Hydrogen

Presented to: CIBO
Presented by: Andrew Duin, Partner

Date September 12, 2023

The business of sustainability

ERM

About ERM

Shaping a sustainable future with the world's leading organizations

ERM is the world's largest pure play environmental, health and safety, risk and sustainability consultancy

History
Leading sustainability consultancy providing environment, social and governance services for 50 years to global corporate clients and the financial services industry

People
Unique blend of 7,000+ staff i.e. technical, strategy, commercial and financial experience, in over 170 offices in 39 countries

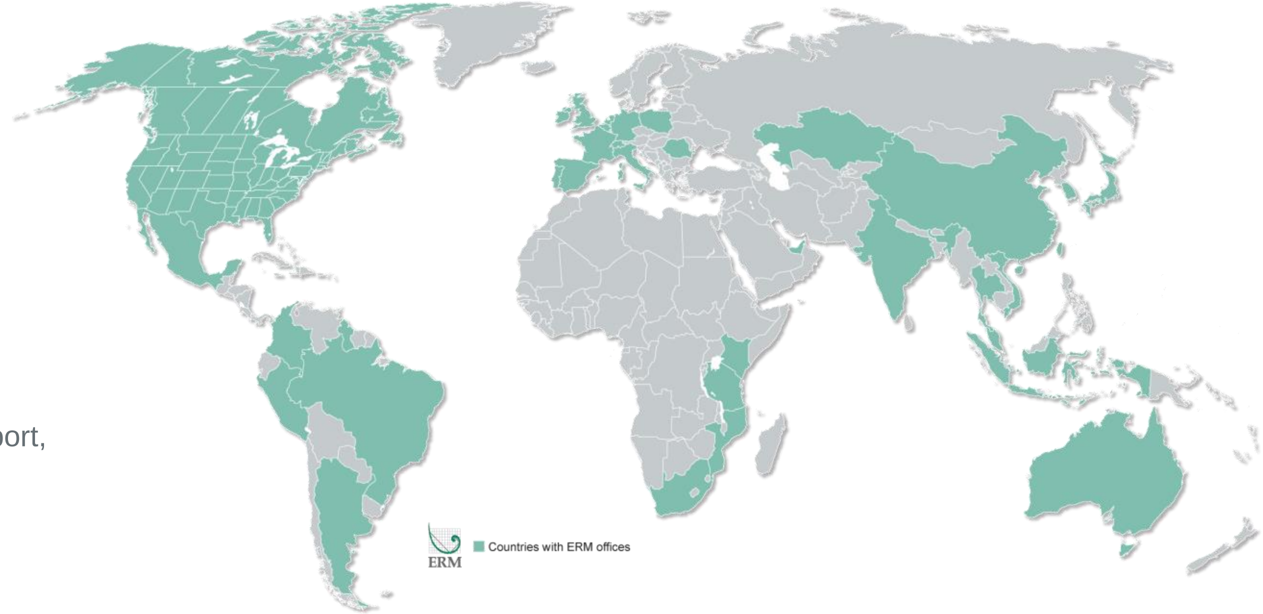
Sustainability Services
We understand business and provide transaction and financing environmental and social risk management support, at the assessment and implementation stages

Thought Leader
Based on over 10 years of climate change scenario analysis, we supported the Taskforce on Climate-related Financial Disclosure to develop its recommendations for applying scenarios

152 countries where we worked on projects

8,000+ employees

$1 billion+ annual revenue



50+ year history

3,000+ clients

23,000 projects worked on in FY23

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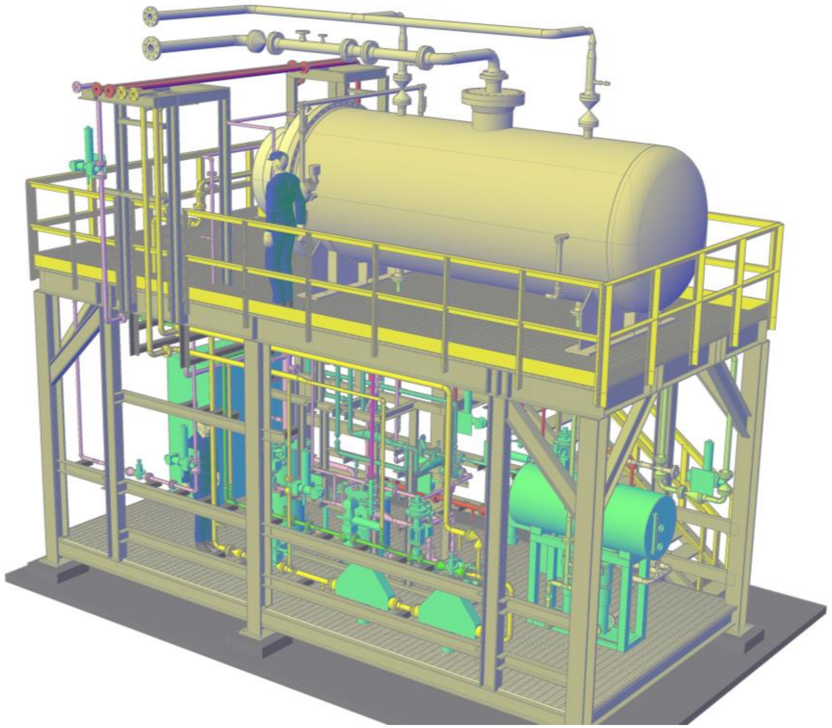
Introduction to hydrogen - Recent News

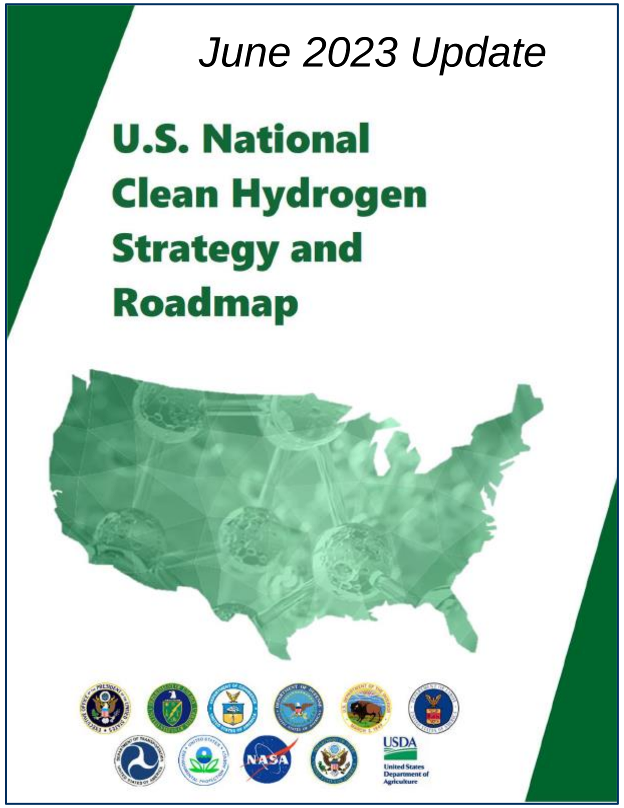


Hydrogen Technologies HHO Boiler

https://hydrogentechnologiesllc.com/

Nikola / FFI Green H2 Project

https://www.nikolamotor.com/press_releases/fortescue-future-industries-ffi-and-nikola-to-collaborate-and-invest-in-the-co-development-of-large-scale-u-s-green-hydrogen-production-projects-225/



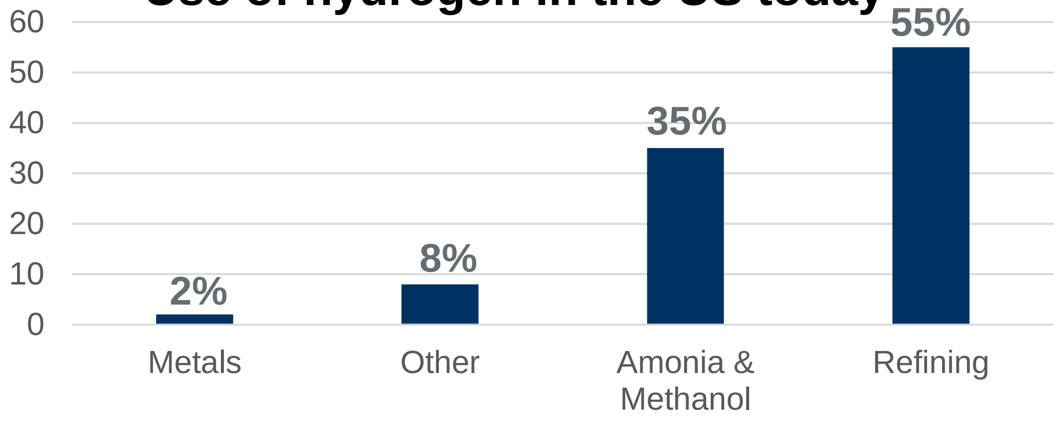
Introduction to hydrogen

Some Current Uses

- Petroleum refining
- Chemicals
- Fertilizer
- Fuel Cells
- Energy Storage

1% of H_2 comes from renewables currently

Use of hydrogen in the US today



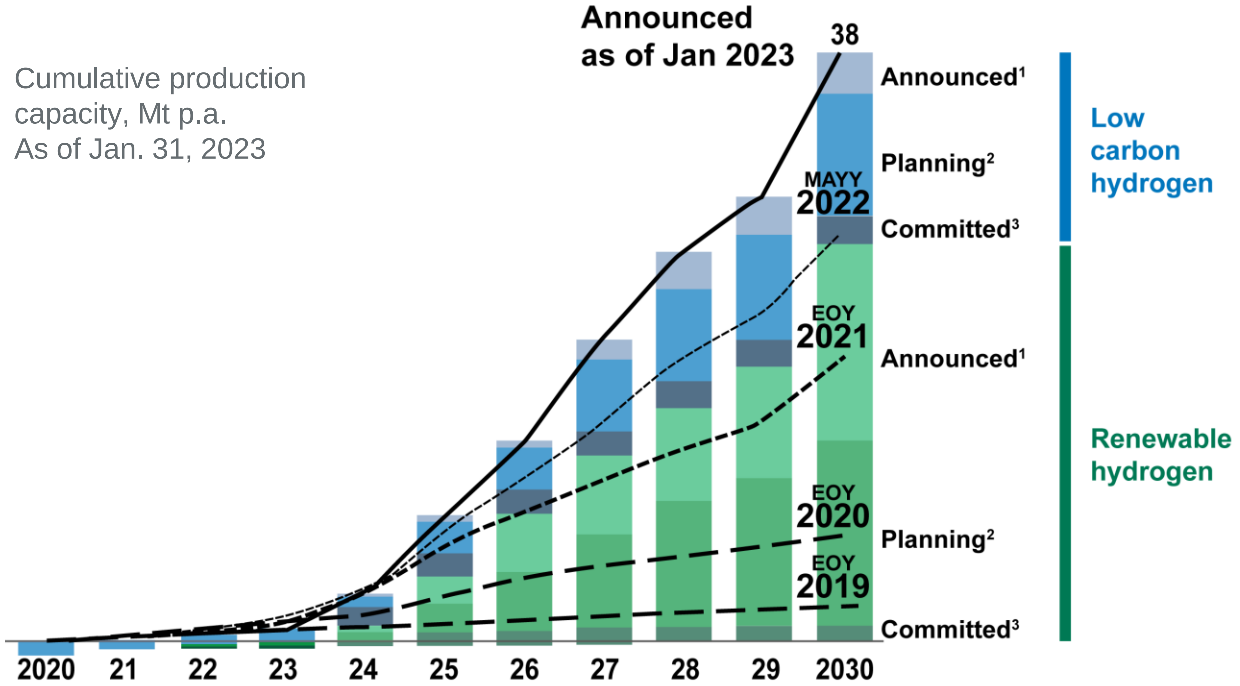
Source: DOE Hydrogen and Carbon Sequestration Programs (energy.gov)

Introduction to hydrogen

Where will Hydrogen go from here?

- Ammonia
- Natural Gas blending
  - Appliances and impacts using hydrogen
- Uninterruptable power supply (UPS) system for data centers, buildings, electrical equipment
- Transport
  - Fuel Cell Electric Vehicles (FCEV)
  - Shipping
  - Aviation
- Industry
  - Warehouses, generators, ports, airports, steel, process heat for steam
- Power Generation

Projected Hydrogen Projects



[1] Preliminary studies or at press announcement stage
[2] Feasibility study or front-end engineering and design stage
[3] Final investment decision has been taken, under construction, commissioned or operational

Source: DOE Hydrogen and Carbon Sequestration Programs (energy.gov)
Source: Hydrogen Council, Hydrogen Insights 2023

Data reveals that developing and deploying projects can take longer than initially estimated by Developers. 2021 6GW announced by end of 2022, actual deployment was 700MW

Hydrogen interest and key off takers

ERM is seeing increased interest across various end-uses:

- **Transportation -** Medium and heavy-duty vehicles Also shipping, maritime applications, and ports including replacing diesel generators with Fuel Cells to provide electricity for docked ships. H2 in rail system (bio fuels and fuel cells)

- **Bio Fuels -** (incl. SAF, 40B tax credit although same facility cannot also claim 45v) and Power to Liquid fuels

- **Industry -** Steel (potential to decarbonize up to 70% using clean H2 in Electric Arc Furnace), Refining & Chemicals

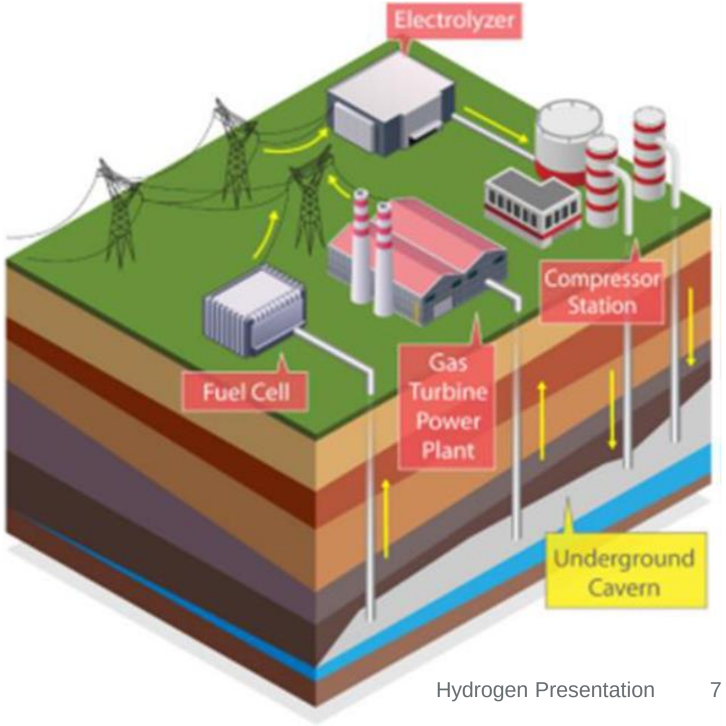
- **Ammonia -** Early opportunities and potential to decarbonize by over 90% by utilizing clean H2

- **Energy Storage -** Early opportunities including fuel cells and ability to replace diesel generators and Power Generation*

- **MeOH (Methanol)**

- **Heat -** Including H2 blending with CH4, LCA important to understand for blending, also RD&D funding for up to 100% H2 for industrial burners. DOE's HyBlend initiative supports addressing challenges associated with using H2 for heat.

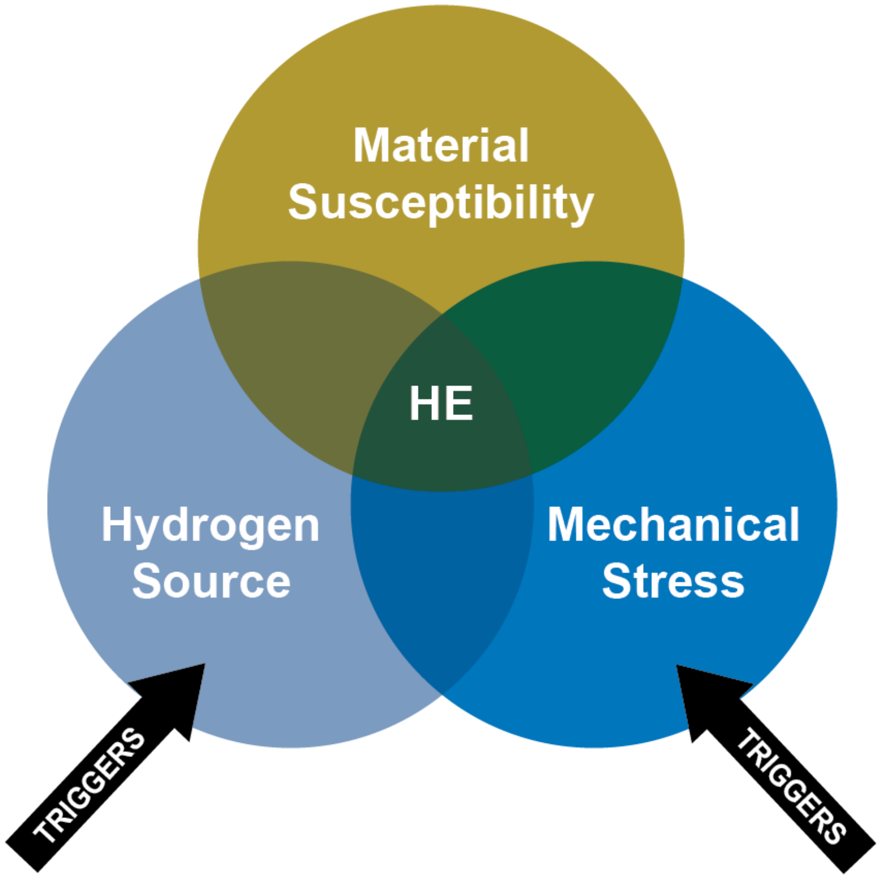
*EPA proposal requiring H2 co-firing w/CH4 as a compliance option for CO2 emission limits on fossil fuel-fired power plants (111 Clean Air Act)



Introduction to hydrogen

Properties of Hydrogen

- Generally considered an ideal gas
- At standard temperature and pressure (STP) it is colorless, odorless, non-toxic, non-corrosive
- Very low density
- Highly diffusive and buoyant, rapidly mixes with air (if there is a leak it is highly diffusive)
- High potential for leakage due to small size and molecular weight (threaded fittings, flanges are problematic)
- At elevated temperatures and pressures, it causes decarburization (pulling out carbon from metal) and embrittlement (stress cracking)



Introduction to hydrogen

Properties of H2

- Liquid phase occurs at -423F (37 deg Rankine), absolute zero is -460F
- Hydrogen coexists in 2 different forms, ortho and para, dependent on temperature
  - At STP 75% is ortho (nuclear spins aligned) and 25% para (spins anti-aligned)
  - At lower temperatures para hydrogen is more stable, around -423 deg F >99% para.
  - Reason for mentioning this is the large molecular energy difference between

    the two varieties as well as some physical differences (boiling point higher for ortho)

    Heat released during ortho decay can boil off a significant amount of liquid hydrogen
- Negative Joules-Thomson effect (increase in temperature)
  - Upon depressurization the temperature of hydrogen gas increases (3,000psig drop results in a 11 deg. F increase)
  - Common class IV vessels range from 350bar (5,076psi) to 700bar (10,153psi)
    - 350bar results in around 18F temp change
    - 700bar results in around 36F temp change
- Broad flammability range (4 to 75%) (adequate ventilation is critical for confined spaces and leak detection is key)

Different forms of hydrogen

Ortho hydrogen molecules have spins of two nuclei in the same direction

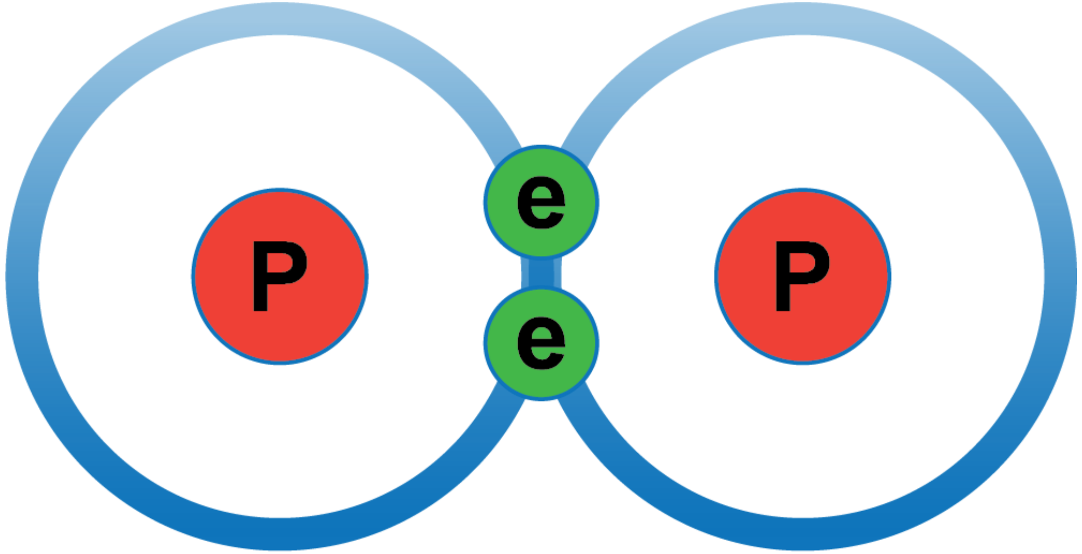
Para hydrogen molecules have spins of two nuclei in opposite directions

Introduction to hydrogen

Properties of Hydrogen

- Mass energy of hydrogen is very high,
  - 1kg of H_2 = 132.5MJ which is 2.5 times more energy than 1kg of CH_4
    - 1kg of H_2= approx. 125.5k BTU (132.5MJ)
    - 1kg of CH_4 = approx. 49k BTU (52MJ)
  - However!! Due to the density of hydrogen, you need approx. three times the volume of hydrogen compared to natural gas (CH_4) to get the same amount of energy
- Combustion of H_2 w/oxygen results in H_20, combustion of H_2 with air results in H_20 and some NO_x.
- Very high flame speed (potential for flashback) and it can propagate through a very small gap, however this can be a benefit if a vessel ruptures or leaks, if ignited the flame may quickly dissipate

Shared electrons



Hydrogen Gas

Hydrogen Roadmap

The time to commit to hydrogen is now.

2020 - 2022
Immediate Next Steps

- Decarbonization goals at state & federal level
- Public incentives to breakdown barrier and increase public awareness and acceptance
- Second generation fuel cells electric vehicles (FCEV) and fueling stations for light-duty vehicles
- First generation FCEV and fueling stations for heavy-duty vehicles (HDV)
- Introduction of hydrogen tolerant equipment
- Initial pilots for energy storage, enabling intermittent renewables, nuclear, data centers, and industrial applications

2023 – 2025
Early Scale Up

- Policy incentives for early markets to transition
- Spread public incentives beyond pioneer states
- Regulatory framework for hydrogen energy storage
- Implementation of cross-sectoral decarbonization
- Large scale eletrolyzer plant (50 MW+)
- Hydrogen pipeline & delivery systems
- New FCEVs to market
- Second generation FCEV for HDVs
- Introduction of pure hydrogen tolerant equipment

2026 – 2030
Diversification

- Transition of policy incentives to scalable market-based mechanisms
- Enabling policies to broaden applications beyond transport
- Development of electrolytic hydrogen production with dedicated renewables and nuclear
- Development of blue hydrogen plus carbon capture, utilization and storage (CCUS) to support increasing hydrogen demand
- First hydrogen pipelines to connect production sites with demand centers
- Scale up hydrogen equipment production

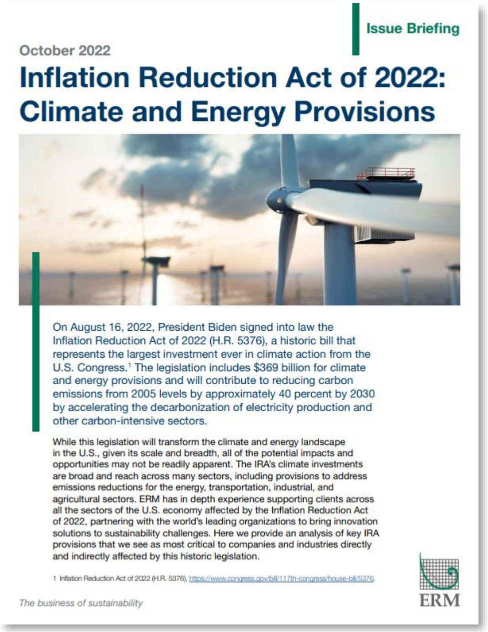
Post 2030
Broad Rollout

- Reduced/no direct policy support in certain applications when reaching cost parity
- Robust hydrogen code at federal level
- Expanding use of hydrogen across sectors
- Retrofitting of reforming capacity with CCUS
- System compatibility to scale hydrogen in existing gas infrastructure
- Variety of vehicle models available

Source: "ROADMAP TO A US HYDROGEN ECONOMY" https://www.fchea.org/us-hydrogen-study
Source: "ROADMAP TO A CANADIAN HYDROGEN ECONOMNY" https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf

Hydrogen Roadmap - Inflation Reduction Act

$369B of incentives, targeting economy-wide reductions of 40% below 2005 levels by 2030



Issue Briefing

October 2022

Inflation Reduction Act of 2022: Climate and Energy Provisions

On August 16, 2022, President Biden signed into law the Inflation Reduction Act of 2022 (H.R. 5376), a historic bill that represents the largest investment ever in climate action from the U.S. Congress.[1] The legislation includes $369 billion for climate and energy provisions and will contribute to reducing carbon emissions from 2005 levels by approximately 40 percent by 2030 by accelerating the decarbonization of electricity production and other carbon-intensive sectors.

While this legislation will transform the climate and energy landscape in the U.S., given its scale and breadth, all of the potential impacts and opportunities may not be readily apparent. The IRA's climate investments are broad and reach across many sectors, including provisions to address emissions reductions for the energy, transportation, industrial, and agricultural sectors. ERM has in depth experience supporting clients across all the sectors of the U.S. economy affected by the Inflation Reduction Act of 2022, partnering with the world's leading organizations to bring innovation solutions to sustainability challenges. Here we provide an analysis of key IRA provisions that we see as most critical to companies and industries directly and indirectly affected by this historic legislation.

1 Inflation Reduction Act of 2022 (H.R. 5376), https://www.congress.gov/bill/117th-congress/house-bill/5376.

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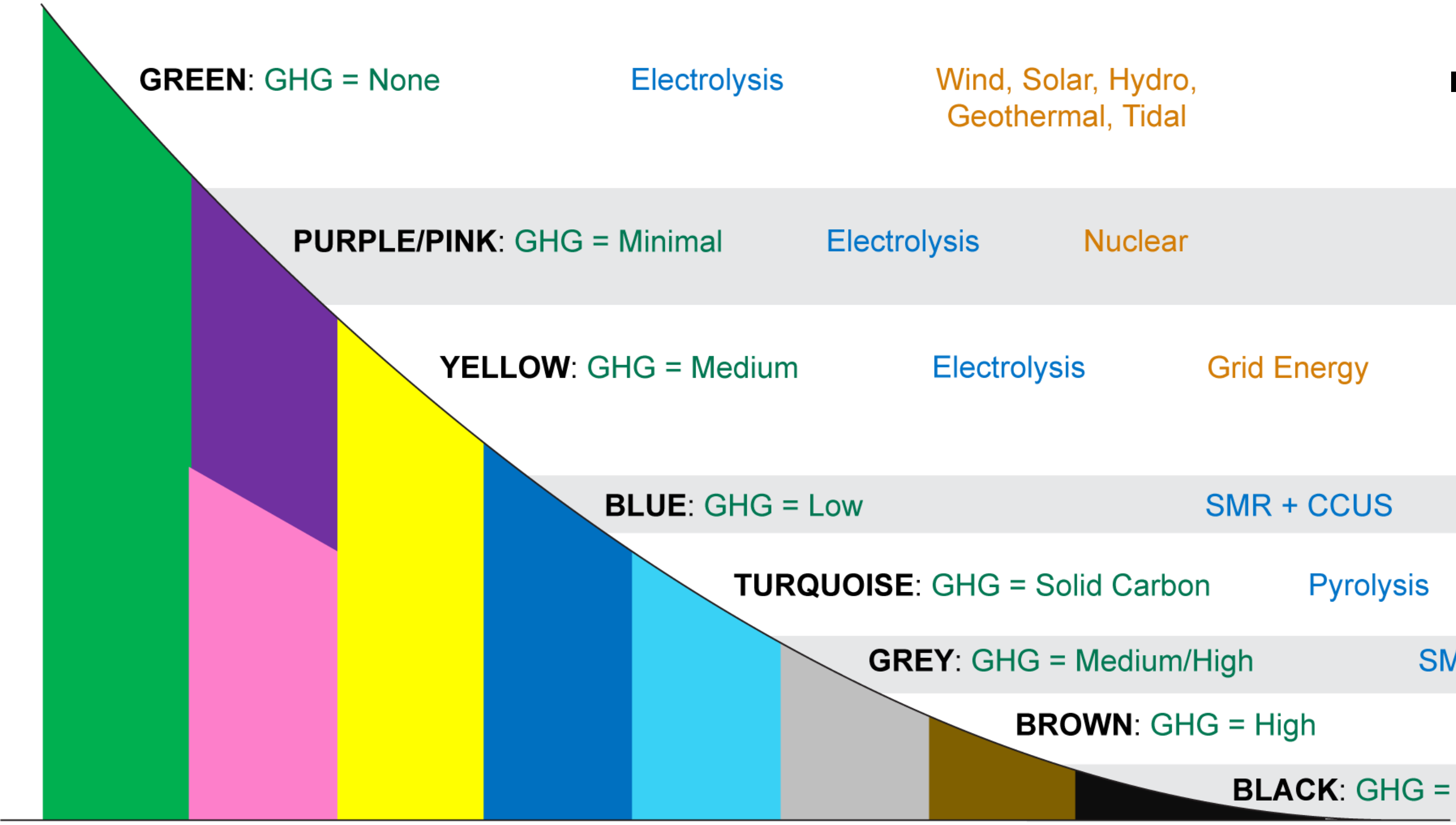
Source:
[Inflation Reduction Act of 2022: Climate and Energy Provisions (erm.com)]

Hydrogen Roadmap - Inflation Reduction Act

The different colors of hydrogen



GreenHouse Gases	Technology	Feedstock
GREEN: GHG = None	Electrolysis	Wind, Solar, Hydro, Geothermal, Tidal
PURPLE/PINK: GHG = Minimal	Electrolysis	Nuclear
YELLOW: GHG = Medium	Electrolysis	Grid Energy
BLUE: GHG = Low	SMR + CCUS	Natural Gas
TURQUOISE: GHG = Solid Carbon	Pyrolysis	Natural Gas
GREY: GHG = Medium/High	SMR	Natural Gas
BROWN: GHG = High	Gasification	Brown coal
BLACK: GHG = High	Gasification	Black coal

$$$$** Credit goes down as carbon intensity increases → **$

- **Hydrogen Production Tax Credit** (PTC)
  - Credit dependent on greenhouse gas lifecycle carbon intensity (GREET)
  - Up to $3/kg credit (0.45kg CO_2e/kg H_2)
- Many different colors of hydrogen and the IRA addresses this by adjusting the credit value (depending on the GHG lifecycle carbon intensity value)

Greenhouse Gas Lifecycle

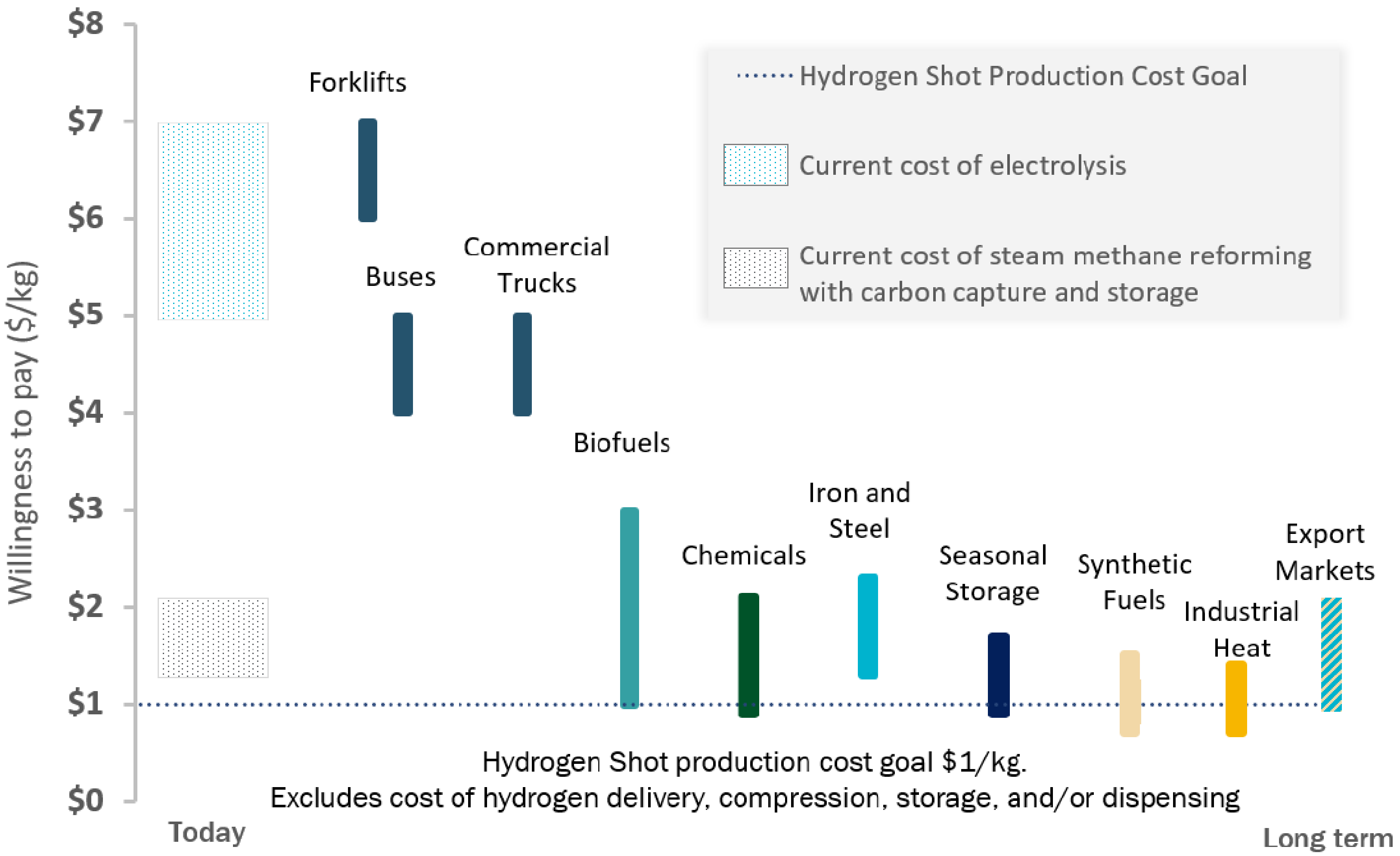
The lifecycle target system boundary terminates at the point at which hydrogen is delivered for end use. This system boundary does not include potential liquefaction, compression, dispensing into vehicles, etc.,

Generation of electricity	Extraction of feedstock	Feedstock delivery	H2 production and CO2 capture	CO2 Delivery	CO_2 Sequestration
Fuel combustion	*Fuel combustion*	*Fuel combustion*	*Fuel combustion*	*Fuel combustion for compression, etc.*	*Potential Emissions/ leakage*
Fugitive emissions	*Fugitive emissions*	*Fugitive emissions*	*Fugitive emissions*	*Fugitive emissions*	
	Feedstock treatment (e.g. drying, purification. Fertilizer for biomass)		*Process emissions*		

Hydrogen Roadmap - Inflation Reduction Act

Kg of CO2 per kg of H2	Credit Value ($)
4 - 2.5 kg CO2	$0.60 / kg of H2
2.5 - 1.5 kg CO2	$0.75 / kg of H2
1.5 - 0.45 kg CO2	$1.00 / kg of H2
0.45 - 0 kg CO2	$3.00 / kg of H2

Current "grey" GHG CO2e values range from 9 - 11



Source: US DOE H2 roadmap

Hydrogen Roadmap - Department Of Energy (DOE)

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Prioritizing three key strategies

1 Target strategic, high impact uses for clean H_2

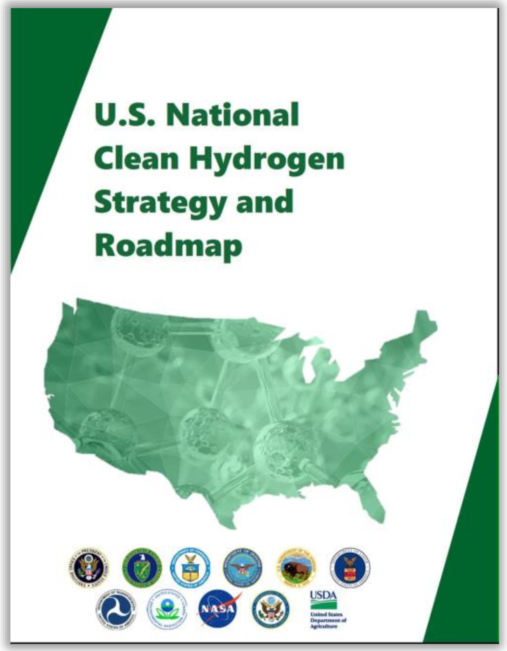
Examples include chemical, steel, refining, heavy-duty transport, long-duration energy storage, production of liquid fuels, and exporting H2 (gaseous, liquid, LOHC, ammonia, etc.)

2 Reduce the cost of clean H_2 (Earthshot)

Target: $1 per 1 kilogram in 1 decade (“1 1 1”)
Address material and supply chain vulnerabilities, efficiency, durability, and recyclability
Investments in midstream infrastructure (i.e. storage, distribution)
Current costs for delivering H2 to California fueling stations is more than $13/kg which is not competitive

3 Focus on regional networks

- Hydrogen Hubs & additional DOE funding to drive demand
- Production close to end-users
- Leverage regional resources and feedstocks
- Focused on equity, inclusion, and sustainability
- Reduce environmental impacts, create jobs, securing long-term offtake contracts, jumpstarting domestic manufacturing and private sector investment



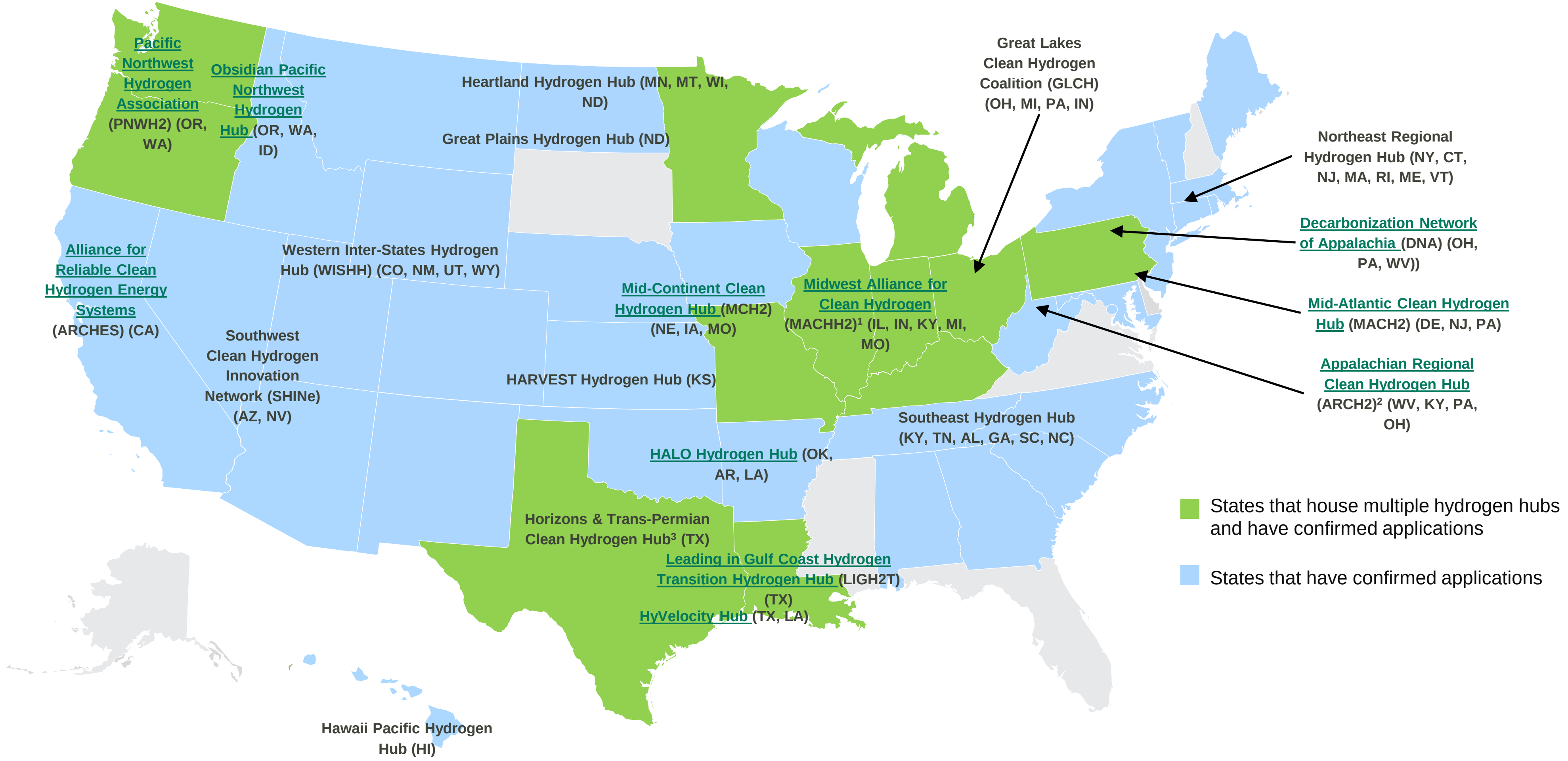
The National Clean Hydrogen Strategy and Roadmap aligns with the Administration’s goals, including:

- Achieve 50-52% GHG reduction from 2005 levels by 2030
- 100% "carbon pollution free" electricity by 2035
- Net zero by 2050
- 40% of the benefits of Federal climate investments are delivered to disadvantaged communities
- Reduce cost of clean hydrogen to $1/kg by 2030 (1 dollar, 1 kg, 1 decade - "1,1,1 rule", called Hydrogen Shot)

Source: Program Plans, Roadmaps, and Vision Documents : DOE Hydrogen Program (energy.gov)

H2Hub (21 Confirmed Applications)

States' H2Hub Announcements



As of July 15, 2023.

1. Indiana Hydrogen Hub joined MachH2.
2. Press articles indicate that the Ohio Clean Hydrogen Hub Alliance joined ARCH2.
3. On February 14, 2023, it was announced that the Port of Corpus Christi Horizons Clean Hydrogen Hub and the Trans Permian H2Hub would submit a combined application to DOE in April 2023.

Sources: At least 20 hubs submitted final applications for US hydrogen hub funding | S&P Global Commodity Insights (spglobal.com)

Timeline

We are here (Summer 2023)

September 22, 2022	Funding Opportunity Announcement Issue Date
November 7, 2022, by 5pm ET	Submission Deadline for Concept Papers
December 2022	Concept Paper Encourage/Discourage Notifications
April 7, 2023, by 5pm ET	Submission Deadline for Full Applications
May 31, 2023, by 5pm ET	Expected Submission Deadline for Replies to Reviewer Comments
June 5, 2023	Final version of the *U.S. National Clean Hydrogen Strategy and Roadmap released*[1]
July 5, 2023	DOE released a NOI, including an RFI, to invest $1 billion demand-side initiative for the H2Hubs[2]
Summer 2023	Pre-Selection Interviews
Fall 2023	Expected Date for DOE Selection Notifications
Winter 2023-2024	Expected Timeframe for Award Negotiations

[1] The Biden-Harris Administration released the final version of the *U.S. National Clean Hydrogen Strategy and Roadmap*, which highlights the DOE's Regional Clean Hydrogen Hubs (H2Hubs) as part of one of the three key strategies being prioritized.

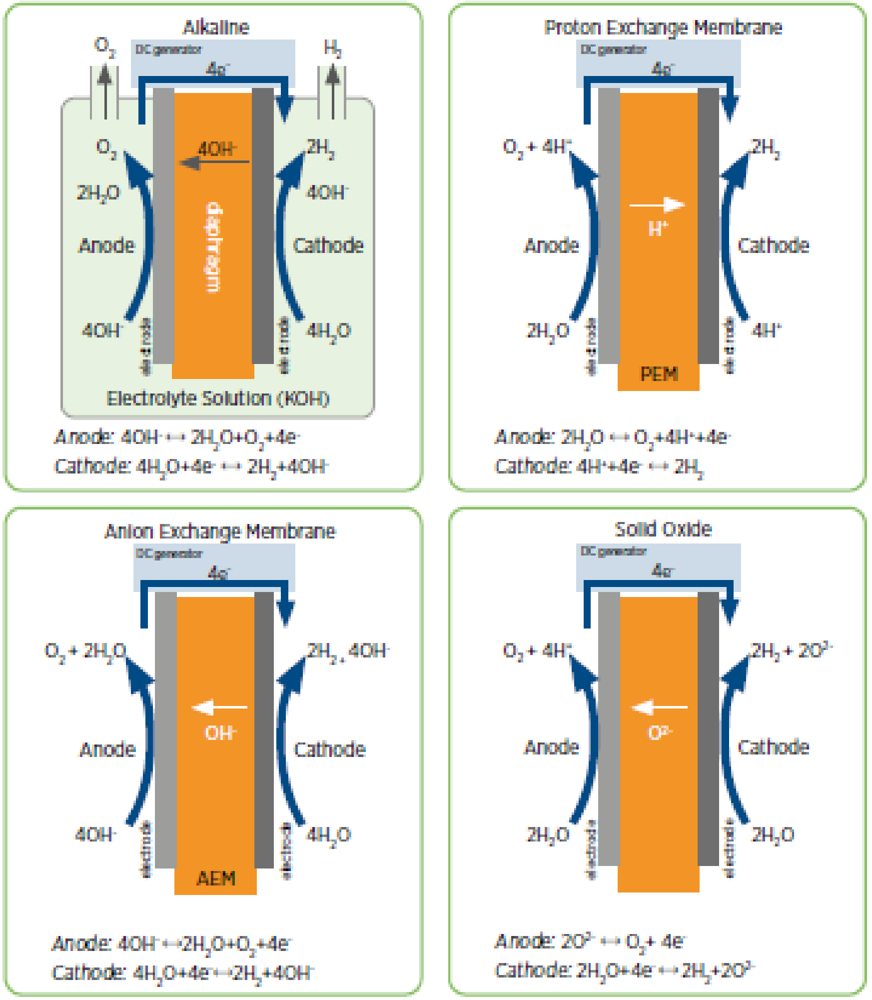
[2] The DOE released a Notice of Intent (NOI), including a Request for Information (RFI), to invest up to $1 billion in a demand-side initiative to support the H2Hubs. This initiative will aid in the advancement of hydrogen production as it will ensure that both producers and end-users in the H2Hubs will have market certainty surrounding production, encouraging private investment and allowing them to realize the full potential of clean hydrogen.

Hydrogen Production

- Production
  - Electrolyzers
    - Consist of an anode, a cathode, electrolyte, and electricity
  - Alkaline
    - Utilize liquid alkaline solution (KOH), hydrogen ions move through electrolyte from cathode to anode
    - Alkaline exchange membranes (AEM)
    - HHO membraneless electrolyzers
  - Proton Exchange Membrane (PEM)
    - Utilizes membrane, hydrogen ions move from anode (across membrane)

      to cathode. Allows for high current density and high-pressure differentials.
  - Solid oxide
    - Solid ceramic membrane, High temperature (800C/1,472F), high efficiency
  - Other: Anion Exchange Membrane (AEM), Biological, Solar Water Splitting,

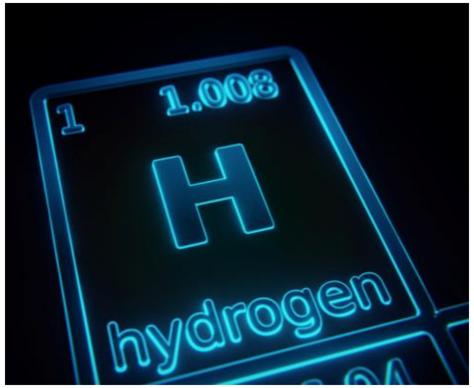
    Steam Methane Reformation (SMR) w/Carbon Capture Utilization and Storage (CCUS)



Source: *IRENA*

Regulations & Standards

- Design Standards & Safety (Some key standards)
  - ASME B31.12 Piping Design (>10% H_2 up to 3,000psi)
  - OSHA 29 CFR 1910 Subpart H - Hazardous Materials
  - Department of Transportation (DOT) 49 CFR Part 192 – Transportation of Natural and Other Gas by Pipeline (up to 10% blends)
  - Compressed Gas Association
  - NFPA (2 & 55)



Center for Hydrogen Safety

Codes and Standards | Hydrogen Tools (h2tools.org)

Hydrogen Blending - Safety

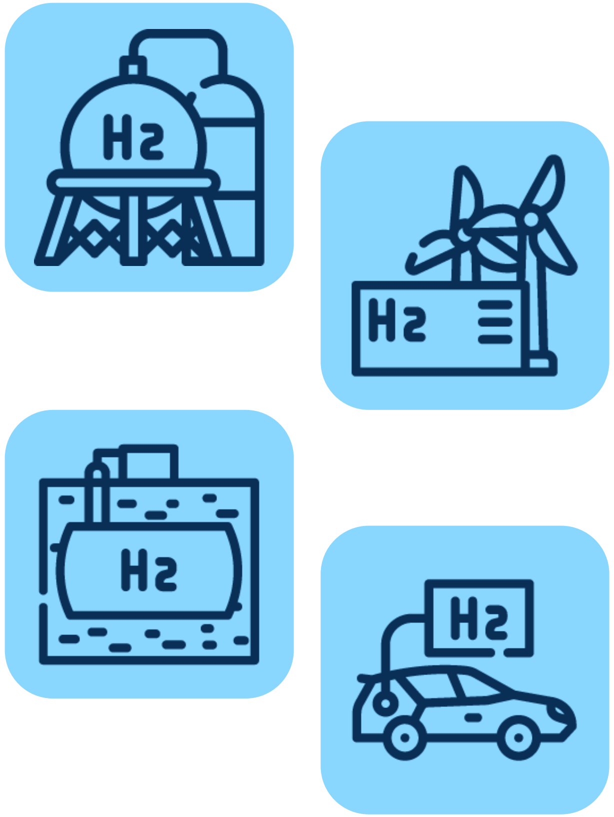
Safety Measures

- Multiple and redundant analyzers
  - The lag time on a gas chromatograph makes it so you cannot depend on it for real-time blending data.
  - Using real-time H_2 analyzers helps
  - Determine the best metering for each application. Coriolis meters and specific gravity meters are good options
- Leak Detection
  - Thermal conductivity, very sensitive to hydrogen
  - Semiconductor sensors, more sensitive to H_2 than CH_4, use correction factors
  - CO sensors are very sensitive to H_2, may shorten equipment life and may require equipment changeout
  - Laser doesn't sense the H_2 portion well and is not a good option for H_2 blends
- Flame Detection (infrared)
- Consider a shipping container to house a blending skid for security and containment
- Emergency alarms (strobe/horn)

Hydrogen Blending - Design

Storage

- Liquid – Higher mass storage, good for higher volumes of blending, BOG is a challenge
- Gaseous – Lower mass storage vs. LH2, generally use ASME Class IV vessel, no need to vaporize, good for long term storage, may not be considered “permanent”
- Depending on permit and safety requirements, a fire wall may be necessary
- NFPA 55 and International Fire Code provide guidance for fire protection and storage
  - NFPA 55 chapters 7, 10, and 12 provide system design, fire protection, storage, and gas generation. This outlines required valves, pressure relief, storage locations and spacing requirements.
  - The storage pressure and quantity defines the distance the storage location needs to be from other infrastructure. For process conditions that do not fall within the spacing table of NFPA, there are calculations that can be used.
  - International Fire Code also provides guidance for locating the hydrogen storage area. Depending on the installation, this may be a larger radius than NFPA 55.



Hydrogen Blending - Design

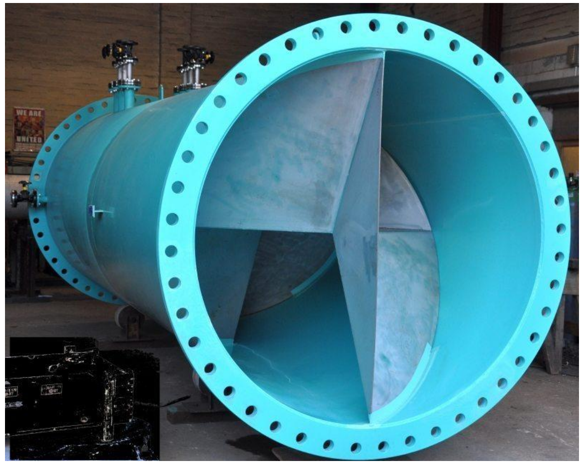
Hazardous Area Classification

- Hydrogen quickly dissipates
- Broad flammability range 4% to 75%

Injection

- Recommend using a non-pulsing injection system to provide a continuous flow rate of hydrogen into the delivery system such as metering and control valves. (solenoids difficult to maintain stable flow)
- Coriolis meters are good options
- Use static mixers for blending. Smaller footprint and better blending compared to use of bends, fittings, filters, etc.

Solenoid injection not recommended



Research examples:

Hyblend (DOE)
GTI (Impacts of H2/CH4 blends)
NREL (H2 Blending)
UC Irvine H2 Impacts Study
NYSEARCH (Range Plus, other studies)

Hydrogen Blending – End Users

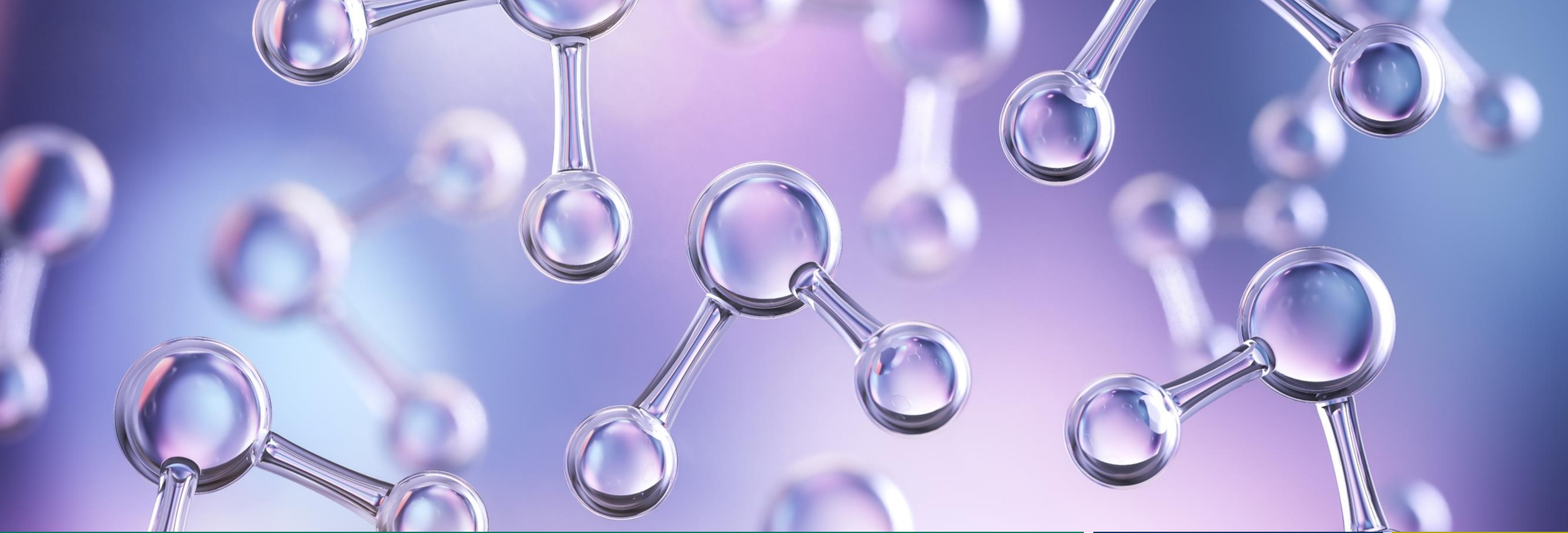
Pilot Programs

- Appliances found in residential subdivisions are well known. And many have been tested for performance on hydrogen blends. Generally, there is little concern with low hydrogen concentrations. In fact, improvements in certain performance characteristics such as reduced flame lifting are expected.
- Larger industrial equipment generally requires modifications, tuning, and fuel switching options
  - Combustion Systems
  - Heating Surfaces
  - Air System (flue gas recirculation)
  - Controls (Boiler and NOx Emissions), Automation, Burner Management System
- Perform materials assessment. Piping, meters, valves, permeation through various materials.
- Revised O&M Procedures, Safety & Emergency Response, Integrity Management
- Currently can be expensive and inefficient to convert to H2

Hydrogen Blending – End Users

End User Equipment Testing

- Determine acceptable H_2 content for end-use equipment
  - General blend levels are between 1% to 5% with successful testing upward of >20%
- Develop testing plan, methods, and instrumentation for testing of residential appliances
  - Flue gas concentrations of oxygen, carbon monoxide, NO_x.
  - Flue gas temperature, flame characteristics (AGA flame code, yellow tipping, flame lifting)
- Impacts to larger commercial equipment (reciprocating engines, turbines, generators, burners, boilers, etc.)
- If possible, consider a continuous hydrogen delivery system, as opposed to a batch injection.



Thank you

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Appendix

Additional Information For Reference

Key IRA provisions for hydrogen and hydrogen derivatives

Clean fuels: up to \$1/gal base
up to \$1.75/gal for SAF

Hydrogen PTC/45V: up to \$3/kg H_2

Low-carbon hydrogen cannot be eligible for both carbon capture 45Q credit and hydrogen 45V

CCUS 45Q credit[4]: utilized – sequestered
DAC: \$130 - \$180/tCO_2
Point source: \$60 – 85/tCO_2

Renewable PTC[2]: \$26/MWh

Details of the hydrogen PTC [1,2]

Who will qualify?

- Projects that emit <4 tCO_2/tH_2 (with max \$3/kg credit available to facilities) <0.45 tCO_2/tH_2)
- Projects that are based in the US
- Greenfield projects put into service before 2033
- Facilities that do not claim 45Q or clean fuel tax credits

How will credits work?

- Based on the full lifecycle, GHG emissions calculated with GREET model[3]
- Eligible for 10 years from the COD date, with 5 years of direct pay, 5 years of tax credits
- Can be stacked with renewable PTC
- No cap on the credit program

What questions remain?

- Can producers power with grid electricity with RECs to reduce CI?
- What is CI calculation methodology and validation process?
- Are there further details on rules related to prevailing wage rate and apprenticeship requirements?
- Can CCUS and clean fuels credits at separate facilities be stacked (e.g., can H_2 Co. sell to SAF Co. and each claim H_2 and SAF credits, respectively?

Disclaimer:
Intended to provide insight based on currently available information for consideration and not specific advice

1. DoE has up to 1 year to establish final rule making
2. Projects that do not pay prevailing wage and apprenticeship lose 80% of credit value
3. <0.45 tCO_2/tH_2 = \$3/kg; 0.45 – 1.5 = \$1/kg; 1.5 – 2.5 = \$0.75/kg; 2.5 – 4 = \$0.6/kg
4. Low-carbon hydrogen can receive the 45Q credit regardless of carbon intensity of the hydrogen

Source: US Inflation Reduction Act of 2022

Hydrogen Market & Value Chain

- Demand
  - Transportation
    - Fuel Cell Electric Vehicles (FCEV)
  - Chemical & Industrial Processes
    - Ammonia
    - Oil refining
    - Steel
    - Cement
    - Food processes (heat)
  - Power
    - Power generation
    - Heat & Power
    - Backup Power
  - Hybrid Energy Systems
    - Generation
    - Storage
    - Conversion

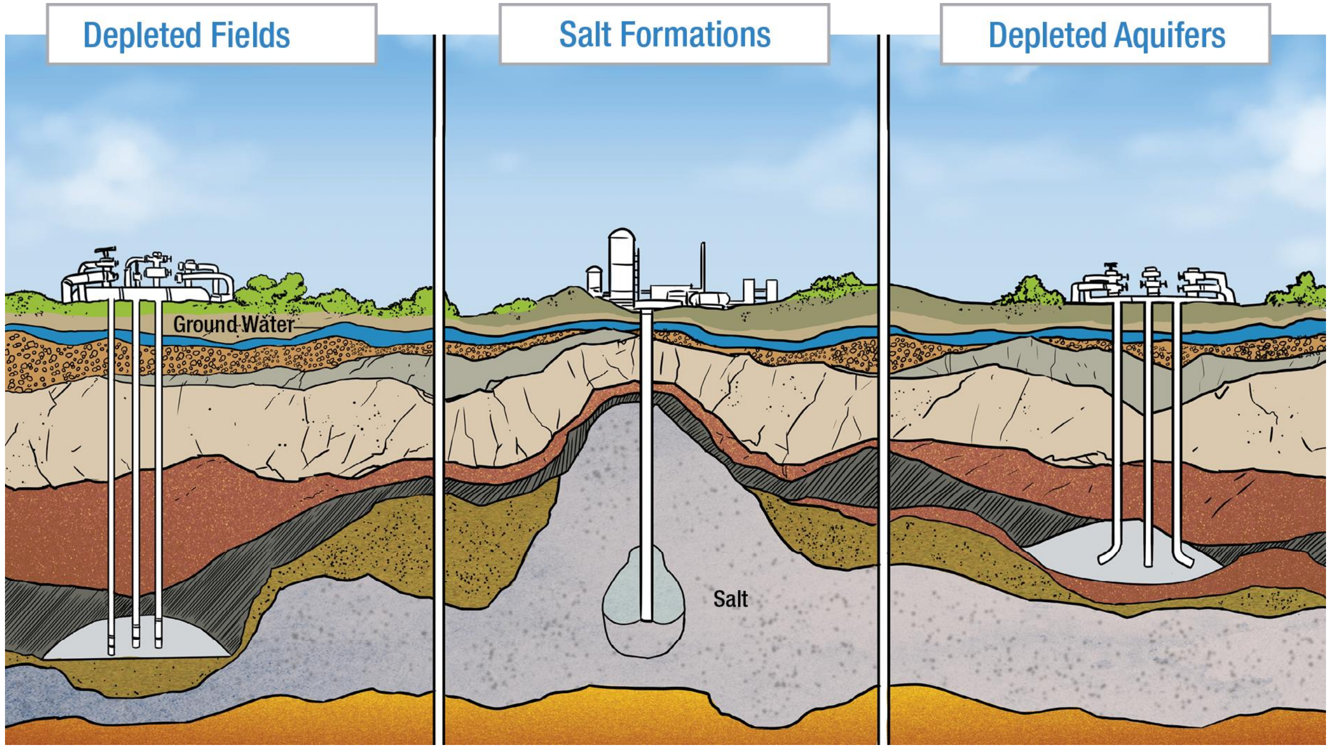
Hydrogen Market & Value Chain

- Transportation
  - **Liquid Organic Hydrogen Carrier (LOHC)**
    - Chemically binds hydrogen to a carrier to avoid transporting elemental hydrogen
    - LOHCs absorb and release hydrogen through chemical reactions
    - Easier to transport (liquid at ambient conditions) (example is Methanol)
    - Need to unbind hydrogen upon delivery or for end use
  - **Pipeline**
    - Proven to be a safe and reliable transport method for natural gas
    - Transport significant volumes
    - Materials compatibility a concern, also leak detection, operations, and maintenance
  - **Trucking**
    - 350bar and 700bar gaseous tube trailers
    - Liquid hydrogen
  - **Hubs**
    - Production, Storage, Transport, End-use in a regional area

Liquefied hydrogen carrier SUISO FRONTIER, built by Kawasaki Heavy Industries

Hydrogen Market & Value Chain

- Storage
  - **Salt Caverns**
    - High pressures
    - Safe storage (low migration potential)
    - High purity (new caverns)
    - Geographical scarcity
  - **Depleted Reservoirs & Aquifers**
    - Hydrogen losses for base gas
    - Potential for migration
    - Potential for biogeochemical reactions
    - Lower pressure vs. salt dome
    - Potential production challenges
    - Contamination potential



Hydrogen Market & Value Chain

- Storage
  - **Vessels and tube trailers**
    - LH2 vessels can store 4000+kg of hydrogen
      - Often need liquefaction and vaporization equipment, compression, truck loading/unloading, M&R
      - Large footprint
      - NFPA and local requirements for offsets of storage
    - Tube trailers
      - 350bar (5,076psi) to 700bar (10,153psi) gaseous tube trailers
      - 150 to 1000+ kg of capacity
      - Easy to transport
      - Drop in place for longer term storage
      - Great for hydrogen fueling stations as no compression is necessary

Ideal Gas Law

$pV=mZRT$

- p=pressure (psi)
- V=volume (ft^3)
- m=mass (lb_m)
- Z-compressibility factor
- R=gas constant ($ft\text{-}lb_f$ / lb_m°R)

Hydrogen Blending – Skid and Storage Costs

4000kg mass storage			
*30,000gal tank (9ft diameter x 65ft length) - GASEOUS			
Pressure	Tanks	Costs	
		Low	High
150psig	40	$7M	$12M
Approx. $175,000 (low end) up to $300,000 (high end) per tank			
1,000psig	7	$1.8M	$3.1M
Approx. $263,000 (low end) up to $450,000 (high end) per tank			

*60,000gal tank (11ft diameter x 91ft length) - GASEOUS			
Pressure	Tanks	Costs	
		Low	High
150psig	20	$4.5M	$9M
Approx. $225,000 (low end) up to $450,000 (high end) per tank			
1,000psig	4	$1.3M	$2.7M
Approx. $337,500 (low end) up to $675,000 (high end) per tank			

18,000gal tank (11ft diameter x 49ft tall) - LIQUID			
Pressure	Tanks	Costs	
		Low	High
150psig	1	$1M	$1.5M

1000kg tube trailer		Costs	GASEOUS
350bar to 700 bar		Low	High
		$2.2M	$3.7M

Prices are rough order magnitude and should only be used for high-level planning purposes.

- 4' x 10' skid
  - 1" piping
  - $400,000
- 10' x 30' skid
  - 4" piping
  - $800,000
- 12' x 45' skid
  - 6" piping
  - $1.5M

*Tanks are based on typical 250psi LPG storage vessels and would require additional reinforcement, heavier wall, and likely internal lining to handle H2 at these higher pressures.

Hydrogen Blending – Appliances & Equipment

- Boilers: Low NO_x burners may be sensitive to flashback when hydrogen content increases due to air-fuel premixing
  - Certain burners are fully premixed and utilizes a surface combustion element.
  - These units should be monitored closely during start-up of the hydrogen blending system.
  - Also note that many boilers are equipped with pilots to light the main flame. These pilots typically premix air with natural gas and, thus, could be sensitive to flashback. If so, adjustment of the pilot air-fuel ratio can likely prevent flashback.
- Appliances for cooking: Most of these appliances premix air with natural gas. Thus, flashback is of concern when hydrogen content increases.
  - Multiple interchangeability index analysis performed in studies show, in general, flashback becomes a concern for certain appliances at about 10 vol% hydrogen.

Interchangeability Parameters	Applications	Performance Characterized	Limits
Wobbe Number	• Appliances • Furnaces and Boilers • Gas Turbines	• Energy Input	Index limits have been prescribed by equipment manufacturers and by the natural gas industry.
AGA Indices	• Appliances	• Flame Lifting • Yellow tipping • Flashback	
Weaver Indices	• Appliances	• Flame lifting • Yellow Tipping • Flashback • Incomplete combustion	
Methane Number	• Reciprocating engines	• Engine knock	