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Webinars

Development and Deployment of Low-Carbon-Intensity Hydrogen at Scale

December 15, 2022

11:00 AM-12:00 PM CST

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Webinars

Development and Deployment of Low-Carbon Intensity Hydrogen At-Scale

Eugene Holubnyak, University of Wyoming

SPE International

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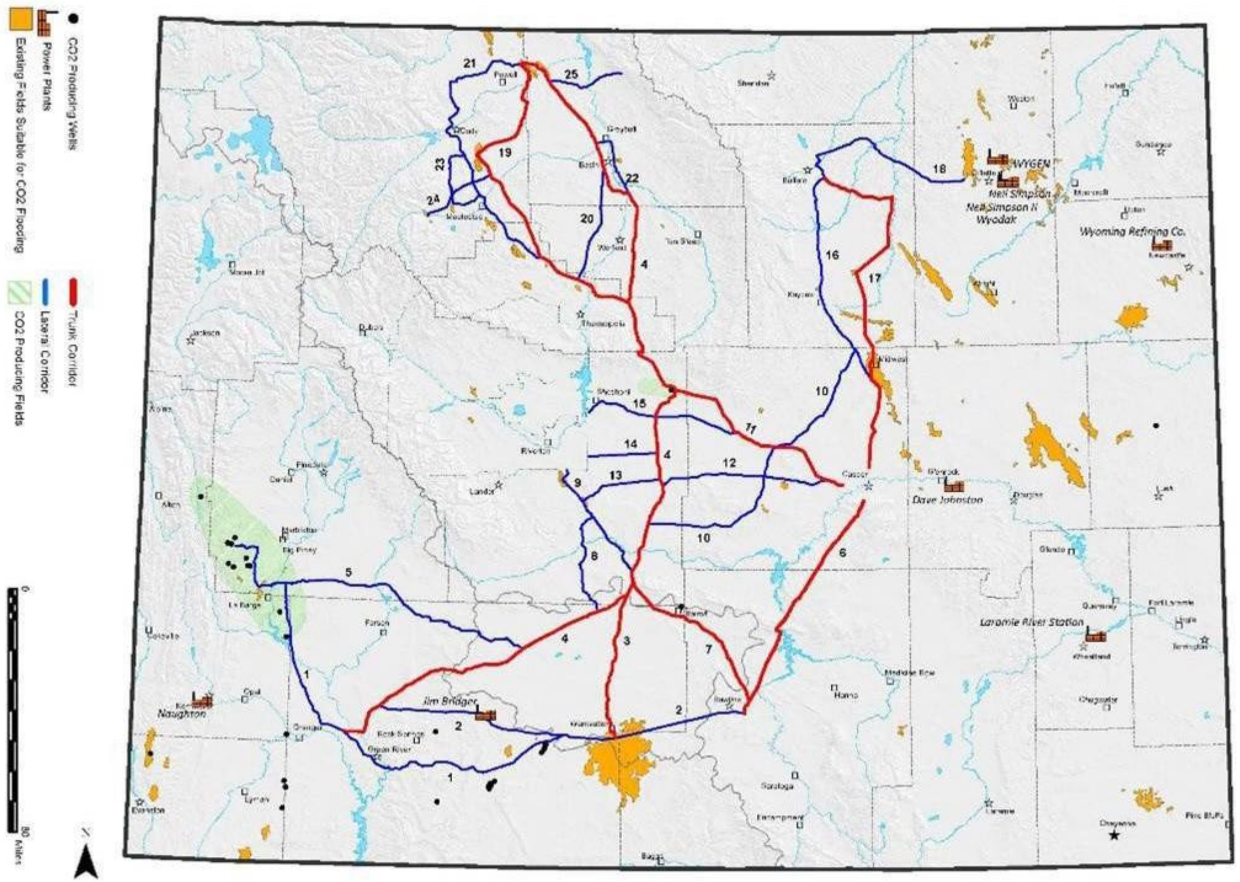
Outline

- Background
- Policies and incentives
- Current status of H_2 production
- Carbon intensity and life-cycle considerations
- Supply chain
- Ammonia
- Water



Relevance – 2020's Decade of Hydrogen

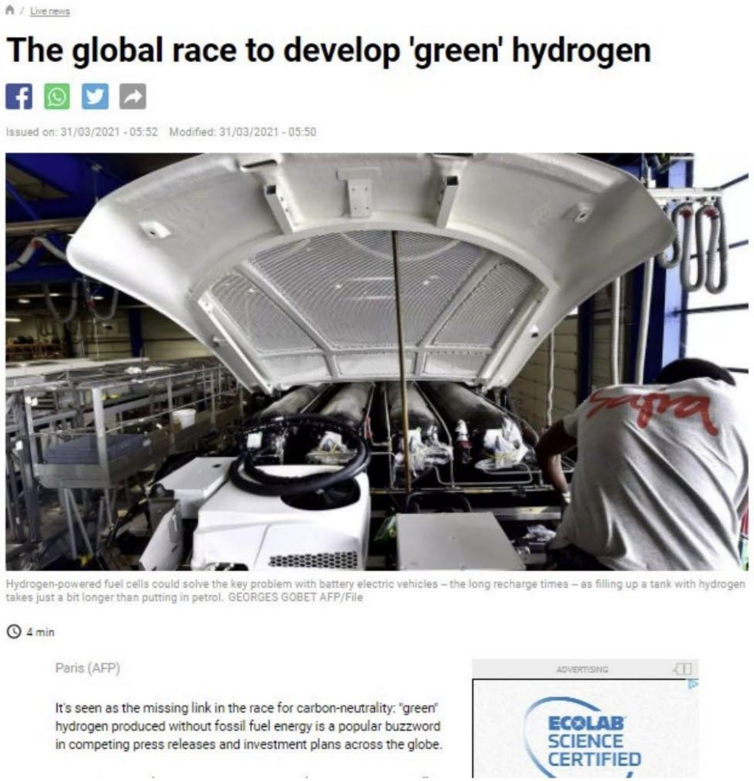
Hydrogen Council

CLIMATE CH2AMPION: HYDROGEN IS THE MISSING PIECE OF THE ENERGY PUZZLE

HYDROGEN COST TO FALL SHARPLY AND SOONER THAN EXPECTED

HYDROGEN DEPLOYMENT ACCELERATING WITH MORE THAN $300 BILLION IN PROJECT PIPELINE

> ***Potential Impacts from Hydrogen Council Roadmap Study. By 2050:***
> - *$2.5 trillion in global revenues*
> - *30 million jobs*
> - *400 million cars, 15-20 million trucks*
> - *18% of total global energy demand*



Live news

The global race to develop 'green' hydrogen

Issued on: 31/03/2021 - 05:52 Modified: 31/03/2021 - 05:50

Hydrogen-powered fuel cells could solve the key problem with battery electric vehicles – the long recharge times – as filling up a tank with hydrogen takes just a bit longer than putting in petrol. GEORGES GOBET AFP/File

4 min

Paris (AFP)

It's seen as the missing link in the race for carbon-neutrality: "green" hydrogen produced without fossil fuel energy is a popular buzzword in competing press releases and investment plans across the globe.

https://www.france24.com/en/live-news/20210331-the-global-race-to-develop-green-hydrogen

Politics

Hydrogen Is 'Jump Ball' in Global Clean-Energy Race, Kerry Says

By Jennifer A Dlouhy and Will Wade
March 2, 2021, 9:38 AM MST

- Climate envoy touts oil-industry opportunity at CERAWeek
- Says tensions with China won't block aggressive climate action

Most Read

MARKETS
Coinbase Hangover Rattles Crypto Assets With Bitcoin in Freefall

MARKETS
SPAC Wipeout Is Punishing Followers of Chamath Palihapitiya

TECHNOLOGY
Amazon Cancels Lord of the Rings Game Announced Two Years Ago

TECHNOLOGY
Covid Survivors May Require Just One Shot of a Two-Dose Vaccine

BUSINESS
Covid Claims 3 Million Lives as Burden Shifts to Poorer Nations

https://www.bloomberg.com/news/articles/2021-03-02/hydrogen-is-jump-ball-in-global-clean-energy-race-kerry-says

Sustainable Investment is a Trend

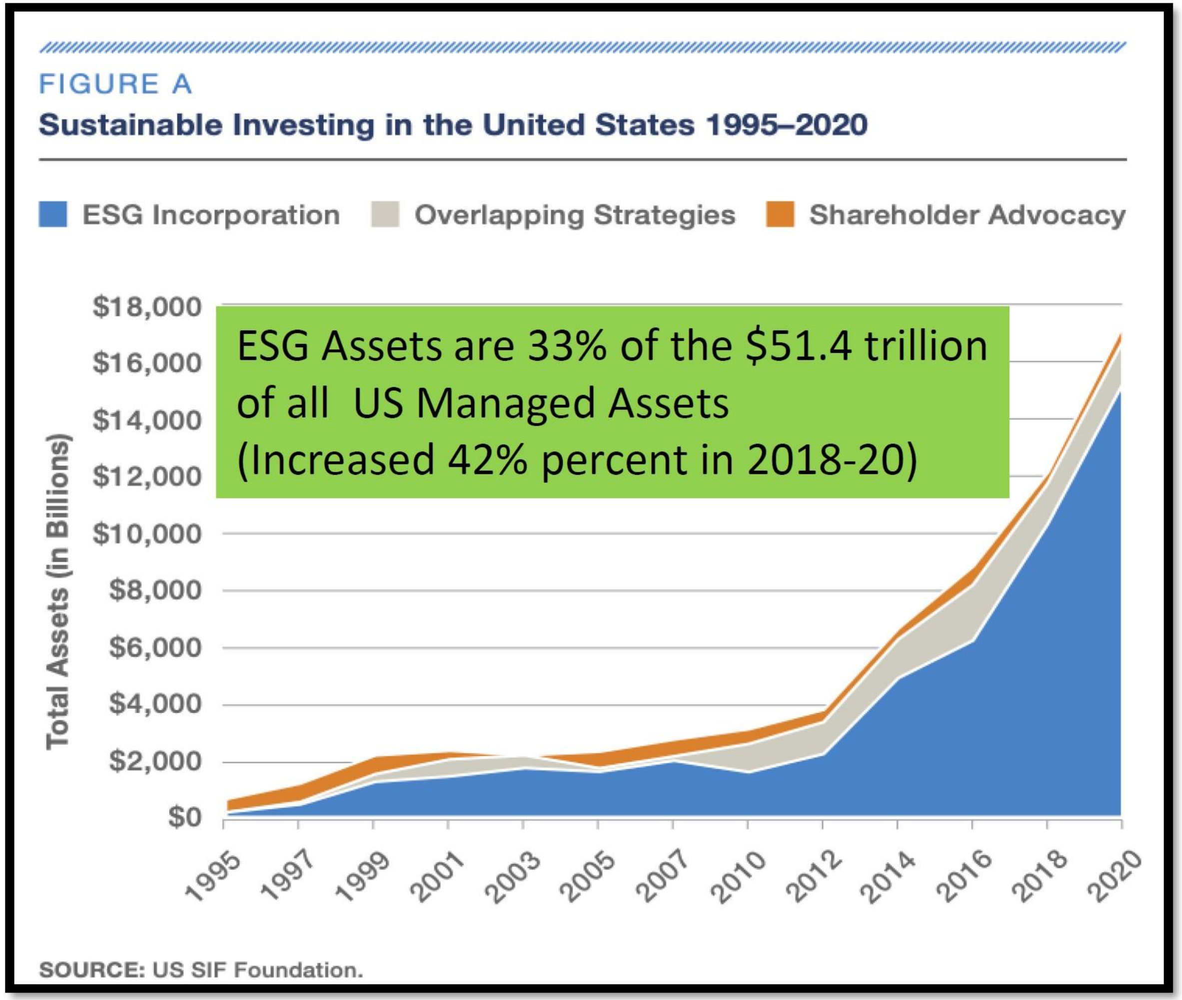


FIGURE A

Sustainable Investing in the United States 1995–2020

ESG Assets are 33% of the $51.4 trillion of all US Managed Assets (Increased 42% percent in 2018-20)

SOURCE: US SIF Foundation.

“Global ESG Assets Rising to $50 Trillion Will Reshape $140.5 Trillion of Global AUM* by 2025”
Bloomberg Intelligence, Press Announcement: July 21, 2021

*Assets Under Management (AUM)

Zero-Emission Vehicle Mandates

- Norway 2025
- Denmark 2030
- Netherlands 2030
- Sweden 2030
- India 2030
- France 2040
- United Kingdom 2040
- Sri Lanka 2040
- Canada - British Columbia (2040)
- China (no date set)

Governor Newsom Announces California Will Phase Out Gasoline-Powered Cars & Drastically Reduce Demand for Fossil Fuel in California's Fight Against Climate Change

Published: Sep 23, 2020

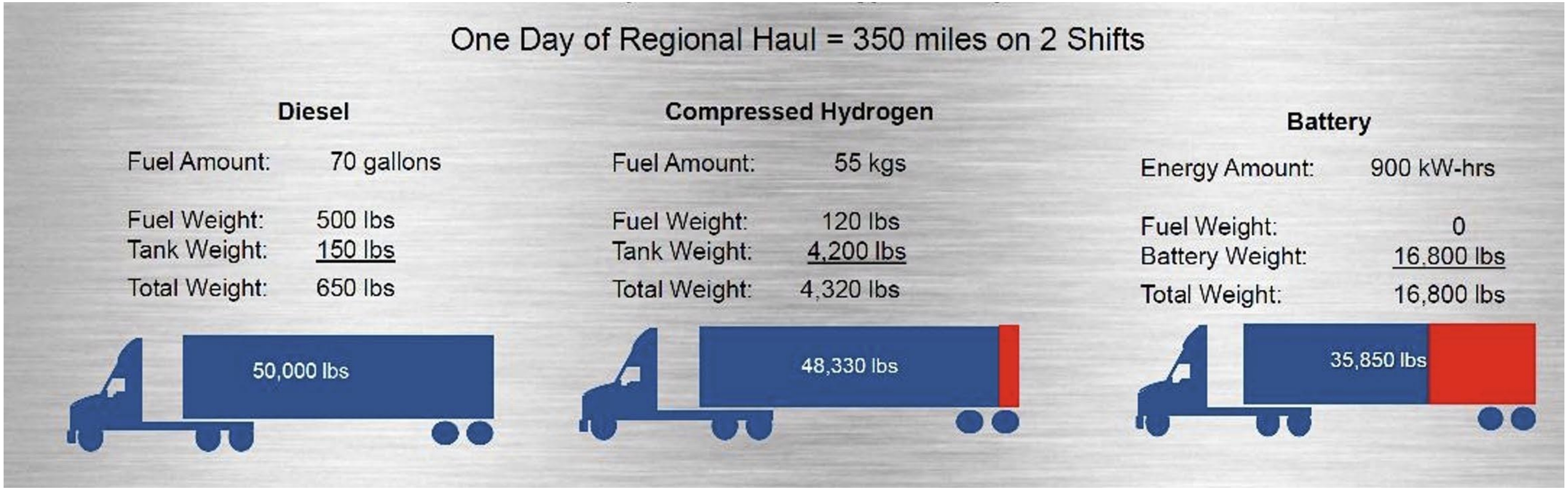
Zero-Emission Vehicles

[1] 2 Next 43 items »

OCTOBER 27, 2022 TESTIMONY TO CARB
Proposed Advanced Clean Fleets Regulation

OCTOBER 24, 2022 LETTER TO EPA
NESCAUM Requests that EPA Promptly Approve CA HDV Waivers

Payload and Energy Density



One Day of Regional Haul = 350 miles on 2 Shifts

Diesel

Fuel Amount: 70 gallons

Fuel Weight: 500 lbs
Tank Weight: 150 lbs
Total Weight: 650 lbs

Compressed Hydrogen

Fuel Amount: 55 kgs

Fuel Weight: 120 lbs
Tank Weight: 4,200 lbs
Total Weight: 4,320 lbs

Battery

Energy Amount: 900 kW-hrs

Fuel Weight: 0
Battery Weight: 16,800 lbs
Total Weight: 16,800 lbs

Brian Lindgren, Kenworth Truck Company, California Hydrogen Business Council (CHBC) , April 14, 2020

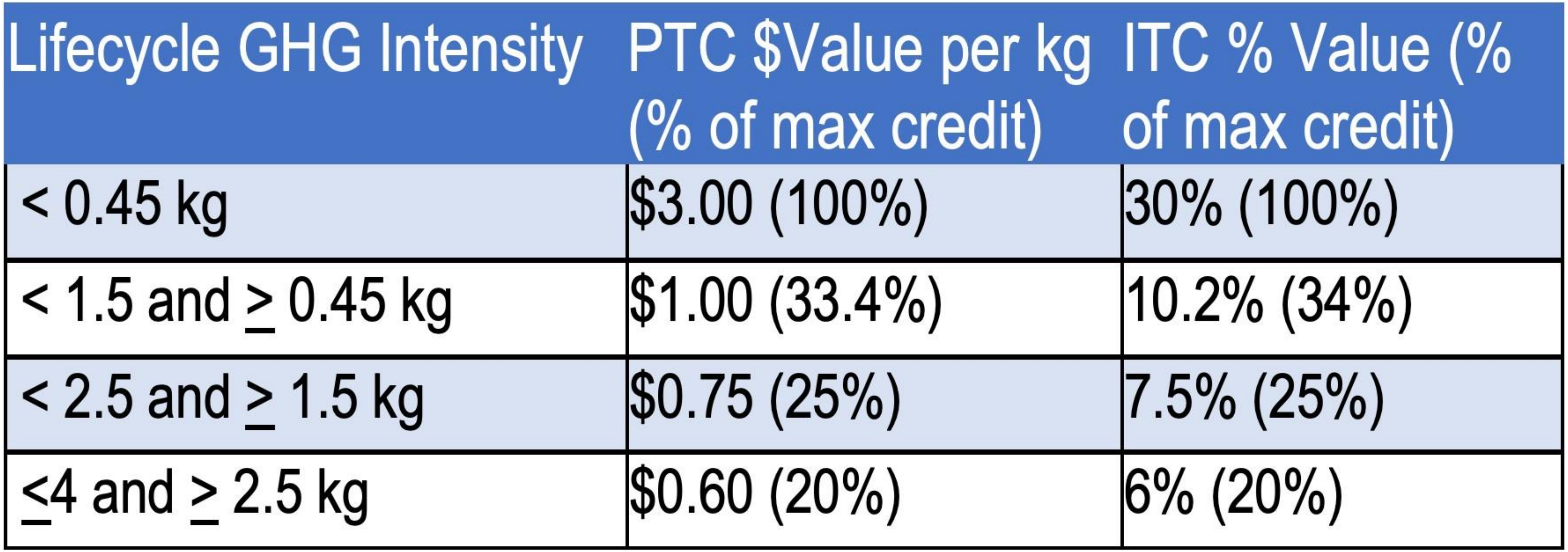
Infrastructure Investment and Jobs Act

- Signed into law on November 5, 2021
- Electrolysis research ($1B)
- Clean hydrogen technology manufacturing and recycling ($500M)
- Appropriations for Hydrogen Program ($8B):
  - Feedstock diversity, including clean hydrogen from fossil fuels
  - End use diversity
  - Geographical diversity, including at least two hydrogen hubs be located in regions of the U.S. with the greatest natural gas resources
  - Create opportunities for skilled training and long-term employment
  - 4-6-8-? Hubs will be selected

- **TOTAL: $9.5B over 5 years**

Production Tax Credit for Clean Hydrogen

- Base credit is $0.60 / kg, but multiplied by 5X if projects pay at or above the prevailing wage; additional enhancement for facilites in coal-affected communities
- Additional enhancement if located in coal-affected regions (10%, but confirm it applies)
- The Investment Tax Credit can be applied for hydrogen uses (i.e. fuels cells)



Lifecycle GHG Intensity	PTC $Value per kg (% of max credit)	ITC % Value (% of max credit)
< 0.45 kg	$3.00 (100%)	30% (100%)
< 1.5 and ≥ 0.45 kg	$1.00 (33.4%)	10.2% (34%)
< 2.5 and ≥ 1.5 kg	$0.75 (25%)	7.5% (25%)
≤4 and ≥ 2.5 kg	$0.60 (20%)	6% (20%)

Infrastructure Investment and Jobs Act

- CCUS Demonstration Projects - $2.5 billion
- CCUS Pilot Projects - $937 million
- Carbon Storage Validation and Testing - $2.5 billion
- Carbon Dioxide Infrastructure Finance and Innovation - $2.1 billion
- Class VI Well Permitting - $75 million
- Front-End Engineering and Design Studies for Carbon Dioxide Transport Infrastructure - $100 million
- Carbon Dioxide Utilization - $310.14 million
- Regional Direct Air Capture Hubs - $3.5 billion
- Commercial Direct Air Capture Technology Prize - $100 million
- Precommercial Direct Air Capture Prize - $15 million

- **TOTAL: $12.1 billion**

45Q Enhancements in the Inflation Reduction Act

- Increase from \$50 to **\$85/tonne** for CCS on industrial and power generation facilities
- Increase from \$35 to **\$60/tonne** for CCUS from industrial and power generation carbon capture
- **The credit can be realized for 12 years** after the carbon capture equipment is placed in service and will be inflation-adjusted beginning in 2027 and indexed to base year 2025
- **Commence construction** window is extended seven years to **January 1, 2033**
- Carbon capture project developers can receive **45Q as a fully refundable direct payment** as if it were an overpayment of taxes
  - For-profit organizations 5 years
  - Tax-exempt entities such as states, municipalities, Tribes, and cooperatives – 12 years
- Broad transferability of credit is extended 12-year credit window
- **Capture threshold** for credit-eligible power **generation facilities - 18,750 tonnes**
- **Capture threshold industrial facilities - 12,500 tonnes**
- **Power generation facilities** must capture of not less than **75% of the CO_2**

Wyoming's Primary Export (State) Markets for Natural Gas

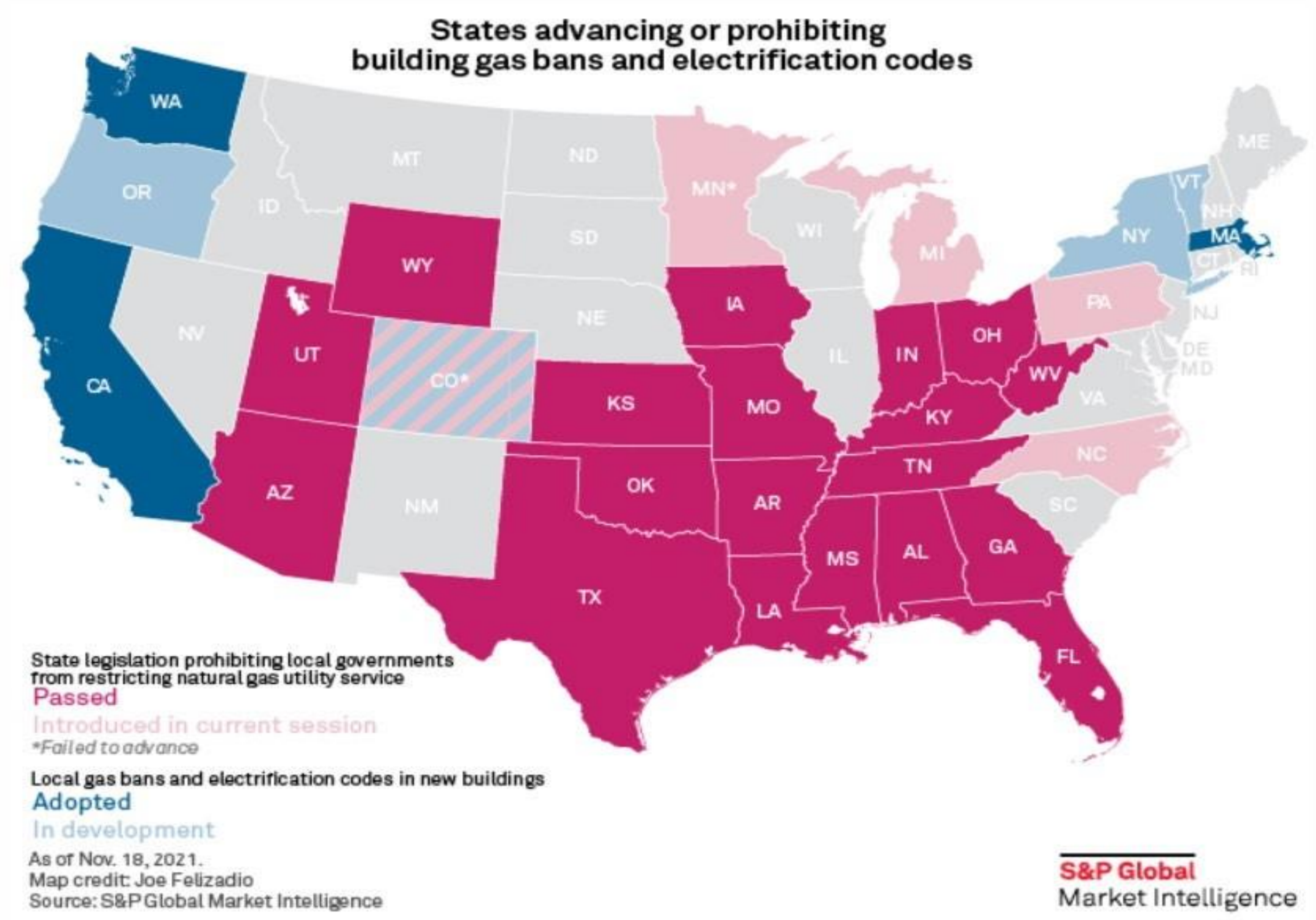
- Competitive Position of Wyoming Fossil Energy
  - Third largest energy producer in USA
  - Largest net energy exporter
  - #1 Coal Producer – 218 million tons
  - #8 Crude Oil producer – 232 thousand barrels per day
  - **#9 Natural Gas Producer – 1.3 trillion cubic feet**
    - **California, Nevada, Oregon, Washington**
- Economic Impacts of Fossil Energy in Wyoming
  - Direct: 16,265 full & part-time jobs, $7.9 billion in GDP
  - Total Impacts including direct, indirect (supply chain) & induced (household spending) roughly 32,000 jobs and $10 billion in GDP
- Property & Severance Tax Revenues – $1.7 billion
- Federal Royalties – $860 million (Wyoming receives about half)

Renewable Portfolio Standards, Clean Energy Standards Greenhouse Gas Reduction

State	Renewable Portfolio Standards/ Clean Energy Standards	Greenhouse Gas Reduction
California	RPS/CES: 50% by 2026 60% by 2030 100% by 2045 Blue H_2 acceptable “so far” CCUS methodology for the LCFS	Carbon neutrality by 2045 AB32 scoping plan revision general negative as to natural gas
Nevada	RPS: 50% by 2030 (with interim targets)	Zero or near-zero by 2050
Oregon	RPS: 50% by 2040 (with interim targets)	100% below baseline by 2040
	RPS/CES: 100% by 2045 (with interim targets)	95% below baseline by 2050 Cap and invest program being implemented

Other Policy Considerations

- Natural gas bans
- ESG
- Carbon Markets
  - Regulated
  - Voluntary
    - American Carbon Registry
    - Verra (expected early 2023)


States advancing or prohibiting
building gas bans and electrification codes

State legislation prohibiting local governments from restricting natural gas utility service
Passed
Introduced in current session
*Failed to advance

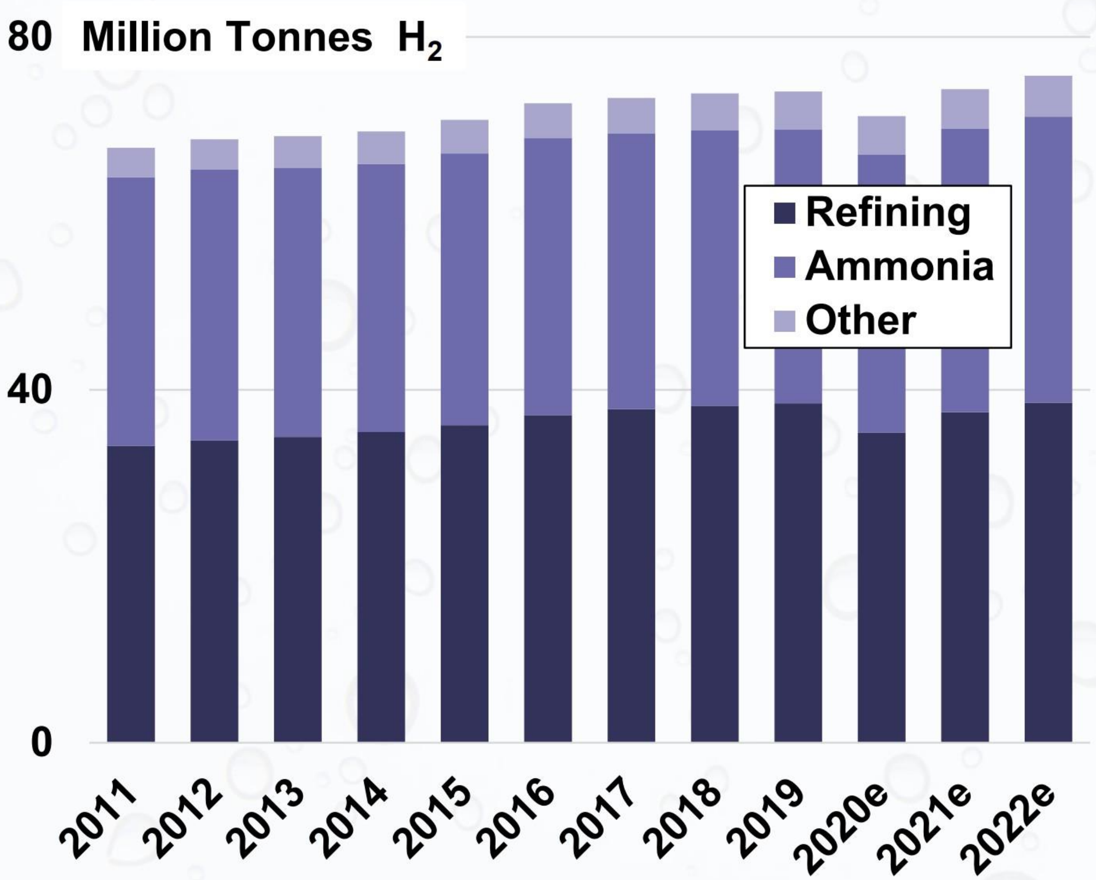
Local gas bans and electrification codes in new buildings
Adopted
In development

As of Nov. 18, 2021.
Map credit: Joe Felizadio
Source: S&P Global Market Intelligence

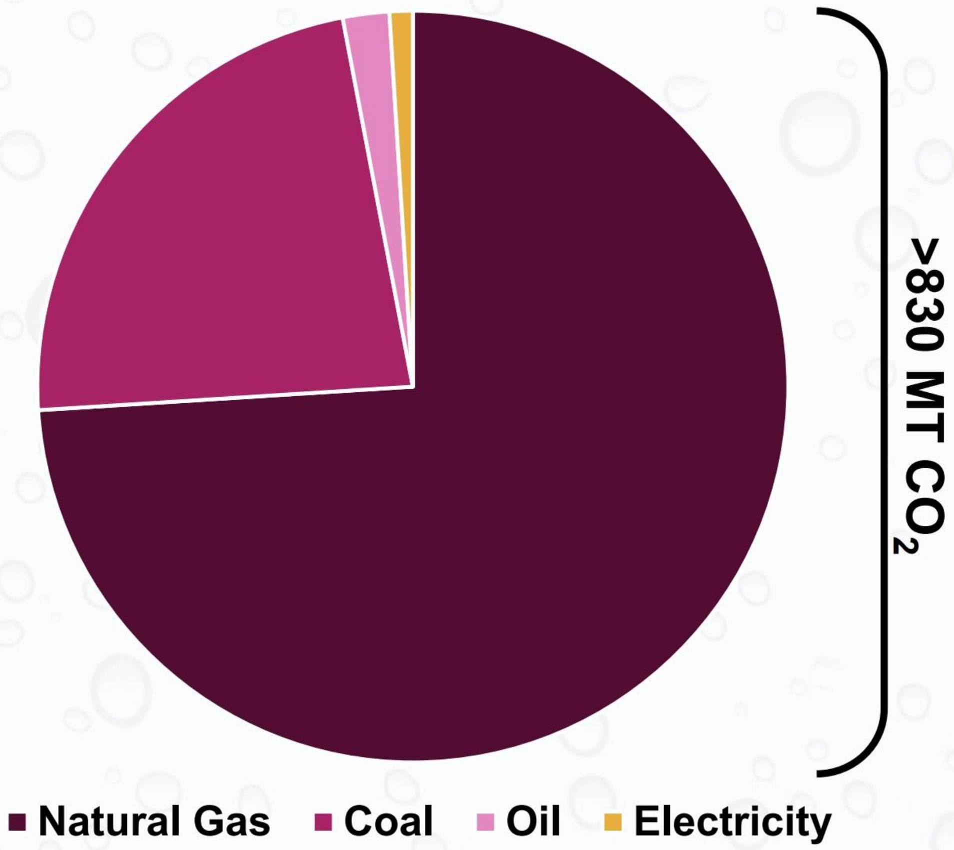
S&P Global
Market Intelligence

Current State of Hydrogen

Global Pure H_2 Demand



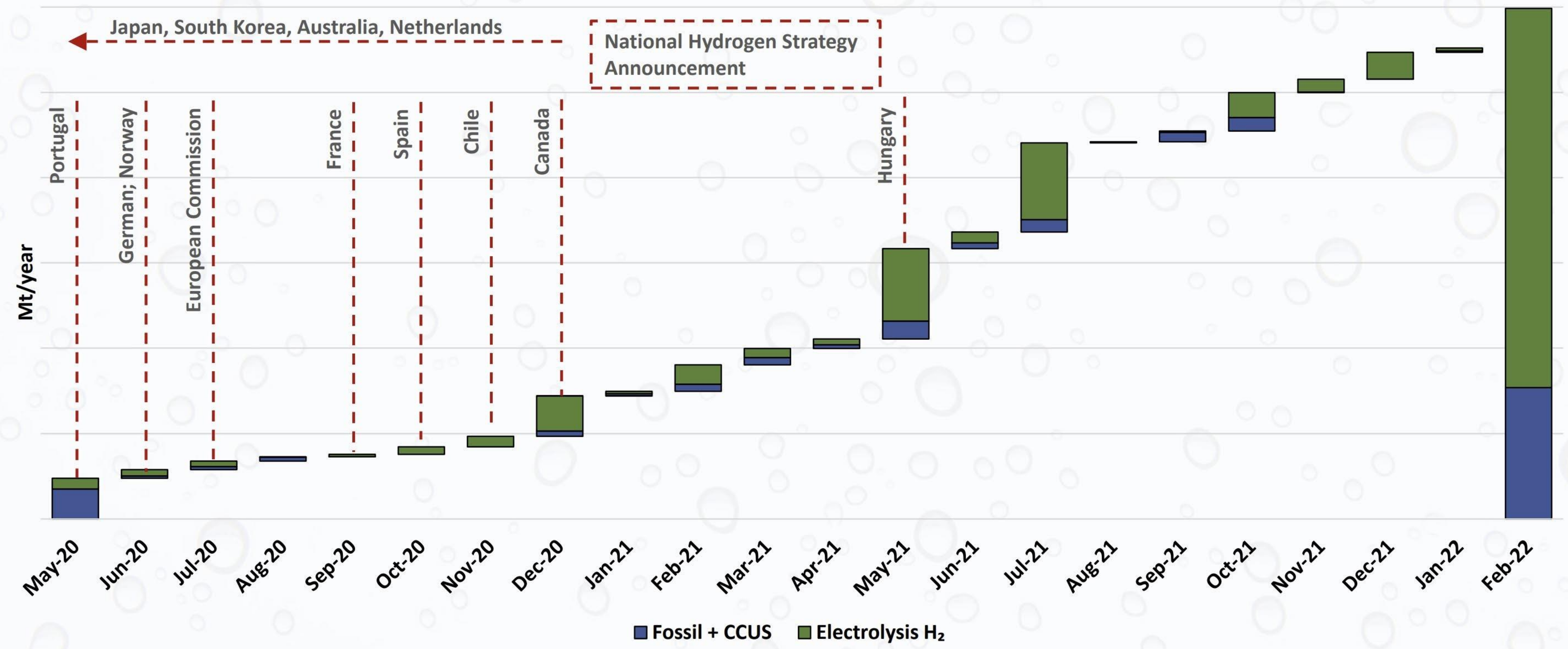
Hydrogen Production Feedstock Energy (2019)



Contact: OHI@gti.energy

Source: S&P Global Commodity Insights Hydrogen Market Monitor

Hydrogen Market is Growing



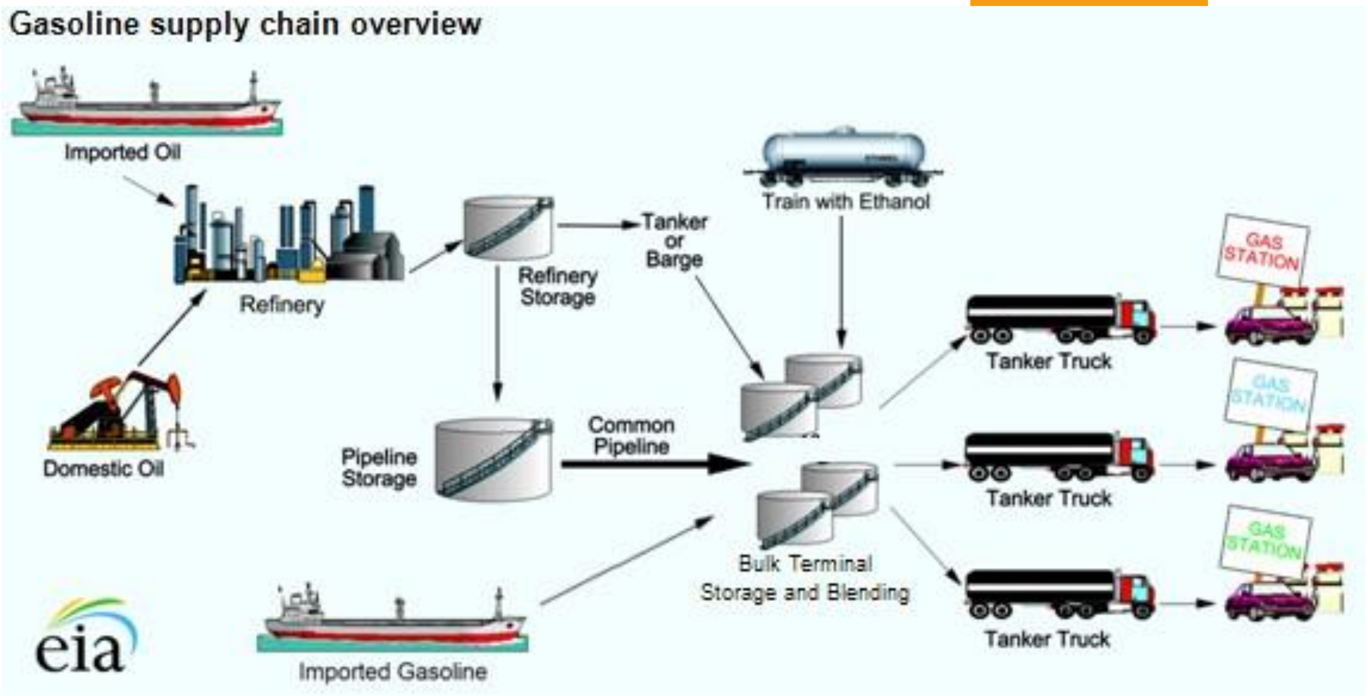
Contact: OHI@gti.energy

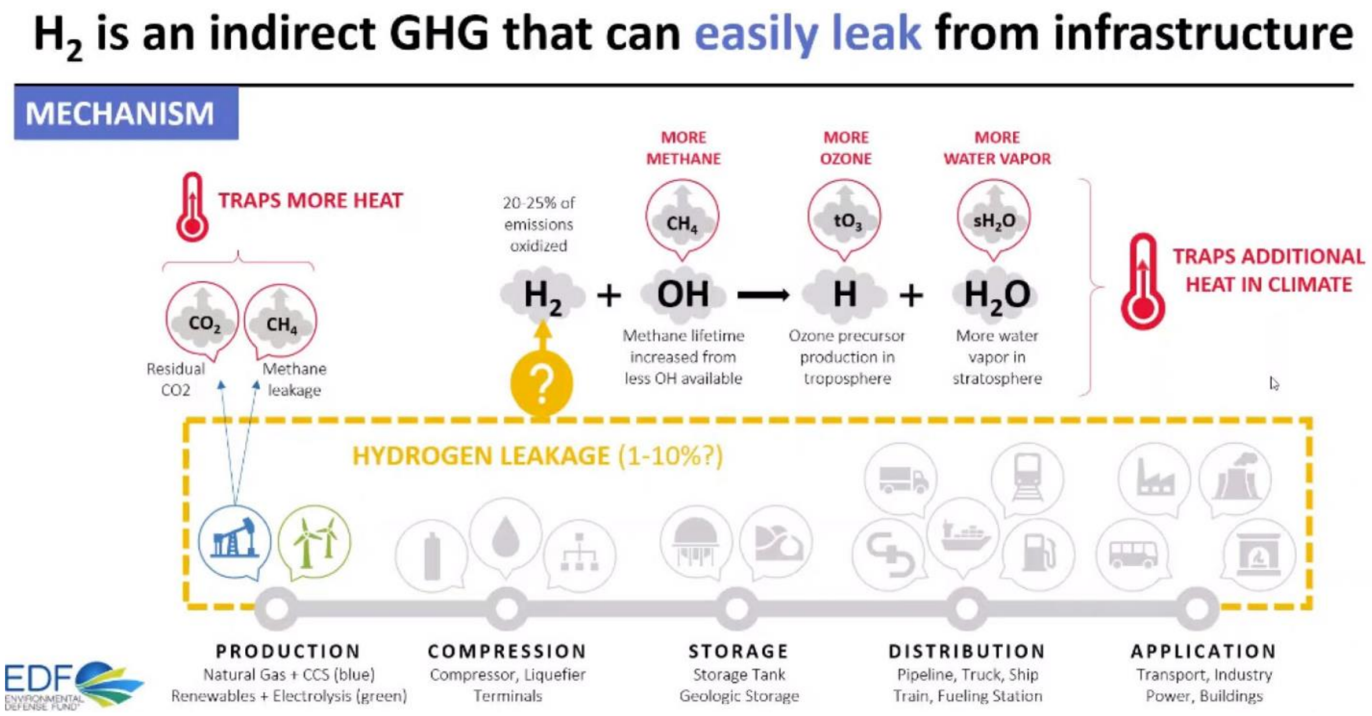
Source: S&P Global Commodity Insights Hydrogen Market Monitor

OPEN **HYDROGEN** INITIATIVE

Supply Chain Challenges

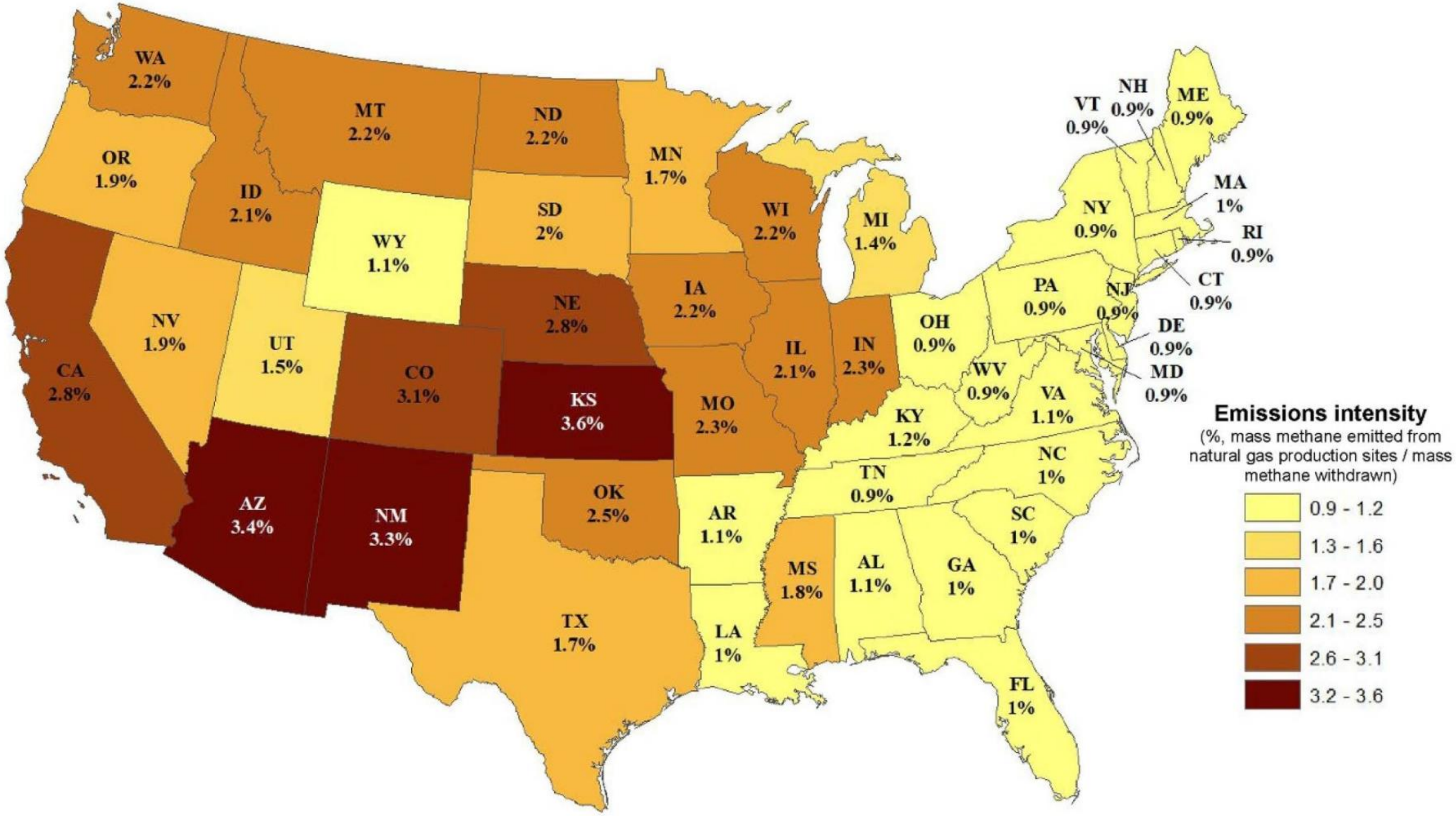
- Materials
  - Embrittlement
  - High pressure
- High energy use
- Monitoring
- Emissions
- New infrastructure requirements
- Cost





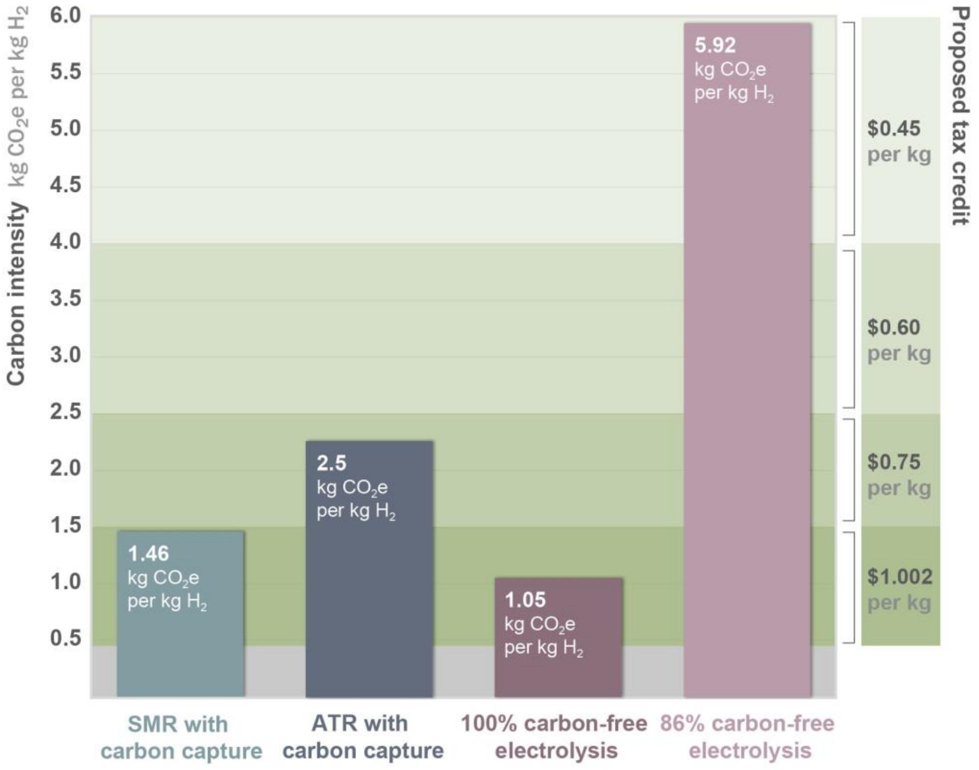
Estimated Production-Stage Methane Emissions For Natural Gas Consumed In Each State

- Emission intensity is source dependent
- Markets dictate change and producers comply with new demands
- Public-private collaboration success story
  - The School of Energy Resources' Center for Air Quality

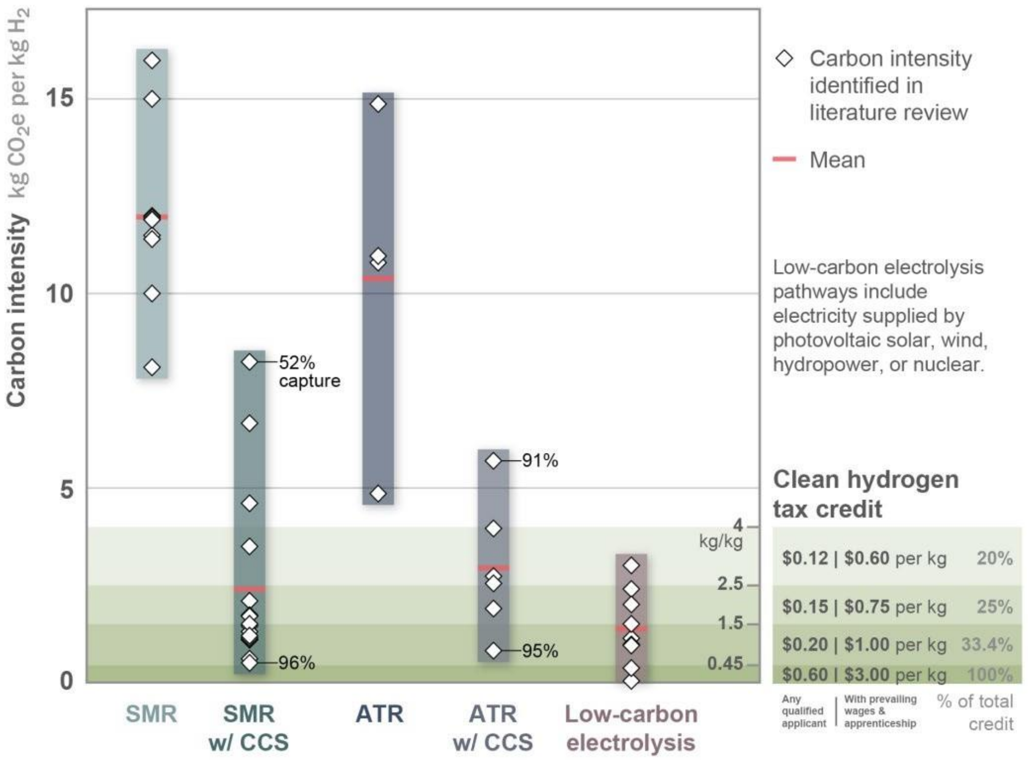


D Burns and E Grubert, Environ. Res. Lett. 16 (2021) 044059

Carbon Intensity and Incentives


Proposed tax credit values for typical ranges of hydrogen lifecycle intensity

Elizabeth Abramson, Carbon Solutions LLC, 2022.


Hydrogen lifecycle carbon intensity in published literature

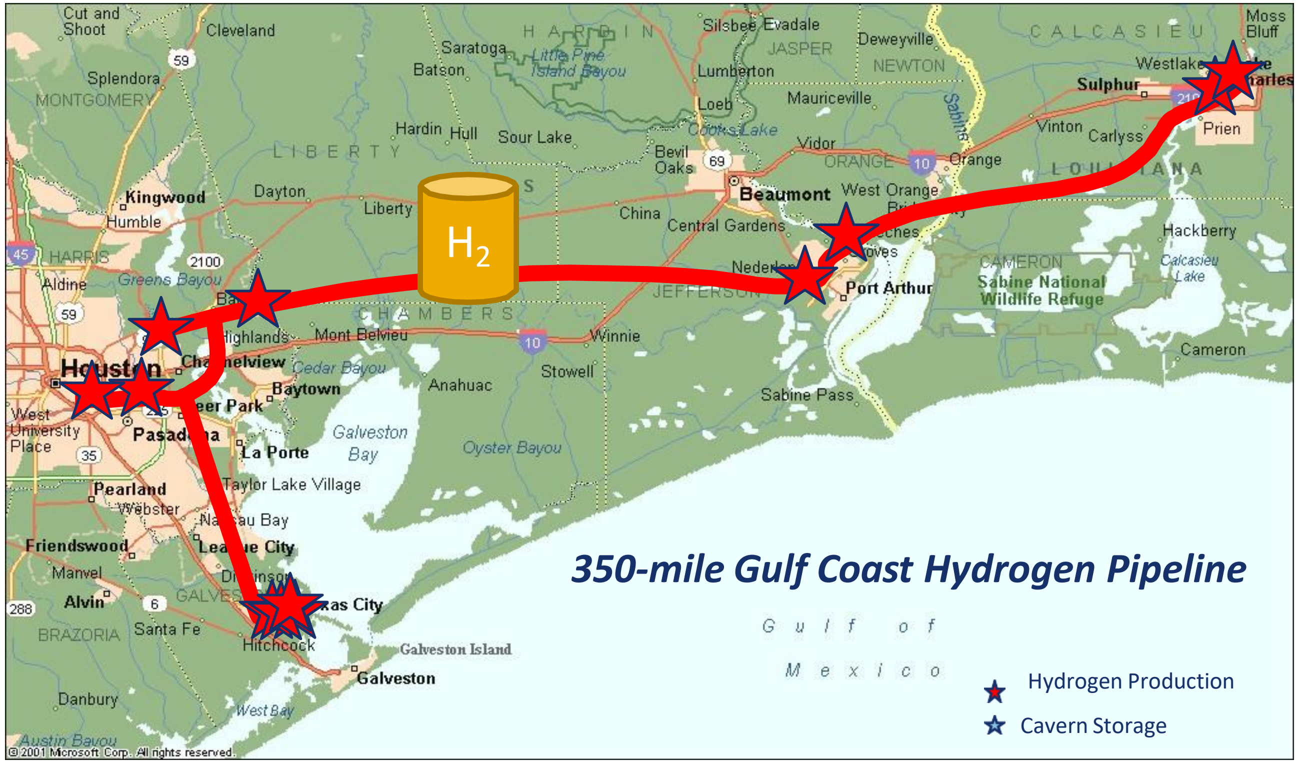
Low-carbon electrolysis pathways include electricity supplied by photovoltaic solar, wind, hydropower, or nuclear.

Elizabeth Abramson, Daniel Rodriguez & Dane McFarlane, Carbon Solutions LLC, 2022.

Dane McFarlane, Daniel Rodriguez, and Elizabeth Abramson. Carbon Solutions LLC., 2022

Hydrogen Pipelines

- 1,600 miles of hydrogen pipelines are currently operating in the US
- The potential for hydrogen to embrittle the steel and welds used to fabricate the pipelines
  - Fiber reinforced polymer (FRP) pipelines (installation costs 20% less)
- The need to control hydrogen permeation and leaks
- The need for lower cost, more reliable, and more durable hydrogen compression technology
- Blending hydrogen (5-15%) into the existing natural gas pipeline network to increase the output of renewable energy systems



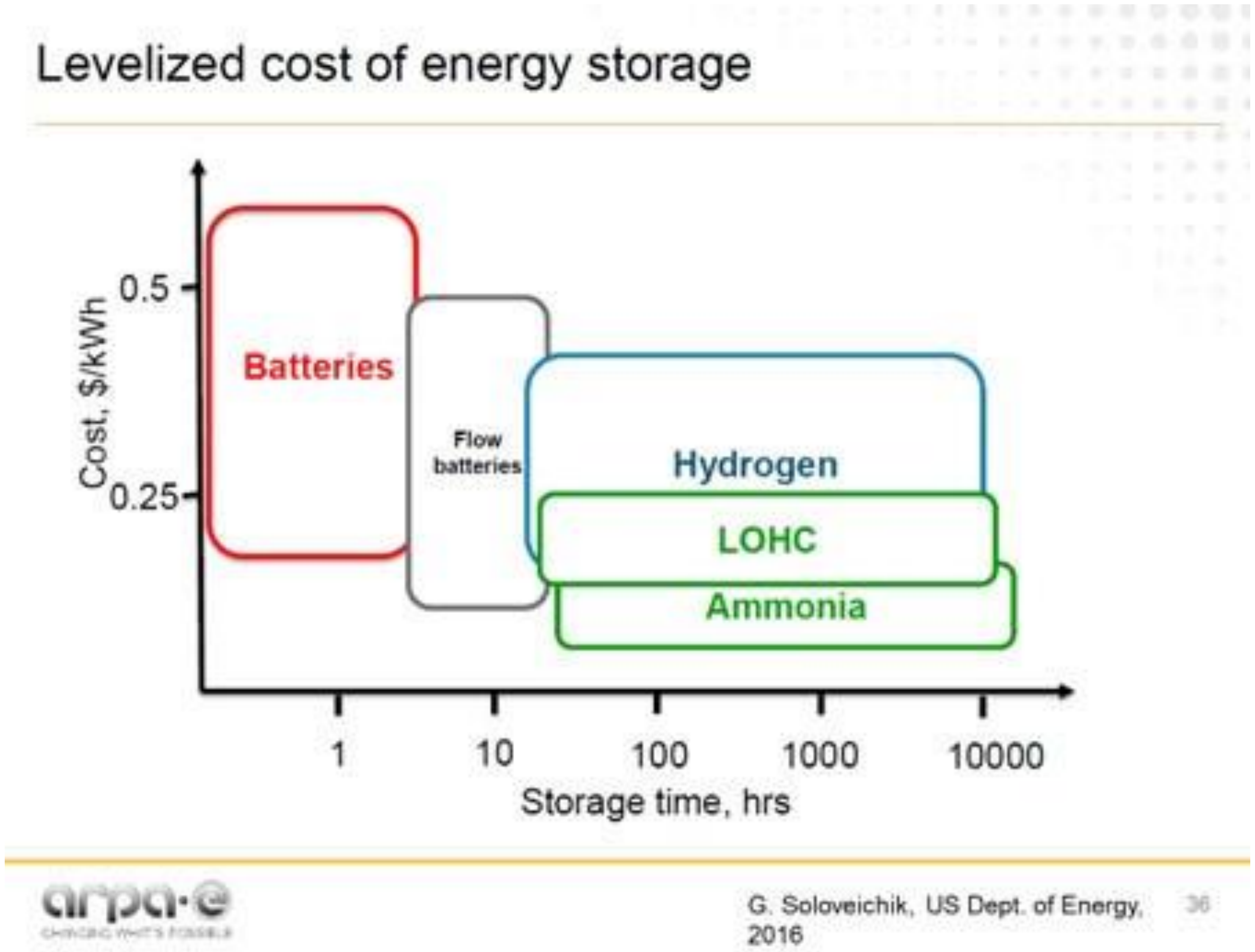
Hasiuk, 2022

Folga, S M, and Decision and Information Sciences. Natural gas pipeline technology overview.. United States: N. p., 2007. Web. doi:10.2172/925391

Melaina, M W, Antonia, O, and Penev, M. Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues. United States: N. p., 2013. Web. doi:10.2172/1068610

Hydrogen as Energy Storage Vehicle

- Energy storage is important
  - To prolong life of fossil fuel energy generators →CO_2 storage will manage emissions
  - To help with manage variable power from wind/solar
- Underground hydrogen is the largest “battery” we can build
- Hydrogen storage also works on longer times scales (seasonal)

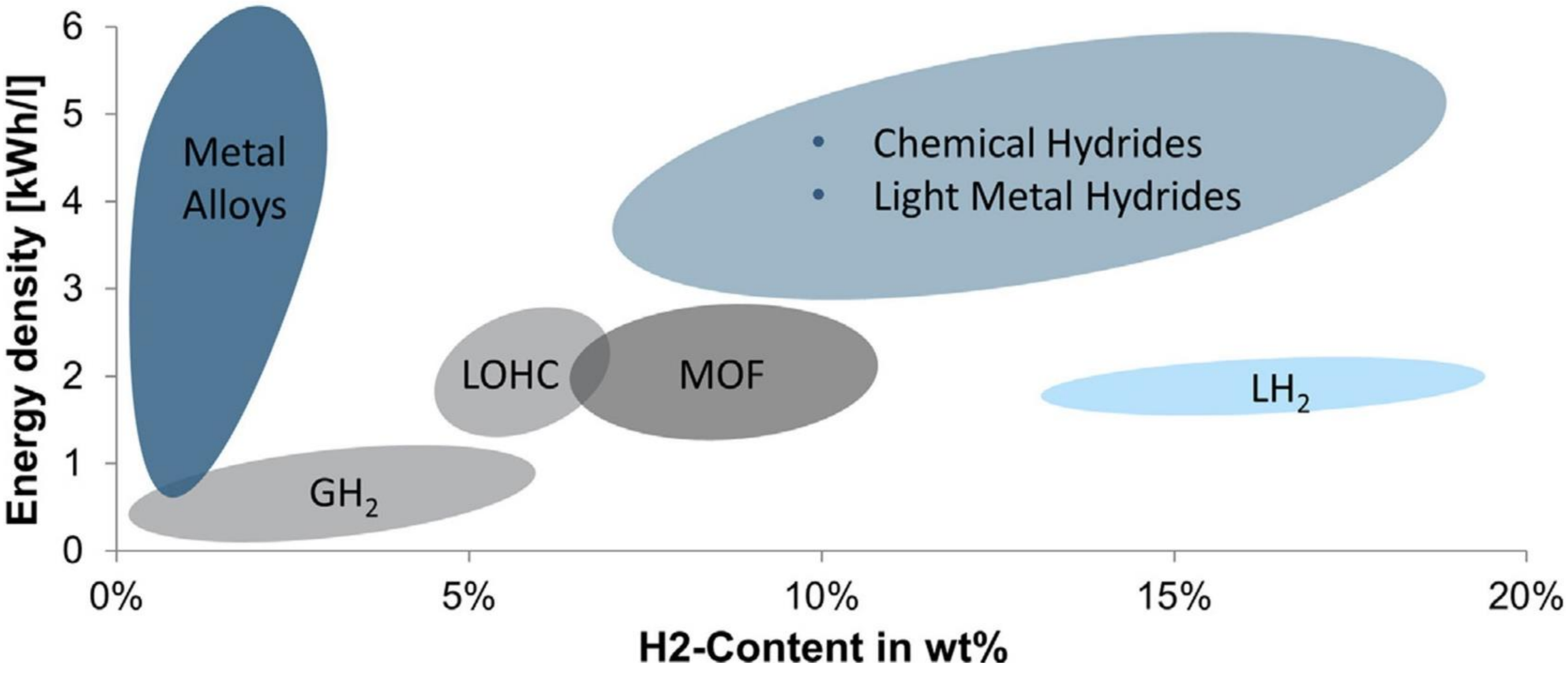


Levelized cost of energy storage

G. Soloveichik, US Dept. of Energy, 2016

Comparison of Different Hydrogen Storage Technologies

- LOHC– Liquid Organic Hydrogen Carriers
- MOF– Metal Organic Frameworks
- GH_2– Gaseous Hydrogen
- LH_2– Liquid Hydrogen



M. Reuß et al./Applied Energy 200 (2017) 290–302
Edwards R et al. Well-to-Tank Report Version 4.a. In: Godwin S et al., editors. JEC Well-to-Wheels Analysis. Joint Research Centre; 2014. p. 148.

Standard Energy Carriers

Energy Carrier	Gasoline	Compressed H_2 (2,700 psi)	Compressed H_2 (7,000 psi)	Liquid H_2 (-252 ^oC)
Density kg/m³	720	14	30	70
Product delivered, kg	27,000	284	665	3,890
Energy delivered, MJ	1,220,000	34,100	79,800	467,000
Truck Capital Cost, $	165,000	250,000	465,000	725,000
Labor, hr	4.0	5.5	5.5	7.5
Car miles	270,000	19,880 (14)	45,550 (6)	272,370

Modified from:
Chen T-P. Hydrogen delivery infrastructure option analysis. Nexant; 2010.

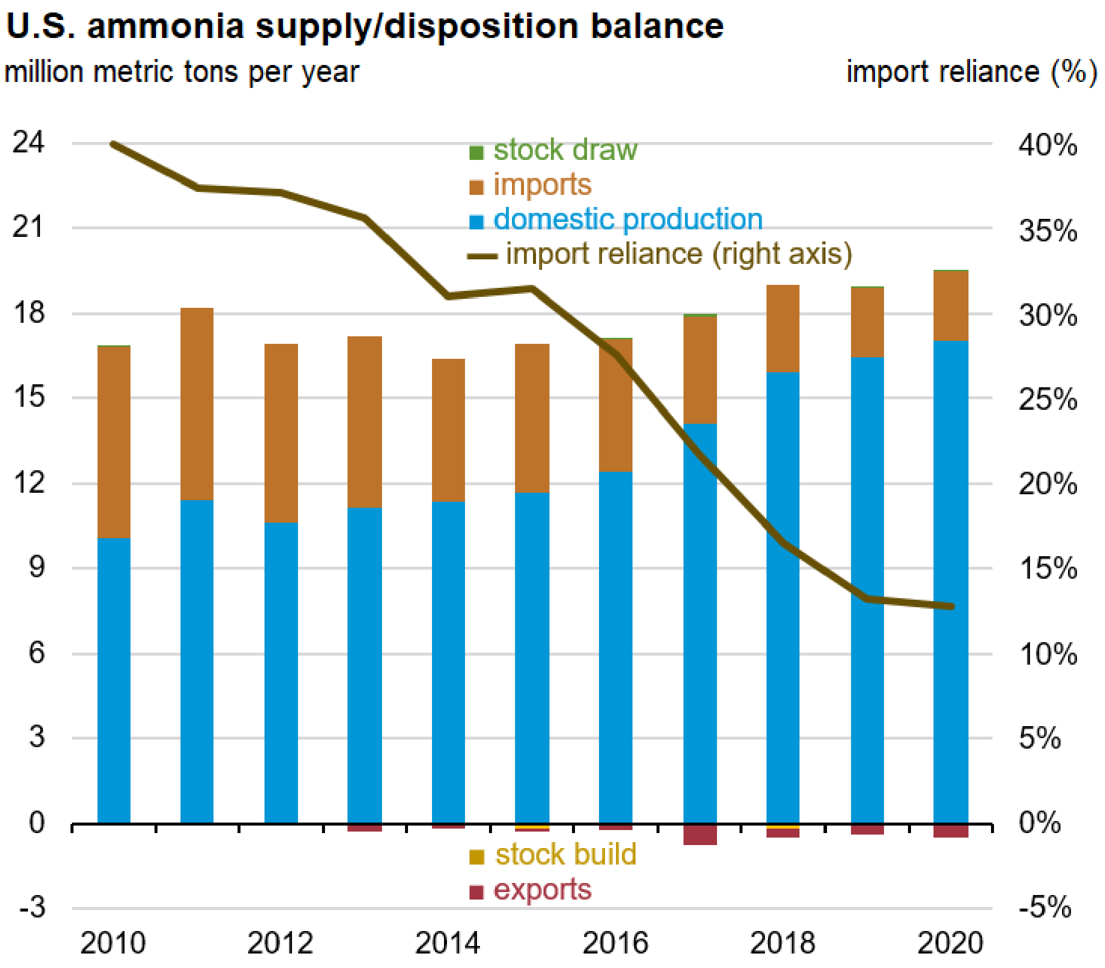
Reformed Liquid Fuels

Energy Carrier	Anhydrous Ammonia 200 psi	Aqueous Ammonia 2.3 psi	Methanol	Ethanol
Chemical formula	NH_3	NH3 H_2O (71%)	CH_3OH H_2O (52-63%)	C_2H_5OH
Density kg/m³	618	900	791	790
Product delivered, kg	27,000	27,000	27,000	27,000
Energy delivered, MJ	580,000	168,000	608,000	716,000
Additional energy, MJ	74,000	21,500	-	205,000
H_2 yield, %	18	5	19	22
Truck Capital Cost, $	300,000	180,000	180,000	180,000
Labor, hr	6.0	4.0	4.0	4.0

Modified from:
Chen T-P. Hydrogen delivery infrastructure option analysis. Nexant; 2010.

Ammonia Production

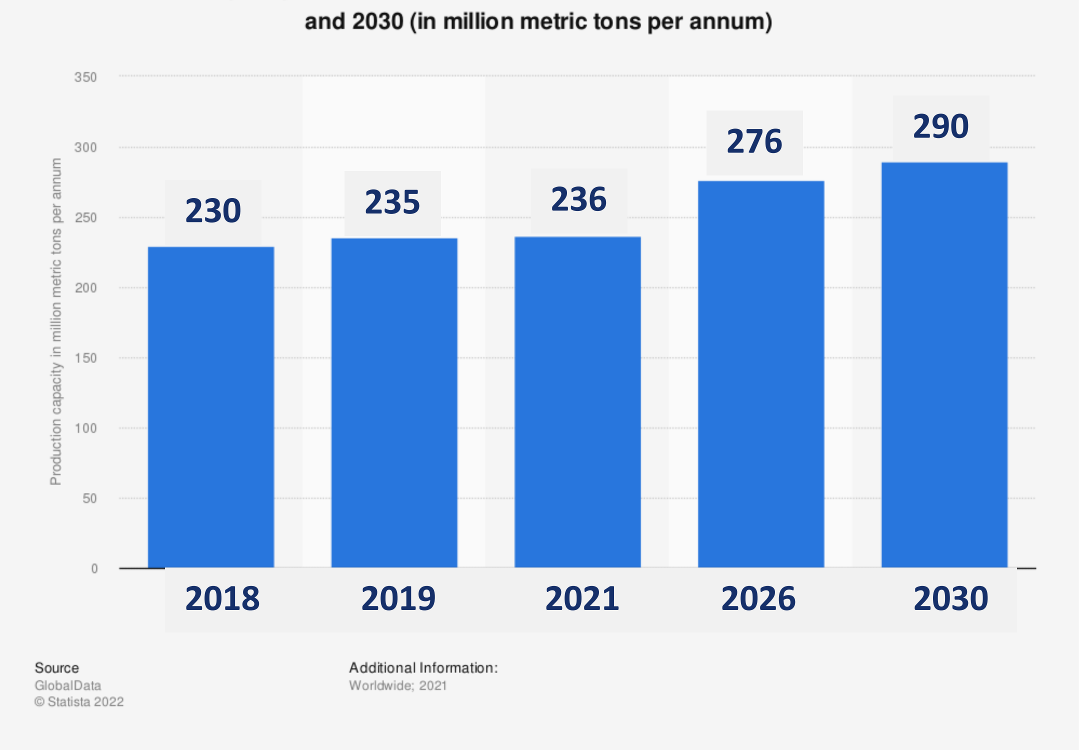
- The current domestic ammonia production capacity is **21M** metric tons per year.
- If this flow could be diverted to hydrogen production with an overall dissociation efficiency of **70%**, approximately **2.2B kg** of hydrogen would be generated.
- Assuming 1 kg of hydrogen in a fuel cell vehicle is equivalent to 2 gallons of gasoline in today's cars, the hydrogen from ammonia would displace about **2.5% of the current gasoline demand.**



Source: U.S. Geological Survey

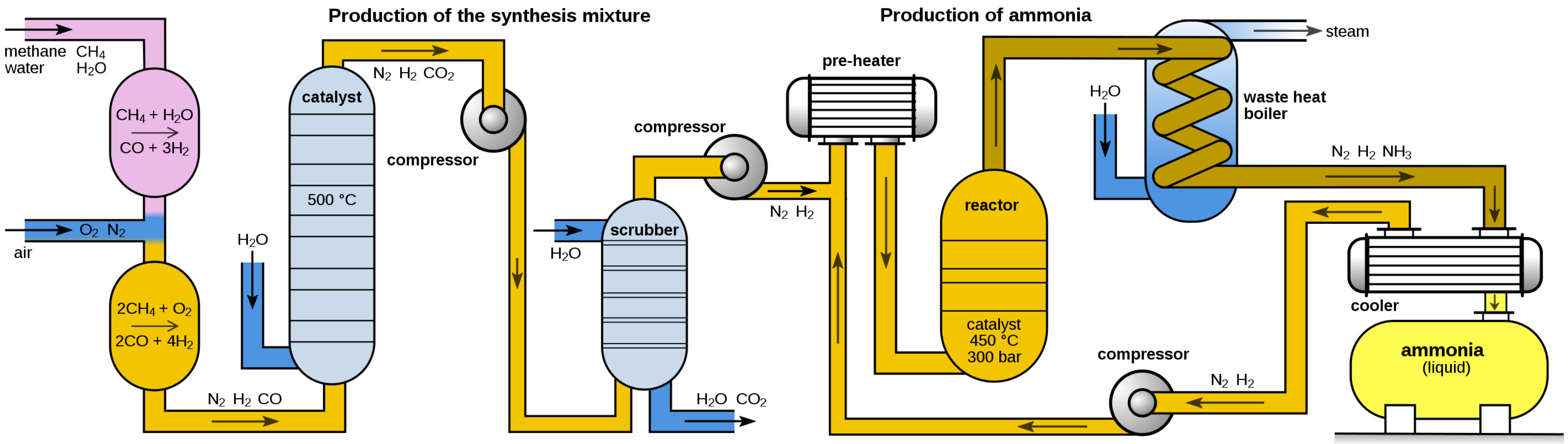
Ammonia Production

- Haber and Bosch in the early 20th century:
  N_2 (g) + 3 H_2 (g) → 2 NH_3 (g)
  ΔH_2 = -92 kJ/mole (-46 kJ/mole for 1 mole of NH_3)
- Iron catalysts; T is 400-600°C ; P is 2,900-5,900 psi
- Coupled with hydrogen production to increase efficiency.
- Feedstock: natural gas, petroleum coke, biomass.



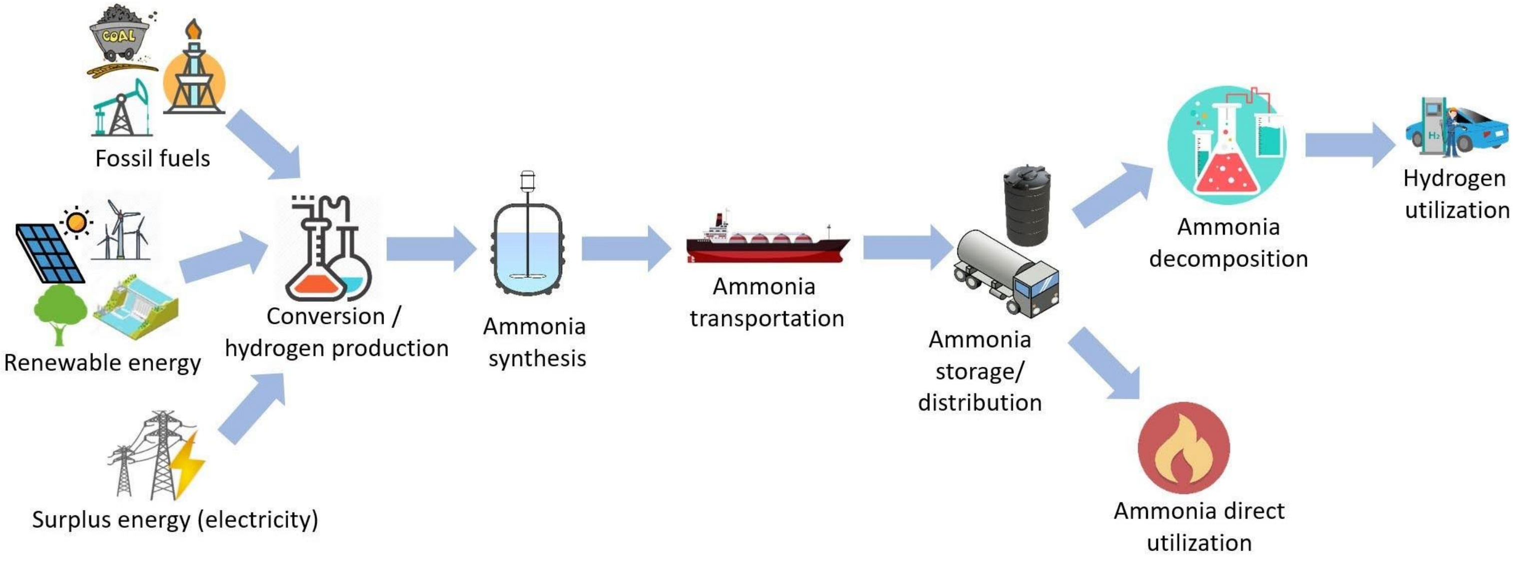
Source
GlobalData
© Statista 2022

Additional Information:
Worldwide; 2021



Ammonia Supply Chain

- Ammonia decomposition (cracking):
- NH_3 (g) → 1/2 N_2 (g) + 3/2 H_2 (g) $\Delta H = +46$ kJ/mol



Fossil fuels

Renewable energy

Surplus energy (electricity)

Conversion / hydrogen production

Ammonia synthesis

Ammonia transportation

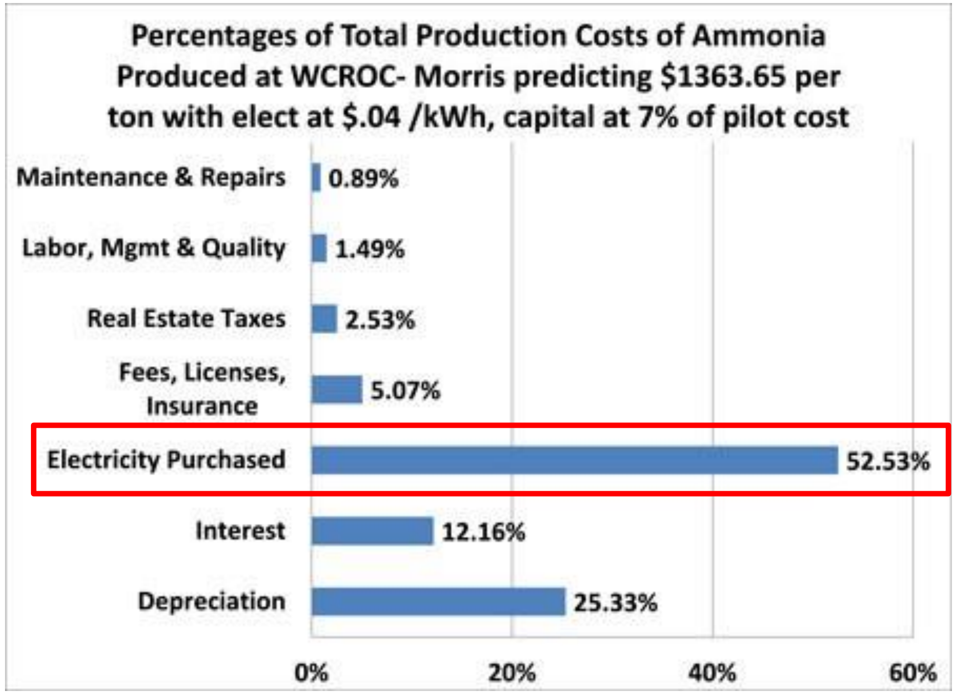
Ammonia storage/ distribution

Ammonia decomposition

Hydrogen utilization

Ammonia direct utilization

Aziz M, Wijayanta AT, Nandiyanto ABD. Ammonia as Effective Hydrogen Storage…, 2020; 13(12):3062. https://doi.org/10.3390/en13123062

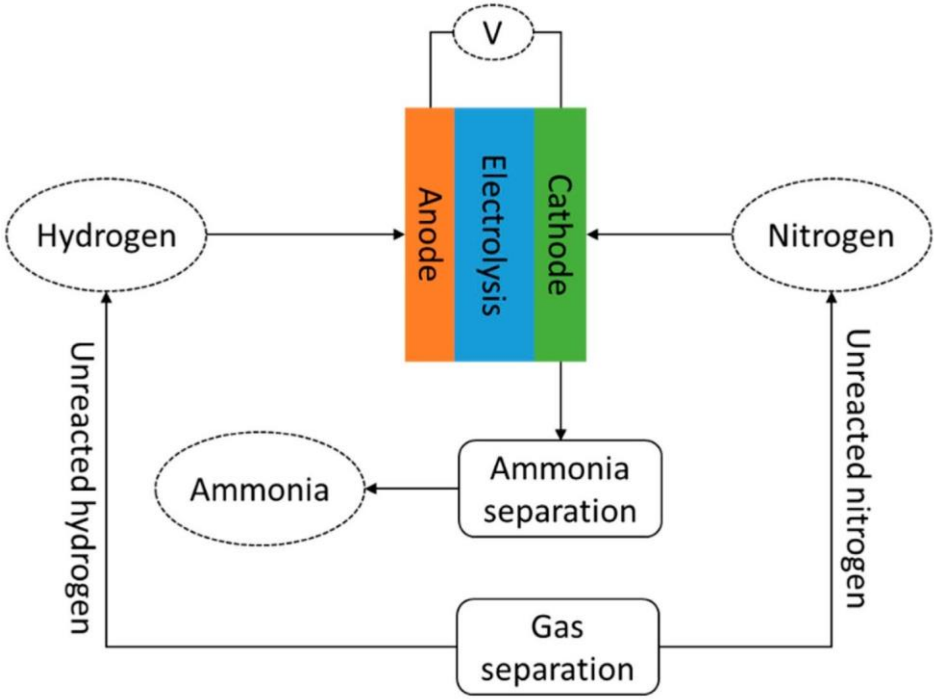


Percentages of Total Production Costs of Ammonia Produced at WCROC- Morris predicting $1363.65 per ton with elect at $.04 /kWh, capital at 7% of pilot cost

https://wcroc.cfans.umn.edu/research/renewable-energy/ammonia-wind

Ammonia Decomposition

- High capacity for hydrogen storage, 17.6 wt.%,
- Energy intensive
  - Endothermic reaction >500 °C
- Thermo-catalytic reaction
  - Ru shows the highest catalytic activity – expensive
  - K, Na, Li, Ce, Ba, La and Ca
  - K-based compounds: KNO_3, KOH, K_2CO_3, KF, KCl, K_2SO_4 and KBr
- Incompatibility of polymer electrolyte membrane (PEM) fuel cells and trace levels of ammonia
  - > 0.1ppm
- Safety and toxicity issues, actual and perceived



Thomas G and Parks G , Potential Roles of Ammonia in a Hydrogen Economy, US DOE, 2006

Aziz M, Wijayanta AT, Nandiyanto ABD. Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization. Energies. 2020; 13(12):3062. https://doi.org/10.3390/en13123062

Water Consumption by Hydrogen Production – World Outlook

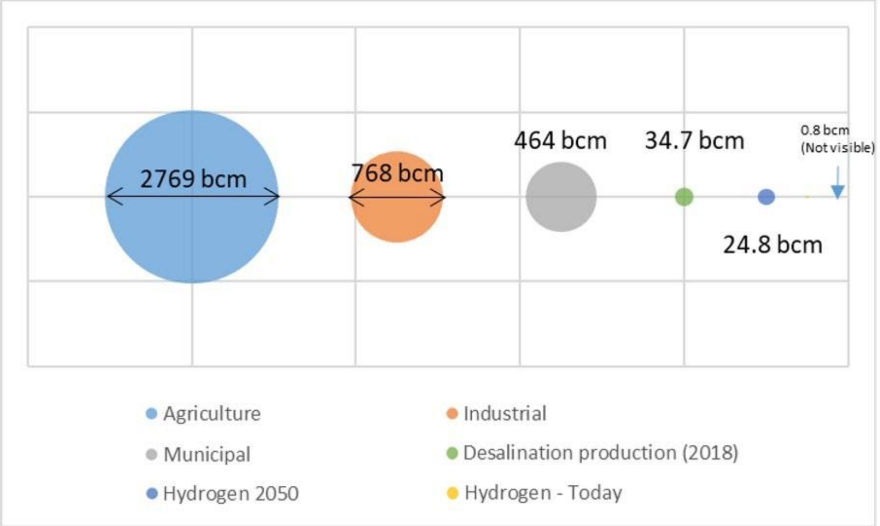
- Assumption: 70EJ of electrolytic hydrogen by 2050
- Hydrogen production
- Production of the upstream energy carrier

- Minimum water electrolysis **~9 kgh_2o/kgh_2**
- De-mineralization **~18-30 kgh_2o/kgh_2**

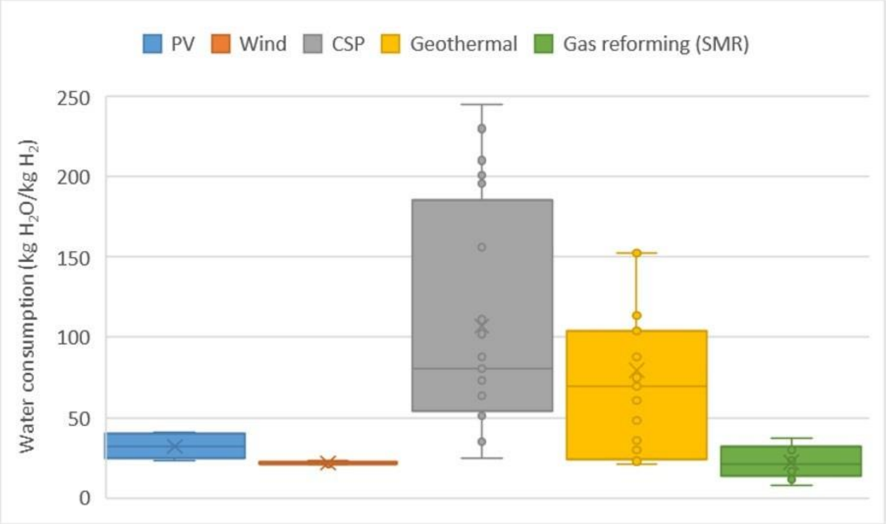
- Steam reforming of methane **~4.5 kgh_2o/kgh_2**
- Water cooling **6.4-32.2 kgh_2o/kgh_2**

The total 2050 hydrogen production would be equivalent to a country with 62 million inhabitants

Social license to operate?



- Water consumption by application (circle size is proportional to water use in each application with agriculture at almost 2,800 km^3/yr)



- Lifecycle water consumption for various hydrogen production pathways

Blanco, 2021; ***https://energypost.eu/hydrogen-production-in-2050-how-much-water-will-74ej-need/***

Permian Basin:
Produced Water Reuse and Marketplace

- Challenge and opportunity
- Optimize hydrogen production methods with desalination/water treatment
- Water demand: 1.3B bbls/annum
- Produced water: 1.6B bbls/annum
- Asking prices $0.48-1.02/barrel

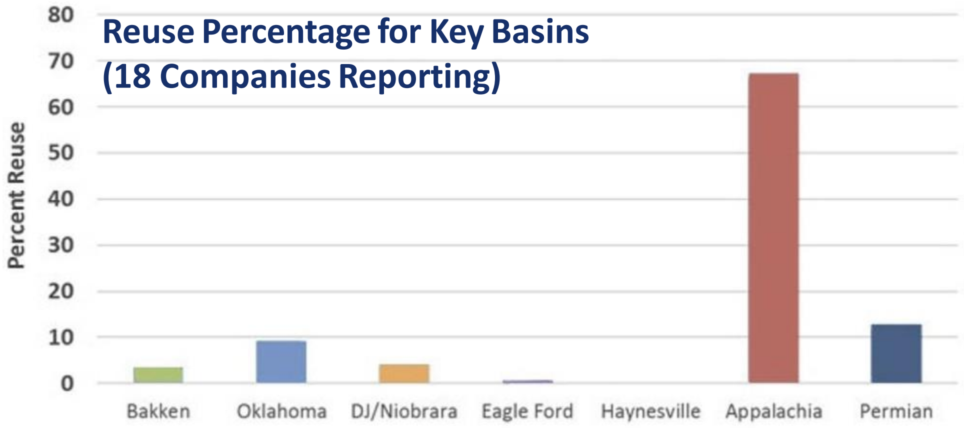
https://doi.org/10.1016/j.scitotenv.2020.137085

Water Acquisition Costs per Barrel for Seven Counties in the Permian Basin

State	Data Points	County	Price High	Price Low	Price Average	Price Median	Today's Volume Median
TX	36	Reeves	$2.00	$0.30	$0.58	$0.57	50,000
TX	33	Yoakum	$1.00	$0.45	$0.77	$1.00	20,572
TX	33	Martin	$1.40	$0.35	$1.06	$0.50	8,572
TX	31	Midland	$3.00	$0.10	$0.52	$0.50	6,857
TX	14	Howard	$0.65	$0.30	$0.48	$0.48	30,000
NM	60	Lea	$1.00	$0.50	$0.80	$1.00	17,142
NM	21	Eddy	$1.25	$1.00	$1.02	$1.00	27,428

Sourcewater https://www.sourcewater.com/

www.genesiswatertech.com



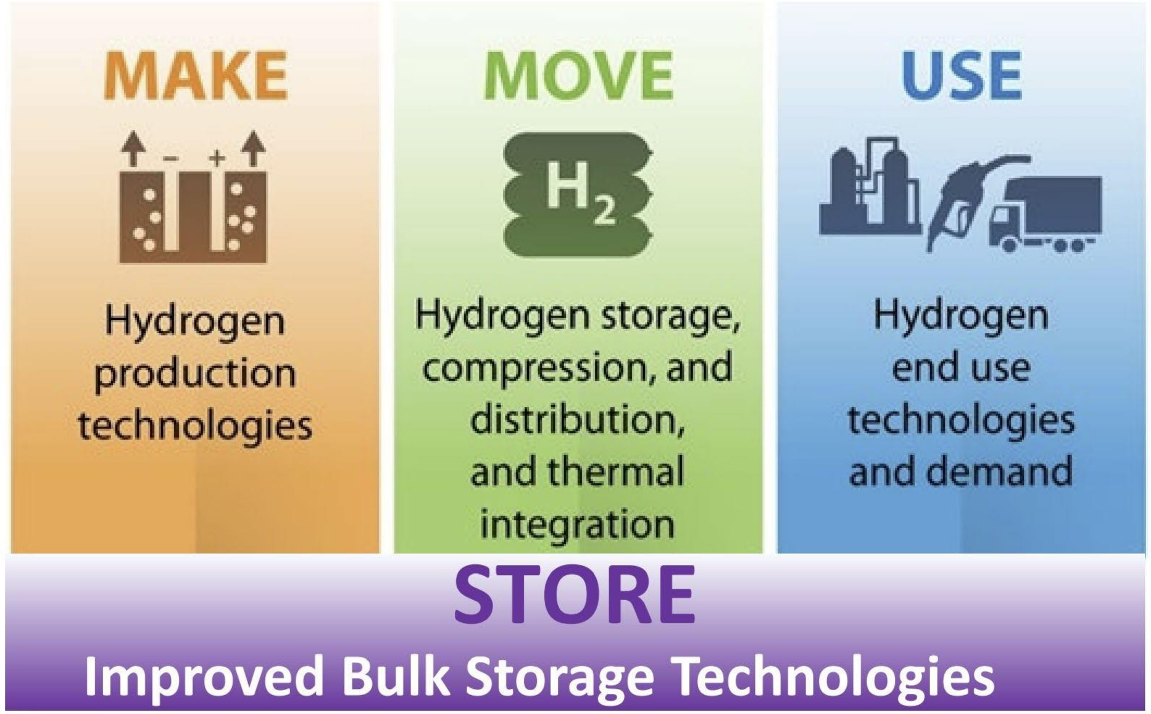
Reuse Percentage for Key Basins (18 Companies Reporting)

GWPC: Produced Water Report: Regulations, Current Practices, and Research Needs, 2019

Source: Jacobs Engineering

Improving Hydrogen Economics

Early-stage research is required to evolve and de-risk the technologies.



MAKE

Hydrogen production technologies

MOVE

Hydrogen storage, compression, and distribution, and thermal integration

USE

Hydrogen end use technologies and demand

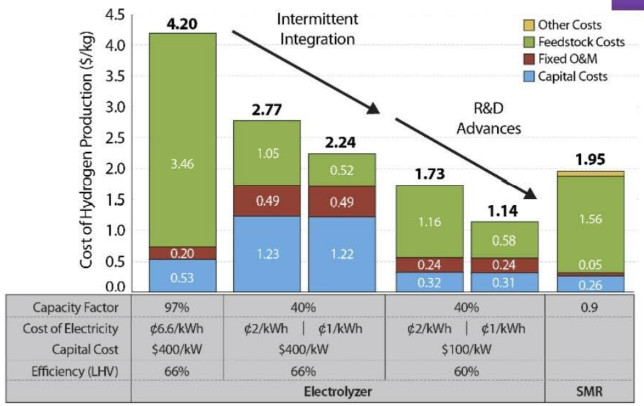
STORE

Improved Bulk Storage Technologies

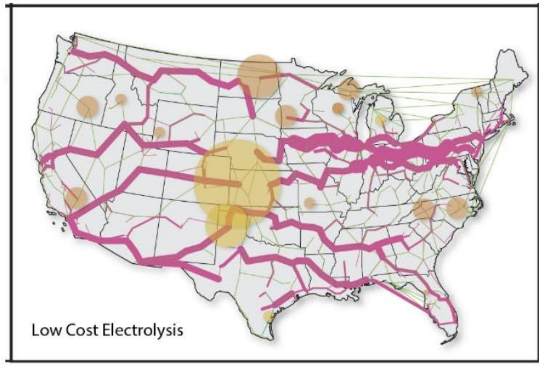
Preliminary

Use	Potential MMT/yr
Refineries & CPI	8
Metals	12
Ammonia	4
Synthetic Chemicals	14
Biofuels	1
Natural Gas	10
Light Duty Vehicles	57
Other Transport	17
Electricity Storage	28
Total	**151**

Decreasing cost of H_2 production



Capacity Factor	97%	40%		40%		0.9
Cost of Electricity	¢6.6/kWh	¢2/kWh	¢1/kWh	¢2/kWh	¢1/kWh	
Capital Cost	$400/kW	$400/kW		$100/kW		
Efficiency (LHV)	66%	66%		60%		
	Electrolyzer					SMR



Optimizing H_2 storage and distribution

Leveraging of national laboratories' early-stage R&D capabilities needed to develop affordable technologies for production, delivery, and end use applications.

https://www.hydrogen.energy.gov/pdfs/review18/tv045_ruth_2018_o.pdf

Webinars

Hydrogen Economy Infrastructure: Transmission & Storage

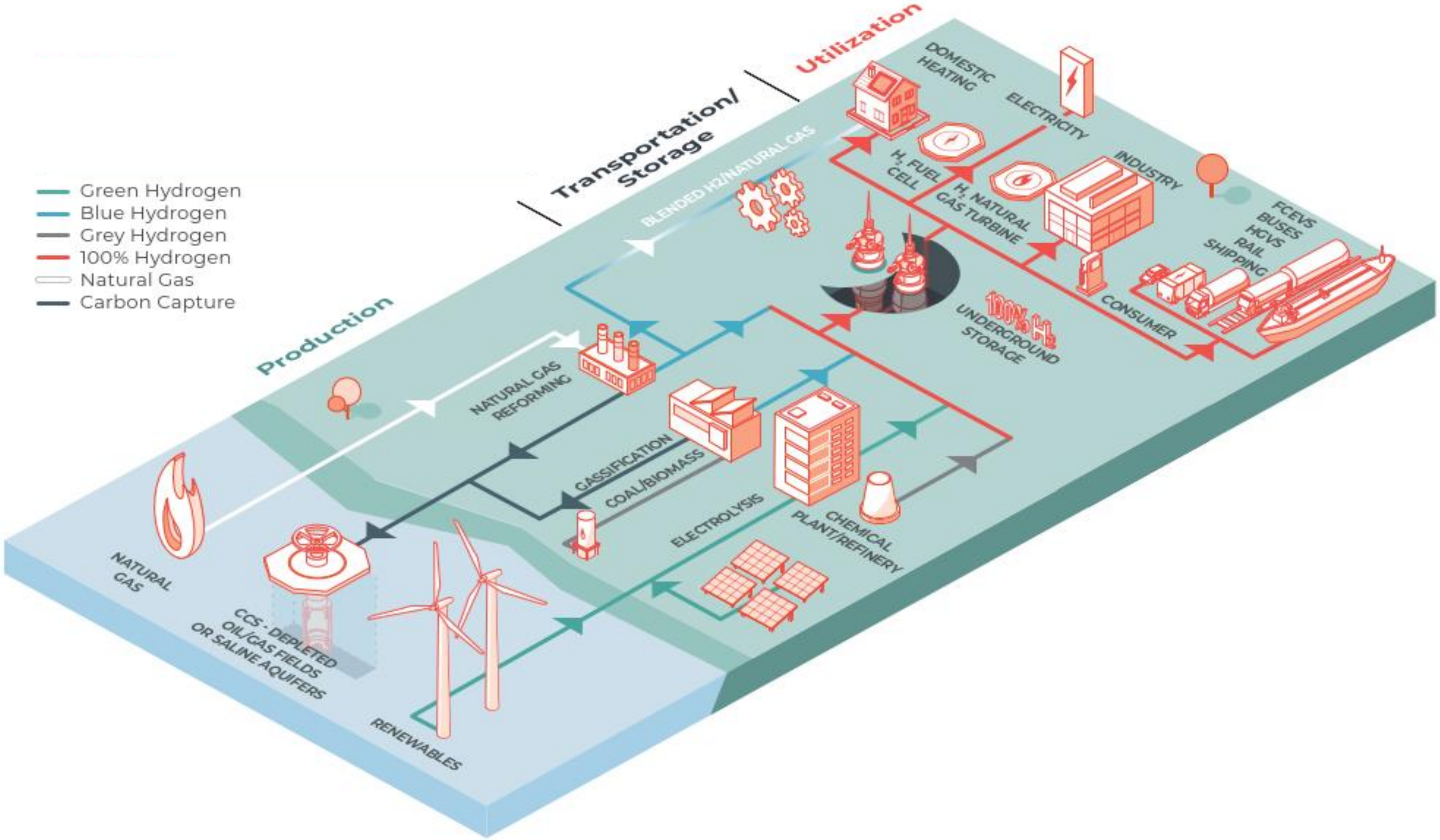
Zachary Evans, WSP

SPE International®

INTERSTATE Oil & Gas COMPACT COMMISSION

EDF ENVIRONMENTAL DEFENSE FUND®
Finding the ways that work

The Hydrogen Road Map



Hydrogen Infrastructure Overview

- As with all energy commodities, efficient and commercially viable applications are only possible if supply and demand markets are linked by **effective transportation networks and reliable storage facilities at scale**.

- Analogs can be found in the well-established **domestic natural gas infrastructure** as well as growing facilities for **transport and sequestration of CO_2**.

- Existing **hydrogen pipelines are in place**, primarily located along the U.S. Gulf Coast, to serve feedstock needs of refineries and chemical processing plants.

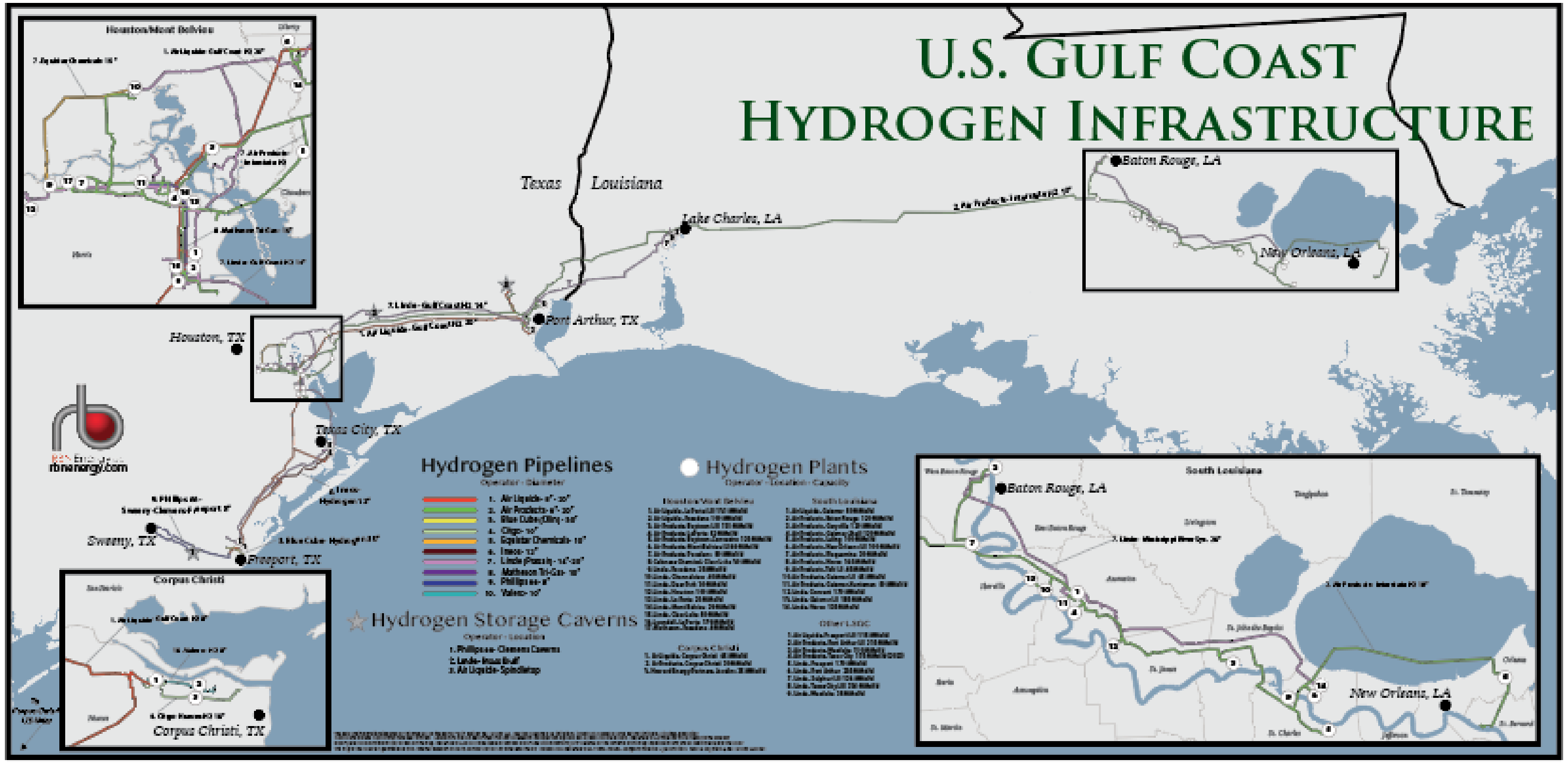
- However, though comparisons are useful in forecasting hydrogen economy needs, due to differing supply and demand markets and different end user business models, standing up **hydrogen infrastructure may not exactly mimic existing gas framework**.

  - *On-Site Sourcing Potential*
  - *No Residential Usage Component*
  - *Electron vs. Molecule Transmission Options (Power Generation)*
  - *No Enhanced Oil Recovery (EOR) Applications*
  - *Material Longevity Issues*
  - *Tremendous Capital Investment*

- **Options include pipelines, rail, long-haul trucking, and electricity (power gen).**

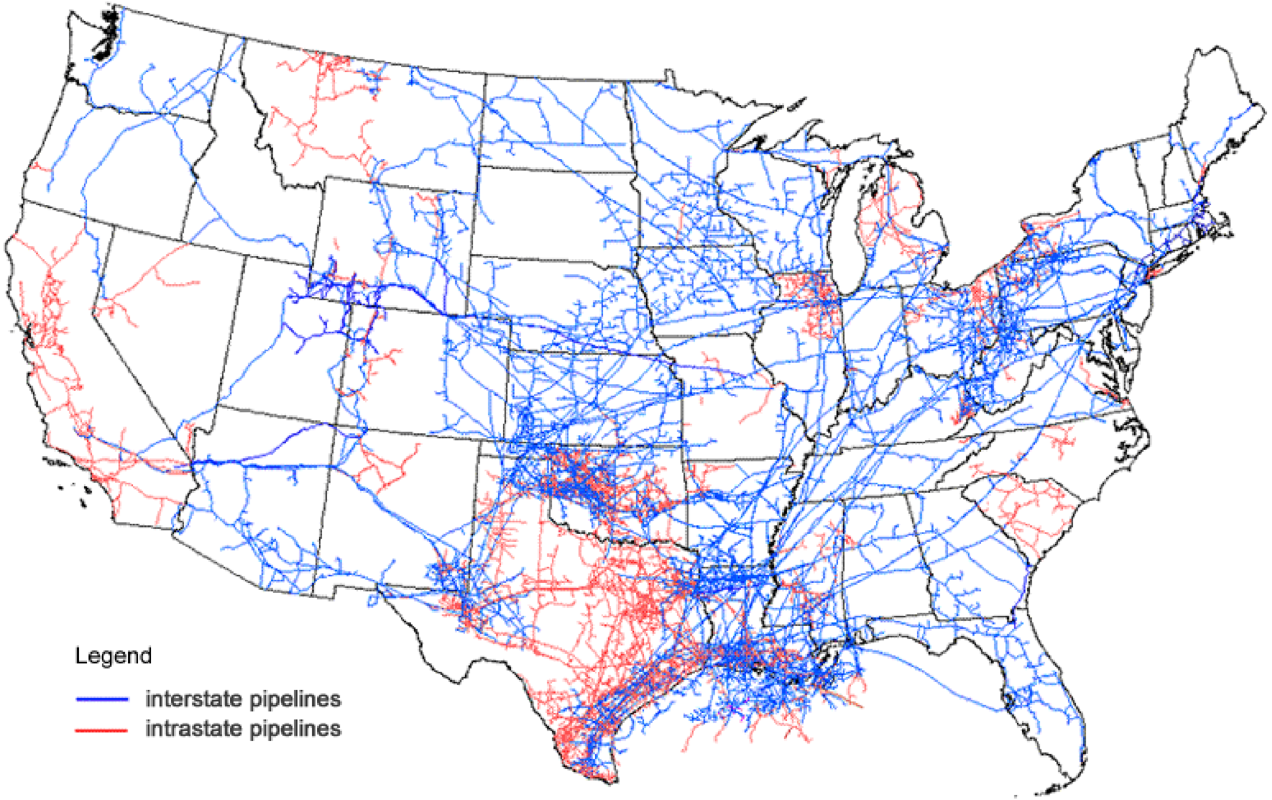
Existing Hydrogen Pipelines

Approximately 1,600 miles of hydrogen pipelines are currently operating in the U.S., though over 90% of this capacity is located along the Gulf Coast.



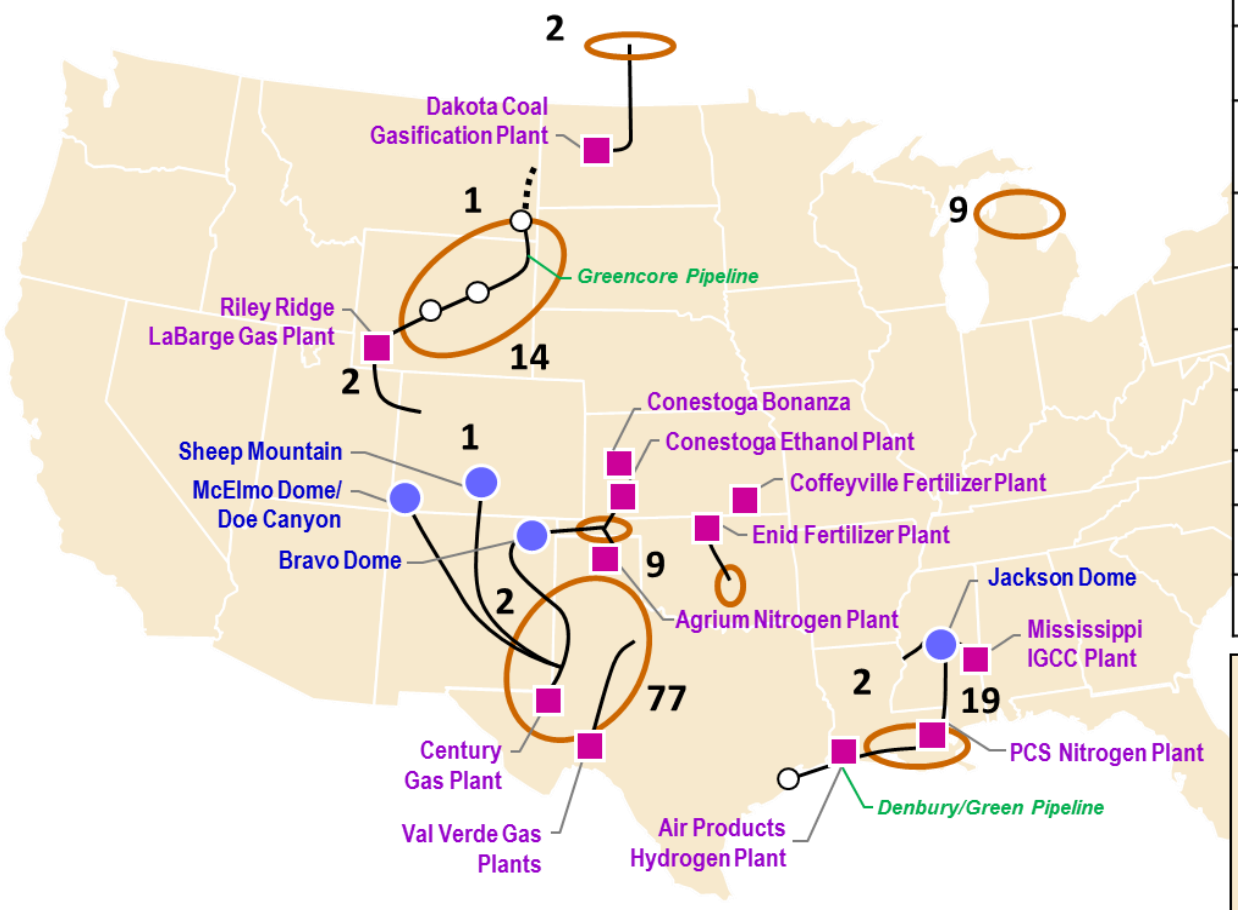
Natural Gas Infrastructure Analogs

Existing natural gas pipeline footage outpaces hydrogen facilities by orders of magnitude, totaling **3 million miles**. Blended hydrogen transport currently targets **10% H_2 concentration**.



Source: U.S. Energy Information Administration, *About U.S. Natural Gas Pipelines*

CO_2 Infrastructure Analogs



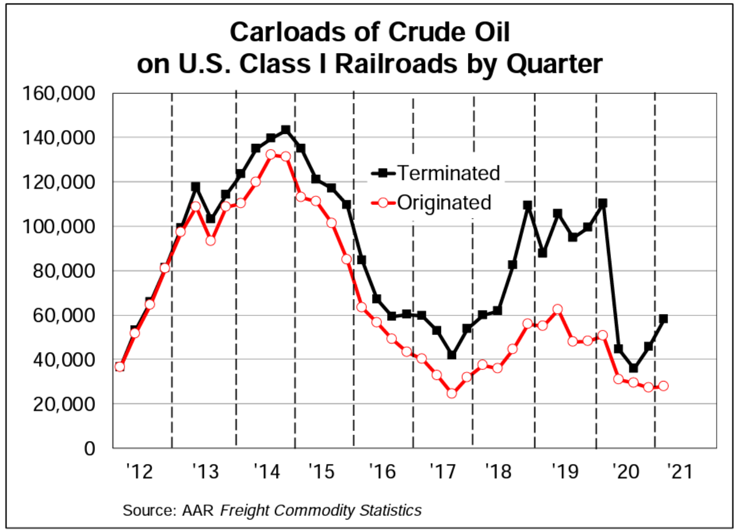
Oil Production (2014)	
CO_2-EOR Projects	136
Oil Production (MBbl/d)	300
CO_2 Supplies (2014)	
Number of Sources	17
• *Natural*	5
• *Industrial*	12
CO_2 Supply (Bcf/d)	3.5
• *Natural*	2.8
• *Industrial*	0.7

136	No. of U.S. CO_2-EOR Projects
●	Natural CO_2 Source
■	Industrial CO_2 Source
———	CO_2 Pipeline
▪▪▪▪▪▪▪	CO_2 Proposed Pipeline
○	CO_2-EOR Region

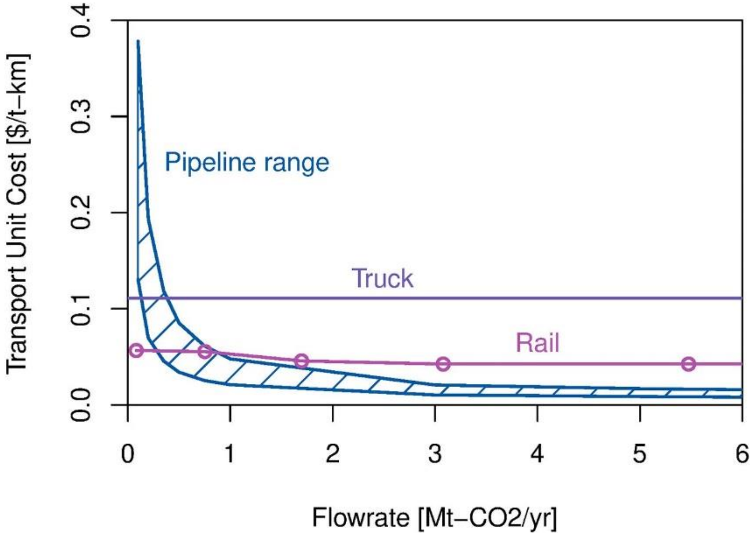
Source: Advanced Resources International, Inc., based on Oil and Gas Journal, 2014 and industry sources.

Rail & Trucking Analogs

- In 2021, U.S. Class I railroads moved approximately **236,069 carloads of crude oil (165 million barrels).**
- For comparison, 1 train car of crude oil contains the same BTU content as **3,000 cars of uncompressed H_2**.



Source: AAR *Freight Commodity Statistics*

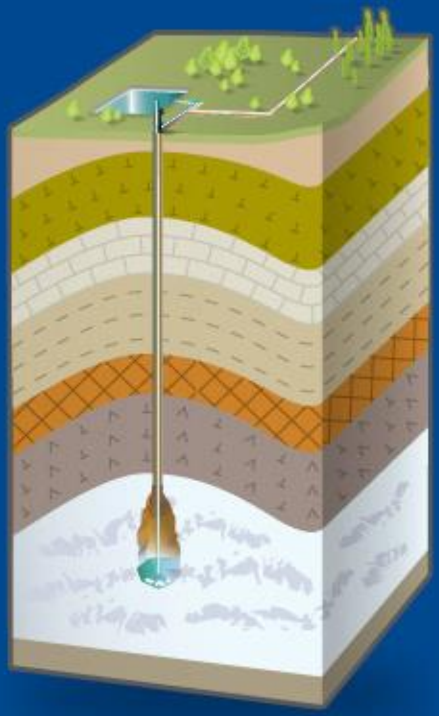


- Current single consumer (Linde) annual CO_2 purchases by truck totals roughly 1,100 truckloads, totaling 21,784 U.S. tons with an average of **120 tons (374 MMcf) per day**.
- With CO_2, at low volumes, costs are **dominated by truck leasing and purchasing** but converge to a minimum as hauling nears capacity.

Hydrogen Storage Volumetrics

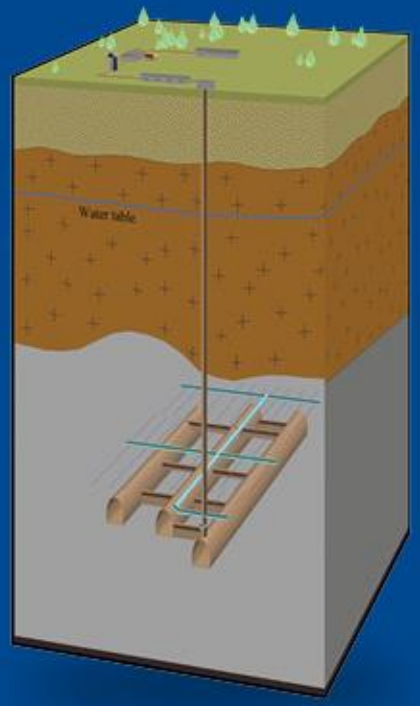
- Hydrogen has 3x more energy by weight than hydrocarbons, but when comparing volumes, hydrogen is **8.5x less dense than natural gas** at standard conditions.
- Hydrogen has roughly **30% energy content** on a per cubic foot basis compared to natural gas, meaning greater volumes are need to store the same volume of end user energy.
- Due to **high pressure requirements and issues at scale**, surface storage of hydrogen poses a variety of practical problems.
- As with natural gas and other critical commodities, **underground storage** of hydrogen is a primary focus of scalability.

Types of Underground Storage



Salt Caverns
(Domal and Bedded)

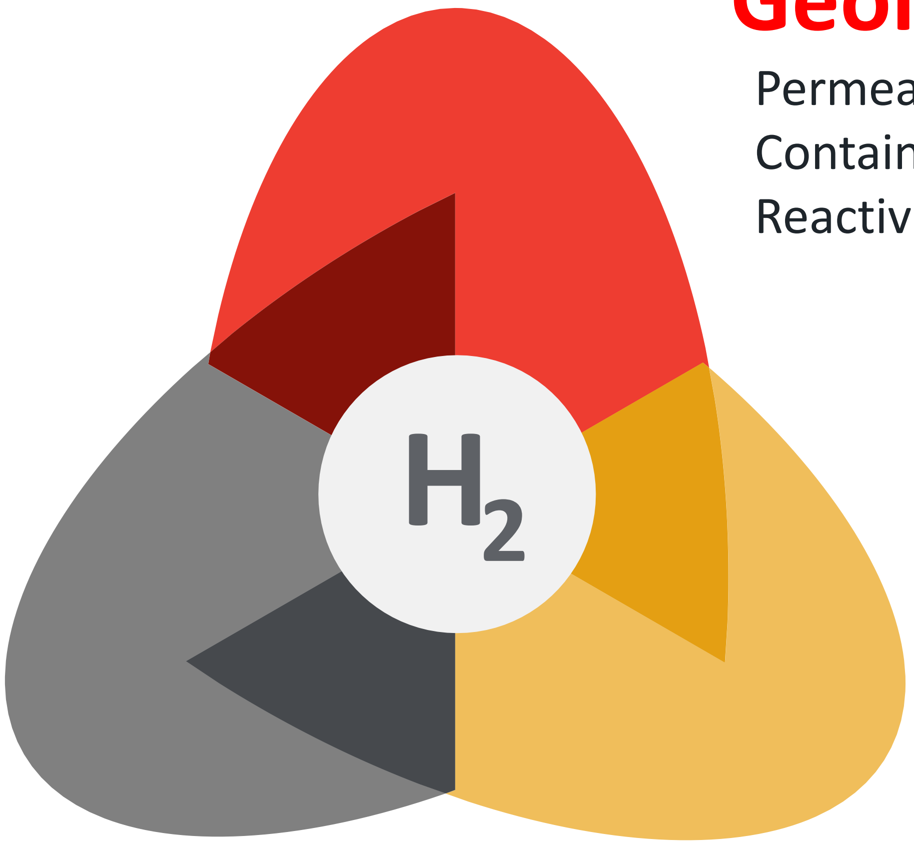
Aquifers and Depleted Fields



Mined Rock Caverns
(Lined or Unlined)

The Challenges of Hydrogen Storage

Webinars



Geology

Permeability
Containment
Reactivity

Chemistry

Compressibility
Molecular Sizing
Heat Transfer

Compatibility

Embrittlement
Seal Deterioration
Operational Stress

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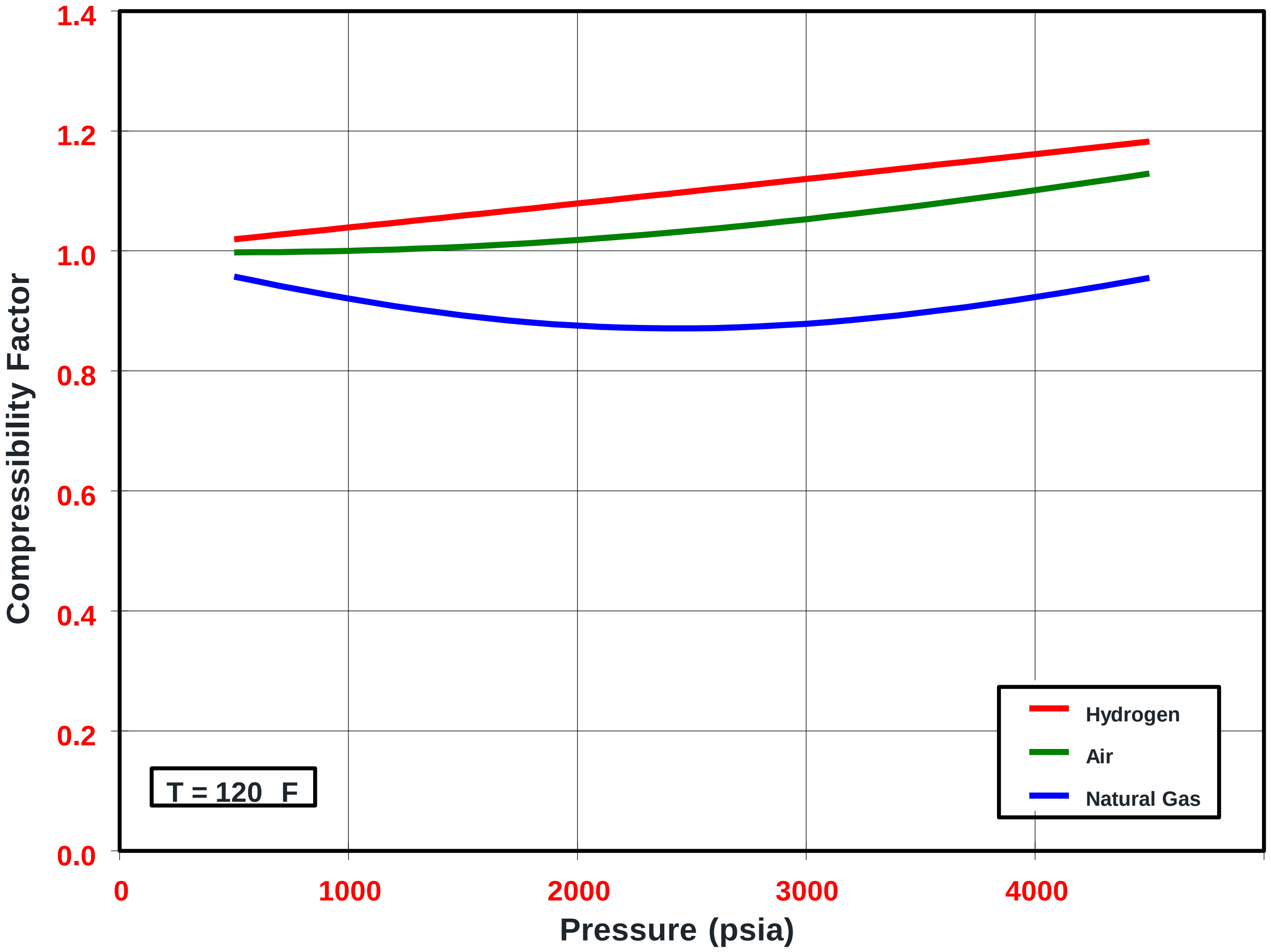
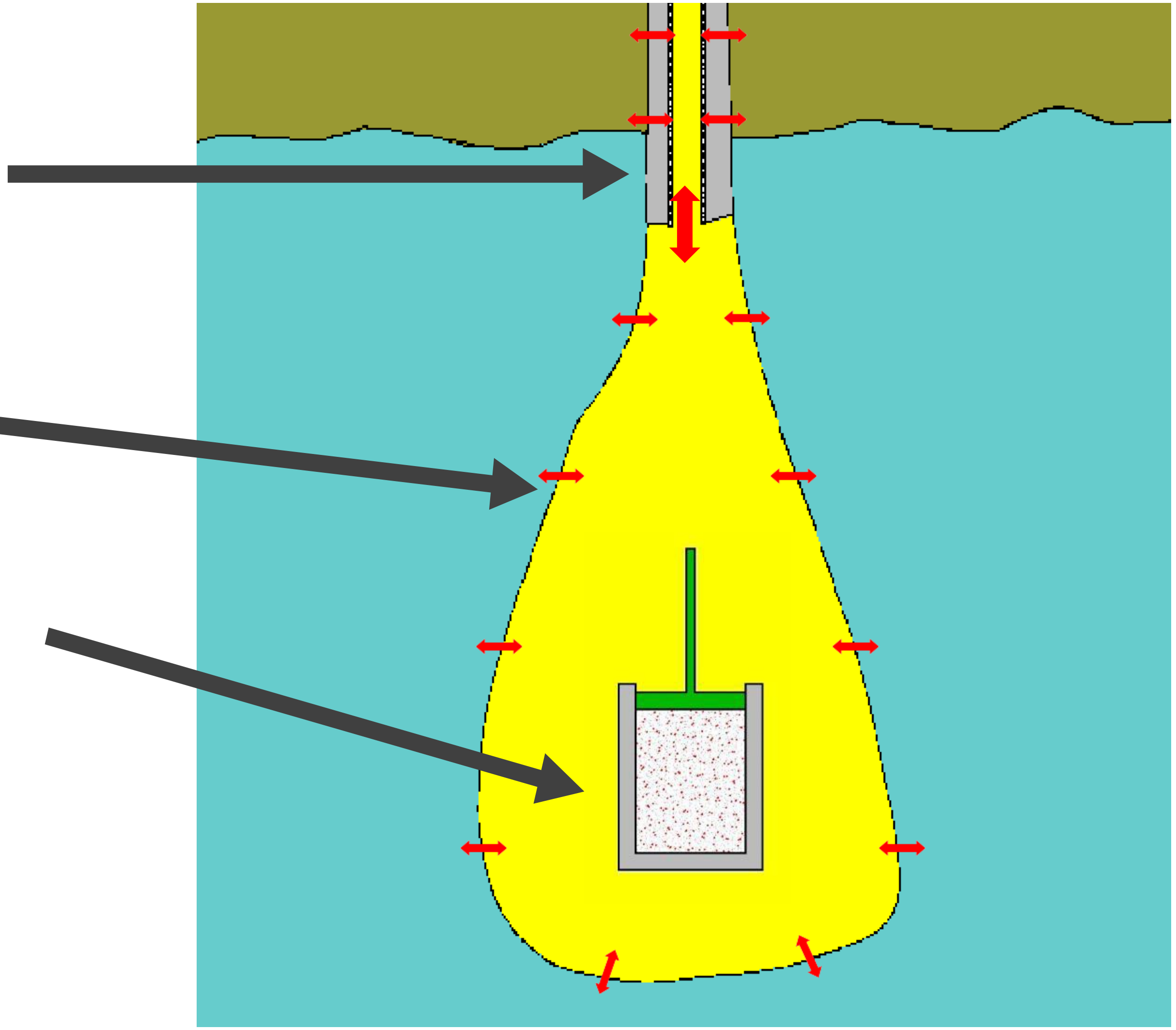
Hydrogen Thermodynamics

- With a compressibility factor over 1.0, hydrogen is **much harder to compress than natural gas**.
- Less compressibility creates both operational challenges as well as **less energy deliverability impact at higher pressures** than in traditional gas storage operations.
- Compressibility also causes **high working gas volumes** for underground storage.



Hydrogen Thermodynamics

- Hydrogen has a negative Joule-Thompson coefficient, which means it **heats up when flowing out of a restriction**, such as the casing shoe of a storage well.
- Concerns also exist over heat transfer to surrounding salt face, as **temperature rise during compression** is considerable.
- Significant compression and decompression of gas is also a cavern integrity risk, as **expansion effects are more significant than similar natural gas operations**.



Hydrogen Geology

Webinars

Permeability

Hydrogen is an incredibly small molecule, much smaller than any other commodity, so migration concerns in certain geologies are significant.

Geochemistry

Unlike methane, hydrogen is not inert and may have unwanted reactions with the matrix and reservoir fluids.

Microbial

Microbial organisms can consume hydrogen and produce unwanted byproducts. High temperatures and salinity are needed to avoid organic growth.

Diffusion

Hydrogen is capable of diffusing into the molecular structure of the host geologic formation, leading to further volumetric losses.

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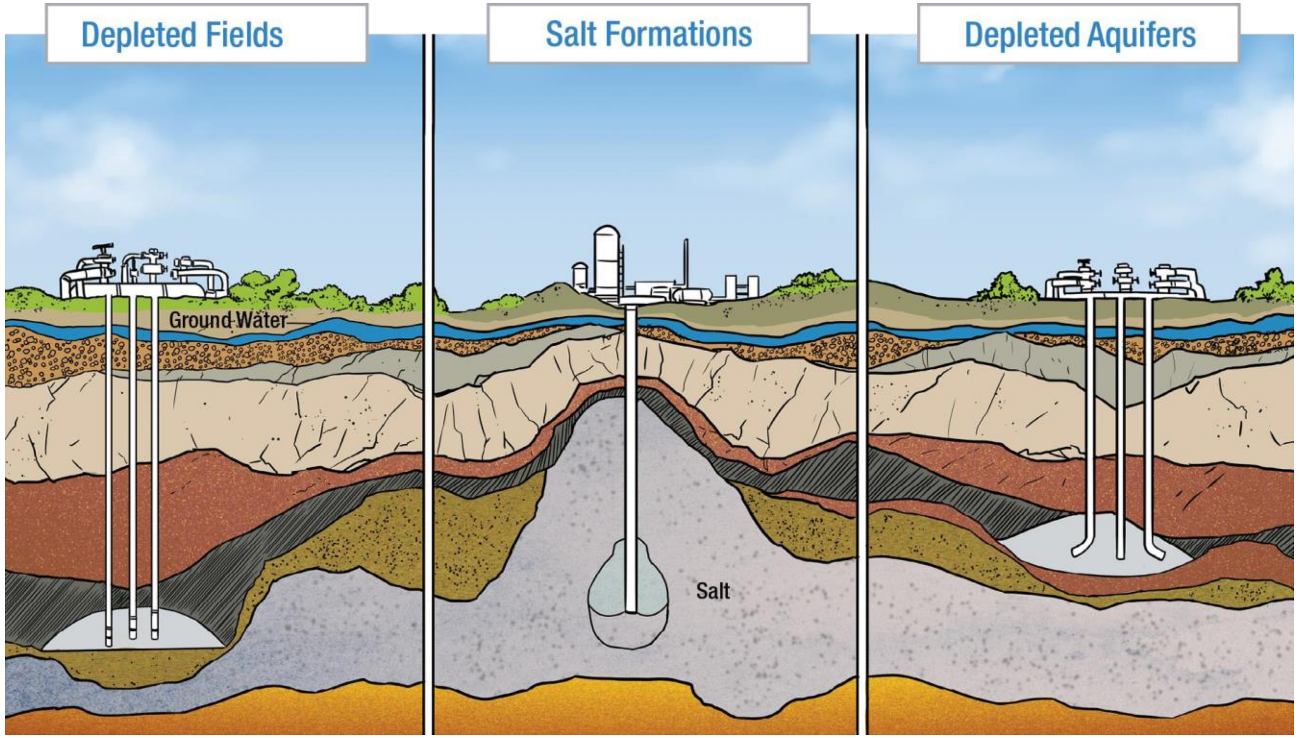
Hydrogen Storage Geology

- **Domal Salt Caverns**
  - Clean, Integral Geology
  - Finite Containment
  - Few Geochemical Concerns
  - Facilities Currently in Service

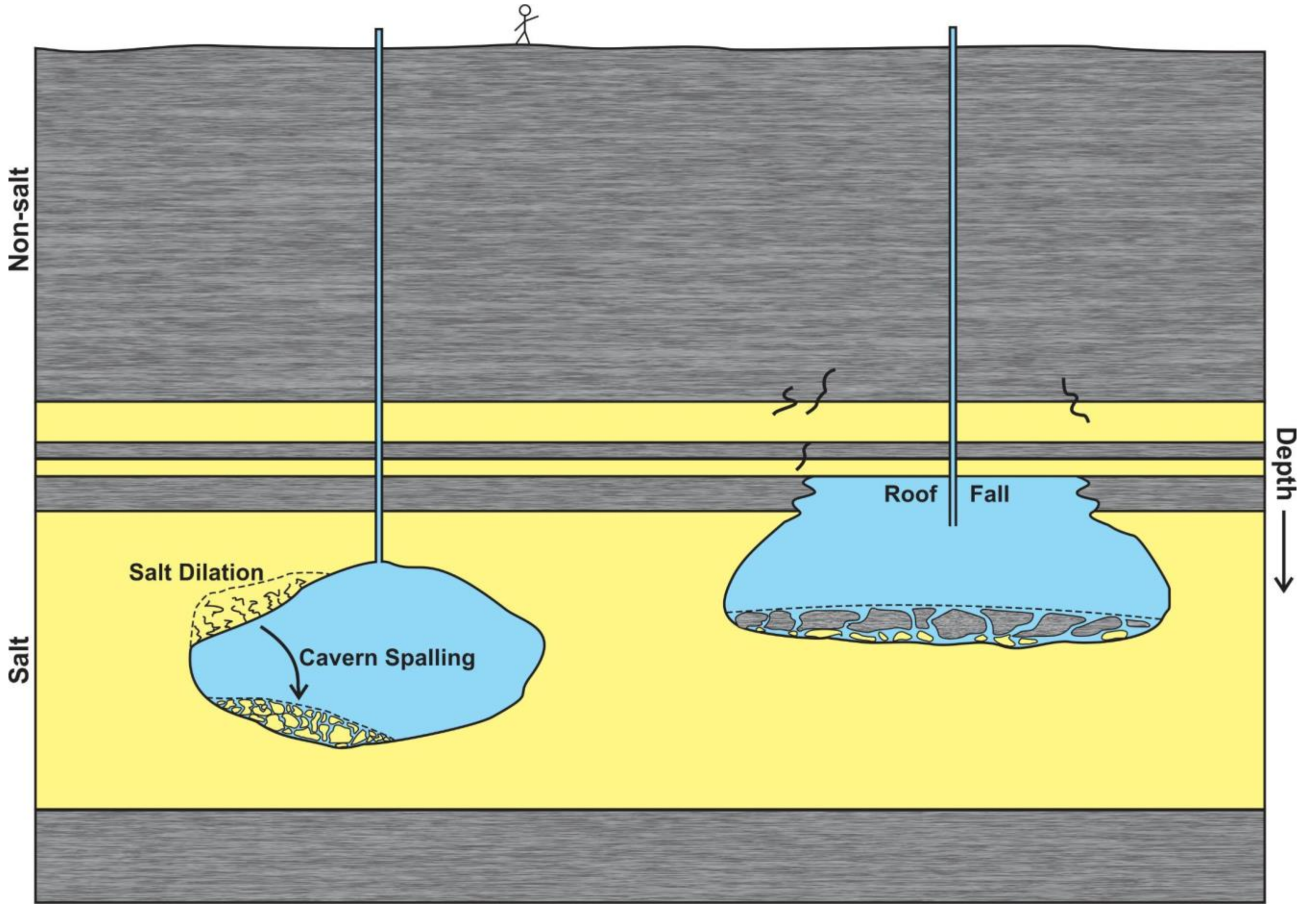
- **Bedded Salts**
  - Interbeds Pose Migration Risk
  - Higher Salt Variation
  - Higher Geographical Frequency
  - No Proof of Concept to Date

- **Porous Reservoirs**
  - Unproven Geochemistry
  - Volumetric Scalability Issues
  - Commercial Challenges
  - No Proof of Concept to Date



Hydrogen Geology

- In terms of geologic stability and integrity, **controlled pressure cycling is critical** regardless of what material is being stored.
- For hydrogen, **drastic differences in operational behavior** may create unique geologic concerns.
- Wither low energy content, hydrogen storage may require **more aggressive cycling** and a desire to increase the pressure envelope to maximize storage capacity, adding stress to caprock, salt roof and cavern walls.



Hydrogen Material Compatibility

- Hydrogen's chemical reactivity poses a variety of **material compatibility issues**.

- Hydrogen **diffusion and embrittlement** are major concerns in terms of long-term storage integrity, affecting casing, pipelines, and surface equipment.

- Compatibility issues are also **exacerbated by added stress** associated with likely aggressive operational cycles.

- As a result, specific materials and coatings for H_2 usage are necessary, and **though longevity is a concern**, data from petrochemical industry applications can be used to establish guideposts.

Hydrogen Storage Regulation

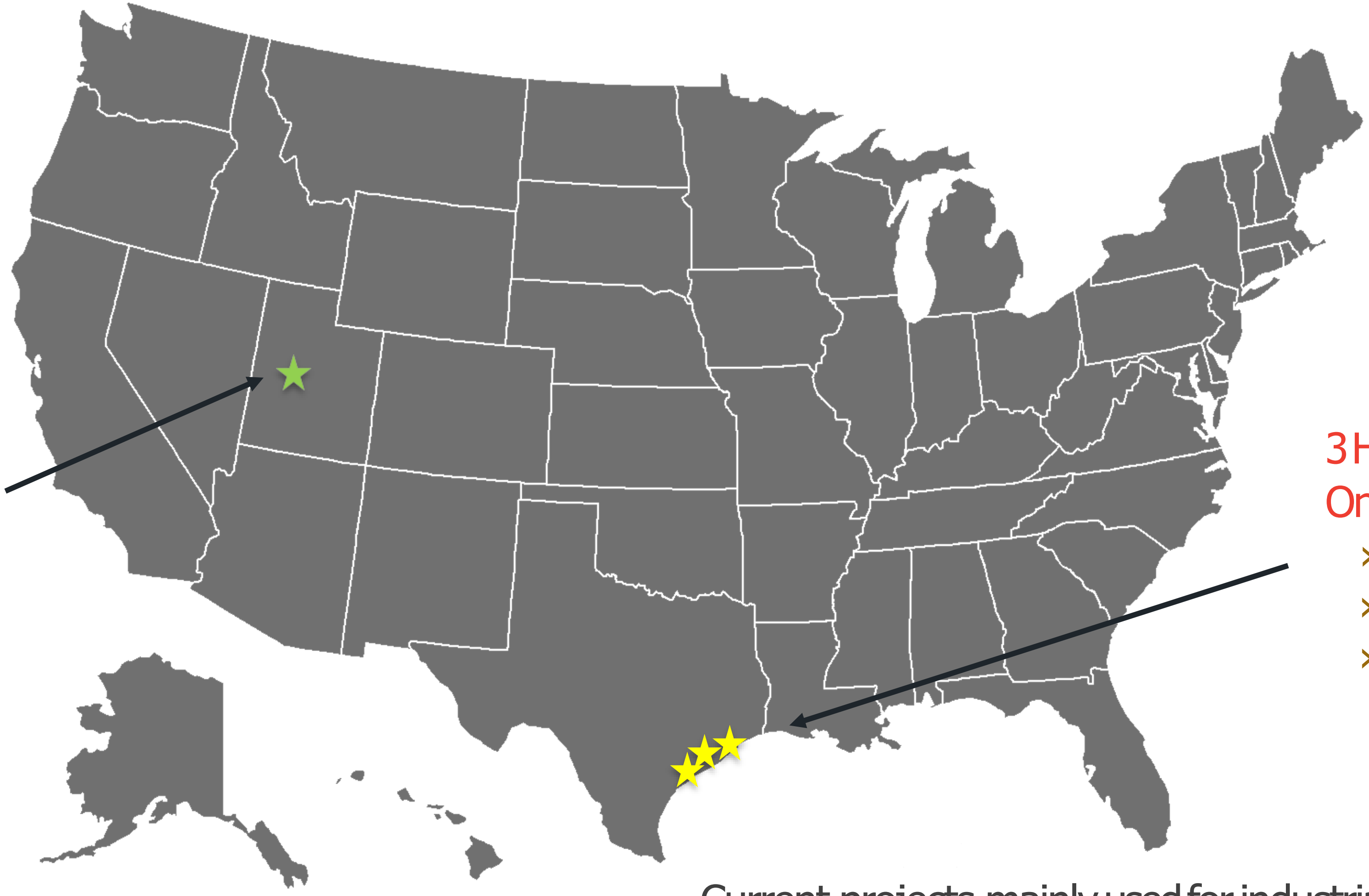
- Underground natural gas storage is currently regulated by the **Federal Energy Regulatory Commission** (FERC - DOE) and the **Pipeline Hazardous Material Safety Administration** (PHMSA - DOT) in conjunction with various state and local authorities with specific jurisdictions.

- While a robust regulatory framework exists for gas storage, primarily through PHMSA's adoption of the American Petroleum Institute's **API Recommended Practices 1170 & 1171**, no such specific structure is currently in place for large scale storage of hydrogen.

- The American Society of Mechanical Engineers (ASME) has developed **codes and standards for hydrogen piping and pipelines** (B31), but scale of these facilities leads to very specific stakeholders when it comes to implementation at scale.

- Regulators, operators, and other industry stakeholders will need to collaborate in coming years to **develop and implement a hydrogen storage regulatory strategy** that provides appropriate consumer and safety oversight while addressing practical concerns and differences to the previously established natural gas analog, such as **leak detection and reservoir integrity**.

Existing Hydrogen Storage Facilities



New Hydrogen Salt Cavern Project in Utah (ACES)

3 Hydrogen Salt Caverns On the U.S. Gulf Coast

- Praxair (Moss Bluff)
- Air Liquide (Spindletop)
- Phillips 66 (Clemens)

Current projects mainly used for industrial purposes (refining).

Hydrogen Storage Caverns

Nation's first hydrogen storage cavern, developed in 2007, to provide 600-700 MMcf/d of hydrogen service to **industrial pipeline customers** in Texas gulf region.

PRAXAIR

Spindletop cavern is the **largest hydrogen storage cavern** in the world, providing reliability along the Gulf Coast Pipeline System with 5.6 million barrels of capacity.

Air Liquide

Portion of 8 billion barrel multi-cavern facility dedicated to hydrogen storage, including both **new and repurposed capacity**, supporting operator-owned refinery.

PHILLIPS 66

Magnum & Mitsubishi joint venture currently building the **world's largest green hydrogen storage facility** at 9 million barrels to fuel a 1,000 MW power plant.

ACES DELTA

End-Use: Long Ridge Energy Terminal

- As part of the Long Ridge Energy Generation Project, the Monroe County, OH power plant is one of the **most energy efficient power plants** of any type in the world.

- Delivering 485 megawatts of electricity to the regional grid by burning a **blend of hydrogen and natural gas** in a GE H-Class gas turbine. Currently using a roughly 5% blend with an **equipment threshold of 15-20% (by volume)**, the plant has long term plans to transition to 100% hydrogen over time.

- Long Ridge is the **first purpose-built hydrogen-burning power plant** in the United States with commercial operations beginning in 2021. The facility is compact, low-impact and significantly more advanced and efficient than earlier generations of natural gas fired power plants.

Hydrogen Infrastructure Research

Webinars

National-lab led effort with 20 industry partners to address technical barriers related to blending **blending hydrogen in natural gas pipelines**, including economic evaluation.

HyBlend
U.S. DEPARTMENT OF ENERGY

Pipeline industry consortium exploring a variety **hydrogen transportation and usage applications** involving key industry stakeholders from around the globe.

PRCI Pipeline Research Council International
LEADING PIPELINE RESEARCH

Project led by multiple national labs to explore the viability, safety, and reliability of **hydrogen storage**, including biogeochemistry and material interactions.

SHASTA
Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Academic research project at the University of Edinburgh to explore the effects and potential challenges of long-term **storage of hydrogen in porous media reservoirs**.

HyStorPor

SPE International

QUESTIONS / DISCUSSION

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