NYSERDA Presents:

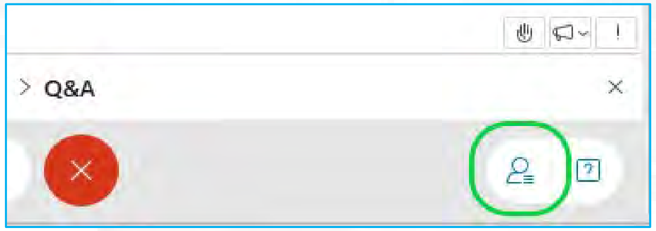
Hydrogen in NYS: State of the Science

Kickoff Webinar
May 31, 2022

NEW YORK STATE | NYSERDA

Meeting Procedures:

- Attendees are muted upon entry
- Questions and comments may be submitted using the Q&A feature during the event



- The Chat feature will be disabled (outside of facilitation sessions)
- Materials + recording from today's event will be made available online at www.nyserda.ny.gov/hydrogen
- If technical problems arise, please contact Tricia.King@nyserda.ny.gov

Opening Remarks:

Doreen Harris

President & CEO, NYSERDA

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Agenda:

- **Hydrogen (H_2) Introduction & Overview**
- **H_2 in NYS:**
  - Role of H_2 in the Climate Act
  - NYS Activities & Programs
- **Environmental & Climate Justice Considerations**

10-Min. Break

- **H_2 Primer Sessions:**
  - Production Overview
  - Electrolyzers & Fuel Cells
  - Delivery & Storage
  - Safety Considerations
- **Ideation & Taking Stock**

Ground Rules

- Honor the agenda
- Use the Q&A feature to provide questions throughout the event
- The Chat feature will only be accessible during facilitation activities at beginning/end of today's program
- Please share and/or ask questions which contribute to a meaningful discussion
- Recording & materials will be made available online at www.nyserda.ny.gov/hydrogen

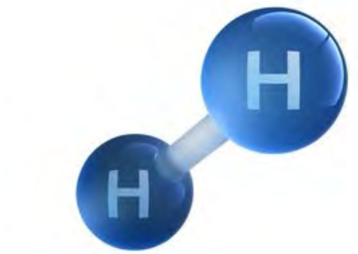
Facilitation:

Preliminary Interest Engagement Exercise

Hydrogen Introduction & Overview

Introduction to Hydrogen (H_2)

The What:



- The most abundant (and simplest) element in the universe
- Energy carrier vs. energy source
- Unique characteristics: high energy density by weight, low energy density by volume
- A versatile tool in the decarbonization toolbox

Introduction to Hydrogen (H_2)

The How:

How:

You *produce* it

You *power* its production

You *use* it

- Despite its ubiquity on Earth, H_2 does not occur on its own
- Rather, it must be derived / separated from other compounds:

H_2O	C_2H_6O	CH_4	C_8H_{18}
(Water)	(Ethanol)	(Methane)	(Octane)

- Once separated, H_2 is and can be utilized for a variety of applications / purposes

Introduction to Hydrogen (H_2)

The Why:

- **H_2 is neither novel nor (relatively) niche:**
  - **U.S. currently produces ~10 million metric tons/year (nearly all fossil)**
  - **Primary uses today are for oil refining + industrial applications (ammonia, methanol, steel, chemical feedstock)**
- **Feasibility / availability of renewables**
- **Decarbonization & emissions reduction targets**
  - Numerous potential applications: low carbon fuel, feedstock, energy carrier
- **Excitement, interest, and caution at a variety of levels (local, state, federal, global)**

Fireside Chat:

Hydrogen Introduction & Overview

Participant:

- Michael Colvin, Environmental Defense Fund
  Director, Regulatory and Legislative Affairs

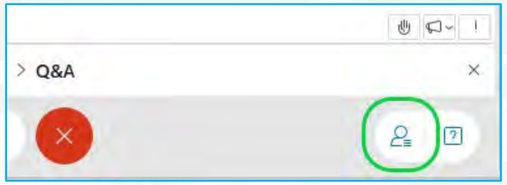
Relevant/Referenced Material:

EDF Studies/Reports:

- ‘Study: California can Reach a Decarbonized Electric Grid Affordably and Reliably by 2045’
- ‘Climate consequences of hydrogen leakage’

Q&A

Please use the
Webex Q&A Feature



Role of Hydrogen in the CLCPA

Key Findings from the Scoping Plan Integration Analysis

James Wilcox, NYSERDA

Kevin Steinberger, Energy and Environmental Economics (E3)

May 31, 2022

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Contents

More information on the Climate Act can be found at https://climate.ny.gov/

For the full Integration Analysis, see the Climate Action Council Draft Scoping Plan Appendix G: *Integration Analysis Technical Supplement*
https://climate.ny.gov/Our-Climate-Act/Draft-Scoping-Plan

Climate Leadership and Community Protection Act (CLCPA, or Climate Act) – Overview

Carbon neutral economy, mandating at least an 85% reduction in emissions below 1990 levels

40% reduction in emissions by 2030

100% zero-emissions electricity by 2040

70% renewable electricity by 2030

9,000 MW of offshore wind by 2035

6,000 MW of distributed solar by 2025

3,000 MW of energy storage by 2030

185 TBtu on-site energy savings by 2025

Commitments to climate justice and just transition

Process for developing the Draft Scoping Plan

The Climate Act requires the CAC to develop a draft Scoping Plan to meet statutory emission limits by the end of 2021

> The Draft Plan is informed by recommendations of Advisory Panels, Just Transition Working Group, and Climate Justice Working Group

> Reflects the consensus recommendations from the Advisory Panels and JTWG as the strategies to achieve the emissions limits

> Considers climate justice, job creation, cost reductions, public health benefits, minimizing emission leakage

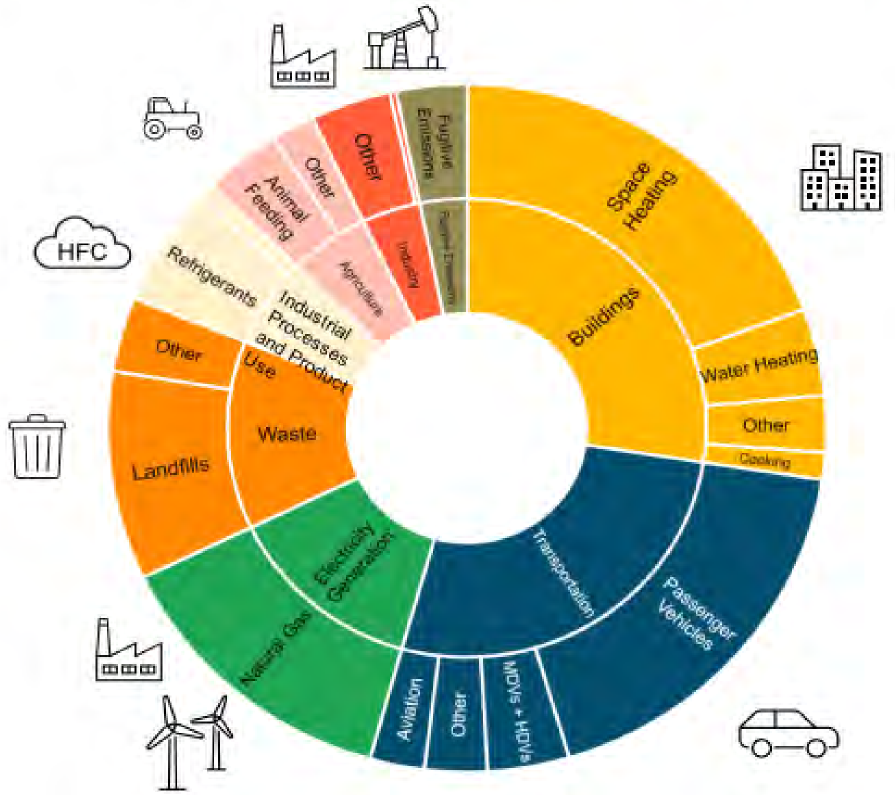
> Emissions addressed include upstream emissions associated with fossil fuels from out-of-state

> Undertakes comprehensive benefit-cost analysis

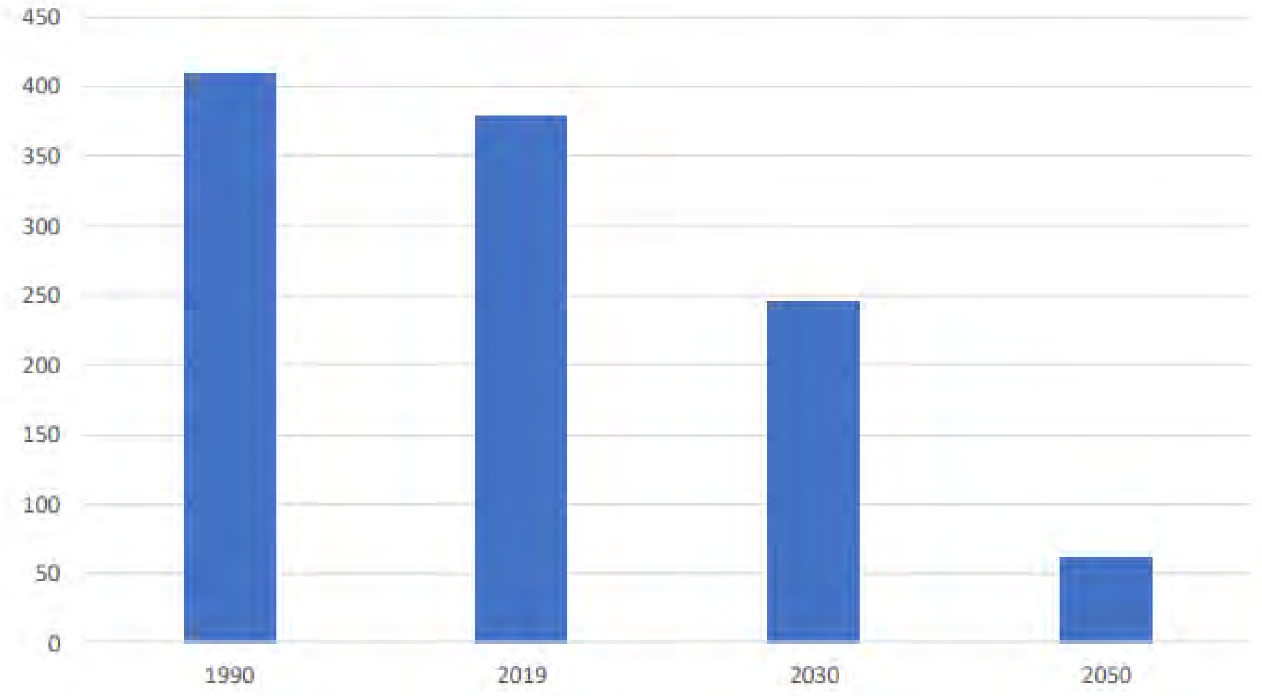
> The recommendations formed basis of scenario modeling to show impact of interaction of strategies across sectors
- 3 scenarios to achieve emissions limits – seeking public feedback on the mix of strategies and level of ambition

GHG Emission Reduction Requirements

Current Estimated GHG Emissions by Sector



New York State GHG Emissions ($MMtCO_2e$)



Scenario Overview

> **Integration Analysis assessed three mitigation scenarios that meet or exceed GHG emission limits, achieve carbon neutrality by midcentury**

- Foundational themes across **<u>all</u>** mitigation scenarios based on findings from Advisory Panels and supporting analysis
  - Zero emission power sector by 2040
  - Enhancement and expansion of transit & vehicle miles traveled reduction
  - More rapid and widespread end-use electrification & efficiency
  - Higher methane mitigation in agriculture and waste
  - End-use electric load flexibility reflective of high customer engagement and advanced techs
- **Scenario 2: Strategic Use of Low-Carbon Fuels**
  - Includes the use of bioenergy derived from biogenic waste, agriculture & forest residues, and limited purpose grown biomass, as well as green hydrogen, for difficult to electrify applications
- **Scenario 3: Accelerated Transition Away from Combustion**
  - Low-to-no bioenergy and hydrogen combustion; Accelerated electrification of buildings and transportation
- **Scenario 4: Beyond 85% Reduction**
  - Accelerated electrification + limited low-carbon fuels; Additional VMT reductions; Additional innovation in methane abatement; Avoids direct air capture of CO_2

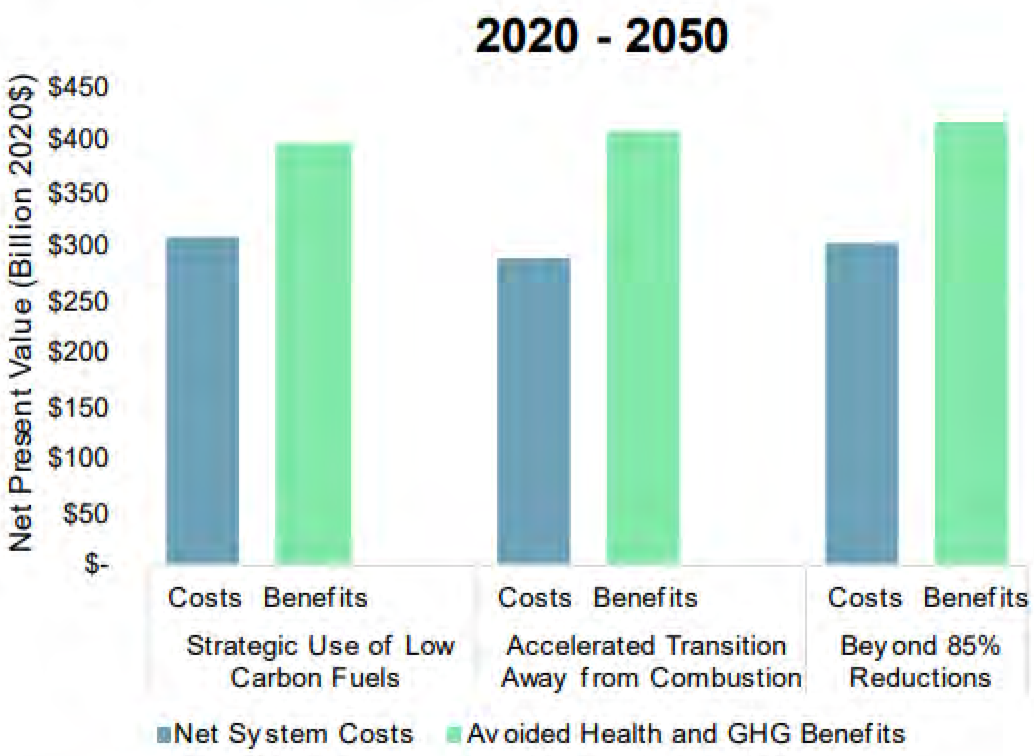
Level of Transformation by Mitigation Scenario

	Scenario 2: Strategic Use of Low-Carbon Fuels	Scenario 3: Accelerated Transition Away from Combustion	Scenario 4: Beyond 85% Reduction
Efficiency and Electrification	High	Very High	Very High
Transit and Smart Growth	High	High	Very High
Zero-Emission Vehicles	High	Very High	Very High
Clean Electricity	High	High	High
Low-Carbon Fuels	High	Low	Medium
Emissions Mitigation in Agriculture & Waste	High	High	High / Very High
Carbon Sequestration in Lands and Forests	High	Very High	Very High
Negative Emissions Technologies	High	Medium	None

Key Benefit-Cost Findings

Cost of Inaction Exceeds the Cost of Action by more than $90 billion

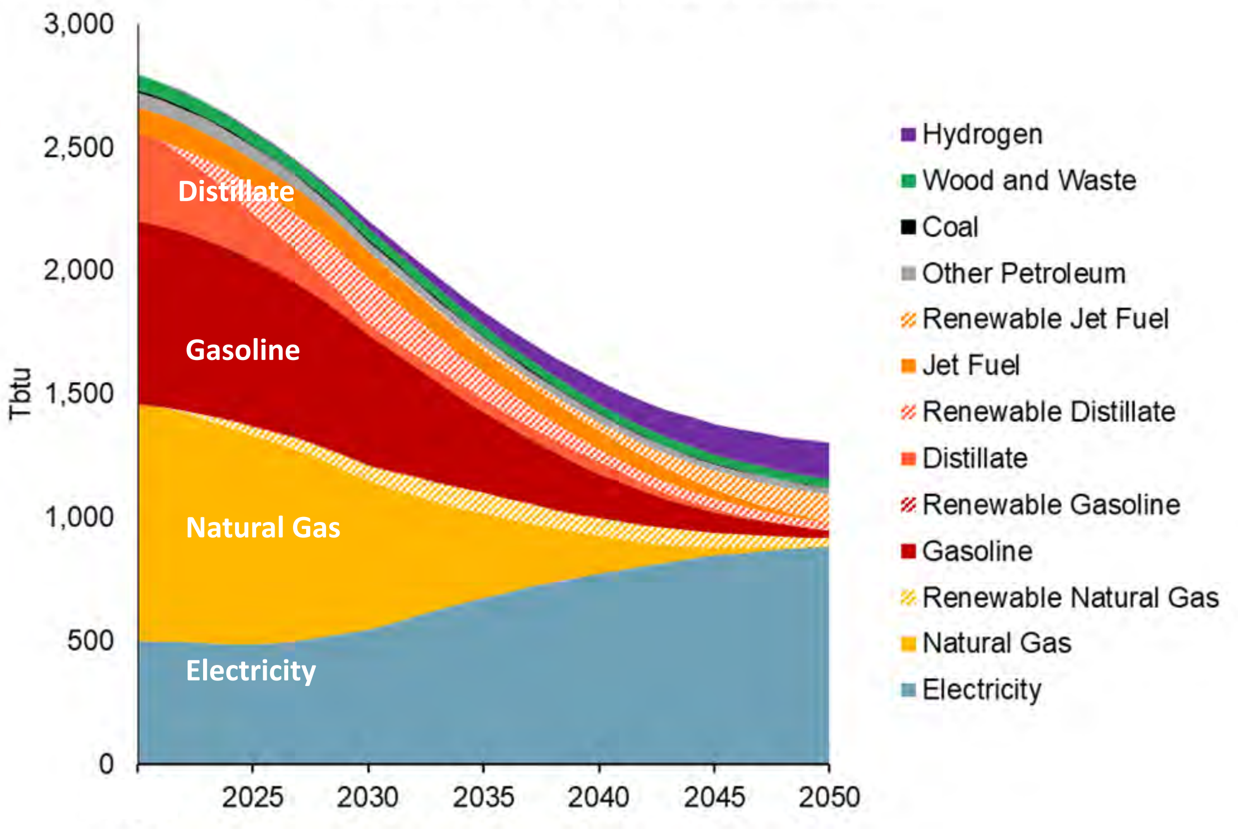
There are significant required investments to achieve Climate Act GHG Emissions Limits, accompanied by even greater external benefits and the opportunity to create hundreds of thousands of jobs

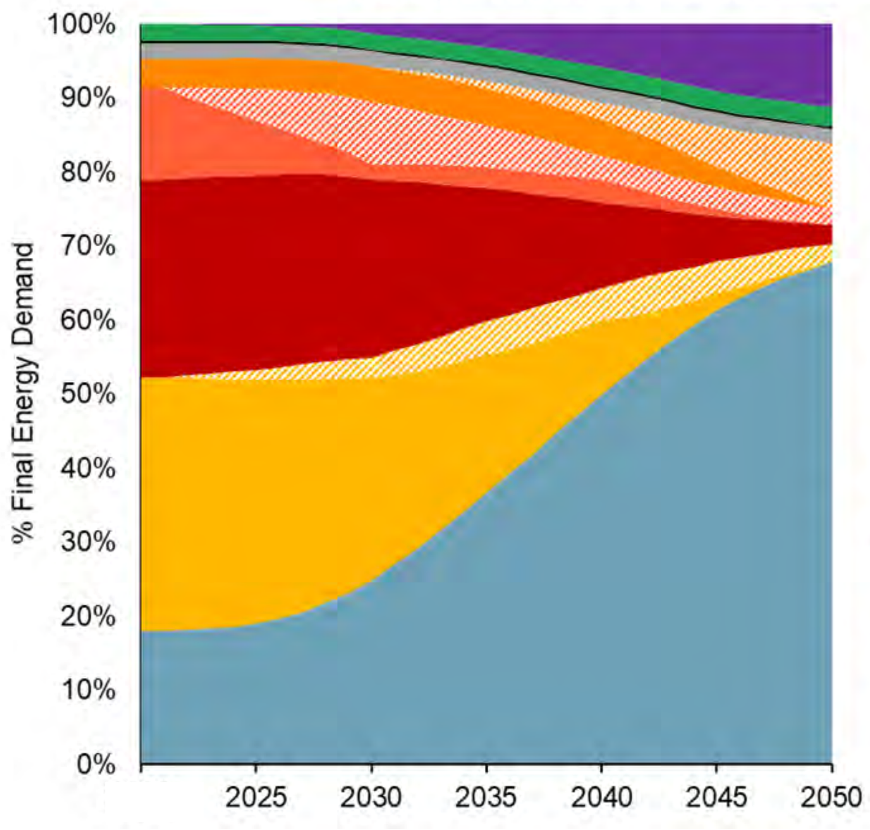


- **Net *benefits* range from $90-$120 billion**
- Costs are a small share of **New York's economy:** 0.6-0.7% of GSP in 2030 and 1.4% in 2050
- As a share of current overall **system expenditures,** costs are moderate: 9-11% in 2030 and 25-26% in 2050

Total Energy by Fuel

Scenario 2: Strategic Use of Low-Carbon Fuels





Hydrogen: 11%

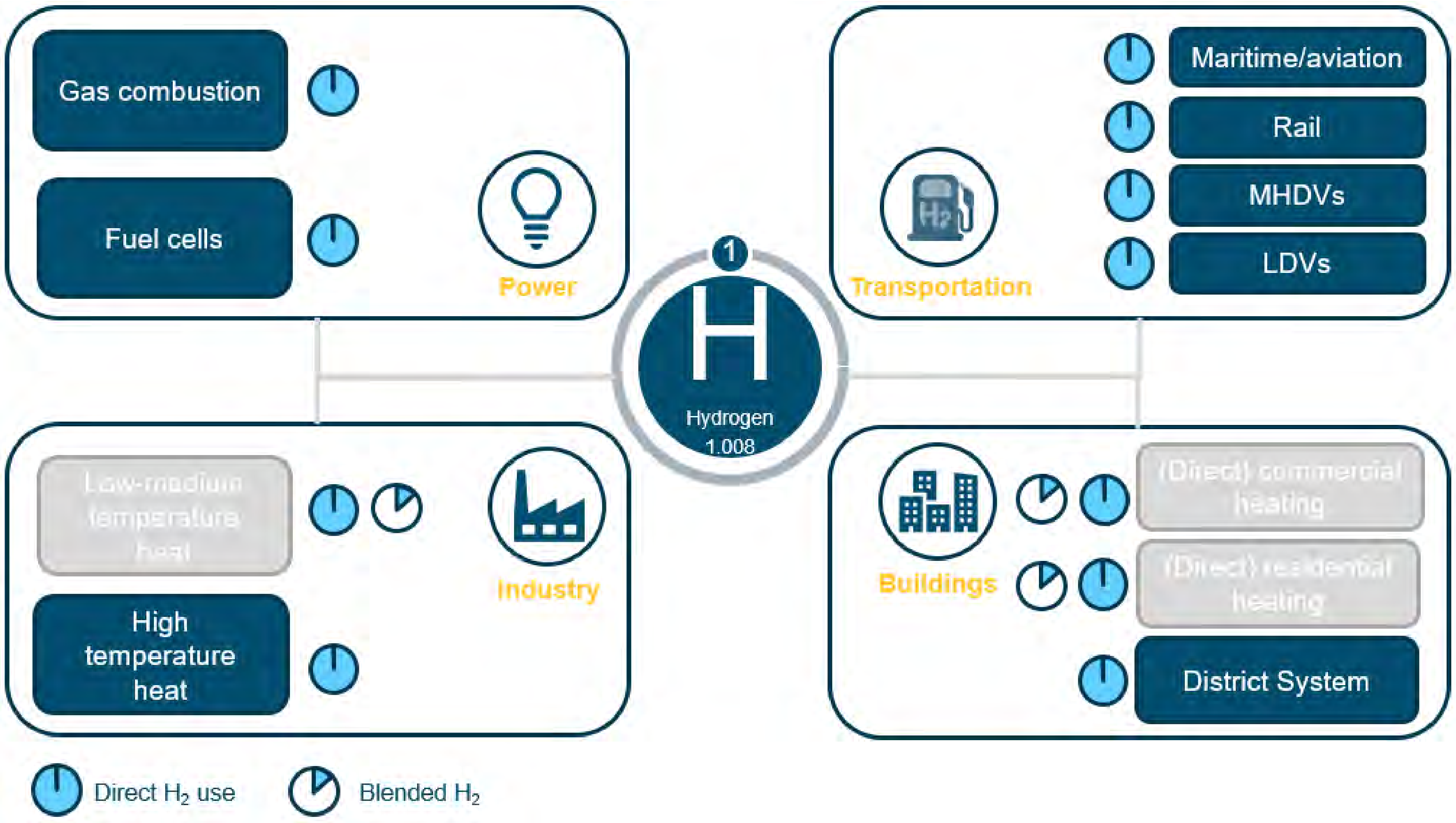
Biofuels: 13%

Electricity: 68%

Includes energy use from transportation, industrial, commercial, and residential sectors.
2020 is a modelled year, reflecting historical trends

Role of Hydrogen in the Integration Analysis

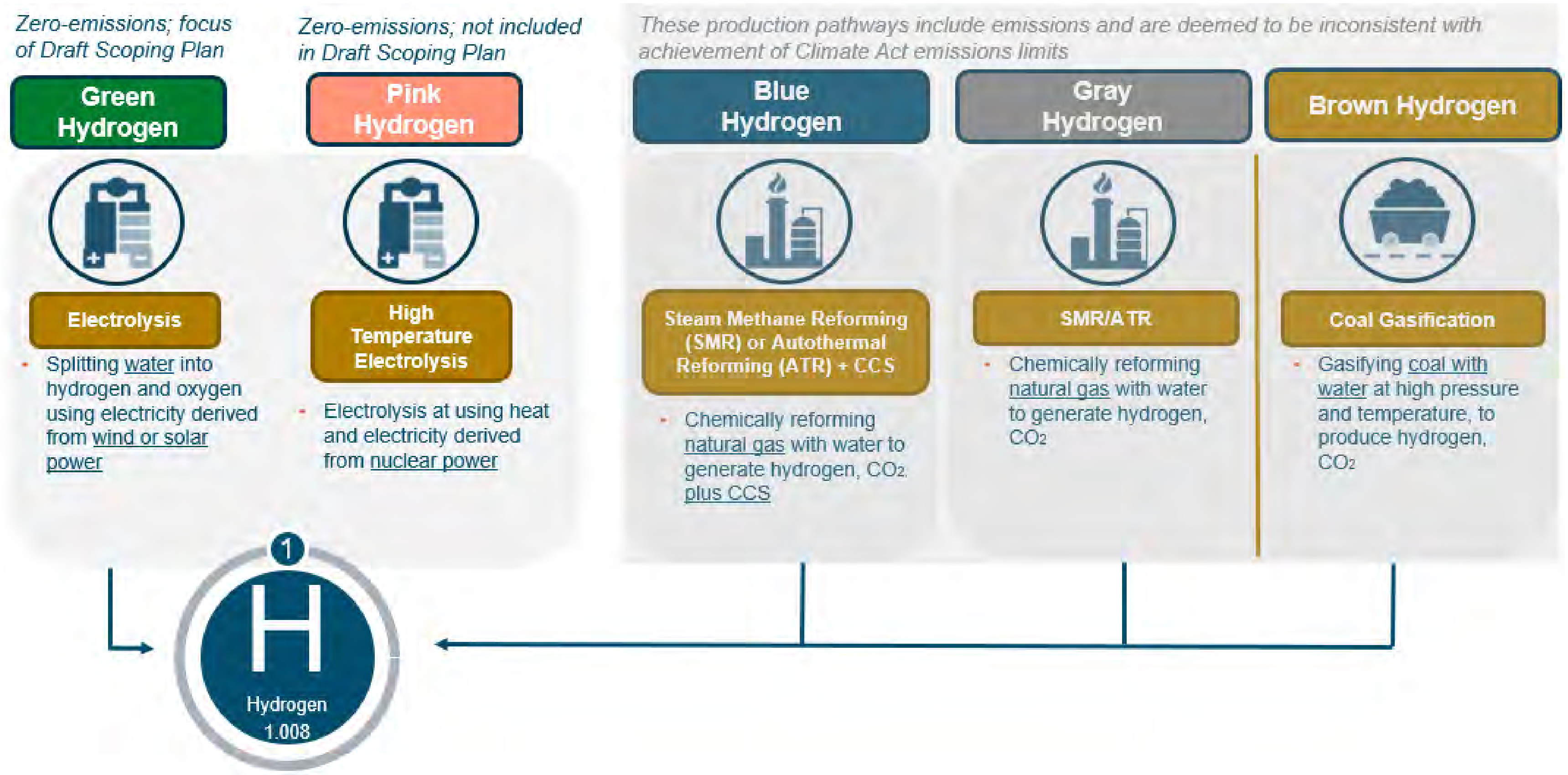
- Hydrogen can play critical role in decarbonizing hard-to-electrify applications
- In near-term, NY may need to spur initial adoption of hydrogen to help decarbonize:
  - Medium and heavy-duty vehicles
  - High-temperature industrial applications
- In longer term, low-carbon fuels may support decarbonization of:
  - District heating systems
  - Non-road transportation
  - Power generation



Overview of Hydrogen Production Methods

Applicability in Climate Act

> Focus of Draft Scoping Plan was on zero-emissions hydrogen to achieve carbon neutrality by 2050

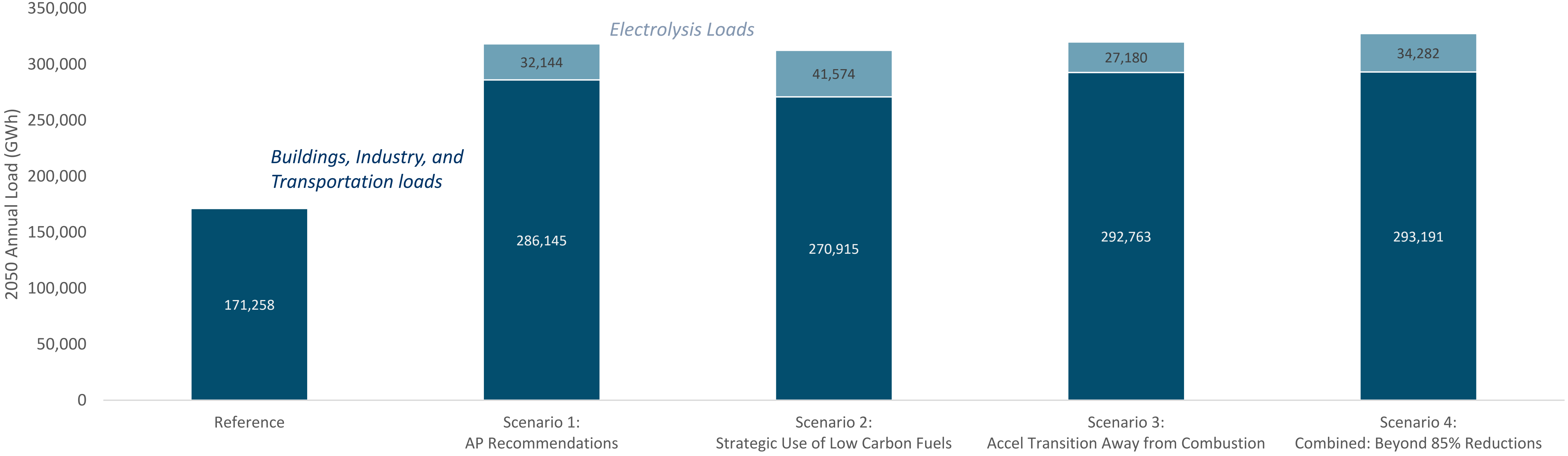


Note: Hydrogen is colorless and odorless at standard conditions; these color codes are just shorthand for production pathway

Annual Loads

Impacts of Electrolysis Loads by 2050

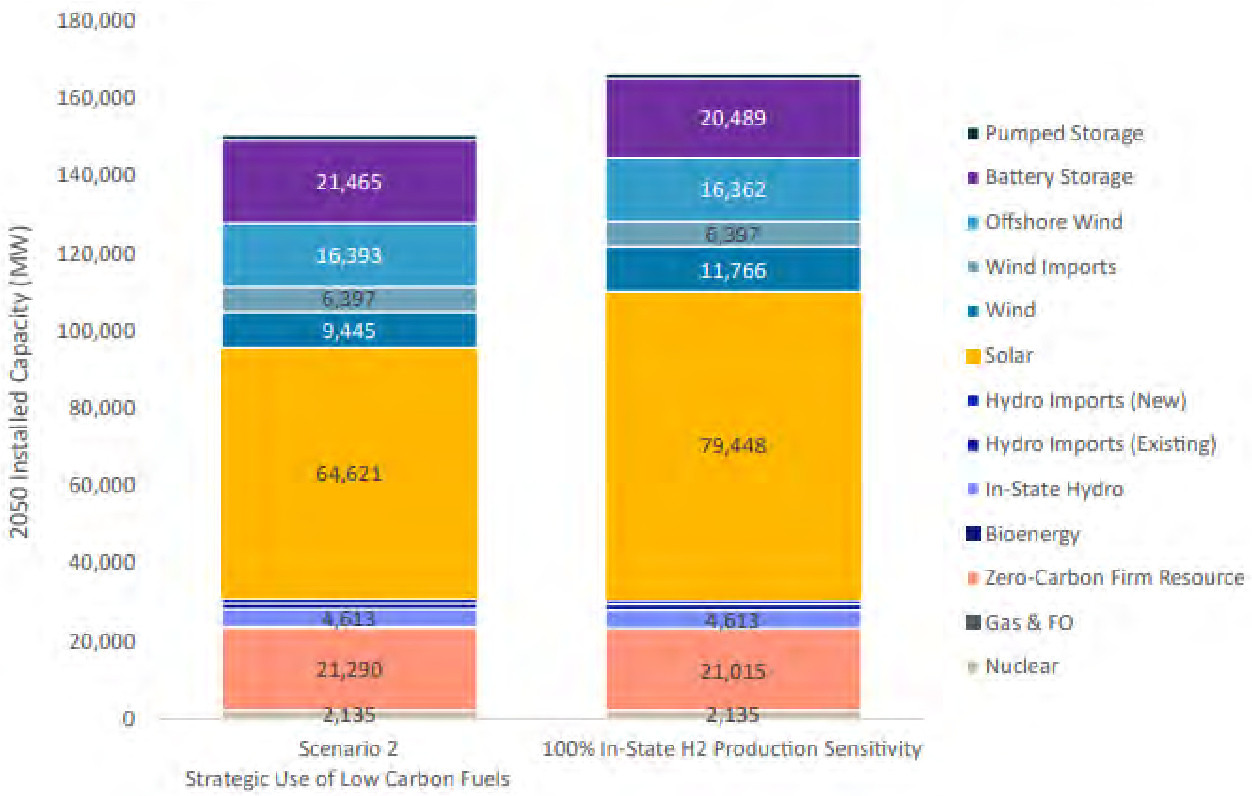
- > Analysis assumes that 50% of New York's hydrogen demand must be supplied with in-state electrolysis loads
  - 100% supply of H2 with in-state electrolysis loads explored as an additional sensitivity analysis, which more than doubles electrolysis demand by 2050
- > Electrolysis loads are significant contributor to total loads by 2050 across all Mitigation scenarios (27-42 TWh)
- > Electrolysis is modeled as a highly flexible end use that does not contribute to peak loads



Note: this slide has been updated to reflect a minor update to load forecasts in Scenarios 3 and 4.

Impacts of Electrolysis on Resource Builds

- > Electrolysis loads are modeled as highly flexible and can absorb renewable curtailment, but additional dedicated renewable resources are also needed at this scale
- > Sensitivity examined impacts of producing 100% of New York’s hydrogen demand with in-state renewables
- > Required 14.6 GW of new solar resources and 2.3 GW of new land-based wind resources

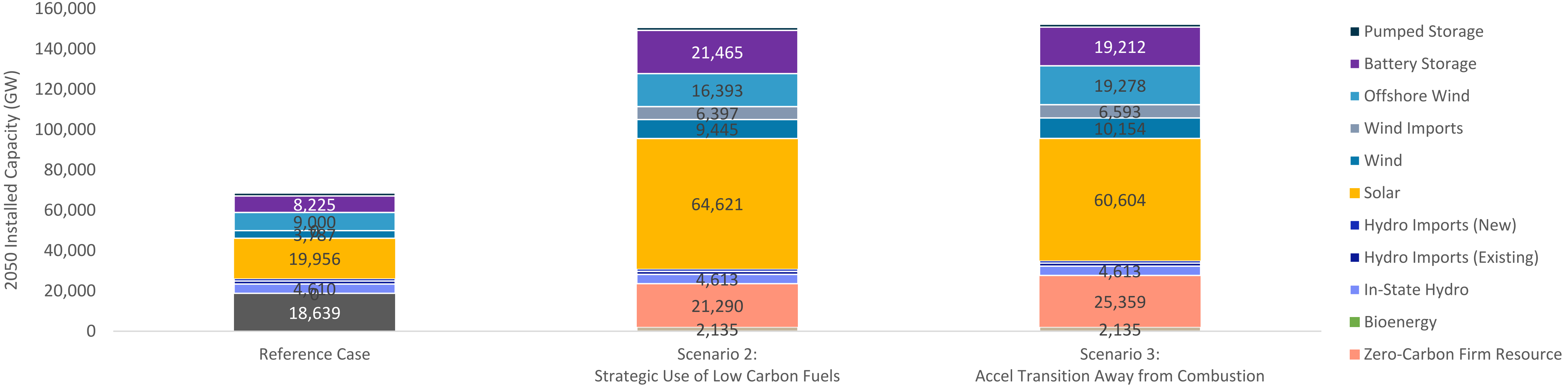


Hydrogen as Long Duration Storage Medium

Electricity Generation

Comparison of 2050 Installed Capacity

- In these Scenarios, firm capacity is provided by hydrogen resources to meet multi-day reliability needs, ranging from 21-25 GW
- Significant expansion of foundational resources (wind, solar, and storage) is needed across scenarios
  - Offshore wind: 16-19 GW
  - Land based wind: 16-17 GW
  - Solar: 61-65 GW
  - Storage: 19-21 GW

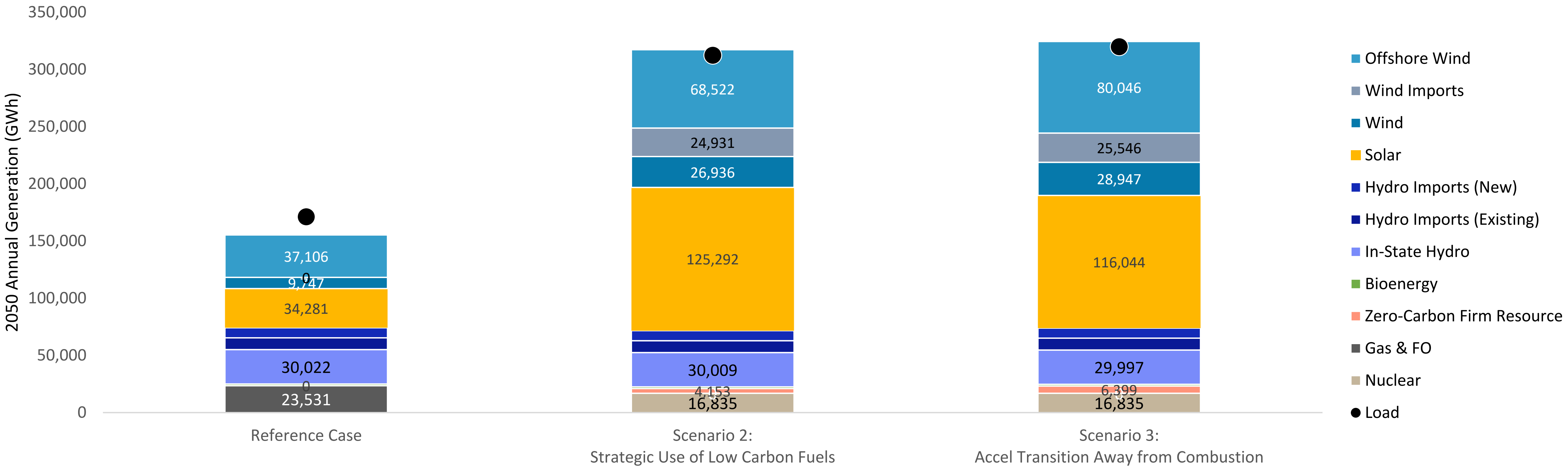


Note: In Scenario 3, existing fossil fuel resources are retired by 2040 and no new combustion-based (CCGT or CT) capacity is permitted. New firm capacity is provided by a combustion-free resource (e.g. hydrogen fuel cells).

Electricity Generation

Comparison of 2050 Annual Generation

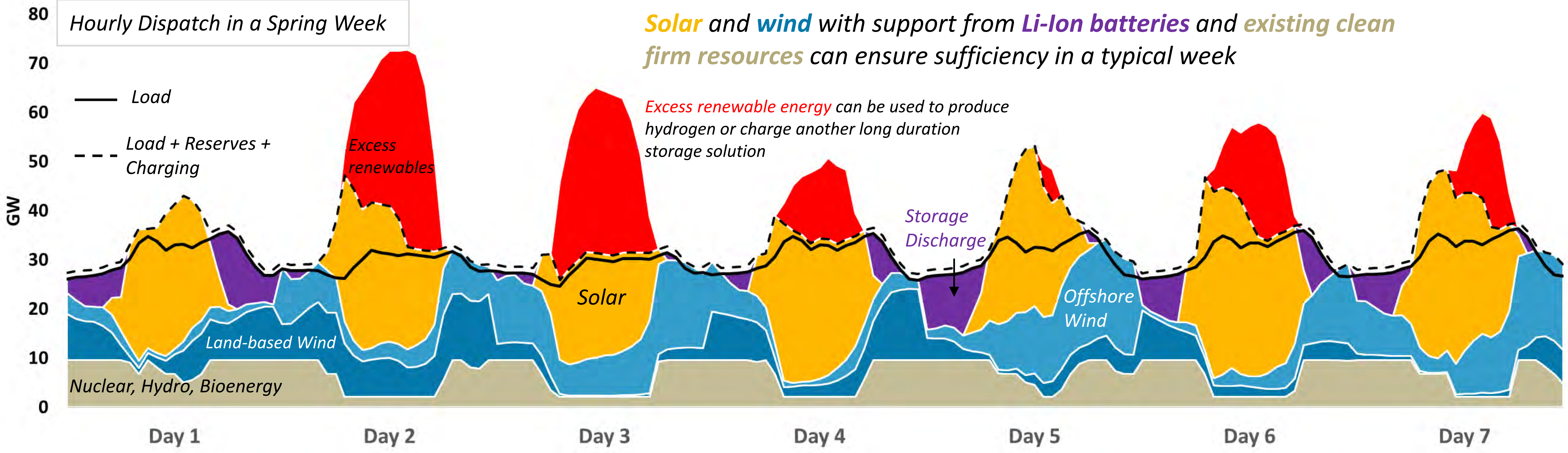
> Share of annual generation across mitigation scenarios:
- Solar: 36-40%
- Wind: 39-42%
- Zero-carbon firm resource: 1-2%

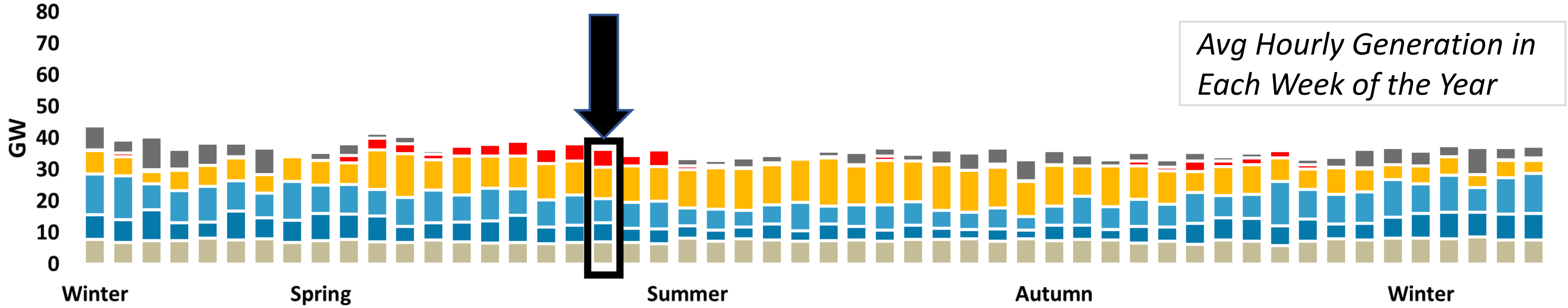


Typical Spring Week in 2050

Scenario 3

Solar and wind with support from Li-Ion batteries and existing clean firm resources can ensure sufficiency in a typical week

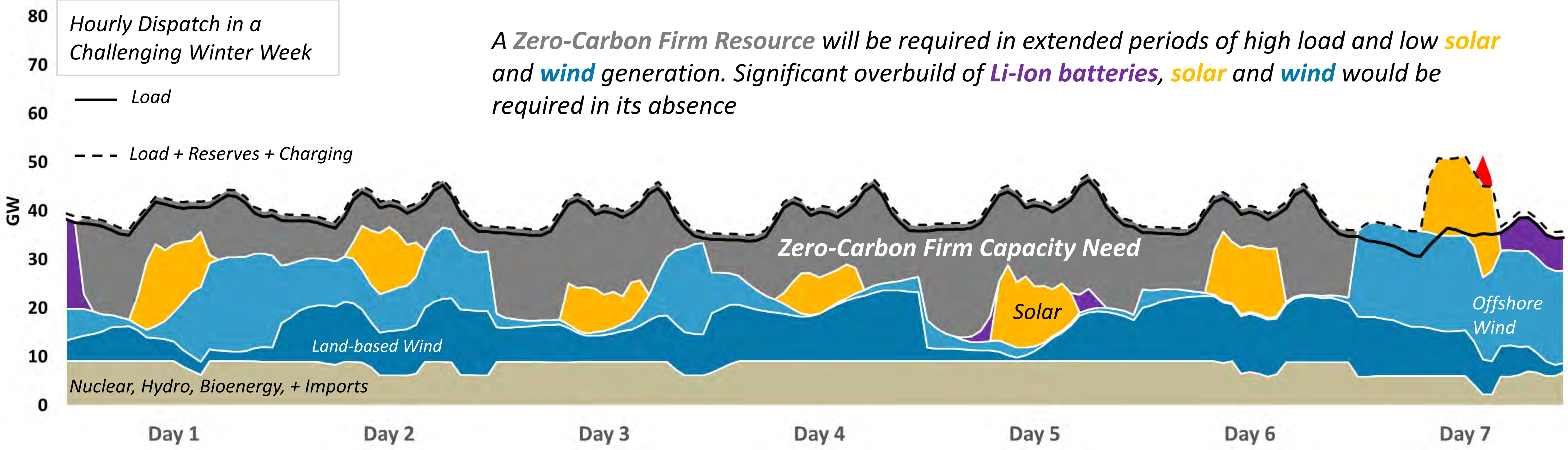


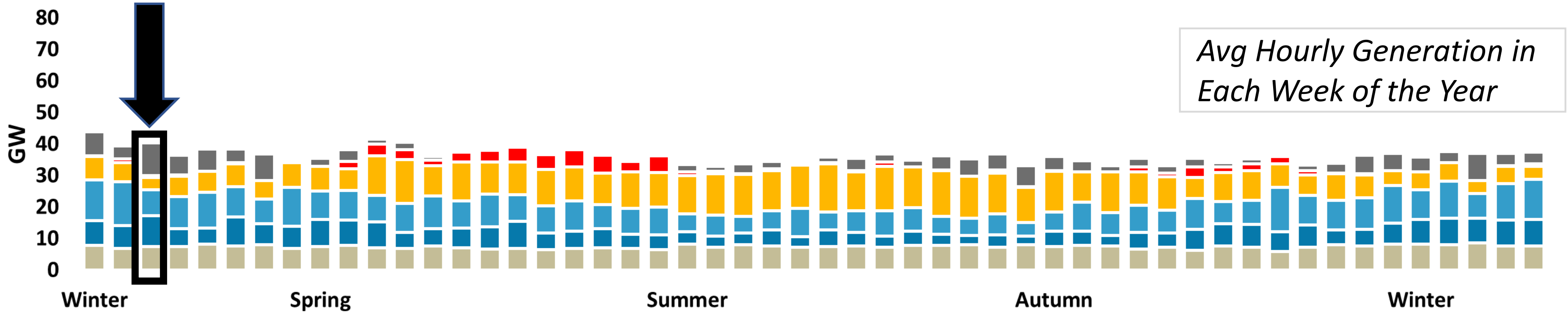


Multi-Day Reliability Needs in 2050

Scenario 3

*A **Zero-Carbon Firm Resource** will be required in extended periods of high load and low **solar** and **wind** generation. Significant overbuild of **Li-Ion batteries**, **solar** and **wind** would be required in its absence*





Hydrogen in NYS: Activities & Programs

NYS H_2 Planning Activities

Hydrogen Opportunity and Strategy Study

- Compile foundational and baseline information and data
- Evaluate production & end-use opportunities for clean hydrogen

H_2 Policy Options Analysis

- Catalogue and evaluate hydrogen policy and incentive options
- Analyze potential impacts, pros/cons to inform decision making

H_2 Economic Development & Supply Chain Analysis

- Market analysis examining potential economic opportunities and impacts
- Assess applications and workforce requirements across H_2 value chain

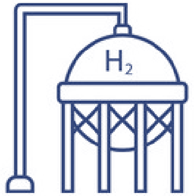
Center for Hydrogen Safety

- Enables access to an expert Hydrogen Safety Panel for safety review
- Provides access to information and best practices on hydrogen safety

HyBlend Collaborative

- Identifying principles of operation of blended hydrogen/natural gas delivery system
- Evaluating the use of existing natural gas infrastructure for hydrogen

NYS H_2 Planning Activities (cont.)



Long Duration Energy Storage

- ❑ Encourage product development & demonstration projects targeting 6+ hours of storage
- ❑ Applicable technologies include hydrogen, mechanical, thermal, and others

Danish Ministry of Energy, Utilities and Climate

MOU with Danish Ministry

- ❑ Collaborate and exchange information on decarbonization solutions
- ❑ Focus on carbon capture, utilization, storage & green hydrogen

Stakeholder Engagement & Education

- ❑ Looking to engage with and understand perspectives from across the stakeholder landscape
- ❑ Aim to provide programming & forums that are relevant and responsive to stakeholder priorities, interests, and concerns

NYS H_2 Planning Activities (cont.)

- **Governor Hochul's 2022 State of the State signaled a commitment to bolstering clean hydrogen in NYS, including:**
  - Intention to **compete for ~$10 billion in federal funding for hydrogen**, including $8 billion for hydrogen hubs.
  - Development of a **hydrogen regulatory framework** to measure emissions reduction and health benefits, as well as development of **codes and standards**.
  - Focus on **clean hydrogen fuel cell microgrids**, aiming to replace fossil fuel backup systems
  - Deployment of $27 million in **Hydrogen Innovation funding** through competitive solicitations
  - Development of a proposal for a clean hydrogen demonstration focused on **district heating & cooling**
  - Support **industry collaboration** and clean hydrogen **firm expansion** in NYS

Federal Funding Opportunities for H_2:

Infrastructure Investment & Jobs Act allocated $9.5 billion for hydrogen-related activities and infrastructure development:

$8B for at least 4 regional clean hydrogen hubs

- 5 years: 2022-2026
- Program purpose: Develop regional/federal networks of connected hydrogen producers, consumers, and connective infrastructure; focus on building a diverse portfolio in terms of energy sources, applications, and regionality

$1B for electrolysis RD&D

- 5 years: 2022-2026
- Program purpose: to improve the efficiency, increase the durability, and reduce the cost of producing clean hydrogen using electrolyzers.

$500M for clean hydrogen process manufacturing & recycling R&D

- 5 years: 2022-2026
- Program purpose: to increase the reuse and recycling of clean hydrogen technologies.

NYS H_2 Planning Activities

In late-March, Governor Hochul announced a multi-state agreement to develop a proposal for a Northeast Regional Hydrogen Hub, noting:

- Collaboration with New Jersey, Connecticut, and Massachusetts
- 40+ early-stage partners from across the hydrogen ecosystem

As of late-May, the Hydrogen Hubs funding opportunity remains outstanding, and is expected to be shared in late-Summer/early-Fall!

Q&A

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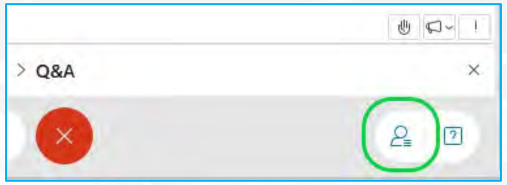


Climate & Environmental Justice Considerations

Fireside Chat:

Climate & Environmental Justice Considerations

Participants:

- **Josh Berman, Sierra Club**
  Senior Attorney, Environmental Law Program
- **Meagan Burton, Earthjustice**
  Senior Attorney

Relevant/Referenced Material:

- **Earthjustice Report: "Reclaiming Hydrogen for a Renewable Future"**
- **Sierra Club: Hydrogen: Future of Clean Energy or a False Solution?**

10-Minute Break!

Returning at ~11:05 AM for:

Primer Session:
Hydrogen Production Overview

Hydrogen Production Overview

Mark Ruth

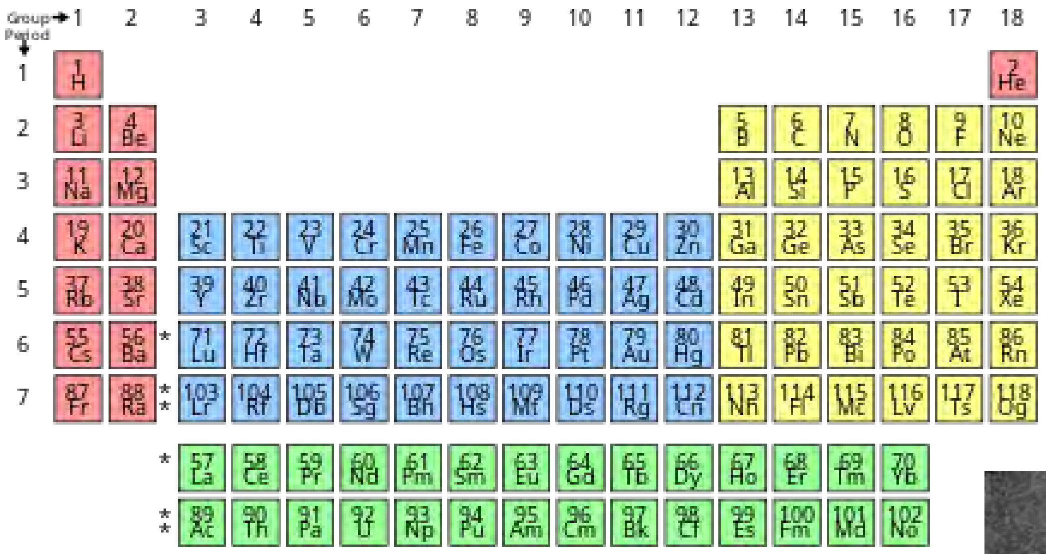
May 31, 2022

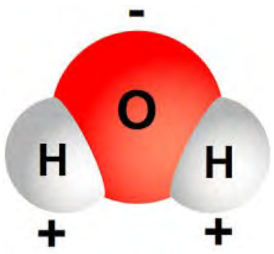
Overview

- Hydrogen Background
- Hydrogen in the United States
- H2@Scale
- Hydrogen Production Technologies and Carbon Intensities
- Department of Energy Targets and Funding

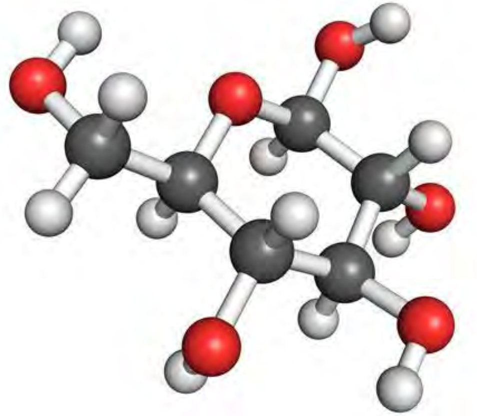
Hydrogen Background

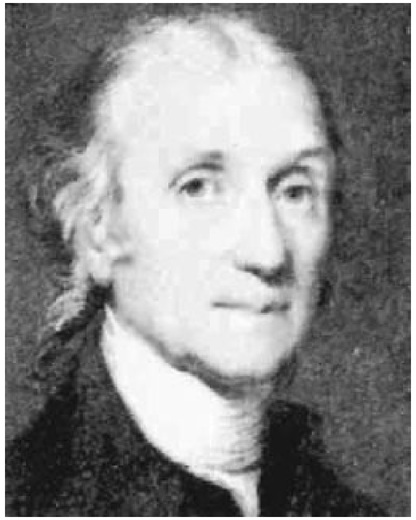
- Hydrogen is the smallest and simplest element (atomic number 1 and atomic weight 1.00794)
- Hydrogen is the most abundant element in the universe (≈75% of normal matter)
- Hydrogen fusion is the dominant process that generates energy in stars
- On earth, hydrogen atoms are almost all contained in more complex molecules
- Robert Boyle produced hydrogen gas in 1671 (experimenting with iron and acids) but no one realized that it was a distinct element before 1766 (Henry Cavendish)
- Like electricity, hydrogen is an energy carrier
- Michael Faraday discovered electrolysis in 1800 and Sir William Robert Grove is credited with creating the first hydrogen fuel cell a few years later
- Jules Verne imagined a hydrogen future in *The Mysterious Island*





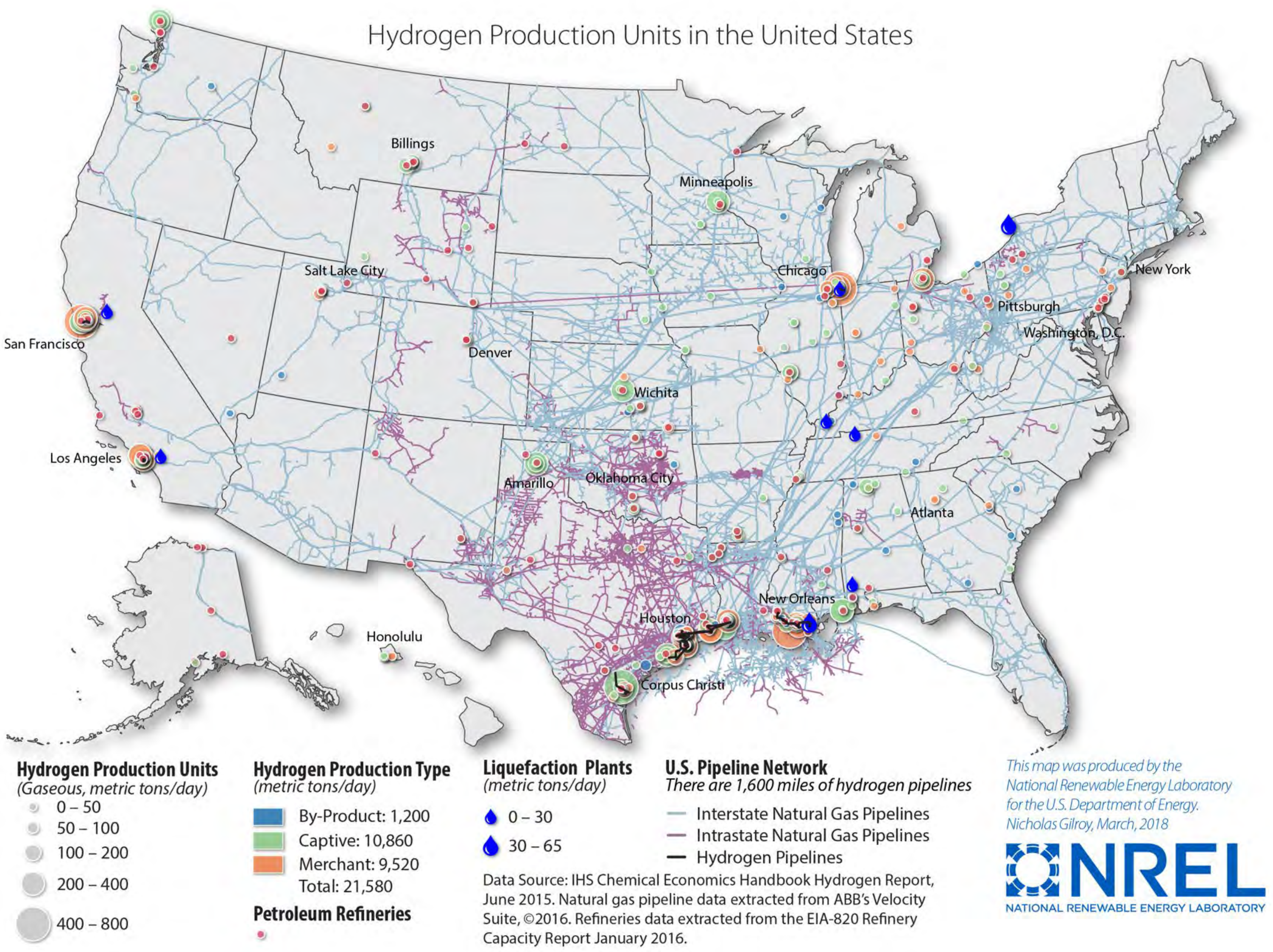
Water molecule


Glucose molecule


Henry Cavendish

Current Hydrogen Energy in the U.S.

- ≈10 MMT H_2/yr primarily for oil refining and ammonia production
- Almost all the hydrogen is produced by reforming natural gas which requires about 2 quad natural gas annually: ≈2% of total energy use
- The U.S. has ≈1600 miles of hydrogen pipelines including ≈40 miles in the L.A. Basin



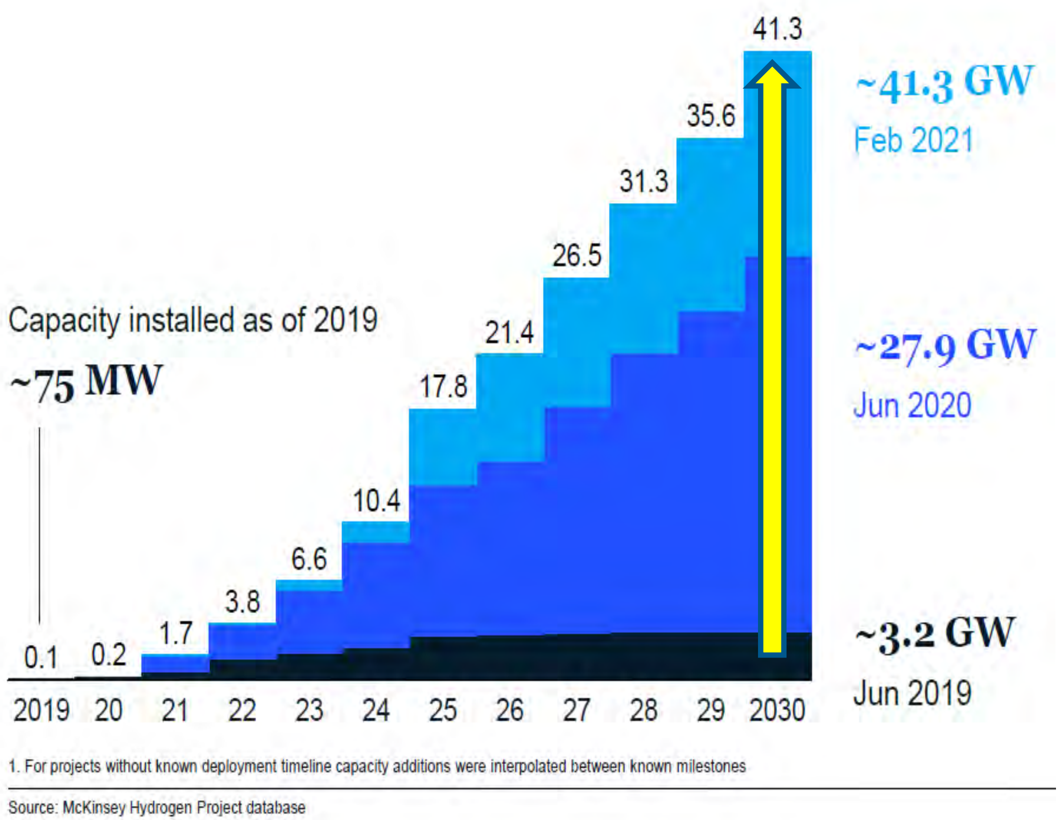
Recent Increased Interest in Hydrogen: Global Drivers

✓ **Low-cost renewables** are now available

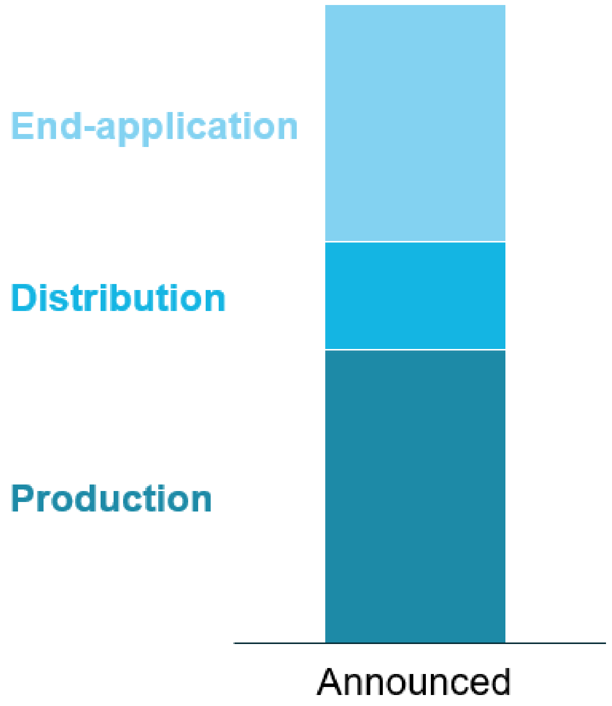
✓ **Countries see clean H_2 can help meet climate goals**

- Hard to decarbonize sectors
- Energy storage
- Import/export opportunities

200-fold electrolyzer growth by 2030
Over 40 GW planned



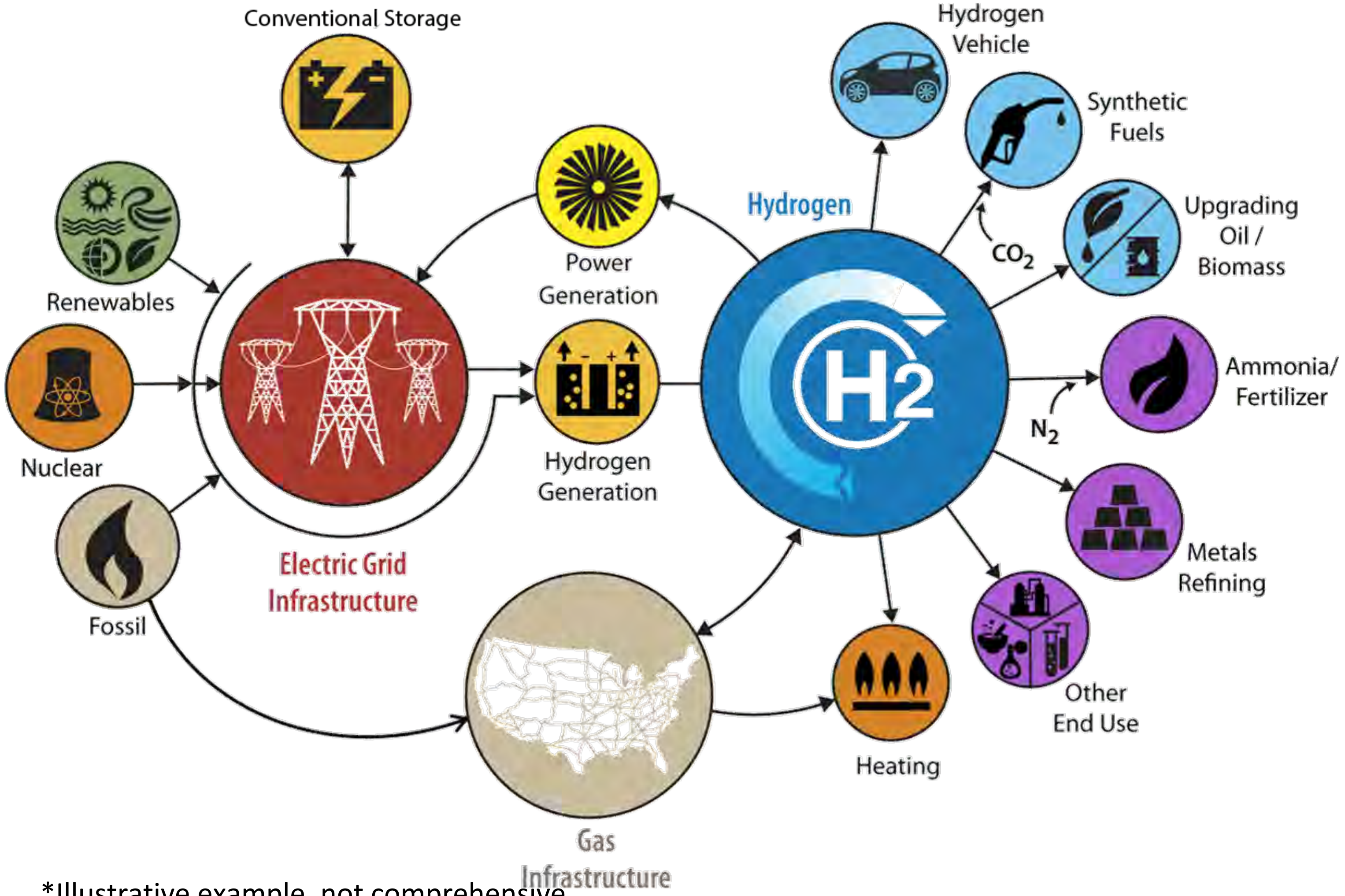
$80B Global Government Funding. 6X More with Private Sector through 2025



Source: McKinsey, H2 Council, Spring 2021
(From Sunita Satyapal, HFTO)

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

H2@Scale and Hydrogen's Potential



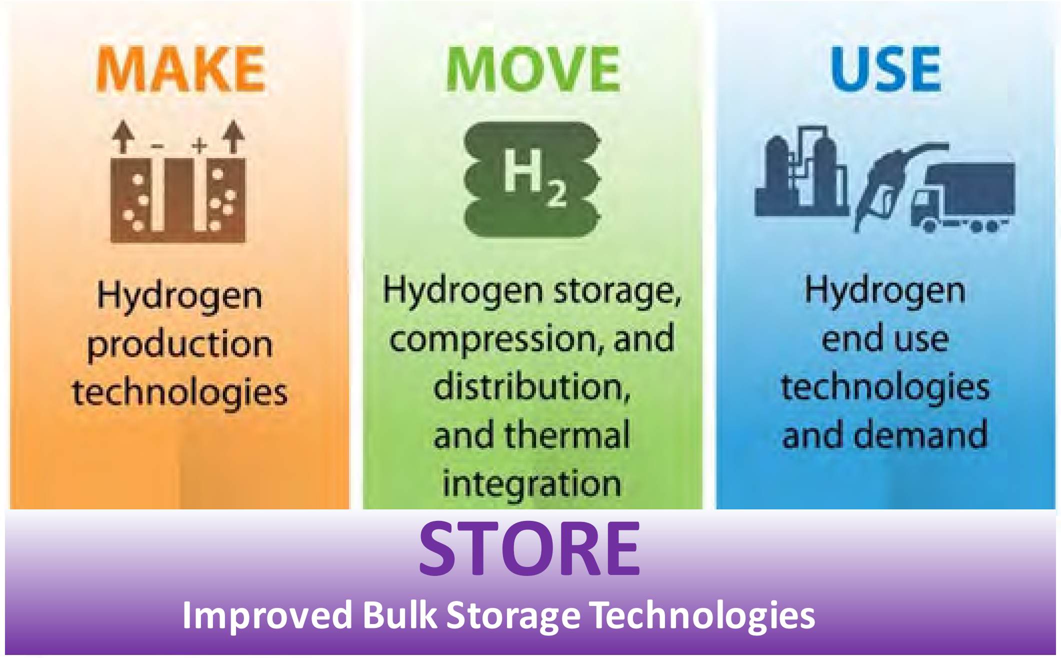
*Illustrative example, not comprehensive

Current DOE focus is moving to hydrogen as an energy carrier and in additional chemical operations

DOE is Investing in RD&D Across the Hydrogen Supply Chain

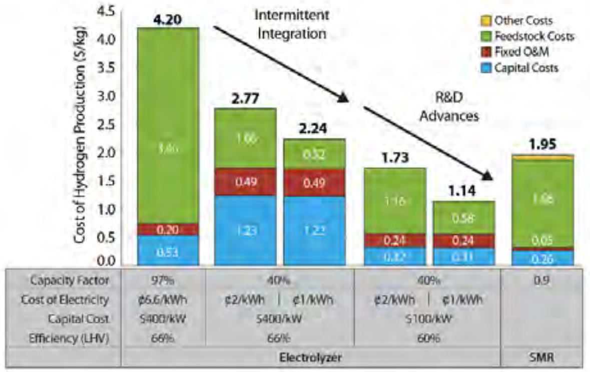
DOE is focused on developing technologies to make, move, use, and store hydrogen and cost-sharing deployment of systems that integrate the four areas.

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



Preliminary

Use	Potential MMT/yr
Refineries & CPI	8
Metals	6
Ammonia	5
Methanol	1
Biofuels	1
Natural Gas	7
Light Duty Vehicles	28
Other Transport	3
Electricity Storage	28
Total	**87**



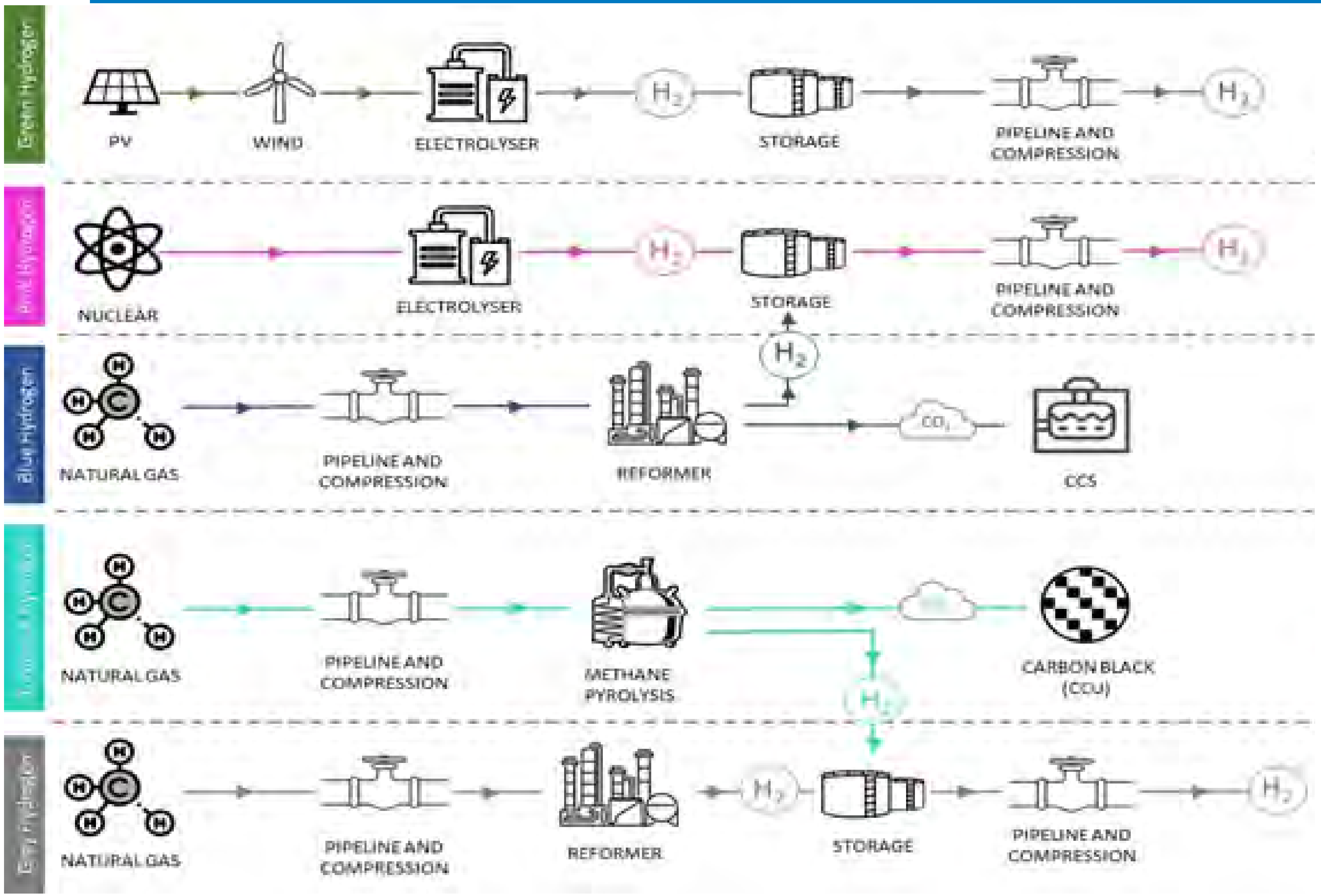
Decreasing cost of H_2 production

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

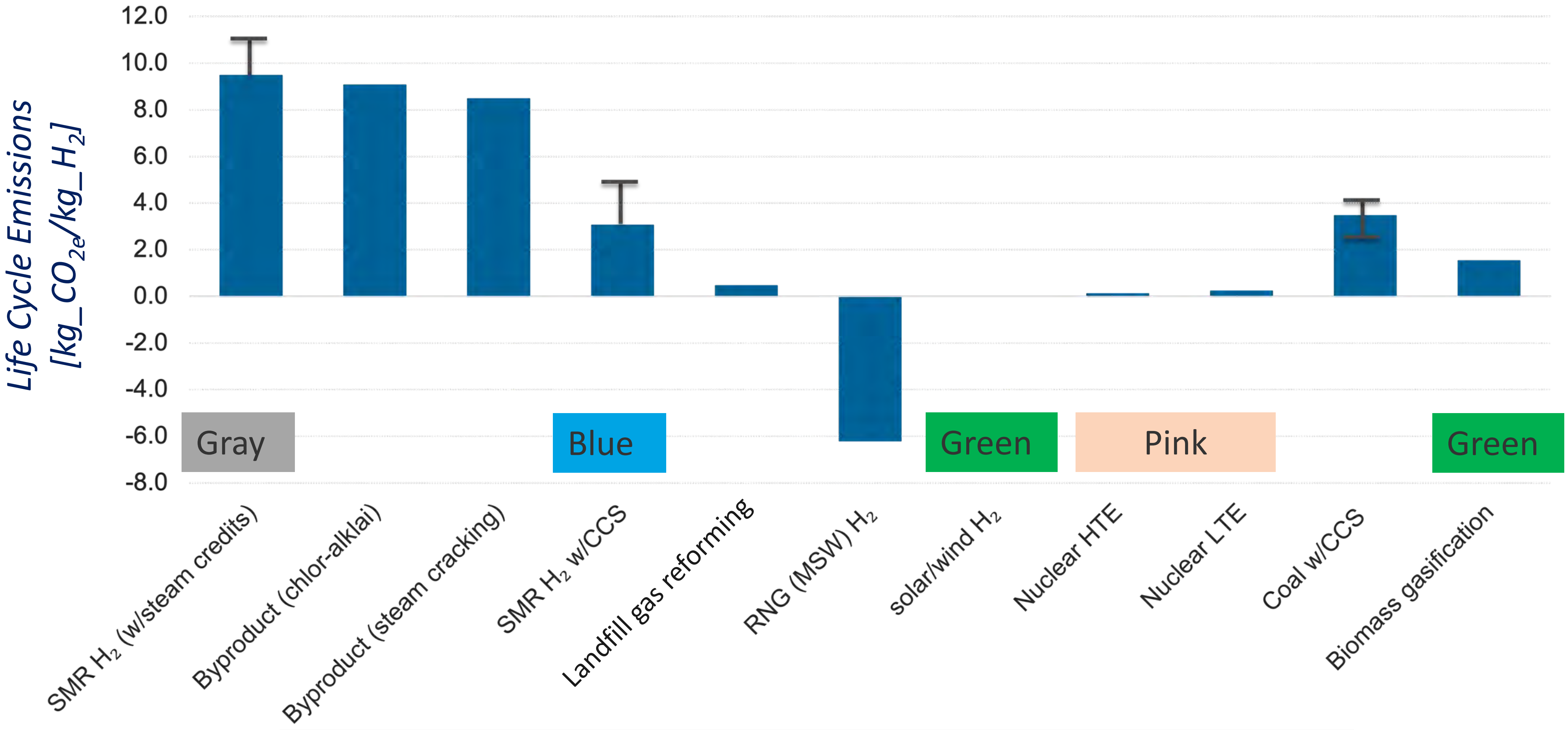
Hydrogen Production Technologies



A number of alternative hydrogen production technologies are being developed.

Source: Tanase, Lavinia. "Underpinning the Transition: European Commission Prefers Green H2" (April 21, 2021) https://laviniatanase.medium.com/underpinning-the-transition-european-commission-prefers-green-h2-3a61e7169ecb

DOE Uses Carbon Intensity Instead of Colors to Discuss Environmental Impacts



Ranges shown reflect potential variability in upstream methane leak rates, plant energy efficiency, and CO_2 capture rates. Baseline assumes 90% capture rate

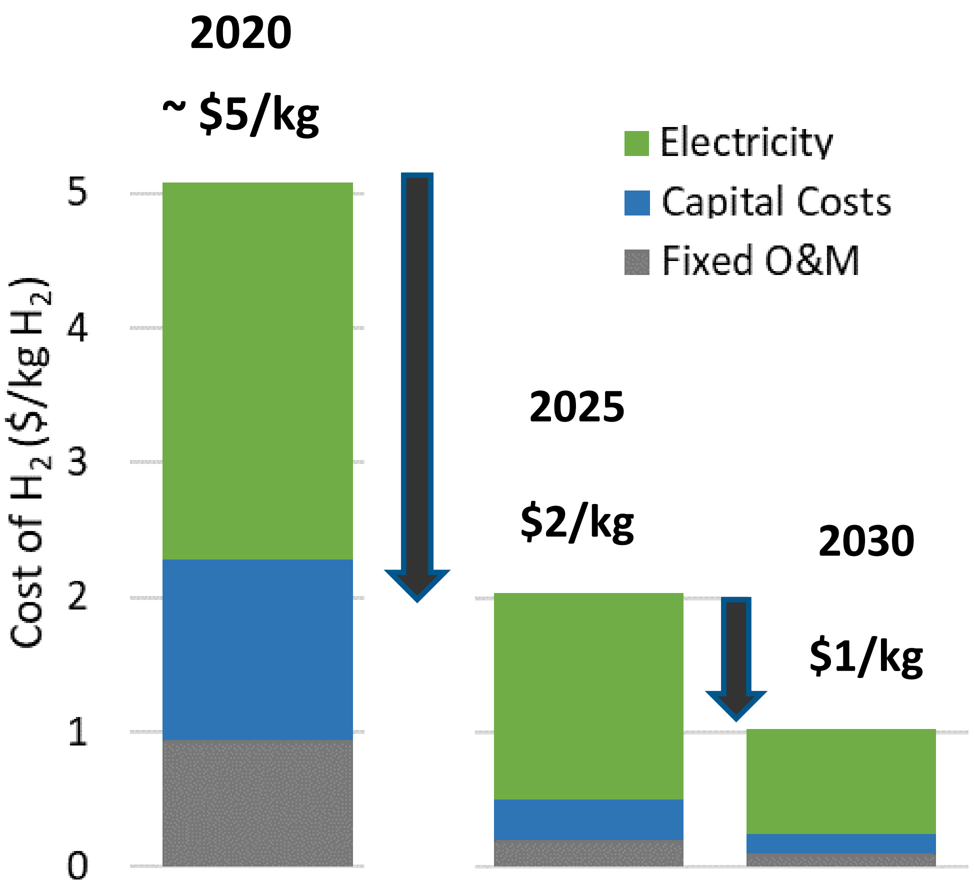
Source: Elgowainy. H2IQ October 28, 2021

Hydrogen Shot: "1 1 1"

$1 for 1 kg in 1 decade for clean hydrogen

Launched June 7, 2021
Summit Aug 31-Sept 1, 2021

Example: Cost of Clean H_2 from Electrolysis



Electrolysis: One of several pathways to reach goals

- Reduce electricity cost from >$50/MWh to
  - $30/MWh (2025)
  - $20/MWh (2030)
- Reduce capital cost >80%
- Reduce operating & maintenance cost >90%

All pathways for clean hydrogen included: Thermal conversion w/ CCS, advanced water splitting, biological approaches, etc.

Bipartisan Infrastructure Law – $9.5B H2 Highlights

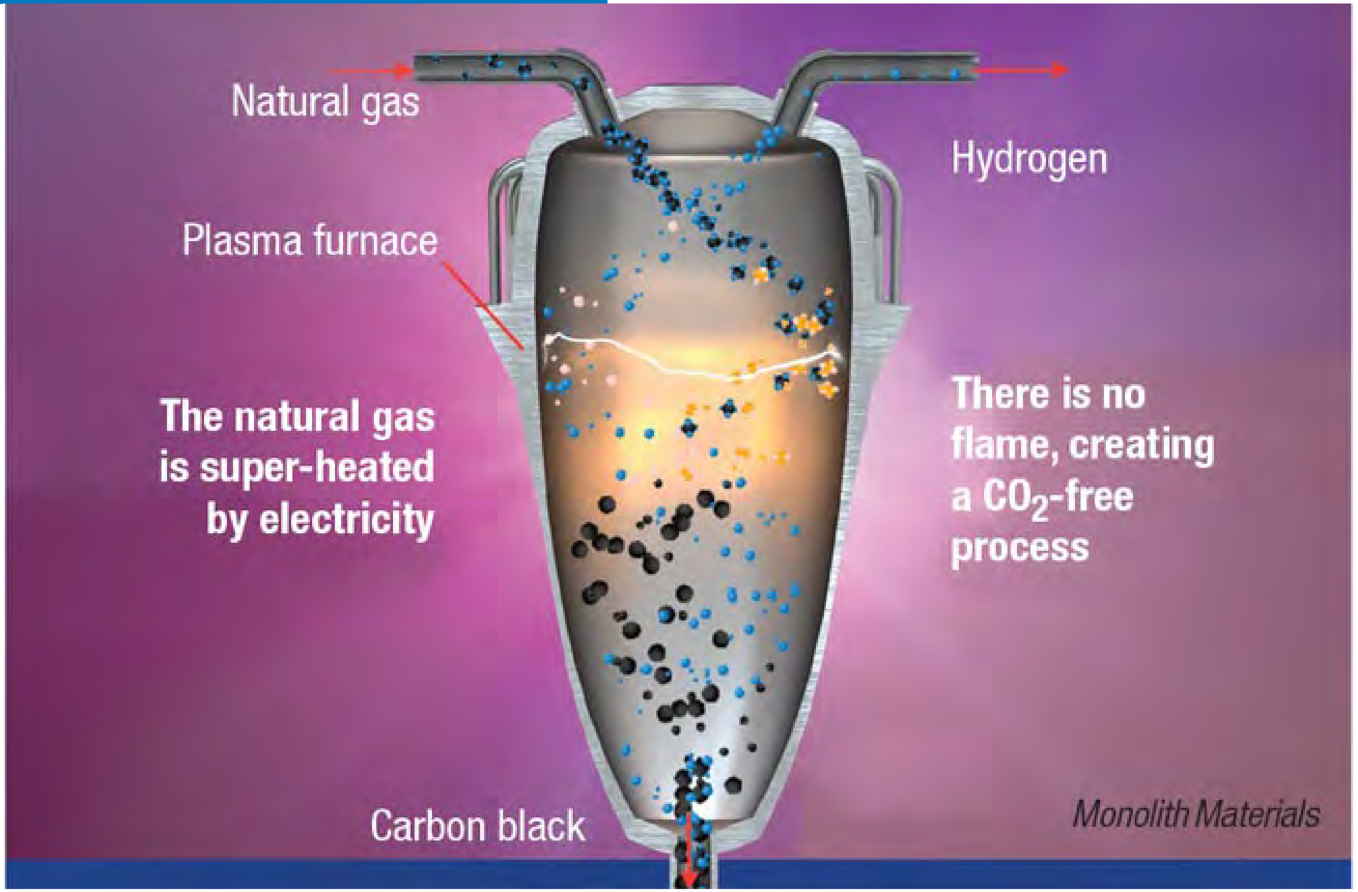
- $8B for at least 4 regional clean H2 Hubs
- $1B for electrolysis (and related H2) RD&D
- $0.5B for clean H2 technology mfg. & recycling R&D
- Aligns with H2 Shot priorities by directing work to reduce cost of clean H2 to $2/kg by 2026
- Requires developing a National H2 Strategy & Roadmap

2020 Baseline: PEM low volume capital cost ~$1,500/kW, electricity at $50/MWh. Need less than $300/kW by 2025, less than $150/kW by 2030 (at scale)

(Adapted from multiple briefing slides from Sunita Satyapal, DOE's HFTO)

Monolith Methane Pyrolysis

- DOE provided conditional approval of a $1.04B loan guarantee for Monolith Nebraska
- Monolith has an offtake agreement with Goodyear Tire & Rubber
- Monolith claims a carbon intensity of 0.45 kg CO_2e/kg H_2 if using renewable electricity



Sources: Image: https://www.chemengonline.com/methane-pyrolysis-process-uses-renewable-electricity-split-ch4-h2-carbon-black/
https://www.eenews.net/articles/doe-unveils-1b-loan-for-hydrogen-plant-but-is-it-clean/#:~:text=On%20Dec.,gas%2C%20known%20as%20methane%20pyrolysis.
https://www.ammoniaenergy.org/articles/monolith-materials-new-deal-with-goodyear-1-billion-loan-from-doe/
https://monolith-corp.com/process-comparison

Advanced Clean Energy Storage (ACES) Project

- DOE issued $504M in loan guarantees for hydrogen storage in Delta, UT
- Recipients: Mitsubishi Power Americas Inc. and Magnum Development LLC
- Design: 220 MW electrolysis and 5,500 tons of H_2 storage
- Agreements with Intermountain Power Plant (1900 MW) with High Voltage DC connection to Los Angeles
- Plant converting from coal to 70% natural gas – 30% hydrogen to 100% hydrogen

Sources: Image https://www.canarymedia.com/articles/hydrogen/massive-green-hydrogen-hub-in-utah-wins-504m-federal-loan-guarantee#:~:text=The%20Advanced%20Clean%20Energy%20Storage,tons%20of%20hydrogen%20a%20day. https://www.eenews.net/articles/doe-unveils-500m-loan-for-massive-clean-hydrogen-project/

Thank you!

www.nrel.gov

Q&A

Please use the
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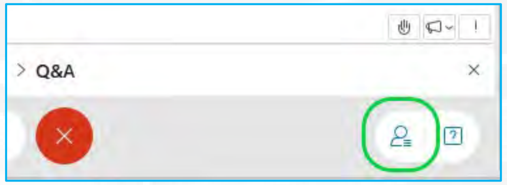


Hydrogen Color Spectrum

Figure 2 – Hydrogen Color Spectrum

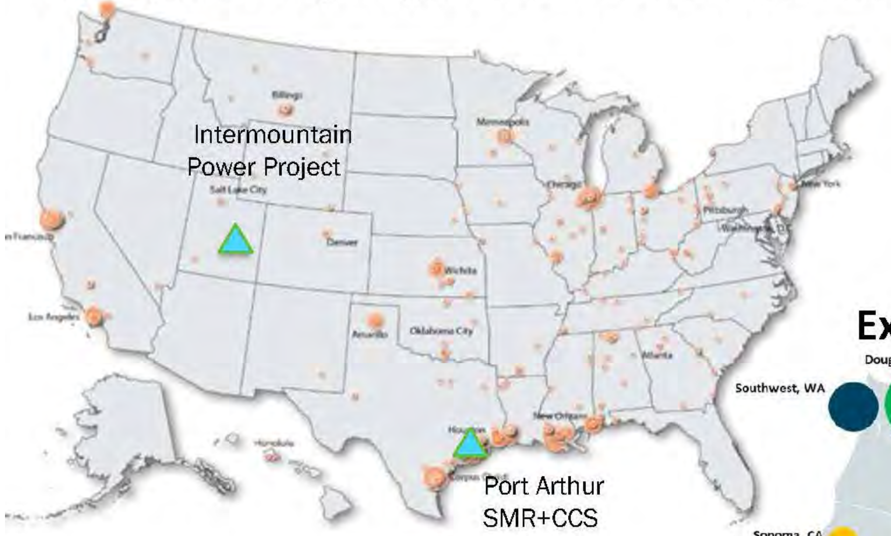
Source: NARUC "Coal and Carbon Management Guidebook: Coal-to-Hydrogen Opportunities and Challenges"(Sept 2021) https://pubs.naruc.org/pub/63211779-1866-DAAC-99FB-C7D38972AEB8

Advanced Hydrogen Production in the U.S.

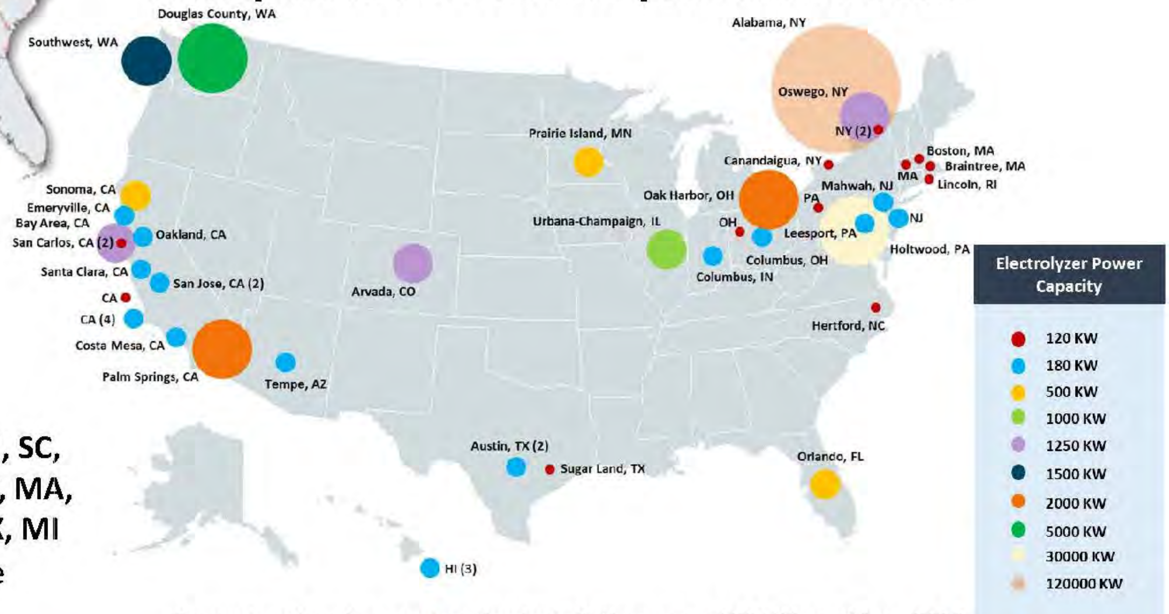
Electrolysis and other technologies are expanding in the U.S.

- 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 Hydrogen Production Locations



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

Source: Satyapal, Sunita "U.S. DOE Hydrogen Production Program & LAWE Meeting" January 26, 2022

H2NEW Hydrogen from Next-generation Electrolyzers of Water

U.S. DEPARTMENT OF ENERGY

Hydrogen Technologies: Electrolyzers and Fuel Cells

Bryan Pivovar, National Renewable Energy Laboratory (NREL)

Date: 5/31/22

NYSERDA Webinar

NREL Transforming ENERGY · INL Idaho National Laboratory · Argonne NATIONAL LABORATORY · BERKELEY LAB Bringing Science Solutions to the World · Lawrence Livermore National Laboratory · Los Alamos NATIONAL LABORATORY EST. 1943 · NATIONAL ENERGY TECHNOLOGY LABORATORY · OAK RIDGE National Laboratory · Pacific Northwest NATIONAL LABORATORY

Relevance – 2020’s Decade of Hydrogen

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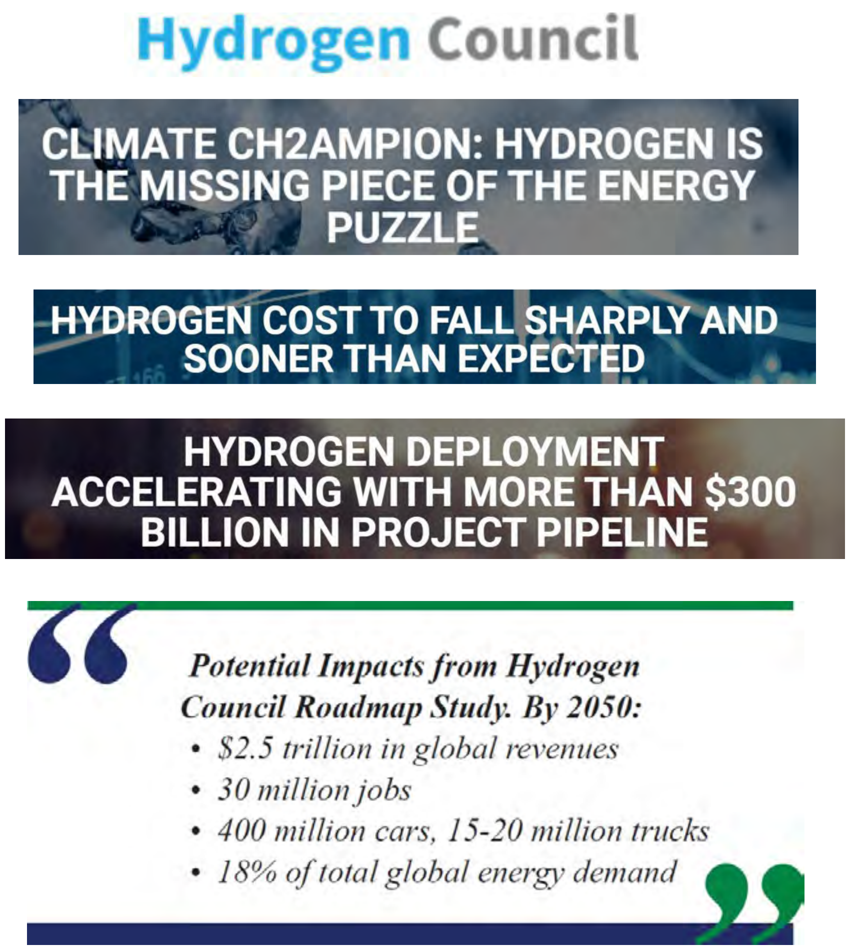

https://hydrogencouncil.com/en/

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.

ECOLAB SCIENCE CERTIFIED

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

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► Says tensions with China won't block aggressive climate action

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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

Now is the time for hydrogen and the “global race” is on

Hydrogen Energy Earthshot

"Hydrogen Shot"

"1 1 1"

$1 for 1 kg clean hydrogen in 1 decade

Launched June 7, 2021

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 and demonstration
  - $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**

https://www.energy.gov/sites/default/files/2021-12/h2iq-12082021.pdf

Fuel Cells/Electrolyzers

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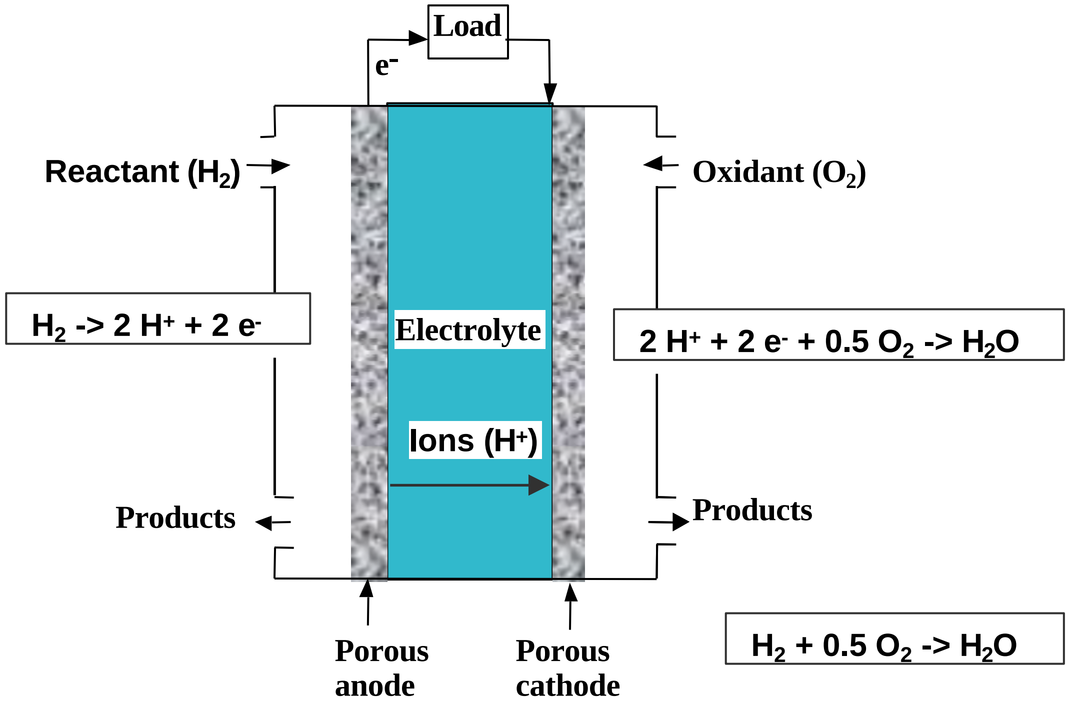
Fuel Cells: electrochemical devices that convert chemical energy directly into electrical energy.

Electrolyzers: electrochemical devices that convert electrical energy directly into chemical energy.

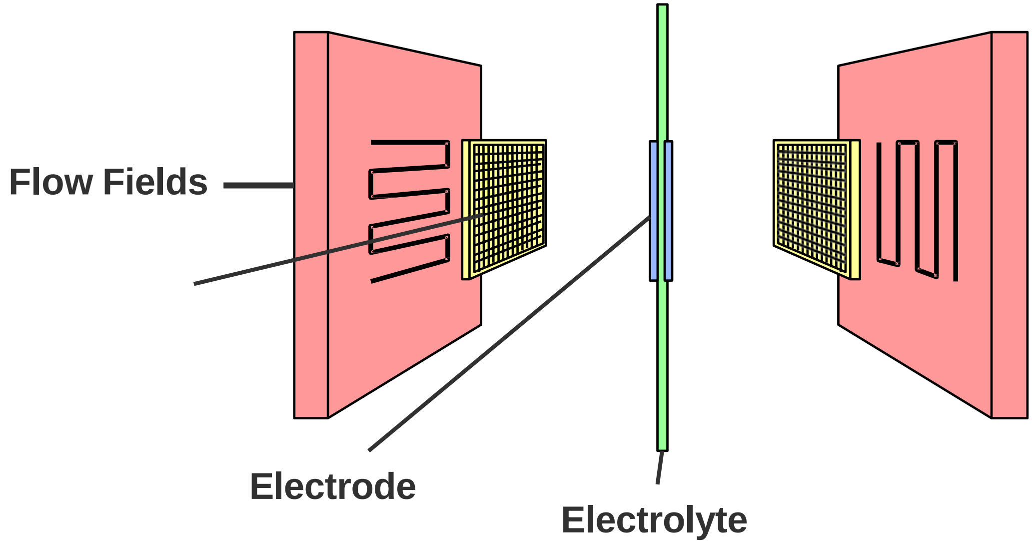


Characterized by electrolyte:

- Polymer Electrolyte
- Alkaline
- Phosphoric Acid
- Molten Carbonate
- Solid Oxide

General Cell/Stack Structure

Single cell



Stack

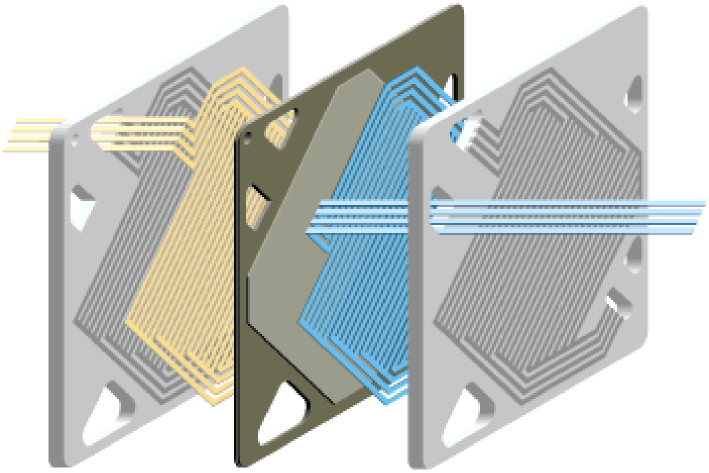
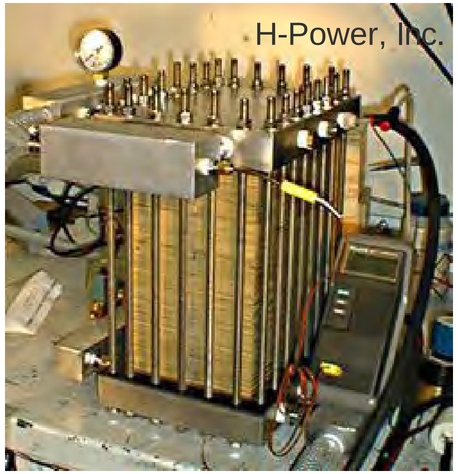
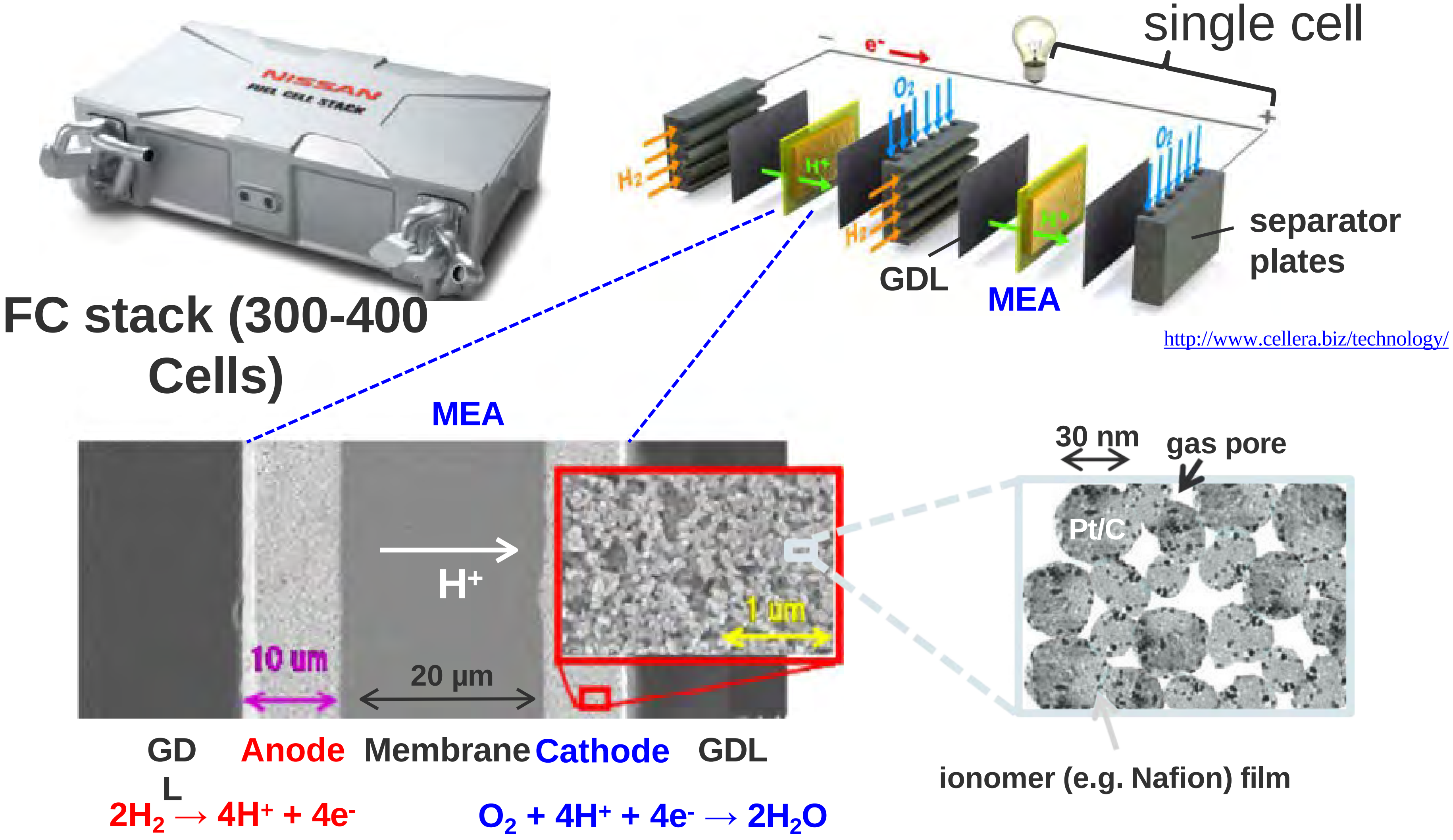


Figure by Ballard Power Systems



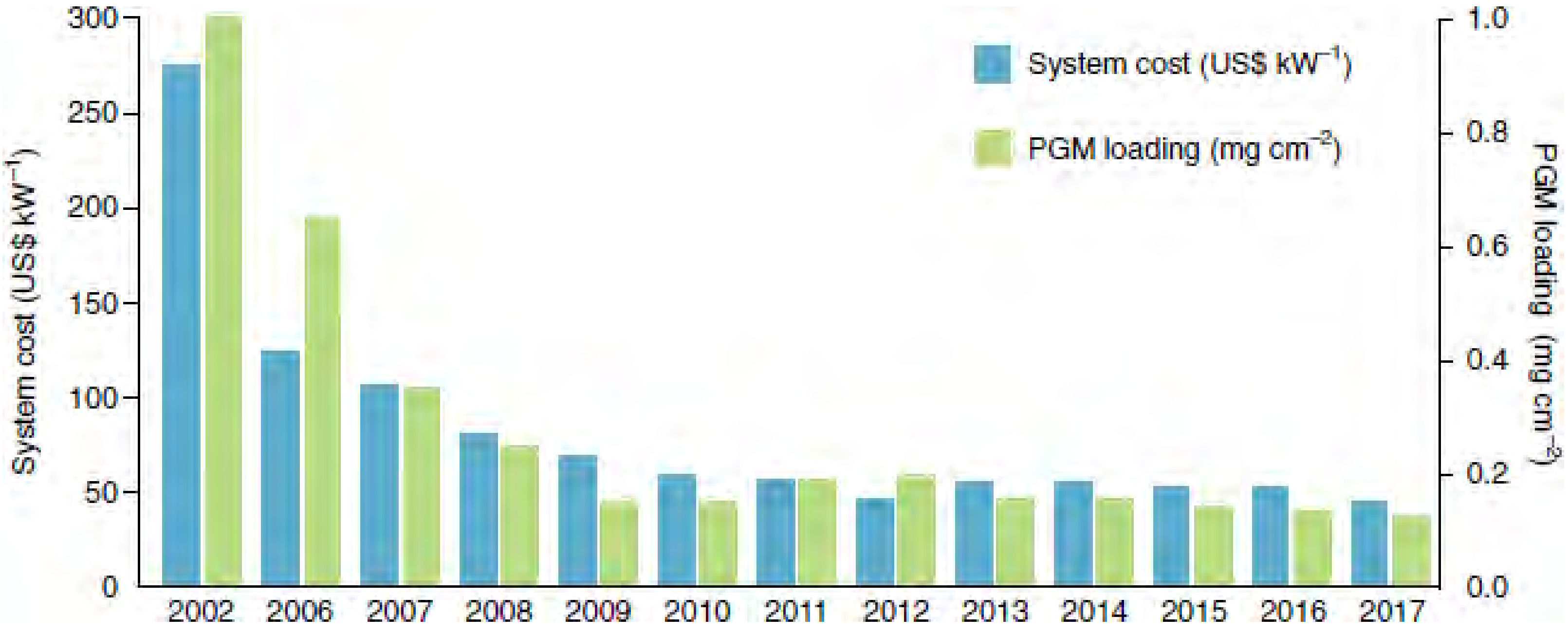
End Use

Membrane Electrode Assembly



Ohma et al., *Electrochim. Acta*, **56**, 10832 (2011)

PEMFC Cost Advances



- Billions in RD&D investments have significantly reduced FC transportation system costs
- They have reached the ability to near parity in light duty vehicle markets
- BEVs have significantly advanced as well
- Scale and supply chain remain challenges.

B. Pivovar, Nature Catalysis, 2, 2019, 562–565.

Use

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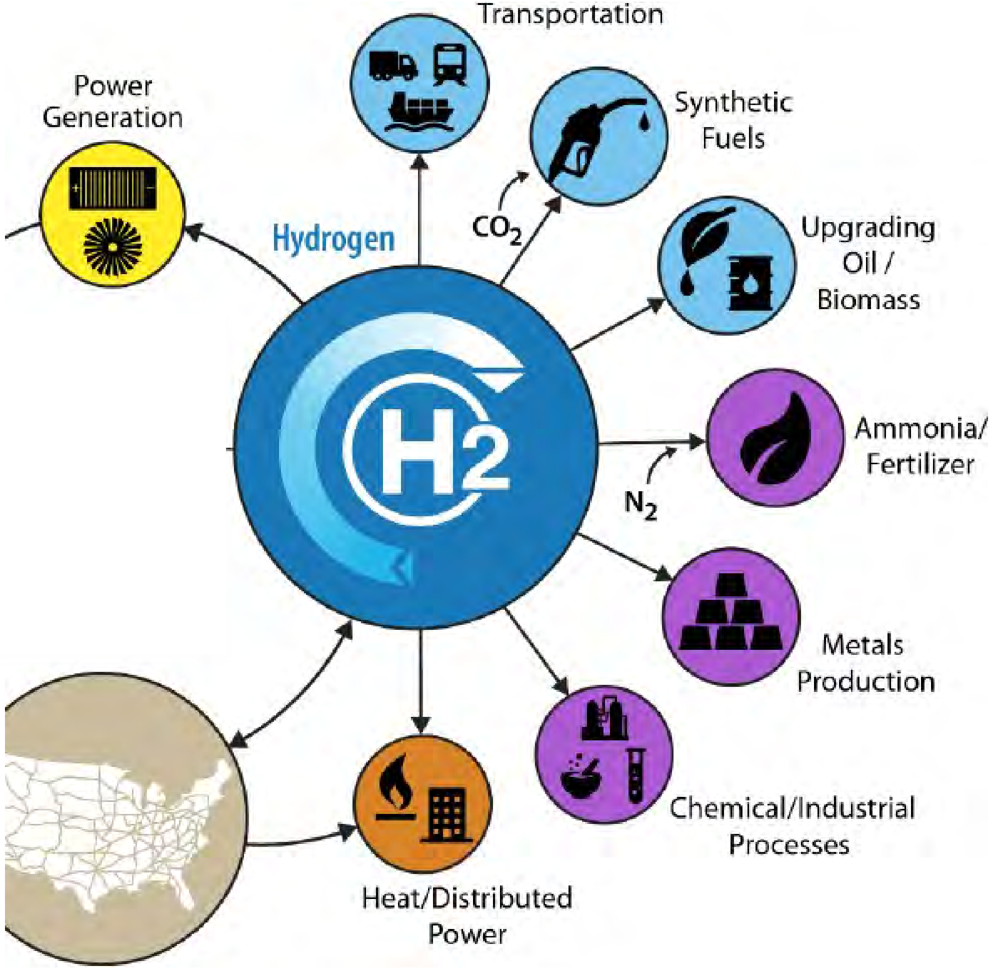


https://www.energy.gov/eere/fuelcells/h2-scale

https://www.nrel.gov/docs/fy21osti/77610.pdf

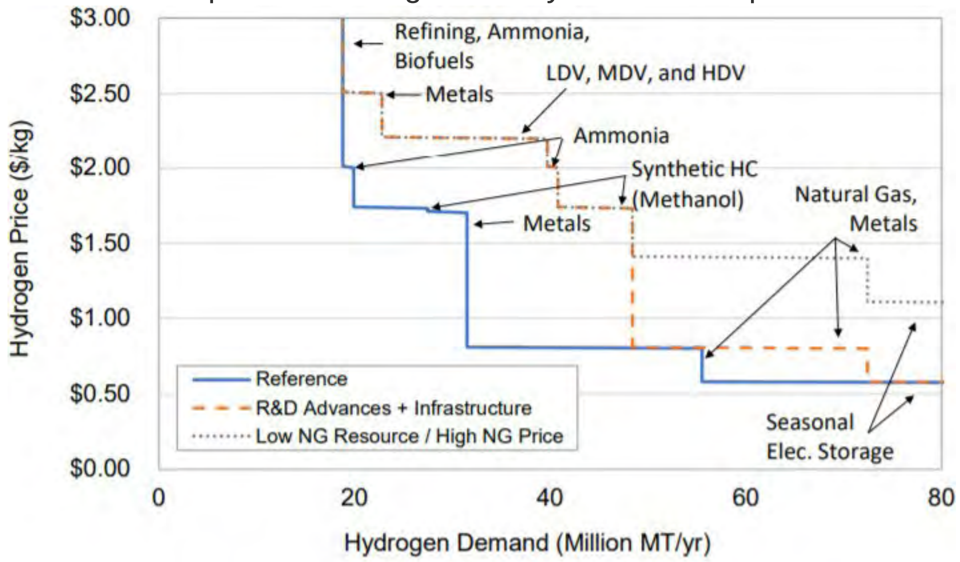
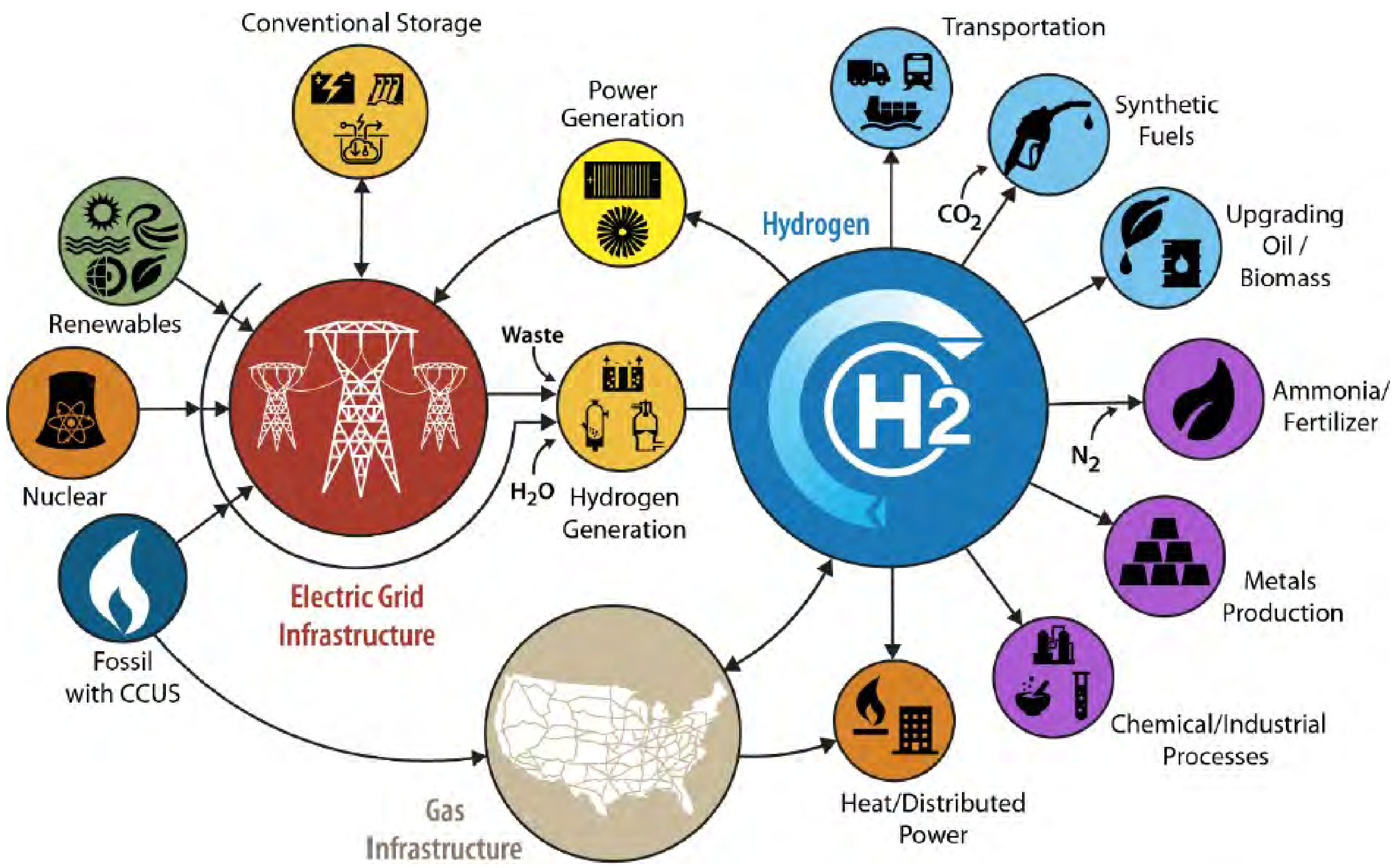


Figure 24. Aggregated demand curves for H2@Scale scenarios

- Transportation and Industry are strongest economic sectors (also difficult to decarbonize)
- Many of the processes are or could be electrochemical
- Difficult or impossible to fully electrify
- R&D needs are significant
  - Fuel Cells (M2FCT), NH3, Steel, burners/turbines

H2NEW connection to H2@Scale



- Making H2 is the inherently obvious, first step to spur the wide-ranging benefits of the H2@Scale vision.
- Electrolysis has most competitive economics and balances increasing renewable generation challenges.

Illustrative example, not comprehensive

https://www.energy.gov/eere/fuelcells/h2-scale

Electrolyzers by Type

Type	Pros	Cons
Alkaline	Well established, lower capital cost, more materials choices at high pH, high manufacturing readiness, can leverage established supply chains, demonstrated in larger capacity	Corrosive liquid electrolyte used, higher ohmic drop, lack of differential pressure operation, shunt currents, limited intermittency capabilities, efficiency
Polymer Electrolyte Membrane	Low ohmic losses/high power density operation, differential pressure operation, DI water only operation, leverages PEM fuel cell development and supply chain, load following capability	Requires expensive materials (Ti, Ir, Pt, perfluorinated polymers), lower manufacturing and technology readiness, efficiency
Solid Oxide	High efficiency, low-cost materials, integration with continuous high temperature electricity sources (e.g., nuclear energy), leverages SOFC development and supply chain, differential pressure operation	High temperature materials challenges, limited intermittency capabilities, thermal integration, lower manufacturing and technology readiness, steam conversion and separation challenges

Low Temperature (0 - 200ºC)

High Temperature (>500ºC)

Badgett, Ruth and Pivovar, "Economic considerations for hydrogen production with a focus on polymer electrolyte membrane electrolysis," accepted 2021.

H2NEW : H2 from Next-generation Electrolyzers of Water

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U.S. DEPARTMENT OF ENERGY

A comprehensive, concerted effort focused on overcoming technical barriers to enable affordable, reliable & efficient electrolyzers to achieve <$2/kg H_2

- Launching in Q1 FY21
- Both low- and high-temperature electrolyzers
- $50M over 5 years

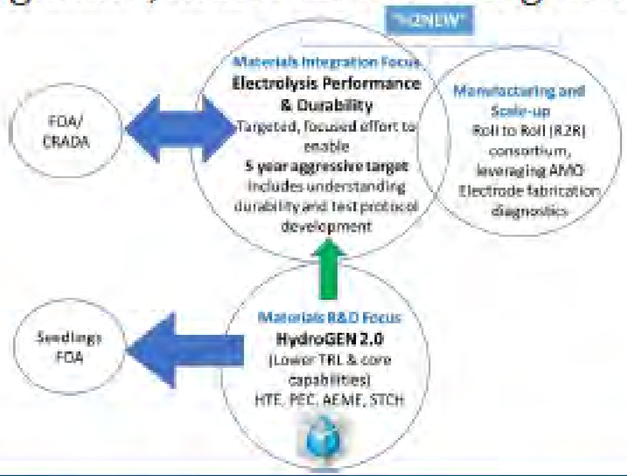
National Lab Consortium Team

NREL National Renewable Energy Laboratory
INL Idaho National Laboratory
Argonne National Laboratory
Berkeley Lab
Pacific Northwest National Laboratory
Los Alamos National Laboratory
Lawrence Livermore National Laboratory
Oak Ridge National Laboratory
NETL National Energy Technology Laboratory

Clear, well-defined stack metrics to guide efforts.

Draft Electrolyzer Stack Goals by 2025		
	LTE PEM	HTE
Capital Cost	\$100/kW	\$100/kW
Elect. Efficiency (LHV)	70% at 3 A/cm^2	98% at 1.5 A/cm^2
Lifetime	80,000 hr	60,000 hr

The focus is not new materials but addressing components, materials integration, and manufacturing R&D

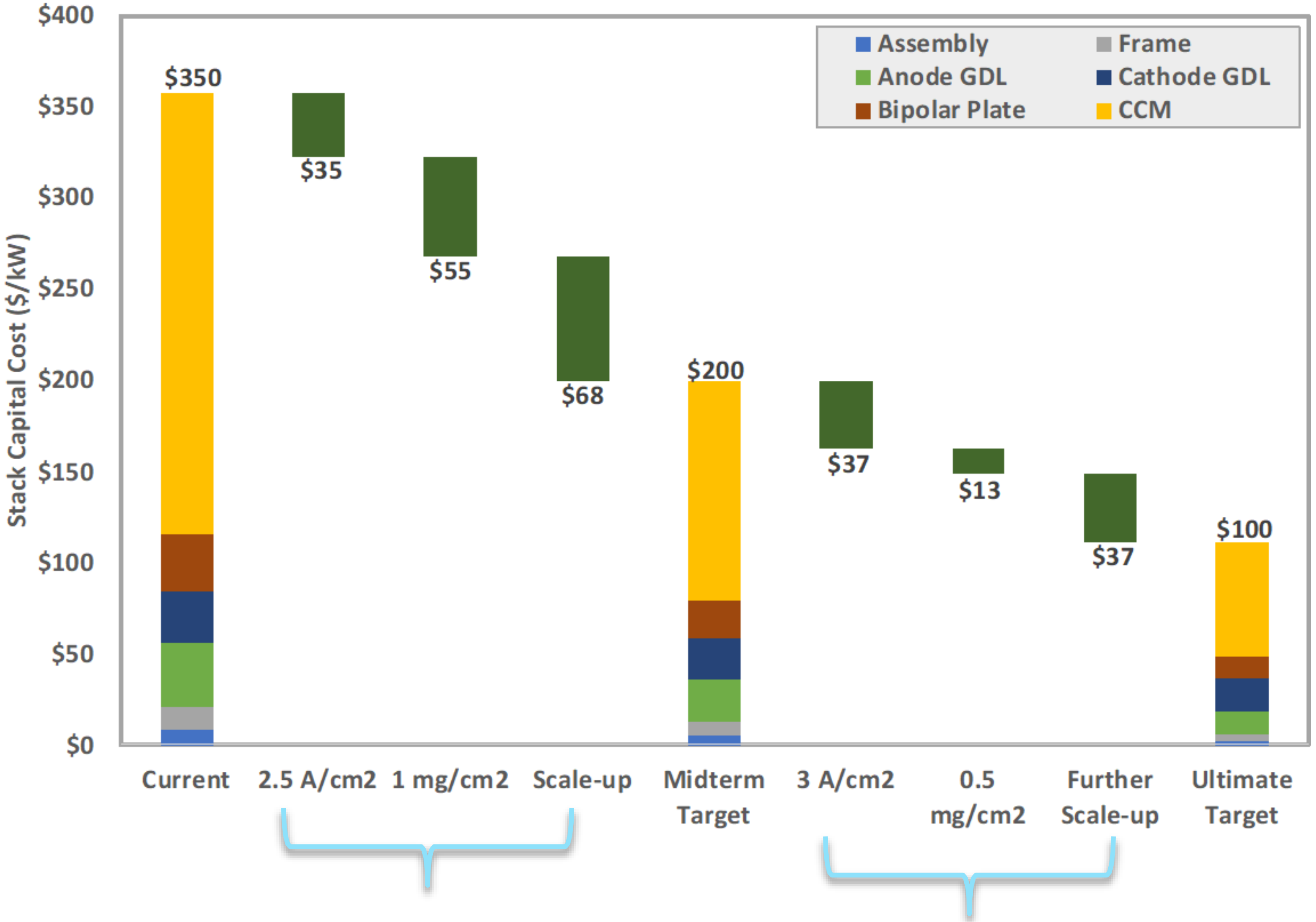


Utilize combination of world-class experimental, analytical, and modeling tools

Durability/lifetime is most critical, initial, primary focus of H2NEW

- Limited fundamental knowledge of degradation mechanisms.
- Lack of understanding on how to effectively accelerate degradation processes.
- Develop and validate methods and tests to accelerate identified degradation processes to be able to evaluate durability in a matter of weeks or months instead of years.
- National labs are ideal for this critical work due to existing capabilities and expertise combined with the ability to freely share research findings.

Relevance: Stack Costs (PEM Centric)



Stack Targets	Status	2023	2025
Cell (A/cm²@1.9V)	2.0	2.5	3.0
Efficiency (%)	66	68	70
Lifetime (khr)	60	70	80
Degradation (mV/khr)	3.2	2.75	2.25
Capital Cost ($/kW)	350	200	100
PGM loading (mg/cm²)	3	1	0.5

These 3 areas

1. Increased efficiency/current density
2. Decreased PGM loading
3. Scale-up

Are the strongest levers for addressing stack costs.

https://www.hydrogen.energy.gov/pdfs/review21/p196_pivovar_boardman_2021_o.pdf

Thank You!!!!

Happy to take questions

Bryan.Pivovar@nrel.gov

Materials Needs

Materials Needs for PEM

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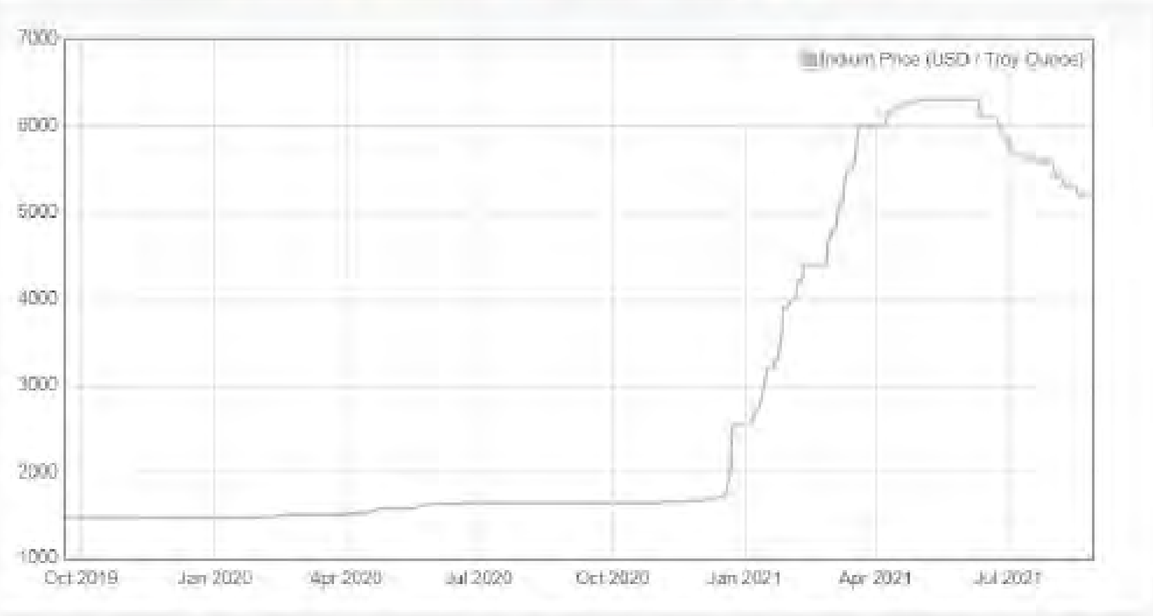
- Thrifting/replacing of Ir
  - Supports
  - Novel compositions/structures
  - Electrode fabrication impacts
- Improved membranes
  - Increased selectivity, thin membranes
  - Improved durability
  - Recombination layers
- Novel Porous Transport Layers (PTLs)
  - Materials
  - Morphology
  - Coatings

Iridium Prices for the Last 2 Years



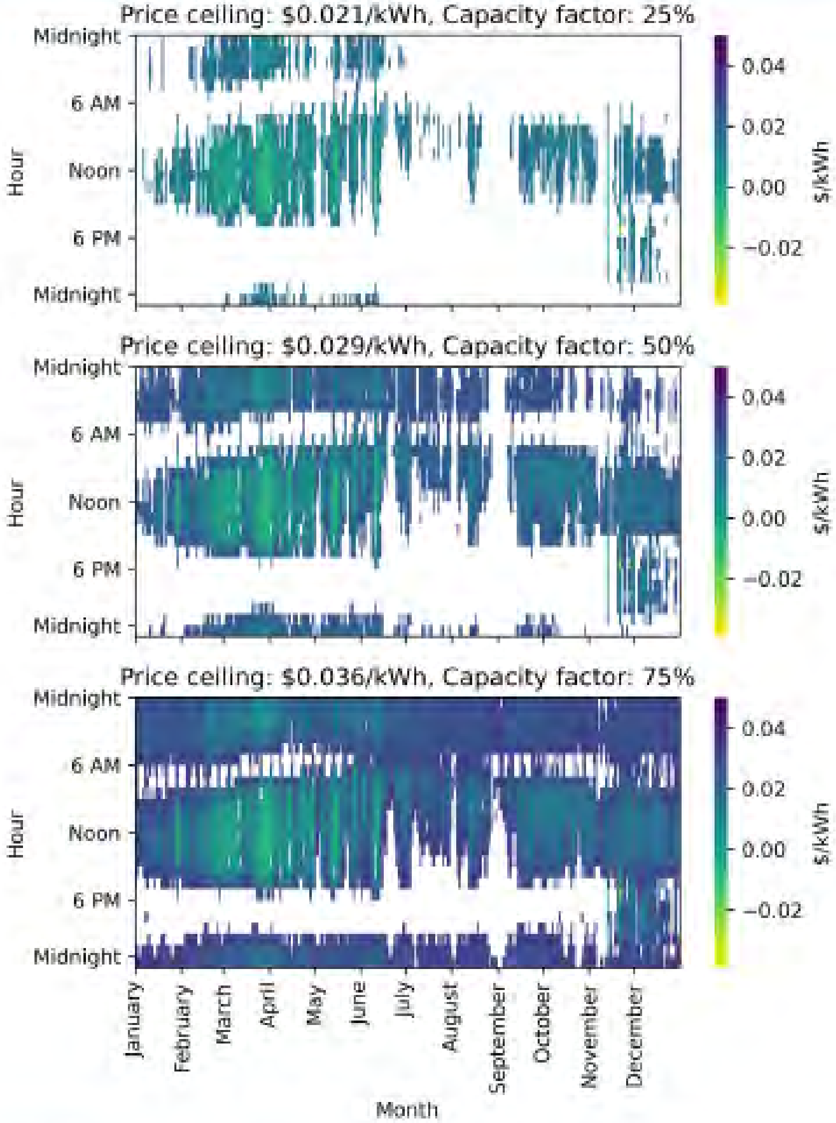
https://www.dailymetalprice.com/metalpricecharts.php?c=ir&u=oz&d=120

Alkaline Needs

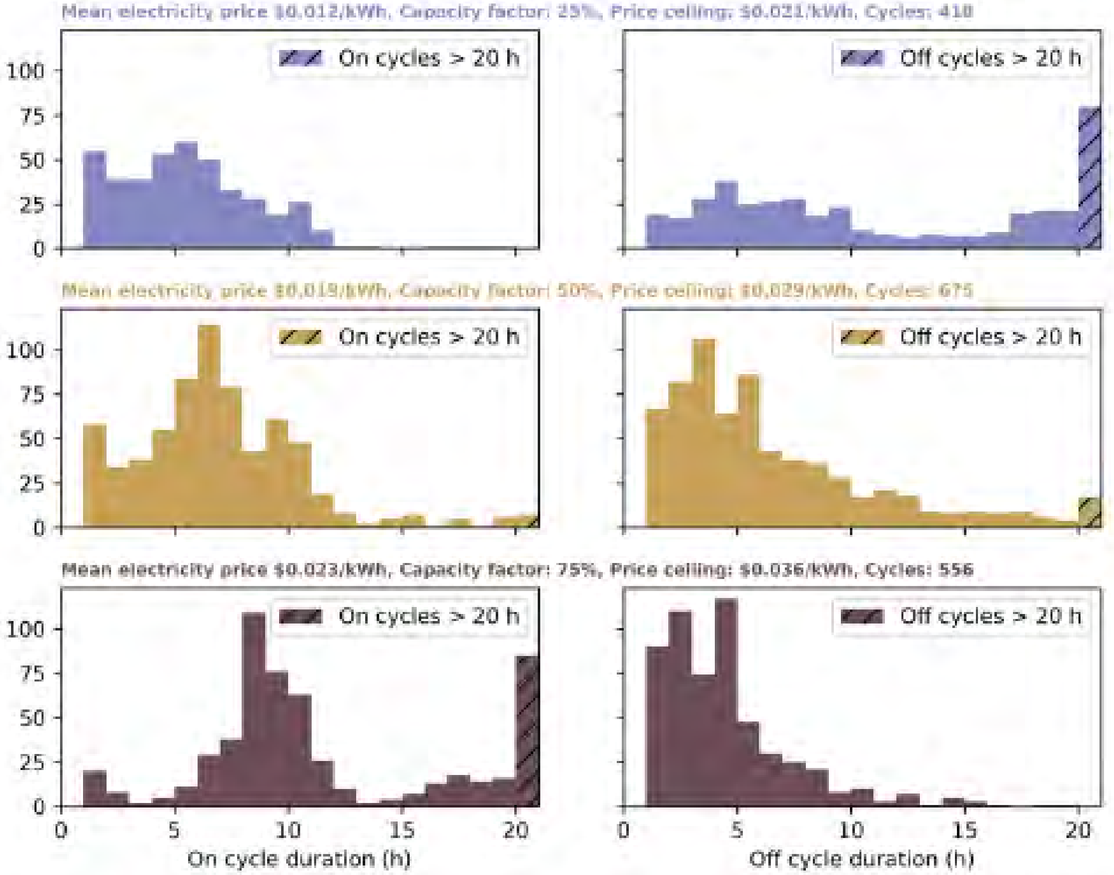
- Traditional (Conc. KOH)
  - Intermittent operating capability
  - Operating pressure
  - Degradation mechanisms/ASTs
  - Performance/efficiency improvements

- AEM/hybrid (low conc/KOH-free systems)
  - Novel materials development
    - Stable polymers
    - Advanced catalysts
  - Performance dependence on electrolyte
  - Degradation mechanisms/ASTs

Accomplishment: Duty cycle implications for ASTs

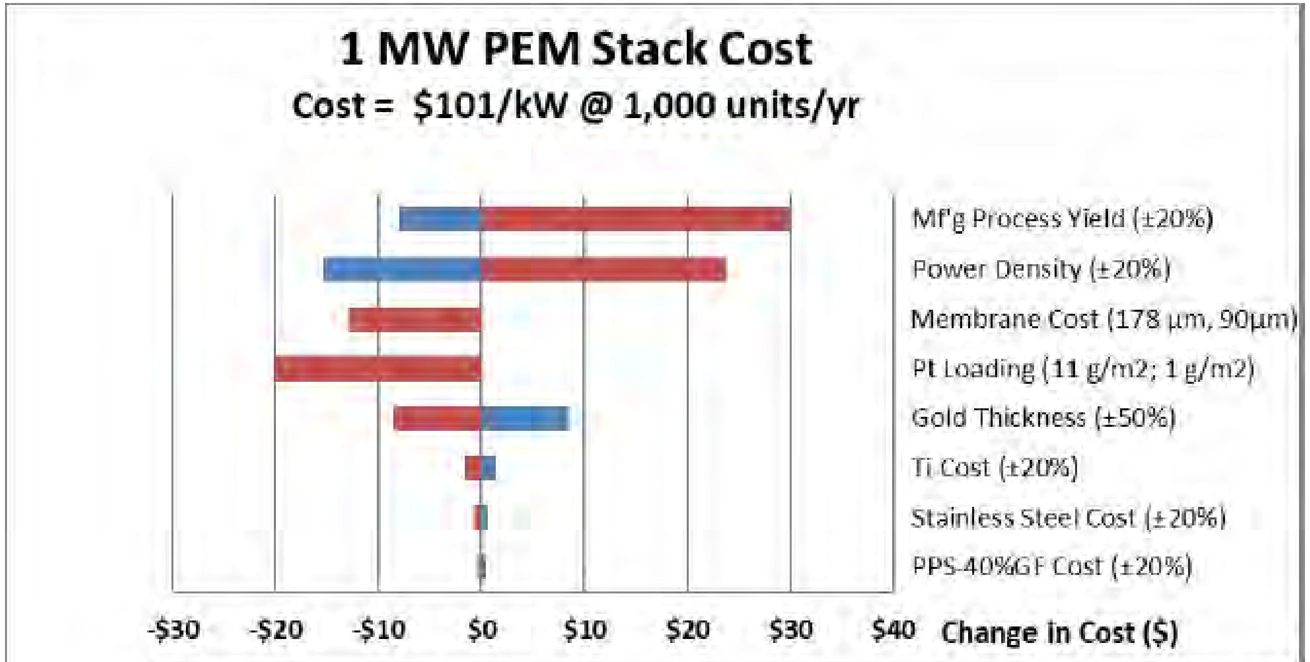


LMP heatmaps can give insight into potential operating strategies



On-off cycle duration and frequency can help support AST development.

Sensitivity Analysis



	PPS-40%GF Cost (±20%)	Stainless Steel Cost (±20%)	Ti Cost (±20%)	Gold Thickness (±50%)	Pt Loading (11 g/m2; 1 g/m2)	Membrane Cost (178 µm, 90µm)	Power Density (±20%)	Mf'g Process Yield (±20%)
Increase	$0.32	$0.65	$1.48	$8.49	$-	$-	$(15.27)	$(8.01)
Decrease	$(0.32)	$(0.65)	$(1.48)	$(8.49)	$(20.16)	$(12.87)	$23.76	$29.83

- Yield insight into primary cost drivers for PEMEC stacks
- Membrane cost, Pt loading, precious metal coatings are easily identifiable materials advances for impact
- Manufacturing processes and yields are important
- Power density can be impacted by materials advances

Q&A

Please use the
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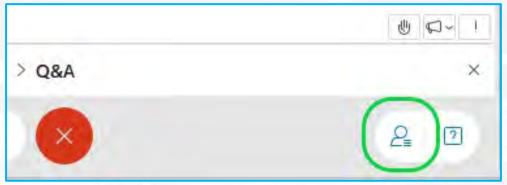


Hydrogen Delivery and Storage: Implications for Structural Integrity

Chris San Marchi
Sandia National Laboratories (Livermore CA)

NYSERDA Hydrogen State of the Science Workshop

31 May 2022

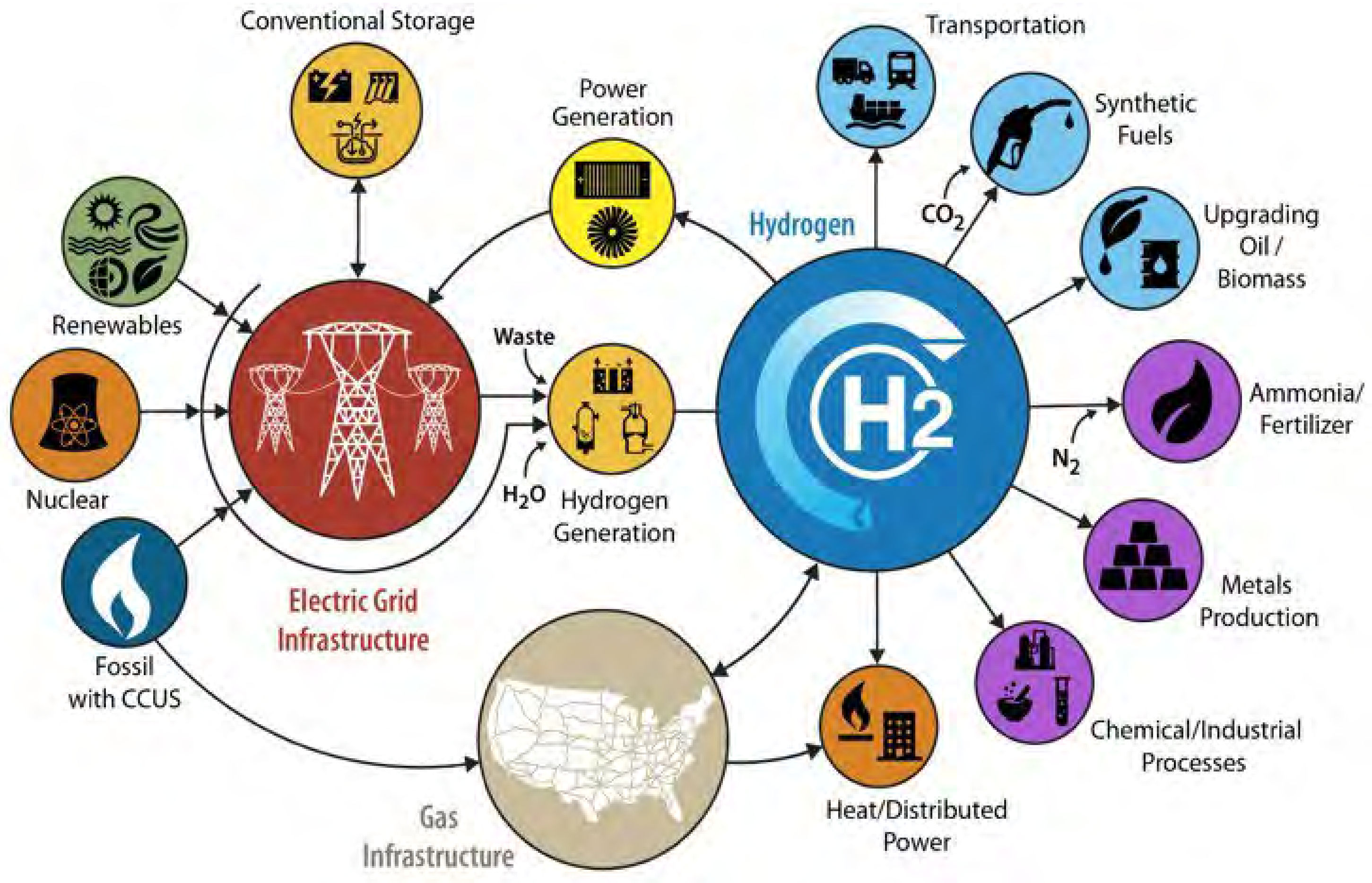
H-Mat Hydrogen Materials Compatibility Consortium

HyBlend U.S. DEPARTMENT OF ENERGY

SAND2022-7231 PE

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Hydrogen has broad potential for decarbonization



H2@Scale enables deep decarbonization across sectors

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

"Hydrogen is the Swiss Army knife of decarbonization"

– Julio Friedmann, former Principal Deputy Assistant Secretary for DOE's Office of Fossil Energy

Source: Washington Examiner

1 **H** 1.008	=	• **simple** • **clean** • **flexible**

Motivation and Outline

- How is hydrogen delivered and stored?
- What is hydrogen embrittlement and when is it important?
- How does gaseous hydrogen affect fatigue and fracture of (pipeline) steels?
  - Is there a threshold below which hydrogen effects can be ignored?
- What is the implication of hydrogen on life of pipelines and piping?

materials

structures

Motivation and Outline

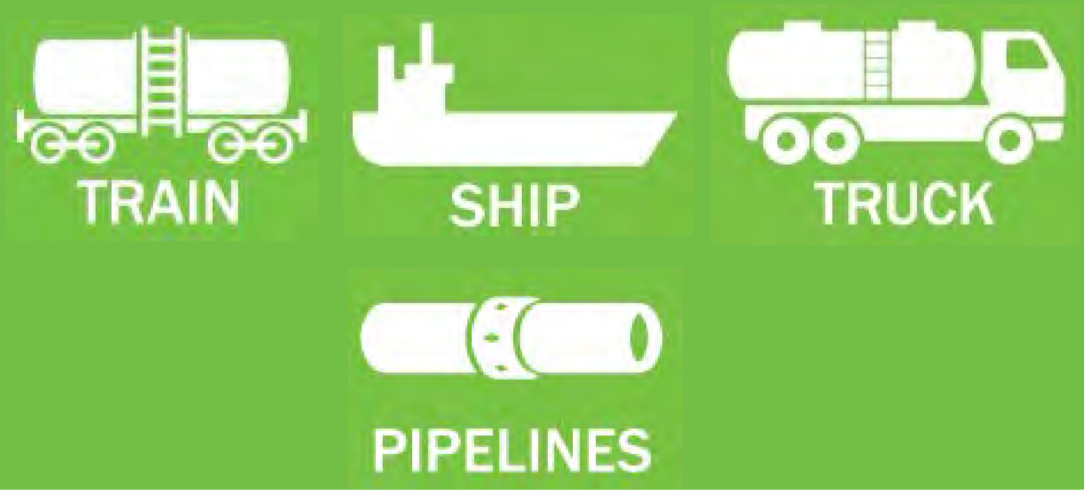
- **How is hydrogen delivered and stored?**
- What is hydrogen embrittlement and when is it important?
- How does gaseous hydrogen affect fatigue and fracture of (pipeline) steels?
  - Is there a threshold below which hydrogen effects can be ignored?
- What is the implication of hydrogen on life of pipelines and piping?

materials

structures

Hydrogen can be managed like other fuel gases

Gaseous



Vessels

Geologic

Delivery

Storage

Liquid

Carriers

SOLID

LIQUID

GAS

What is the best method to transport and store H_2?

- "It depends…"
  - The standard engineering answer to a poorly posed question
- <u>Gaseous</u>
  - Typically high-pressure to achieve volumetric density
  - Current state-of-the-art for vehicle fuel, very large (geologic) storage, and long distance, high volume transport (e.g., pipelines)
- <u>Liquid</u>
  - Very low temperature (20K – lower than liquid N_2)
  - Current state-of-the-art for some transport and storage applications
- <u>Carriers</u>
  - Not economical at present
  - Often toxic

What are the hydrogen challenges?

- **Hydrogen technologies are not new**
  - Cornerstone of astronautics
  - "Chemical" hydrogen is used extensively in industry (10B kg/yr in US)
  - Hydrogen pipelines exist to serve industry (>2,500 km in US)
- **Commercial uses are emerging**
  - Fuel cell cars, buses, trains, boats, back-up power, etc.
  - H_2-powered materials handling equipment (e.g., forklifts)

economics

- **Non-industrial (green) hydrogen is too expensive**
  - Supply chain for non-industrial use is nascent
  - Infrastructure at scale cannot be replaced/developed overnight
    - Gas network is estimated to be valued at >$1,000B
    - Over 150,000 gasoline stations in US (value ~$100B)

safety

- **Hydrogen is managed as chemical, not as energy/fuel**
  - We need "*non-hardhat*" relationship with hydrogen

Example hydrogen technology deployment in the US

>500 MW
Backup Power

>35,000
Forklifts

>14 MW
PEM Electrolyzers

>60
Fuel Cell Buses

>45
H_2 Retail Stations

>9,000
Fuel Cell Cars

International scale is greater in some areas: eg, >2000 buses

Motivation and Outline

- How is hydrogen delivered and stored?
- **What is hydrogen embrittlement and when is it important?**
- How does gaseous hydrogen affect fatigue and fracture of (pipeline) steels?
  - Is there a threshold below which hydrogen effects can be ignored?
- What is the implication of hydrogen on life of pipelines and piping?

materials

structures

Motivation

With growing interest in decarbonization, hydrogen is being considered as a means to reduce carbon in energy infrastructure

Challenge

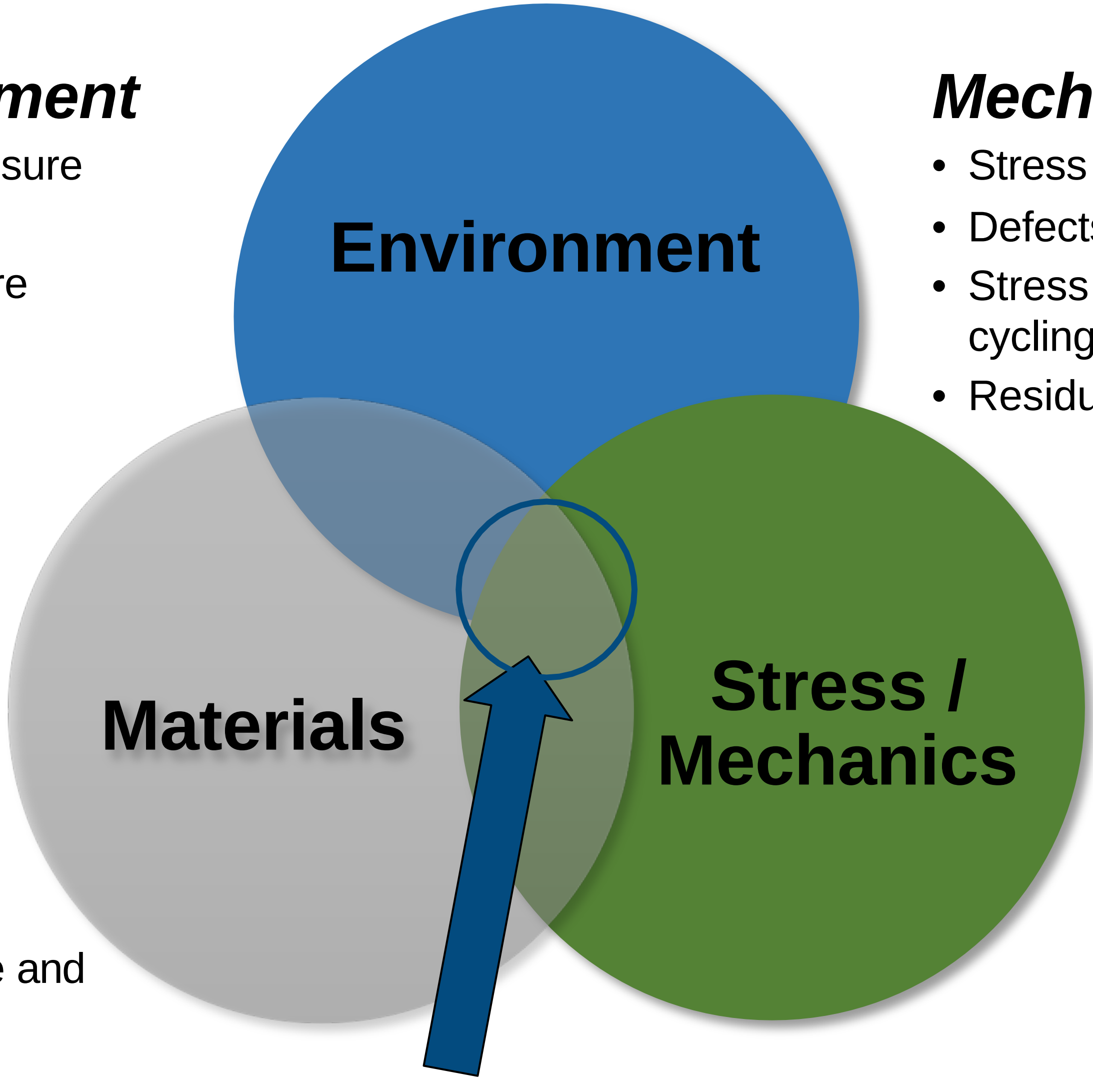
Hydrogen degrades fatigue and fracture resistance of steels, and the effects on pressure vessel and line pipe steels are significant

Environment

- Partial pressure
- Impurities
- Temperature

Mechanics

- Stress
- Defects
- Stress (pressure) cycling
- Residual stresses

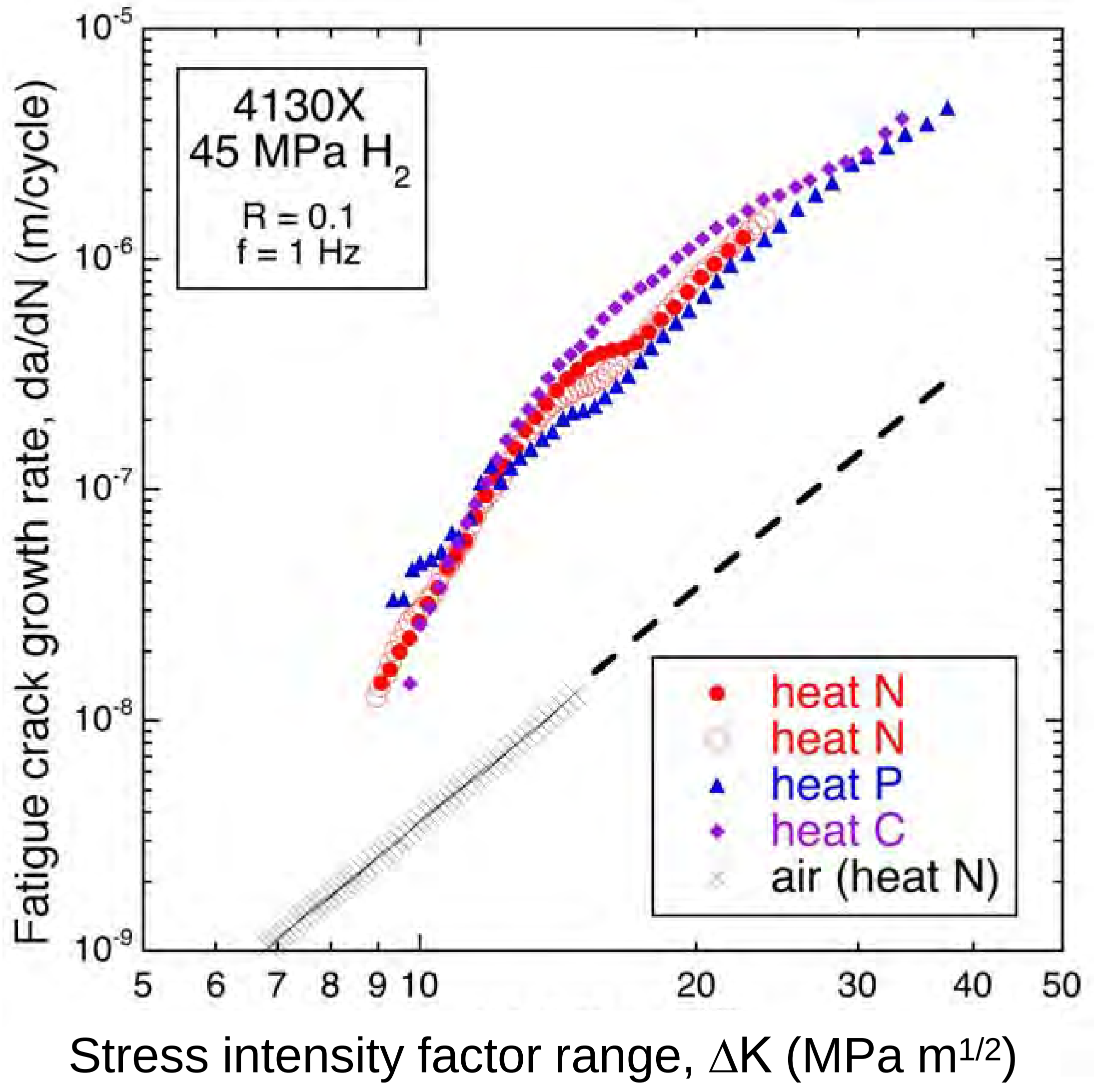


Materials

- Strength
- Microstructure and homogeneity

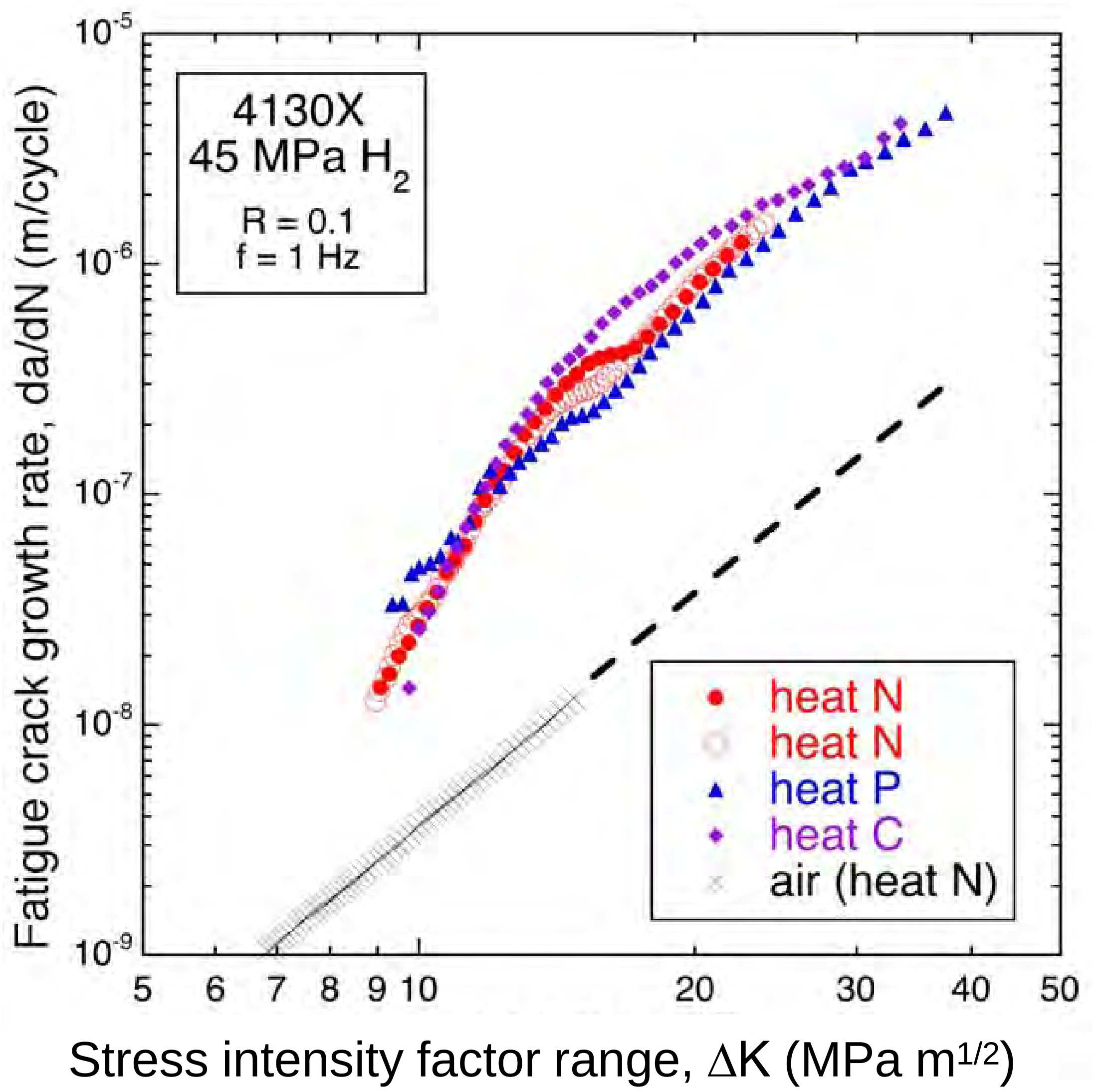
*Hydrogen embrittlement occurs in **materials** under the influence of **stress** in hydrogen **environments***

Is hydrogen embrittlement a showstopper?



- **Fatigue crack growth rate is accelerated by 10X in H_2 compared to air**
  - **Typical of many construction steels**
- **Is this material safe to use in gaseous hydrogen?**
  - **Yes – No – Maybe**

Construction steels are used in hydrogen applications



Hydrogen-powered forklift with steel fuel tank

Motivation and Outline

- How is hydrogen delivered and stored?
- What is hydrogen embrittlement and when is it important?

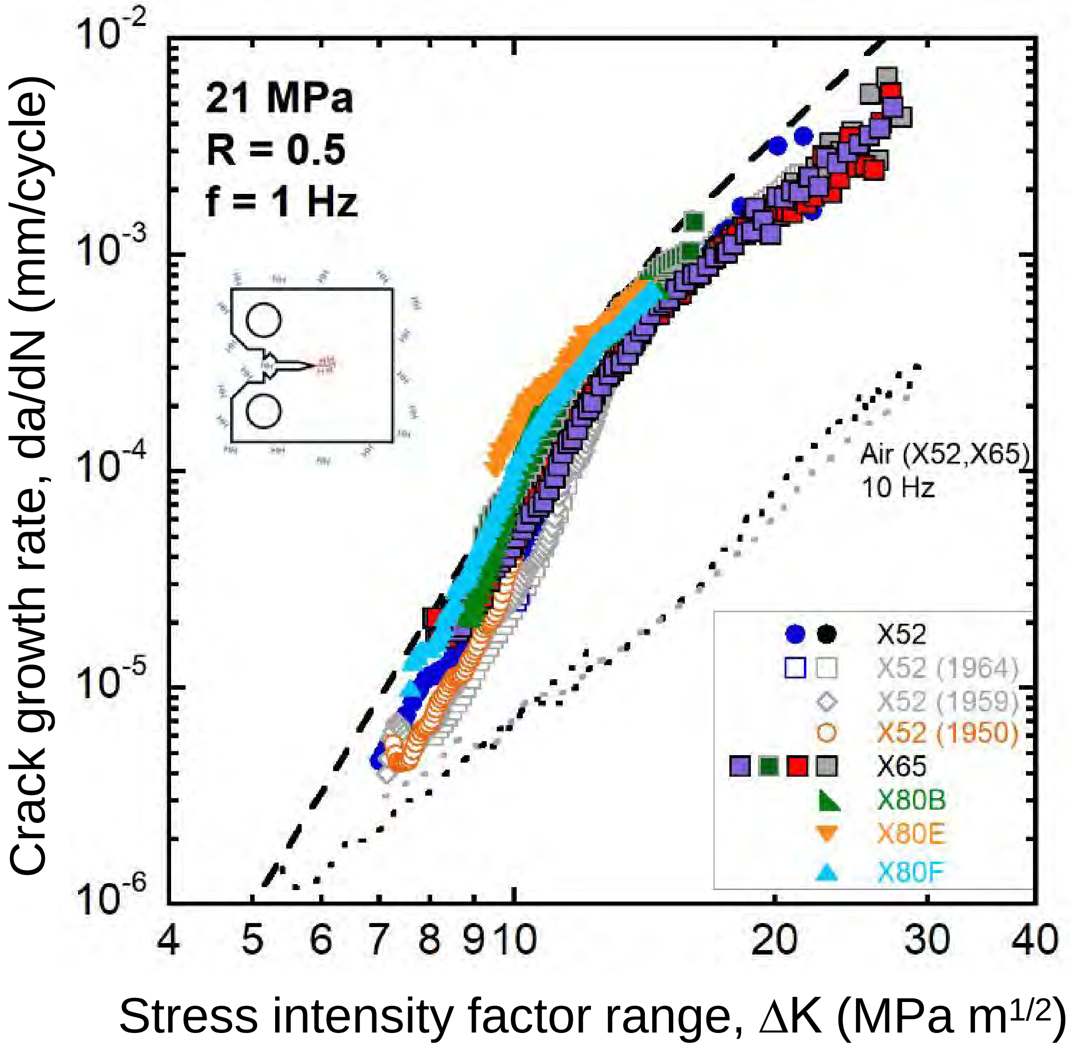
materials

- **How does gaseous hydrogen affect fatigue and fracture of (pipeline) steels?**
  - **Is there a threshold below which hydrogen effects can be ignored?**

structures

- What is the implication of hydrogen on life of pipelines and piping?

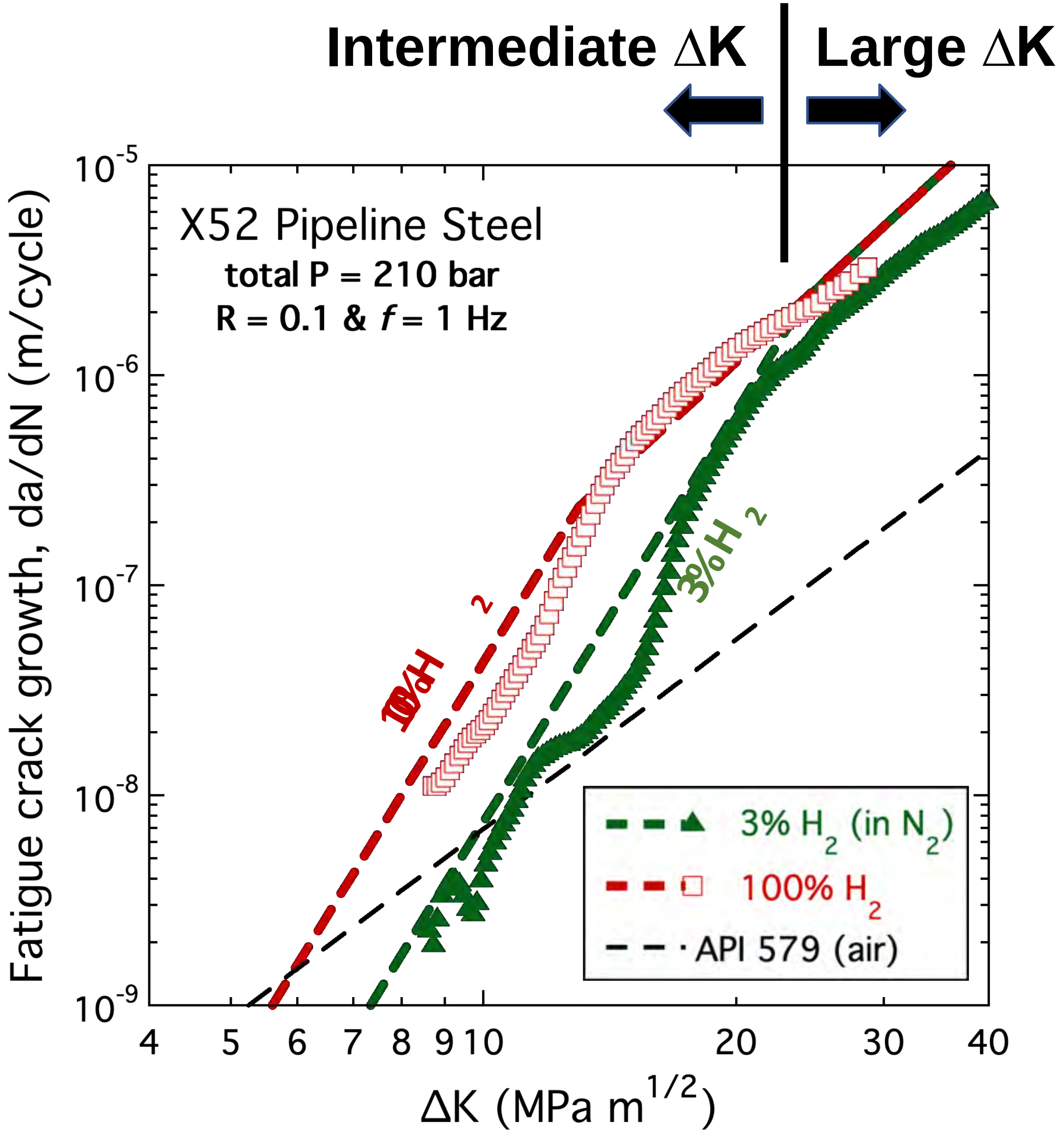
Fatigue crack growth is not a strong function of pipeline grade



- **Pipeline steels show very consistent behavior in gaseous hydrogen, including**
  - **Wide range of steel quality**
  - **Wide range of steel grade**
- **Effects of pressure and 'load ratio' are predictable**

Fatigue performance can be codified, thus negating the need for extensive fatigue testing

Low hydrogen partial pressure = large effect on fatigue



- **Large ΔK**
  FCG is independent of pressure
  - Fatigue crack growth rate in 3% H_2 is the same as in 100% H_2
- **Intermediate ΔK**
  FCG is dependent on hydrogen partial pressure
  - Fatigue crack growth rate is slower in 3% H_2 than in 100% H_2

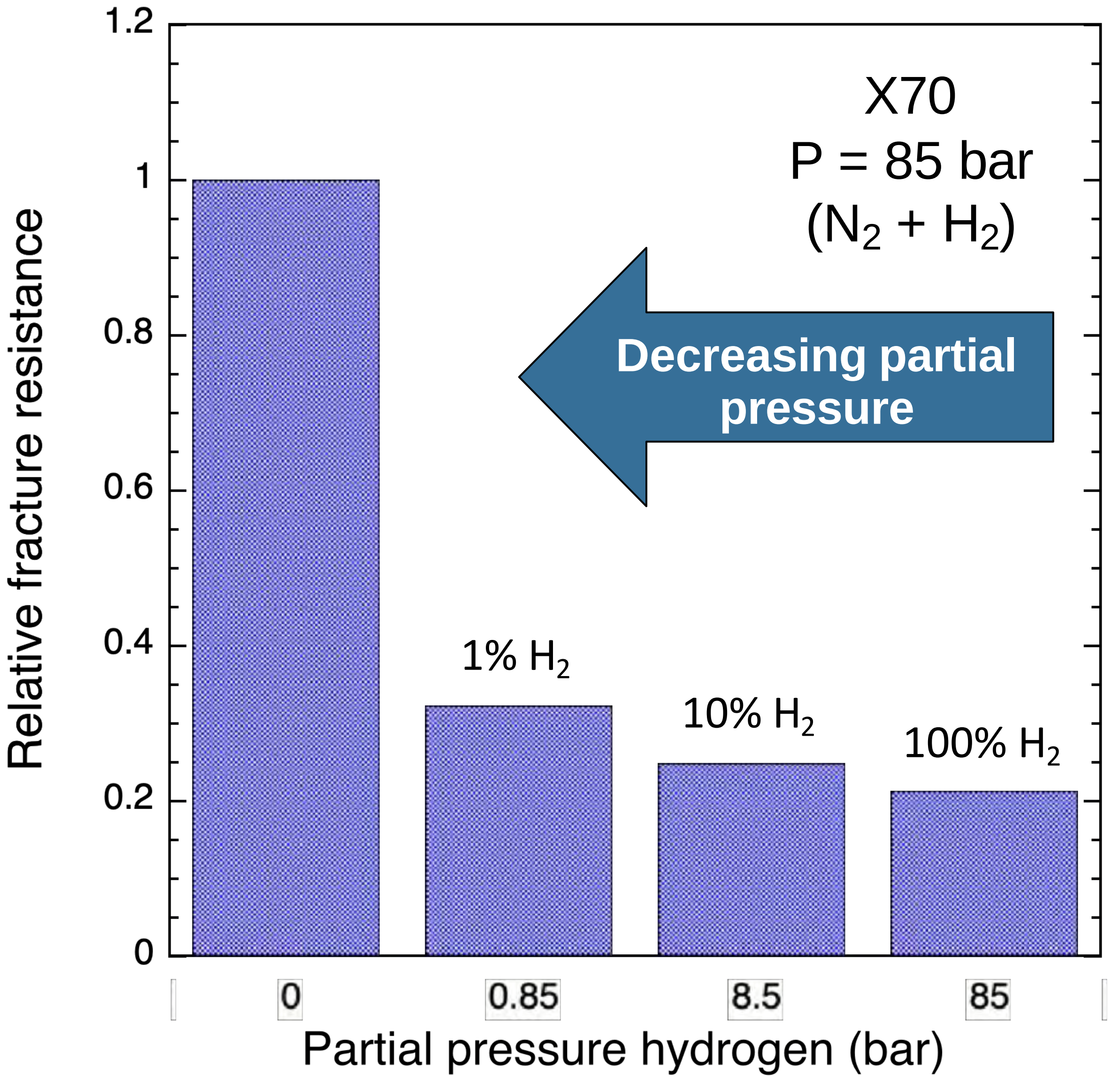
Design curves predict fatigue crack growth rates as a function of H_2 partial pressure (fugacity)

Ref: San Marchi et al, PVP2021-62045

Low hydrogen partial pressure = large effect on fracture

- **Measurements of fracture resistance in gaseous mixtures of H_2 and N_2 show substantial effects of H_2**
- **1% H_2 is only modestly different than 100% H_2**
- **Fracture resistance does not scale linearly with pressure/fugacity**

<1 bar of H_2 substantially reduces fracture resistance



Ref.: Briottet et al, PVP2018-84658

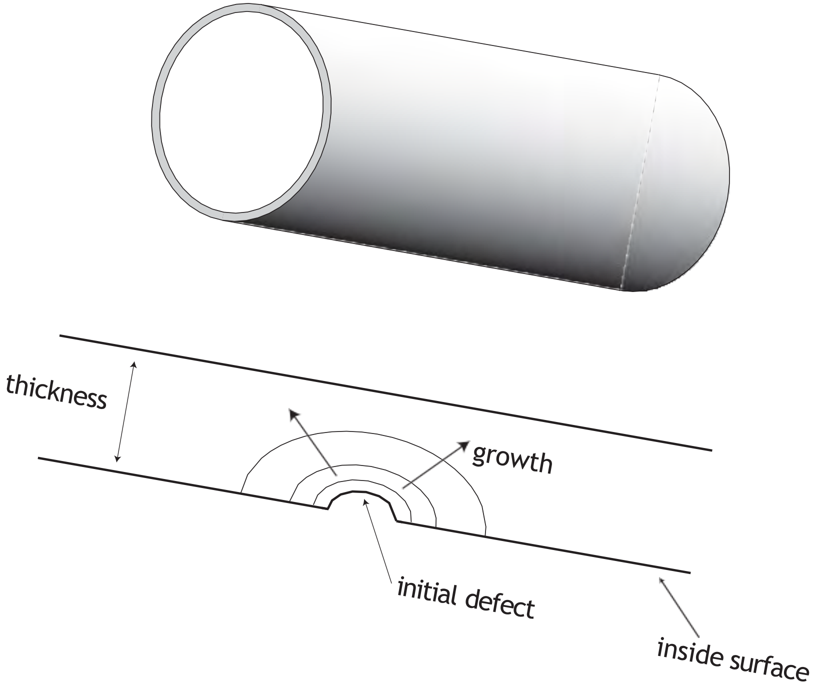
Motivation and Outline

- How is hydrogen delivered and stored?
- What is hydrogen embrittlement and when is it important?
- How does gaseous hydrogen affect fatigue and fracture of (pipeline) steels?
  - Is there a threshold below which hydrogen effects can be ignored?
- **What is the implication of hydrogen on life of pipelines and piping?**

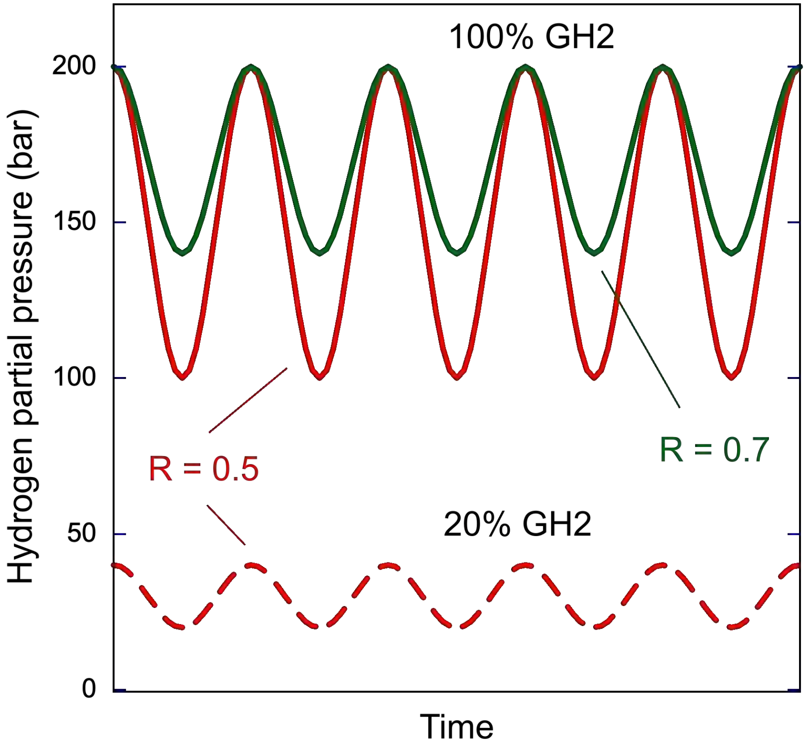
materials

structures

Application of materials behavior to structural integrity analy
example)

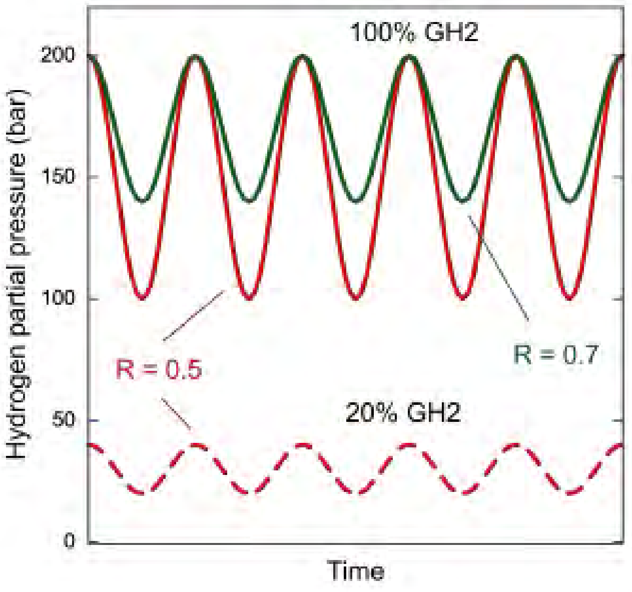


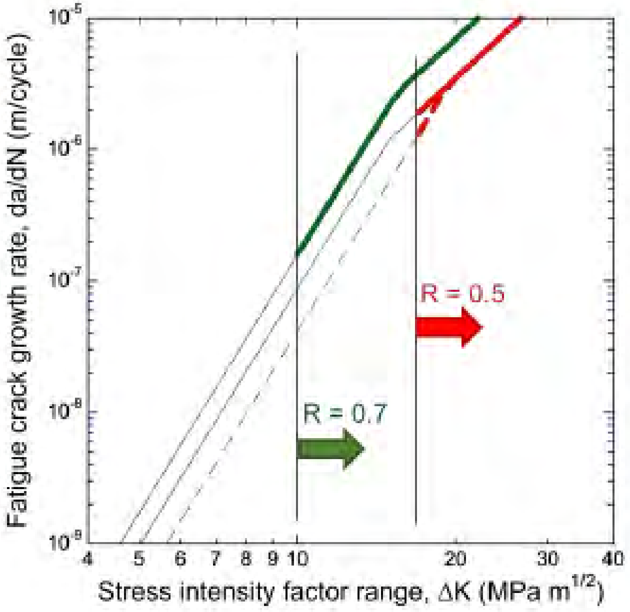
- ***Material***:
  - API grade X52 pipe
  - OD = 324 mm
  - t = 12.7 mm
- ***Environment***:
  - Pressure = 200 bar
  - GH2 = 20%, 100%
- ***Stress***:
  - Hoop stress: 68% SMYS
  - Cyclic pressure: $R = P_{min}/P_{max} = 0.5, 0.7$
  - Flaw
    - depth: 25% of wall thickness (a/t =0.25)
    - length: 40 mm (2c = 40mm) – propagate with constant aspect ratio

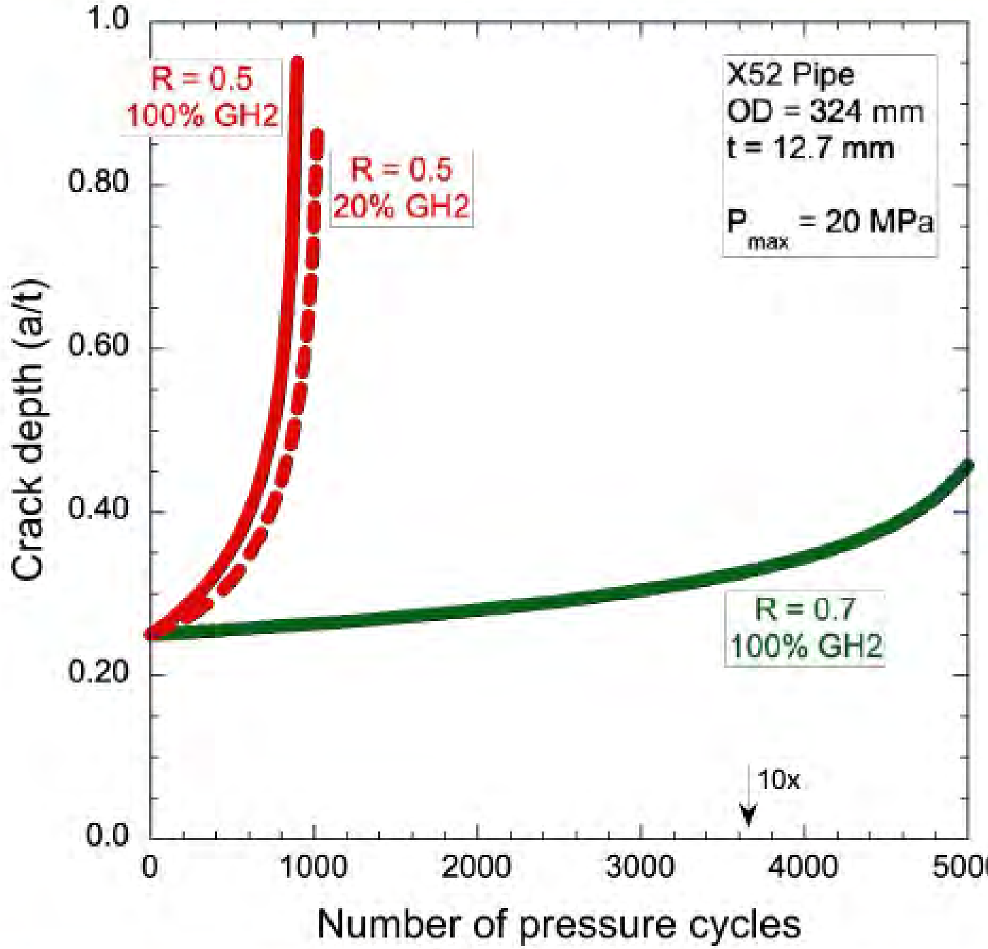


Analysis of transmission pipe structure (simple example)

- **Stress is <u>large</u> in this example**
  - P_{max} = 20 MPa
  - σ_{hoop} ~ 68% SMYS
- **Initial crack/flaw: a/t = 0.25**
  - $K_{applied}$ = 33 MPa $m^{1/2}$







The blending ratio has no effect on fatigue response (for R = 0.5)

Summary

- **How is hydrogen delivered and stored?**
  - **Much like natural gas: as gas or liquid depending on use case**
- **What is hydrogen embrittlement and when is it important?**
  - **Hydrogen reduces fatigue and fracture resistance of steels whenever is present; outcome of this degradation depends on use case**

materials

- **How does gaseous hydrogen affect fatigue and fracture of (pipeline) steels?**
  - **Is there a threshold below which hydrogen effects can be ignored?**
    - **No, there is no general threshold below which hydrogen does not affect fatigue and fracture properties of metals**

structures

- **What is the implication of hydrogen on life of pipelines and piping?**
  - **Depends on characteristics of the structure**

Thank You!

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https://h-mat.org/

https://www.sandia.gov/matlsTechRef/

https://granta-mi.sandia.gov/

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Brandon Talamini
Ben Schroeder
Austin Glover

Q&A

Please use the
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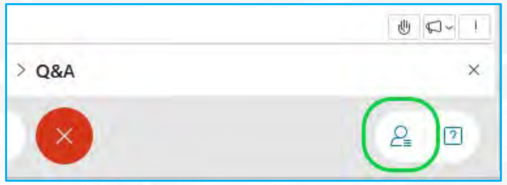


Informational resources

- **Technical Reference for Hydrogen Compatibility of Materials**
  - **https://www.sandia.gov/matlsTechRef/**
  - Report no. SAND2012-7321 (Technical Reference v.2)
  - Report no. SAND2013-8904 (polymers)
- **Technical Database for Hydrogen Compatibility of Materials**
  - **https://granta-mi.sandia.gov/**
- **Study Group on Materials Testing and Qualification for Hydrogen Service**
  - Annual topical discussion group: international and industrial participation
- **ASME Pressure Vessels and Piping Division Annual Conference (2005 - current)**
  - *Materials for Hydrogen Service*: session organization (2014-current)
- **Expanded resources under development at**
  - **Including H-Mat DataHUB (https://h-mat.org)**

Background: thermodynamics (origin of fugacity)

H in metals: $\mu^H = \mu_o^H + RT \ln c_H$

Gas phase: $\mu^{HH} = \mu_o^{HH} + RT \ln f_{HH}$

At equilibrium: $\frac{1}{2}H_2 \leftrightarrow [H]$

$$\frac{1}{2}\mu^{HH} = \mu^H$$

$$\frac{\frac{1}{2}\mu_o^{HH} - \mu_o^H}{RT} = \ln \frac{c_H}{(f_{HH})^{1/2}}$$

General form of Sieverts' Law $\quad K = \frac{c_H}{(f_{HH})^{1/2}}$

Equation of state for H_2
Abel-Noble formulation

$$V_m = \frac{RT}{P_{HH}} + b$$

Pure gaseous H_2:

$$f_{HH} = P_{HH} \exp\left(\frac{bP_{HH}}{RT}\right)$$

Blended H_2:

$$f_{HH} = P_{HH} \exp\left(\frac{bP_{total}}{RT}\right)$$

Background: stress intensity factor, *K*

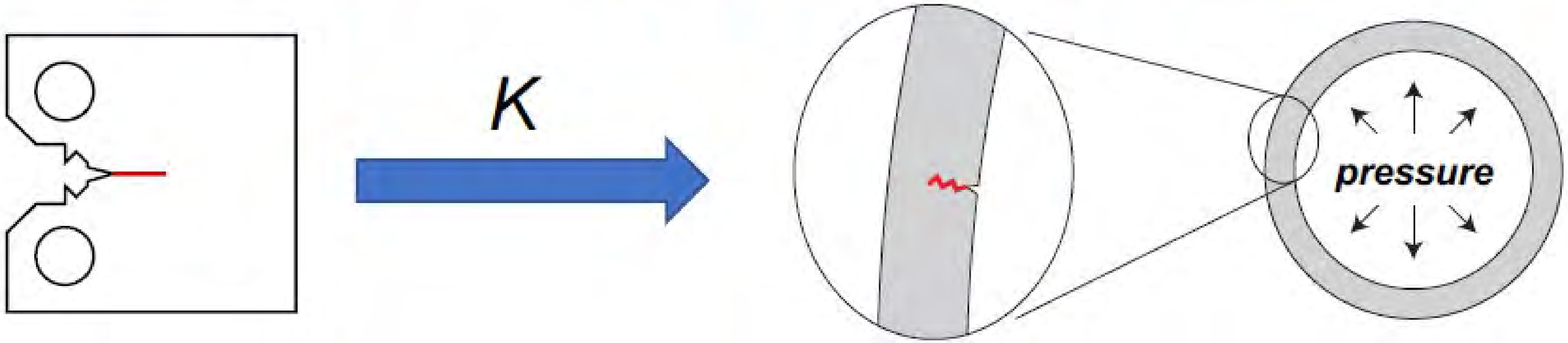
What is this in the stress intensity factor, *K*?

$$K = \sigma\sqrt{\pi a} \times f(geometry) \qquad \sigma = stress, \quad a = crack\ size$$

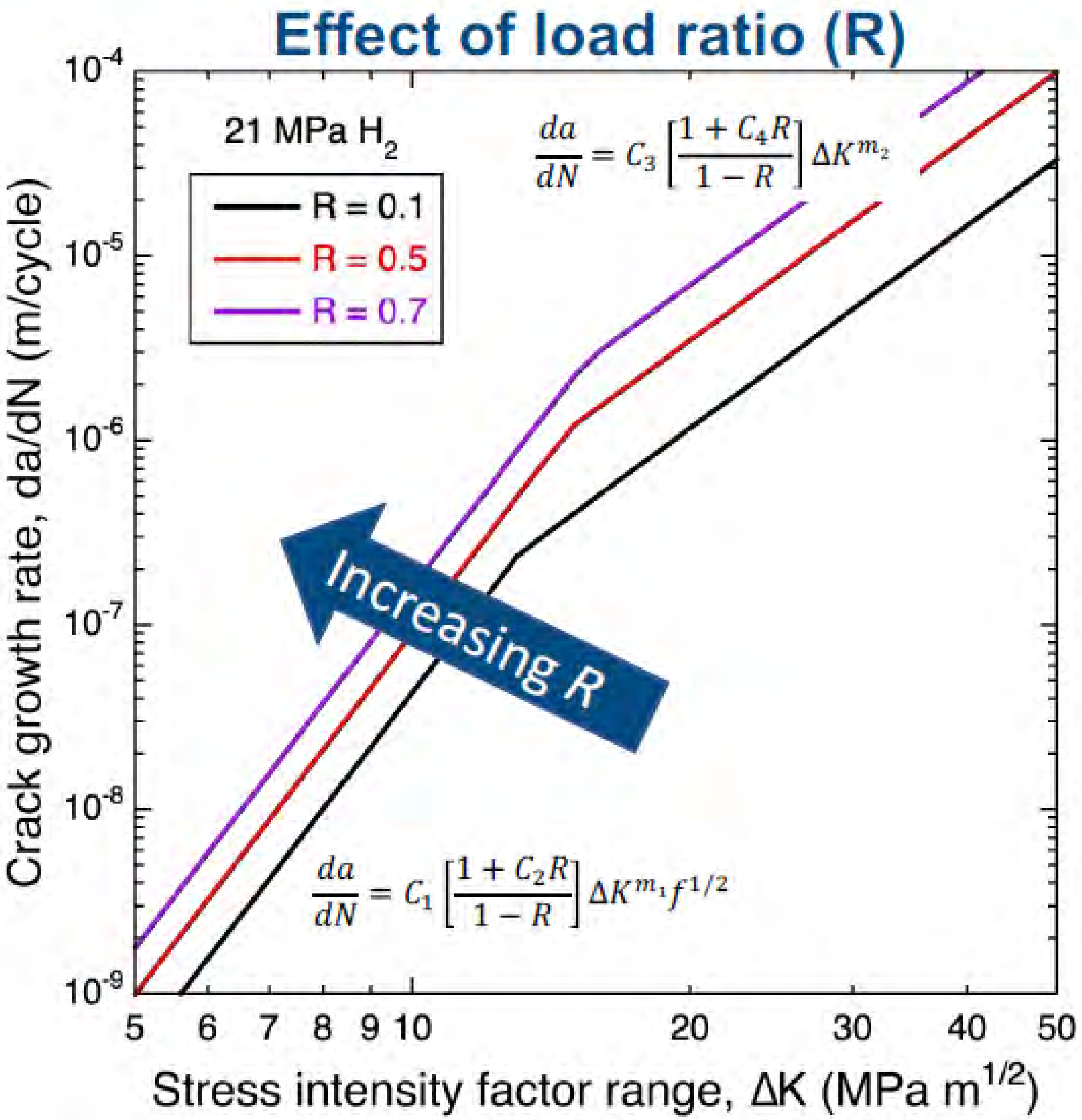
$$\Delta K = K_{max} - K_{min}$$

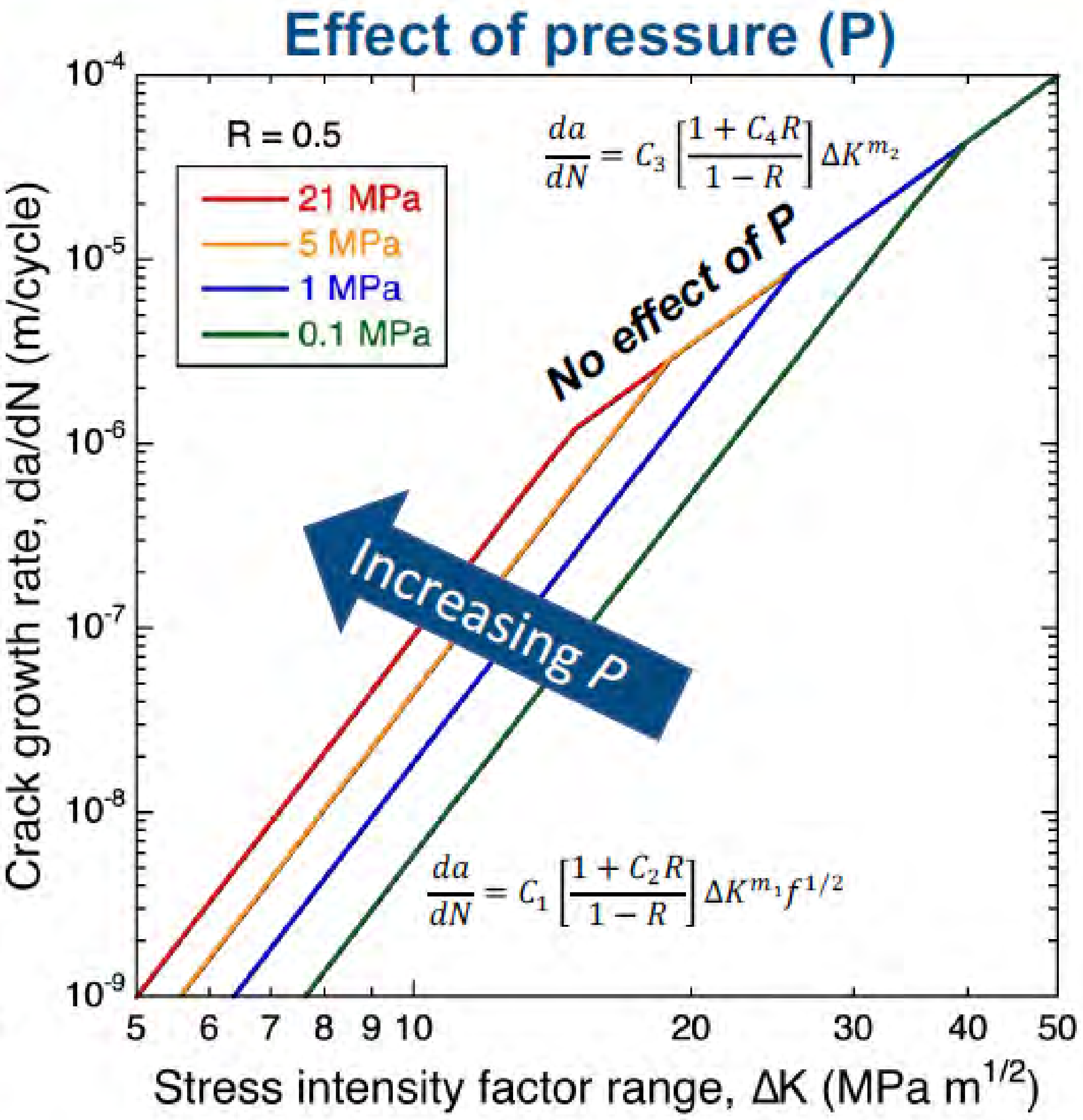
$$R = \frac{K_{min}}{K_{max}}$$

- ***K*** **characterizes the stress state at a crack tip**
  - **analogous to the stress, but for the case of cracks in structures**
- ***K*** **is a transferable parameter that is used to generalize the state of a crack and transfer information between one geometry and another**
  - **for example between a laboratory test and a real-world application**



Design curves enable upper bound prediction for fatigue crack growth as function of loading and pressure





CENTER FOR Hydrogen SAFETY
Connecting a Global Community

Hydrogen Safety Considerations and Resources

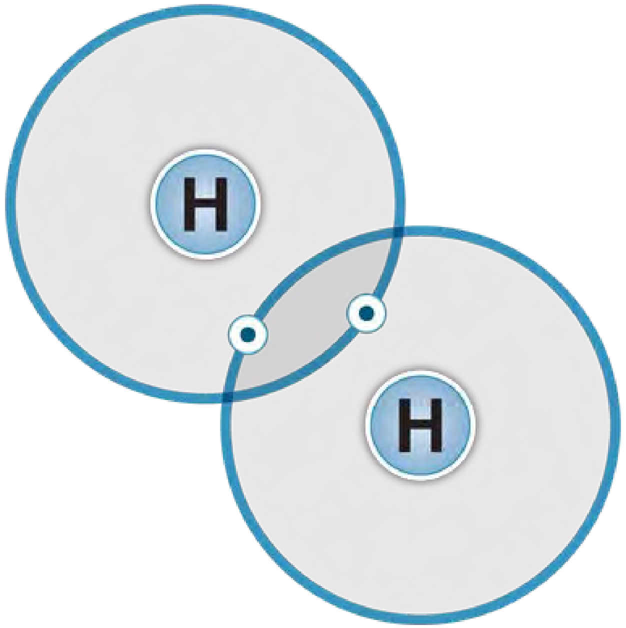
Nick Barilo
Executive Director, Center for Hydrogen Safety

May 31, 2022

Hydrogen's Great Potential

Hydrogen Properties and Behavior

- **Gas** at ambient conditions
  - Rises and disperses rapidly (14x lighter than air)
  - Flammable range 4-75% in air
- **Liquid** at -253°C (-423°F) – a *cryogen*
  - LH_2 stored at 50 psi in vacuum insulated tanks
  - No liquid phase in compressed gas H_2 storage
  - Liquid hydrogen expands about 850 times when transitioning transforming from liquid to gas phase
- **Energy content comparison** :
  - 1 kg of hydrogen ~ 1 gallon gasoline
  - 33.3 kWh/kg hydrogen vs. 32.8 kWh/gal gasoline



Molecular Hydrogen Model:
2 protons (H+) sharing 2 electrons (e-)

Additional Properties of Hydrogen

- **Description**
  - Colorless, odorless, tasteless
- **General Properties**
  - Flammable
  - Non-irritating, nontoxic, asphyxiant
  - Non-corrosive
  - Lightest gas, buoyant, can escape earth's gravity
- **Physical Properties**

GH_2 density @ NTP	0.0838 kg/m^3 (1/15th air)
GH_2 specific gravity	0.0696 (Air = 1.0)
Viscosity	33.64 x 10^{-3} kg/m hr (1/2 air)
Diffusivity	1.697 m^2/hr (4x NG in air)
Thermal Conductivity	0.157 kcal/m hr K (7 x air)

Potential Hazards

- Combustion (fire and explosion)
- Pressure hazards
- Low temperature
- Hydrogen-induced material embrittlement
- Asphyxiation (rare)

Hydrogen Properties: *A Comparison*

	Hydrogen Gas	Natural Gas	Gasoline
Toxicity	None	Some	High
Odor	Odorless	Yes (mercaptan)	Yes (benzene)
Buoyancy *Relative to **Air***	14X Lighter	2X Lighter	Vapor is 3.75X Heavier
Flammable Range by volume in air	4-75%	5-15%	1.4-7.6%
Autoignition Temperature (C)	585°	539°	232°
Minimum Ignition Energy (mJ)	0.017	0.288	0.250-0.300
Energy by Weight	2.8X > Gasoline	~1.2X > Gasoline	43 MJ/kg
Energy by Volume	4X < Gasoline	1.5X < Gasoline	120 MJ/Gallon

State of Hydrogen Safety

Safety issues can be a 'deal breaker' and must be addressed for successful hydrogen technology acceptance and deployment

Its Use as a Fuel is New to Many

- Users may lack experience or expertise for its safe use
- Some users have misconceptions… and may not know that they don't know

Stable Foundation

- Hydrogen can be used safely… It has been for nearly a century by industry
- Safety knowledge and best practices exist

Dangerous Assumptions

- "We already know how to use hydrogen safety" (apathy - established users)
- "Hydrogen is like any other flammable gas" (misconceptions - new players)
- "Hydrogen is too dangerous" (fear - general public/AHJ's)

Failure to address the knowledge gaps can result in impactful incidents and industry setbacks

Hydrogen Incidents… Seeing the Common Thread

- **Electrolyzer**
  - Personnel did not fully understand the interrelation of electrolyzer membrane gas permeability, membrane degradation, and dynamic operating range
- **Hydrogen Vehicle Fueling Station**
  - Assembly error of an end plug for the high-pressure hydrogen tank
- **Hydrogen Transport**
  - Incorrect pressure relief devices installed during maintenance
- **Hydrogen Tanker Loading**
  - Unauthorized repair and failure to follow procedures
- **Hydrogen Bus Fueling Station**
  - Incompatible pressure relief device installed


Courtesy of Gangwon Fire HeadQuarter

Damage from Electrolyzer Incident

Common Fuels Incidents

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All fuels contain energy and can be hazardous if handled improperly

- **Gasoline**
  - ~1,000 fueling station fires per year in the U.S. as a result of gasoline ignition (2004-2008) (NFPA)
  - ~171,500 highway vehicle fires in the U.S. between 2014 and 2016 (FEMA)
    - 345 deaths
    - 1,300 injuries
    - $1.1 billion USD in property loss
    - 13% of all fires responded to by fire departments
- **Natural Gas** – average/year (U.S. 2007-2011) (NFPA)
  - 13,730 fires
  - 35 deaths
  - 254 injuries
  - $303 million USD property damage

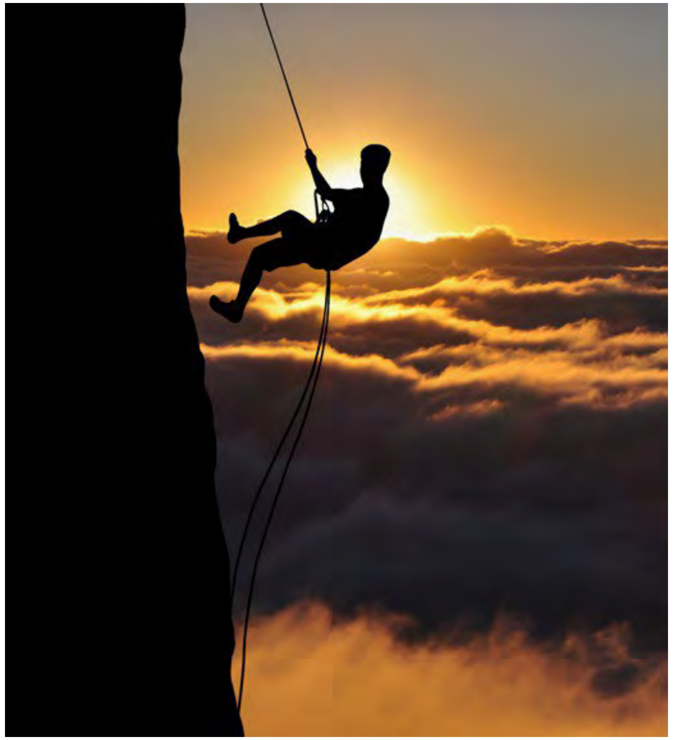
2019 Gasoline Station Fire

Safety…

Three Parts, One Purpose, Strong Together

A threefold cord is not quickly broken

Be Invested in Safety



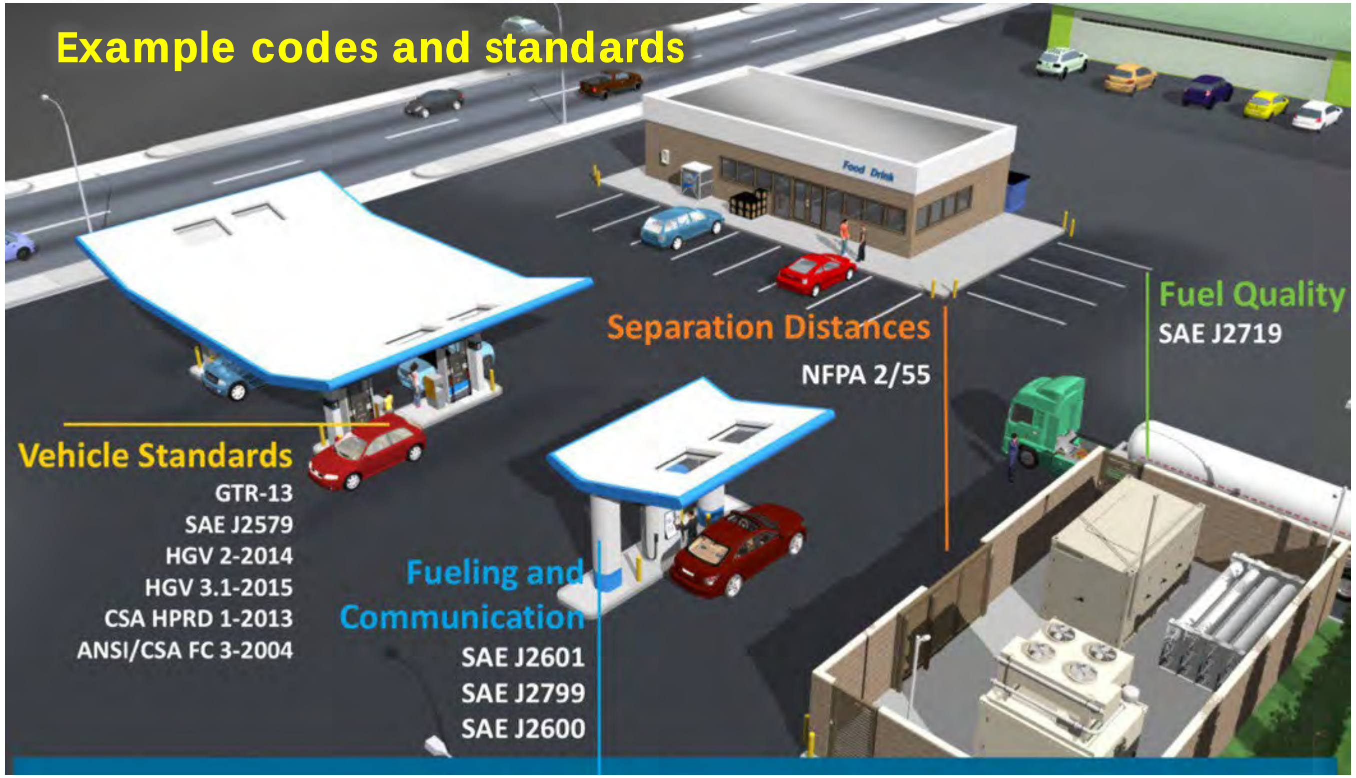
Implement Regulations, Codes and Standards

Utilize Best Safety Practices

Implement Regulations, Codes and Standards

Hydrogen regulations, codes and standards (RCS) are maturing quickly for many mainstream fuel cell applications

- RCS provide the information needed to safely build, maintain, and operate equipment, systems, and facilities
- Ensures uniformity of safety requirements
- Provides inspectors and safety officials the information needed to approve systems and installations
- Bolsters public and stakeholder confidence and helps protect investments



Did you know? Many codes and standards were developed using industry best practices.

See [http://www.fuelcellstandards.com/...](http://www.fuelcellstandards.com/) a database of international codes and standards

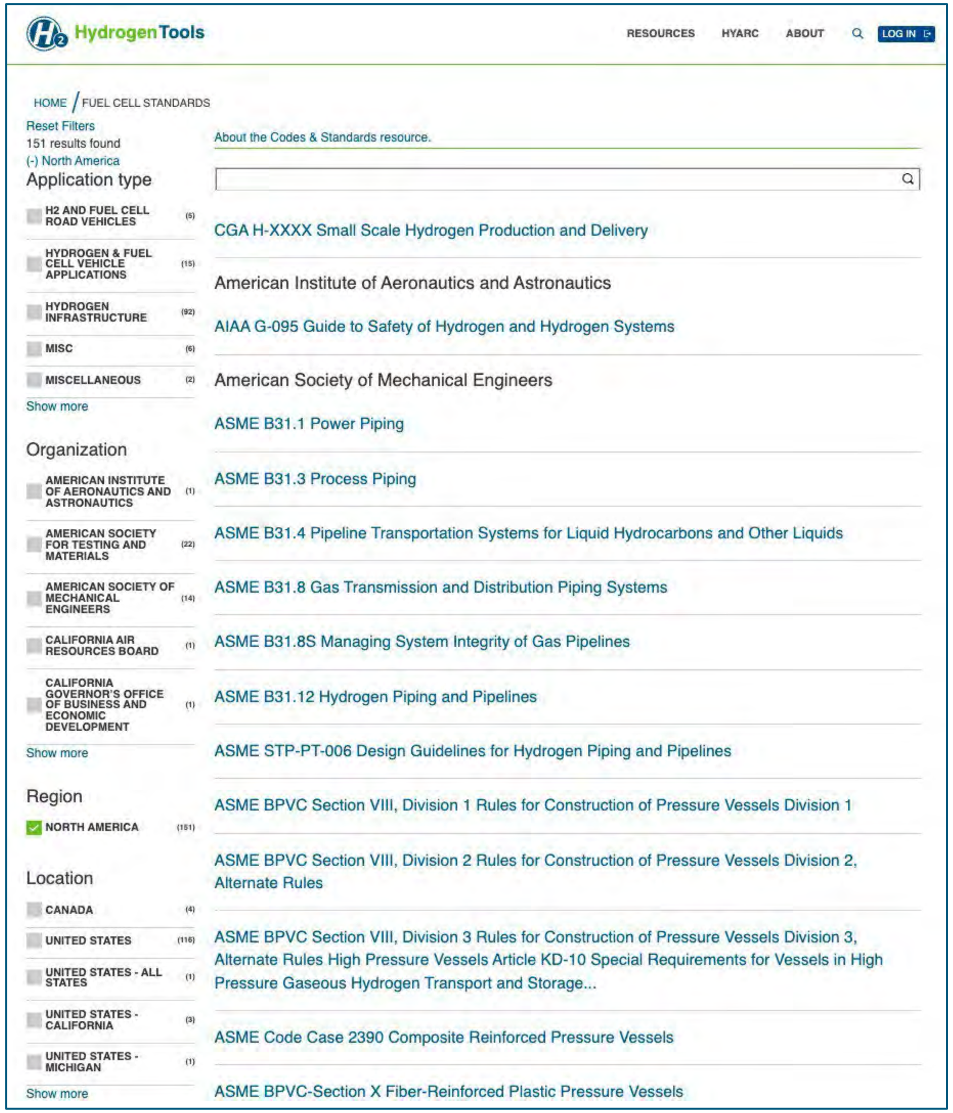
Example International Codes and Standards

International

- ISO TC/197 Hydrogen Technologies
  - 17 published standards (4 in development)
  - 22 participating countries
- IEC TC/105 Fuel Cell Technologies
  - 24 published standards (11 in development)
  - 19 participating countries

North America

- NFPA 2 *Hydrogen Technologies Code*
- CAN/BNQ 1784 *Canadian Hydrogen Installation Code*



Codes and Standards Resource: https://h2tools.org/codes-standards

U.S. Codes and Standards for Hydrogen Facilities

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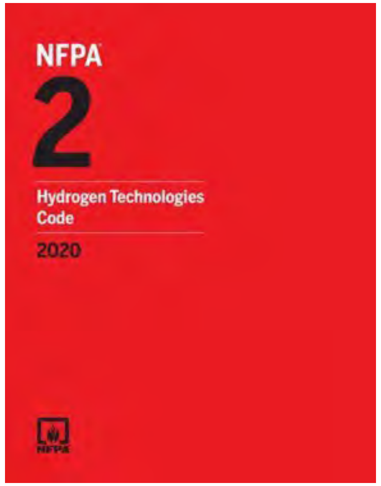
Model Code References to NFPA 2



National Hydrogen Specific Codes[78]

- NFPA 2 Hydrogen Technologies Code
- NFPA 30A Motor Fuel Dispensing Facilities and Repair Garages
- NFPA 55 Compressed Gases and Cryogenic Fluids Code

Component Design Standards

- ASME Boiler and Pressure Vessel[79]
- ASME B31.12–Hydrogen Piping and Pipelines
- ASME B31.1–Power Piping
- ASME B31.8–Gas Transmission and Distribution Piping Systems
- ASME B31.8S–Managing System Integrity of Gas Pipelines
- ASME B31.3–Process Piping
- CGA S-1.1-3: Pressure Relief Device Standards
- CGA-G-5.5: Hydrogen Vent Systems
- SAE J2600–Compressed Hydrogen Surface Vehicle Fueling Connection Devices
- UL 2075–Standard for Gas and Vapor Detectors and Sensors
- NFPA 77 and API RP 2003 offer guidance on grounding and static electricity

Model Codes

- International Fire Code
- International Building Code

Component Listing and Design Standards

Currently, few existing components are tested to listing standards implemented by a nationally recognized testing laboratory (NRTL). AHJs may allow the station manufacturer to provide technical information to prove that the compression, storage, and dispensing components used are fit for service. As the market develops, the list of listed components (and systems) is expected to grow.

Station Developer Standards (For informational use)

- SAE J2601–Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles[80]
- SAE J2799–Hydrogen Surface Vehicle to Station Communications Hardware and Software
- SAE J2719–Hydrogen Fuel Quality for Fuel Cell Vehicles
- HGV CSA Series Standards (currently being updated)

Utilize Best Safety Practices

***Best practice**... a technique or methodology that has reliably led to a desired result*

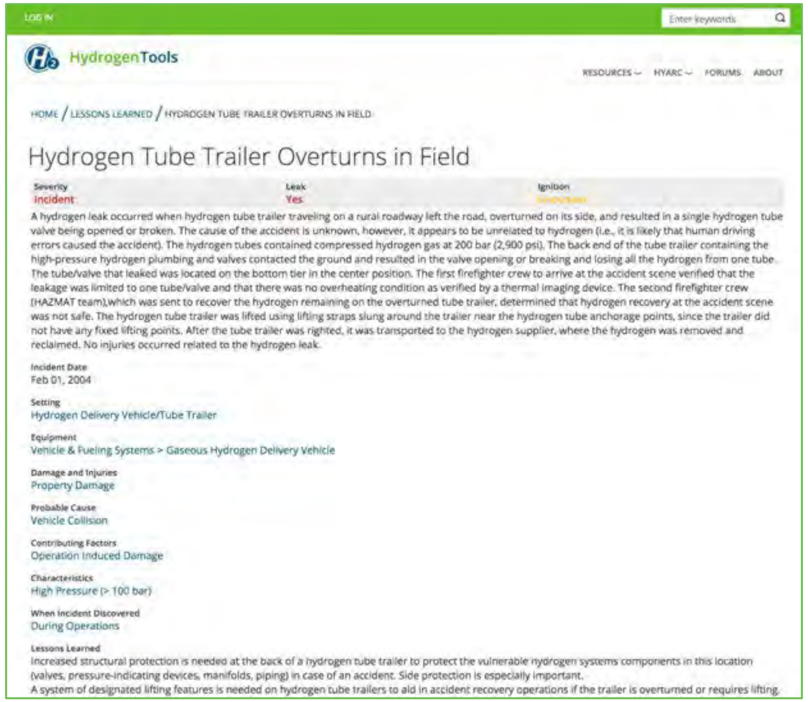
Utilizing Best Safety practices:

- Implements the benefits of extensive experience in the safe use of hydrogen
- Protects people, equipment and environment and minimizes risk of incidents
- Is demonstrated by their incorporation into designs, standard operating procedures, etc.

Those who cannot remember the past are condemned to repeat it.
- George Santayana

More info... https://h2tools.org/bestpractices/best-practices-overview

Did you know? Hydrogen best safety practices are based on a wealth of knowledge and experience related to safe use and handling of hydrogen exists as a result of an extensive history in a wide variety of industrial and aerospace settings.



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HOME / LESSONS LEARNED / HYDROGEN TUBE TRAILER OVERTURNS IN FIELD

Hydrogen Tube Trailer Overturns in Field

Severity	Leak	Ignition
Incident	Yes	[illegible]

A hydrogen leak occurred when hydrogen tube trailer traveling on a rural roadway left the road, overturned on its side, and resulted in a single hydrogen tube valve being opened or broken. The cause of the accident is unknown, however, it appears to be unrelated to hydrogen (i.e., it is likely that human driving errors caused the accident). The hydrogen tubes contained compressed hydrogen gas at 200 bar (2,900 psi). The back end of the tube trailer containing the high-pressure hydrogen plumbing and valves contacted the ground and resulted in the valve opening or breaking and losing all the hydrogen from one tube. The tube/valve that leaked was located on the bottom tier in the center position. The first firefighter crew to arrive at the accident scene verified that the leakage was limited to one tube/valve and that there was no overheating condition as verified by a thermal imaging device. The second firefighter crew (HAZMAT team),which was sent to recover the hydrogen remaining on the overturned tube trailer, determined that hydrogen recovery at the accident scene was not safe. The hydrogen tube trailer was lifted using lifting straps slung around the trailer near the hydrogen tube anchorage points, since the trailer did not have any fixed lifting points. After the tube trailer was righted, it was transported to the hydrogen supplier, where the hydrogen was removed and reclaimed. No injuries occurred related to the hydrogen leak.

Incident Date
Feb 01, 2004

Setting
Hydrogen Delivery Vehicle/Tube Trailer

Equipment
Vehicle & Fueling Systems > Gaseous Hydrogen Delivery Vehicle

Damage and Injuries
Property Damage

Probable Cause
Vehicle Collision

Contributing Factors
Operation Induced Damage

Characteristics
High Pressure (> 100 bar)

When Incident Discovered
During Operations

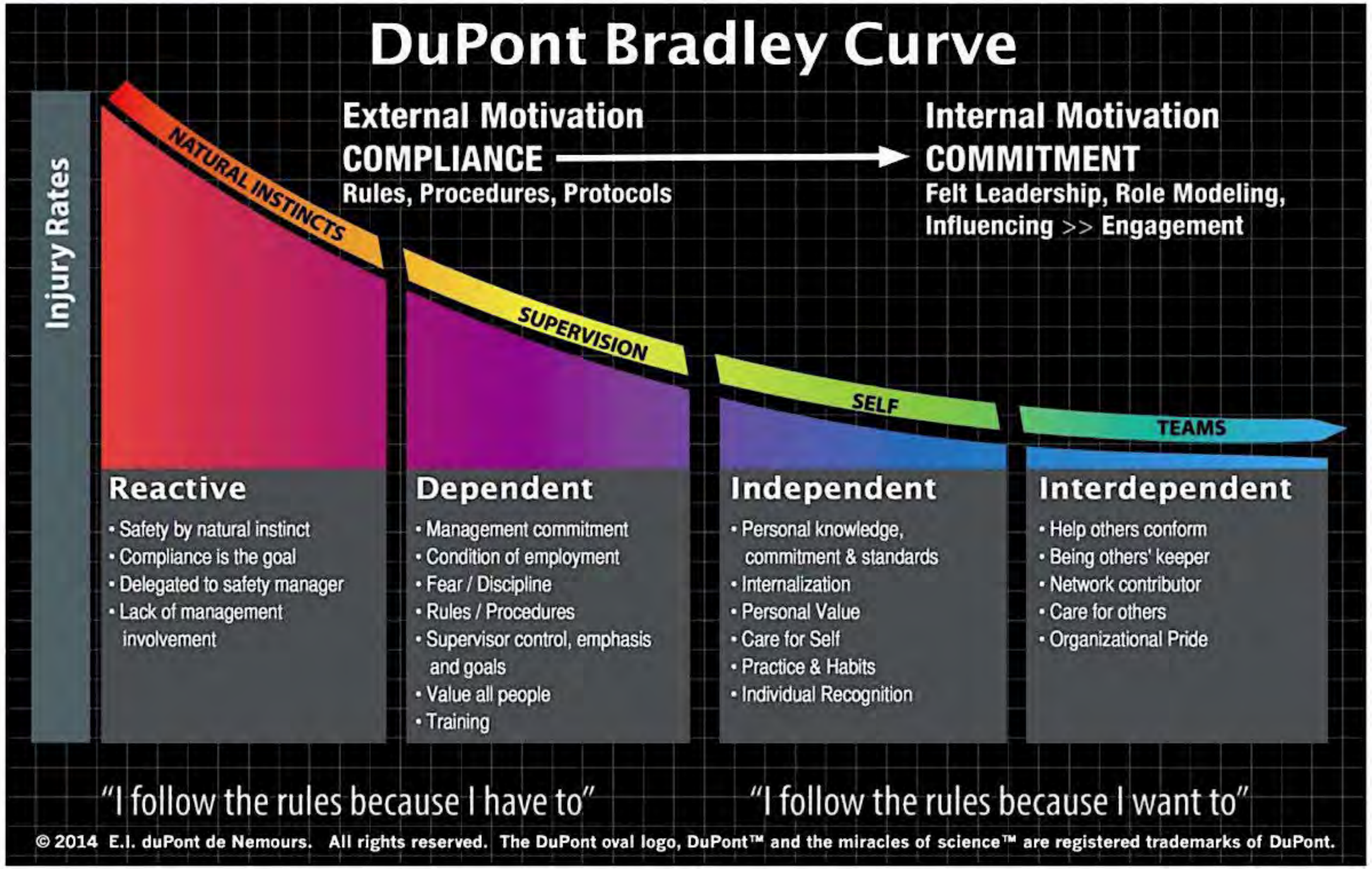
Lessons Learned
Increased structural protection is needed at the back of a hydrogen tube trailer to protect the vulnerable hydrogen systems components in this location (valves, pressure-indicating devices, manifolds, piping) in case of an accident. Side protection is especially important.
A system of designated lifting features is needed on hydrogen tube trailers to aid in accident recovery operations if the trailer is overturned or requires lifting.

A best practice record from h2tools.org

Be Invested in Safety

Investment in Safety:

- Is directly impacted by your organization's:
  - Beliefs
  - Perceptions
  - Values
- Is critical for:
  - Building a sustainable legacy
  - Maximizing an organization's impact and reaching goals
  - Ensuring long-term acceptance of the hydrogen industry
- Must be demonstrated
  - A culture of safety



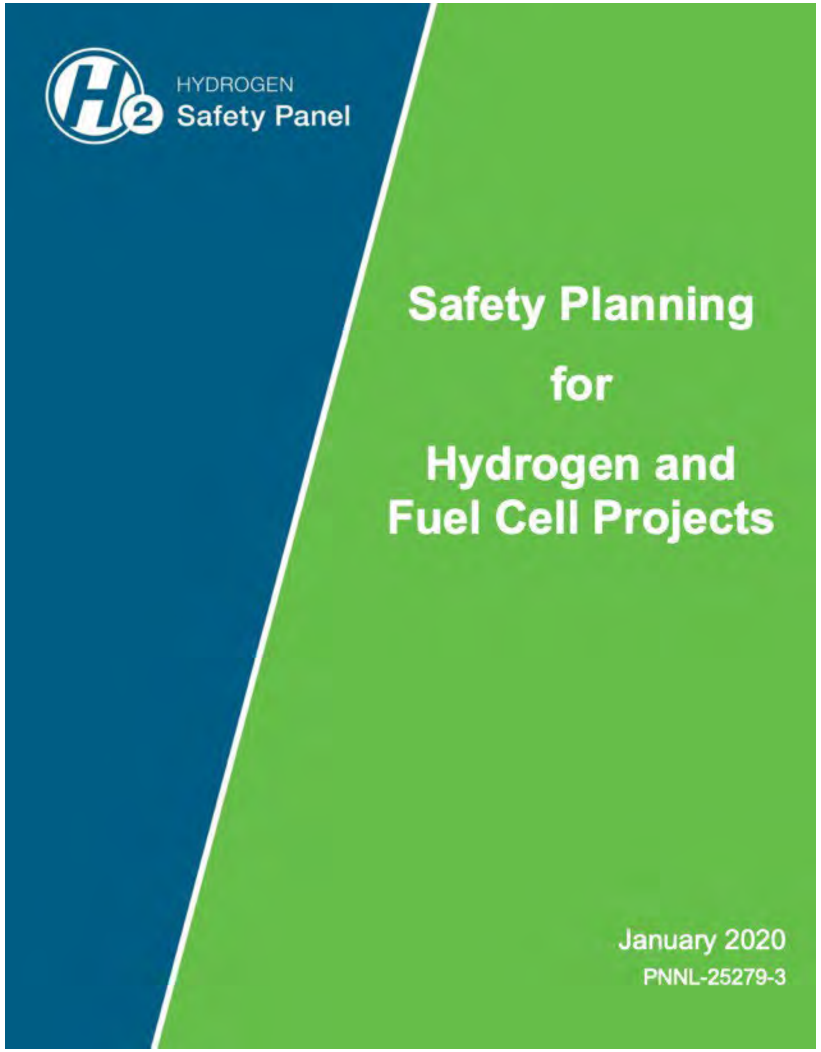
General Safety Planning

- Safety planning should be embraced as an integral part of the design, construction, operation and maintenance of a system rather than being considered an after thought or a barriers to overcome

- Safe practices in the production, storage, distribution, and use of hydrogen are **essential to protect people from injury or death, and to minimize damage to facilities**

- Safe practices will also help avoid negatively impacting the public's perception of hydrogen systems

- Helpful guidance on safety planning can be found at https://h2tools.org/bestpractices/safety-planning.



The Safety Basics

Hydrogen safety, like all flammable gas, relies on these key safety considerations:

- Eliminate hazards or define mitigation measures
- Ensure system integrity
- Provide proper ventilation to prevent accumulation
- Manage discharges
- Detect and isolate leaks
- Train personnel

Photo courtesy of Cummins

There is Much to Consider for Hydrogen Safety

Resources to Help You Navigate to Safety

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HydrogenTools

An online hydrogen information portal

URL: **h2tools.org**

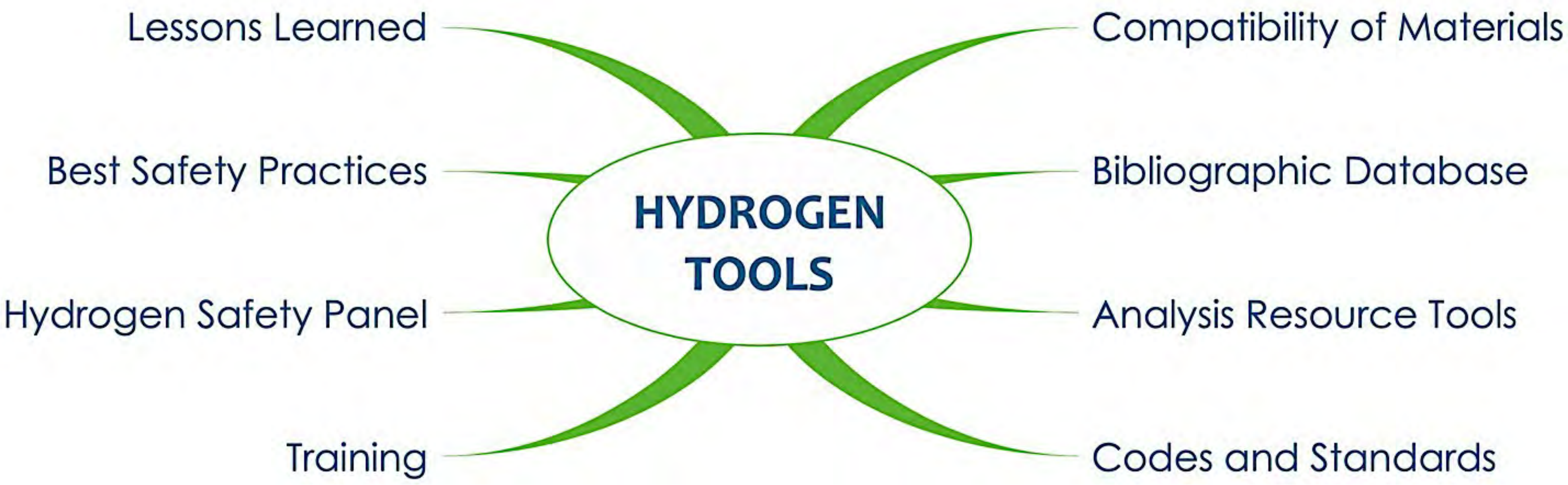
CENTER FOR Hydrogen SAFETY

An international nonprofit focused on applied hydrogen safety

URL: **www.aiche.org/chs**

URL: h2tools.org

Significant hydrogen safety resources in one location



- Supports implementation of the safe handling practices and procedures
- Brings together a variety of tools and web-based content on safety of hydrogen
- Informs designers, stakeholders and first responders

Center for Hydrogen Safety's Strategic Vision

Champion hydrogen safety and best practices worldwide

Empower stakeholders and the workforce

Ensure the safe and timely transition to hydrogen and fuel cell technology

Bringing together a global nonprofit membership to expand the body of safety knowledge

CHS Focus

- **Collaborate** in a global hydrogen safety community
  - Demonstrate commitment to safety - “License to do business”
  - Participate in member meetings
  - Contribute to working groups and conferences

- Access resources to **remove barriers** and manage risk
  - Hydrogen Safety Panel
  - Hazard analysis, site evaluation, custom training
  - Outreach, incident investigation

- **Increase knowledge** and expertise
  - Training courses, credentialing, and webinars
  - Conferences and workshops
  - Best practices and incident resources
  - Technical bulletins

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Connecting a Global Community

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STRATEGIC PARTNERS

Asia-Pacific Hydrogen Association, Australian Hydrogen Council, California Fuel Cell Partnership, CGA Compressed Gas Association The Standard For Safety Since 1913, DECHEMA, U.S. Department of Energy Energy Efficiency & Renewable Energy, Hydrogen Council, HySafe, HySUT, INERC BV Quality Services for Operations, IPHE, RHA Renewable Hydrogen Alliance, SCEJ The Society of Chemical Engineers, Japan

Education and Training

https://tinyurl.com/CHS-Course

Fundamental Hydrogen Safety E-Courses

- Hydrogen as an Energy Carrier
- Properties and Hazards
- Safety Planning
- Facility Design
- Equipment and Components
- Liquid Systems
- Material Compatibility
- System Operation
- Inspection & Maintenance
- Laboratories*
- Electrolyzer Safety*
- Fueling Stations*
- Hazard Analysis for H_2 Facilities*

First Responder Hydrogen Safety E-Courses

- Introduction to Hydrogen Safety for First Responders
- First Responders Micro Training Learning Plan
- Introduction to Hydrogen Fuel Cell Vehicles for Incident Response
- Fire Response & Extrication of a Hydrogen Fuel Cell Vehicle
- Transport of Hydrogen Fuel
- Hydrogen Fueling Station Incident Response

Other Training Resources

- Safety of Water Elecrolysis [Recorded Webinar]
- Global Hydrogen Safety Codes and Standards [Recorded Webinar]
- Ventilation Considerations for Hydrogen Safety [Recorded Webinar]
- Material Compatibility Considerations for Hydrogen [Recorded Webinar]
- Custom Virtual or In Person Hydrogen Safety Training

* Available late 2022 or early 2023

Concluding Thoughts

We must recognize that with the promise of hydrogen comes the responsibility of safety

- Applications using hydrogen will grow in volume and diversity
- Because hydrogen as a fuel is still new, the best methods of handling, storage, transport, and use may not be well understood by participants
- Safe practices for the production, storage, distribution, and use of hydrogen are essential
- CHS and the Hydrogen Tools Portal are available to help project participants to understand and apply safe practices

Thanks for Your Attention!

CENTER FOR Hydrogen SAFETY

Connecting a Global Community

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CHS… Bringing together individuals and organizations to develop and share best safety practices and learnings

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Q&A

Please use the
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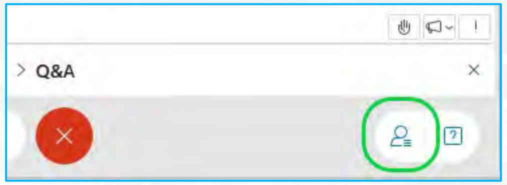

Facilitation:
Ideation & Taking Stock

Closing & Next Steps

- **Materials, recordings, and additional information to be made available at www.nyserda.ny.gov/hydrogen**
- **Join our email list for future updates/events: https://www.nyserda.ny.gov/Researchers-and-Policymakers/Hydrogen/Contact-Us**
- **Questions can be shared at cleanhydrogen@nyserda.ny.gov**

Thank you!