U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

Welcome and an Introduction to the DOE Hydrogen Program

Dr. Ned Stetson (Program Manager),
Hydrogen and Fuel Cell Technologies Office

Bulk Gaseous Hydrogen Storage Virtual Workshop, February 10-11, 2022

Workshop Agenda

- **Day 1 – Feb. 10**
  - **Overview & Perspectives – 12:00 – 1:00 pm**
    - Ned Stetson – DOE-EERE
    - Tim Reinhardt – DOE-FECM
    - Serge van Gessel – TNO
    - Eric Lewis – NETL
  - **Hydrogen Production Panel – 1:00 – 1:35 pm**
    - Raja Amirthalingam – Plug Power
    - Tony Leo – Fuel Cell Energy
  - **Break – 1:35 – 1:50 pm**
  - **Energy Storage Panel – 1:50 – 2:45 pm**
    - Michael DeBortoli – NCPA
    - Upshur Quinby – Microsoft
    - Hilary Petrizzo – So. Cal. Gas
  - **Industry, Transport & Export Panel – 2:45 – 4:00 pm**
    - Greg Wright – Wabtec
    - Nico Bouwkamp – CAFCP
    - Robert Smith – DOT PHMSA
    - Vincent Holohan – DOT PHMSA
  - **Adjourn – 4:00 pm**

- **Day 2 – Feb. 11**
  - **Overview for Day 2 – 12:00 – 12:05 pm**
  - **Subsurface Storage – 12:05 – 12:50 pm**
    - Nik Huerta - PNNL
    - Tim Reichwein – Lane Power and Energy Solutions
    - Mariel Schottenfeld – Air Products
  - **Surface Storage – 12:50 – 1:35 pm**
    - Kevin Harris – Hexagon Purus
    - Brian Weeks - GTI
    - Claudio Lanzarini – FIBA Tech
  - **Break – 1:35 – 1:50 pm**
  - **Breakout Sessions – 1:50 – 3:50 pm**
    - Surface Storage – A&B
    - Subsurface – A&B
  - **Break – 3:50 – 4:10 pm**
  - **Breakout Session Report Out – 4:10 – 4:25 p,**
  - **Closing Remarks – 4:25 – 4:30 pm**
  - **Adjourn – 4:30 pm**

Note – all times EST

Workshop Objectives

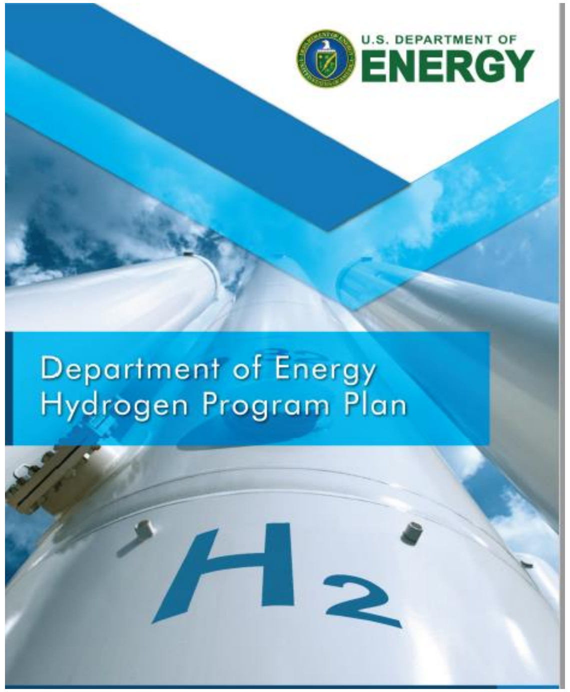
- With increasing use of hydrogen in large-scale applications, the need for low-cost, bulk H_2 storage technologies that are geographically agnostic, and meet application performance requirements, is a challenge

- Workshop Objectives
  - Identify bulk H_2 storage needs for upcoming, large-scale applications
  - Review current state-of-the-art bulk H_2 storage technologies
  - Identify performance gaps of current technologies and application needs
  - Identify R&D needs to narrow the performance gaps
  - Identify innovative concepts to pursue
  - Address other considerations

The U.S. DOE Hydrogen Program

Key DOE Hydrogen Authorizations in Energy Policy Act (2005, 2020) and Infrastructure Investment and Jobs Act (2021)

Hydrogen is one part of a broad portfolio of activities



www.hydrogen.energy.gov

The DOE Hydrogen Program is an agency wide effort, encompassing efforts from across the DOE

EERE – Hydrogen and Fuel Cell Technologies Office –
H_2 Program Coordination Lead

Office of Energy Efficiency and Renewable Energy
Office of Fossil Energy and Carbon Management
Office of Nuclear Energy
Office of Electricity
Office of Science
Office of Clean Energy Demonstrations
Advanced Research Projects Agency – Energy
Office of Technology Transition
Loan Program Office

Priorities

1. **Low-cost, clean hydrogen**
2. **Low-cost, efficient, safe hydrogen delivery and storage**
3. **Enable end-use applications at scale for impact**

Workforce development, safety, codes, standards, and Environmental Justice priorities

Hydrogen Program Areas of Focus across Multiple Offices

NEAR-TERM → LONGER-TERM

Production
- Gasification of coal,* biomass, and waste with carbon capture, utilization and storage (*waste coal, other waste)
- Advanced fossil and biomass reforming/conversion/pyrolysis
- Advanced biological/microbial conversion
- Electrolysis (low-temperature, high-temperature)
- Advanced thermo/photoelectro-chemical H_2O splitting

Delivery
- Distribution from on-site production
- Tube trailers (gaseous H_2)
- Widespread pipeline transmission and distribution
- Cryogenic trucks (liquid H_2)
- Chemical H_2 carriers

Storage
- Pressurized tanks (gaseous H_2)
- Geologic H_2 storage (e.g., caverns, depleted oil/gas reservoirs)
- Cryogenic vessels (liquid H_2)
- Cryo-compressed
- Chemical H_2 carriers
- Materials-based H_2 storage

Conversion
- Turbine combustion
- Advanced combustion
- Fuel cell/combustion hybrids
- Fuel cells
- Next generation fuel cells
- Reversible fuel cells

Applications
- Fuel refining
- Blending in natural gas pipelines
- Space applications
- Distributed stationary power
- Utility systems
- Portable power
- Transportation
- Distributed CHP
- Integrated energy systems
- Industrial and chemical processes
- Defense, security, and logistics applications

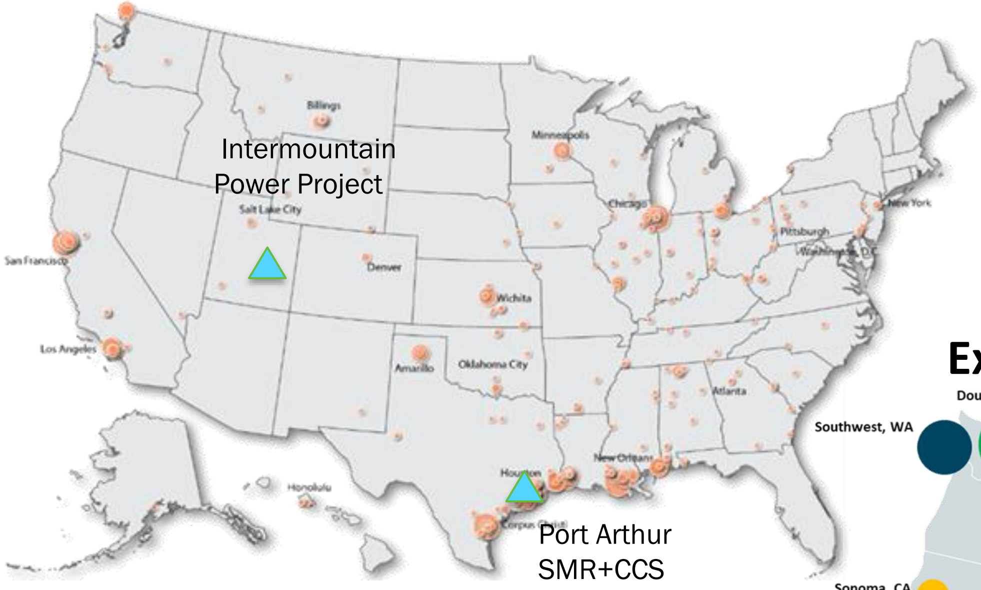
Snapshot of Hydrogen and Fuel Cells in the U.S.

Deployment Examples
June 2021 Snapshot

- **>500MW** Backup Power
- **>40,000** Forklifts
- **>172 MW** PEM* Electrolyzers
- **>60** Fuel Cell Buses
- **>45** H_2 Retail Stations
- **>12,000** Fuel Cell Cars

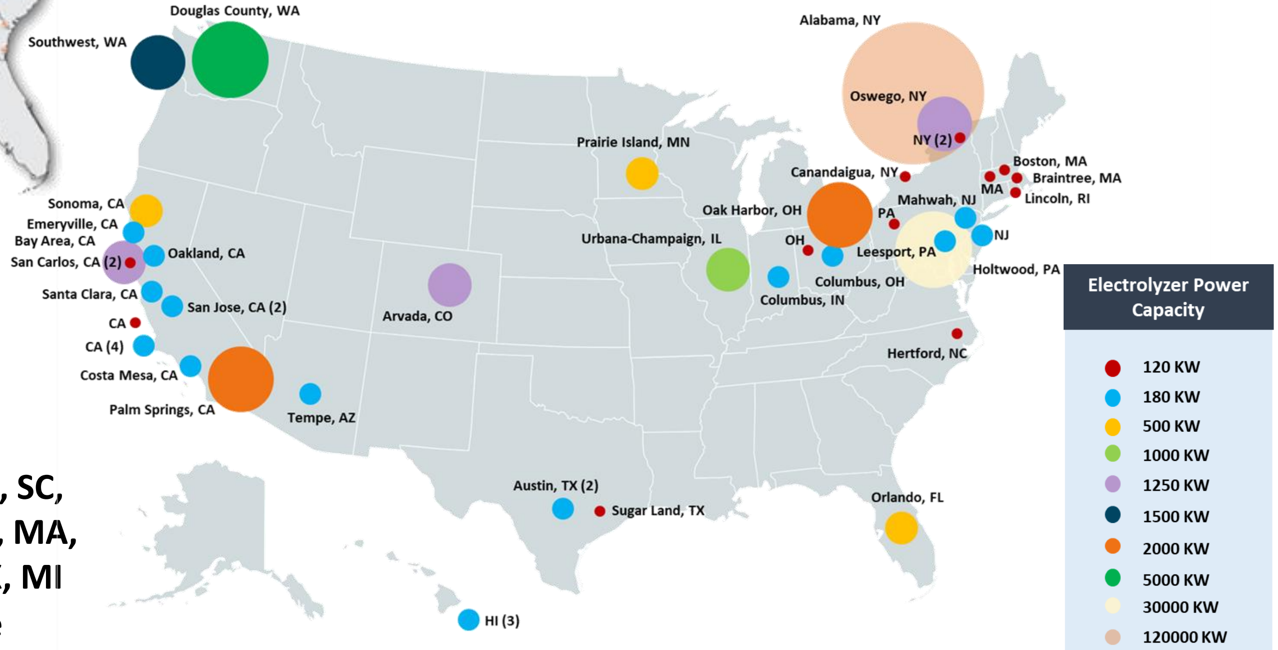
* Polymer electrolyte membrane

Examples of Hydrogen Production Locations



- 10 million metric tons (MMT) H_2/yr
- Over 1,600 miles of H_2 pipelines
- World's largest H_2 storage cavern

Examples of PEM Electrolyzer Installations

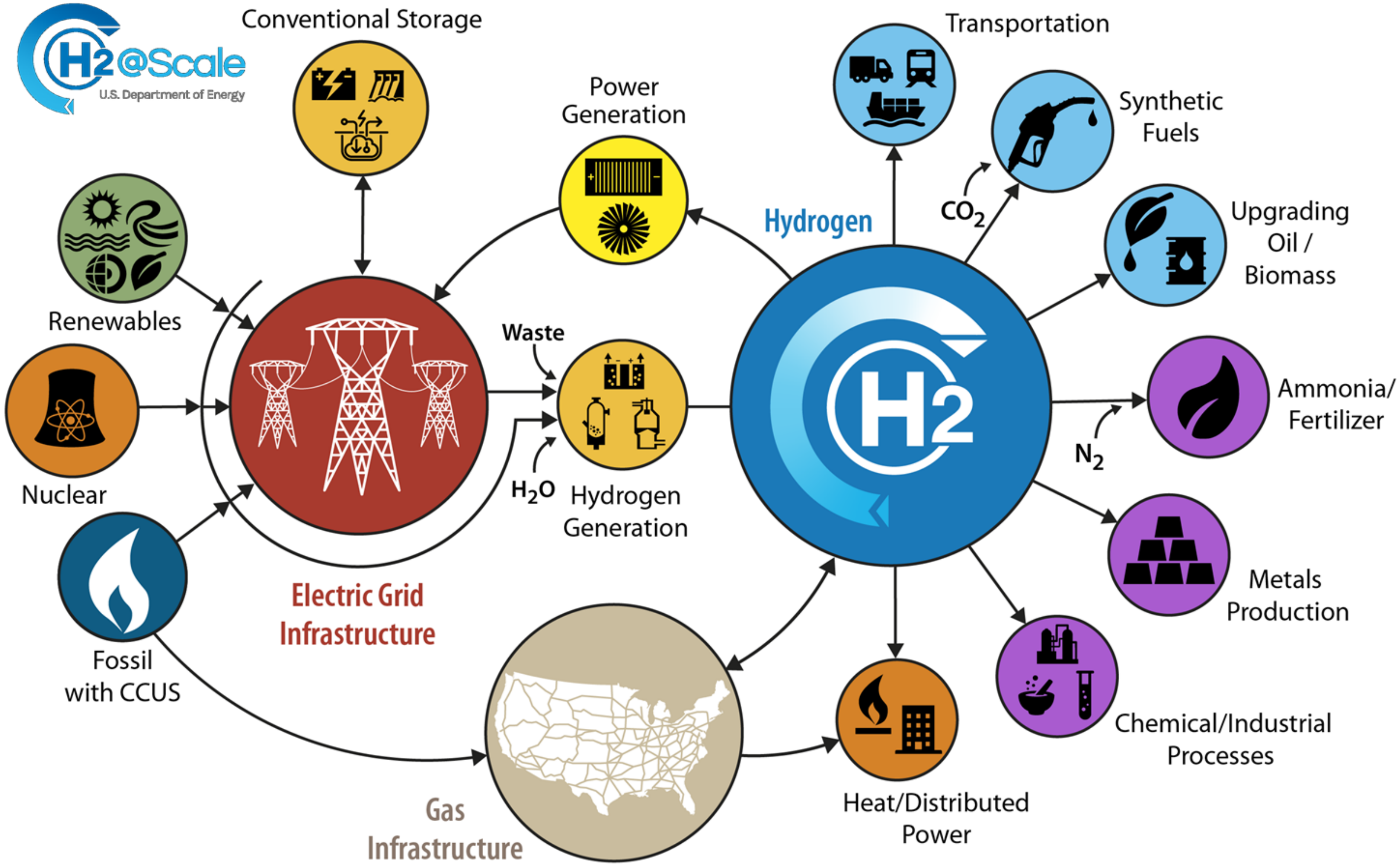


Current and under construction installations over 120 kW as of Jun. 2021
** Source: Arjona, et al, DOE HFTO Program Record, June 2021*

Examples of Hydrogen Station Plans

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

H2@Scale: Enabler for Deep Decarbonization across Sectors and Jobs



Key Opportunities

- **Industry and Chemicals**
  Steel, ammonia, cement, syn fuels (e.g., aviation), exports
- **Transportation**
  Trucks, marine, buses, etc.
- **Power and Energy Storage**
  Long duration storage, NG blending, turbines, fuel cells

U.S. Snapshot

- 10 MMT of H_2/yr produced today with scenarios for 2-5X growth.
- +10 MMT H_2 would ~ double today's solar or wind deployment
- Potential for 700K jobs, $140B by 2030

President Biden and Energy Secretary Granholm at Climate Summit

"…I've asked the Secretary of Energy to speed the development of critical technologies to tackle the climate crisis. No single technology is the answer on its own because every sector requires innovation to meet this moment."

President Joseph R. Biden
April 23, 2021

Launch of Hydrogen Energy Earthshot
First of the Energy Earthshots
June 7, 2021
at DOE Hydrogen Program Annual Merit Review

Secretary Jennifer Granholm
June 7, 2021

Energy earthshots | Hydrogen

U.S. Department of Energy

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

Department of Energy · United States of America

The 2nd DOE Energy Earthshot – Announced September 2021

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Storage™

Long Duration Storage Shot seeks to achieve affordable long duration grid storage—for clean power anytime, anywhere

https://www.energy.gov/eere/long-duration-storage-shot

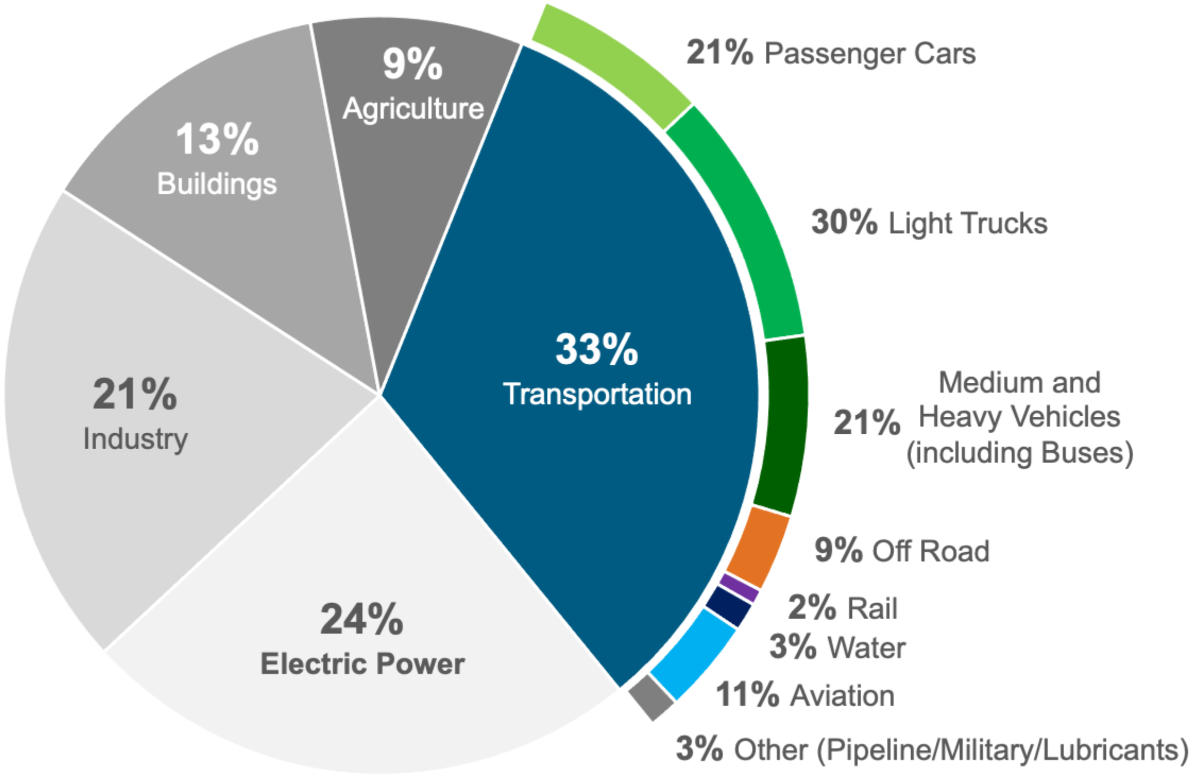
Bipartisan Infrastructure Law - Hydrogen Highlights

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

President Biden Signs the Bipartisan Infrastructure Bill 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**
- **Requires developing a National Hydrogen Strategy and Roadmap**

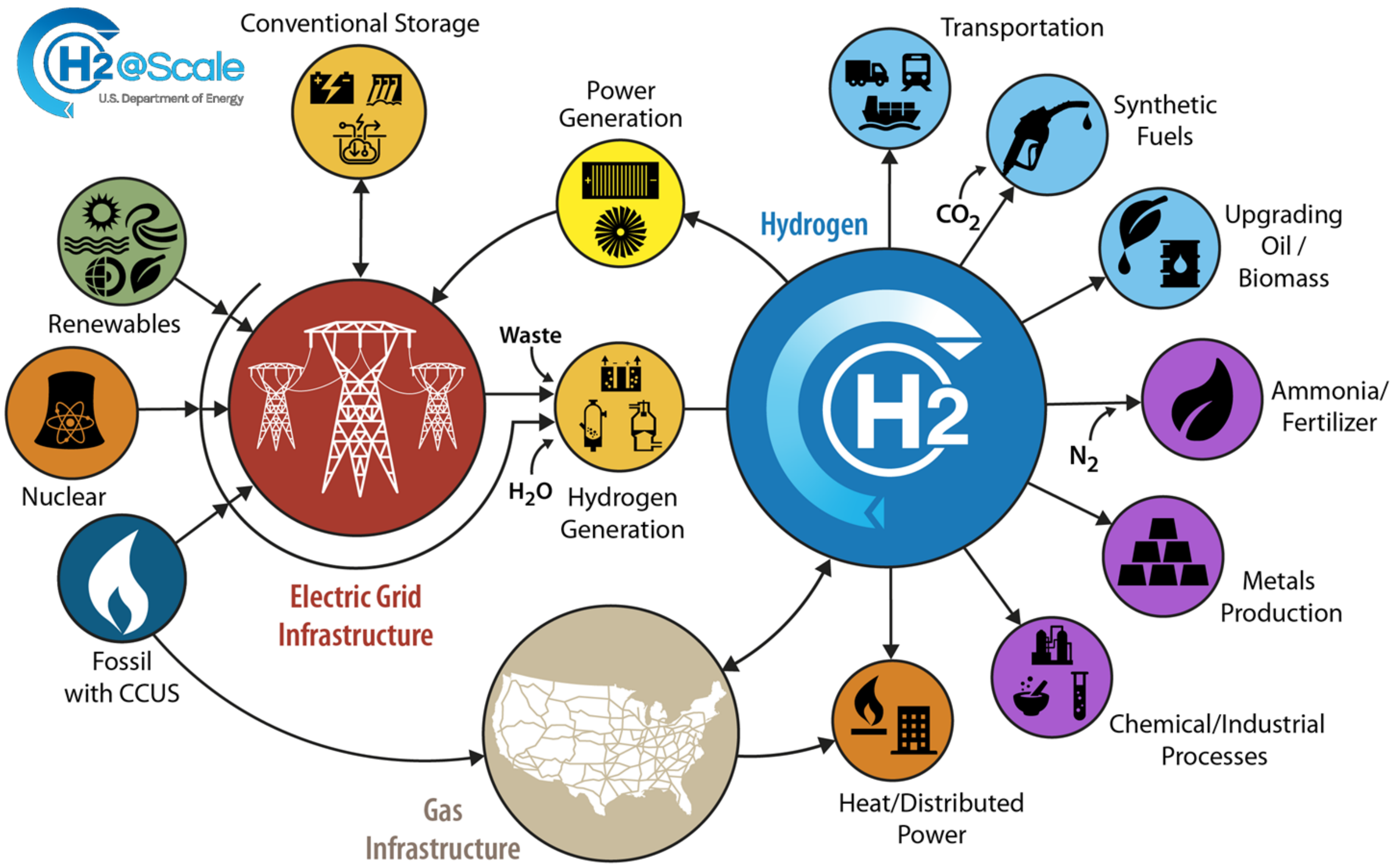
U.S. GHG Emissions by Sector



Aviation and water include emissions from international bunker fuels. Fractions may not add up to 100% due to rounding.

- **Transportation is the largest source of GHG emissions**
  - 50% of **energy expenditures and local pollution issues**
  - Significant implications for global competitiveness, trade, and domestic jobs
- **Industry and Electric Power generation account for another ~45% of GHG emissions**

H2@Scale: Enabler for Deep Decarbonization across Sectors and Jobs



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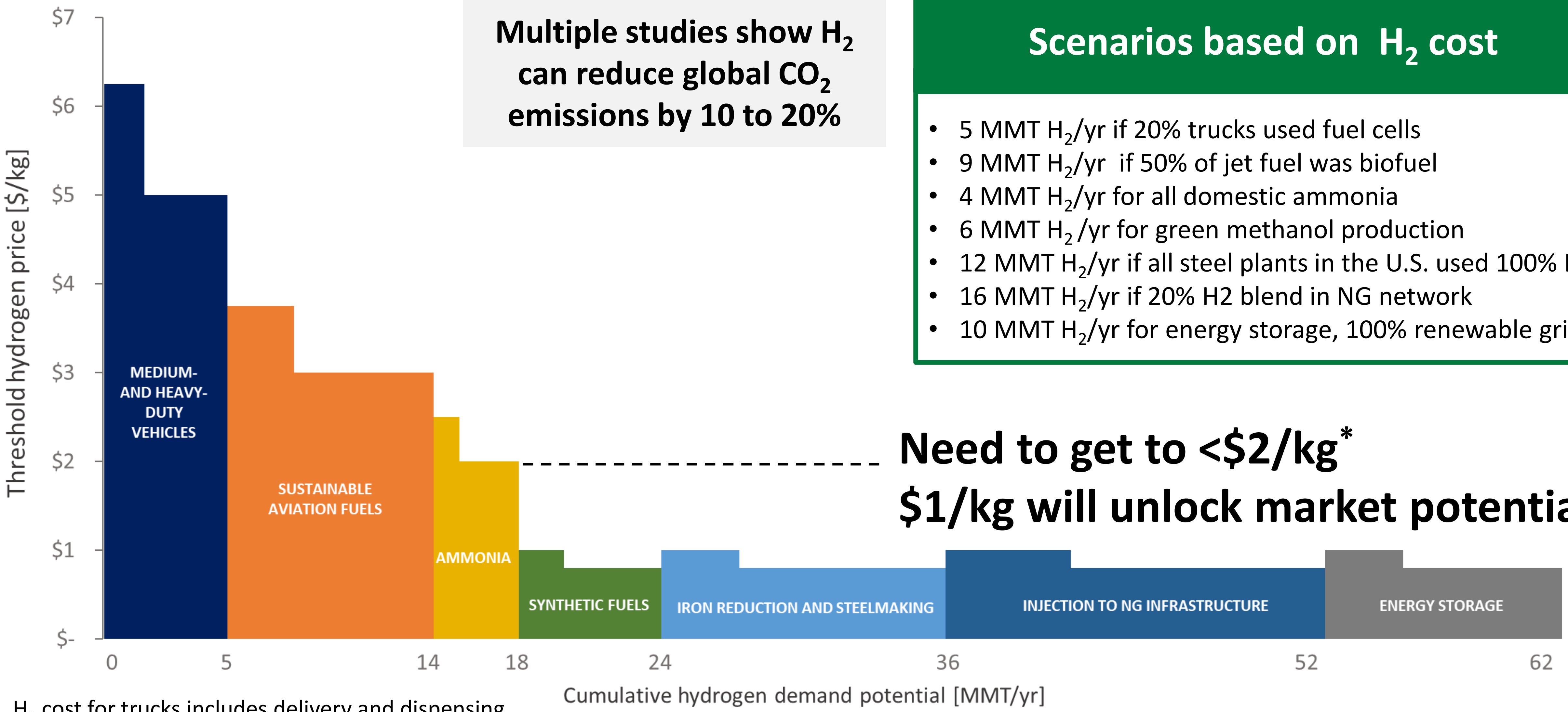
Analysis Determines Market Potential Scenarios



Multiple studies show H_2 can reduce global CO_2 emissions by 10 to 20%

Scenarios based on H_2 cost

- 5 MMT H_2/yr if 20% trucks used fuel cells
- 9 MMT H_2/yr if 50% of jet fuel was biofuel
- 4 MMT H_2/yr for all domestic ammonia
- 6 MMT H_2 /yr for green methanol production
- 12 MMT H_2/yr if all steel plants in the U.S. used 100% H_2
- 16 MMT H_2/yr if 20% H2 blend in NG network
- 10 MMT H_2/yr for energy storage, 100% renewable grid

Need to get to <$2/kg*
$1/kg will unlock market potential

H_2 cost for trucks includes delivery and dispensing

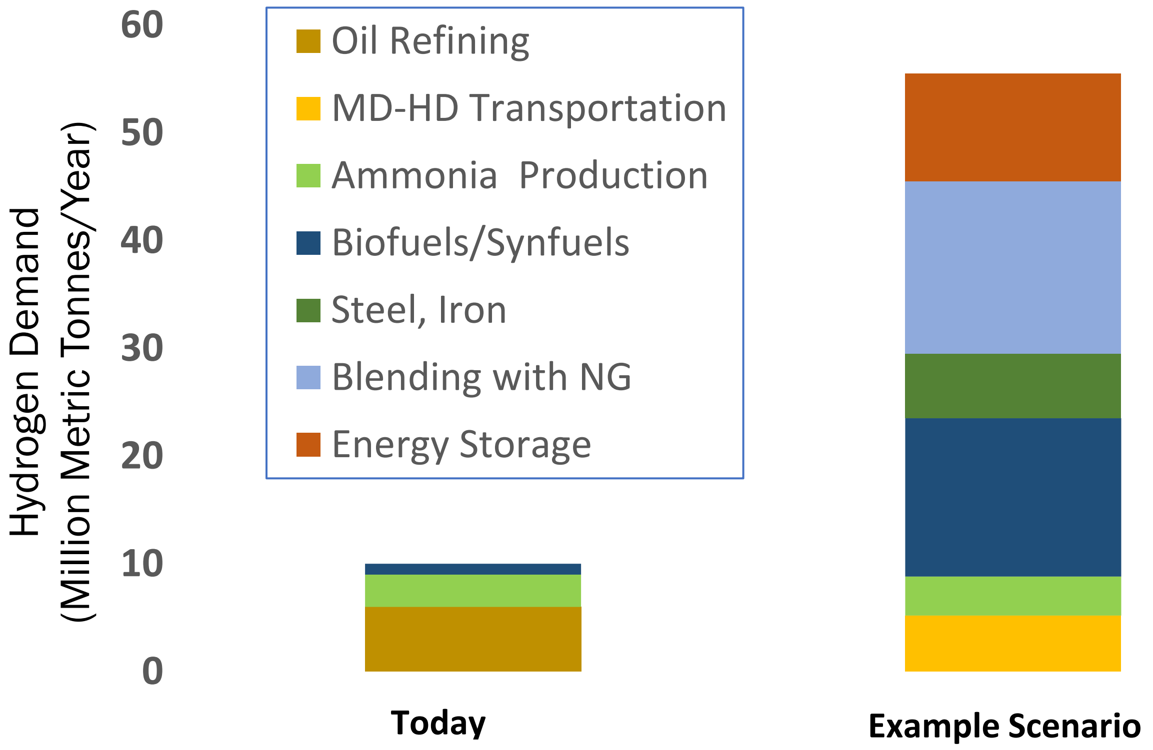
* H_2 could compete at $1 to $2/kg higher cost with a carbon price

Results based on preliminary analysis

Key Reports Released in 2020

NREL NATIONAL RENEWABLE ENERGY LABORATORY | Argonne NATIONAL LABORATORY

Comprehensive multi-lab analysis determined potential for growth in U.S. hydrogen demand of at least 2-5 x current consumption



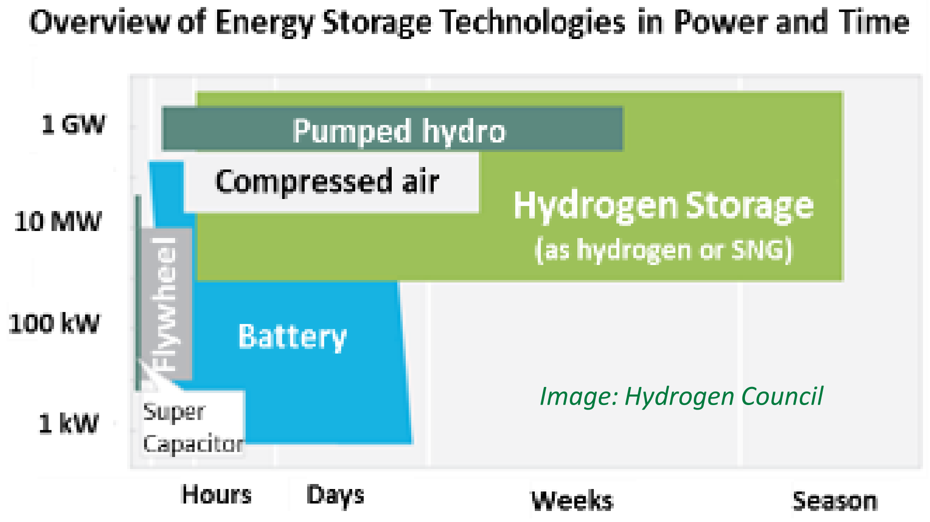
Preliminary demand scenario based on published H2@Scale analysis and additional ongoing TEA

- **Resource Assessment for Hydrogen Production[1]**
  Determined technical potential of hydrogen supply
- **Assessment of Potential for Future Demands for Hydrogen in the United States[2]**
  Assessed price points and market potential for hydrogen in 8 sectors.
- **The Technical and Economic Potential of the H2@Scale Concept within the United States[3]**
  Assessed growth potential for hydrogen supply and demand in 5 scenarios

1. https://www.nrel.gov/docs/fy20osti/77198.pdf
2. https://greet.es.anl.gov/publication-us_future_h2
3. https://www.nrel.gov/docs/fy21osti/77610.pdf

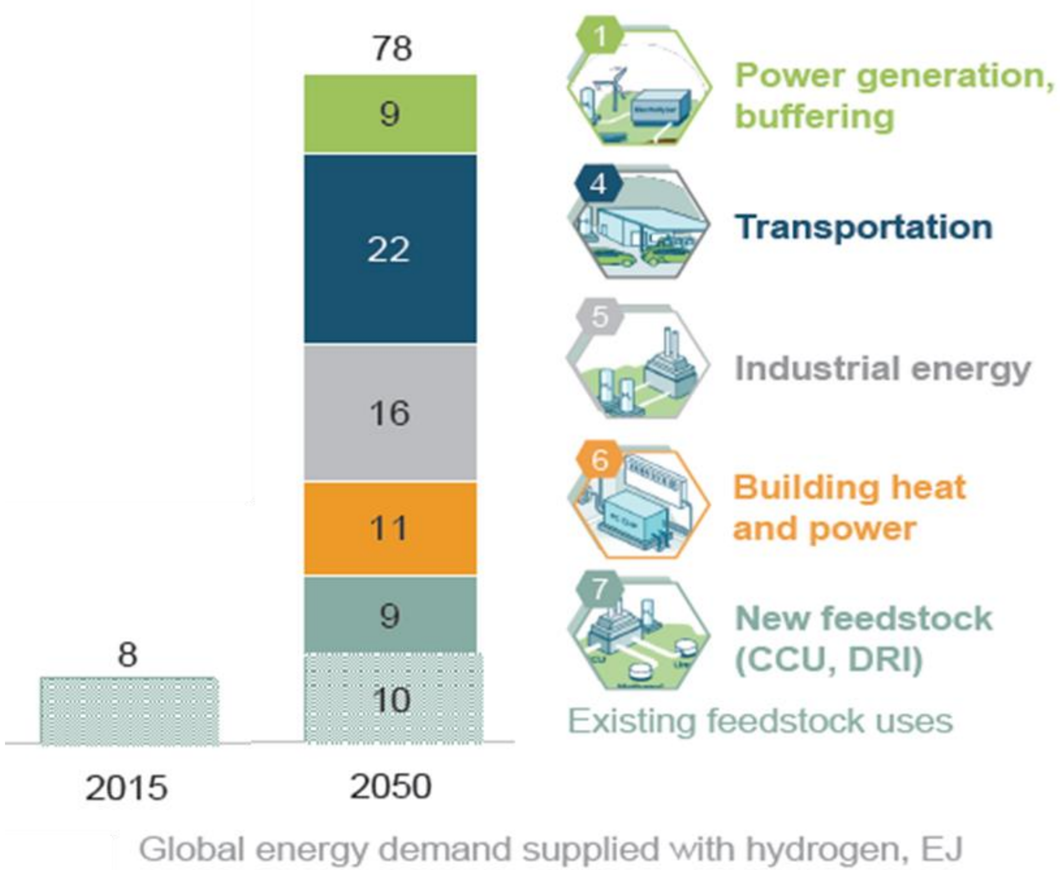
Industry Estimated Opportunities for Hydrogen

Hydrogen can store GWh of energy



H2 Council Global Impact Potential by 2050

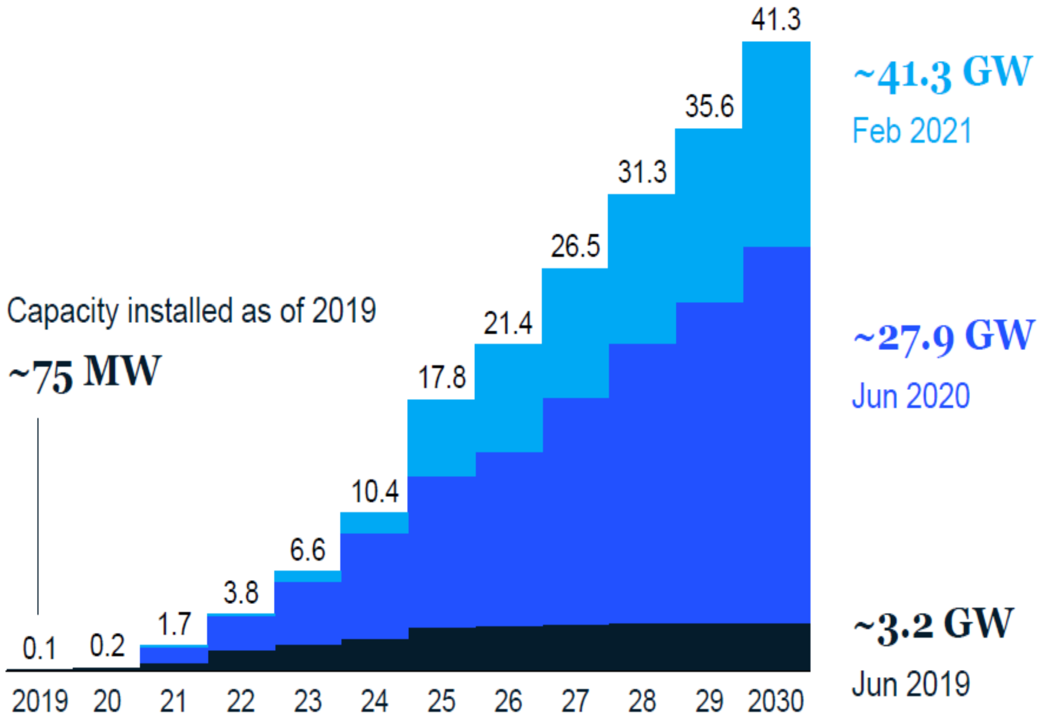
Hydrogen Council: Global industry partnership projects up to 10X increase in H_2 demand by 2050



Recent Increased Interest in Hydrogen: Global Drivers

- ✓ **Low-cost renewables** are now available
- ✓ **Countries see clean H_2 can help meet climate goals**
  - Hard to decarbonize sectors
  - Energy storage
  - Import/export opportunities

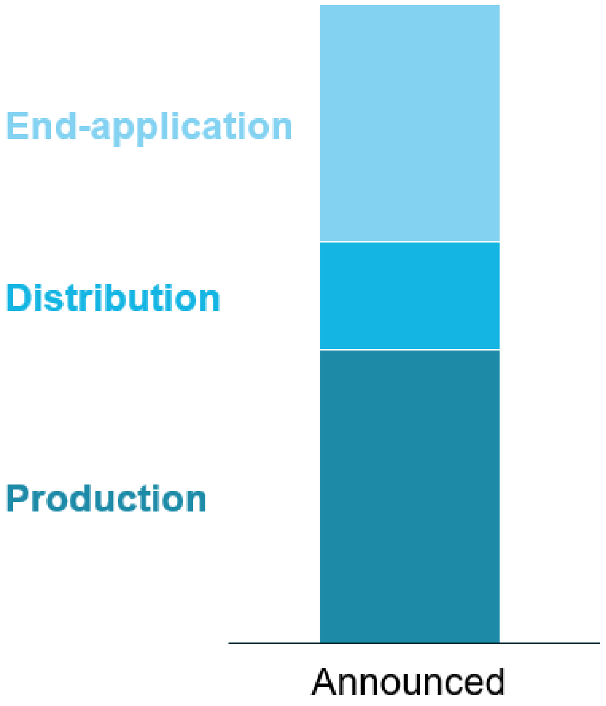
200-fold electrolyzer growth by 2030
Over 40 GW planned



1. For projects without known deployment timeline capacity additions were interpolated between known milestones

Source: McKinsey Hydrogen Project database

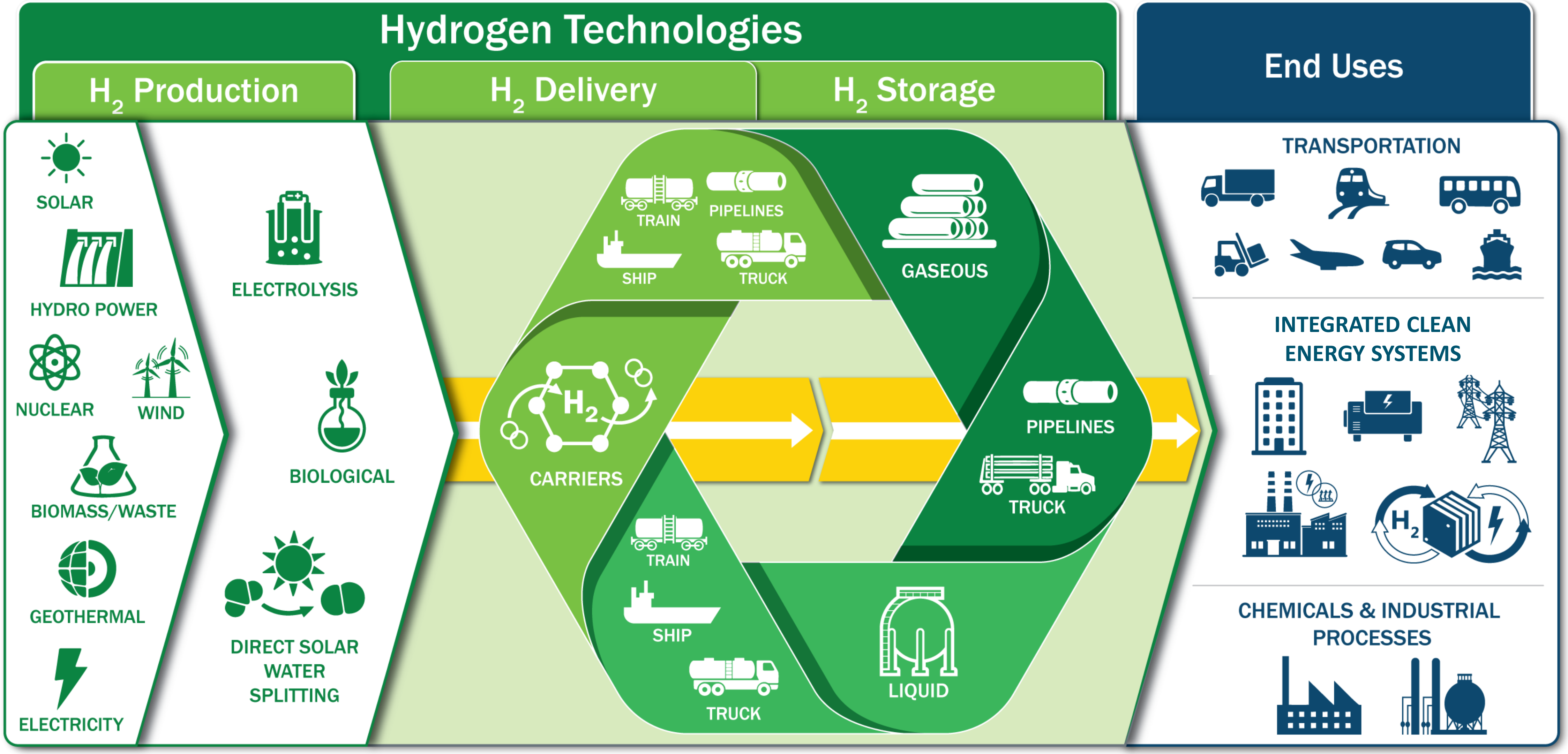
$80B Global Government Funding. 6X More with Private Sector through 2025



Source: McKinsey, H2 Council, Spring 2021

Studies show potential for 10 to 25% global GHG reduction using clean hydrogen. $2.5T Revenue. 30M Jobs.

Hydrogen Technologies RD&D Program



From producing hydrogen molecules through dispensing to end-use applications

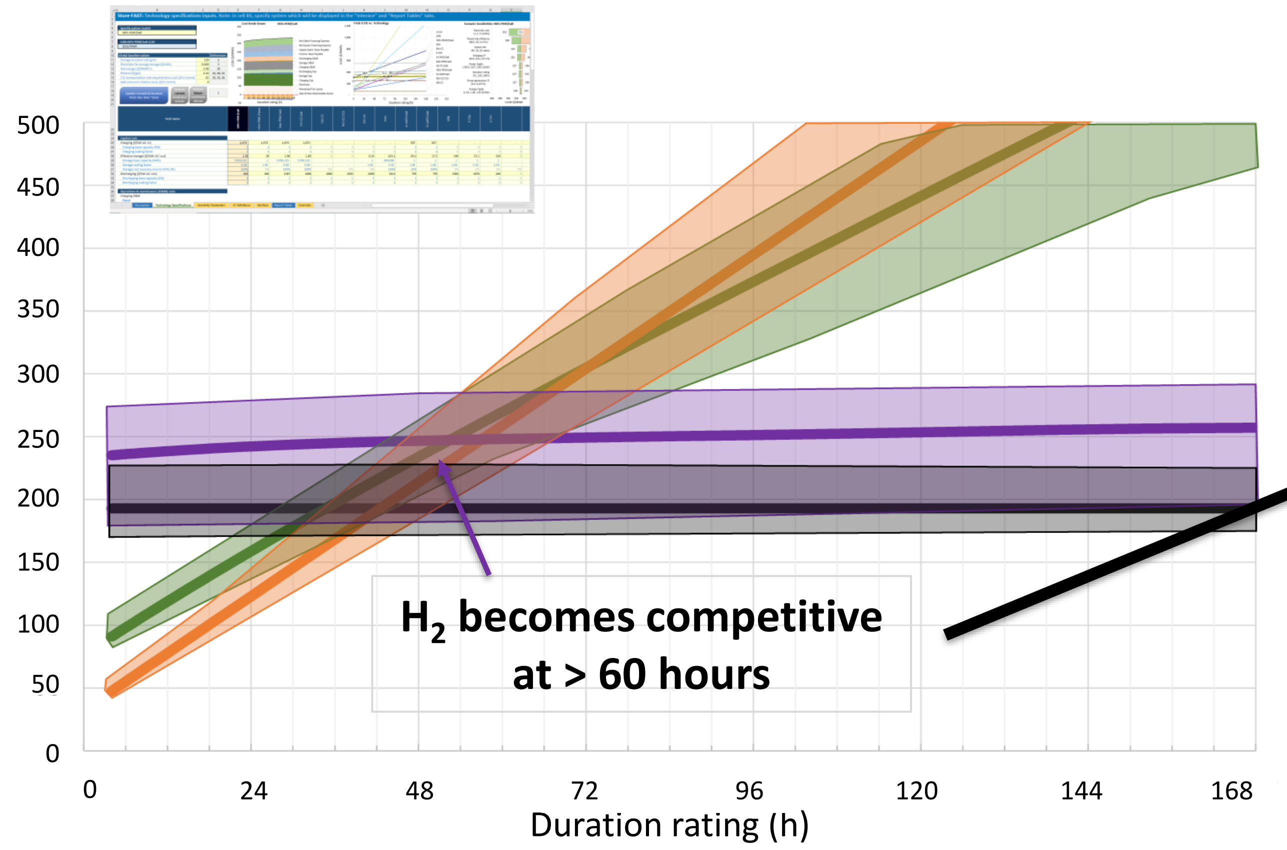
Transportation – example capacity needs

- Light-duty vehicles – 5-6 kg onboard storage
  - Progression of daily fueling capacities for California H_2 fueling stations
    - < 200 kg H_2/day → 300-500 kg/day → **≥ 1000 kg/day** (~200$^+$ vehicles per day)
    - Compressed H_2 delivery via tube trailer: **~1000 kg payload** for new 500 bar composite tube trailers
      - **~ one or more deliveries per day required**
    - Liquid H_2 delivery via tanker truck: **~4500 kg payload**
      - **~ two deliveries per week required**

- Medium/Heavy-duty vehicles – ~40-100$^+$ kg onboard storage
  - H_2 fueling stations
    - One effort focused on **8,000-32,000 kg** capacity (~100 – 400 long-haul trucks per day)
    - Compressed H_2 delivery via tube trailer: ~**8-32 deliveries required per day!**
    - Liquid H_2 delivery via tanker truck: **~2-8 deliveries required per day!**

Long Duration Energy Storage

Newly released StoreFAST model assesses cost of long duration energy storage

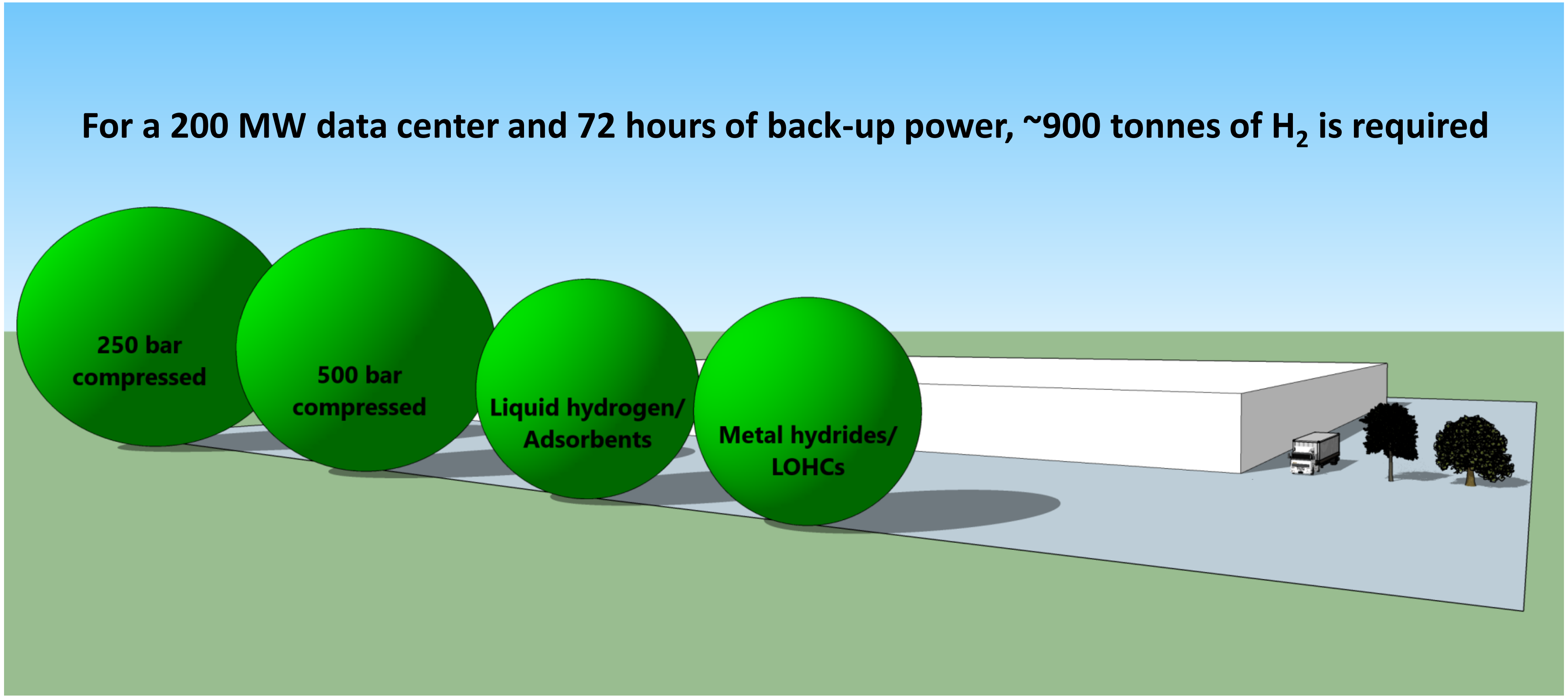


At 10 MW average power, equates to 37,500 kg H_2 needed to be stored

Available at: https://www.nrel.gov/storage/storefast.html (NREL)

Relative H_2 Storage Volumes required for Data Center Back-up Power

Approximately 1,500 kg H_2 required per MW per day with an ~50% efficient fuel cell power system

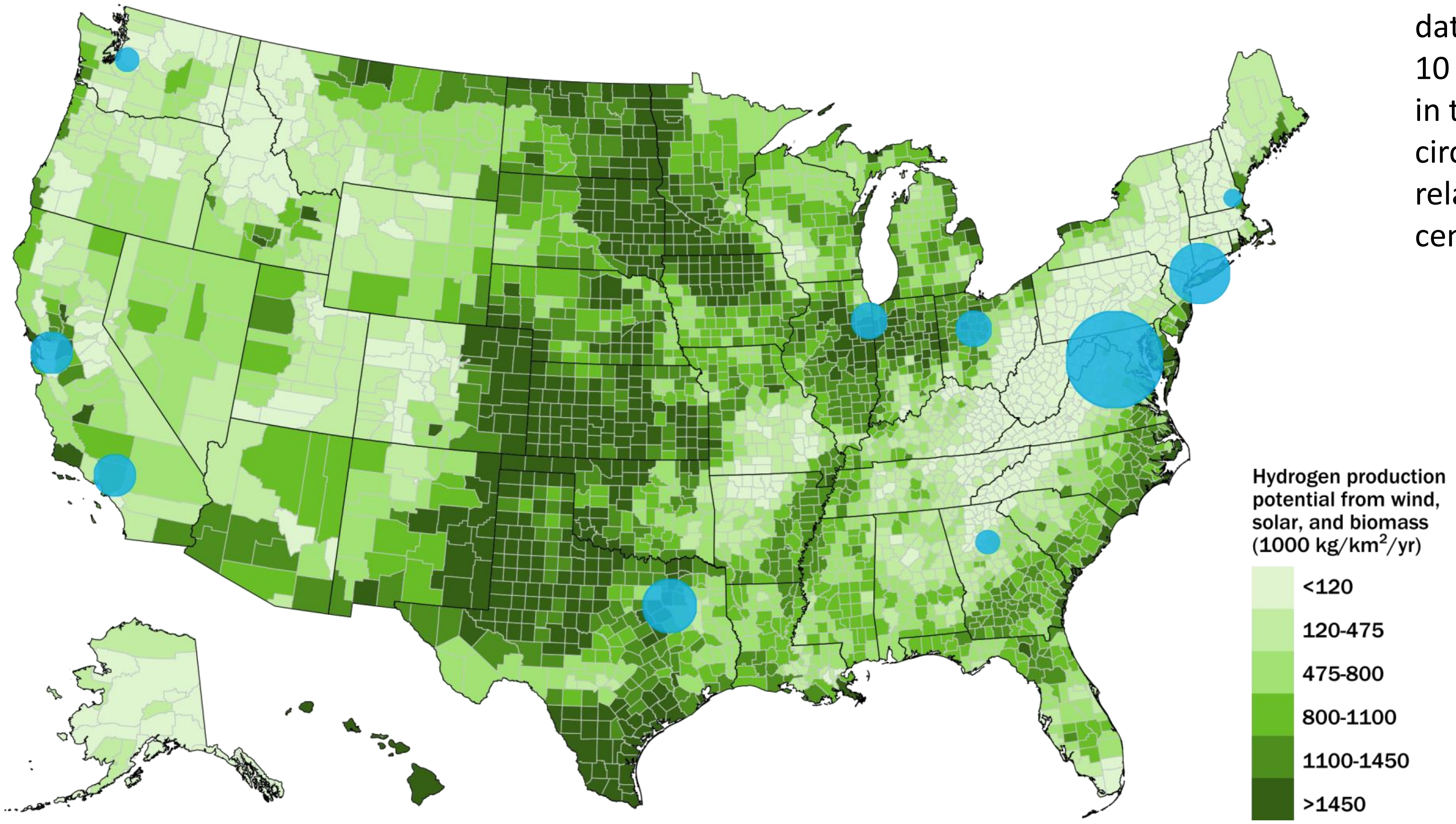


Hydrogen storage volumes required for up to **72 h of backup power for a 200 MW, 9300 m^2 data center facility (~900 tonnes H_2)**. Volumes calculated based on storage medium densities. **Facility is ~12 m in height**. Spherical storage vessels used for illustrative purposes only and do not indicate actual vessel design and configuration.

Celestine, A.-D.N.; Sulic, M.; Wieliczko, M.; Stetson, N.T., *Sustainability* **2021**, *13*, 12654. https://doi.org/10.3390/su132212654

Locations of Data Center Clusters in the U.S.

Blue circles indicate key data center hubs in the 10 metropolitan areas in the US. Size of each circle approximates the relative number of data centers in each area.



There is a need for large-scale bulk storage technologies that can be applied throughout out the country

Workshop Objectives

- With increasing use of hydrogen in large-scale applications, the need for low-cost, bulk H_2 storage technologies that are geographically agnostic, and meet application performance requirements, is a challenge

- Workshop Objectives
  - Identify bulk H_2 storage needs for upcoming, large-scale applications
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Thank you for your participation

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

Hydrogen & Fuel Cell Technology Office (HFTO) - Overview

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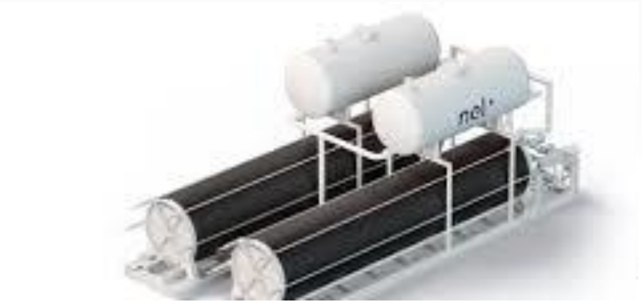
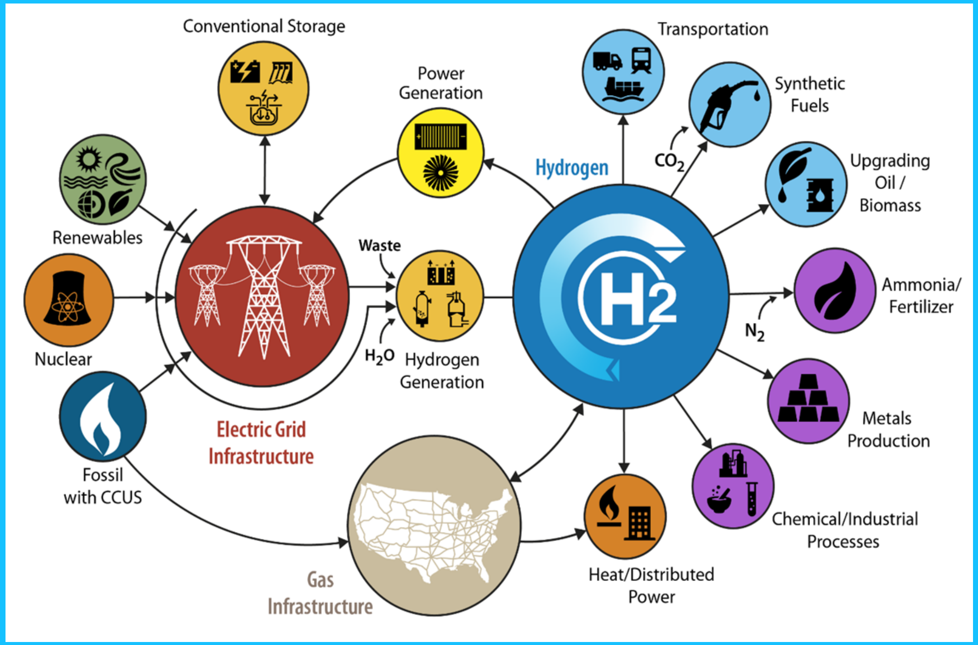
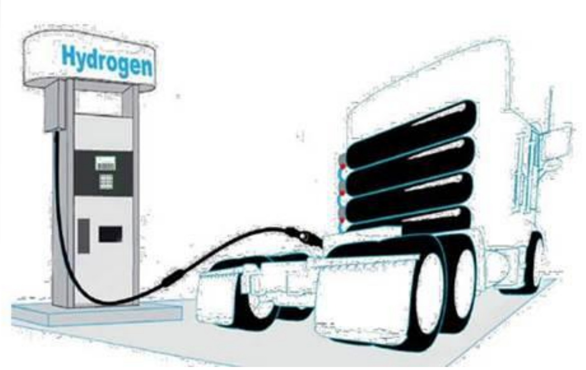


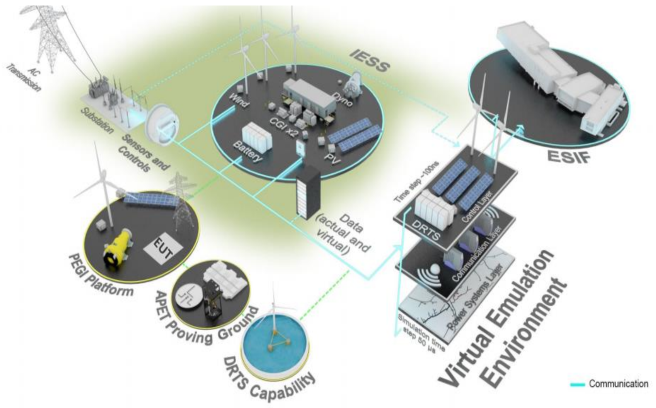
H_2 Production Focus: Electrolyzers

H2 @ Scale





Fuel Cells for Heavy Duty (Focus: Trucks)



Hydrogen for Industry and Energy Storage

H2NEW U.S. DEPARTMENT OF ENERGY

H-Mat Hydrogen Materials Compatibility Consortium

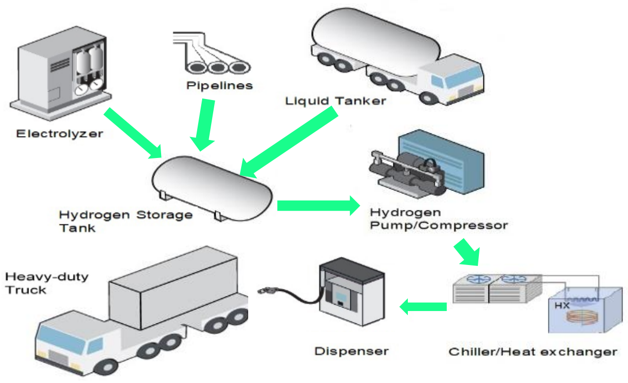
HydroGEN Advanced Water Splitting Materials

FCT U.S. DEPARTMENT OF ENERGY

MILLION MILE FUEL CELL TRUCK

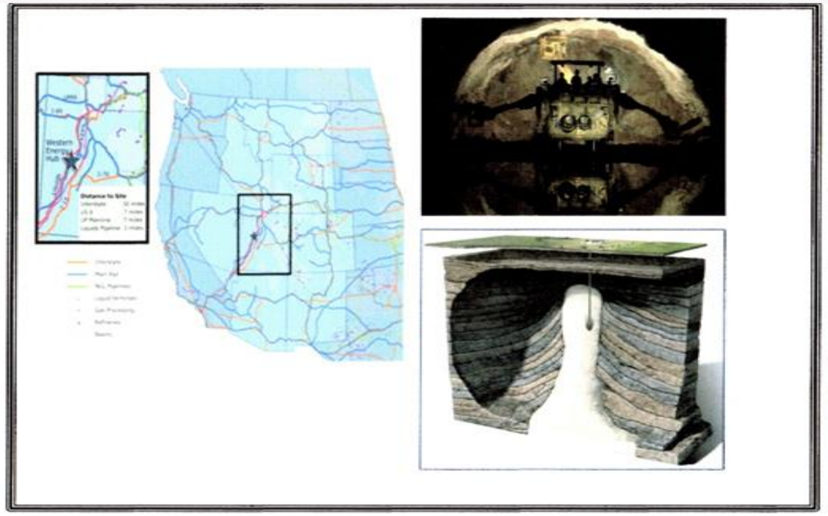
HyMARC Hydrogen Materials Advanced Research Consortium

ElectroCat Electrocatalysis Consortium



H_2 Infrastructure & Materials

Hydrogen Storage Capacity is Commercial but at a Small Scale Currently



There are three H_2 storage sites using salt domes now commissioned in Texas

- Air Products, Praxair, and Air Liquide (presently largest in the world).

New storage site is planned near Delta, Utah (shown in Figure to the right)

- Only “Gulf Coast quality” salt dome in the Western United States.

Total US natural gas storage capacity = 9,231,237 MMcf in 400 sites

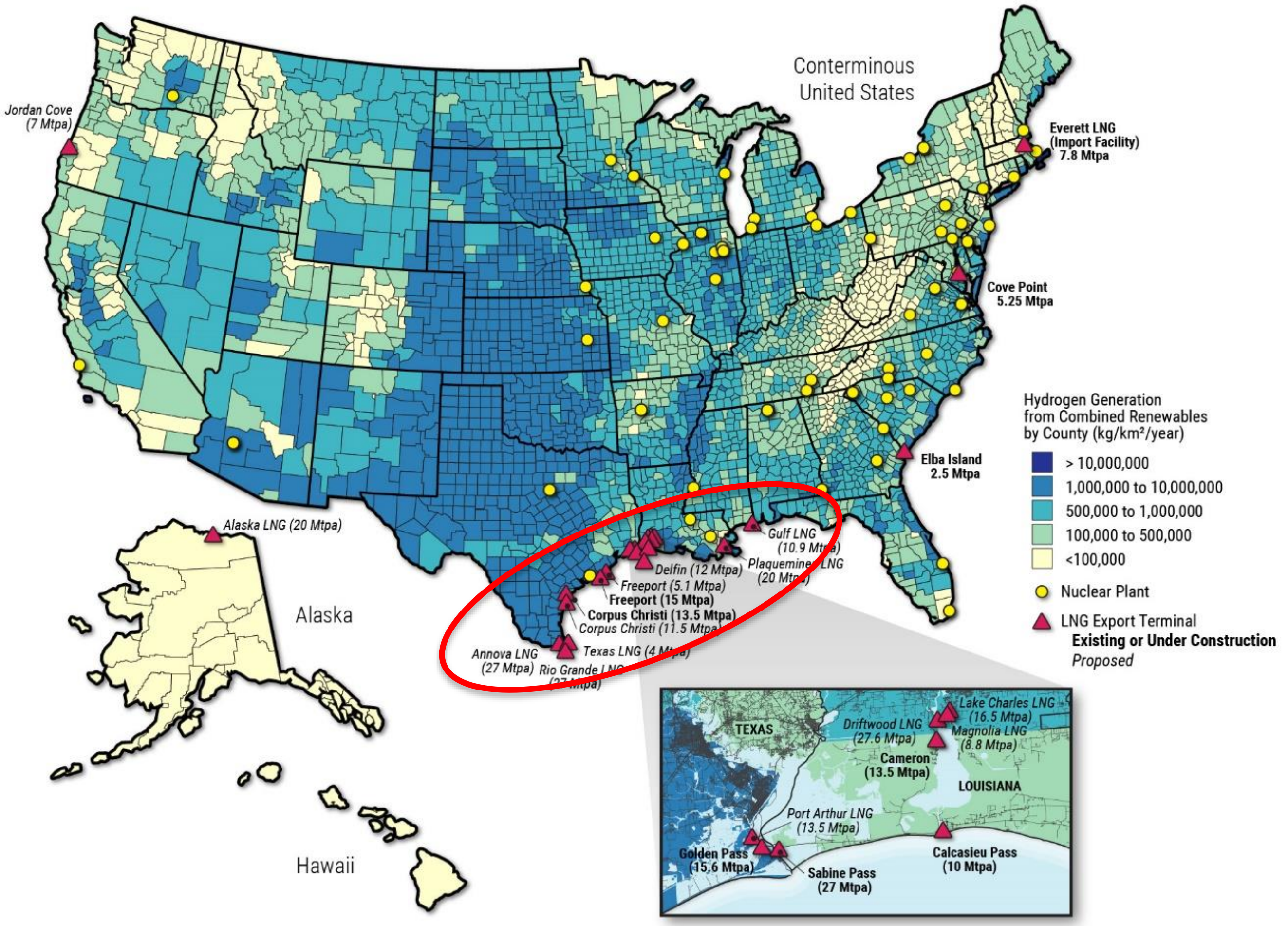
Total TX underground H2 storage capacity = 11,726 MMcf (0.13% vs. NG)

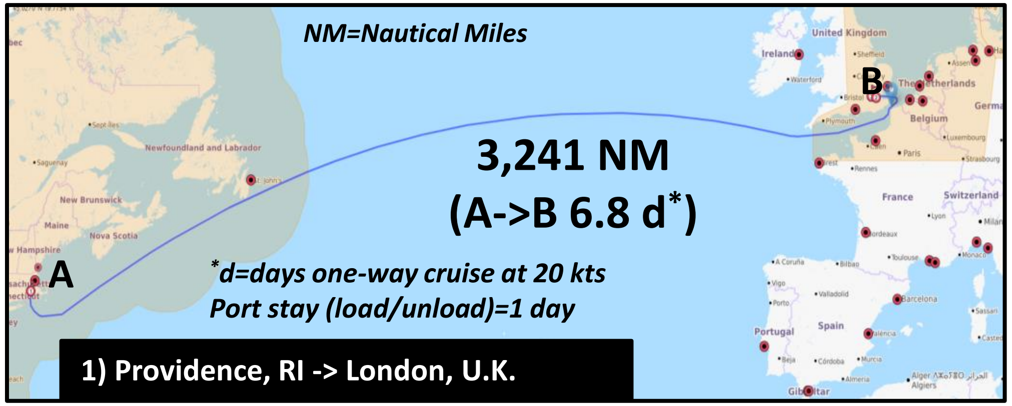
Will need to increase hydrogen storage volume by 770 X to equal natural gas storage volume

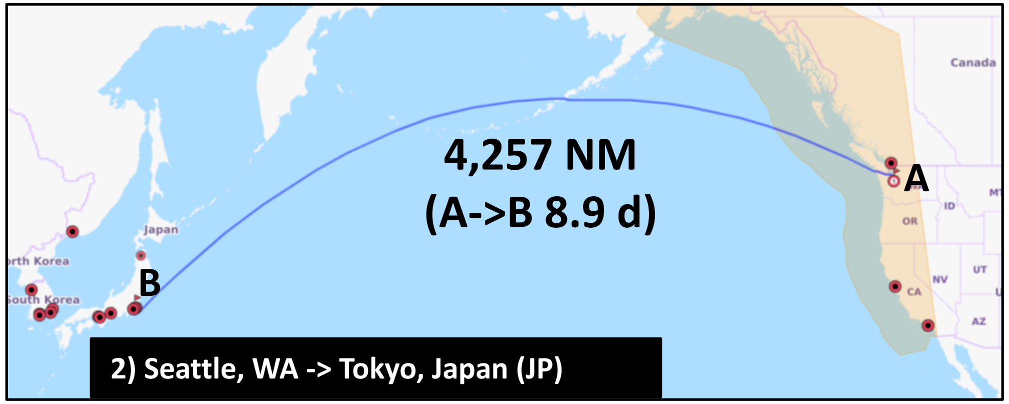
Hydrogen is 1/3 the energy density of natural gas, so need ~2000 X to equal natural gas energy storage capacity

Potential for U.S. Hydrogen Exports: Analysis Underway

Argonne NATIONAL LABORATORY | NREL NATIONAL RENEWABLE ENERGY LABORATORY







Preliminary

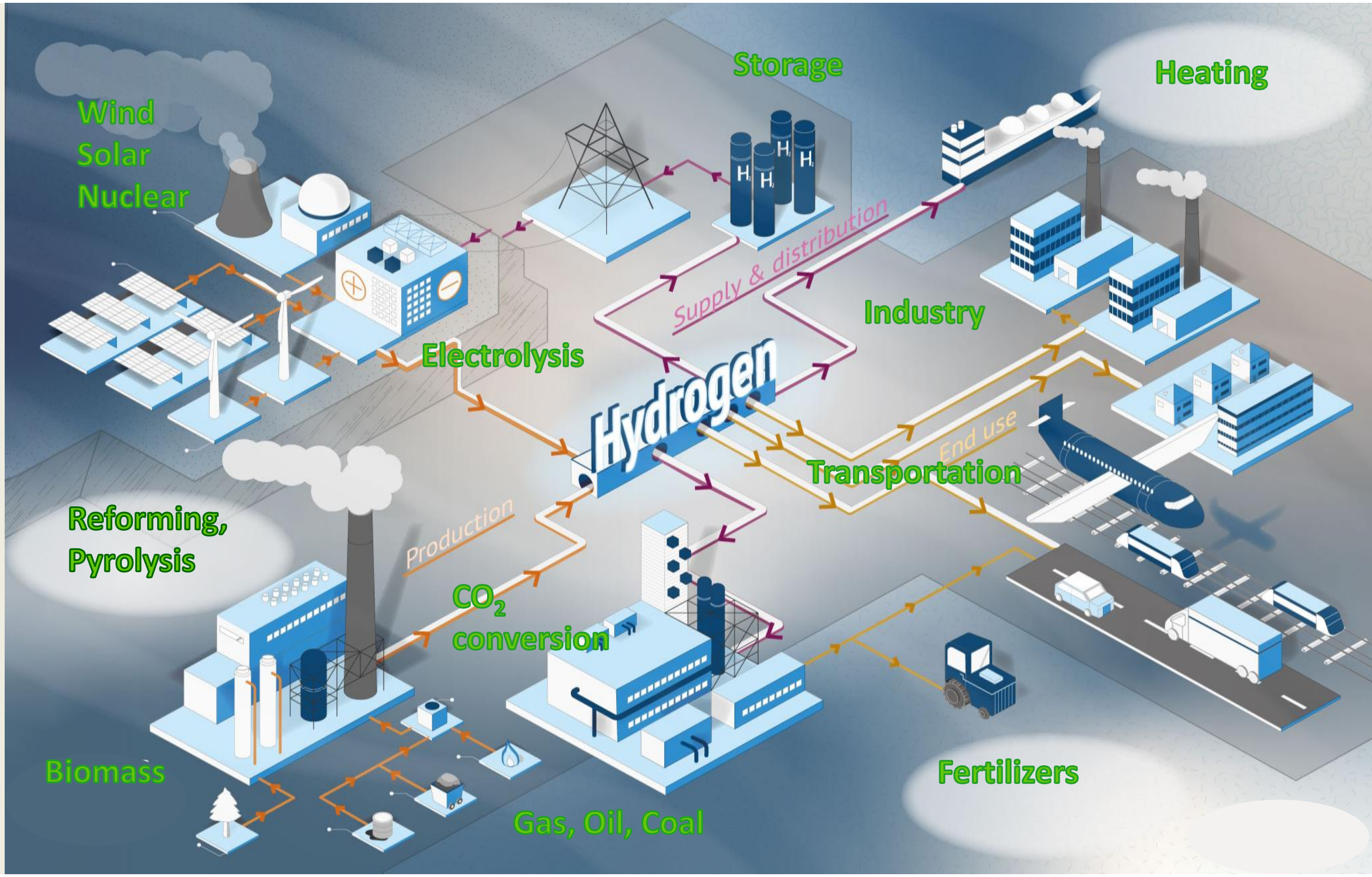
For more information, please see SA177 and ST001

US LNG Export terminals are concentrated in the Gulf Coast near substantial resources for renewable hydrogen supply

Preliminary estimates of the cost of hydrogen export via liquid tanker from the U.S. to Europe or Japan: ~$5-$6/kg

Summary: Strategy and Next Steps

1) **Accelerate R&D to reduce cost**
2) **De-risk demonstration and enable deployments**
3) **Strategic scale up**
   - **Clusters**: co-locate supply and demand (e.g., at ports) and enable infrastructure
   - **RFI feedback** and regional analysis will guide activities



Identify jobs, EJ, and workforce development opportunities (e.g., transition from fossil fuel to H_2, ports, etc.)