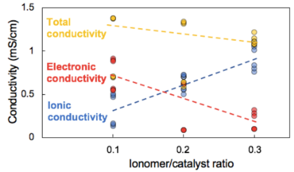
Segmented cells





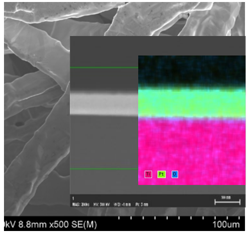
Ionic/electronic conductivity

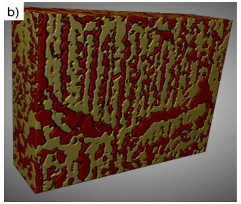




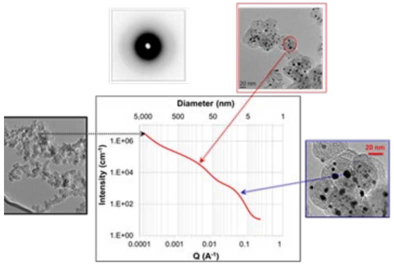
Advanced Characterization

FIB-SEM

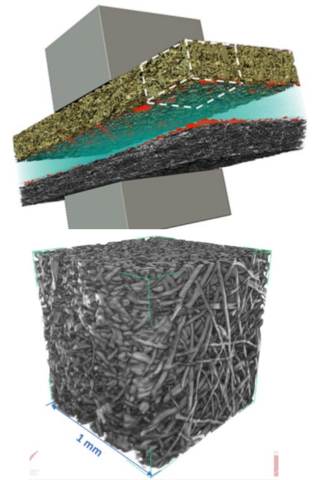




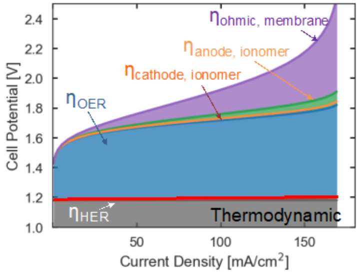
X-ray Scattering

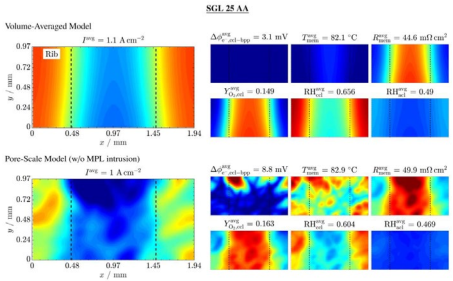


Tomography



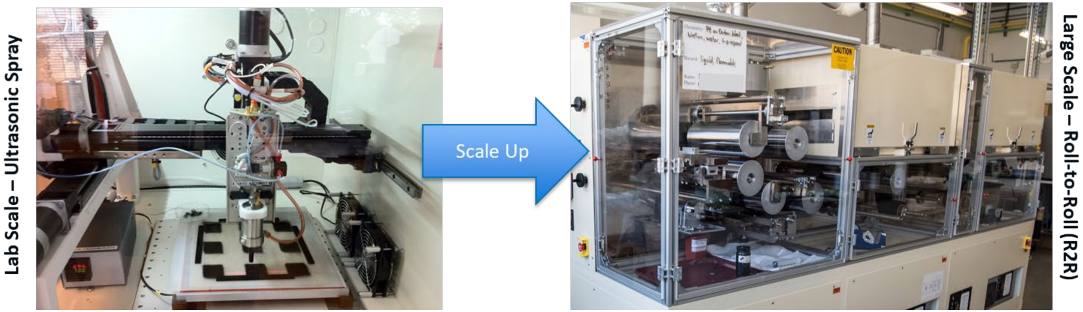
Cell Level Modeling



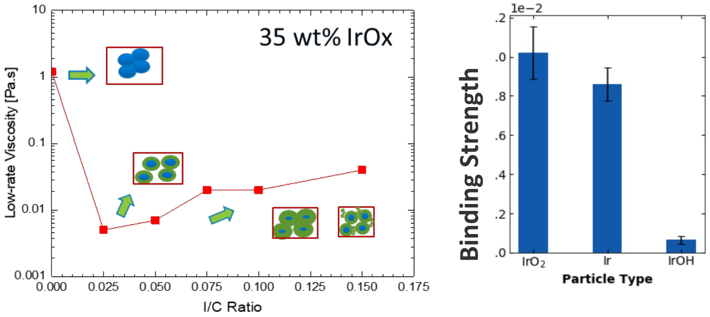


H2NEW's Approach to Addressing Scale Up

Lab Scale to Mass Manufacturing Relevant

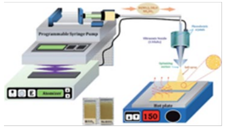


Ink Rheology

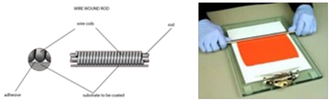


Fabrication Techniques

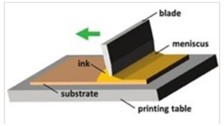
Ultrasonic spray coating Mali *et al.* Nanoscale Advances 1.2 (2019)



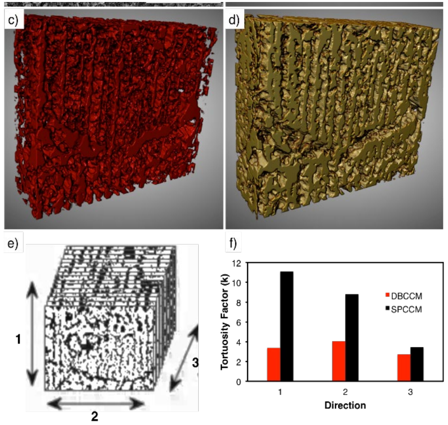
Mayer rod coating http://www.holoeast.com/

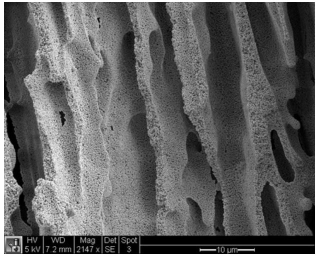


Blade coating Howard *et al.* Advanced Materials 31.26 (2019)

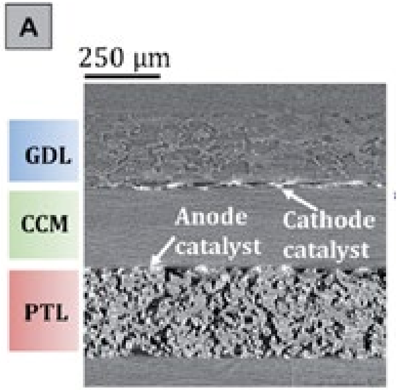


Structure/Function



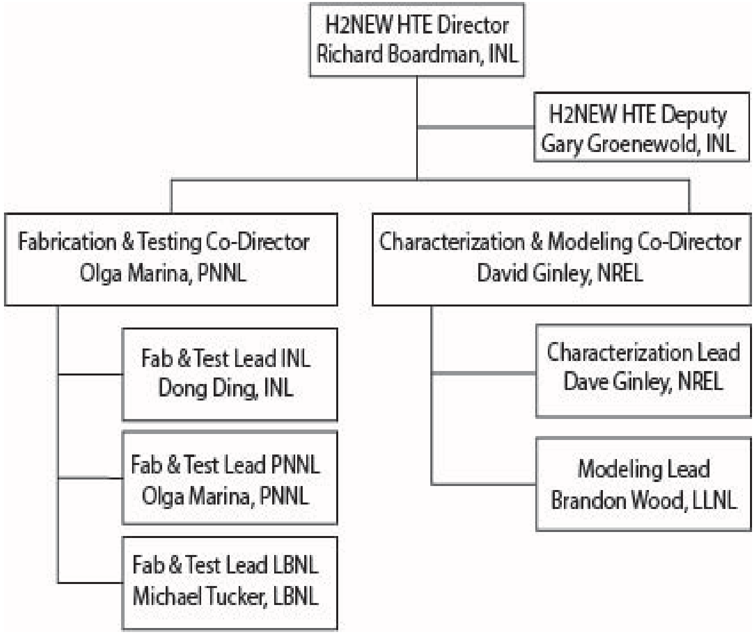


Interface Design



Leonard et al. Solar Fuels (10.1039/c9se00364a)

HTE Overview



Stakeholder Advisory Board.

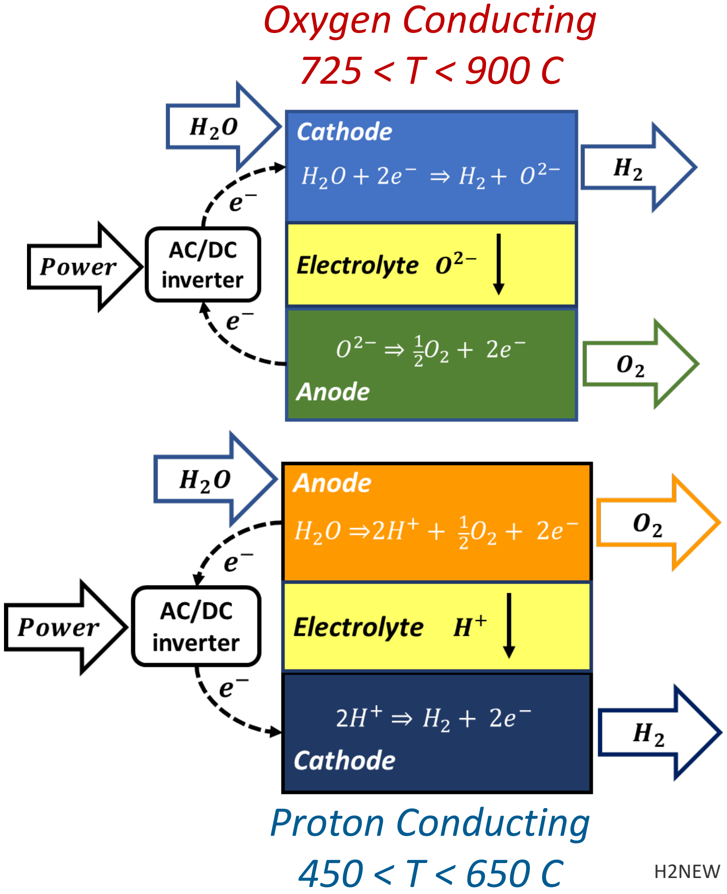
Recruited from industrial and academic candidates

- Engage and leverage significant National Laboratory experience and capability
- Cell and stack fabrication, electrolysis testing -- INL, PNNL, LBNL
- Electrolysis testing, focusing on accelerated stress testing campaigns – INL, PNNL
- Cell characterization, including synchrotron-, and conventional spectroscopy and imaging – led by NREL, engaging ANL, PNNL, SLAC
- Cell modeling – multiscale, led by LLNL, engaging NETL, PNNL

HTE Electrolyzer Stack Goals by 2025	
Capital Cost	\$100/kW
Electrical Efficiency (LHV)	98% at 1.5 A/cm^2
Lifetime	60,000 H

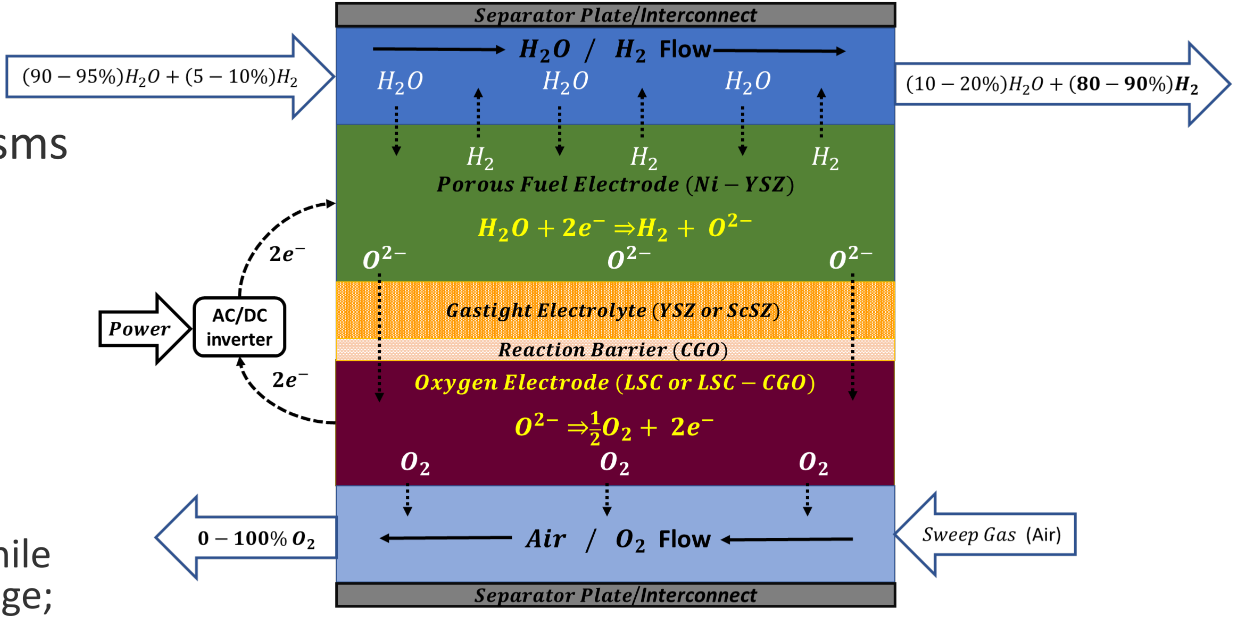
Advancing the current state-of-the-art HTE technology

- Thermodynamic motivation for developing HTE
  - ability to leverage both thermal and electric energy
- HTE is dynamically evolving
  - Oxide-conducting electrolyzers have been extensively studied
    - current state-of-the-art for o-SOECs suggests that refinement of cell and stack architectures, and operating protocols
    - Reduce heat but maintain ion-conductivity
    - Optimize electrolyte/electrode thickness
    - Minimize current leakage
  - Proton-conducting electrolyzers offer the potential for operation at lower temperatures, with the prospect of improved durability, but are at an early stage of development
    - R&D Currently under HydroGEN



o-SOEC Current Impediments

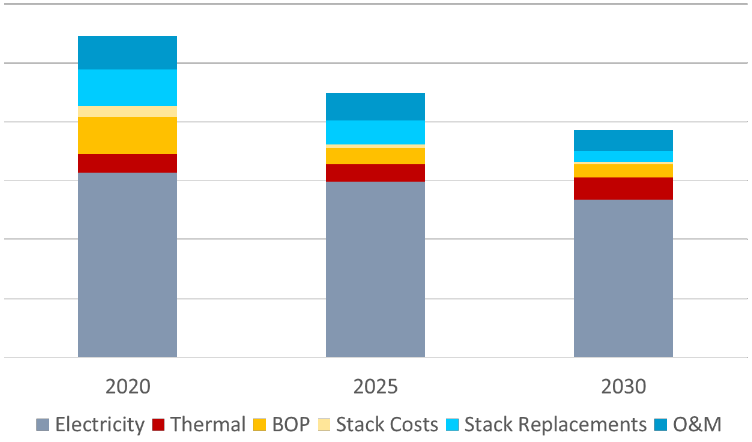
- **Durability.** Failure mechanisms include:
  - cell delamination
  - microstructure coarsening
  - decreased porosity, and catalyst poisoning
- **Performance stability.**
  - Minimize degradation rate
  - Maintain current density, while holding thermoneutral voltage; implies reducing ASA
- If durability could be improved without compromising performance, achieving the $2/kg target would be achievable



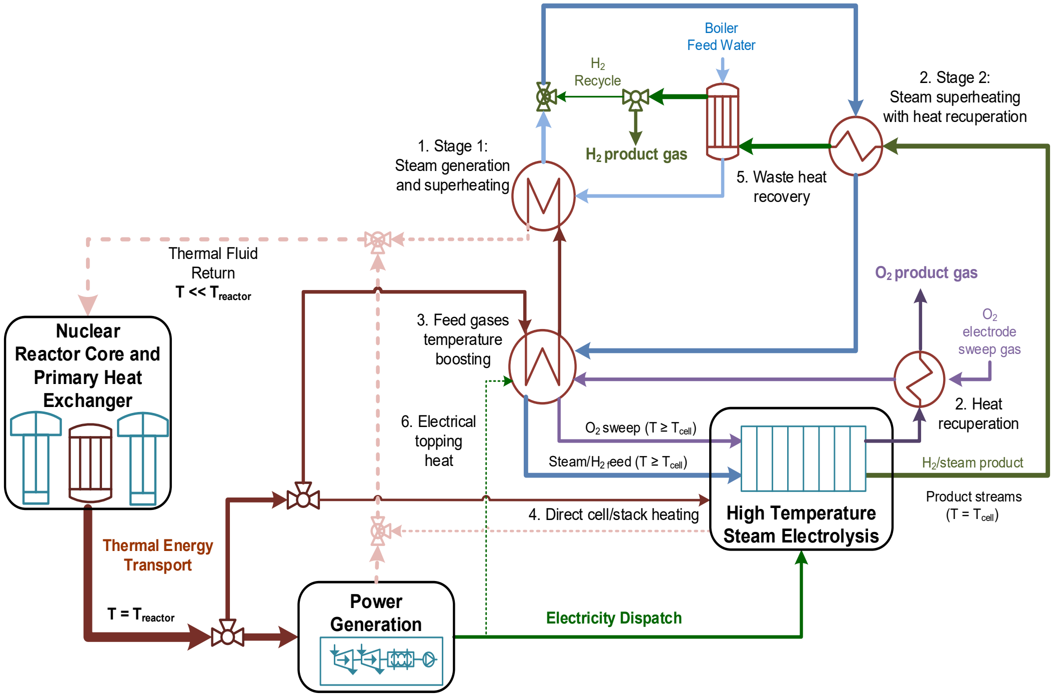
Typical components in an electrode-supported oxygen ion conducting SOEC

(Commence with a standard cell format; ceramic stoichiometries and thicknesses)

HTE Performance & System Interactions



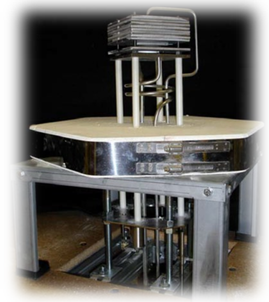
- System Interactions:
  - Steam purity
  - Hydrogen recycle
  - Steam and sweep gas volumetric flows and preheating
  - Oxygen electrode sweep gas choice
  - Materials fugitive contaminants



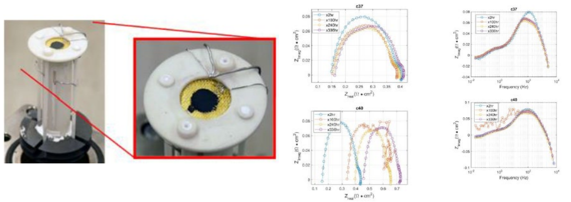
Typical integration with a thermo-electrical power source

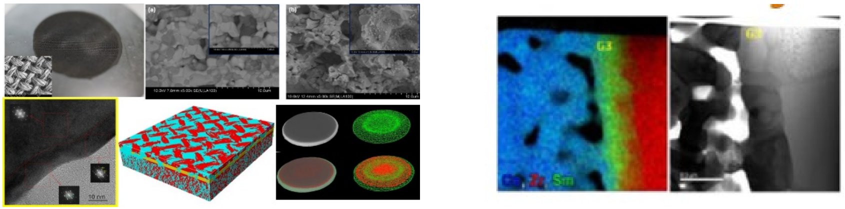
HTE H2NEW Strategy

- Cell testing to identify failure mechanisms
  - Accelerated stress testing to accurately simulate long-term degradation over time-frames compatible with program duration
  - Standardized cells: known compositions, scalable from button-, to large-area planar
  - Experimental replication to ensure representative phenomena
- State-of-the-art characterization: post-mortem ex situ, in operando in situ. Leverage user facilities
- Multiscale modeling, mechanisms and rates, enabling
  - rationalization of degradation phenomena
  - prediction of long-term degradation behavior
- End objective: Extend durability by mitigating degradation through modifications to
  - cell architecture
  - operating protocols

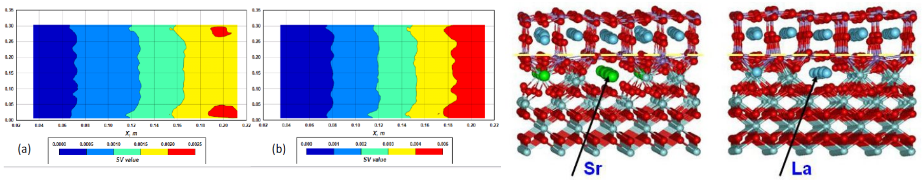


High through-put button cell and integrated cell testing





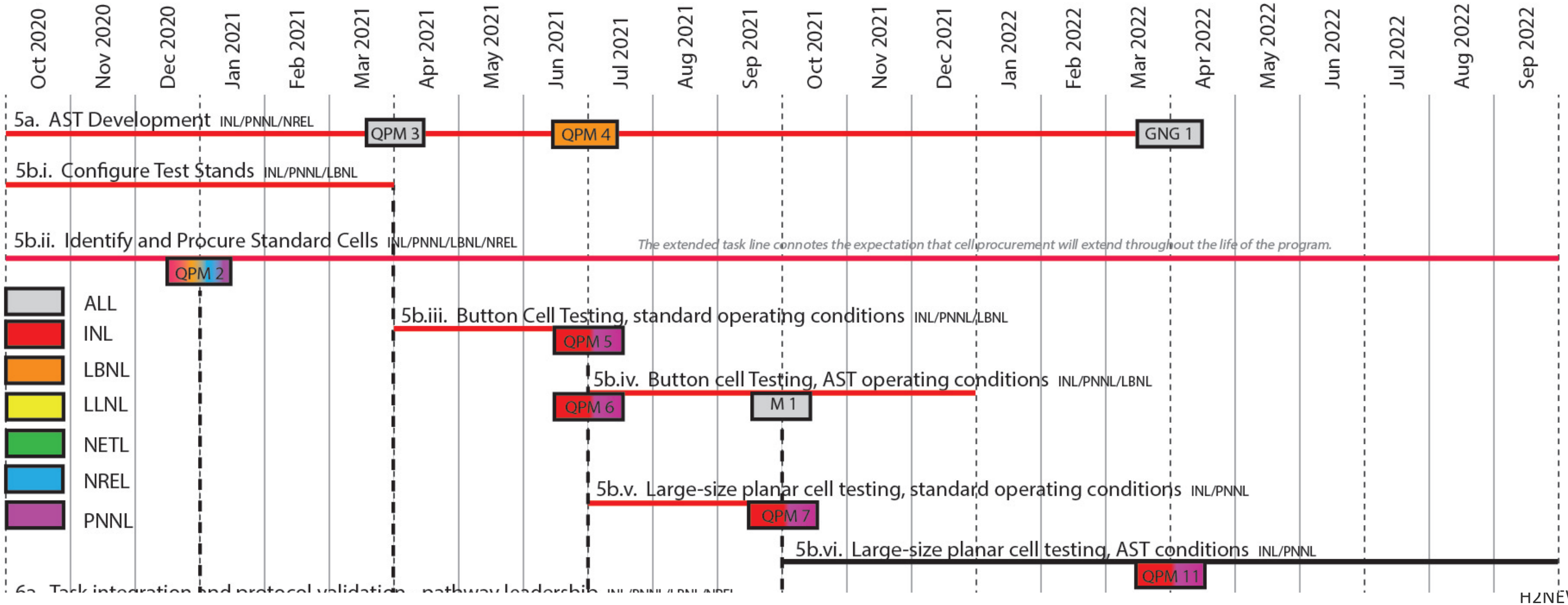
STEM, Dynamic TEM, FIB-TEM, In-Operando XRD



Molecular dynamics and Whole-cell modeling

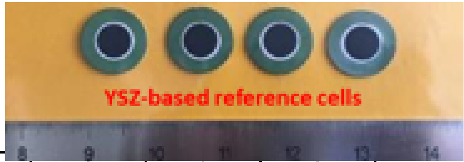
Task 5. Durability and Accelerated Stress Testing Development and Validation

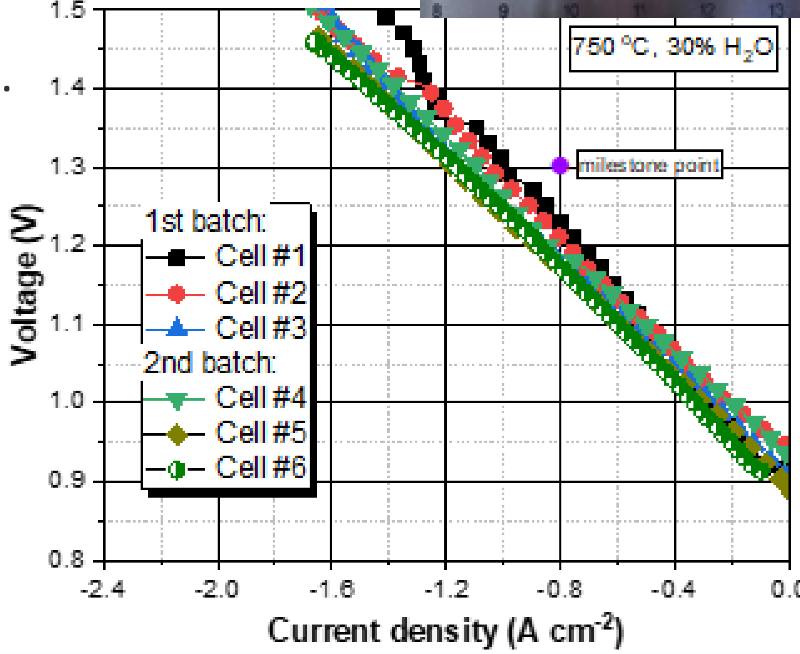
- Achieve reproducible performance for current o-SOEC devices
  - accelerated stress experiments to simulate degradation over long periods of time.



Leveraging HTE accomplishments from HydroGEN 1.0

- **Demonstrated quality control of Roll-to-Roll cell fabrication process (5 layers in cell):**
  - reproducible phase purity, structure, and SOEC performance of YSZ-based cells.
- **Demonstrated metal-supported oxygen-conducting solid oxide electrolysis cells (o-SOEC) with dramatically improved stability:**
  - operated for 1000h, with average 13%/kh degradation.
  - highlighted in landmark first review paper (LBNL).





HTE State-of-the-Art

Existing Systems

- **1.28V @ 1A/cm^2**
- **Degradation rate < 1 mV/khr**
- **12k – 20k laboratory systems**
- **Niche applications**
  - Hydrogen for Power Plants turbine/generator cooling
- **$4.2/kg H_2 production***

Future Systems

- **1.28V @ $\geq$ 1.5A/cm^2**
- **Degradation rate < 1 mV/khr**
- **$\geq$ 60k hours commercial systems**
- **Nuclear, solar and industry heat integration**
  - Grid integrated applications
  - Steel & Synfuels production
- **$1.5/kg H_2 production***

* Assumes availability of low-cost electricity (e.g., ≤3₵/kWh).

H2NEW Consortium: H2 from the Next-generation of Electrolyzers of Water

High Temperature Electrolysis Task

A comprehensive, concerted effort focused on overcoming technical barriers to enable affordable, reliable & efficient electrolyzers to achieve <$2/kg H_2

- Launching in Q1 FY21
- Both low- and high-temperature electrolyzers
- $50M over 5 years

National Lab Consortium Team

NREL – National Renewable Energy Laboratory

INL – Idaho National Laboratory

Pacific Northwest National Laboratory

Berkeley Lab

Lawrence Livermore National Laboratory

NETL – National Energy Technology Laboratory

Los Alamos National Laboratory

Oak Ridge National Laboratory

Argonne National Laboratory

Bryan Pivovar, H2NEW Director LTE Lead

Richard Boardman, HTE Lead

Close cooperation with the Hydrogen and Fuel Cell Technology Office (EERE-HFTO)

- Sunita Satyapal, Director, HFTO
- Dave Peterson, HFTO lead for H2NEW

H2NEW Consortium: H2 from the Next-generation of Electrolyzers of Water

Electrolyzer Stack Goals by 2025		
	LTE PEM	**HTE**
Capital Cost	**$100/kW**	**$100/kW**
Electrical Efficiency (LHV)	**70% at 3 A/cm^2**	**98% at 1.5 A/cm^2**
Lifetime	**80,000 hr**	**60,000 hr**

- Objectives: improve cost, performance and durability.
- Low temperature and high temperature electrolysis both have relevance, H2NEW is 75% LTE due to higher TRL and intermittency
- But, HTE has thermodynamic and kinetic advantages. TRL is increasing, including mitigation of intermittency issues
- Of the stack goals presented, lifetime (more specifically, performance degradation under relevant operating conditions) is the biggest challenge for both LTE and HTE systems.

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