U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Importance of Liquid Hydrogen for Decarbonizing the Energy Sector

Ned Stetson, U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office

18 August 2021

Welcome!

This workshop is being co-hosted by
the *U.S. Department of Energy* and the *U.S. National Aeronautics and Space Administration*

Special acknowledgements for the workshop organization go to:

- **Asha-Dee Celestine**, Hydrogen and Fuel Cell Technologies Office, U.S. DOE Office of Energy Efficiency and Renewable Energy
- **Jeffrey Feller**, NASA Engineering and Safety Center
- **Adam Swanger**, NASA Kennedy Space Center
- **James Fesmire**, NASA Kennedy Space Center
- **Robert Johnson**, NASA Kennedy Space Center

Also, for workshop registration and webinar logistics:

- **Stacey Young**, the Building People, contract support to U.S. DOE-EERE
- **Eric Parker**, Allegheny, contract support to U.S. DOE-EERE-HFTO

The Day's Agenda

11:00 am	**Introduction; DOE Perspectives (Ned Stetson, DOE)** — 30 min.
11:30 am	**Historical Overview of LH_2 Operations at KSC (Robert Johnson, NASA-KSC)** — 30 min.
12:00 noon	**Break** — 15 min.
12:15 pm	**LH_2 Storage and Handling Demonstrations Using Active Refrigeration (Adam Swanger, NASA-KSC)** — 60 min.
1:15 pm	**Lunch** — 30 min.
1:45 pm	**The New LH_2 Sphere (James Fesmire, NASA-KSC)** — 60 min.
2:45 pm	**Break** — 15 min.
3:00 pm	**Economics of Energy-Efficient, Large-Scale LH_2 Storage Using IRAS & Glass Bubble Insulation (Adam Swanger & James Fesmire, NASA-KSC)** — 30 min.
3:30 pm	**Panel Discussion and Q&A: Path Forward and Wrap-Up (DOE & NASA)** — 30 min.
	Panel Participants: Ned Stetson (DOE), Adam Swanger (NASA KSC), Robert Johnson (NASA KSC), James Fesmire (NASA KSC), Peter Ferland (NASA KSC), Michael Meyer (NASA NESC), Jeffrey Feller (NASA NESC), John Barclay (PNNL), and Ian Richardson (Washington State University)

DOE Hydrogen Program Objectives

Examples of Key DOE Hydrogen Program Targets

DOE targets are application-specific and developed with stakeholder input to enable competitiveness with incumbent and emerging technologies. These targets guide the R&D community and inform the Program's portfolio of activities. Examples include:

- $2/kg for hydrogen production and $2/kg for delivery and dispensing for transportation applications
- $1/kg hydrogen for industrial and stationary power generation applications
- Fuel cell system cost of $80/kW with 25,000-hour durability for long-haul heavy-duty trucks
- On-board vehicular hydrogen storage at $8/kWh, 2.2 kWh/kg, and 1.7kWh/l
- Electrolyzer capital cost of $300/kW, 80,000 hour durability, and 65% system efficiency
- Fuel cell system cost of $900/kW and 40,000 hour durability for fuel-flexible stationary high-temperature fuel cells

Priorities

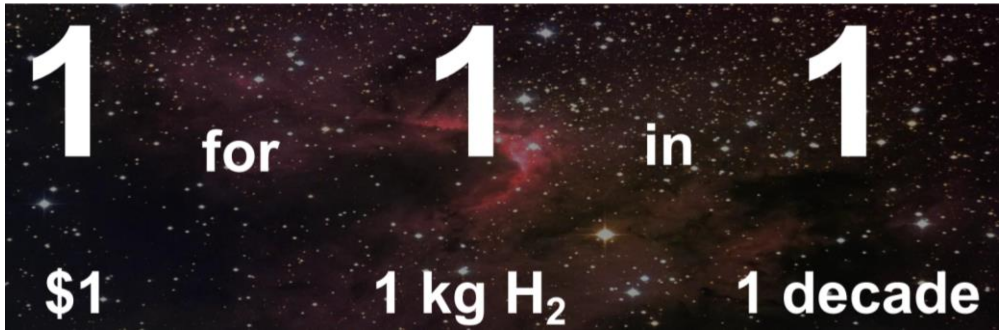
1. **Low cost, clean hydrogen production: $2/kg by 2025, and <u>*$1/kg by 2030*</u>**
2. **Low cost, efficient, safe hydrogen delivery and storage**
3. **End use applications to achieve scale and sustainability, enable emissions reduction and address environmental justice priorities**

Enablers: Workforce development, safety, codes, standards, analysis

Hydrogen Energy Earthshot

“Hydrogen Shot”

- ✓ Launched June 7, 2021
- ✓ First DOE Energy Earthshot
- ✓ ***Goal:*** reduce the cost of clean hydrogen by 80%



ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

“First up: Hydrogen Shot, which sets an ambitious yet achievable cost target to accelerate innovations and spur demand of clean hydrogen. Clean hydrogen is a game changer. It will help decarbonize high-polluting heavy-duty and industrial sectors, while delivering good-paying clean energy jobs and realizing a net-zero economy by 2050.”

US Department of Energy Secretary, Jennifer Granholm

The Hydrogen Shot Summit

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

August 31 & September 1, 2021

- ***Goal:*** Identify pathways to meet **Hydrogen Shot** target of **$1** per **1 kilogram** in **1 decade**.
- ***Target audience:*** stakeholders from industry, research, academia, and government
- ***Breakout sessions:***
  - Hydrogen production pathways
    - Electrolysis
    - Thermal conversion including carbon capture and storage
    - Advanced pathways
  - Deployment and financing

Several Plenary Speakers Announced Yesterday – Aug. 17

*****MEDIA ADVISORY*****

TUESDAY, 8/31: JOHN KERRY, BILL GATES TO JOIN DOE'S HYDROGEN SHOT SUMMIT

WASHINGTON, D.C. — On August 31, **Special Presidential Envoy for Climate John Kerry** and **Breakthrough Energy founder Bill Gates** will speak at the opening session of the Department of Energy (DOE)'s first ever Hydrogen Shot Summit, a virtual gathering of top leaders from around the world to map out strategies for achieving DOE's goal of driving down the cost of clean hydrogen by 80% within the decade.

In addition to the opening session emceed by **Deputy Secretary of Energy David M. Turk**, the summit will also include plenary session panels bringing together high-level government officials, industry members, regional and community leaders, and DOE national laboratories to share perspectives on how clean hydrogen can achieve the scale and impact needed to tackle the climate crisis and transition to an equitable clean energy future.

The EERE Hydrogen and Fuel Cell Technologies Office (HFTO)

Research, development and demonstration (RD&D) of hydrogen and fuel cell technologies that can advance

Key RD&D Sub-Programs

Fuel Cells

- Cost, durability, efficiency
- Components (catalysts, electrodes) & systems
- Focus on heavy duty applications (trucks, marine, data centers, rail, air, etc.)

Hydrogen

- Hydrogen production, infrastructure/delivery, storage (for transport and stationary storage)
- Cost, efficiency, reliability & availability

Systems Development & Integration

- Hybrid, grid integrated systems, energy storage
- Safety, codes & standards
- Technology acceleration
- Workforce development

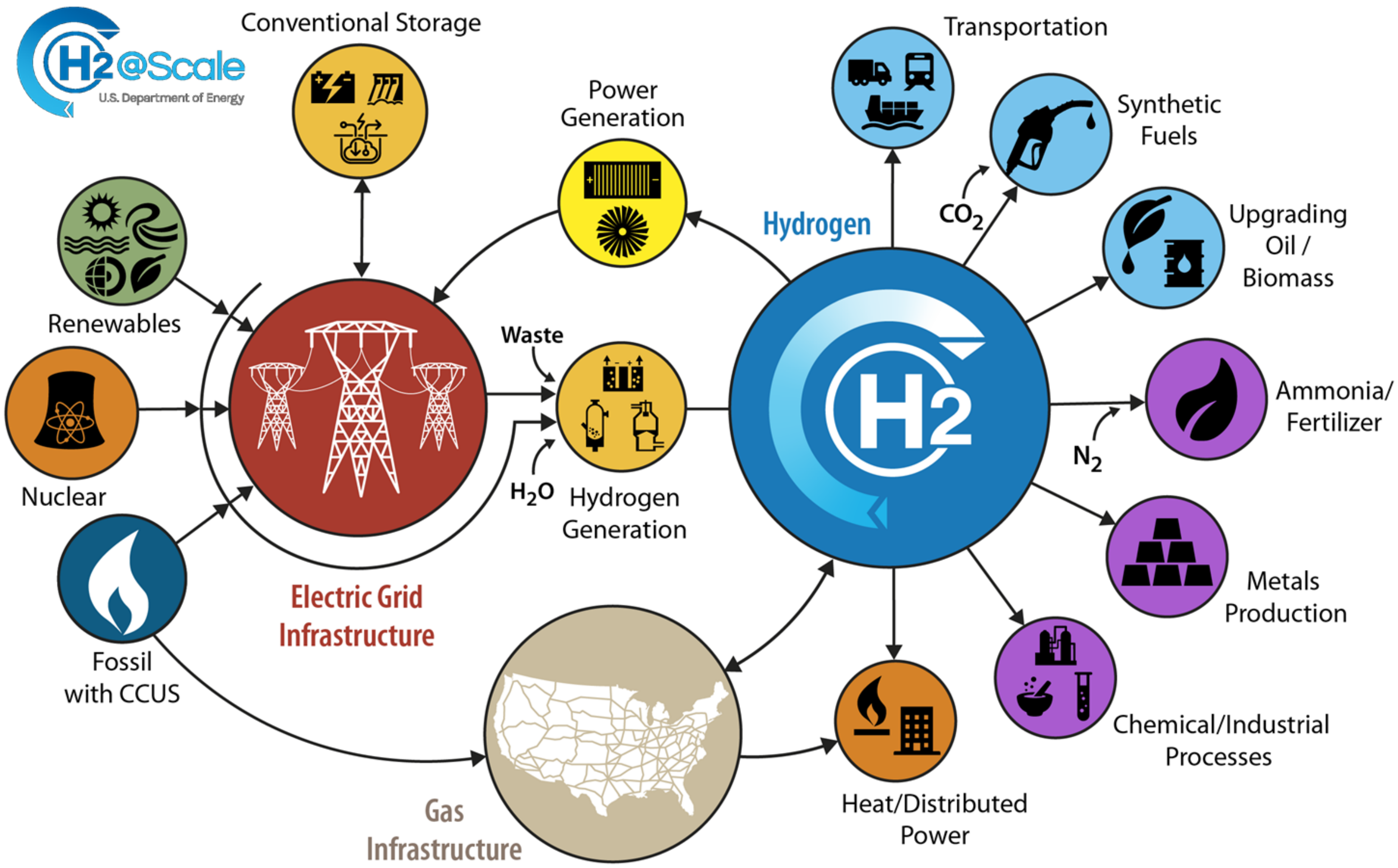
Data, Modeling, Analysis: Assess pathways, impacts; set targets, guide RD&D

Enabling

H2@Scale[SM]
U.S. Department of Energy

Hydrogen is one part of a Comprehensive Energy Portfolio

H2@Scale: Enabling affordable, reliable, clean, and secure energy across sectors



- Hydrogen can address specific applications across sectors that are hard to decarbonize
- Today: 10 MMT H_2/yr produced in the U.S.
- Economic Potential: 2 to 4x more

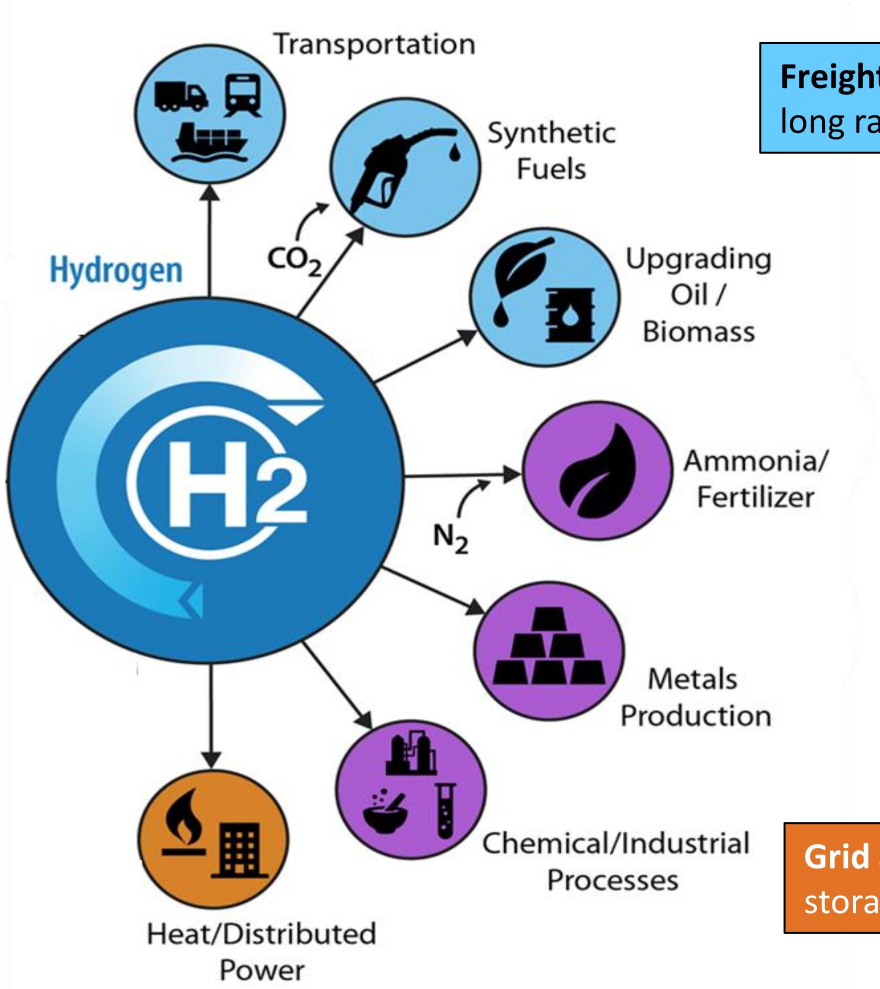
Strategies

- Scale up technologies in key sectors
- Continue R&D to reduce cost and improve performance, reliability
- Address enablers: harmonization of codes, standards, safety, global supply chain, workforce development, sustainable markets

Source: U.S. DOE Hydrogen and Fuel Cell Technologies Office, https://www.energy.gov/eere/fuelcells/h2scale

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.

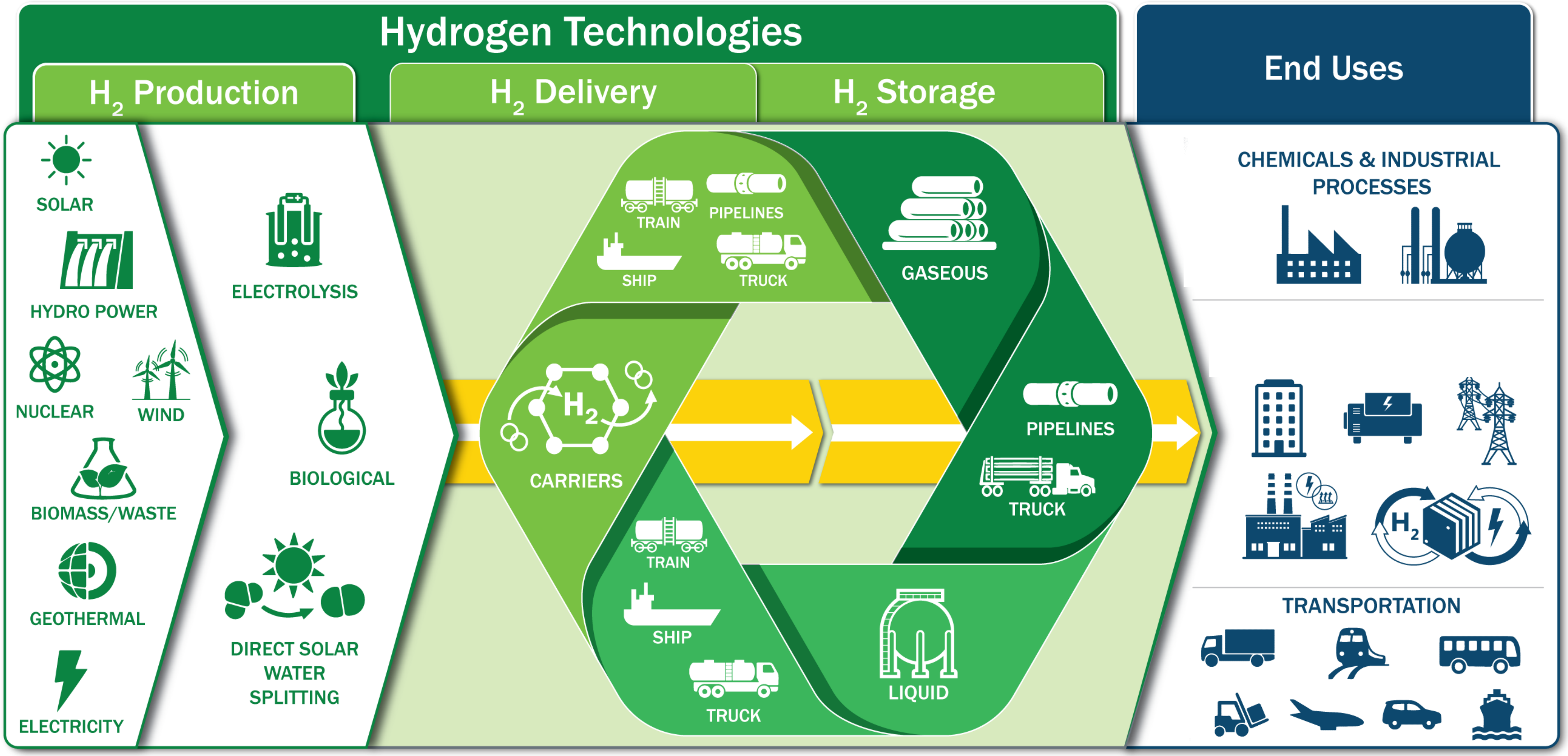
Clean Fuels: H_2 is a feedstock along with CO_2 for synfuels production.

Ammonia: 2nd 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.

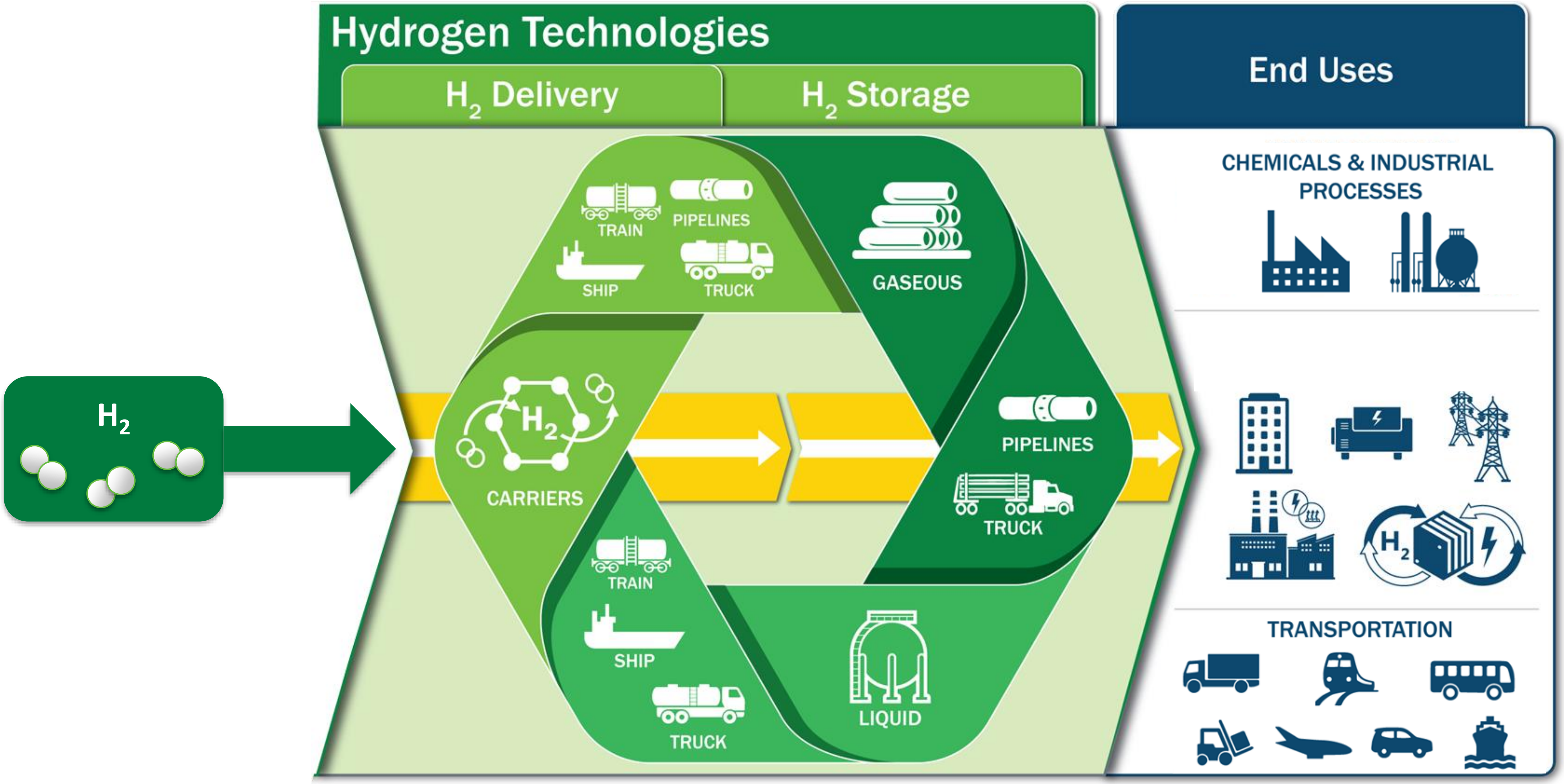
Grid and Buildings: Can enable renewables & baseload (nuclear, fossil) through energy storage and ancillary services and provide fuel for heat or power.

Hydrogen Technologies Program

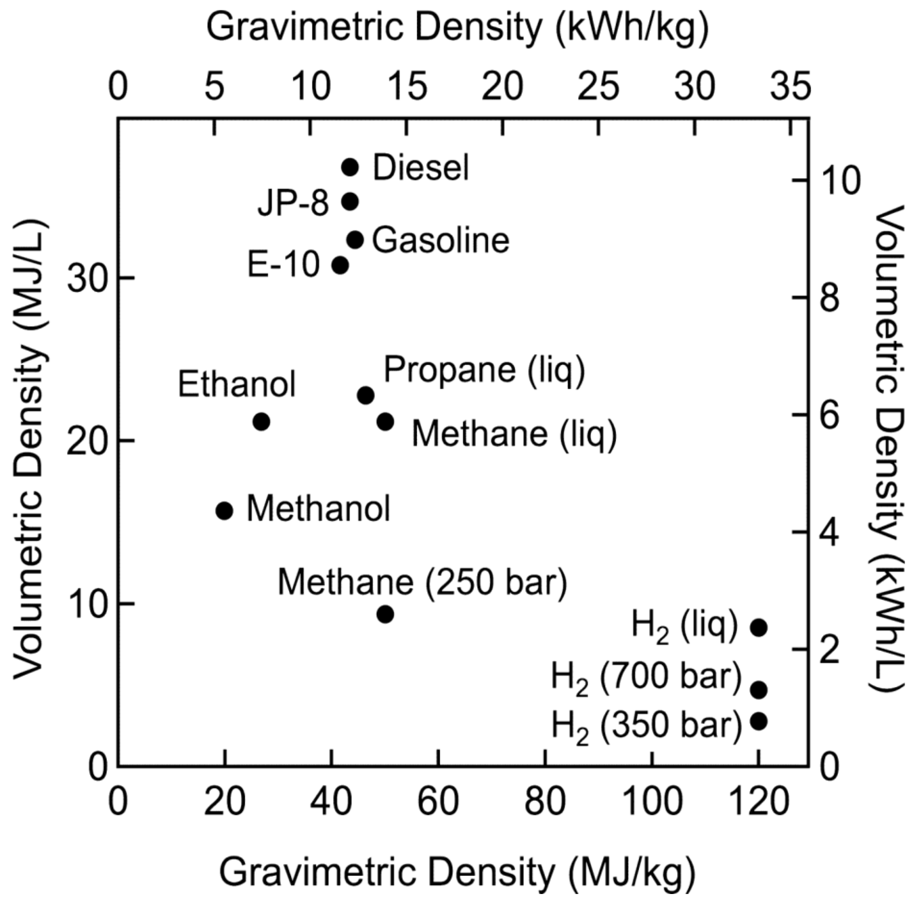


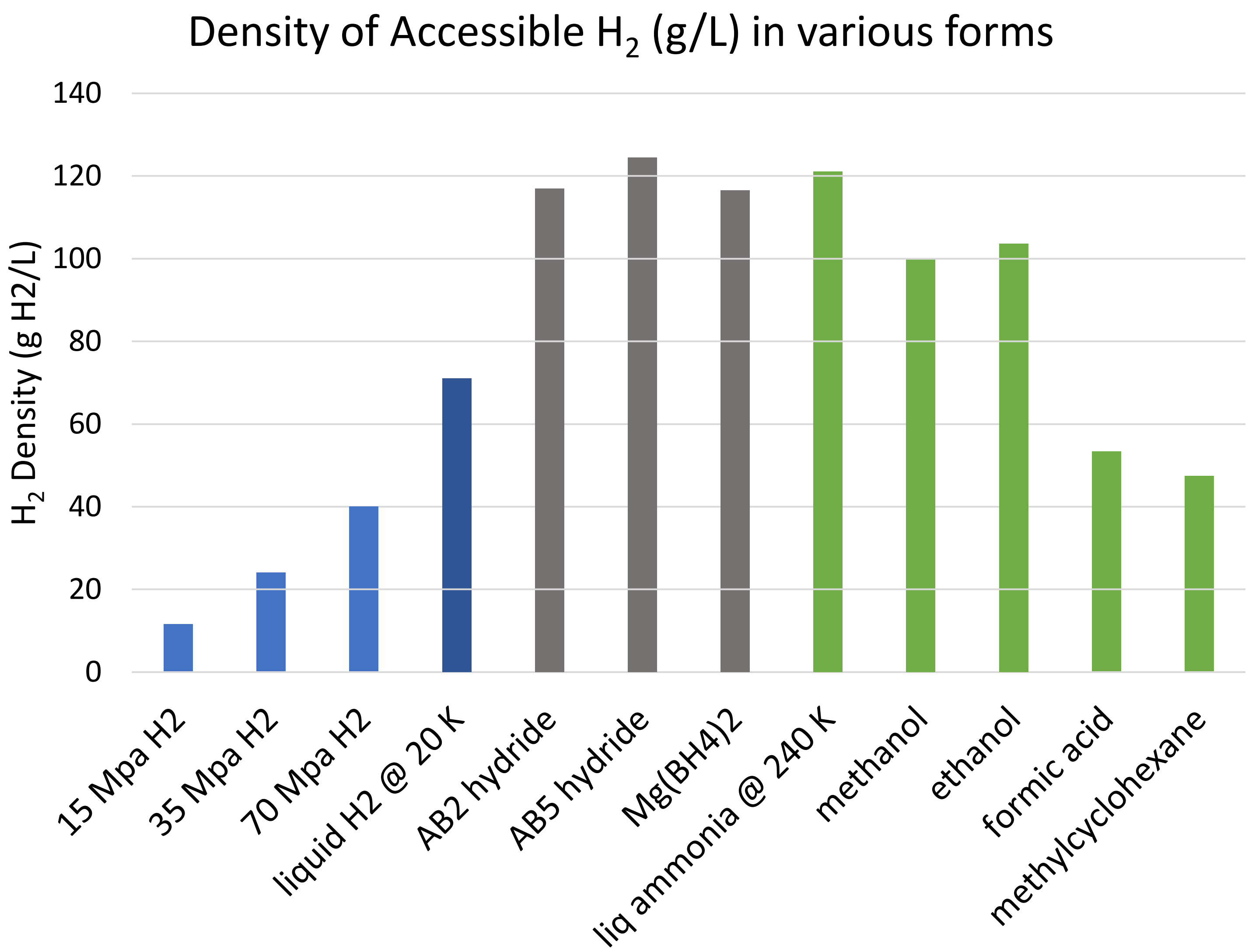
From producing hydrogen molecules through dispensing to end-use applications

Hydrogen Infrastructure: Delivery, Storage and Dispensing



Low Density of H_2 is a Challenge for Transport and Storage

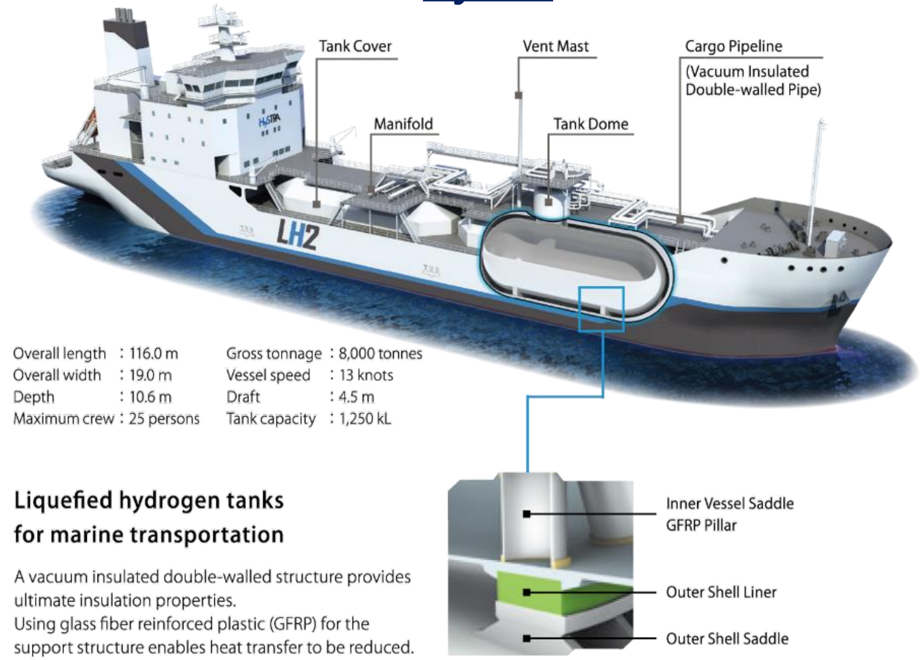




Liquid hydrogen storage – Pros and Cons

- **Benefits**
  - High storage density: 71 kg/m^3
  - Faster refueling rates, longer ranges and higher payloads
- **Potential applications**
  - Vehicle fueling stations (FCEVs and material handling)
  - On-board heavy-duty transportation (road, rail, marine)
  - Industrial applications (up to ~5 tonnes per day delivery)
  - Aerospace
  - Export markets
- **Key challenges**
  - High liquefaction energy - ~1/3 of the energy of the liquefied H_2
  - Boil-off loss mitigation – can be as high as several percent per day
  - System costs – tanks, heat exchangers, insulation

Hystra



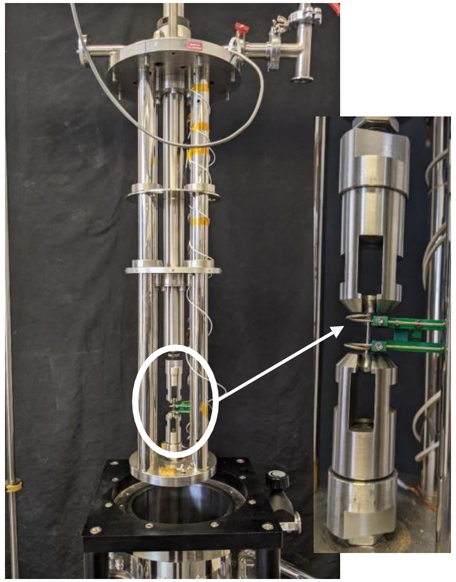
http://www.hystra.or.jp/en/project/

https://www.daimler.com

Some Example DOE Funded Efforts

Hydrogen Effects on Materials in Cryogenic Service

Team: Pacific Northwest National Laboratory, Hydrogen Materials Compatibility Consortium (H-Mat)

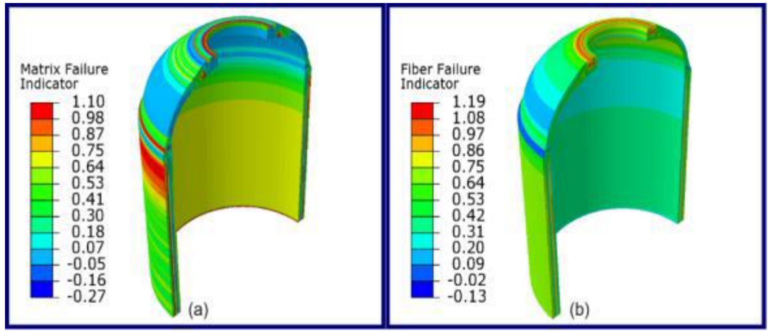


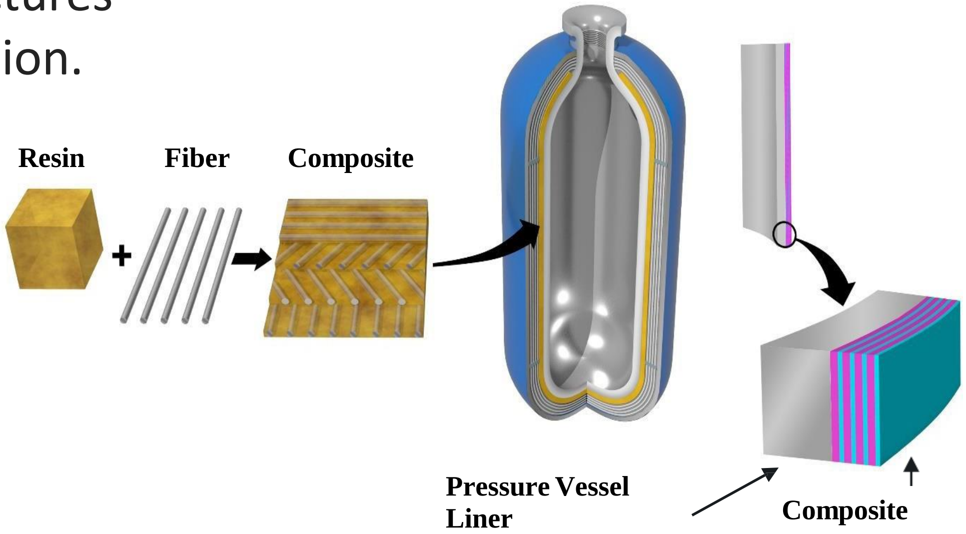
Goal: Identify materials for cryogenic hydrogen service, and develop key technical metrics for viable structural materials for various applications

Objectives:
- Address the challenges of hydrogen degradation
- Elucidate the mechanisms of hydrogen - materials interactions
- Develop science-based strategies to design material (micro)structures and morphology with improved resistance to hydrogen degradation.

Pacific Northwest NATIONAL LABORATORY

H-Mat Hydrogen Materials Compatibility Consortium





https://www.hydrogen.energy.gov/pdfs/review21/in001b_simmons_2021_o.pdf

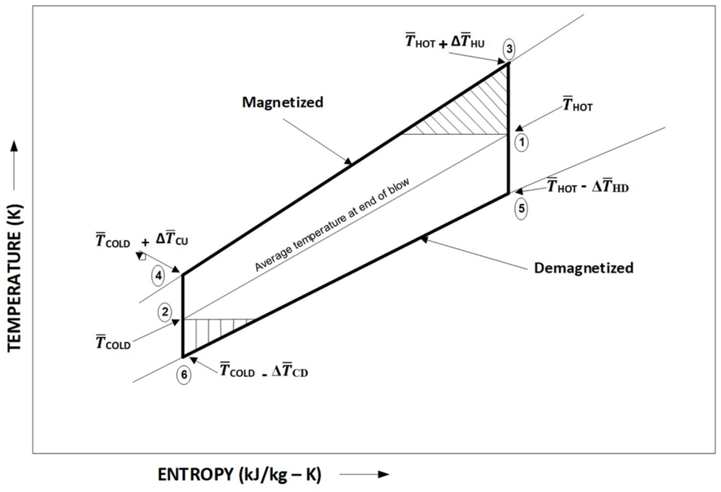
Reducing Liquefaction Energy through Magnetocaloric Liquefaction

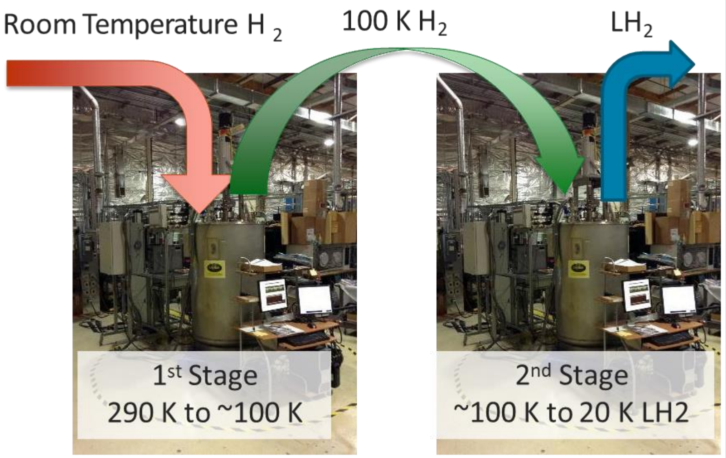
Team: Pacific Northwest National Laboratory, AMES Lab, Iowa State University

Goal: Develop and demonstrate active magnetic regenerative liquefiers (AMRLs) which are more ~50% efficient than and ~20% less expensive than state-of-the-art liquefiers for hydrogen

Key subsystems:

- high performance magnetic regenerators
- heat transfer fluid flows to efficiently couple refrigerants to loads and sinks in AMR cycle
- NbTi superconducting magnets for large *ΔB* for AMR cycle





5 layer reciprocating regenerators, liquid HTF, 6 T; heat sink for 2nd stage

3 layer regenerators, coupled to process HEX with o-p catalysts and condensing CHEX

Pacific Northwest NATIONAL LABORATORY Proudly Operated by Battelle Since 1965

The Ames Laboratory Creating Materials & Energy Solutions U.S. DEPARTMENT OF ENERGY

https://www.hydrogen.energy.gov/pdfs/review21/in004_barclay_2021_o.pdf

Reducing Boil-off Losses with Heisenberg Vortex Tube

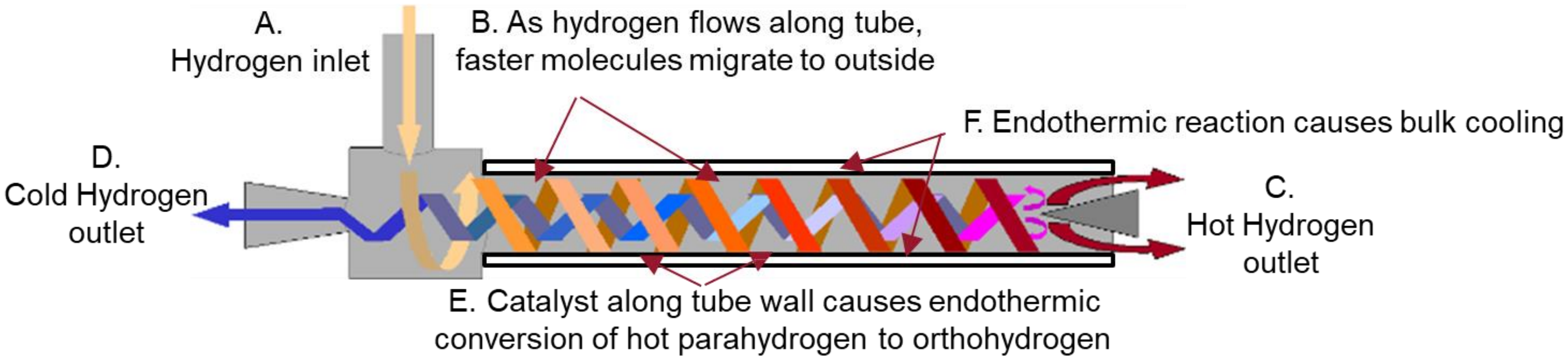
Team: Washington State University, Plug Power

Goal: Validate the Heisenberg Vortex Tube as a tool to improve:

- Liquid hydrogen pump volumetric efficiency through vapor separation and subcooling
- LH_2 storage tank boil-off losses through thermal vapor shielding (TVS)
- Supercritical hydrogen expansion by increasing isentropic efficiency

Heisenberg Vortex Tube:

- WSU patented technology utilizing pressurized fluid power for separation into hot and cold streams with no moving parts
- Hot stream is exposed to catalyst on the periphery to drive endothermic para-ortho hydrogen conversion



https://www.hydrogen.energy.gov/pdfs/review21/in015_leachman_2021_o.pdf

Large-Capacity Liquid Hydrogen Storage Development

Team: Shell, NASA, CB&I, University of Houston

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

Deliverables: LH_2-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)

Evaluation of LH_2 Storage for MD/HD Truck Applications

Team: Argonne National Laboratory, Lawrence Livermore National Laboratory, Sandia National Laboratory

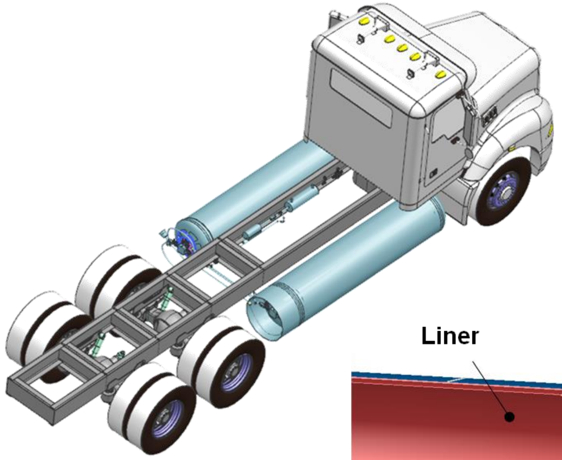
Goal: Conceptualize and analyze a liquid hydrogen (LH_2) storage system for medium- and heavy-duty trucks

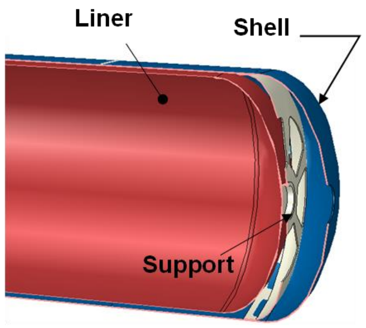
Key System Parameters:

- Type 1 insulated tanks
- H_2 storage capacity for 750-mile range
- Refueling rate of 8-10 kg/min with low-pressure LH_2 pump
- Zero boil-off loss dormancy
- Target cost: $8-9/kWh

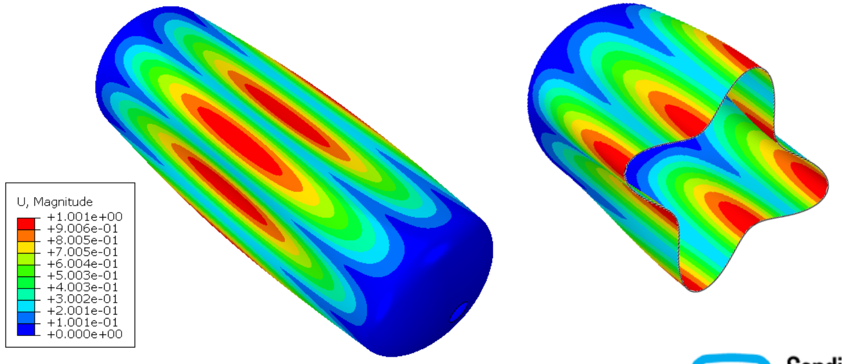
Other Considerations:

- Identify LH_2 refueling interface issues and opportunities
- Address safety issues, codes and standards





Section View of LH_2 Tank showing Liner Support



Argonne NATIONAL LABORATORY

Sandia National Laboratories

Lawrence Livermore National Laboratory

https://www.hydrogen.energy.gov/pdfs/review21/st223_ahluwalia_2021_o.pdf

Thank You

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www.energy.gov/fuelcells
www.hydrogen.energy.gov

Backup slides

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HFTO Comprehensive Strategy

New: $100M/5yrs

H2NEW
U.S. DEPARTMENT OF ENERGY

Focused Consortia with labs, industry, universities

R&D

Core Team: National Labs

FOA

University & Non-Profit | Industry | National Lab

HyMARC
Hydrogen Materials Advanced Research Consortium

HydroGEN
Advanced Water Splitting Materials

ElectroCat
Electrocatalysis Consortium

21CTP
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MILLION MILE FUEL CELL TRUCK

2016 — 2018 — 2020

D&D


Trucks, GSE


Infrastructure


CO_2+H_2


Renewables to H_2


Data Center

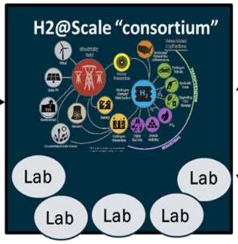

Nuclear to H_2

Ammonia (ARPA-E)

New: Super Truck FOA and more…

Enablers

Government Funding



CRADAs

SPPs

Comprehensive analysis, tools and models to accelerate progress
Safety, codes, standards, workforce development
Systems integration and validation

H2EDGE
Hydrogen Education for a Decarbonized Global Economy

H-Mat
Hydrogen Materials Compatibility Consortium

Center for Hydrogen Safety
Connecting a Global Community

HyBlend
U.S. DEPARTMENT OF ENERGY

Key 2030 Targets

Clean Hydrogen
- $1/kg production
- $2/kg delivery
- $9/kWh storage

Electrolyzers
- $150/kW
- 73% efficiency
- 80Khr durability

Fuel Cells
- $80/kW
- 25Khr durability

Enable EJ40 Priorities, DEI

Deployment in collaboration with Loan Program Office
Examples shown, not exhaustive. Over 190 companies, 109 universities, 16 national labs in the last decade; CRADAs are Cooperative Research And Development Agreements

Snapshot of Hydrogen and Fuel Cell Applications in the U.S.

Examples of Applications Deployed

>500MW	Backup Power
>40,000	Forklifts
>172 MW	PEM* Electrolyzers
>60	Fuel Cell Buses
>45	H_2 Retail Stations
~10,000	Fuel Cell Cars

*Polymer electrolyte membrane

Major Hydrogen Production Sites

- 10 million metric tons produced annually
- More than 1,600 miles of H_2 pipeline
- World's largest H_2 storage cavern

Hydrogen Stations Plans Across States

California	Northeast	HI, OH, SC, NY, CT, MA, CO, UT, TX, MI
200 Stations Planned California Fuel Cell Partnership Goal	12 – 20 Stations Planned	And Others

Hydrogen Demand and H2@Scale Projects