U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

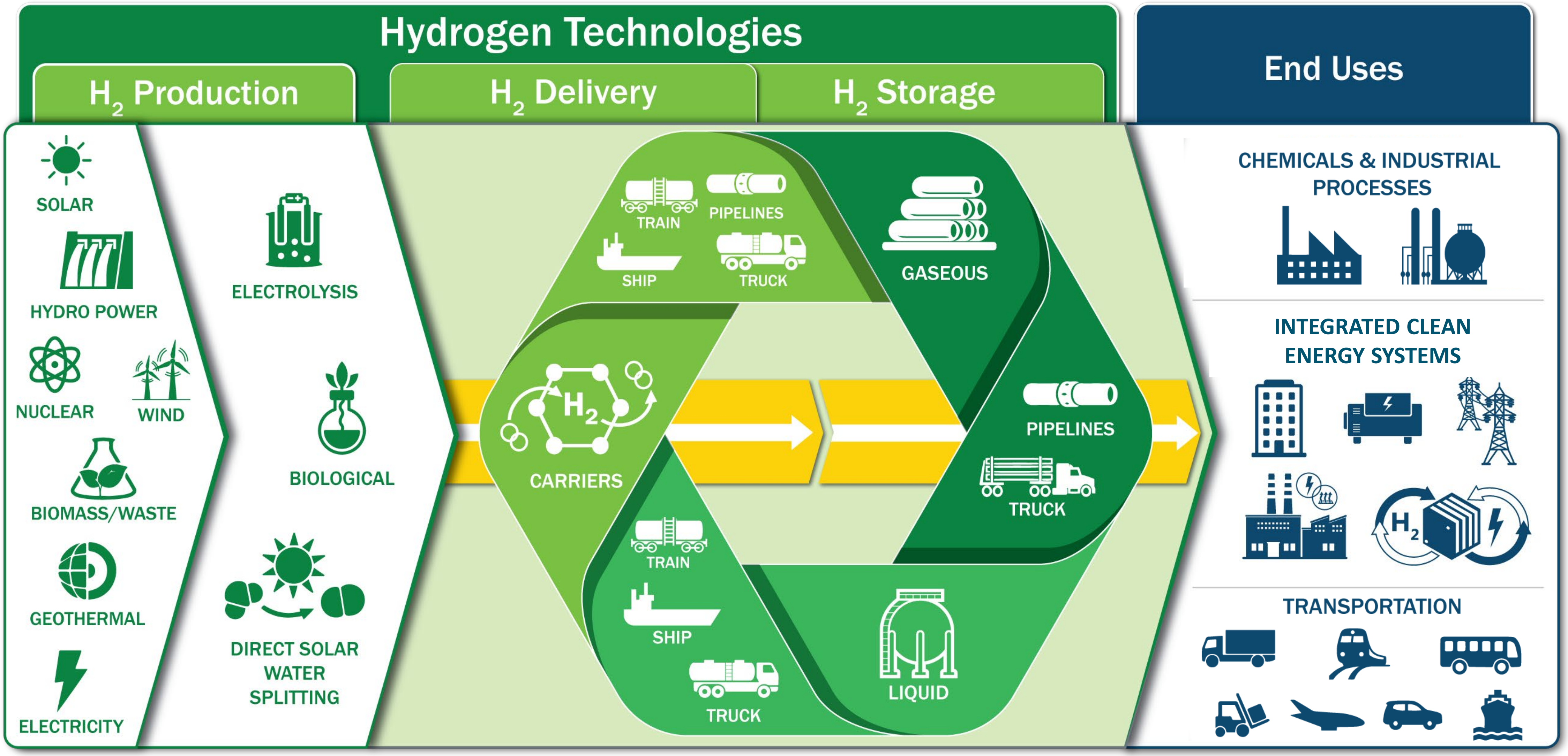
H_2 Technologies Overview

Dr. Ned Stetson, HFTO – Hydrogen Technologies Program Manager

2021 Annual Merit Review and Peer Evaluation Meeting

June 7, 2021 – Washington, DC

Hydrogen Technologies Program



From producing hydrogen molecules through dispensing to end-use applications

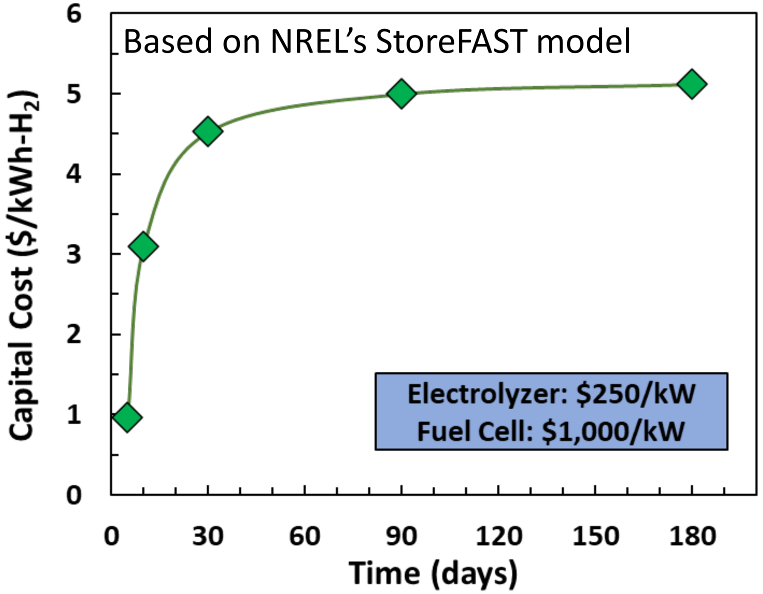
Developing Application-Specific Targets – Examples

H_2 Production

H_2 Production	2025	2030
Hydrogen cost ($/kg)	2	1
PEM Electrolyzer Targets		
Electrical Efficiency (%)	70	tbd
Stack Cost ($/kW)	100	tbd
Durability/Lifetime (hr)	80,000	tbd
System Cost ($/kW)	250	tbd

H_2 Energy Storage

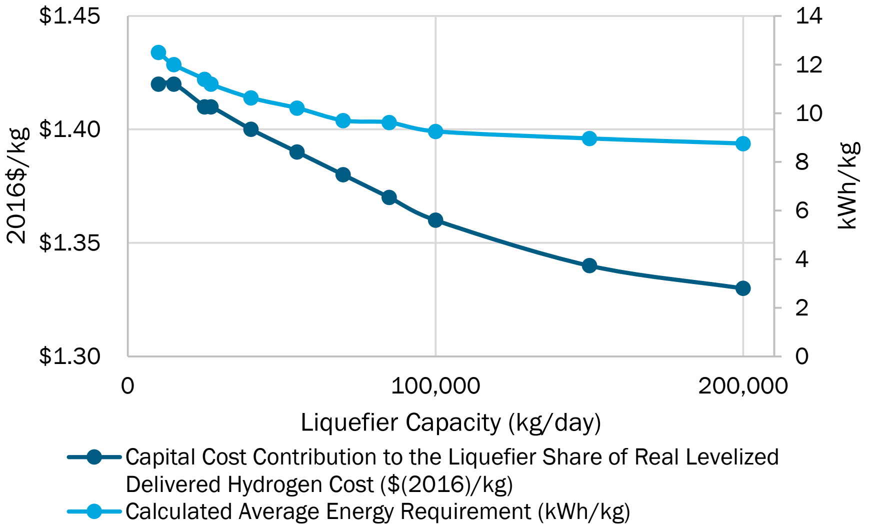
H_2 Storage Costs to be Competitive with CAES in Salt Caverns

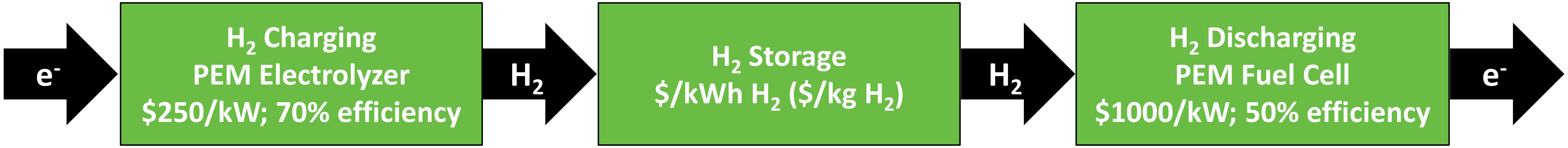


H_2 Liquefaction

Liquefaction efficiency target: 6 kWh/kg
2X improvement over current technology

Average Liquefier Energy Requirement by Capacity[1]



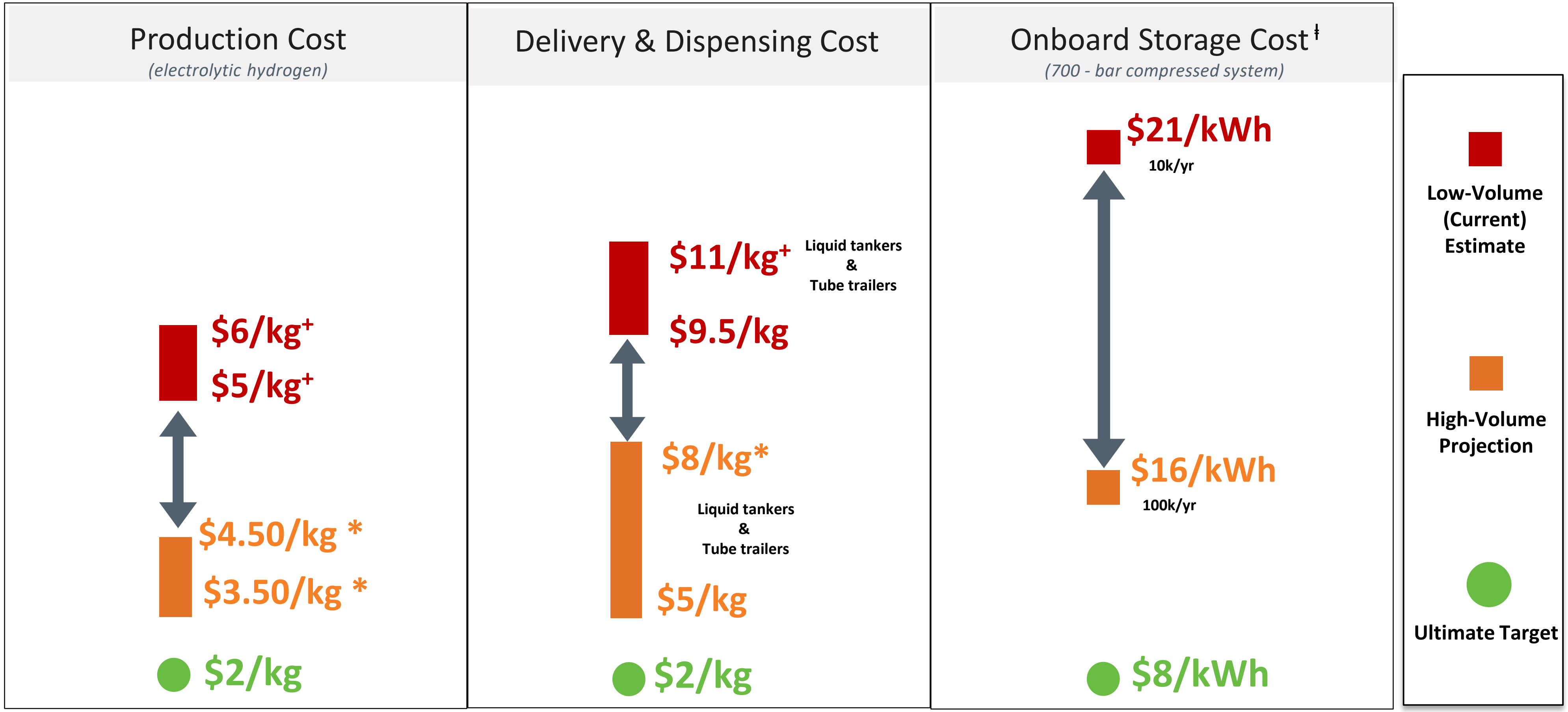


Note: currently not official targets

DOE Targets Guide RD&D - Focus is on Affordability and Performance

Key Goals: Reduce the cost of fuel cells and hydrogen production, delivery, storage, and meet performance and durability requirements – guided by applications specific targets

HYDROGEN TECHNOLOGIES RD&D – Transportation Cost Targets



ǂ 5 to 7 cents/kWh, 90% capacity factor at $1500/kW
*5 to 7 cents/kWh, 90% capacity factor at $460/kW

†For range: Delivery and dispensing at today's (2020) stations with capacity ~450 kg/day
*For range: Delivery and dispensing at today's (2020) stations with capacity 450-1,000 kg/day at high volume manufacturing

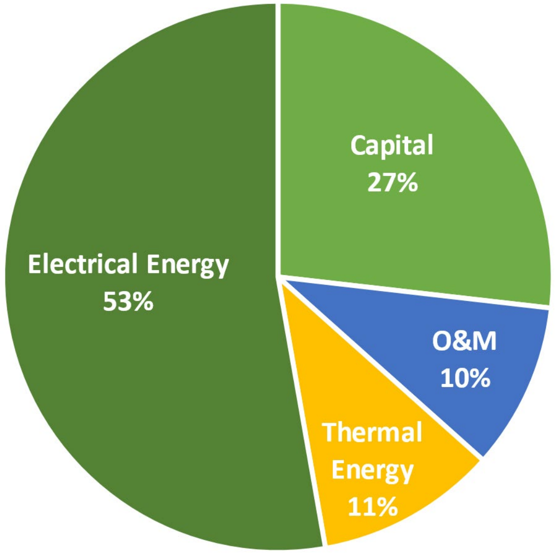
ǂ Storage costs based on 2019 storage cost record

All costs based on $2016

Note: Graph is not at scale. For illustrative purposes only

Examples of Cost Drivers and Focus Areas for Hydrogen Technologies

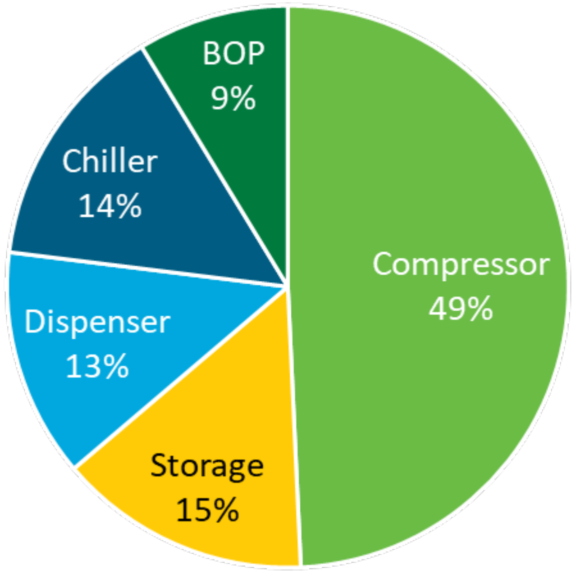
Hydrogen Production Cost
(High Temperature Electrolysis)



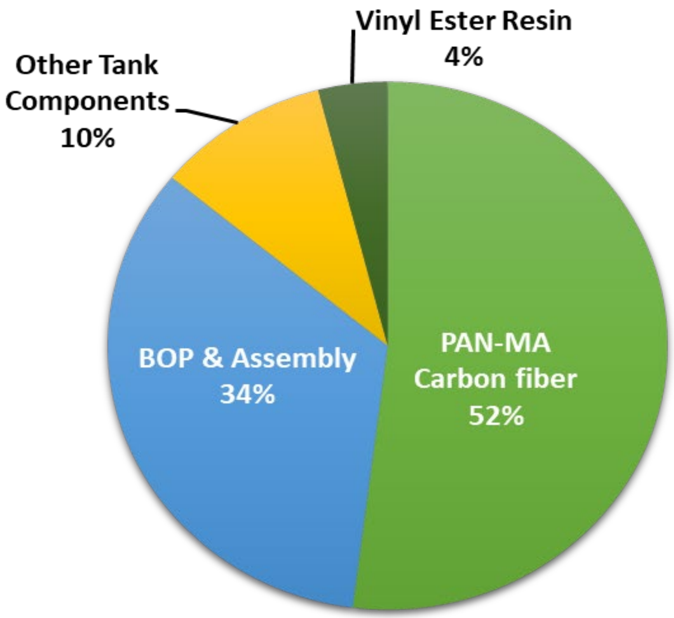
H_2 Production (Electrolysis)
Cost Drivers:
Electrical energy and capital costs

H_2 Infrastructure
Cost Drivers:
Compressors, Chiller, Dispenser and Storage

Hydrogen Fueling Station Levelized Cost
(700 Bar, 800 kg/day Station)



Hydrogen Storage Cost
(700 bar Type IV, 5.6 kg Hydrogen Storage System)

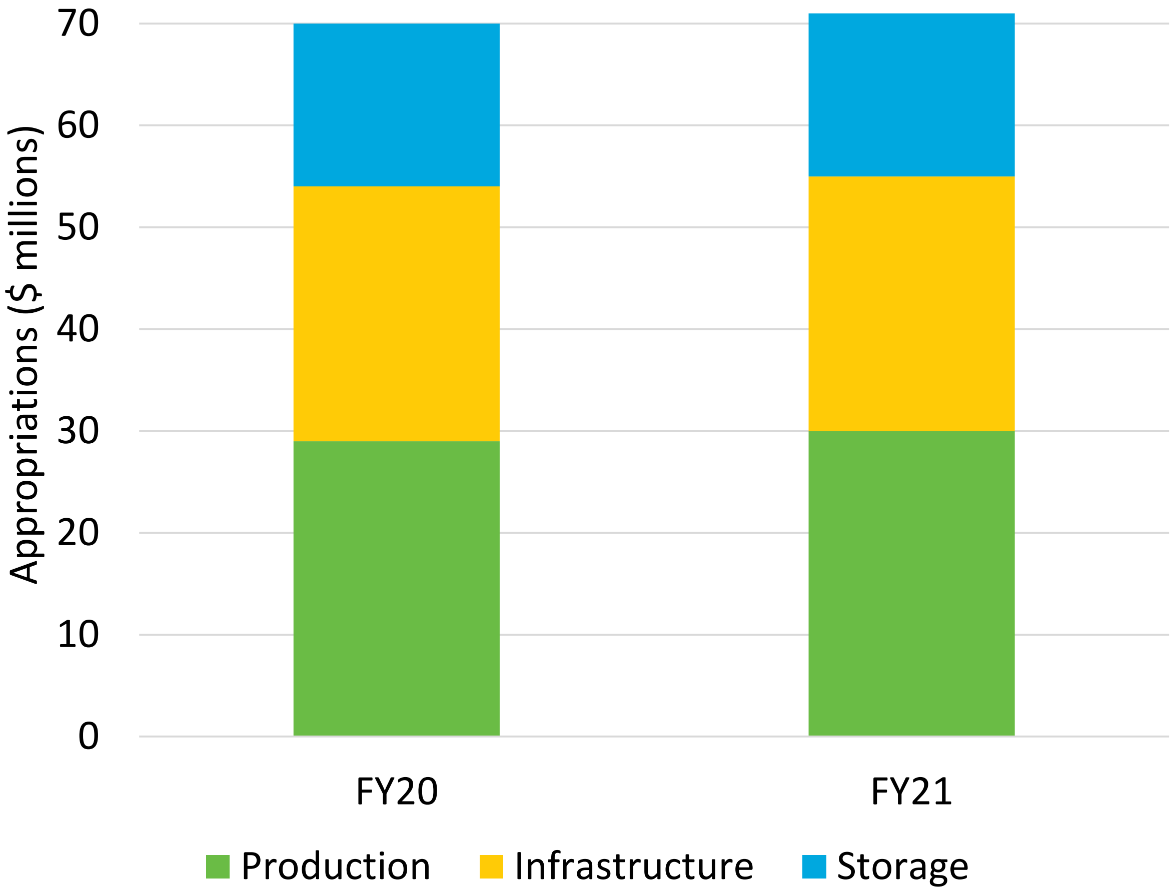


H_2 Onboard Storage
Cost Drivers:
Carbon Fiber Precursors and Processing

Hydrogen Technologies Funding

FY20 Appropriations
$70 million

FY21 Appropriations
$71 million



Program Direction

Hydrogen Production RD&D
- Low- and High-Temperature Electrolyzers
- Advanced Water Splitting Materials
- Electrolyzer Manufacturing Technologies
- Microbial H_2 Production

Hydrogen Infrastructure RD&D
- Materials Compatibility
- H_2-Natural Gas Blends
- Vehicle Refueling Component
- H_2 Liquefaction Technologies

Hydrogen Storage RD&D
- Low-Cost, High-Strength Carbon Fiber
- H_2 Carriers
- H_2 Storage Materials
- Bulk H_2 Storage Technologies

Cost and Performance Analyses

The Hydrogen Technologies Team

Hydrogen Technologies Program Manager,
Ned Stetson

Technology Manager,
Katie Randolph

Technology Manager,
Neha Rustagi

Technology Manager,
Zeric Hulvey

Program Support,
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ORISE Fellow,
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Program Support,
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Technology Manager,
James Vickers

Technology Manager,
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ORISE Fellow,
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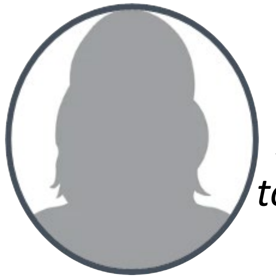
Program Support,
Kim Cierpik-Gold

Technology Manager,
Will Gibbons

Technical Support,
Levi Irwin



ORISE Fellow,
McKenzie Hubert
to start fall of 2021

Hydrogen Production

Oral Project Presentations Tuesday-Wednesday, June 8-9

Hydrogen Production

Office of Fossil Energy

FOSSIL RESOURCES

- Low-cost, large-scale hydrogen production with CCUS
- New options include byproduct production, such as solid carbon

Coal Gasification with CCUS

Natural Gas Conversion with CCUS

EERE Hydrogen and Fuel Cell Technologies Office

BIOMASS/WASTE

- Options include biogas reforming and fermentation of waste streams
- Byproduct benefits include clean water, electricity, and chemicals

Biomass Conversion

Waste to Energy

H_2O SPLITTING

- Electrolyzers can be grid-tied, or directly coupled with renewables
- New direct water-splitting technologies offer longer-term options

Direct-Solar

High Temp. Electrolysis

Low Temp. Electrolysis

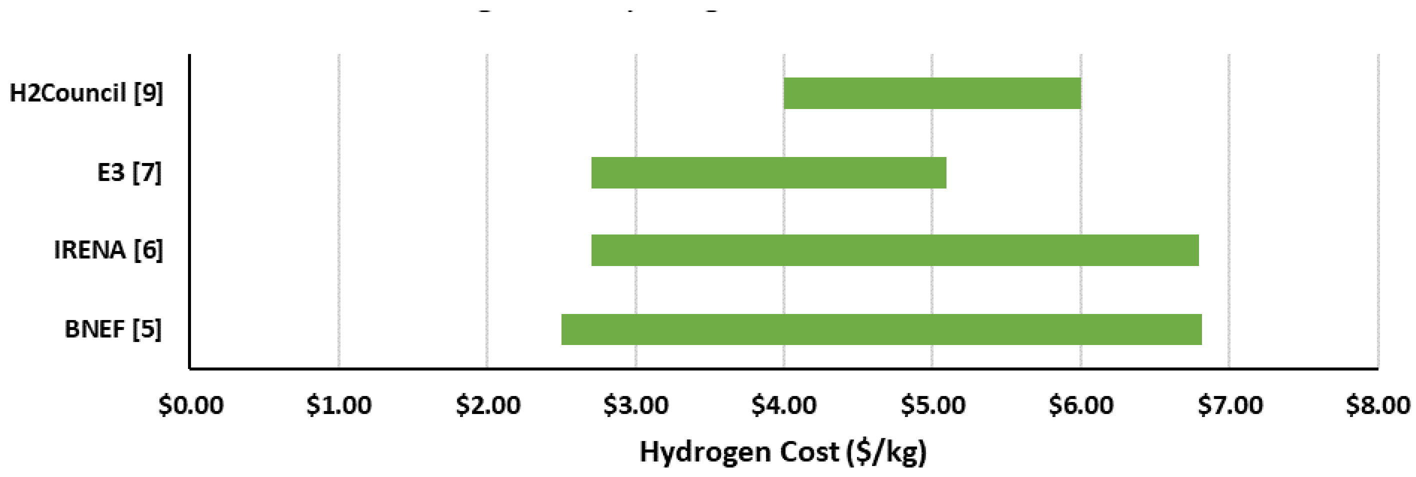
Current Cost of H_2 Produced through Electrolysis - $5-6/kg H_2

Projected cost of electrolytic H_2 with today's technology [1]

HFTO Projections	Electricity Cost (₵/kWh)	Capacity Factor	System CapEx ($/kW)	H_2 Cost ($/kg)
Grid – Low Cost	**5.0**	90.0%	**1,500**	**$5.13**
			1,000	$4.37
Grid – High Cost	**7.0**	90.0%	**1,500**	**$6.27**
			1,000	$5.50
	NREL ATB 2020 [2]			
Solar PV Utility Los Angeles, CA	3.2	31.8%	1,000	$6.09
Solar PV Utility Daggett, CA	2.9	35.1%	1,000	$5.54
Wind Onshore Utility, Class 6	3.8	38.0%	1,000	$5.76
Wind Onshore Utility, Class 1	2.8	52.1%	1,000	$4.22

[1] https://www.hydrogen.energy.gov/pdfs/20004-cost-electrolytic-hydrogen-production.pdf
[2] National Renewable Energy Laboratory, NREL (2020). "2020 Annual Technology Baseline." Golden, CO. https://atb.nrel.gov/

H_2 production costs from various external analysis and associated assumptions

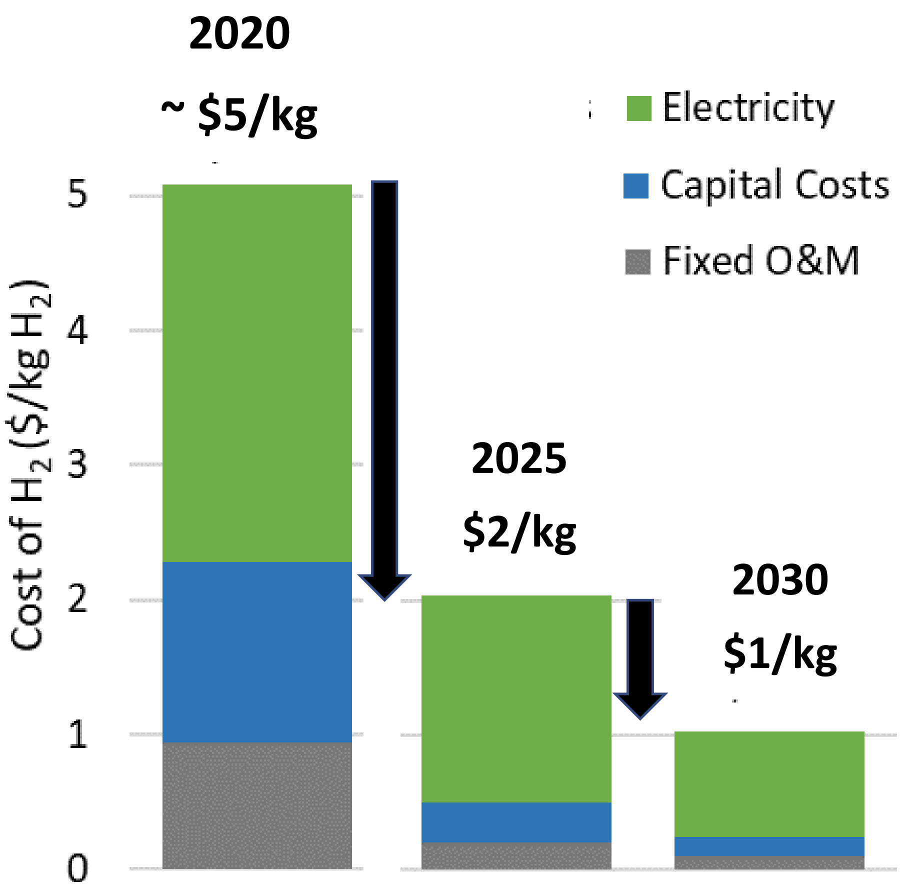


Low	High	Year	Electricity Cost	Capacity Factor	System CapEx	System Efficiency	Reference
($/kg H_2)	($/kg H_2)		(₵/kWh)	(%)	($/kW)	(% LHV)	
4.00	6.00	2020	4.0 – 10.0	20 - 30	**750**	65	H2Council
3.75	5.10	2018	ATB	ATB	**1,124**	63	E3/UCI
2.70	6.80	2018	2.3 – 8.5	26 - 48	**840**	65	IRENA
2.50	6.80	2019	3.5 – 4.5	-	**1,400**	-	BNEF

Current PEM electrolyzer system capital cost range: $750 - $1400/kW

Pathways to Reduce the Cost of Electrolytic H_2

Cost Reduction of Clean 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 at MW-scale**

Electrolyzer goals for 2025	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

A Multi-layered Approach to Electrolyzer Development

Advanced Manufacturing (TRL 6-7) – RD&D on manufacturing processes and techniques suitable for high-volume manufacture of mega-watt scale electrolyzers and electrolyzer components

→ ***Industry-led RD&D projects*** competitively selected through Funding Opportunity Announcements, coordinated with H2NEW

Advanced Components (TRL 4-5) – RD&D on integration of materials into components (e.g., catalysts into MEA) and components into systems (e.g., cells into stacks), developing an understanding of mechanisms and addressing performance barriers for PEM LTE and O^{2-} conducting HTE

→ ***H2NEW*** National Laboratory-led research consortium on advance component development for low and high-temperature electrolysis

Advanced Materials (TRL 1-3) – Foundational R&D on materials with improved performance and durability for water splitting technologies, including low and high-temperature electrolysis and direct thermochemical and photoelectrochemical technologies.

→ ***HydroGEN*** National Laboratory-led research consortium on advance materials development for water splitting technologies

Approach flows from ***foundational materials-development*** addressing multiple technologies to ***advanced integrated component development*** to ***advanced system manufacturing processes***

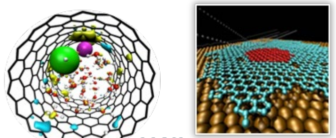
HydroGEN Advanced Water Splitting (AWS) Materials Consortium

HydroGEN
Advanced Water Splitting Materials

Accelerating AWS Materials R&D to Enable <$2/kg H_2

- Leveraging & streamlining access to world-class capabilities & expertise
- Providing a robust, secure, searchable, & sharable Data Hub
- Developing universal standards & best practices for benchmarking & reporting
- Fostering cross-cutting innovation

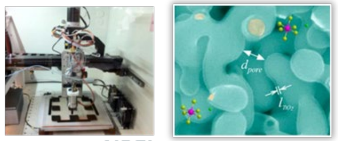
Theory & Computation



LLNL — *Bulk & interfacial models of aqueous electrolytes*

SNL — *LAMMPS classic molecular dynamics modeling*

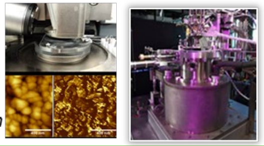
Materials Synthesis



NREL — *High-throughput spray for electrode fabrication*

LLNL — *Conformal ultrathin TiO_2 ALD coating on bulk nanoporous Au*

Characterization & Analytics



LBNL — *Atomic force microscopy: in-situ & operando material characterization*

INL — *TAP reactor: extracting quantitative kinetic data*

Innovative Consortia Model Connecting AWS Community & Enhancing R&D

- Providing **> 40 national lab node capabilities** to accelerate progress of FOA projects
- 76 Publications, 2.87 Impact factor* & 1490 citations
- Cross-cutting activities to exploit similarities and advance material performance & durability
- ***Total planned commitment of $54M over 8 years (FY16-FY23)***

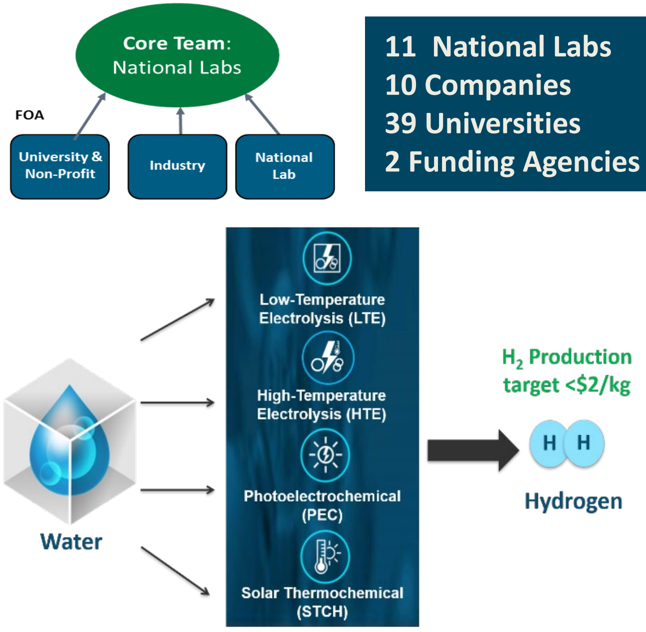
HydroGEN 2.0 Focus Areas

LTE: Enable high efficiency, durable AEMWE without supporting electrolytes

HTE: Identify electronic leakage mechanisms in p-SOEC for higher cell performance at lower temperatures

STCH : Develop global understanding of material structure & composition required to achieve high yield performance

PEC : Scale-up & improved durability through corrosion mitigation & ~neutral pH operation



11 National Labs
10 Companies
39 Universities
2 Funding Agencies

11 Labs, 10 Companies, 39 Universities & > 30 Projects Supported

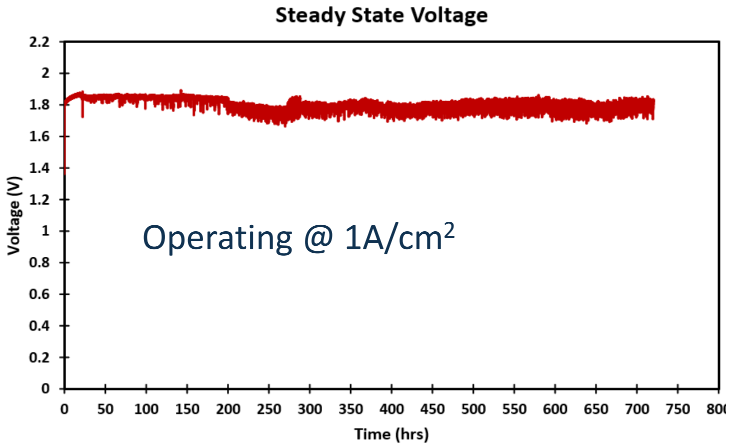
NREL, Sandia National Laboratories, Berkeley Lab, INL Idaho National Laboratory, Lawrence Livermore National Laboratory, The University of Toledo, Colorado School of Mines, University of California Irvine, Chemours, Redox Power Systems, LLC, Stanford, Rice, University of South Carolina, University of Hawaii, Argonne National Laboratory, University of Colorado, Raytheon Technologies, West Virginia University, Northeastern University, University of Michigan, nel, University of Oregon, UCSD, Nexceris, University of Connecticut, Saint-Gobain, Arizona State University, University of Florida, Rutgers, Los Alamos National Laboratory, Georgia Institute of Technology

HydroGEN – Key Accomplishments

HydroGEN
Advanced Water Splitting Materials

LTE

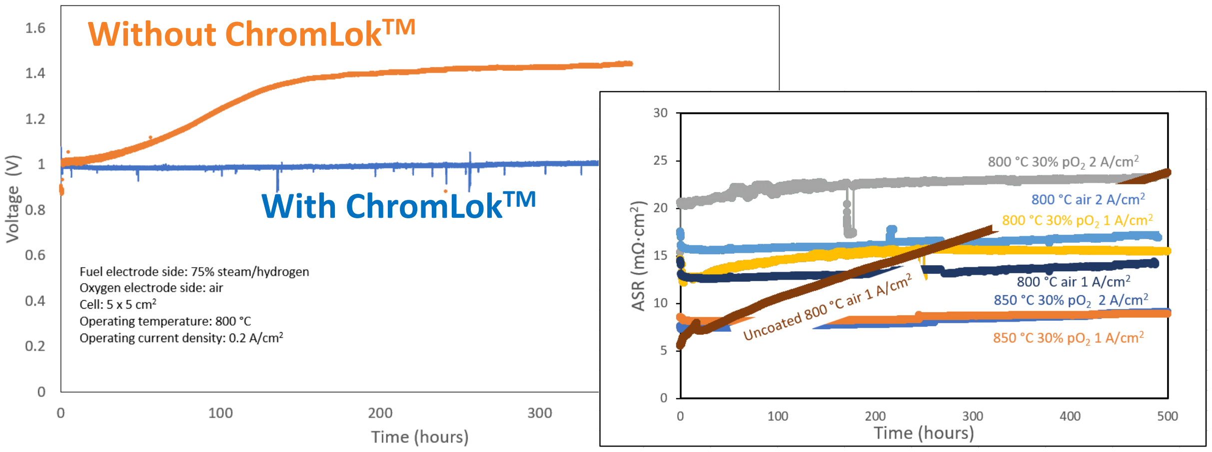
Georgia Tech—Demonstrated improved AEM electrolysis **durability over ~750 hr** at relevant current density



AEM: GT72-10 (30 μm)
Anode: IrOx on TiGDL w/ GT32 ionomer
Cathode: PtNi on C GDL w/ GT69 ionomer
Feed: 0.3M KOH feed to anode only
Temp: 60 °C

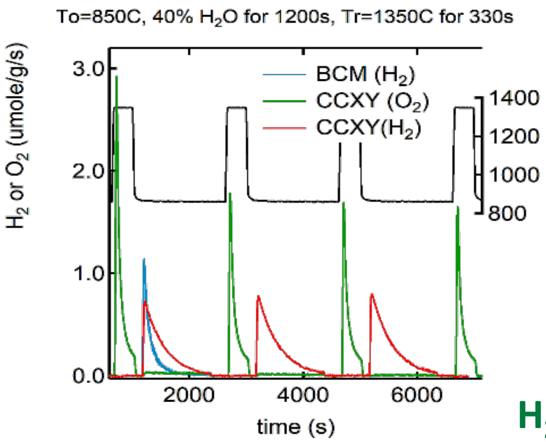
HTE

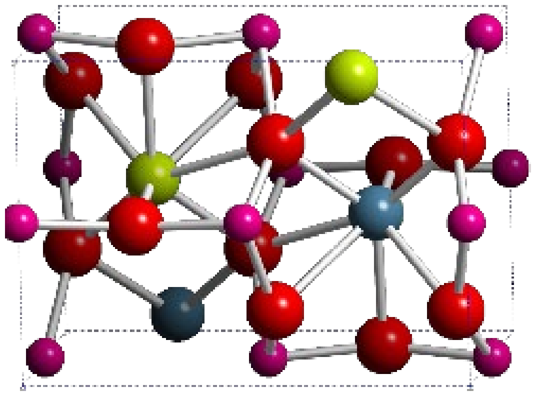
Nexceris—Established promising interconnect **protective coating** for air/O_2 side of HTE stacks



STCH

ASU—HPC-aided discovery of new water splitting material family (Ca,Ce)(X,Y)O_3





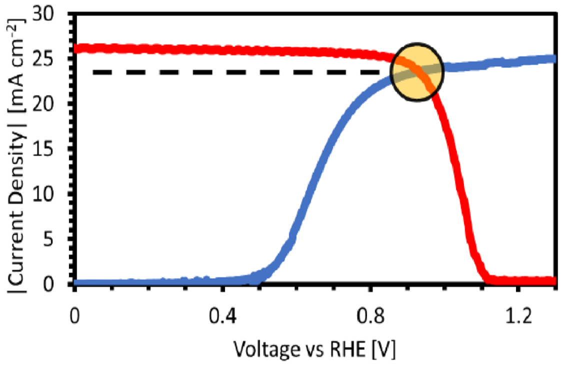
H_2 prod capacity: CCXY > SLMA >> BCM

PEC

Rice—Achieved a **2.5x higher STH efficiency** than SOA perovskite cells in an integrated 3D-printed photoelectrochemical reactor

3D-Printed PEC Reactor

Solar-to-Hydrogen η = 12.4%



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

H2NEW
U.S. DEPARTMENT OF ENERGY

A comprehensive, concerted effort focused on overcoming technical barriers to enable affordable & efficient electrolyzers to achieve <$2/kg H_2 (2025)

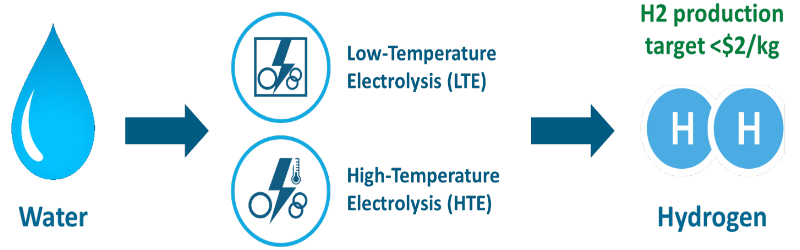
- Launched in Q1 FY2021
- Both low- and high-temperature electrolyzers
- ***Planned commitment of $50M over 5 years***

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
NETL – National Energy Technology Laboratory

Clear, well-defined stack metrics to guide efforts.

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**

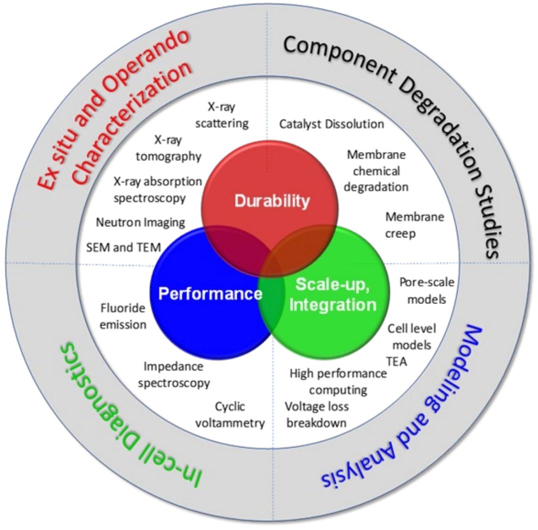


H2NEW focuses on higher TRL electrolyzer technologies:

- PEM for LTE
- Oxide ion conductors for HTE

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

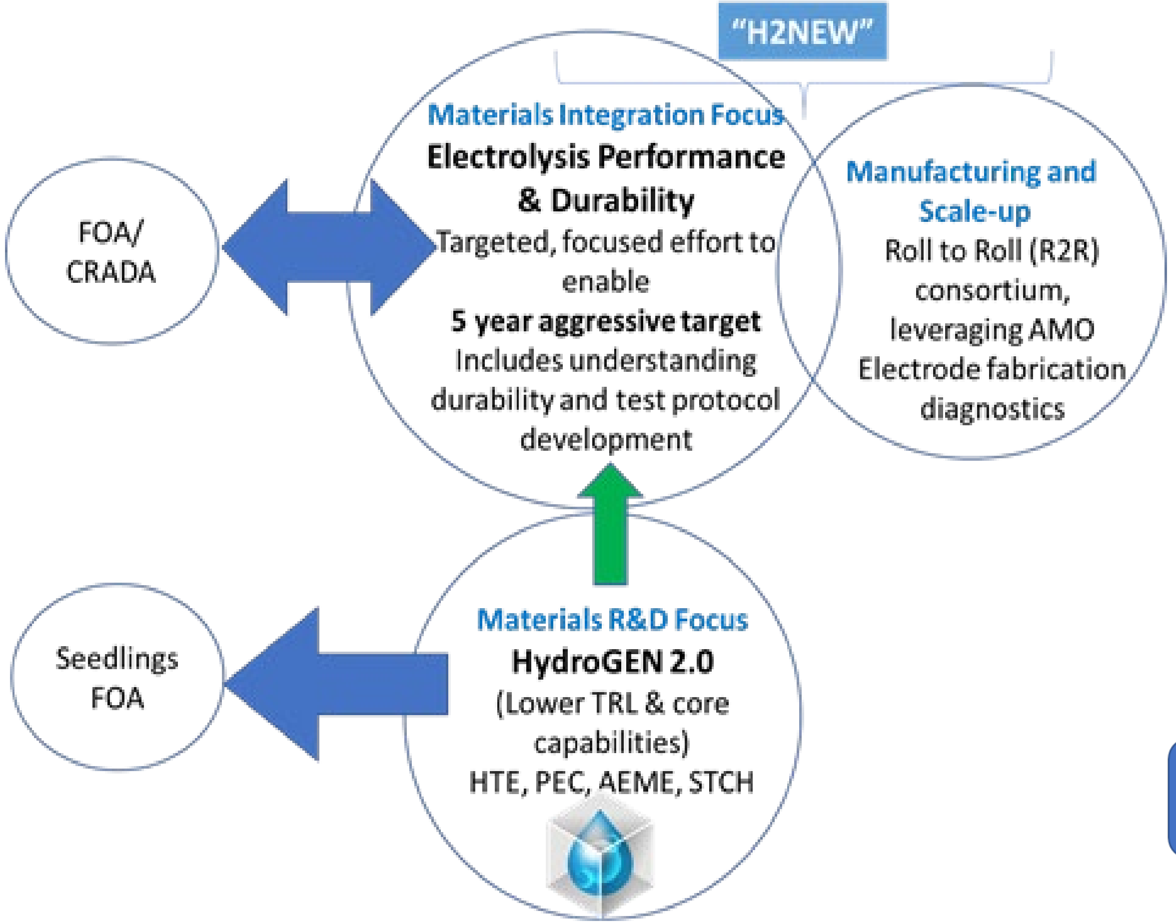
Makes use of a combination of world-class experimental, analytical, and modeling tools



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

- Limited fundamental knowledge of degradation mechanisms including under future operating modes
- Lack of understanding on how to effectively accelerate degradation processes.
- Develop and validate methods to accelerate identified degradation processes to evaluate durability in 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 Structure and Approach



Task-Based Structure Split between:

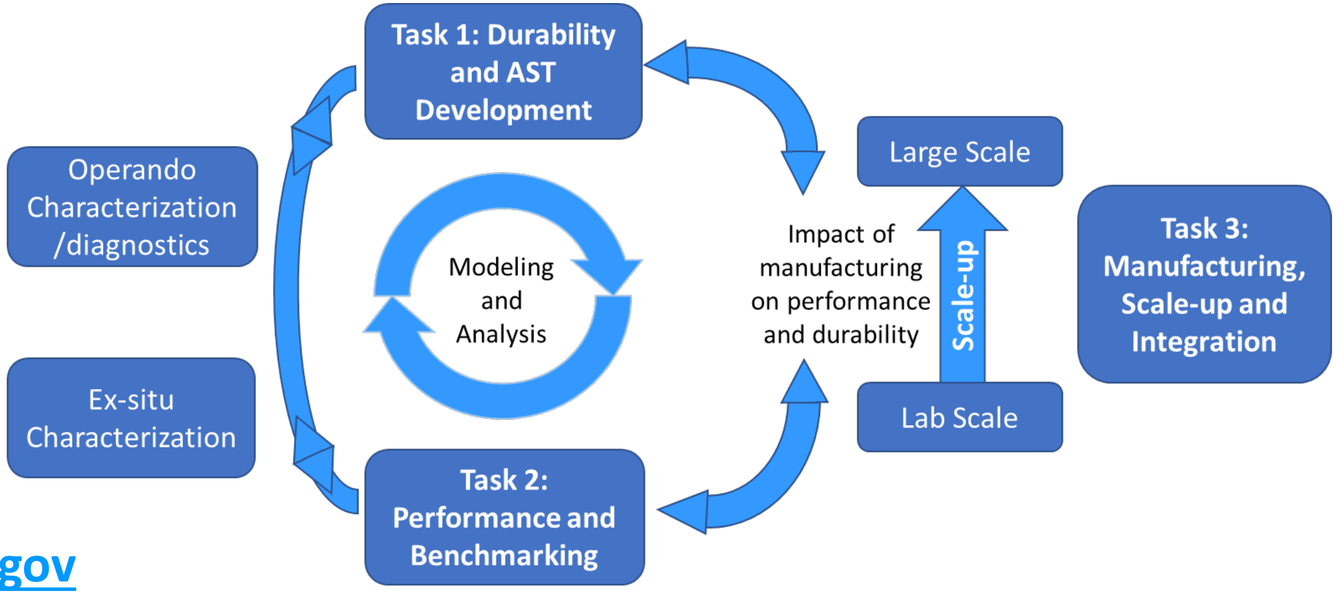
Low Temperature Electrolysis (LTE), 75%:

- Task 1: Durability and AST Development (P196a)
- Task 2: Performance and Benchmarking (P196b)
- Task 3: Manufacturing, Scale-up, and Integration (P196c)
- Task 3c: System and Techno-economic Analysis (P196d)

High Temperature Electrolysis (HTE), 25%:

- Task 5: Durability and AST Development (P196e)
- Task 7: Advanced Characterization (P196f)
- Task 8: Multiscale Modeling (P196g)

AMR posters provided in parenthesis



- Close coordination of electrolyzer manufacturing efforts
- Stakeholder Advisory Boards established, representing OEM, tier 1 suppliers, manufacturing, and academia

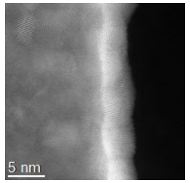
External website being established: h2new.energy.gov

Enabling MW-Scale Manufacturing of Electrolyzers Critical to H2@Scale

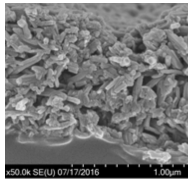
Advanced components, sub-systems, & systems for multi-MW-scale electrolyzers

Advanced Components

Catalyst



Electrode

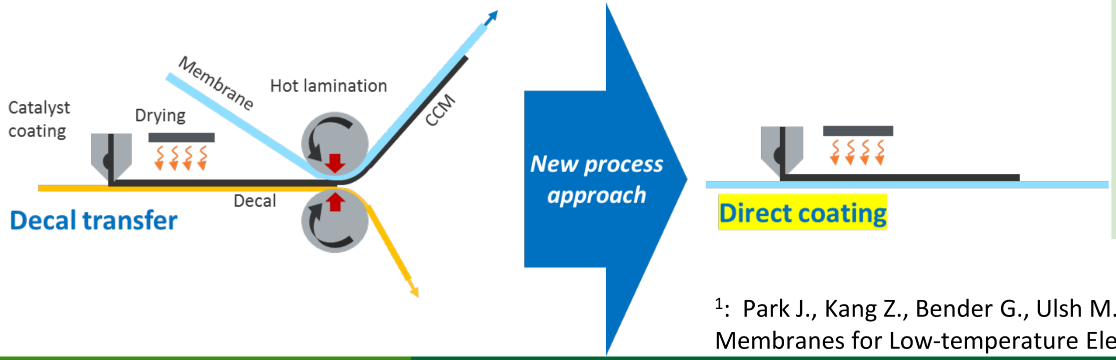


GW-Scale Manufacturing

MW-Scalable Electrolyzers

Courtesy of Plug Power Inc.

Manufacturing solutions for low cost, efficient, durable & reliable multi-MW scale deployments [1]



Close coordination of Manufacturing efforts with H2NEW

5 year, \$10M/yr Multi-Lab Consortium

Objective: Overcome technical barriers & enable affordable, reliable & efficient low and high temperature electrolyzers at <\$100/kW

FOAs

Addressing components, materials integration, & manufacturing R&D

LTE ($14M Effort - 3 New Projects)	HTE ($10M FY21 FOA Topic)
• **Plug Power**: Single-piece multi-functional integrated membrane anode assembly • **3M:** Advanced manufacturing technology enabling fabrication of SOA catalysts & electrodes • **Proton Energy:** Develop & optimize manufacturable PTL at >1000 cm^2	• Decrease part count, reduce processing steps, standardize processes & components • Develop real-time quality control metrology techniques • Manufacturing techniques targeting cost of $300/kW ***Selection announcements expected soon***

[1]: Park J., Kang Z., Bender G., Ulsh M., Mauger S.A. "Roll-to-roll Production of Catalyst Coated Membranes for Low-temperature Electrolyzers." *Journal of Power Sources*, 479, 2020.

Benchmarking & Protocol Development for AWS Technologies

Project Goal:

- Develop **best practices** in materials **characterization & benchmarking** critical to accelerating AWS materials discovery & development

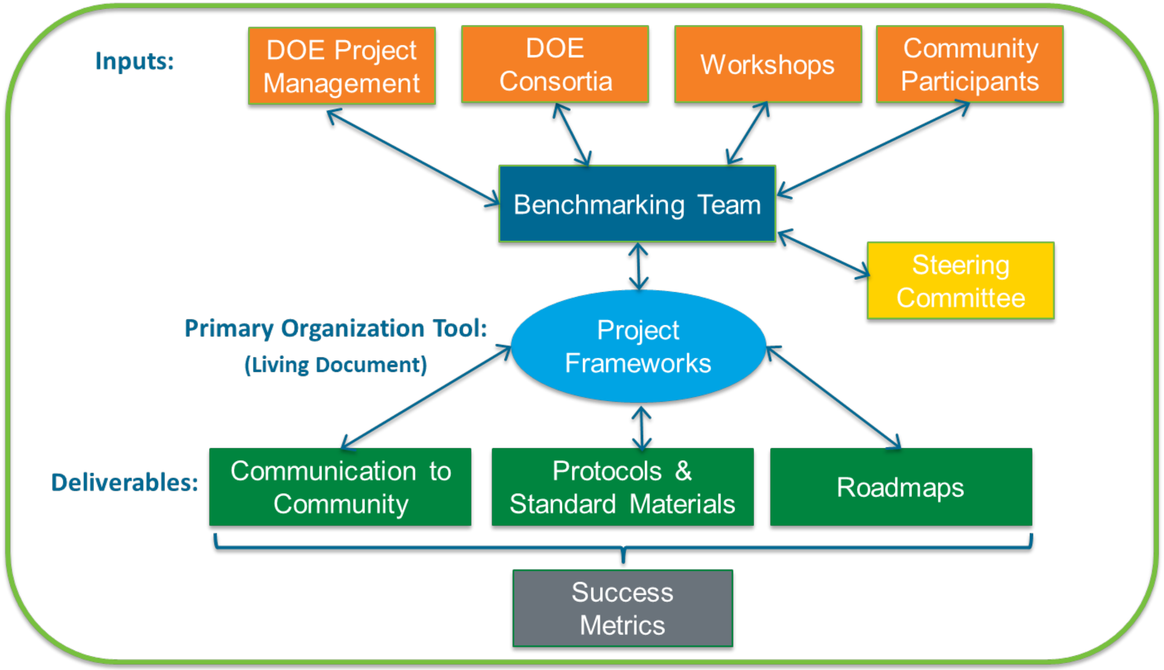
LTE PEC HTE STCH

Community Engagement

- 2nd Annual AWS benchmarking workshop (ASU, Oct. 29–30, 2019)
- 3rd Annual AWS benchmarking workshop (Virtual, March 1–3 & 8, 2021) **~200 attendees** & **15 countries** represented

Roadmaps & Protocols

- 4 AWS pathways **Roadmaps** drafted
- **45 test protocols drafted** & reviewed
- 25 additional protocols being drafted
- **Protocols to be published by end of 2021 in the journal *Frontiers in Energy***

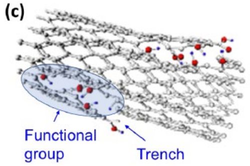


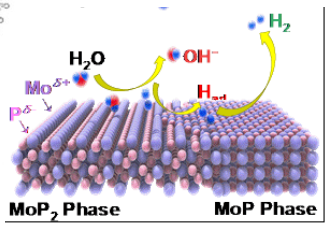
nel number one by nature™ ASU Arizona State University Caltech PNNL

Innovative H_2 Production from Biomass & Waste Streams

Opportunities

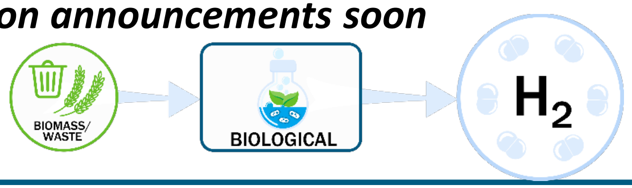
- Microorganisms can **consume & digest organic matter** & release H_2
- **77 million dry tons of wet waste**
  - Leverage for sustainable H_2 production
  - Avoid high costs of waste treatment, transportation, & disposal





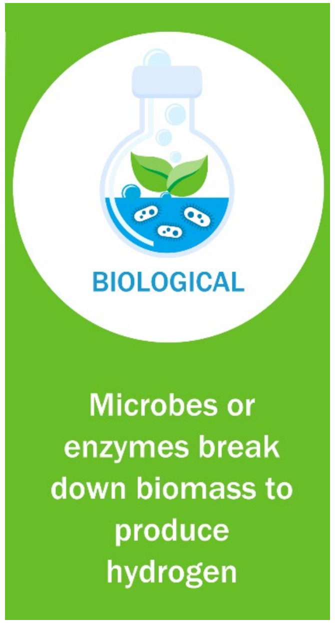
FY21 FOA Topic: *Innovative H_2 Production from Biomass Waste Streams*

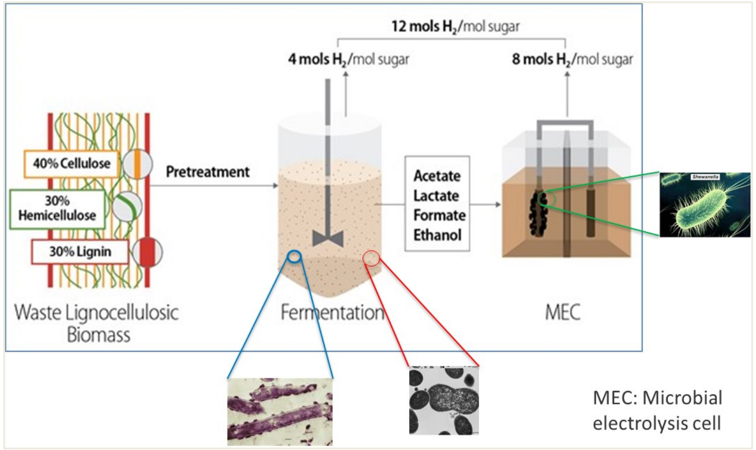
- Potential for \$2/kg-H_2 while simultaneously **addressing waste disposal issues**
- **\$2M in Federal Funds**
- ***Selection announcements soon***



R&D Needs

- Novel MECs & reactors to improve H_2 yield & reduce costs
- Improved MEC lifetime & robustness
- Optimized hybrid systems for maximum H_2





MEC: Microbial electrolysis cell

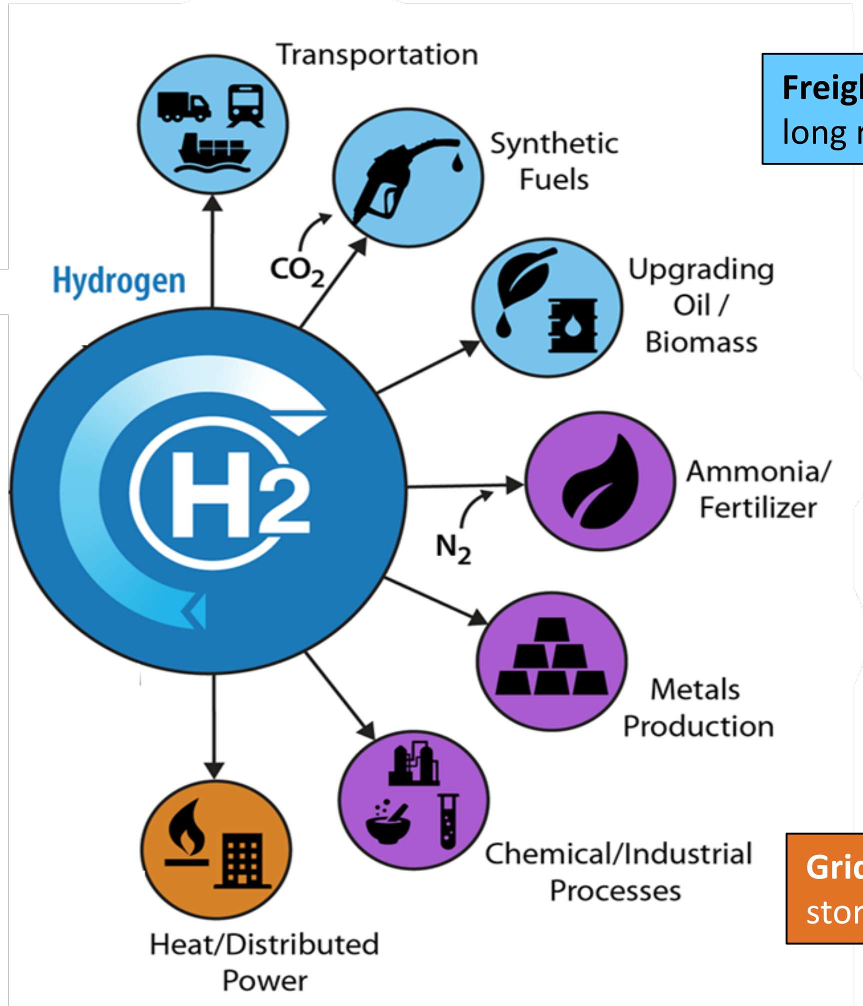
Key Technical Accomplishments

- 33% increase in H_2 production from original baseline via better hemicellulose & cellulose co-utilization
- Doubled H_2 production at 60 g/L crystalline cellulose loading via fed-batch operation scheme
- 100% increase in H_2 production over the SOA using brewery wastewater

Hydrogen Infrastructure for Diverse End-Uses

H_2 Can Help Decarbonize Many Applications and Sectors

Different end-uses are expected require different delivery and dispensing conditions, such as for hydrogen quality, flow rate, pressure and temperature



Freight Trucks: Consume 22% of fuel and transport 70% of U.S. freight. H_2 can enable long range and fast fueling.

Marine Vessels: >3% of global CO_2 emissions are from marine vessels. Initial IMO GHG Strategy aims to halve GHG emissions by 2050.

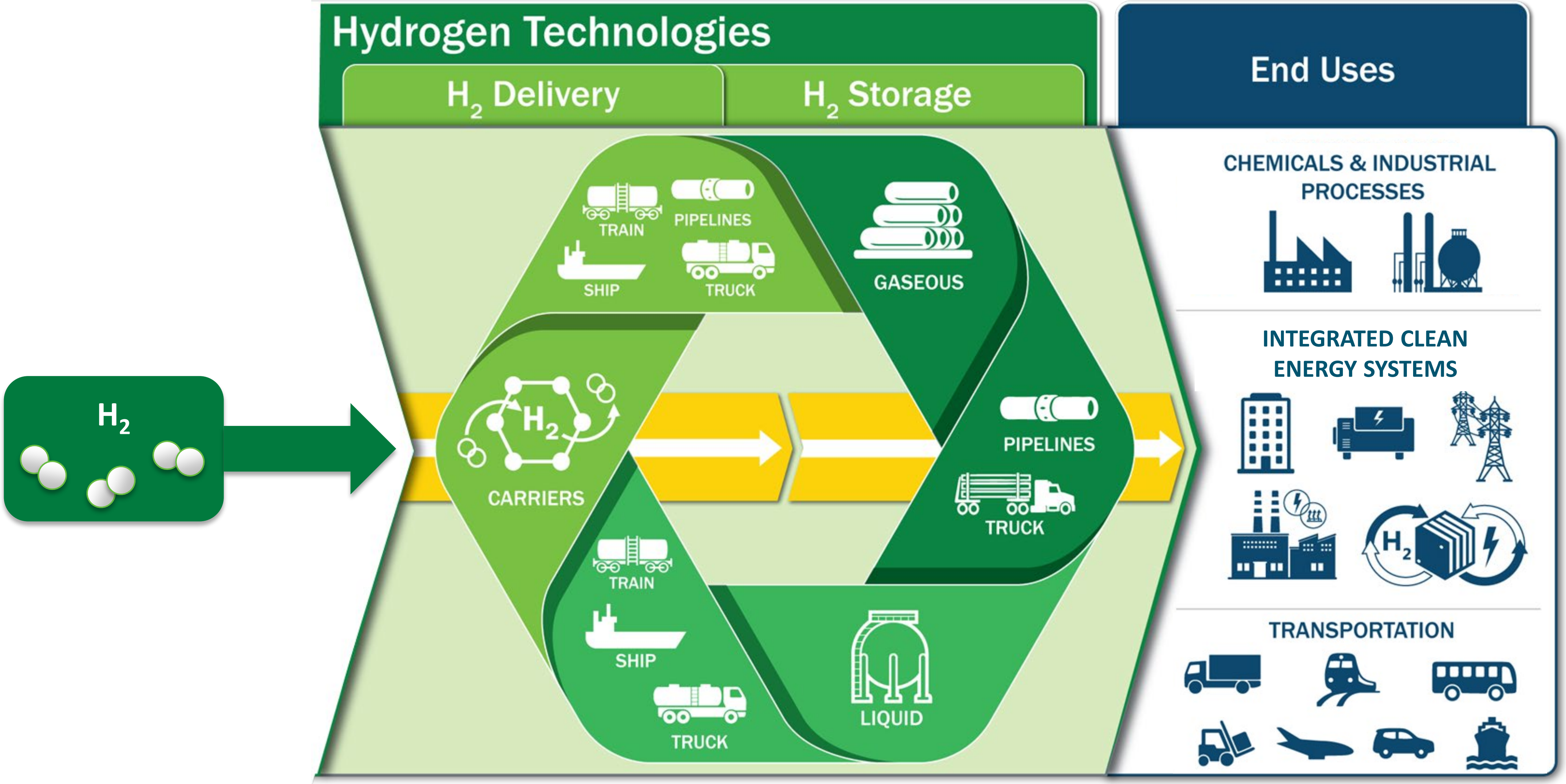
Clean Fuels: H_2 is a feedstock along with CO_2 for synfuels production.

Ammonia: 2^{nd} most widely produced chemical worldwide (by wt). 1-2% of global CO_2 emissions. Can serve as H_2 carrier as well as its use in fertilizer and as a chemical reagent.

Iron, steel and cement: 15% of global CO_2 emissions.

Grid and Buildings: Can enable renewables & baseload (nuclear, fossil) through energy storage and ancillary services and provide fuel for heat or power.

Hydrogen Infrastructure: Delivery, Storage and Dispensing



Hydrogen Infrastructure
Delivery and Dispensing
Oral Project Presentations Wednesday-Thursday, June 9-10

H-Mat (Hydrogen Materials Compatibility) Consortium

Materials Development to Enable 50% Increase in Life of Materials in Hydrogen Environments

- Damage in materials used in fueling stations commonly due to pressure cycling in H_2.
- Storage is the second most expensive component at fueling stations; commonly replaced in <5 years due to limited life in H_2.

H_2 can diffuse into materials and reduce their durability. Effects are exacerbated in materials that experience pressure cycles.

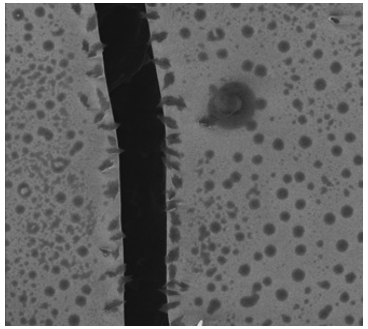
World-Class Materials R&D Capabilities

- Mechanical testing in high-pressure, temperature-controlled hydrogen environments, advanced imaging, and computational modeling tools
- National laboratory expertise developed through decades of R&D that informed hydrogen codes & standards and component design
- Two online portals for metals and polymers, to enable data sharing with global community

H-Mat Focus Areas

- **Polymers**: Improve life of seal materials in H_2 by 50%.
- **Metals:** Increase life of storage vessels in hydrogen by 50%.
- **Pipelines:** Characterize life of metal and polymer pipe materials in hydrogen blends.
- **Cross-cutting:** Support industry and academia in development of novel low-cost materials for H_2 service.

R&D can identify operating conditions and materials engineering techniques that increase component life.



More info at https://h-mat.org

Collaboration between 5 national labs & teams from industry and academia

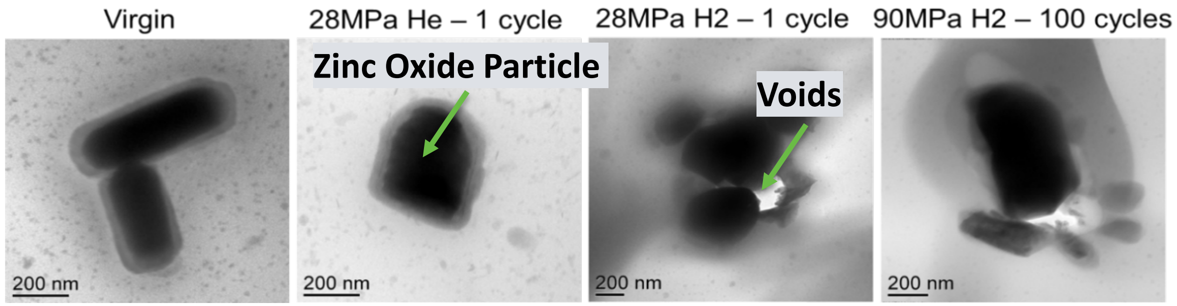
- Partners engaged through FOAs, SBIRs, and CRADAs
- International MOUs and "Affiliate Memberships" to enable coordination and collaboration with world leaders in the field.
- Online data portal to share information with R&D community worldwide

Sandia National Laboratories | PNNL | Oak Ridge National Laboratory | SRNL | Argonne National Laboratory

H-Mat – Key Accomplishments

Hydrogen Materials Compatibility Consortium

Polymers



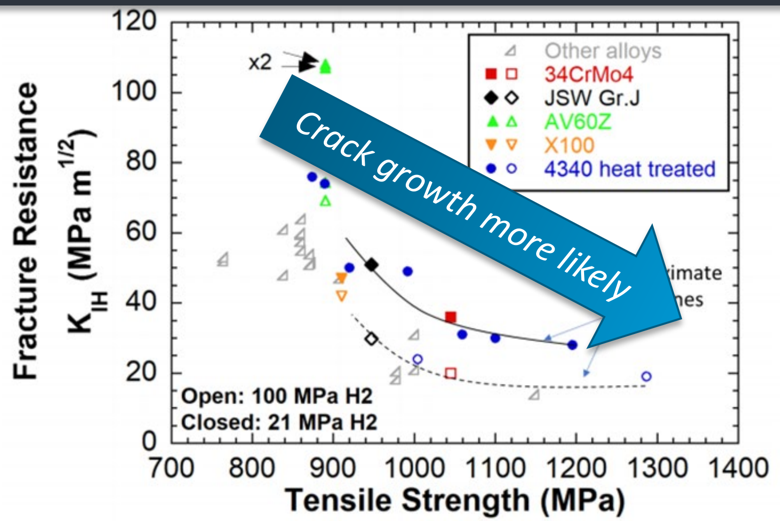
Increasing hydrogen pressure and cycles cause void formation

Identified microstructural features within EPDM materials that are likely locations for void formation

- *Cycled polymer materials from industry partner (Takaishi Industries) in up to 90 MPa hydrogen and conducted TEM to visualize microstructure changes*
- *Validated phase field models of EPDM to predict void formation, and inform materials development*

For more information, please see ***IN001b***

Metals



Systematic in situ testing of 9 microstructural variants of a PV steel confirm strong correlation between strength and reduced fracture resistance.

- *Conducted molecular dynamics simulations and imaging to identify features most likely to contribute to crack growth*
- *Simulations will inform synthesis of experimental microstructures with enhanced resistance to fatigue*

For more information, please see ***IN001a***

HyBlend: Assessing Feasibility of Hydrogen Blending in Natural Gas Pipelines

HyBlend
U.S. DEPARTMENT OF ENERGY

Blending can reduce emissions from heating and power generation

- 30% blend = 10% ↓ CO_2 emissions[1]
- Blend percentages vary greatly by region/country, from <1% to 30%.
  - Up to 15% may be feasible without significant changes to infrastructure.[2]

1. Source: IEA 2. Source: Melaina, et. al., NREL, 2010

>20 Stakeholders & 6 National Labs

Labs: NREL, SNL, PNNL, ANL,ORNL, NETL

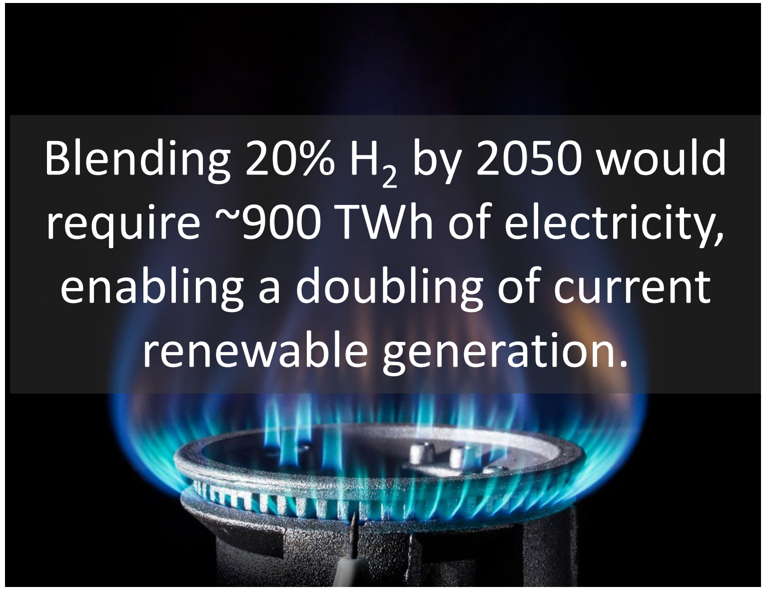
Stakeholders: Air Liquide, Chevron, DNV GL, Enbridge, EPRI, Exxon, GTI, HI Gas, Hydril, National Grid, NJNG, OneGas, OTD, PRCI, SMUD, Southern Company Gas, Stony Brook University, SWRI, Tenaris, and more

HyBlend Tasks

Test materials in varying blends (pressure, temperature, composition)

Develop public model of pipeline integrity to inform operating conditions.

Technoeconomic and life cycle analysis of blending relative to renewable natural gas.



Prior Accomplishments of Lead Labs

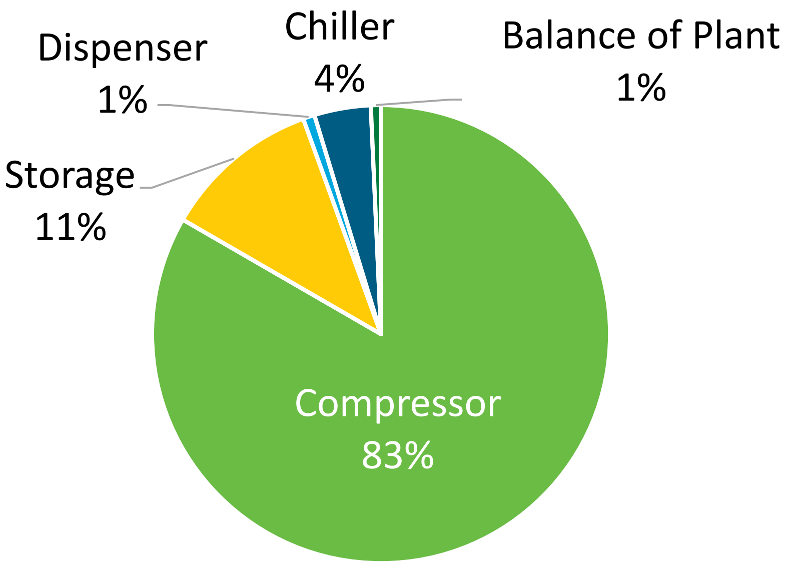
- Materials testing that informed revisions to ASME Code for Hydrogen Piping and Pipelines (SNL)
- Development of the GREET life cycle analysis model, with >40,000 users worldwide. (ANL)
- Performance validation of electrolyzers in grid-integrated conditions, and technoeconomic analysis of H2@Scale (NREL)

HD Hydrogen Fueling Station Component RD&D

Key Barriers to Deployment of MD/HD Hydrogen Fueling Stations:

1. Limited supply chain of critical components
2. Capital cost of fueling components

Levelized Cost of Hydrogen Dispensing ($/kg) Heavy Duty Trucks



Assumes fueling 50 vehicles at 700 bar in 6 hours.
Actual costs will vary depending on station design.
Source: Heavy Duty Refueling Station Analysis Model, Argonne National Laboratory
https://hdsam.es.anl.gov/index.php?content-hdrsam

FY20 CRADA Call: 5 projects selected (total: ~10M), focused on design of fueling stations for MD/HD applications and ports, R&D and cost analysis to inform fueling methods, chiller technologies, cyber-security.

FY21 FOA Topic: Solicits proposals for ***Domestic Supply Chain for High-flow Hydrogen Stations***. Projects are to be up to 3 years in duration with $1-3 million in DOE funding. Total DOE funding commitment of up $8 million. ***Selection announcements expected soon.***

Focus Areas of Ongoing Projects:

- Development of nozzles, hoses, meters and wireless communications
- Novel concepts (e.g. piston expander) for hydrogen pre-cooling
- High-throughput compressors and cryopumps, mitigating need for cascade storage
- Cross-cutting materials R&D to lower cost and improve reliability

Hydrogen Infrastructure

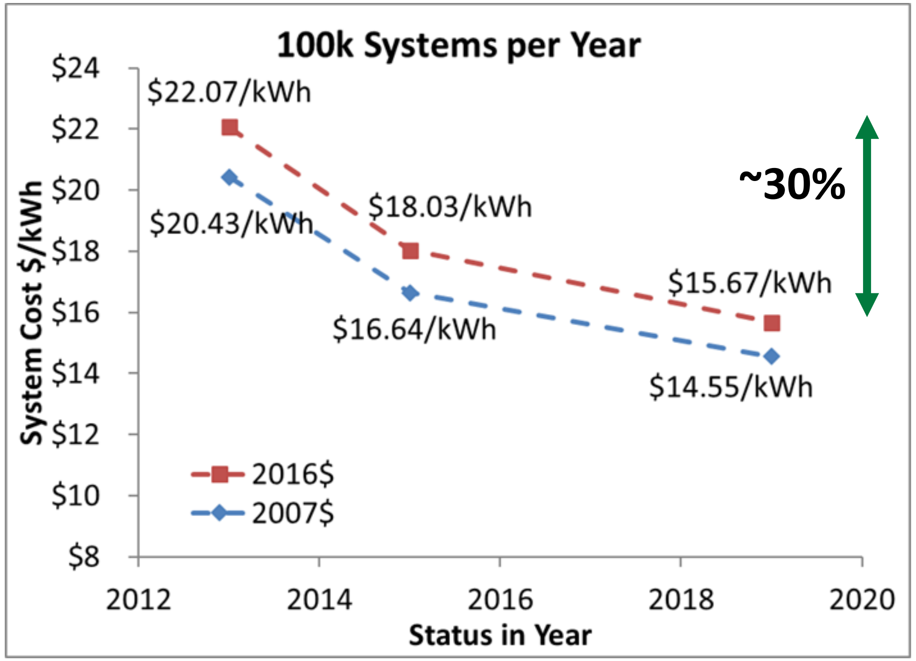
Hydrogen Storage

Oral Project Presentations Friday, June 11

Hydrogen Storage System Cost Analysis

Onboard LDV *System* Cost Record Updated in 2019

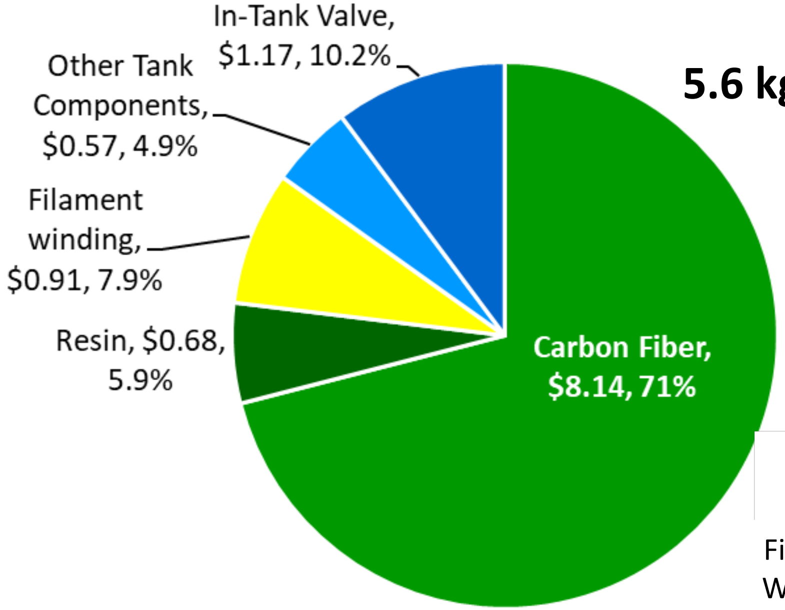
- ~30% cost reduction from 2013 to 2019 at 100k annual production rates



Type IV, 700 bar, 5.6 kg usable capacity, single tank system

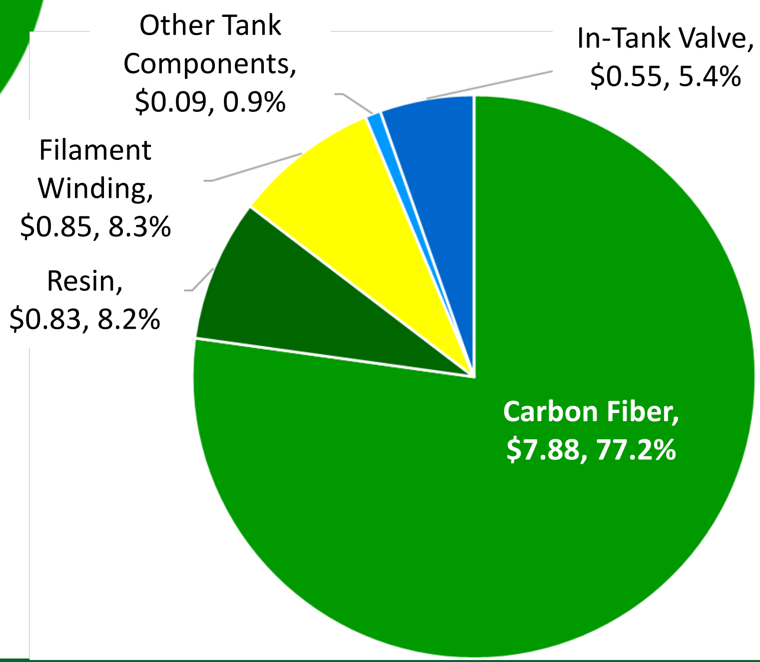
Cost Breakdown Comparison between LDV and HDV *Tanks*

Type IV, 700 Bar Tank with an In-Tank Valve @ 100k units/yr



5.6 kg usable H_2Capacity
$11.47/kWh

20 kg usable H_2 Capacity
$10.21/kWh



Note: Not the cost for the whole system but just a tank with an in-tank valve!

https://www.hydrogen.energy.gov/pdfs/19008_onboard_storage_cost_performance_status.pdf

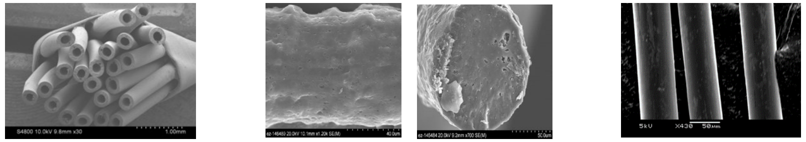
Advanced Carbon Fiber for Compressed Hydrogen Storage Tanks

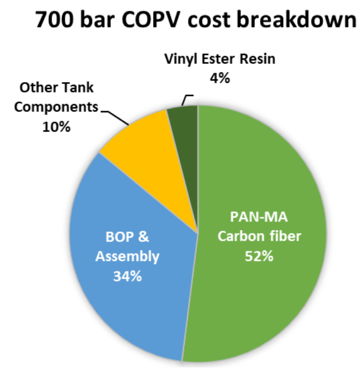
Technical goals

- ***Targets 50% cost reduction for compressed hydrogen storage systems***
- Full scale carbon fiber development
  - Lower cost carbon fiber
  - Improved carbon fiber properties
- Improved carbon fiber composite performance
- Increased gravimetric energy density

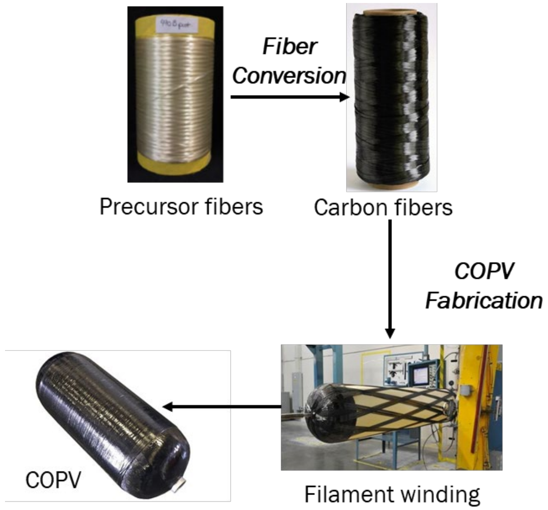
Status

- Carbon fiber production accounts for ~ 50% total cost of onboard storage tanks
- Previous work: reduce cost via novel fiber precursors
  - *Teams:* Penn State University, University of Kentucky, Oak Ridge National Laboratory (ORNL)
  - *Accomplishments:* potential for 18% decrease in carbon fiber cost





	Current Status	2025 Targets	Ultimate Targets
Gravimetric capacity (KWh/kg)	1.5	1.8	2.2
Cost ($/KWh)	16	9	8



New projects

Development and demonstration of enhanced carbon fibers and COPV for onboard hydrogen storage

- University of Kentucky - hollow carbon fibers
- University of Virginia - low-cost precursor fibers
- Hexagon LLC - optimized fiber synthesis & conversion
- CCSC (IACMI) - melt spinning precursor fibers
- *ORNL stand-alone efforts - gel spinning*

HEXAGON

UK University of Virginia Oak Ridge National Laboratory The Composites iacmi Institute

Project details

- Develop low-cost carbon fibers and COPV tanks for hydrogen storage
- Two phases: Phase I (2 years) & Phase II (3 years)
- Only one project advances to Phase II
- Joint effort across 3 EERE offices: Hydrogen and Fuel Cell Technologies Office (HFTO), Advanced Manufacturing Office (AMO) and Vehicle Technologies Office (VTO)
- ***DOE Funding Commitment: $15 million***

Bulk Hydrogen Storage RD&D

Large-capacity liquid hydrogen (LH2) storage

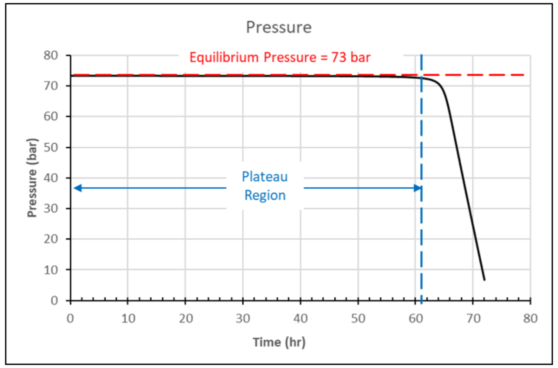
Develop large-capacity, double-walled, insulated pressure tanks

- Deliverables: LH2-based cryostat, sub-scale demo tank
- **Targets:**
  - *Volume:* 20,000 m^3 - 100,000 m^3
  - *Boil-off rate:* 0.01-0.3%/day;
  - *CAPEX:* <$175 million (100,000 m^3 tank)

Metal Hydride-based storage for FC powered data centers

Technoeconomic analysis to determine viability of MH-based storage to satisfy needs for data center operation

- Deliverable: Detailed report on feasibility of the concept
- **Targets:**
  - Identification of top candidates
  - 20 MW/72 hr of back-up
  - $450-600/kg H_2 stored



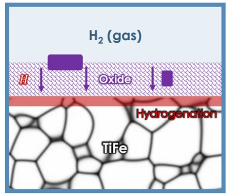
Savannah River National Laboratory

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Surface engineering of TiFe intermetallic hydrides for improved hydrogenation activation

Multiscale modeling of the relationship between activation/incubation time and surface oxide to guide engineering of TiFe alloys with improved hydrogen storage properties.

- **Targets:**
  - Demonstrate reduction of activation time to < 5 hours at 100 °C and 25 bar H_2

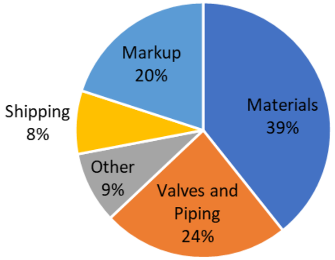


Lawrence Livermore National Laboratory

Bottoms-up Cost Analysis of Bulk Liquid H_2 Storage for Refueling Stations

Develop cost models for bulk liquid storage installations suitable for use at ≥1000 kg/day fueling stations

- **Targets:**
  - Benchmark against vendor quotes
  - 68 m^3 volume (~4500 kg) capacity



STRATEGIC ANALYSIS

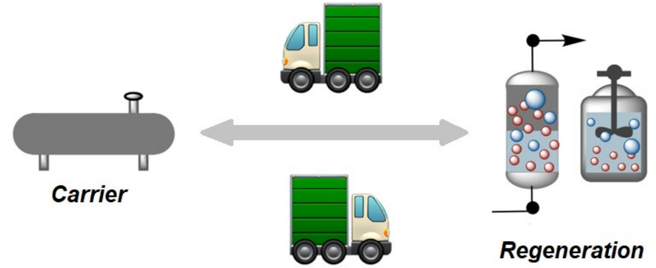
Argonne NATIONAL LABORATORY

Pacific Northwest NATIONAL LABORATORY

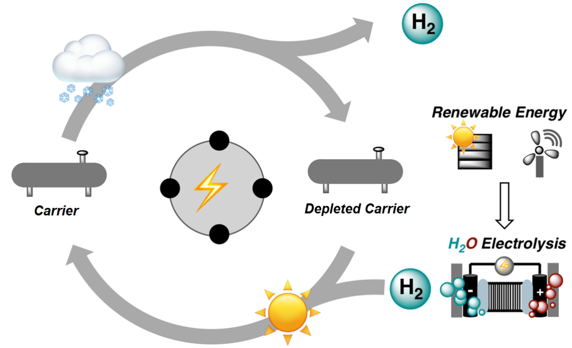
Hydrogen Carriers RD&D

Hydrogen Carrier scenarios

- 1) Used at distributed sites but regenerated at central facility



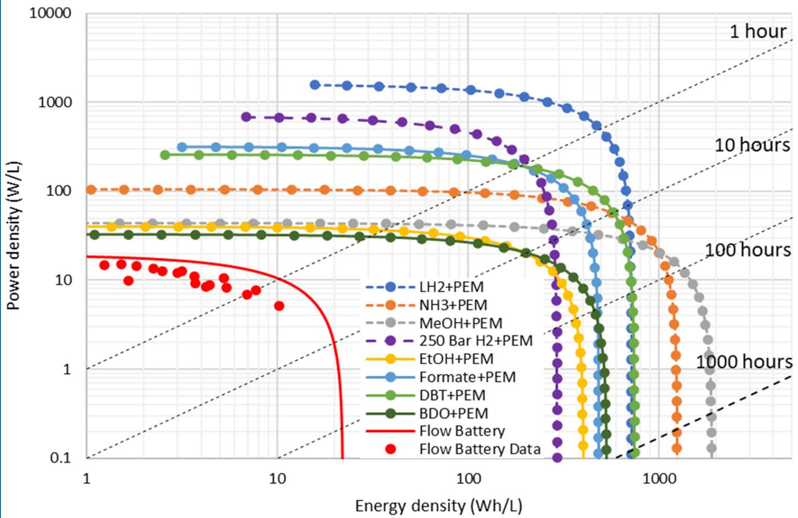
- 2) Release/regeneration both carried out on-site



- Analysis on material needs for specific use cases is guiding carriers materials development R&D

Materials Development R&D

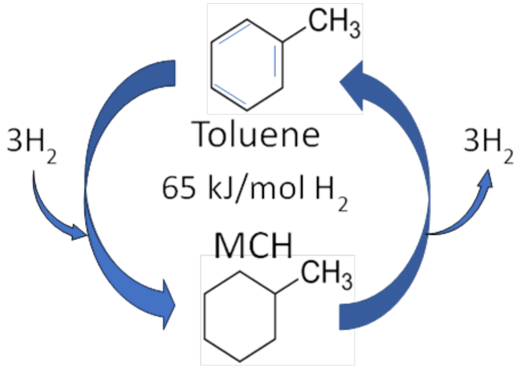
- Several carriers outperform 700 bar/ LH2 in certain scenarios



- Materials efforts focus on catalyst synthesis and operation to improve release/regeneration; evaluating reactor designs; development of new types of carriers (i.e. porous liquids, flexible adsorbents)

Example: Carrier system for renewable steel production (LBNL/ANL/PNNL)

- Methylcyclohexane is a carrier being used industrially today



- Project is evaluating the performance and cost of MCH-based carrier system in place of 700 bar/LH2 on-site storage technologies
- Separate ANL-led project evaluating dibenzyltoluene for grid energy storage application

HyMARC Hydrogen Materials Advanced Research Consortium

Berkeley Lab | Argonne National Laboratory | Pacific Northwest National Laboratory

Hydrogen Materials—Advanced Research Consortium

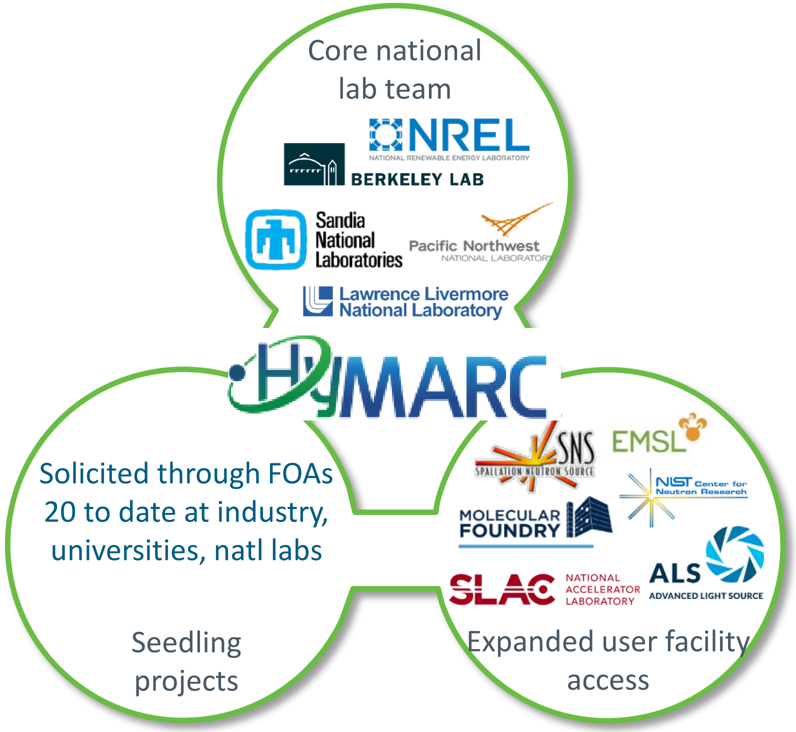
Accelerating H_2 storage materials development to enable 2x energy density

- Addresses critical R&D gaps, leveraging advances in multiscale modeling, *in situ* characterization, and novel materials synthesis techniques
- Develops foundational understanding of thermodynamics and kinetics of hydrogen release and uptake in all classes of storage materials
- Joins world-class national lab capabilities with innovative ideas from academia and industry

Key Accomplishments

- First material that binds 2 H_2 molecules at a MOF open metal site
- Synthesized best performing MOFs for room temperature hydrogen adsorption
- Improved MgB_2—$Mg(BH_4)_2$ hydrogenation by 100 °C and 200 bar over state-of-the-art
- Demonstrated 2x hydride (de)hydrogenation rates through nanoconfinement in carbons
- Applied machine learning and modeling to identify thousands of MOFs with potential to exceed state-of-the-art H_2 capacities

HyMARC Structure



Core lab group works synergistically with new seedling projects solicited through funding opportunity announcements, with all groups having streamlined and expanded access to characterization tools at world-class user facilities

Tasks

- Task 1: Sorbents
- Task 2: Hydrides
- Task 3: Carriers
- Task 4: Advanced Characterization
- Task 5: Seedling Support
- Task 6: Data Hub

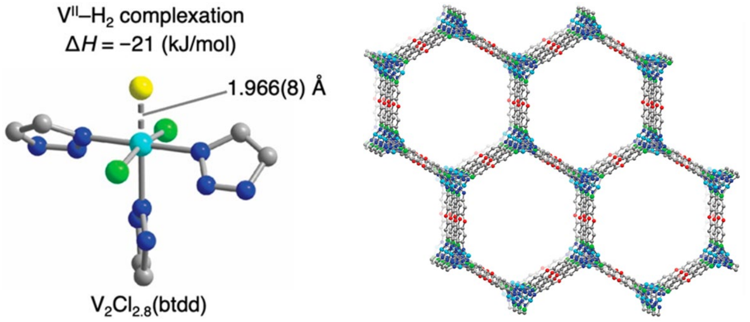
HyMARC by the numbers

130+ publications and 1 book chapter
9 patents and 2 pending
60+ lab staff/scientists
57 postdocs
35 grad students
13 undergrads involved

HyMARC – Key Accomplishments

First MOF with binding energy in the 15-25 kJ/mol range (LBNL/NIST) [1]

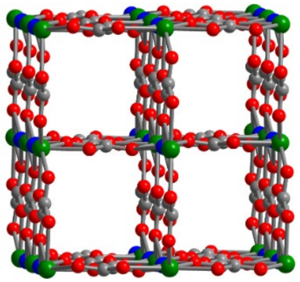
- $V_2Cl_{2.8}$(btdd), 21 kJ/mol – Ideal range predicted to enable RT operation
- 38% higher than cH_2, 27% improvement over SOA

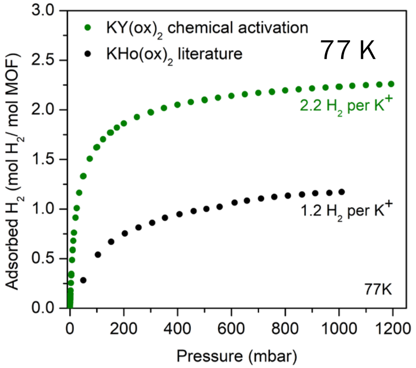


[1] D. E. Jaramillo, J. R. Long, et al *J. Am. Chem. Soc.* 2021 doi 10.1021/jacs.1c01883

Oxalates may bind > 2 H_2/metal (LBNL)

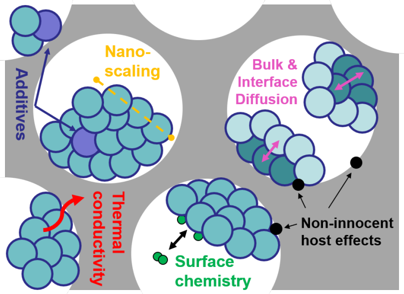
- KY(ox)$_2$ adsorbs 2.2 H_2 per K^+ at 77 K; NPD pending

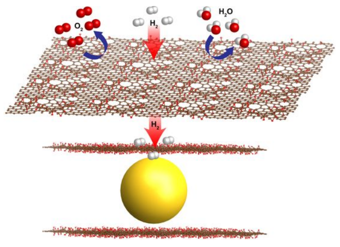




Encapsulated and nanostructured MHs (NREL/SNL/LLNL/LBNL)

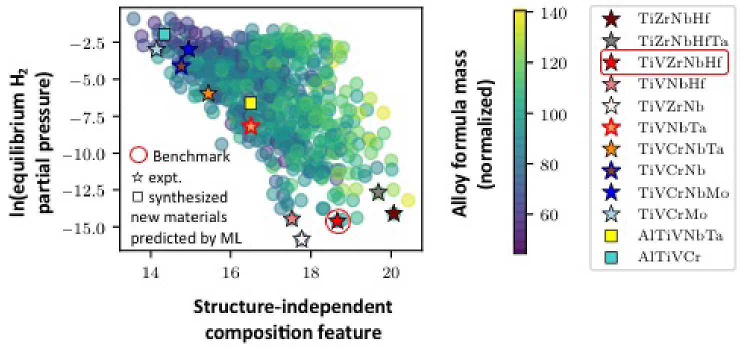
- Reduction of thermodynamic and kinetic barriers in metal hydrides shown with multiple types of synthetic techniques





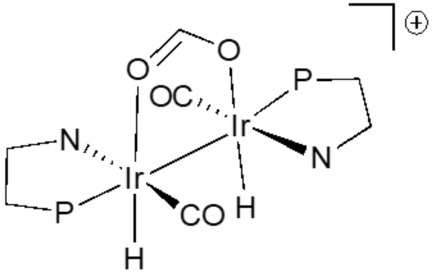
MH discovery using machine learning (SNL)

- ML model + MH database data dramatically reduces material discovery time
- New materials made; performance validated



Formic acid dehydrogenation (USC/PNNL)

- Ir catalyst improves H_2 dehydrogenation rates and can generate 170+ bar pressure
- Potential extension to blended fuels for carrier systems with higher H_2 capacities



4

Programmatic information and wrap-up

Hydrogen Technologies Program: Collaboration Network

Fostering technical excellence, economic growth and environmental justice

Efforts Support Over:
12 national laboratories
34 universities
25 companies

DOE H_2 Program Collaborations		
VTO	AMO	BETO
SETO	BTO	ARPA-E
SC	FE	NE
DOE Cross-Cutting Initiatives		
Energy Storage Grand Challenge	Advanced Transportation	Advanced Manufacturing
Space	Alternative Fuels	AI/ML
Decarbonize Agriculture/Buildings/Electricity/Industry/Transportation		

Cross-Agency Collaborations			
DOC-NIST	NASA	DOD	NSF

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

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

Hydrogen Technologies Program: Highlights and Milestones

FY2019

- *Data Centers Workshop*
- *FY19 DOE H_2 Program AMR*
- *FY19 FOA on H_2 carriers, H-Mat, HydroGEN seedlings and BioH_2*
- *FY19 Joint HFTO/VTO Joint FOA on H_2/NG storage for MD/HD*
- *1st Annual AWS benchmarking workshop*
- *Program Record: H_2 Production Cost From PEM Electrolysis - 2019*
- *Program Record: Onboard Type IV Compressed H_2 Storage System – Cost and Performance Status*
- *Program Record: Current Status of H_2 Liquefaction Cost*
- *H_2 Carriers Workshop*

FY2020

- *Compressed Gas Storage Workshop*
- *FY20 FOA on PEM Electrolyzer Manufacturing and Low-cost CF for Tanks*
- *FY20 Lab Call on H2NEW and HydroGEN 2.0*
- *Merger of US DRIVE Delivery and Storage Tech Teams into the HDSTT*
- *2nd Annual AWS benchmarking workshop*
- *Program Record: Cost of Electrolytic H_2 Production with Existing Technology*
- *Program Record: H_2 Production Cost From High Temperature Electrolysis – 2020*
- *Program Record: H_2 Delivery and Dispensing Cost*

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*
- *Commissioning of 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

- *FY22 FOA – topics tbd*
- *FY22 Lab Call – topics tbd*
- *2nd Liquid H_2 Workshop*
- *Bulk H_2 Storage Workshop*
- *Electrolyzer Workshop*
- *FY22 DOE H_2 Program AMR*
- *8th International Hydrogen Infrastructure Workshop*

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.

Hydrogen Technologies is currently seeking two candidates

- 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.

HFTO Contacts:

H_2 Production
Katie.Randolph@ee.doe.gov

Infrastructure
Neha.Rustagi@ee.doe.gov

To apply: https://www.zintellect.com/Opportunity/Details/DOE-EERE-STP-HFTO-2020-1804

Thank You

Dr. Ned Stetson

Program Manager, H_2 Technologies RD&D, HFTO

Ned.Stetson@ee.doe.gov

hydrogenandfuelcells.energy.gov