U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

H_2 Technologies Overview

Dr. Ned Stetson, HFTO – Hydrogen Technologies Program Manager

2022 Annual Merit Review and Peer Evaluation Meeting

June 6, 2022 – Washington, DC

The Hydrogen Technologies Team

Technology Managers


Dave Peterson


Katie Randolph


Neha Rustagi


Zeric Hulvey


James Vickers


Will Gibbons


Mark Richards


Marika Wieliczko

Support Contractors


Kim Cierpik-Gold


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Cassie Osvatics


Nikkia McDonald

ORISE Fellows


McKenzie Hubert

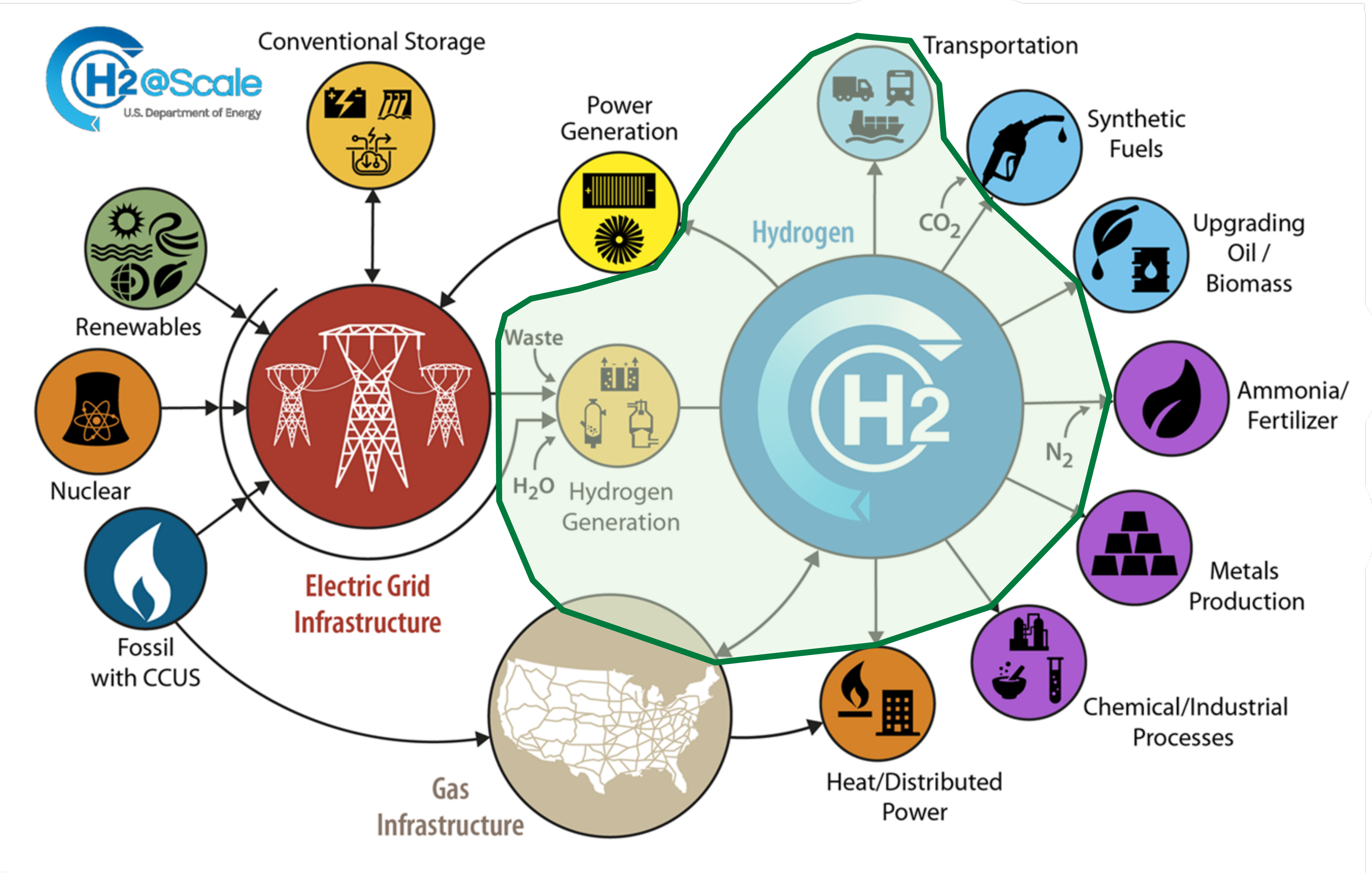

Anne Marie Esposito


Angela Macedo Andrade

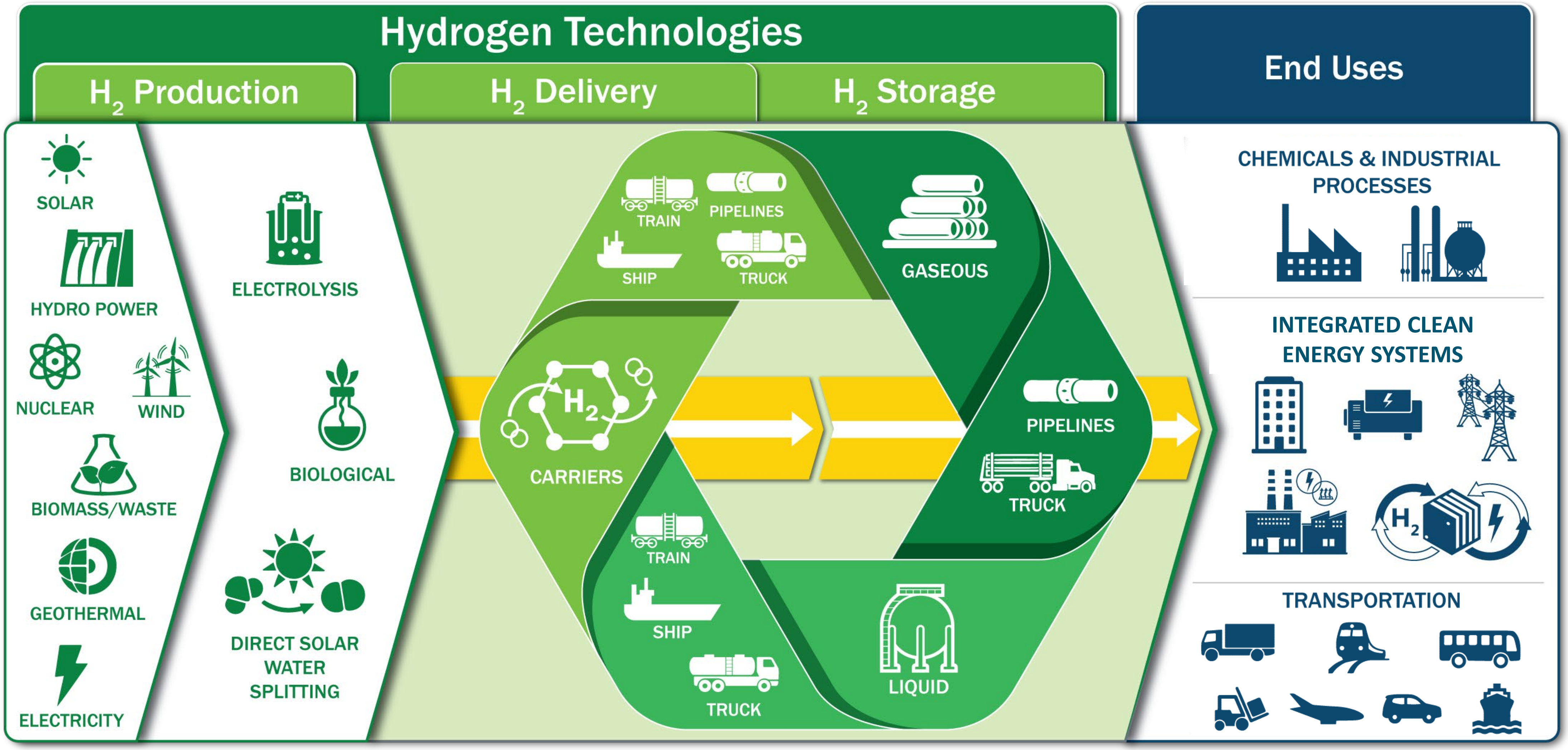

Asha-Dee Celestine


Martin Sulic

Hydrogen Technologies and H2@Scale

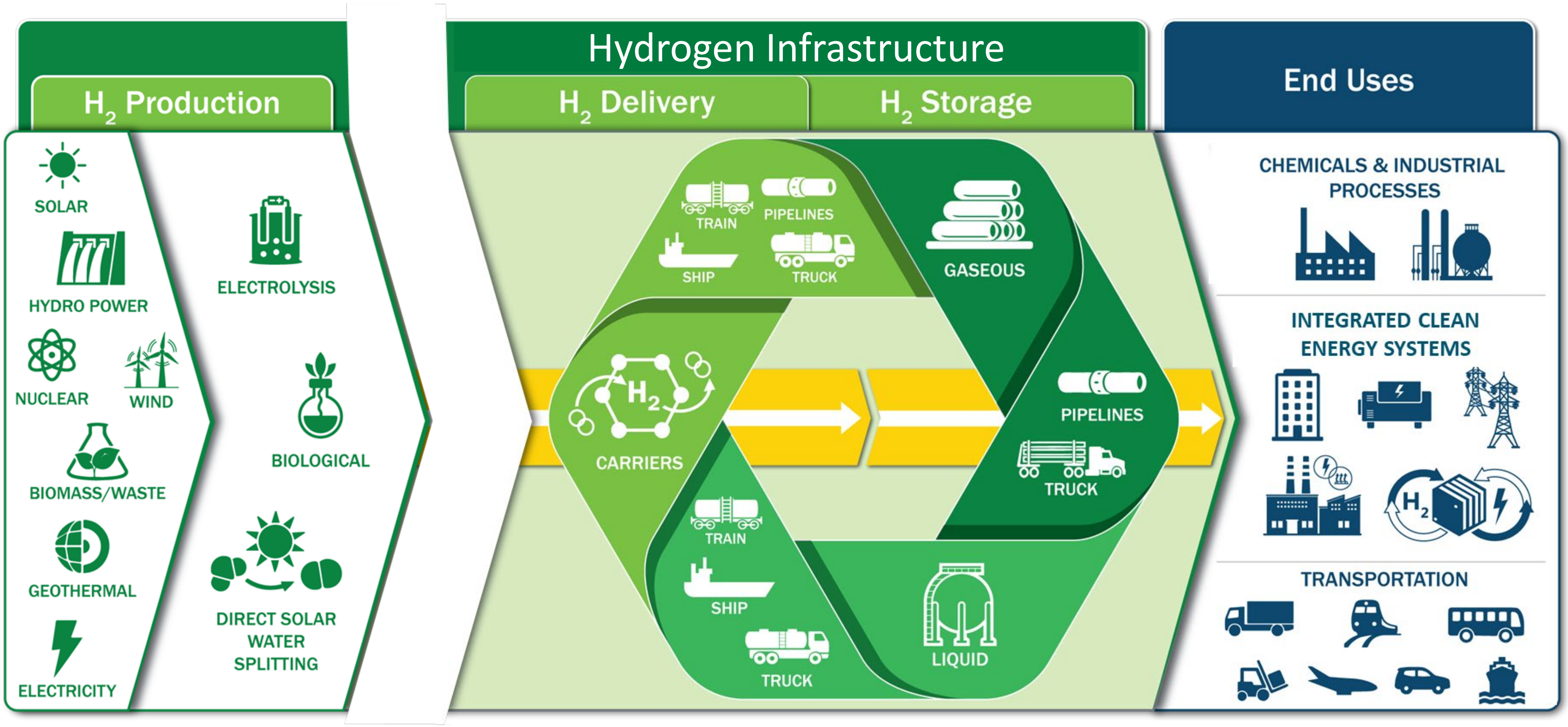


Hydrogen Technologies Program



From producing hydrogen molecules through dispensing to end-use applications

Hydrogen Technologies: Production & Infrastructure



From producing hydrogen molecules through dispensing to end-use applications

Hydrogen Production

Oral Project Presentations:

Wednesday, June 8, 11:00 AM – 3:00 PM

ENERGY earthshots
U.S. DEPARTMENT OF ENERGY

Hydrogen

Hydrogen Energy Earthshot

“Hydrogen Shot”

“1 1 1”
$1 for 1 kg clean hydrogen in 1 decade

Launched June 7, 2021
Summit Aug 31-Sept 1, 2021

Bipartisan Infrastructure Law - Hydrogen Highlights

- **Includes $9.5B for clean hydrogen:**
  - **$1B for electrolysis research, development and demonstration**
  - **$500M for clean hydrogen technology manufacturing and recycling R&D**
  - $8B for at least four regional clean hydrogen hubs

President Biden Signs the Bipartisan Infrastructure Bill into law on November 15, 2021. Photo Credit: Kenny Holston/Getty Images

- **Aligns with Hydrogen Shot priorities by directing work to reduce the cost of clean hydrogen to $2 per kilogram by 2026**
- **Calls for developing a National Clean Hydrogen Standard**
- **Requires developing a National Hydrogen Strategy and Roadmap**

Clean Hydrogen Electrolysis Program: BIL Sec. 40314 (EPACT Sec. 816)

$1,000,000,000 over 5 years (fiscal years 2022 through 2026)

Goal:	Reduce and validate the cost of hydrogen produced using electrolyzers* to **less than $2 per kilogram** of clean hydrogen by 2026
Program Description:	Establish a **research**, **development**, **demonstration**, **commercialization**, and **deployment** program for purposes of commercialization to **improve the efficiency**, **increase the durability**, and **reduce the cost** of producing clean hydrogen using electrolyzers.

*The term 'electrolyzer' means a system that produces hydrogen using electrolysis. The term 'electrolysis' means a process that uses electricity to split water into hydrogen and oxygen.

Focus Areas called for within the BIL Clean H_2 Electrolysis Program

Electrolyzer Technologies

Low-temperature electrolyzers
- -Liquid alkaline
- -Proton exchange membrane
- -Alkaline exchange membrane

High-temperature electrolyzers
- -Oxide-ion conducting
- -Proton conducting

Reversible fuel cells

Other advanced electrolyzers

Specific Components

Electrocatalysts/electrodes (including minimizing PGM use)

Membranes/separator materials

Porous transport layers

Bipolar plates

Component design

Material integration

Integration with…

Compression /drying technologies

Storage

Transportation / stationary systems

Impure water sources

Renewable or nuclear power

Distributed and bulk-power systems

Manufacturing

Improve component design and material integration…to allow for scale-up and domestic manufacturing of electrolyzers at a high volume.

Demonstration Projects

Validate information on the cost, efficiency, durability, and feasibility of commercial electrolyzer technologies through demonstrations of integrated energy systems.

Stakeholder Engagement for Program Planning

- Recent workshops and experts' meetings
  - Power and Control Electronics for Hydrogen Technologies – Dec. 2-3, 2021
  - Advanced Liquid Alkaline Water Electrolysis - January 26-27, 2022
  - Bulk Storage of Gaseous Hydrogen – February 10-11, 2022
  - Liquid Hydrogen Technologies – February 22-23, 2022
  - High-Temperature Electrolyzer Manufacturing - March 8-9, 2022
  - Advanced Materials for PEM Electrolyzers – March 30-31, 2022
  - Clean Hydrogen Manufacturing Automation and Recycling – May 24-26, 2022
- Webinar - February 24, 2022
- Request for Information on Clean Hydrogen Manufacturing, Recycling, and Electrolysis Programs – Closed March 29th
- Listening sessions with industry stakeholders
- Electrolyzer CEO Roundtable with EERE

Extensive stakeholder engagement (7 workshops/experts' meetings, webinar, & RFI) have helped inform program strategy and RD&D priorities

Request for Information on BIL Sections 815 & 816

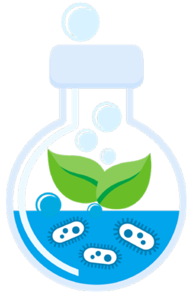
DE-FOA-0002698 RFI on Clean Hydrogen Manufacturing, Recycling, and Electrolysis

- Opportunity:
  - released February 15th, 2022
  - closed March 29th, 2022
- Input received from more than 120 stakeholder entities, and included more than 1200 pages

Questions for Section 816, Clean Hydrogen Electrolysis Program included:

- Innovations and metrics to measure progress for achieving $2/kg H_2 by 2026
- Key material, component, cell design and BOP improvements needed for volume manufacturing
- Potential benefits and demonstrations of modular electrolyzers for distributed energy systems
- Requirements and key attributes needed for hydrogen storage and infrastructure
- Barriers for scaling up domestic manufacturing of electrolyzer systems
- Objectives and scale required for meaningful electrolyzer system demonstrations
- Needs for national test facilities for electrolyzer stacks and systems
- Recommendations for incorporation of EJ40 and diversity, equity and inclusion provisions

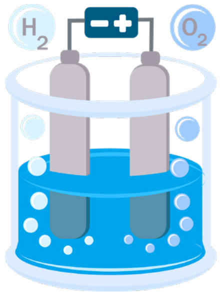
Hydrogen Production: Focused on Clean, Sustainable Pathways



Direct Solar Water Splitting
- Photoelectrochemical (PEC)
- Solar thermochemical (STCH)

Biological Pathways
- Fermentation
- Microbial electrochemical cells (MEC)
- Photobiological

Advanced Pathways – Core Program



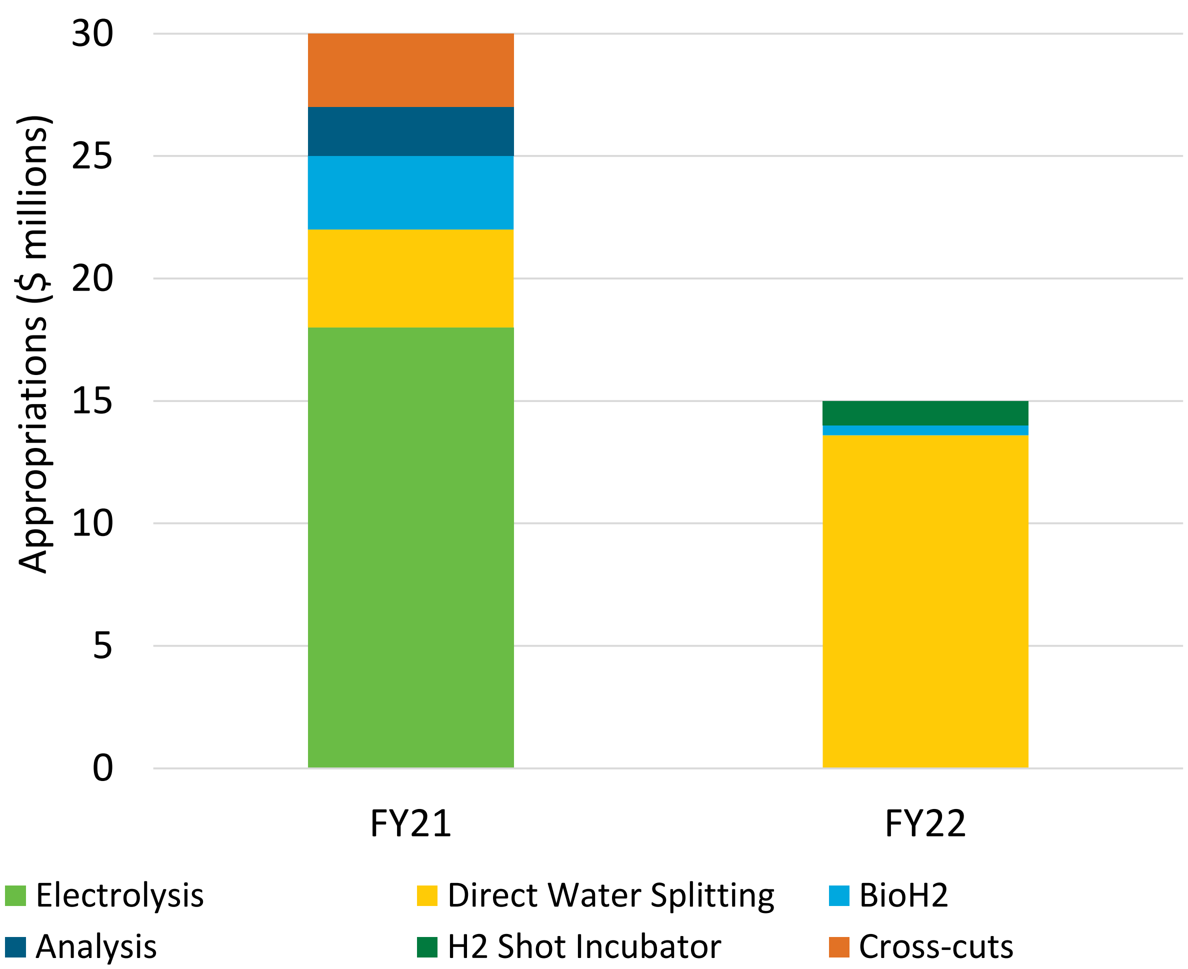
Water Electrolysis
- Liquid Alkaline (LA)
- Proton Exchange Membrane (PEM)
- Anion Exchange Membrane (AEM)
- Oxide-conducting Solid Oxide (O-SOEC)
- Proton-conducting Solid Oxide (P-SOEC)
- Novel – including Reversible Fuel Cells (RFC)

Electrolysis Pathways - BIL Sec. 816

Hydrogen Technologies – Production Funding

FY21 Appropriations
$30 million

FY22 Appropriations
$15 million



Program Direction

Hydrogen Production RD&D

- Direct Water Splitting, including
  - Photoelectrochemical
  - Solar Thermochemical
- BioH2
  - Fermentation
  - Microbial Electrochemical
- H_2 Shot Incubator Prize
- Hydrogen Production Cost Analysis

Starting in FY22, all Water Electrolysis activities planned to be carried out under the Bipartisan Infrastructure Law directed *Clean Hydrogen Electrolysis Program* with BIL funding

FY23 Appropriations Request
$15 million

Clean H_2 Electrolysis Program
$200 M/yr over 5 yrs

H_2 Shot Incubator Prize

https://www.herox.com/HydrogenShotPrize

American-Made Challenges

1,357 Share Follow (98)

Hydrogen Shot Incubator

Accelerating the development of unique and novel technologies that show potential to produce affordable clean hydrogen.

Energy, Environment & Resources | Government

Stage:
Follow the Challenge!

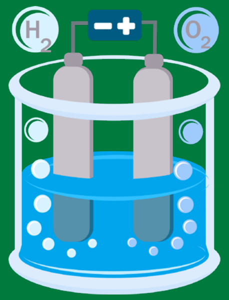
Prize:
$2.6 million Prize Pool

FOLLOW CHALLENGE

Overview | Guidelines | Timeline | Forum | Teams 98 | Resources | FAQ

Hydrogen Production

Electrolysis



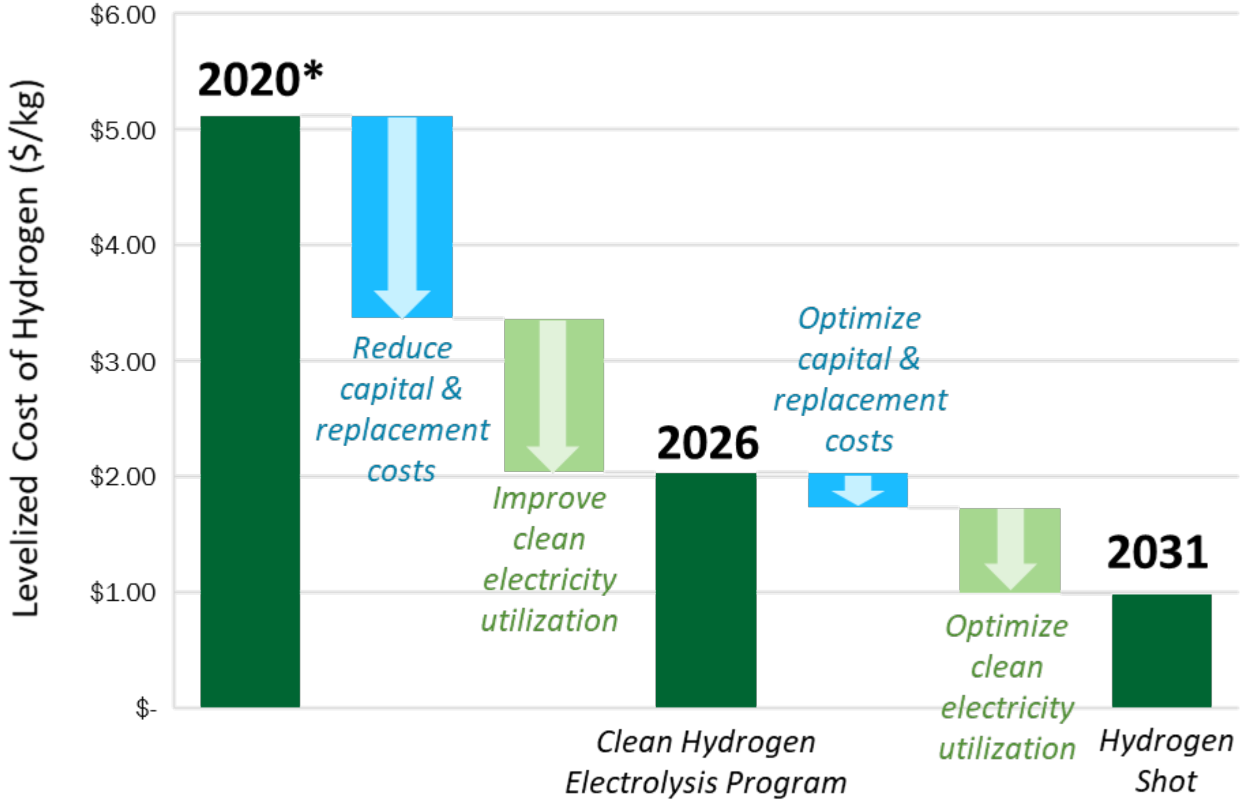
Pathways to Reduce the Cost of Electrolytic H_2

Key enablers for lower cost electrolytic H_2:

- Low-cost electricity
- **High electrical efficiency**
- **Low-cost capital expense**
- **Increased durability/lifetime**
- **Low-cost manufacturing processes**
- **Manufacturing of MW-scale electrolyzers**

Electrolyzer goals for 2026	Unit	PEM	SOEC
Higher electrical efficiency	**% (LHV)**	**≥ 70**	**≥ 98**
Lower stack costs	**$/kW**	**≤ 100**	**≤ 100**
Increased durability	**hours**	**80,000**	**60,000**
Lower system CAPEX	**$/kW**	**≤ 250**	**≤ 300**

Analysis efforts identify possible cost reduction strategies*



* DOE Hydrogen and Fuel Cells Program Record #20004, Sept 2020

Achieving economies-of-scale alone will <u>not</u> meet cost targets, we also need to develop next-generation, advanced technologies

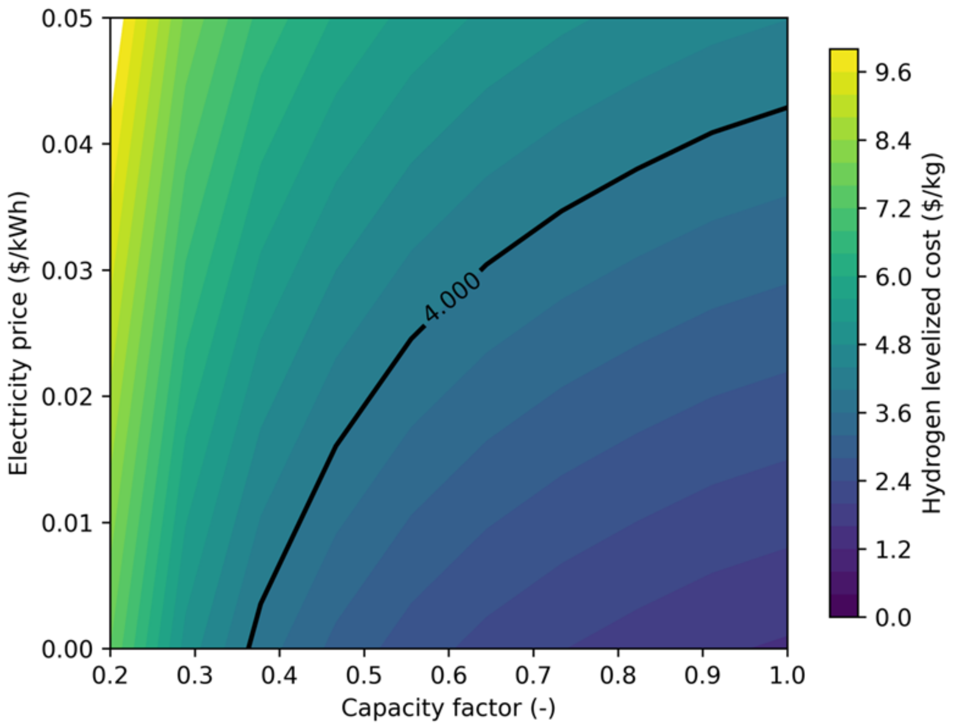
Updating H_2 Production Cost Record – Preliminary Results

Projected H_2 levelized cost produced with today's PEM technology *can be ≤$4/kg* when considering the range of reported renewable electricity power purchase agreement prices. [1]

Values used in H2A Techno-economic Analysis

H2A input	Units	Assumed value
Electrolyzer nameplate	MW	120
Stack capital cost	$/kW	450
Mechanical BOP capital cost	$/kW	550
Electrical BOP capital cost	$/kW	300
Stack installation factor	%	12
Mechanical BOP installation factor	%	0
Electrical BOP installation factor	%	12
Stack lifetime	Hours	40,000
Stack efficiency	kWh/kg H_2	51
BOP efficiency	kWh/kg H_2	4.2
Electricity price	$/kWh	Variable
Capacity factor	%	Variable

Contour plot of H_2 levelized cost at various combinations of capacity factor and electricity price. Black contour line indicates which combinations of these two variables meet $4/kg.



[1] Program Data Record 22002 - Hydrogen Production Cost with Current PEM Electrolyzer Technology – 2022, in review

Clean Hydrogen Electrolysis Development – Pre/Post BIL

HFTO Program

Advanced Manufacturing (TRL 6-7) – High-throughput manufacturing and assembly processes

Advanced Components (TRL 4-5) – Higher performance, durable components, such as membrane electrode assemblies, up through stacks

Advanced Materials (TRL 1-3) – Improved electrocatalyst, catalyst supports, electrolytes, membranes, etc.

Electrolysis Development under IIJA Clean H_2 Programs

System Demonstration and Deployment (TRL 7-9) – Pilot and commercial demonstrations of complete @scale systems coupled with infrastructure and use applications

Advanced Manufacturing (TRL 6-7) – High-throughput manufacturing and assembly processes

Advanced Systems (TRL 5-7) – Higher performance systems, with optimized balance of plant components

Advanced Components (TRL 4-5) – Higher performance, durable components, such as MEAs, up through stacks

Advanced Materials (TRL 1-3) – Improved electrocatalyst, catalyst supports, electrolytes, membranes, etc.

Recycling and Reuse

The Clean Hydrogen Programs within the Bipartisan Infrastructure Investment and Jobs Act allow for inclusion of the complete development and deployment lifecycle for electrolysis technologies

Clean Hydrogen Electrolysis RD&D

Electrolysis Development under IIJA Clean H_2 Programs

Industry-led Activities

System Demonstration and Deployment (TRL 7-9) – Pilot and commercial demonstrations of complete @scale systems coupled with infrastructure and use applications

Advanced Manufacturing (TRL 6-7) – High-throughput manufacturing and assembly processes

Advanced Systems (TRL 5-7) – Higher performance systems, with optimized balance of plant components

H2NEW Hydrogen from Next-generation Electrolyzers of Water
U.S. DEPARTMENT OF ENERGY

Advanced Components (TRL 4-5) – Higher performance, durable components, such as MEAs, up through stacks

ElectroCat Electrocatalysis Consortium
HydroGEN Advanced Water Splitting Materials

Advanced Materials (TRL 1-3) – Improved electrocatalyst, catalyst supports, electrolytes, membranes, etc.

Recycling and Reuse

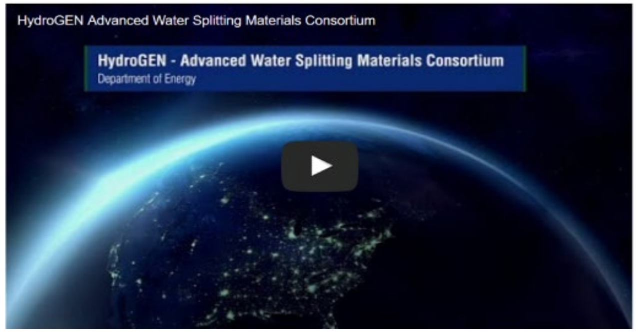
The BIL Clean Hydrogen Electrolysis Program leverages established R&D Consortia and Industry-led activities

HydroGEN Advanced Water Splitting Materials Consortium – P148

HydroGEN
Advanced Water Splitting Materials

Core National Lab Team

NREL Transforming ENERGY
BERKELEY LAB Bringing Science Solutions to the World
Sandia National Laboratories
INL Idaho National Laboratory
Lawrence Livermore National Laboratory

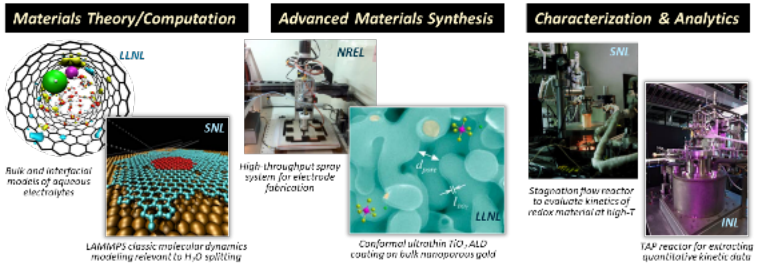


- **118 Publications, Impact factor* = 2.20**
  2,783 citations, 436 authors
- **4 community benchmarking workshops**
- **31 seedling projects supported**
- **46 capabilities utilized across 5 labs**
- **STEM Work Force Development**
- **Diverse leadership and community**

*Field-weighted citation impact (FWCI) indicates how the number of citations received by the Publication Set's publications compares with the average number of citations received by all other similar publications in Scopus.

Non-Disclosure Agreement (NDA)	Intellectual Property Management Plan (IPMP)	Materials Transfer Agreement (MTA)	Cooperative Research and Development Agreement (CRADA)
Information Disclosure	IP Protection	Freedom to Operate	Collaboration

https://www.h2awsm.org/working-with-hydrogen



HydroGEN is vastly collaborative, has produced many high value products, and is disseminating them to the R&D community.

HydroGEN – Key Accomplishments

HTE

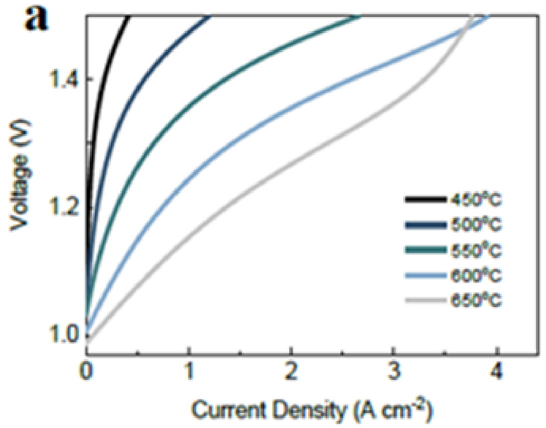
West Virginia University

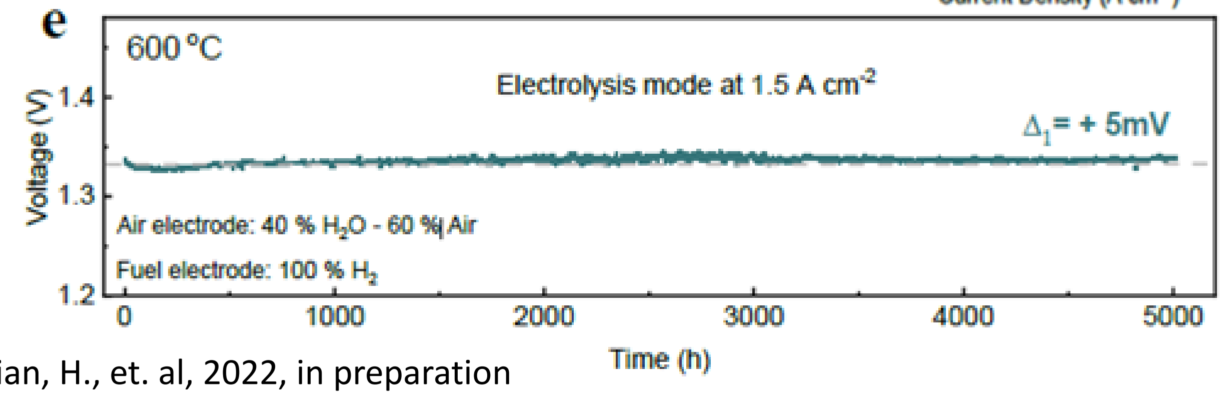
HydroGEN Advanced Water Splitting Materials

Intermediate Temperature P-SOEC with Improved Performance and Durability – P175

Objectives: Develop a P-SOEC with
- Current densities >1.0 A/cm^2 at 1.4 V/cell
- Degradation <10 mV/1000 hr at 600 °C

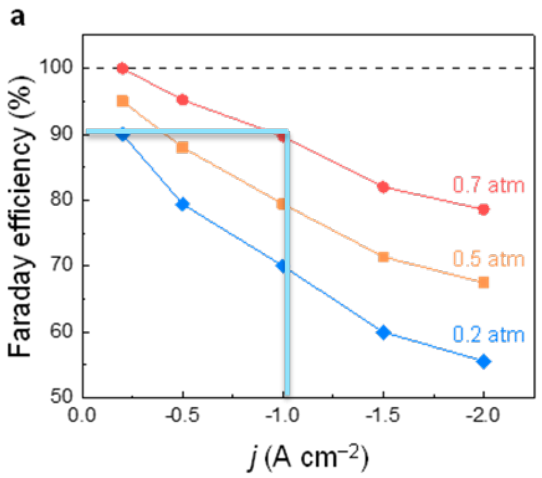
Recent Accomplishments:
- Demonstrated 1.46 A/cm^2 at 1.3V and 600 °C
- Demonstrated 1 mV/1000 hr degradation over 5000 hours

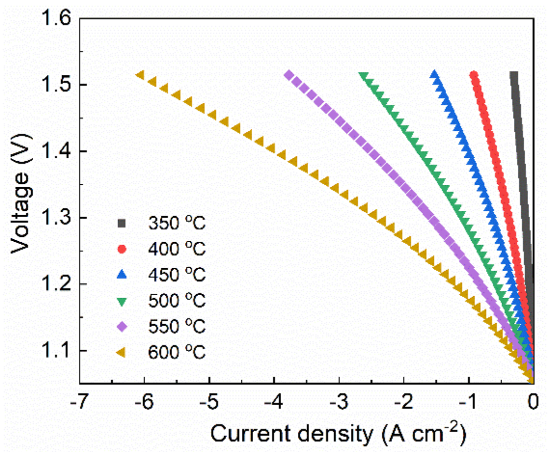




Tian, H., et. al, 2022, in preparation

Bian W, Ding D, et al. Nature, accepted





Improved the Faradaic Efficiency of a P-SOEC – P148

Objectives:
- Demonstrate > 90% FE at current densities >1.0 A/cm^2 at 600 °C and up to 70% steam

Recent Accomplishments:
- Demonstrated 90% Faradaic Efficiency at 1.0 A/cm^2 and 600 °C and 70% steam

HydroGEN – Key Accomplishments

LTE Chemours UNIVERSITY OF OREGON HydroGEN Advanced Water Splitting Materials

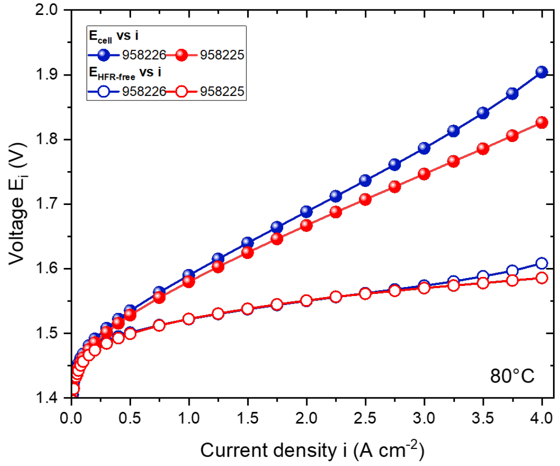
Thin, Low-Crossover Proton Exchange Membranes for Water Electrolyzers – P186

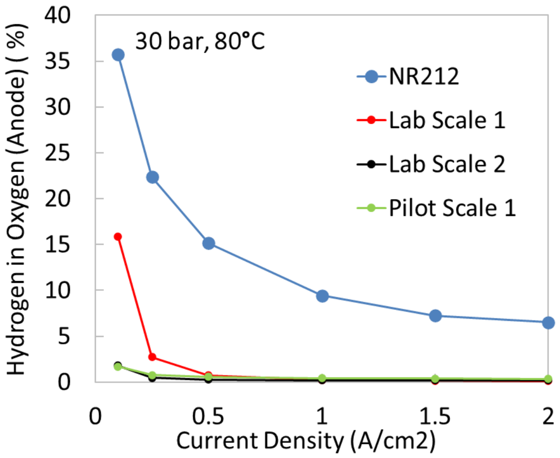
Objectives:

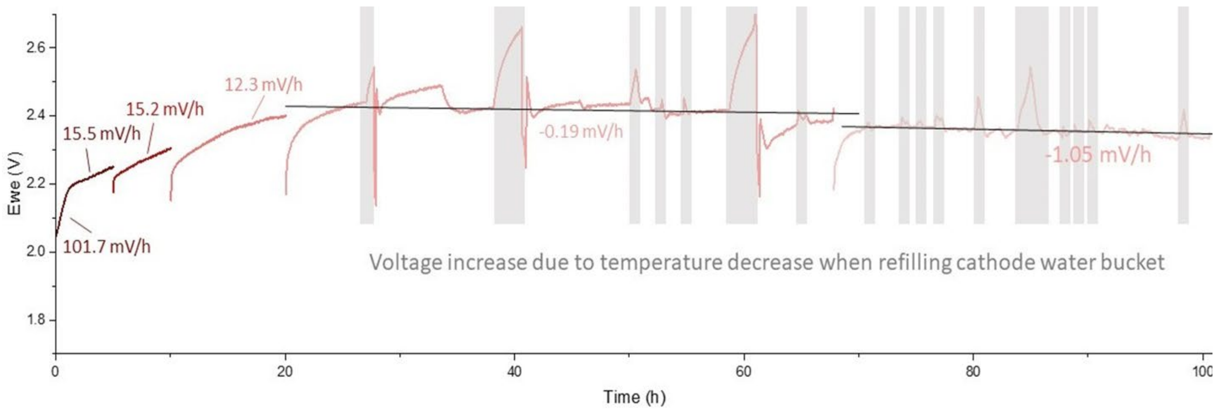
- Develop thin, durable proton exchange membranes with reinforcement, optimized for PEM water electrolyzer application
- Incorporate gas recombination catalyst to mitigate effect of gas crossover under pressure operation

Recent Accomplishments: (50 μm membranes)

- Reduced ohmic resistance, ~50 mV improvement at 3 A/cm^2
- Demonstrated up to 50x reduction in effective H_2 crossover at 80 °C & 30 bar p_{H2}







Pure H_2 Production through Precious-Metal-Free Membrane Electrolysis of Dirty Water – P187

Objectives:

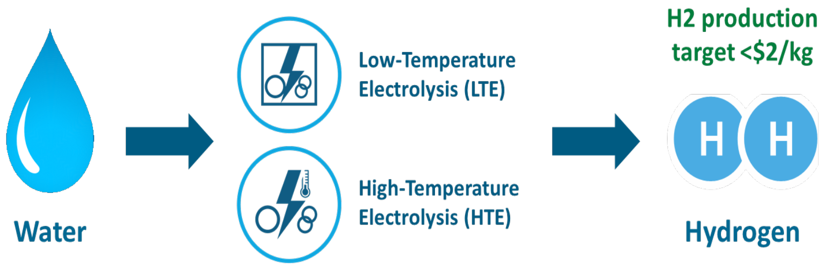
- Develop an understanding of degradation of alkaline and bipolar membrane electrolyzers in pure and dirty water and engineer impurity tolerant systems.

Recent Accomplishments:

- Demonstrated only ~200 mV increase in overpotential after 100 h of operation with tap water fed to anode
- Demonstrated a HfOx protective layer that prevents AEM ionomer oxidation and reduces degradation

H2NEW: H2 from the Next-generation of Electrolyzers of Water - P196

H2NEW
U.S. DEPARTMENT OF ENERGY



Electrolyzer technology focus areas:

- **Low-Temperature -**
  - PEM
  - Liquid Alkaline (*new expansion*)
- **High-temperature -**
  - O-SOEC

The emphasis is on addressing components, materials integration, and manufacturing R&D

Electrolyzer Stack Goals by 2026		
	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**

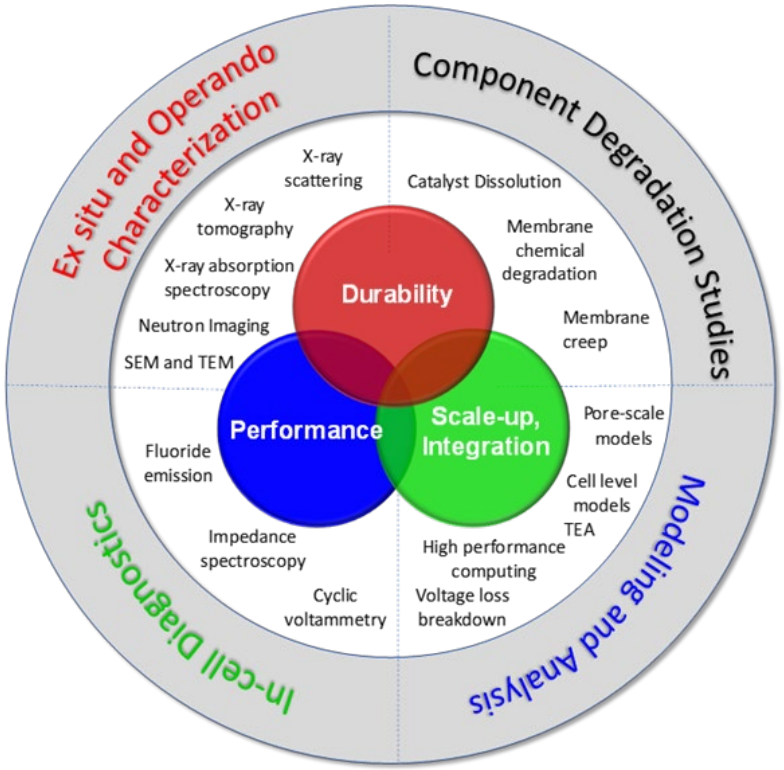
Consortium Team*

NREL National Renewable Energy Laboratory; INL Idaho National Laboratory; Pacific Northwest National Laboratory; Argonne National Laboratory; Oak Ridge National Laboratory; National Energy Technology Laboratory; Los Alamos National Laboratory; Berkeley Lab; Lawrence Livermore National Laboratory; NIST; UC Irvine; Carnegie Mellon University; Colorado School of Mines

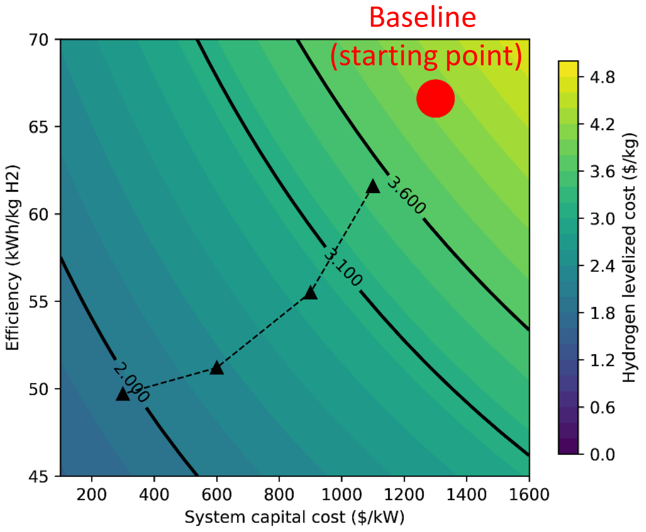
Durability/lifetime is initial focus:

- Develop fundamental knowledge of degradation mechanisms including under future operating modes
- Develop understanding to effectively accelerate degradation processes
- Develop and validate accelerated degradation processes to evaluate durability

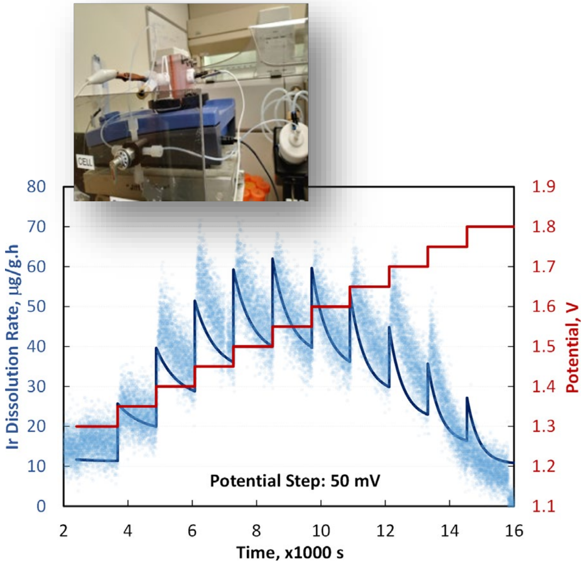
Combines world-class experimental, analytical, and modeling tools



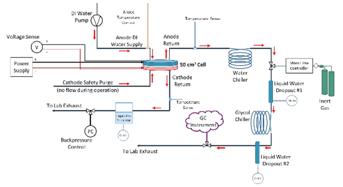
H2NEW – Key Accomplishments

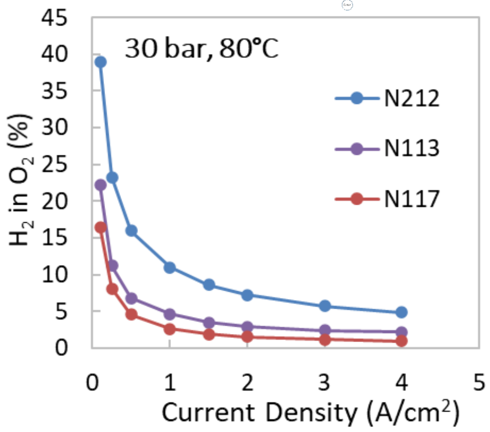


- Performed analysis to identify pathways to achieve BIL H_2 production cost targets of \$2/kg H_2 by 2026.

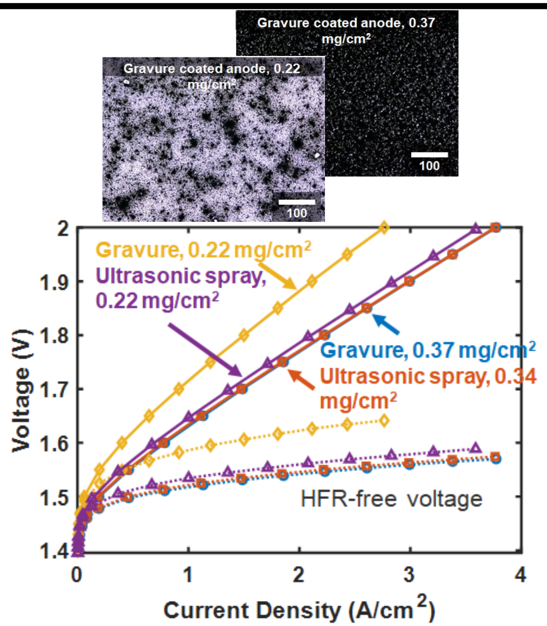


- Probed Ir dissolution through novel ICP-MS
- Coupled theoretical modeling to probe anode catalyst durability, including under dynamic operating conditions.





- Developed and deployed novel pressurized H_2 crossover system to measure safely combustible gas mixtures
- Gained insight on impact of operating and material parameters on H_2 crossover.



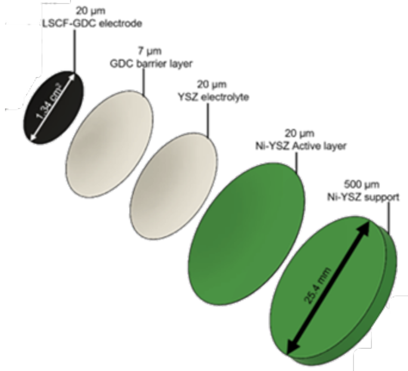
- Demonstrated application of roll-to-roll electrode deposition methods
- Achieved good electrode performance down to 0.4 mg Ir/cm^2
- Compared with lab-based deposition methods, and further optimize to achieve 0.2 mg Ir/cm^2.

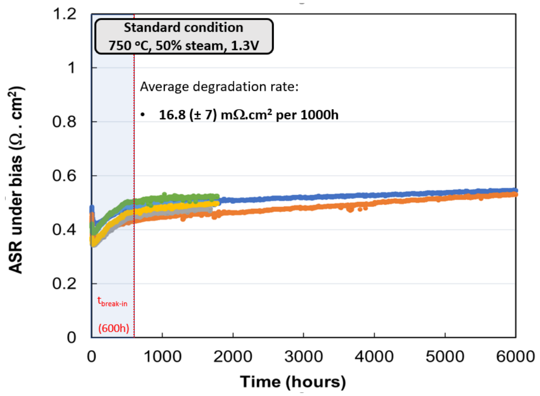
H2NEW – Key Accomplishments

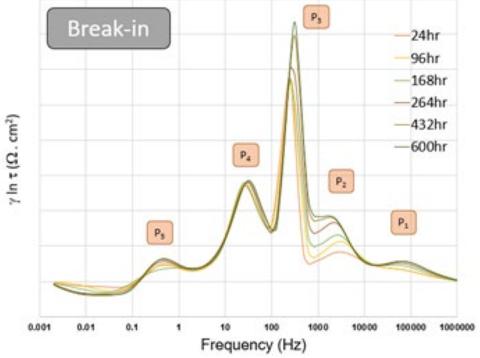
HTE

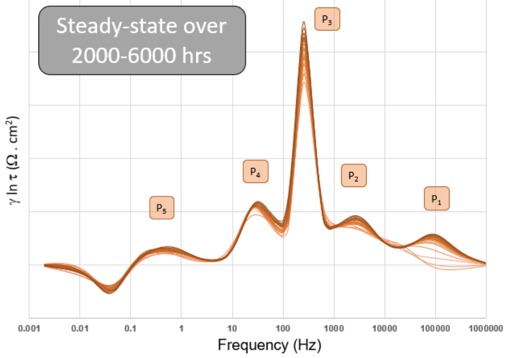
Cell Testing

- Established baseline performance of multiple button cells with SOA materials under standard operating conditions (750°C, in 50% steam at 1.3 Volt) over 1000-6000 hours and obtained reasonably reproducible cell performance data within the labs
- Observed 2 different degradation periods (fast break-in and slower long-term) with different degradation processes
- Examining higher temperature, voltage, and steam concentration as potential AST stressors and as a potential way to shorten break-in period



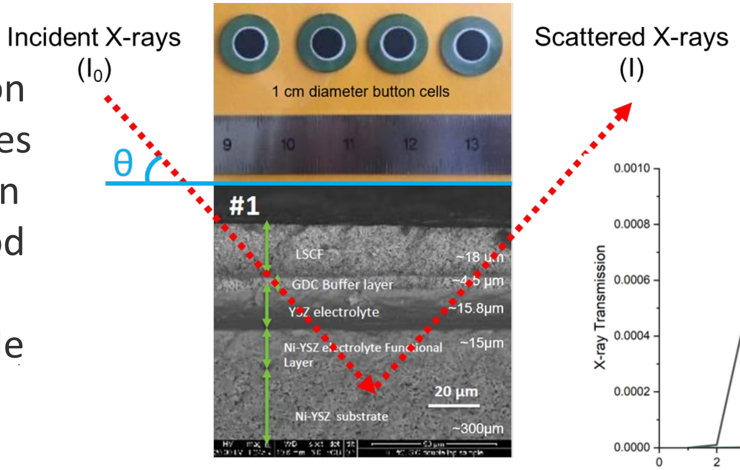


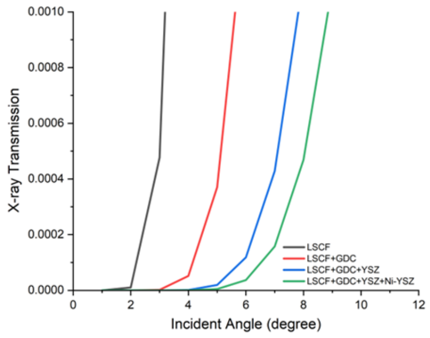




Cell Characterization

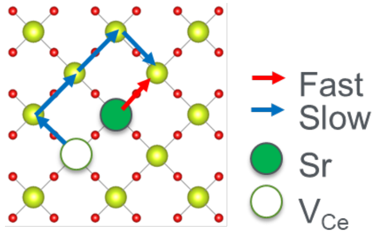
- Employed characterization over multiple length-scales
- Proved use of synchrotron x-rays as potential method for in-operando X-ray attenuation for nano-scale HTE cell depth profiling



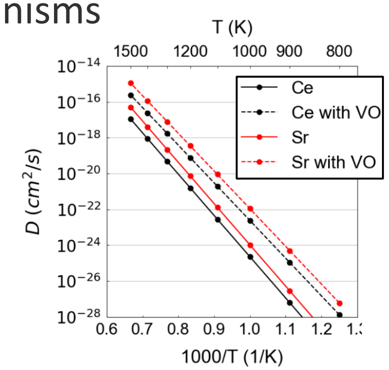


Multi-scale Degradation Modeling

- Formulated first physics-based models to interrogate two key degradation mechanisms



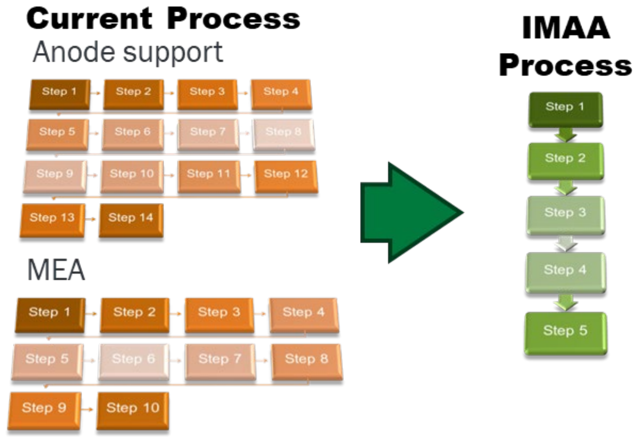
Atomistic: Sr diffusion through GDC interlayer



Enabling GW-scale Manufacturing Processes

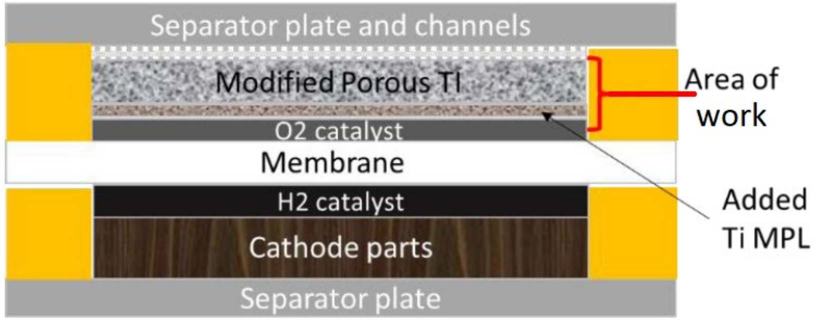
Integrated Membrane Anode Assembly & Scale-up – P199

- Developing a single-piece Integrated Membrane Anode Assembly. (IMAA) for reducing the cost and manufacturing time of a PEM electrolyzer stack
- Targeting 10x reduction in production time, demonstrate an electrolyzer with 1300 cm^2 active area and ≤ 2 μV/hr degradation

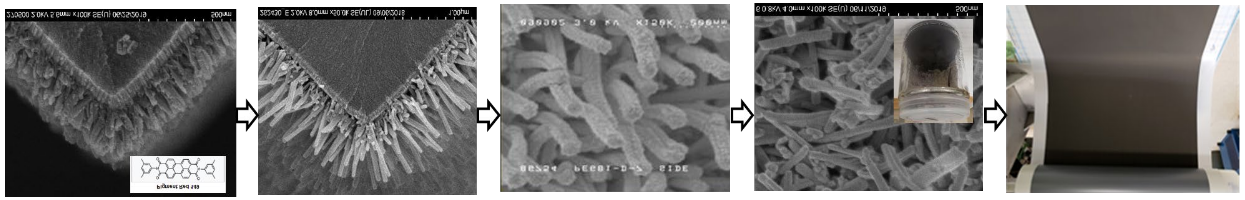


Enabling Low-Cost PEM Electrolysis at Scale – P198

- Develop an optimized low-cost porous transport layer for MEA integration and volume manufacture
- Successfully fabricated PTL/MPL samples and demonstrated 1000 hrs of stable operation



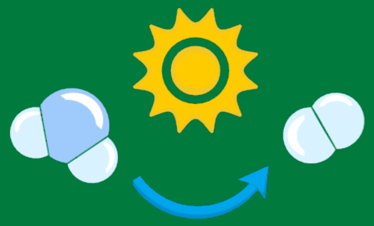
1. Precursor Deposition 1.5 GW/year
2. Support Growth > 3.75GW/year
3. Catalyst Deposition 1.5GW/year
4. Catalyst Powder > 3.75GW/year
5. Electrode Coating > 3.75GW/year



Advanced Manufacturing Processes for GW-Scale PEM Electrolyzers OER Catalysts and Electrodes – P197

- Develop OER catalyst, electrode, and thrifted catalyst coated membranes suitable for GW/year scale.
- 3 of 5 process steps demonstrated in excess of project target rate of 2 GW/year

Hydrogen Production
Advanced Pathways

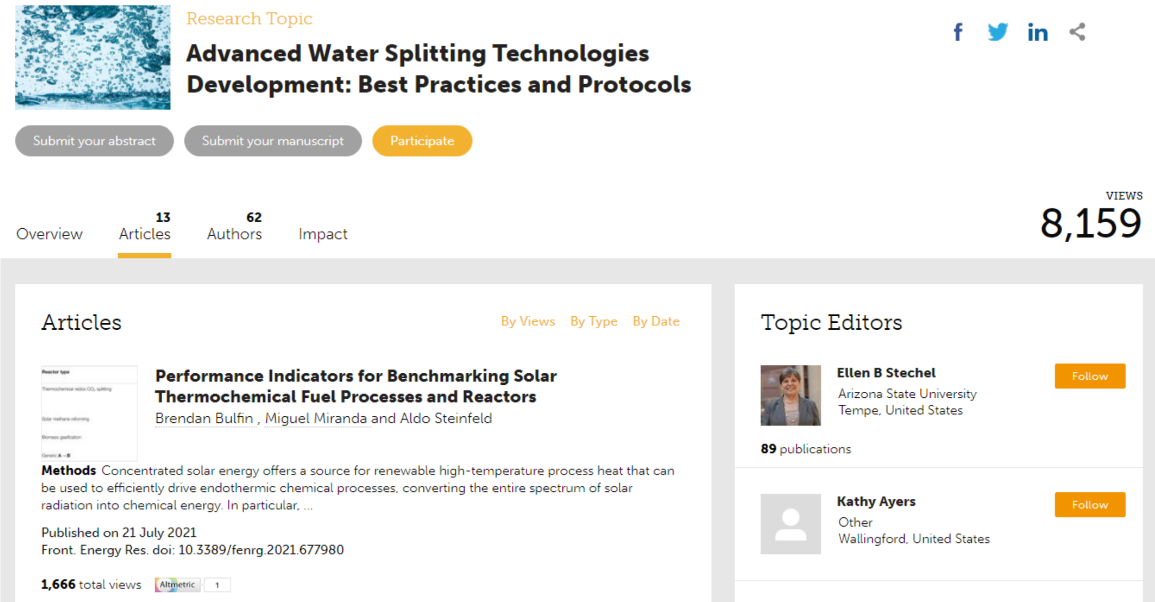


Benchmarking and Protocol Development for AWS Technologies

Objective:

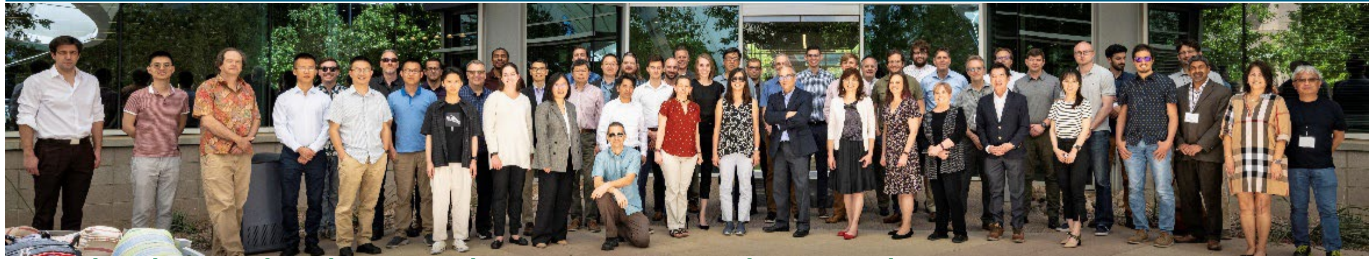
- ***Develop best practices in materials characterization and benchmarking - critical to accelerate materials discovery, development, validation and adoption***

PIs: Kathy Ayers, Nel Hydrogen (LTE)
Ellen B. Stechel, ASU (STCH)
Olga Marina, PNNL (HTE)
CX Xiang, Caltech (PEC)
Consultants: Karl Gross, George Roberts

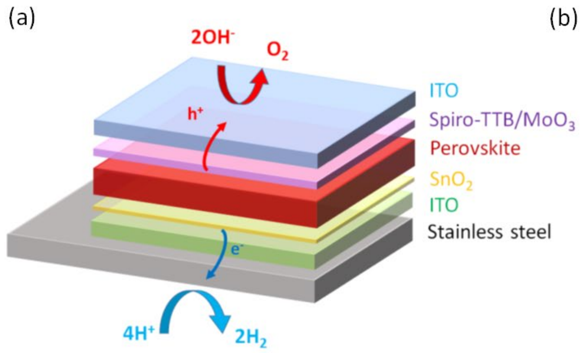


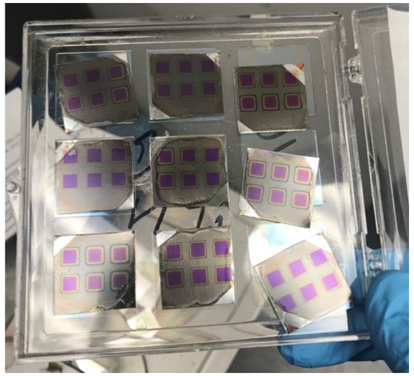
Accomplishments:

- 4 Annual AWS community-wide benchmarking workshops
- 36 test protocols drafted and reviewed
  - 13 test protocols submitted for publication in special issue of *Frontiers in Energy*
  - 11 test protocols reviewed and ready for public dissemination on HydroGEN Data Hub
- 40 additional protocols in drafting process
- Developed high-level roadmaps by AWS technology
- Disseminated information to AWS community through HydroGEN Data Hub, website, SharePoint site, email, quarterly newsletters, and workshops
- Participation from both HydroGEN and H2NEW consortia
- Strong national and international community engagement and participation



https://www.frontiersin.org/research-topics/16823/advanced-water-splitting-technologies-development-best-practices-and-protocols





Perovskite/Perovskite Tandem Photoelectrodes for Low-Cost Unassisted Water Splitting – P191

Objectives:

Develop monolithically integrated perovskite/perovskite tandem photoelectrodes to achieve:

- Low-cost (< $200/m^2),
- High efficiency (> 20% STH), and
- Enhanced stability (> 1,000 hrs)

Recent Accomplishments:

- Demonstrated 17% STH efficiency with a perovskite tandem cell
- Demonstrated 15% STH efficiency with a wired perovskite/perovskite tandem photocathodes

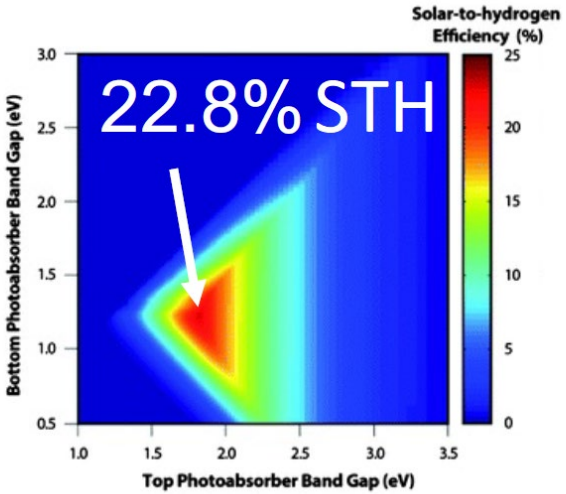
Highly Efficient Water Splitting Using 3D/2D Hydrophobic Perovskites with Corrosion Resistant Barriers - P193

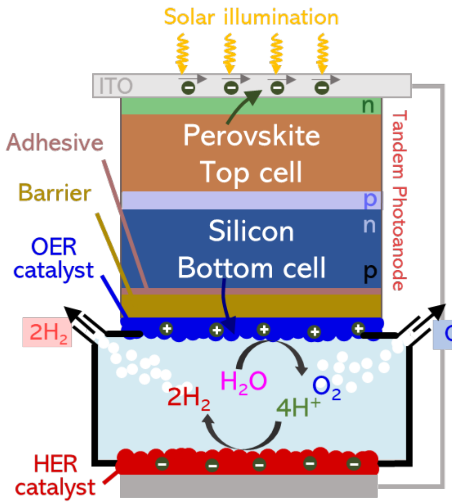
Objectives:

- To develop high-efficiency, stable perovskite-based PECs with barrier coatings and high-performance catalysts

Recent Accomplishments:

- Demonstrated 20% STH with a theoretical maximum 22.8%
- Demonstrated Pt/graphite barrier lifetime of >100 hours





High-Entropy Perovskites with Increased Reducibility and Stability for Thermochemical H_2 Generation – P194

Objectives:

- Use computational modeling to guide selection of promising high-entropy perovskite oxides (HEPOs) for STCH application
- Synthesize, characterize and evaluate promising materials

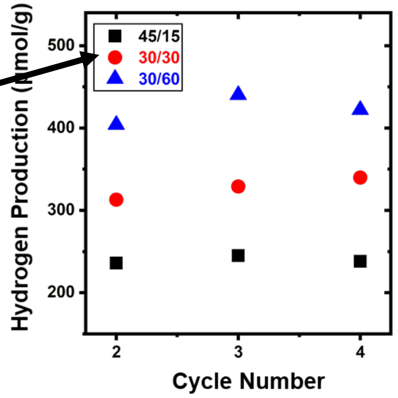
Recent Accomplishments:

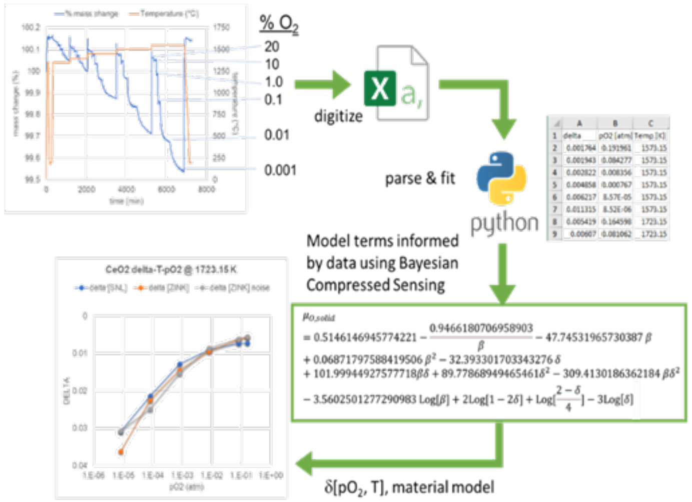
- Evaluated over 60k compositions computationally
- Synthesized and characterized 150 compositions
- Demonstrated > 400 µmol H_2/g production for $(La_{0.8}Sr_{0.2})(Mn_{0.2}Fe_{0.2}Co_{0.4}Al_{0.2})O_3$

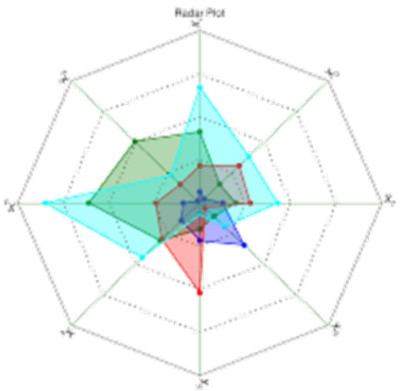
Reduction/Oxidation time (min)

Reduction: 1350ºC under N_2

Oxidation: 1100ºC under 40 vol% H_2O/N_2







Critically Assess STCH Pathway Viability – P148

Objectives:

- Develop software to formulate material thermodynamic model from TGA data
- Link to cycle efficiency model for automated parametric analysis and optimization

Recent Accomplishments:

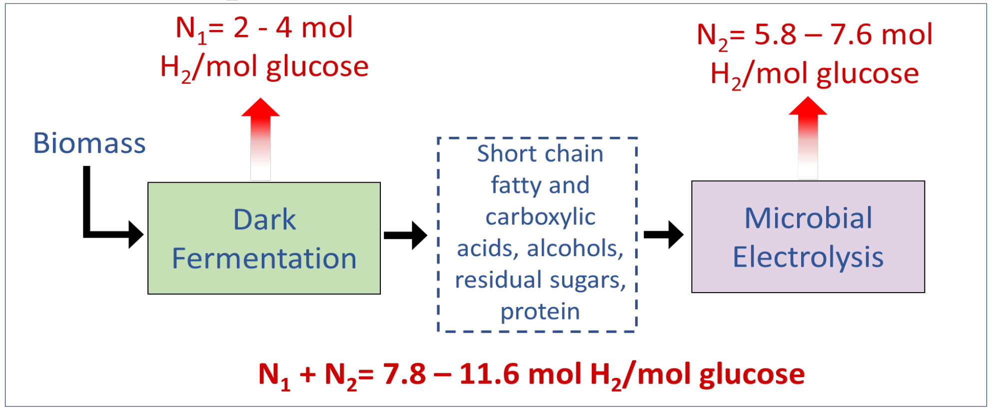
- Graphically depicted materials performance normalized to CeO_2 as radar plot
- Identifying key materials to benchmark

BioHydrogen ($BioH_2$) Consortium to Advance Fermentative H_2 Production – P179

BioH2 Consortium

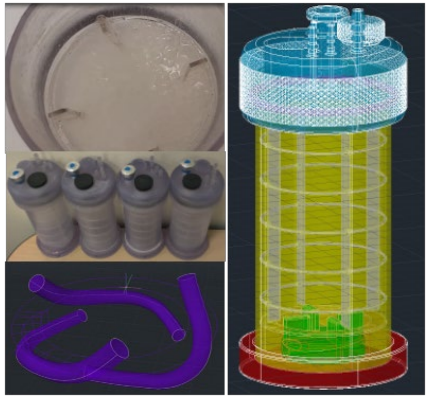
Objectives:

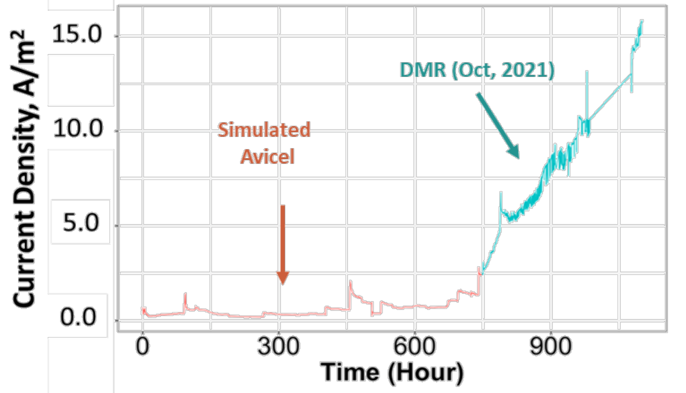
- Engineer *Clostridium thermocellum* strains to efficiently convert both C5 and C6 sugars
- Develop and characterize a high-intensity fermentation system using high solids loading
- Design and integrate a MEC process with dark fermentation to significantly increase H_2 production from biomass
- Carry out techno-economic and lifecycle analyses to evaluate viability



Recent Accomplishments:

- Demonstrated 86% utilization of arabinose (5 g/L), a C5 sugar
- Increased H_2 production by 67% for high loadings by using a fed-batch operation (7.78 L H_2/L for Avicel; 6.47 L H_2/L for DMR-pretreated biomass)
- Achieved ~4 L H_2/L reactor/day and ~10 A/m^2 with a MEC using Avicel
- Demonstrated 10 A/m^2 with a MEC using DMR fermentation effluent





Hydrogen Infrastructure: Delivery, Storage & Dispensing

Oral Project Presentations:

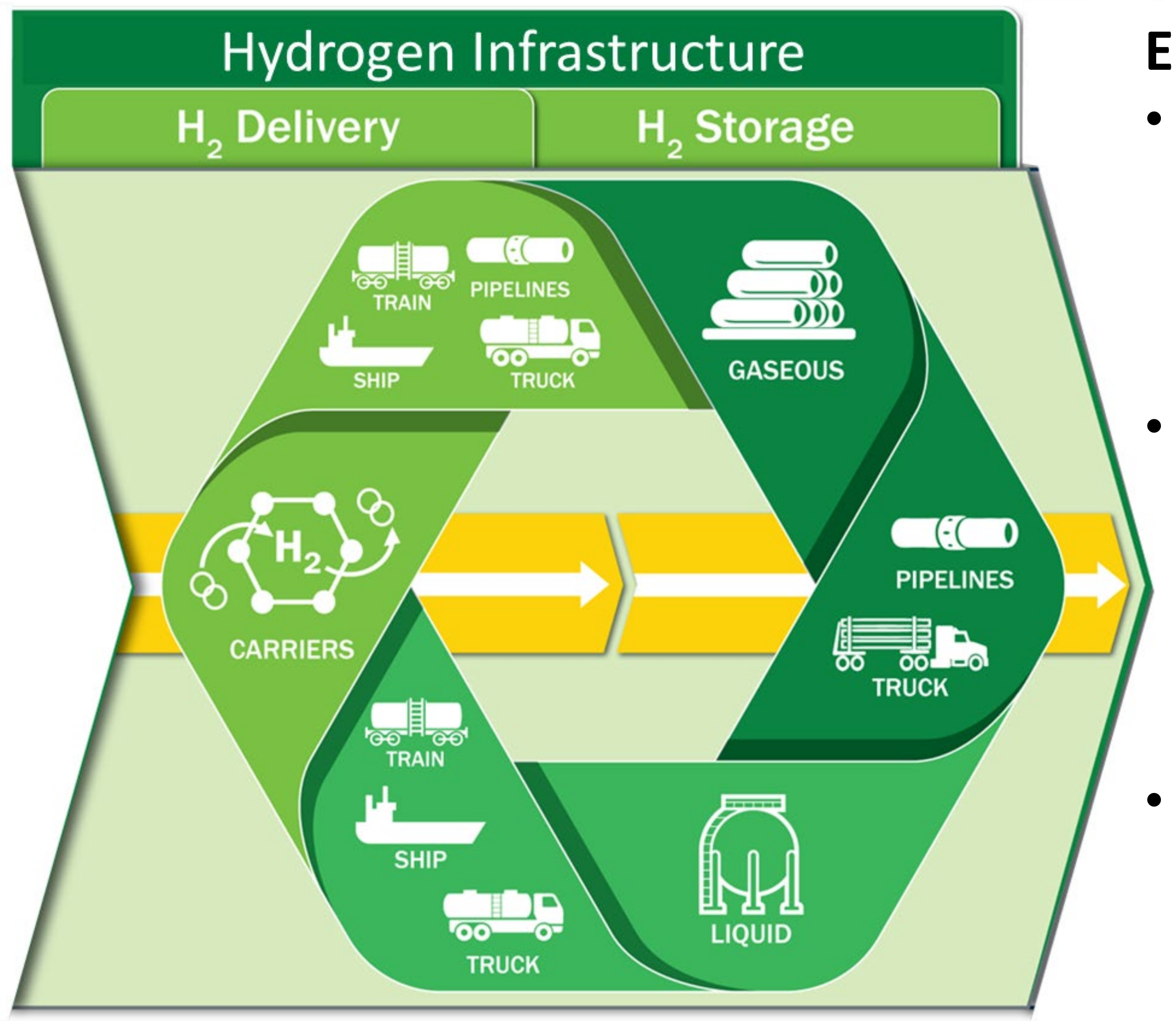
Tuesday, June 7, 1:00 PM – 5:00 PM

Wednesday, June 8, 3:30 PM – 5:30 PM

Hydrogen Infrastructure: Delivery, Storage and Dispensing

Delivery Pathways:

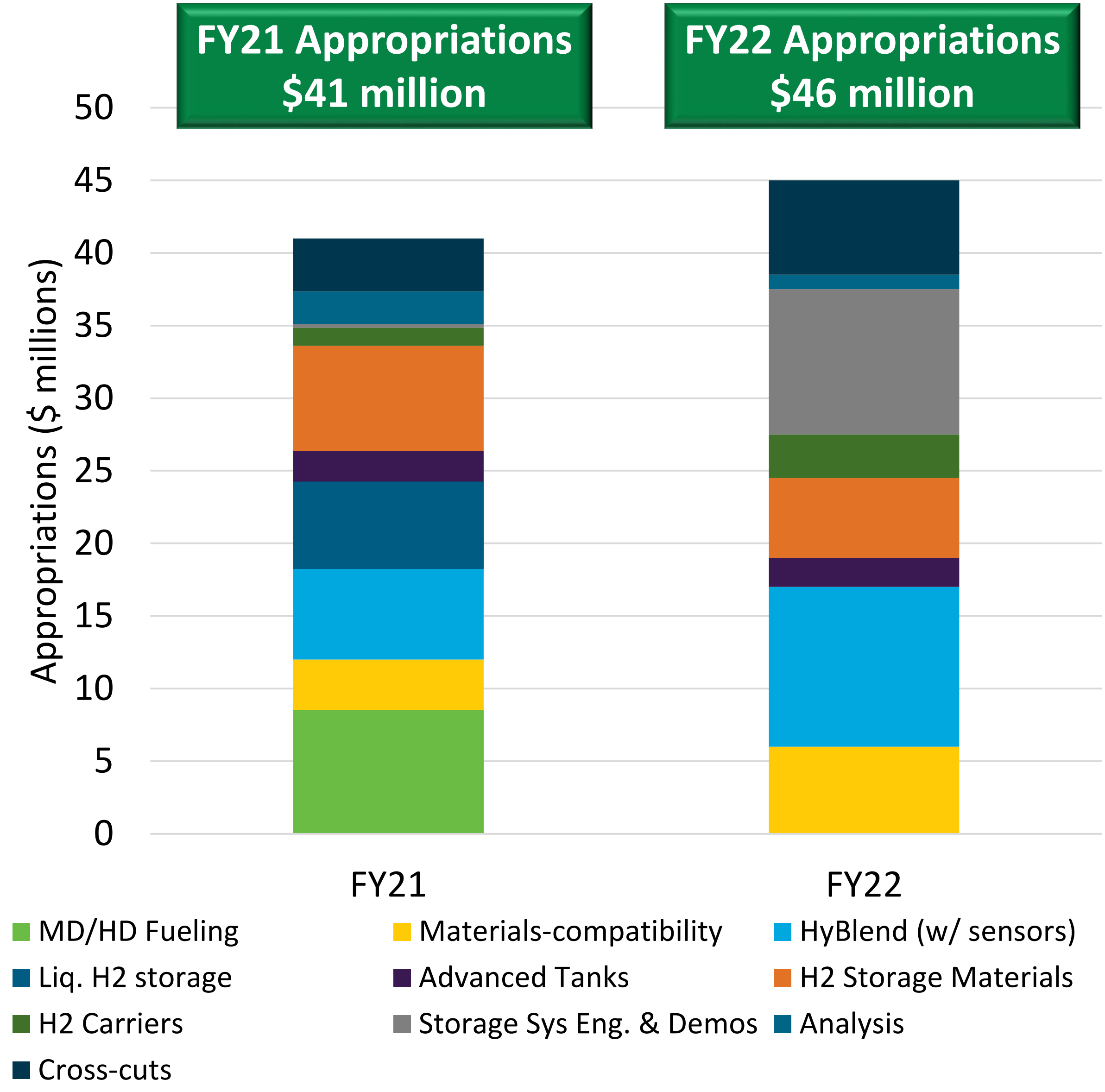
- Gaseous H_2
  - Tube trailers
  - Pipelines
- Liquid H_2
  - Tanker trailers
  - Rail cars
  - Maritime vessels
- H_2 Carriers
  - Pipelines
  - Tanker trailers
  - Rail cars
  - Maritime vessels



End-Use Applications:

- Transportation
  - MD/HD On-road
  - Rail
  - Maritime
  - Off-road/Agriculture
- Energy Storage/Power Generation
  - Load shifting
  - Curtailment mitigation
  - Back-up Power
- Industrial/Chemical Processes
  - Ammonia
  - Steel

Hydrogen Technologies – H_2 Infrastructure Funding



Program Direction

Hydrogen Infrastructure RD&D - includes H_2 Delivery and Storage Activities

- MD/HD Station & Fueling Component Development
- HyBlend Activities
- Materials-compatibility for H_2 Service Applications
- Advanced Tanks, including Low-cost Carbon Fiber
- H_2 Storage Materials R&D
- H_2 Carriers R&D
- Storage System Engineering & Demonstrations
- Cost and Performance Analysis
- Cross-cut Activities

FY23 Request
$56 million

Gaseous H_2 – Fueling Stations

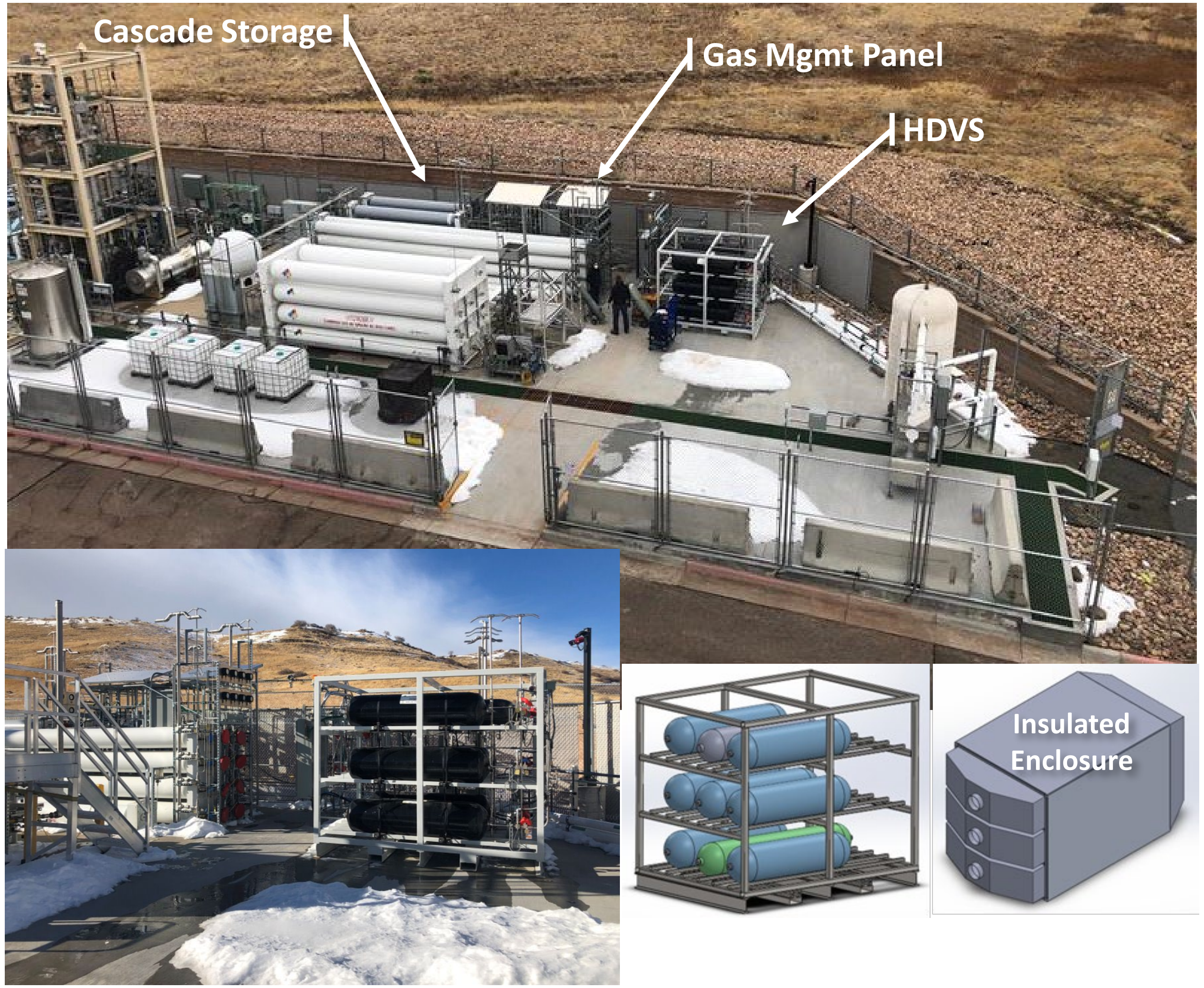
Innovating Hydrogen Station: Heavy-Duty Fueling – H2061

Objectives:

- First-of-its-kind, 10 kg/min (20 kg/min peak), up to 80 kg fueling at 70 MPa and -40°C
  - Heavy-duty vehicle simulator (HDVS) with configurable volume and temperature
- Develop publicly available tools and data for the benefit of hydrogen station stakeholders
  - Modeling and experimental coordination with PRHYDE, SAE, NEDO, and others

Recent Accomplishments:

- Demonstrated during commissioning a 40 kg fill into the HDVS in under 3 minutes at **13 kg/min average (21 kg/min peak)**
- Expecting full operation (60-80 kg fills) in mid-June



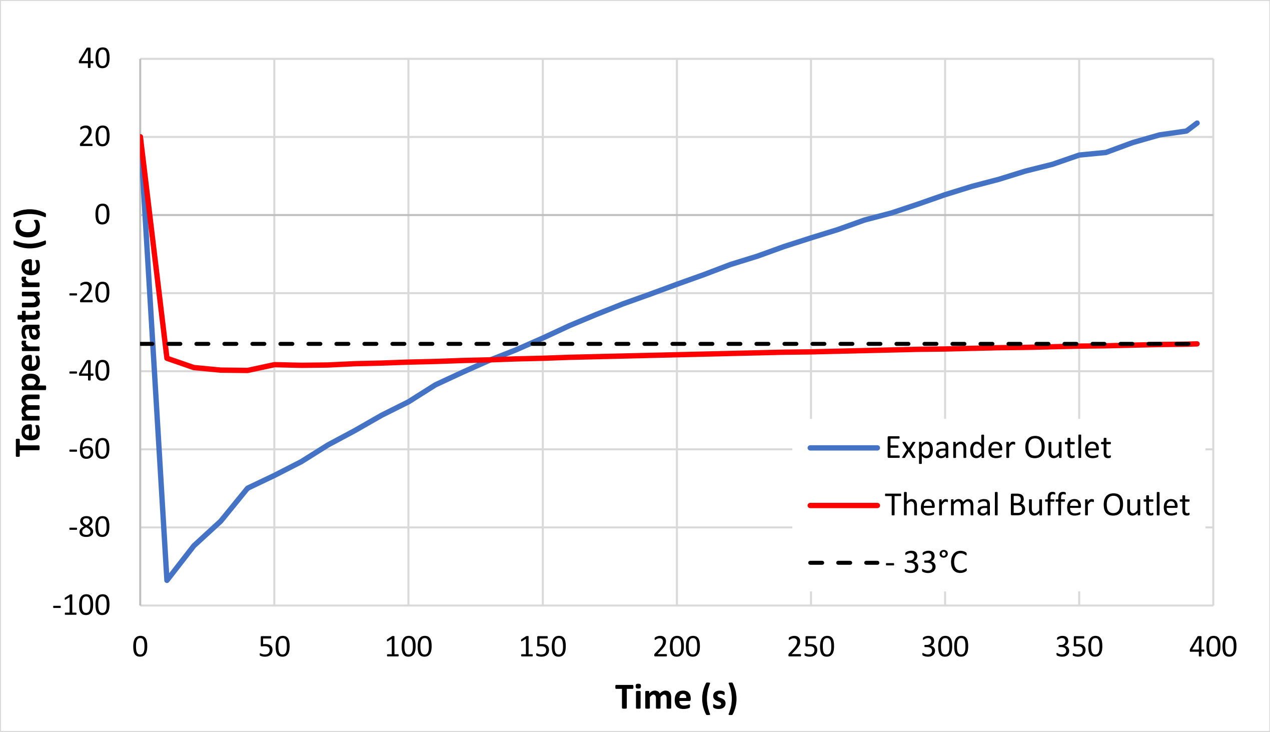
Free-Piston Expansion Chiller – IN016

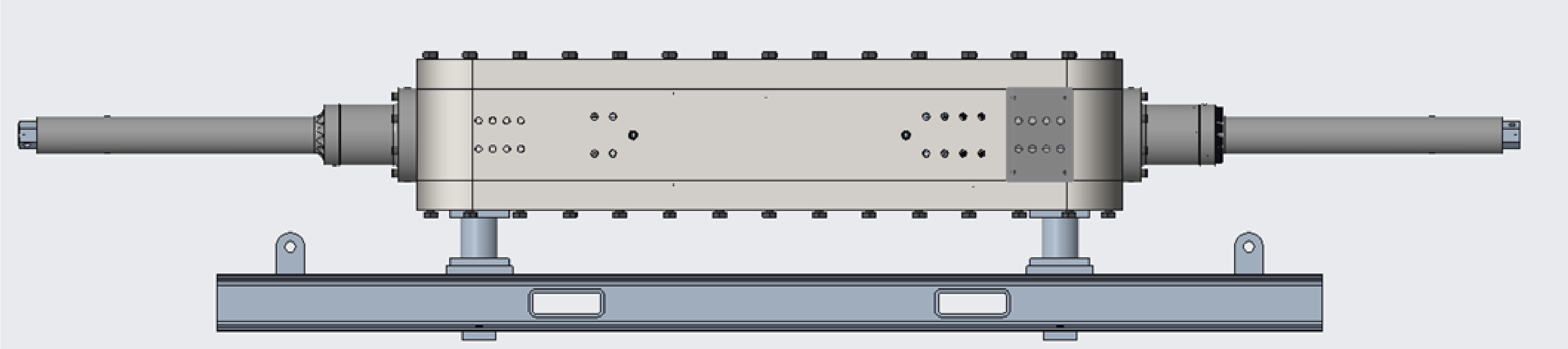
Objectives:

- Targeting ~40% of current capital cost, & <20% of energy consumption
- Eliminates back-to-back fill constraints
- Thermal buffer to control low temperature excursions

Recent Accomplishments:

- Installed new test enclosure, test system build 90% complete
- Expecting commissioning for full chiller system to begin in July





Gaseous H_2 – Onboard Storage

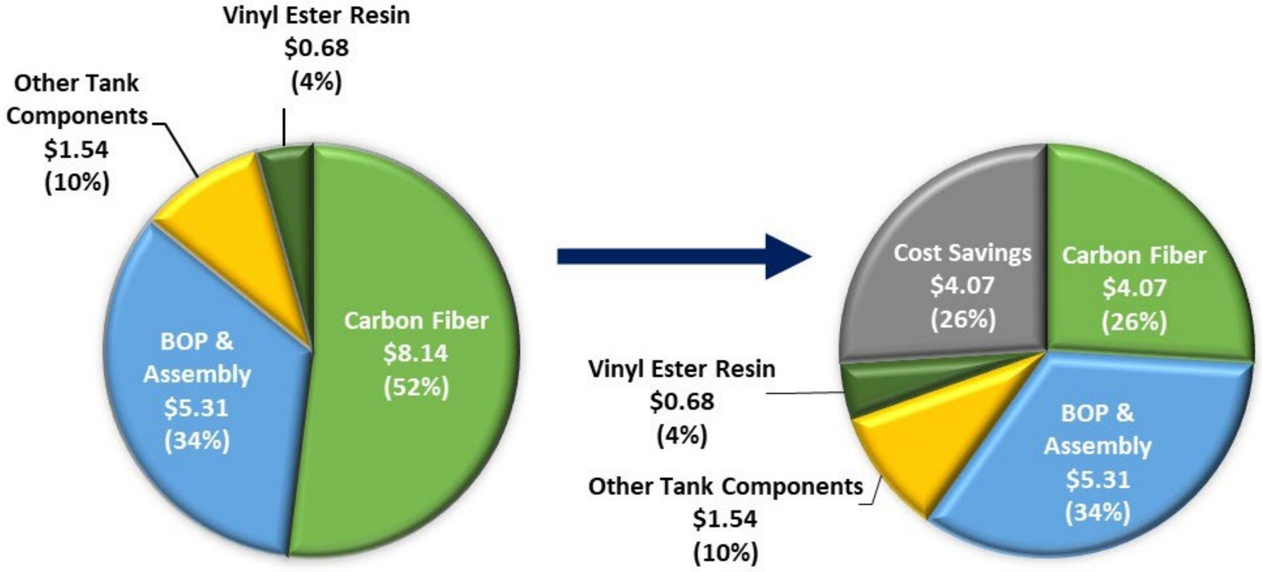
Advanced Low-cost Carbon Fiber – ST236-ST240

Objectives:

- Targeting a 50% cost reduction in carbon fiber used in onboard tanks
- Four teams during initial phase (2 years), with down-selection to a single team for final phase (3 years)
- End of project deliverable are fully wound tanks with developed carbon fiber

Recent Accomplishments:

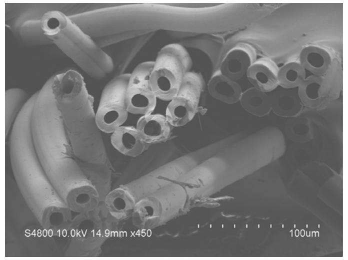
- Production of low-cost precursors with low polydispersity and optimum molecular weight
- Synthesis of preliminary precursor fibers and carbon fibers
- Development of novel fiber sizing for improved load transfer efficiency



Present-day, from storage record
Total cost: **$15.67/kWh**

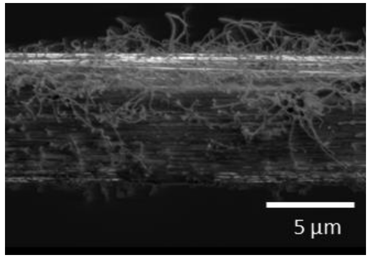
Projected after 50% CF reduction
Total cost: **$11.60/kWh**

Note: cost analysis for a 700 bar onboard system with 5.6 kg usable H_2 capacity, manufactured at 100,000 systems per year



Hollow precursor fibers

Precursor fibers

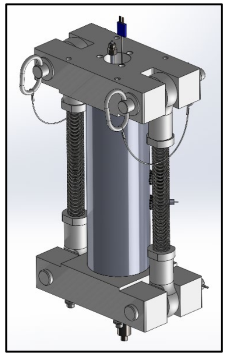


Novel fiber sizing

Hydrogen Materials Compatibility

H-Mat: Foundational R&D on materials compatibility with hydrogen – IN001A/B

- H-Mat team collaborators validated accelerated fatigue testing techniques (HyPerformance Material Testing) and developed high-throughput fracture test techniques (MIT) for metals in hydrogen
- Identified filler materials that mitigate swelling of HNBR rubber materials in hydrogen
- Developed computational frameworks to characterize hydrogen-deformation interactions in steels & aluminum
- Launched MOU with Kyushu University to enable future data and researcher exchange, and collaborative R&D

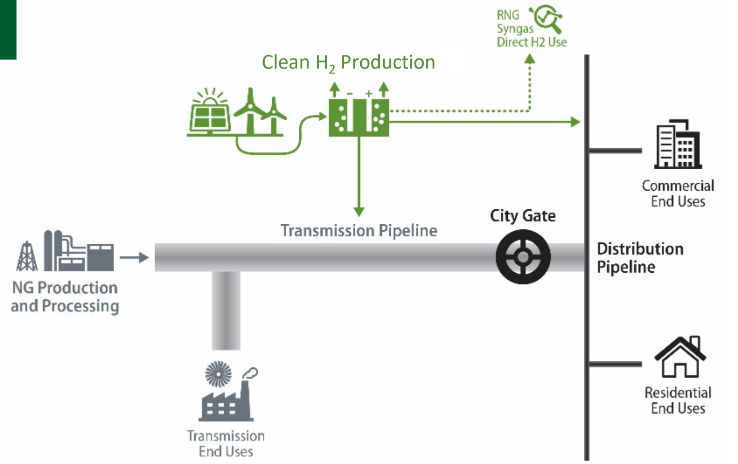


High-pressure test loop under development at SNL to correlate coupon-scale behavior with pipe segments (up to 50 mm OD)

HyBlend: Hydrogen Blending into Natural Gas Pipeline – H2080

Pipeline blending CRADA projects including ~30 industry partners and national labs

- Completed technical report summarizing ASME and NFPA codes and standards relevant to blending[1]
- Developing master curves to characterize life of pipeline materials and mitigate future test requirements prior to deployment (SCS sub-program)
- Initiated testing of metallic and polymer vintage and modern materials in gaseous hydrogen
  - >10 different pipeline materials and weld materials planned for testing in up to 200 bar
  - Test loop under development to validate materials behavior in a piping configuration (engineered defects in pipe at the laboratory scale, up to 50mm OD)



Sandia National Laboratories · Pacific Northwest National Laboratory · Argonne National Laboratory · NREL National Renewable Energy Laboratory · Oak Ridge National Laboratory · NETL National Energy Technology Laboratory

[1] Available at: https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/hydrogen-safety-codes-and-standards/

Liquid H_2 - Energy Storage

First Demonstration of a Commercial Scale LH_2 Storage Tank Designed for International Trade Applications – ST241

Objectives:

- Develop first-of-a-kind, affordable, very-large-scale (20k-100k m^3) LH_2 storage tank for international trade
- Achieve <0.1% per day boil-off rate
- Achieve CAPEX of < $175M for a 100k m^3 tank

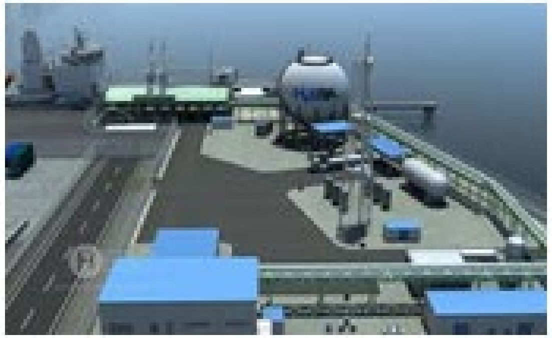
Recent Accomplishments:

- Developed several tank concepts for consideration, down-selected to two concepts for evaluation
- Completed technology safety review for qualitative relative risk comparison between concepts
- Measured K_e of glass bubbles in N_2 and He, prepared for experiments with H_2
- Developed models to predict thermal conductivity of insulation materials with convective contribution

Now

~30X

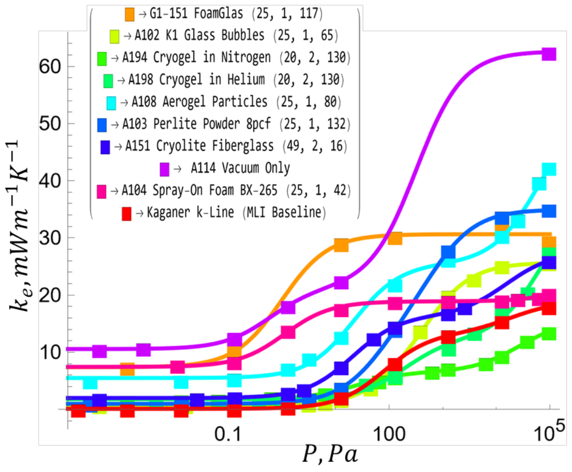
Need



LH_2 storage tank 5,000 m^3

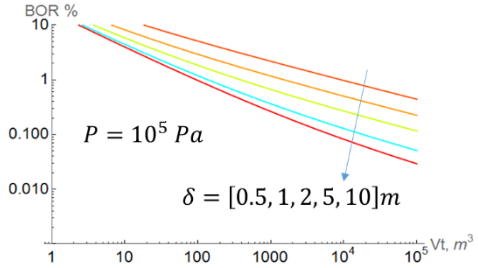
Receiving terminal 100,000 m^3

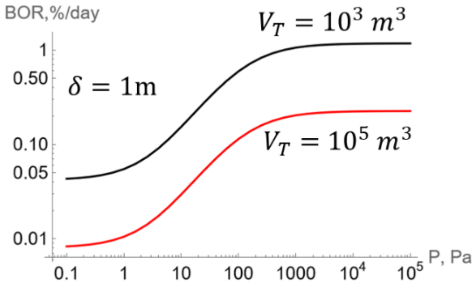
Thermal insulation system property model



- ✓ *Insulation model developed and refined*
- ✓ *External publication in preparation*

BOR prediction





H_2 Carriers – H_2 Storage and Transport

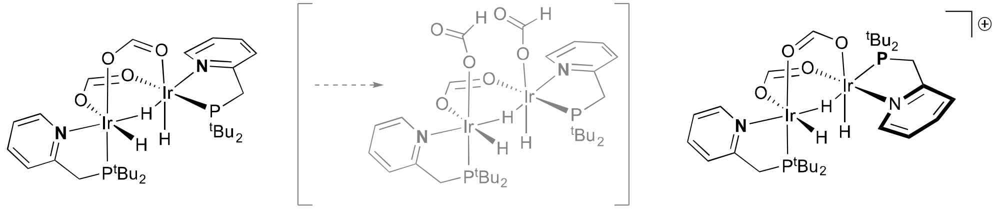
Hydrogen Release from Concentrated Media with Reusable Catalysts – ST216

Objectives:

- Demonstrate on-demand H_2 evolution from formic acid and formic acid blends using a prototype continuous operation reactor
- Demonstrate homogeneous catalyst can meet target flow rate of 300 kg H_2/hr in a continuous flow reactor

Recent Accomplishments:

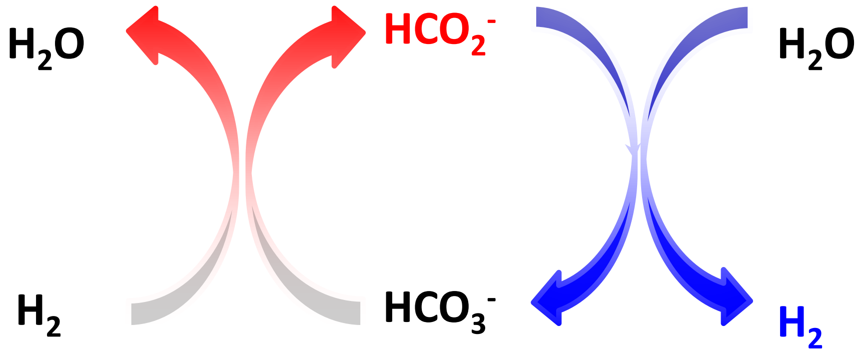
- Demonstrated 160 L/hr peak flow at ~155 bar
- Demonstrated CO and CO_2 scrubbing (< ~5 ppm) at ambient pressure
- Demonstrated 5.3 wt.% from a MeOH/formic acid blend
- Developing a mechanistic understanding of the catalytic dehydrogenation reaction



2

3

formic acid dehydrogenation



Developing an overall understanding of H_2 Carriers for H_2 storage & transport – ST204

Objectives:

- Identify use cases expected to benefit from H_2 carriers
- Identify key physiochemical properties to fulfill application needs
- Evaluate select H_2 carrier systems to meet application requirements

Recent Accomplishments:

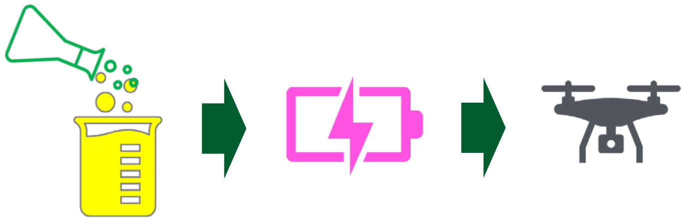
- Demonstrated >10 cycles in a formate/bicarbonate system
  - H_2 release at isobaric and isochoric (< 80 °C) conditions
  - H_2 uptake at < 35 bar and < 50 °C

Materials-based H_2 Storage – Approaching Commercialization

FueL Additives for Solid Hydrogen (FLASH) Carriers in Electric Aviation – ST243

Objectives:

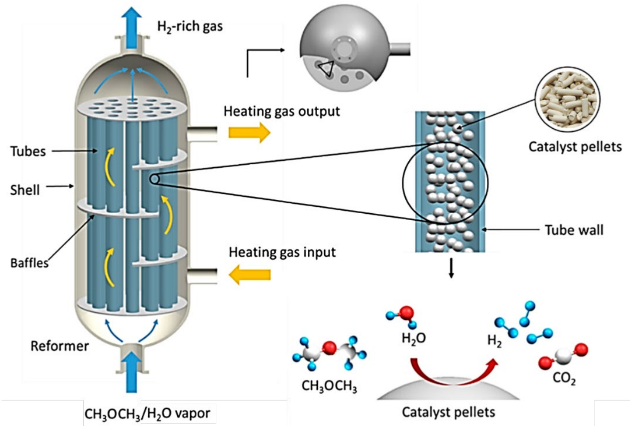
- Develop *FLASH* formulations meeting application operational requirements
- Develop prototype cartridge for Honeywell application platforms
- Demonstrate fuel cell test with the *FLASH* cartridge



Optimize & Scale FLASH formulation

Develop a protype fuel cartridge

Test FLASH with Honeywell fuel cell platform



DME as a Renewable H_2 Carrier: Innovative Approach to Renewable H_2 Production – ST242

Objectives:

- Design, build and demonstrate integrated DME-SR process with LANL's dual-catalyst bed at 25 kg H_2/day scale
- Validate H_2 quality with fuel cell testing
- Provide data and design for Oberon's use in Phase 4 commercialization plan

High Efficacy Validation of Hydride Mega Tanks at the ARIES Lab "HEVHY METAL" – TA063

Objectives:

- Demonstrate two metal hydride HY2MEGA subsystems (520 kg H_2 capacity) installed with MW-scale H_2 infrastructure
- Validate performance: rates, capacity & efficiency
- Investigate supply & demand side techno-economics
- Identify potential commercial use cases

GKN HYDROGEN

Programmatic information and wrap-up

Hydrogen Technologies Program: Collaboration Network

Fostering technical excellence, economic growth and environmental justice

Efforts Support Over:
12 national laboratories
32 universities
20 companies

DOE H_2 Program Collaborations		
VTO	AMO	BETO
SETO	BTO	ARPA-E
SC	FECM	NE

DOE Cross-Cutting Initiatives		
Energy Storage Grand Challenge	Advanced Transportation	Advanced Manufacturing
Space	Alternative Fuels	AI/ML
Decarbonization of Agriculture/Buildings/Electricity/Industry/Transportation		

Cross-Agency Collaborations			
DOC-NIST	NASA	DOD	NSF

Industry Engagements
U.S. DRIVE – Hydrogen TT
21st Century Truck Partnership
AWS Benchmarking and Protocol Development
H2NEW
Workshops/RFIs

Regional and International Collaborations			
IEA H_2 TCP	IEA AFC TCP	AWS Benchmarking and Protocol Dev.	Bilateral Collaborations

Hydrogen Technologies Program: Highlights and Milestones

FY2021

- *Launch of H2NEW*
- *Launch of HydroGEN 2.0*
- *Release of the DOE H_2 Program Plan*
- *3rd Annual AWS benchmarking workshop*
- *FY21 FOA on SOEC Electrolyzer Manufacturing, BioH_2 from Waste, HD Fueling Components and Cost Analysis*
- *FY21 DOE H_2 Program Virtual AMR*
- *Launch of HyBlend Project, and 5 CRADA projects on HD fueling*
- *Commission HD H2 Test Facility at NREL in support of Innovating Hydrogen Stations CRADA*
- *Liquid H_2 Workshop w/ NASA*
- *Program Record: H_2 Fueling Station Cost*

FY2022

- *BIL signed into law*
- *Power Electronics Experts Meeting*
- *Liquid Alkaline Electrolyzer Experts Meeting*
- *Bulk H_2 Storage and 2nd Liquid H_2 Workshops*
- *Webinar on BIL H_2 Provisions and RFIs*
- *Request for Information for BIL Sections 815 & 816*
- *H2 Shot Incubator Prize Launched*
- *HTE Manufacturing and PEM Materials Electrolyzer Workshops*
- *H2 Shot Strategy Document*
- *FY22 Appropriations & BIL Sec. 816 FOA – topics tbd*

FY2023

- *First BIL Sec. 816 Electrolyzer Projects Kicked-off*
- *H_2 Shot Incubator Propose! Phase Winners Announced*
- *FY23 FOAs – topics tbd*
- *H_2 Infrastructure Workshop*
- *Electrolyzer Manufacturing Workshop*
- *Post updated H_2 Production Cost Record*
- *FY23 DOE H_2 Program AMR*

Exciting Fellowship Opportunities…

for DOE's Office of Energy Efficiency and Renewable Energy (EERE)
Hydrogen and Fuel Cell Technologies Office (HFTO)
in Washington, D.C.

ORISE Fellows will engage with HFTO's Hydrogen Technologies Program

Candidates should have experience in: (1) H_2 production technologies such as electrolysis, solar thermochemical, photoelectrochemical, and/or biological processes or (2) H_2 infrastructure R&D areas such as materials compatibility, liquefaction, pipelines, tube trailers, and technologies used at hydrogen fueling stations, such as compressors, storage vessels, dispensers, and cryopumps.

- A degree in the physical sciences or engineering, such as chemistry, physics, materials science, chemical engineering, or related area required.
- Graduate, post-doctoral, or industrial experience in one of the above is preferred
- Good written and oral communication skills are important.

H_2 Technologies Contact:
Ned Stetson
ned.stetson@ee.doe.gov

Hydrogen Technologies encourages interested candidates to submit applications to be a H_2 Shot Fellow

To apply: https://www.Zintellect.com/Opportunity/Details/DOE-EERE-STP-HFTO-2021-1801

Thank You

Ned T. Stetson, Ph.D.

Program Manager, H_2 Technologies, HFTO

ned.stetson@ee.doe.gov

www.hydrogenandfuelcells.energy.gov