Importance of Liquid Hydrogen for Decarbonizing the Energy Sector


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:

- 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

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<th>Time</th>
<th>Event</th>
<th>Duration</th>
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<tr>
<td>11:00 am</td>
<td>Introduction; DOE Perspectives (Ned Stetson, DOE)</td>
<td>30 min.</td>
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<tr>
<td>11:30 am</td>
<td>Historical Overview of LH$_2$ Operations at KSC (Robert Johnson, NASA-KSC)</td>
<td>30 min.</td>
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<tr>
<td>12:00 noon</td>
<td>Break</td>
<td>15 min.</td>
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<tr>
<td>12:15 pm</td>
<td>LH$_2$ Storage and Handling Demonstrations Using Active Refrigeration (Adam Swanger, NASA-KSC)</td>
<td>60 min.</td>
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<tr>
<td>1:15 pm</td>
<td>Lunch</td>
<td>30 min.</td>
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<tr>
<td>1:45 pm</td>
<td>The New LH$_2$ Sphere (James Fesmire, NASA-KSC)</td>
<td>60 min.</td>
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<tr>
<td>2:45 pm</td>
<td>Break</td>
<td>15 min.</td>
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<tr>
<td>3:00 pm</td>
<td>Economics of Energy-Efficient, Large-Scale LH$_2$ Storage Using IRAS &amp; Glass Bubble Insulation (Adam Swanger &amp; James Fesmire, NASA-KSC)</td>
<td>30 min.</td>
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<tr>
<td>3:30 pm</td>
<td>Panel Discussion and Q&amp;A: Path Forward and Wrap-Up (DOE &amp; NASA)</td>
<td>30 min.</td>
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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 $1/kg by 2030
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 Shot”

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

“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

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
***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:

- Clean Energy and Emissions Reduction Across Sectors
- Job Creation and a Sustainable and Equitable Energy Future

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
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 H₂/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
H₂ 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. H₂ can enable long range and fast fueling.

**Marine Vessels:** >3% of global CO₂ emissions are from marine vessels. Initial IMO GHG Strategy aims to halve GHG emissions by 2050.

**Clean Fuels:** H₂ is a feedstock along with CO₂ for synfuels production.

**Ammonia:** 2nd most widely produced chemical worldwide (by wt). 1 2% of global CO₂ emissions. Can serve as H₂ carrier as well as its use in fertilizer and as a chemical reagent.

**Iron, steel and cement:** 15% of global CO₂ 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 H₂ is a Challenge for Transport and Storage

Density of Accessible H₂ (g/L) in various forms
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
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.

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 $\Delta B$ for AMR cycle

https://www.hydrogen.energy.gov/pdfs/review21/in004_barcley_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
- \( \text{LH}_2 \) 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:** LH₂-based cryostat, sub-scale demo tank

**Targets:**
- **Volume:** 20,000 m³ - 100,000 m³
- **Boil-off rate:** 0.01-0.3%/day
- **CAPEX:** <$175 million (100,000 m³ tank)
Evaluation of LH₂ Storage for MD/HD Truck Applications

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

**Goal:** Conceptualize and analyze a liquid hydrogen (LH₂) storage system for medium- and heavy-duty trucks

**Key System Parameters:**
- Type 1 insulated tanks
- H₂ storage capacity for 750-mile range
- Refueling rate of 8-10 kg/min with low-pressure LH₂ pump
- Zero boil-off loss dormancy
- Target cost: $8-9/kWh

**Other Considerations:**
- Identify LH₂ refueling interface issues and opportunities
- Address safety issues, codes and standards
Thank You

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www.energy.gov/fuelcells
www.hydrogen.energy.gov
Backup slides
The Team - Hydrogen and Fuel Cell Technologies Office

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- Dave Peterson
- Pete Devlin
- Michael Hahn
- Brian Hunter
- Vacancy (2)

Systems Development & Integration
Laura Hill

Safety, Codes & Standards

- Neha Rustagi
HFTO Comprehensive Strategy

**Focused Consortia with labs, industry, universities**

**R&D**
- Core Team: National Labs
- HydroGEN: Advanced Water Splitting Materials
- ElectroCat: Electrocatalysis Consortium

**2016**
- MARC: University & Non-Profit
- Industry
- National Lab

**2018**
- CO$_2$ + H$_2$
- Renewables to H$_2$
- Data Center

**2020**
- Nuclear to H$_2$
- Ammonia (ARPA-E)

**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

**Enablers**
- CRADAs: Cooperative Research And Development Agreements
- SPPs
- Comprehensive analysis, tools and models to accelerate progress
- Safety, codes, standards, workforce development
- Systems integration and validation
- Enable EJ40 Priorities, DEI

**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** H₂ Retail Stations
- **~10,000** Fuel Cell Cars

*Molded electrolyte membrane

**Major Hydrogen Production Sites**

- 0 – 50
- 50 – 100
- 100 – 200
- 200 – 400
- 400 – 800

Hydrogen Production Units
Gaseous Metric Tons/Day

**Hydrogen Demand and H₂@Scale Projects**

- 10 million metric tons produced annually
- More than 1,600 miles of H₂ pipeline
- World’s largest H₂ storage cavern

**Hydrogen Stations Plans Across States**

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<tr>
<th>State</th>
<th>Planned Stations</th>
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<td>California</td>
<td>200</td>
</tr>
<tr>
<td>Northeast</td>
<td>12 – 20</td>
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<tr>
<td>HI, OH, SC, NY, CT, MA, CO, UT, TX, MI, And Others</td>
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**California Fuel Cell Partnership Goal**

- 200 Stations Planned

**World’s Largest H₂ Storage Cavern**

- Solar, wind, nuclear, and waste to H₂ projects

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DEPARTMENT OF ENERGY

OFFICE OF ENERGY EFFICIENCY & RENEWABLE ENERGY

HYDROGEN AND FUEL CELL TECHNOLOGIES OFFICE