An Introduction to Hydrogen

From Production to End Uses

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Topics for today

- Why hydrogen?
- The basics
- Environmental, health, and safety
- Current markets
- Production methods
- Moving & storing
- Using hydrogen
- Economics overview

Why hydrogen?
The importance of hydrogen to a low-carbon future.

Decarbonization Pathways Enabled by Innovation

~10-15 years

~15-30 years

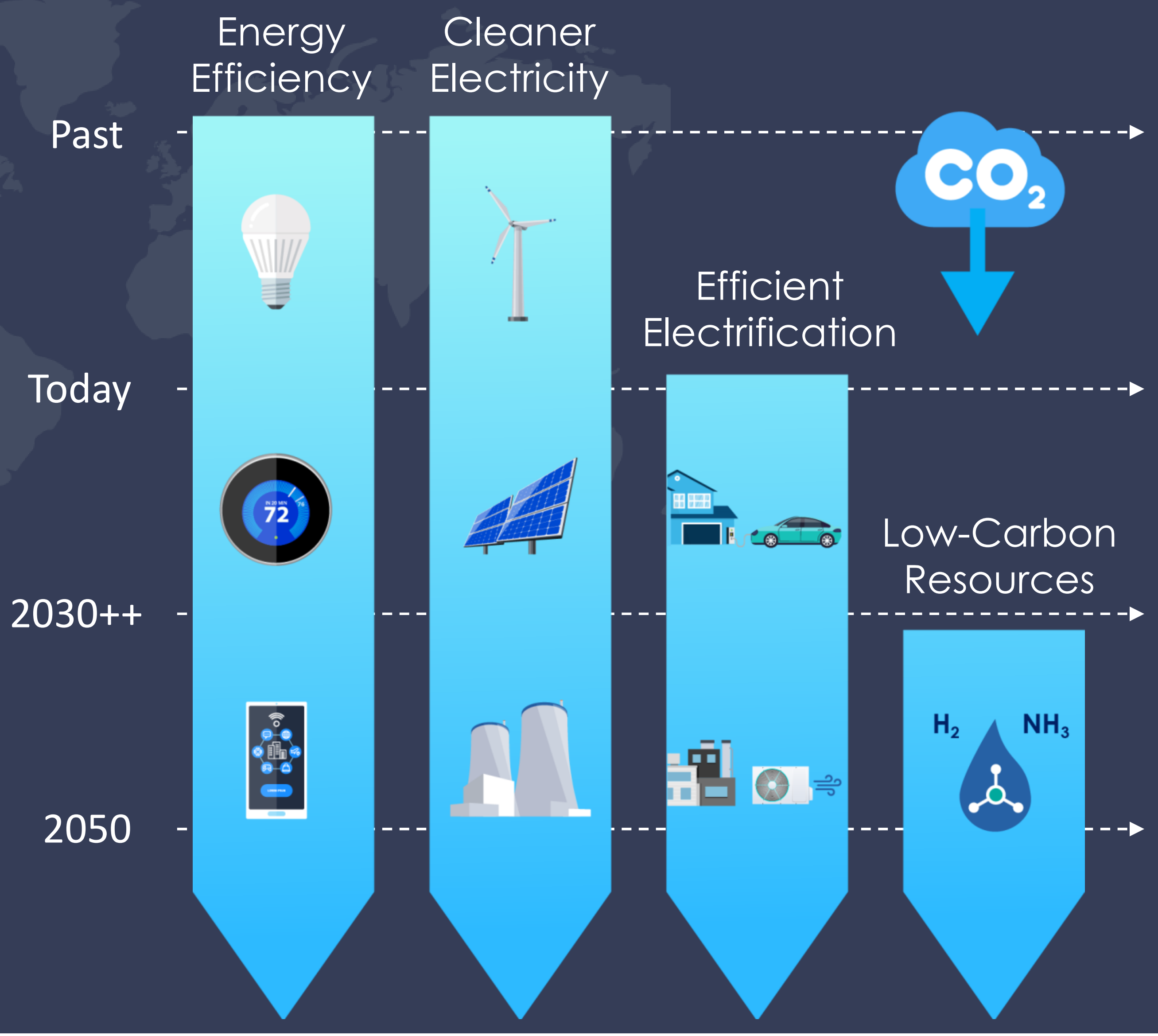
Decarbonization

Accelerate economy-wide, low-carbon solutions

- Electric sector decarbonization
- Transmission and grid flexibility: storage, demand, EVs
- Efficient electrification

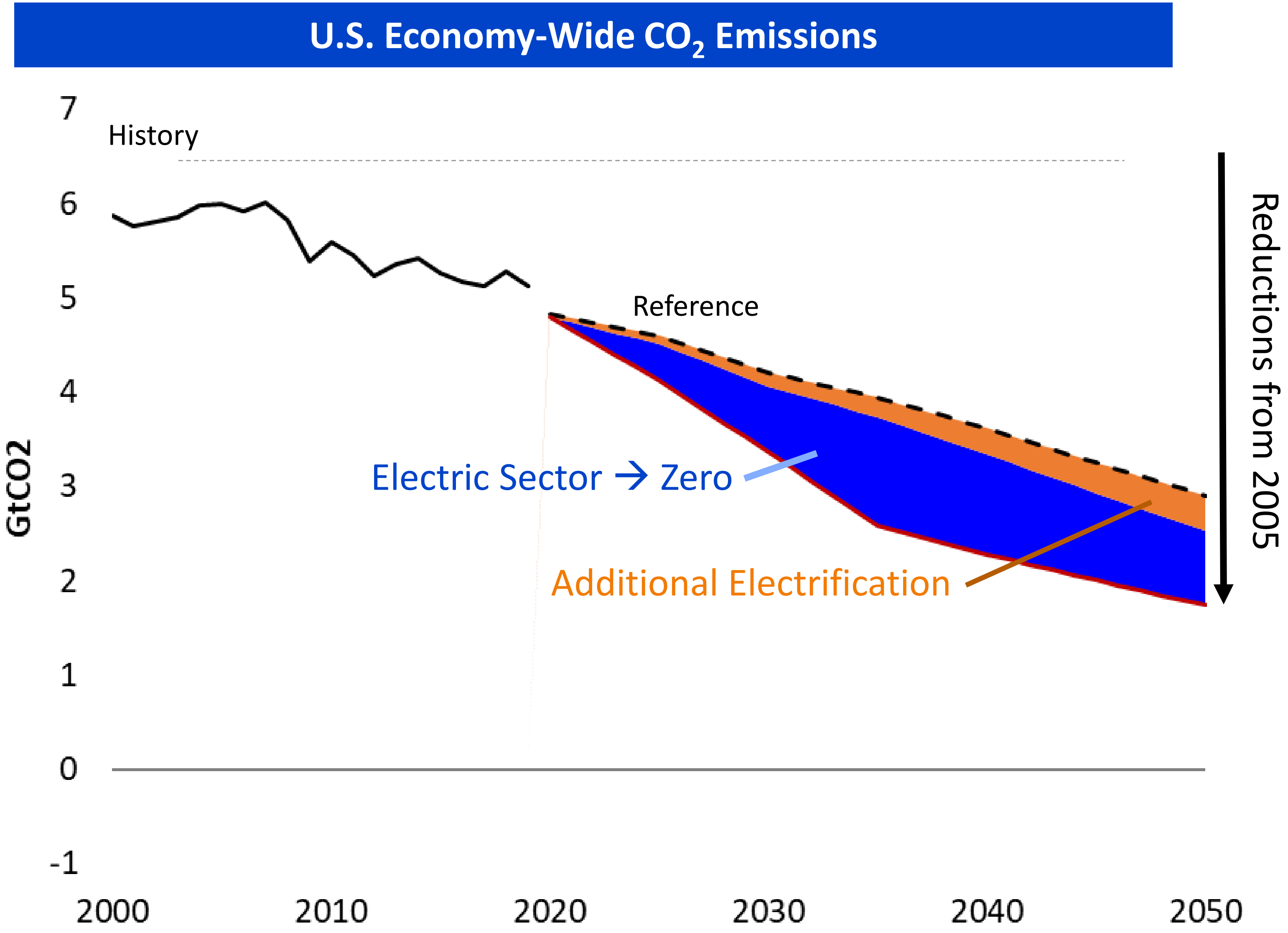
Achieve a net-zero clean energy system

- Ubiquitous clean electricity: renewables, advanced nuclear, CCUS
- Negative-emission technologies
- Low-carbon resources: hydrogen and related, low-carbon fuels, biofuels, and biogas



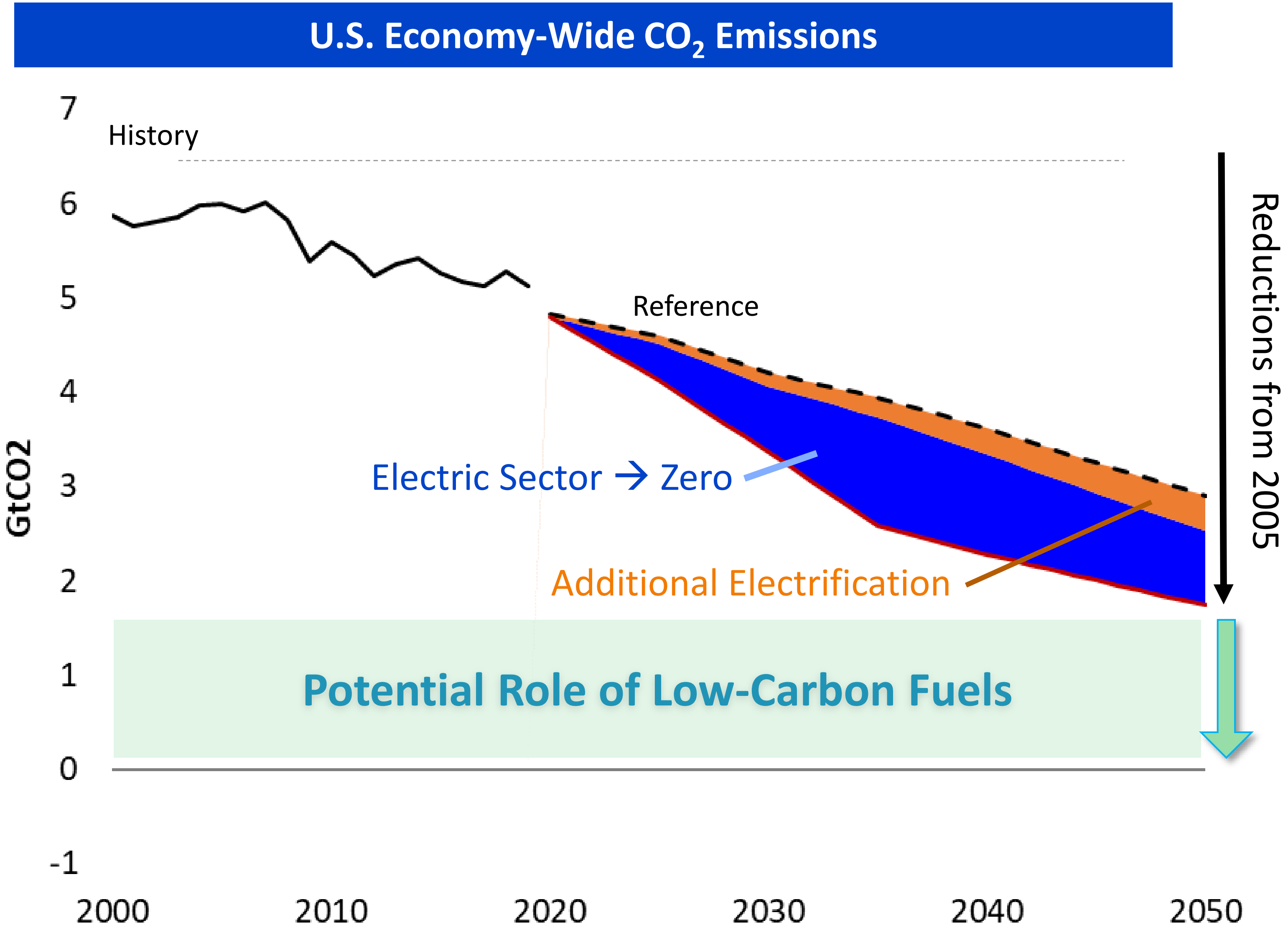
Reducing Economy-Wide CO_2 Emissions

1 Gt = 1000 MMT



Source: EPRI Report [3002020700](3002020700)

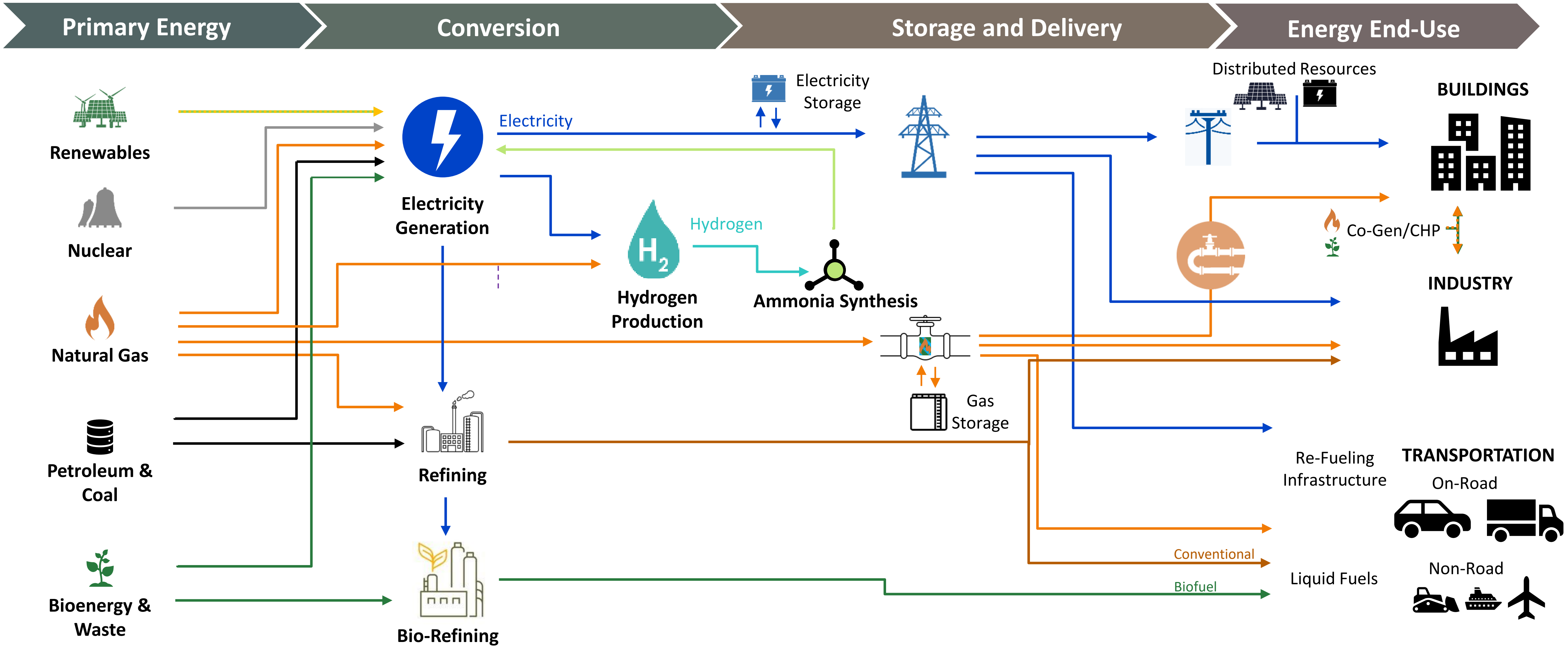
Reducing Economy-Wide CO_2 Emissions



1 Gt = 1000 MMT

Source: EPRI Report [3002020700]

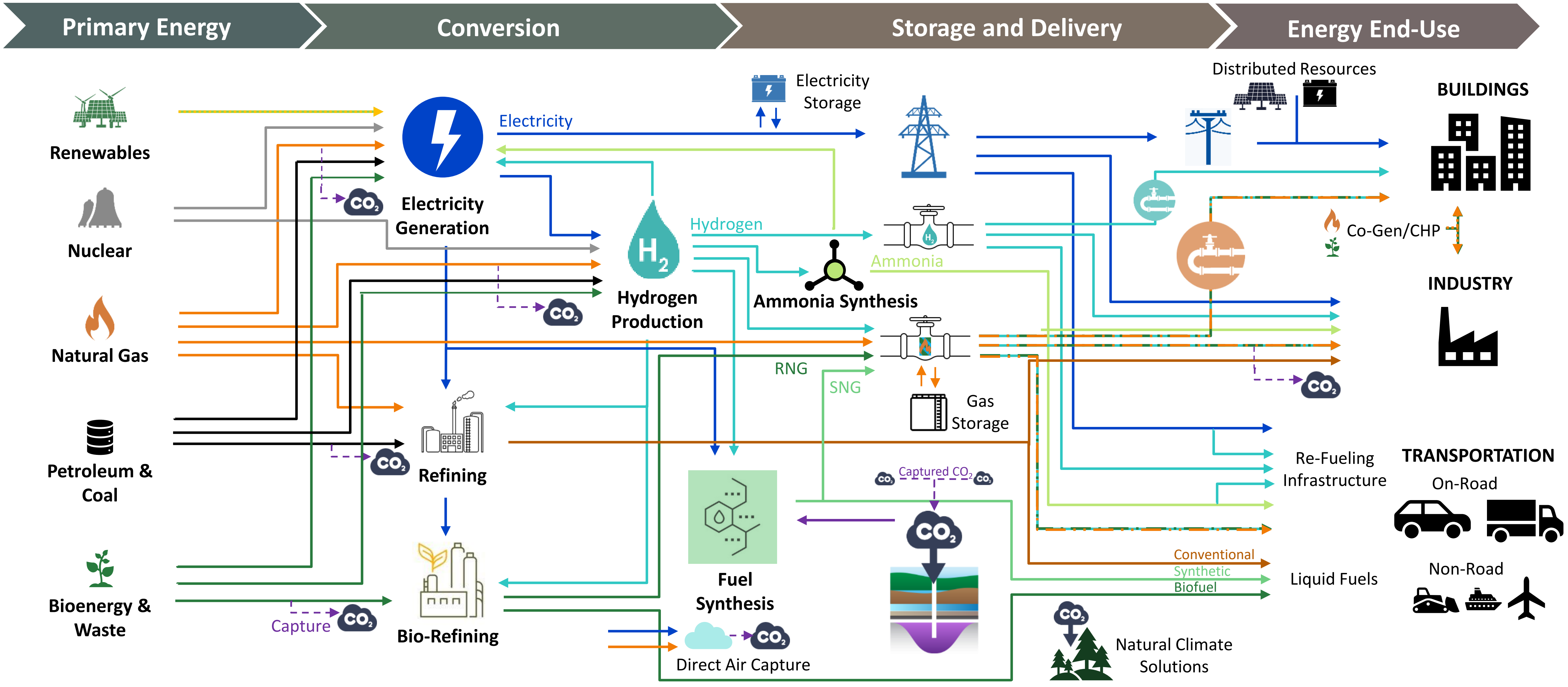
Today's Energy System



A Glimpse into the Future

New Resources and Players

how will they fit and transition?



There are various types of climate risk

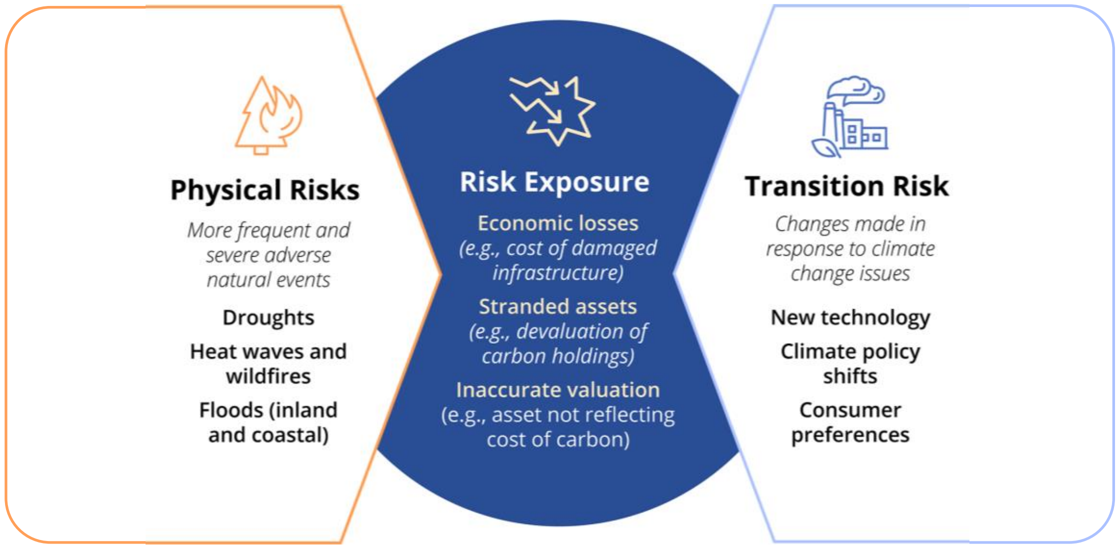
Physical risk: risk associated with changes in physical environmental and natural resource conditions with climate change
Generally greater risk with greater change

Transition risk: risk associated with uncertain transitions to potential low-carbon futures
May include impacts of regulatory, technological, or market changes to address climate change mitigation or adaptation

Society level: address transition risk now via mitigation efforts, reduce physical risk down the road

Company level: must contend with both—climate is changing, but so is the business and regulatory landscape

Different kinds of uncertainty for each



Low-carbon Resources Initiative

What are the available technology pathways?

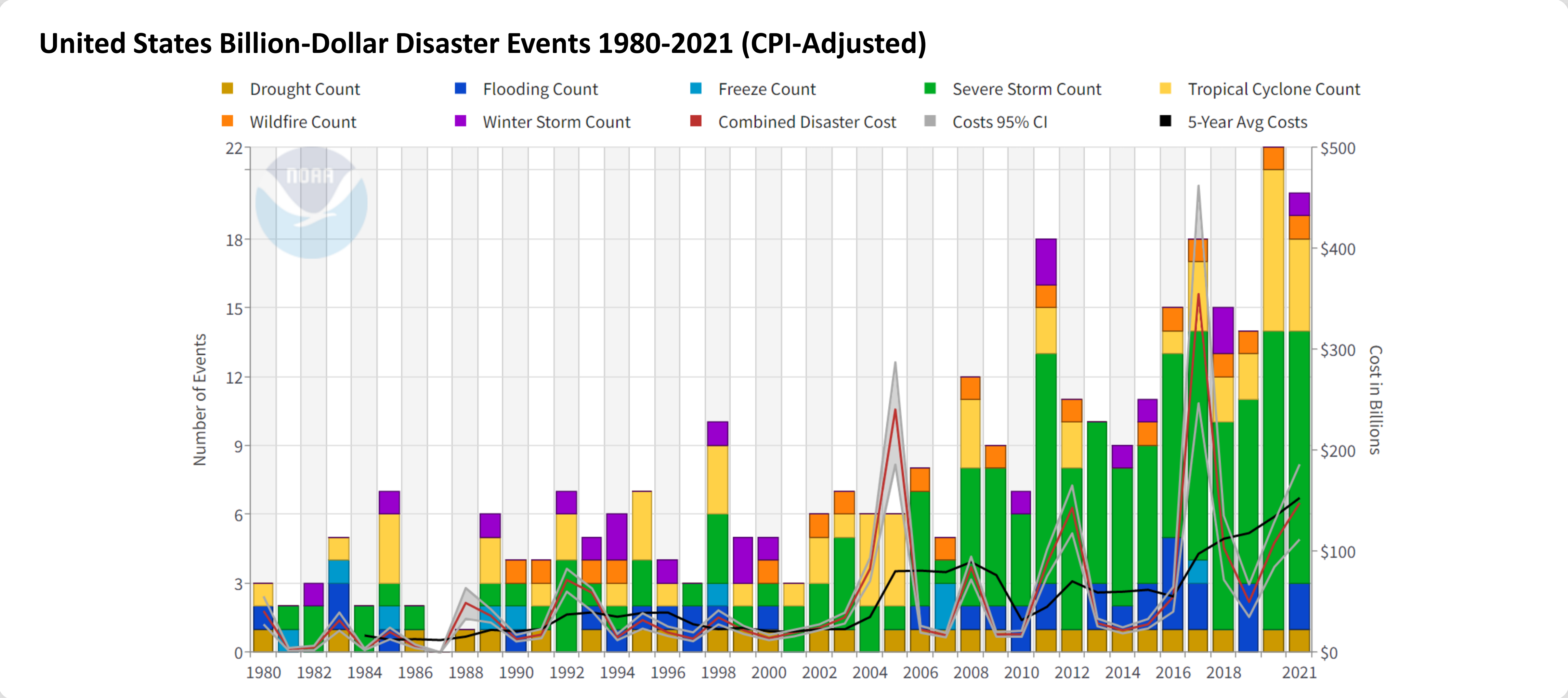
How do we accelerate technology deployment to reduce risk across the energy economy?

Informing company strategies to support risk mitigation through the energy transition

Source: US Government Accountability Office (GAO-21-327)

Source: EPRI 3002025872

And…there is a cost



EPRI 3002025872

Source: NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Distasters (2022).

The basics of hydrogen and its key properties

Basic Chemistry

Molecular Hydrogen: H_2

- Lightest element (H) on the periodic table
  - Contains one proton and one neutron
- Exists at a relatively low concentration in the atmosphere
  - Combines with other elements to form compounds:

Combines with:	→	To form:
Oxygen	→	Water (H_2O)
Nitrogen	→	Ammonia (NH_3)
Carbon	→	Methane (CH_4)

Unique Properties of Hydrogen

- **Low volumetric energy density**
  - Very high energy-to-weight ratio
  - More storage space needed. Compressed or liquified storage increases cost
- **Can be liquified (LH_2)**
  - Allows for much higher energy density compared to gaseous H_2
  - Energy-intensive process and LH_2 can be lost through evaporation
- **Small molecular size**
  - Causes H_2 to disperse a lot more quickly than other fuel
  - Need proper materials and tools to contain and detect
  - Leaks through joints & seals in pipes more easily than natural gas
- **Hydrogen absorption by materials**
  - Allows for storage of hydrogen using metal hydrides
  - Can embrittle steel, cause fatigue cracks, and degrade plastics
- **Non-toxic**
  - Exposure to other fuels & vapors can cause adverse health outcomes
  - Combustion of pure H_2 does not produce poisonous CO gas
  - Combustion still produces NO_x since N_2 and O_2 are the dominant constituents in air and react spontaneously at high temperatures

Hydrogen Embrittlement

Photo by CEphoto, Uwe Aranas or alternatively © CEphoto, Uwe Aranas
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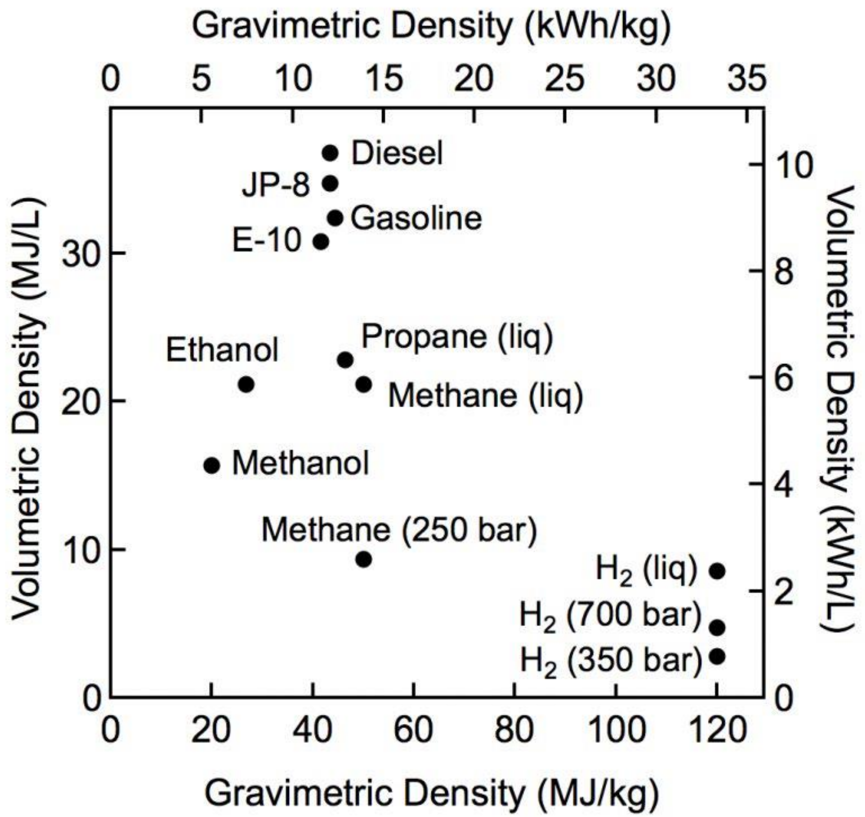
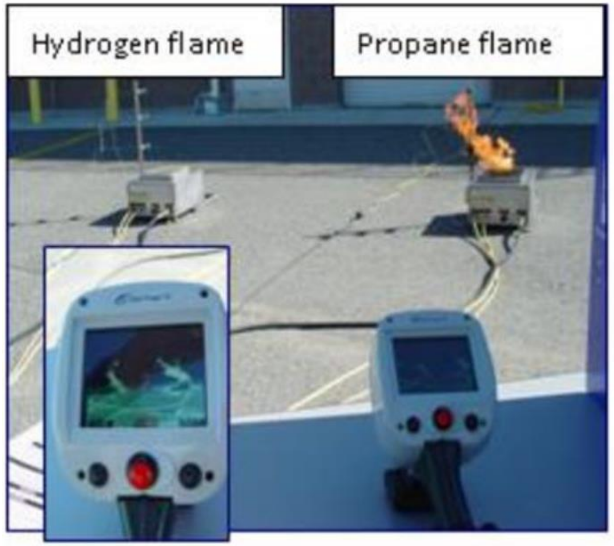


US Department of Energy (DOE). Available online: https://www.energy.gov/eere/fuelcells/hydrogen-storage (accessed on 02/25/23).

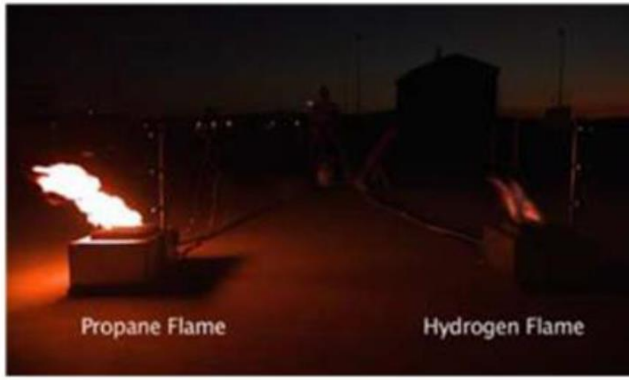
Environmental, health, and safety considerations of hydrogen

Environmental health and safety considerations

Hazards
Very small molecule: need proper materials to contain and detect
Material compatibility: can embrittle some metals, causing cracks and leaks
Fire: highly flammable, potential flame jetting. Pale blue flame when burning is difficult to see in daylight
Explosive: high explosive energy
Pollutants: H_2 generates incremental NO_x when it is combusted alone or blended with natural gas
Detection: H_2 gas is colorless and odorless. Burns with pale blue flame which is difficult to see in daylight.
Storage: Typically transported and stored at high pressure (gas) and very low temperature (liquid)
Asphyxiation: can occur in enclosed areas (unlikely)



Hydrogen and Propane Flames in Daylight
(Photo courtesy of HAMMER)



Hydrogen and Propane Flames at Night
(Photo courtesy of ImageWorks)

Source: h2tools https://h2tools.org/bestpractices/hydrogen-flames

- Lack of odor
- Colorless gas
- Invisible flame
- Broad flammability range
- Low ignition energy

Proper design and procedures must be used to avoid potential fire or explosion

Source: LCRI Report 3002019994

Environmental health and safety mitigations

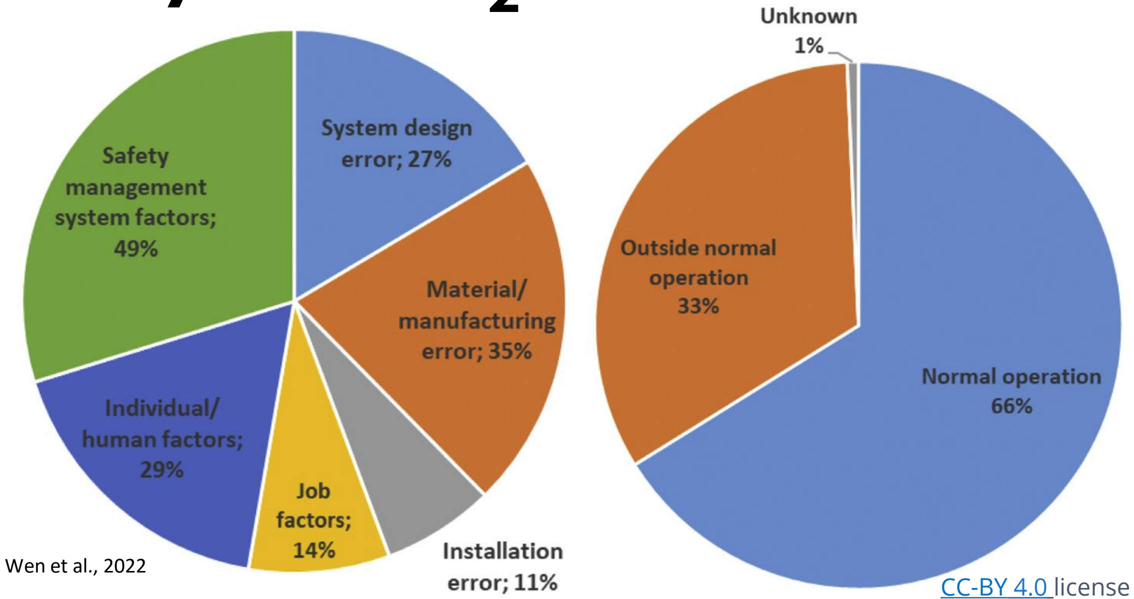
Hazards	Mitigations
Very small molecule: need proper materials to contain and detect	Welded connections and hydrogen-compatible materials. Consult industry standard for hydrogen-specific component requirements
Material compatibility: can embrittle some metals, causing cracks and leaks	Codes & standards (ASME B31.12) outline material requirements for leak protection as well as to minimize **embrittlement** and **corrosion**
Fire: highly flammable, potential flame jetting. Pale blue flame when burning is difficult to see in daylight	Utilize leak and flame **detectors**, proper design and system shutdown planning per NFPA 2, industry best practices, control ignition sources, and regular maintenance
Explosive: high explosive energy	
Pollutants: H_2 generates incremental NO_x when it is combusted alone or blended with natural gas	**NOx emissions** can be reduced by employing new burner designs & selective catalytic reduction systems for post-combustion control
Detection: H_2 gas is colorless and odorless. Burns with pale blue flame which is difficult to see in daylight.	H_2 gas and flame **detectors** commercially available, with newer leak detection methods being explored (e.g., wide-area leak detection)
Storage: Typically transported and stored at high pressure (gas) and very low temperature (liquid)	Gas **storage** in cylinders per DOT/FMVSS requirements (vehicles), or gas/liquid per ASME (stationary tank storage), with general designs per NFPA 2. Salt cavern **storage** being developed
Asphyxiation: can occur in enclosed areas (unlikely)	Hydrogen sensors should be placed in **enclosed** spaces where hydrogen could collect

Follow existing codes and standards and use best practices to minimize hydrogen risks

Source: LCRI Report 3002019994

Source: h2tools https://h2tools.org/bestpractices/best-practices-overview

Analysis of H_2 Incidents in Industry



HIAD and Wen et al., 2022

- Many incidents involve several contributing factors
  - **Human errors** are likely to cause an incident
  - Most occur after ignoring near misses & warnings
- A strong **safety culture**
  - must be established by leadership
  - Leads employees to work effectively and feel comfortable raising concerns

Approaches to Mitigate H_2 Incidents & Consequences

- **Leak reduction:**
  - Early detection via sensors
  - Automatic interlock & alarm activation mechanisms
  - Regular inspections and maintenance
- **Ignition minimization:**
  - Purging: use inert gas for testing equipment
  - Areas electrical classification
  - Ventilation design and management
  - Equipment siting
- **Consequence reduction** (fire or explosion):
  - Maximize distance and shielding
- **Safer process equipment:**
  - Inherent safe design
  - Provide regular and up-to-date training

Many codes and standards are derived from proven best practices

Key Siting Considerations

- **Electrical Source**
  - Baseload operation versus renewable or grid support
  - Long term price contracts
- **Water Source**
  - Sustainable water sources
  - Long term water contracts
  - Equipment to process water
- **Land Use and Footprint**
  - Space available for system
- **Transport or Conversion**
  - Pipeline access, highway, shipping, or transport routes
  - Above or underground storage (salt caverns, etc.)
  - Footprint for chemical conversion (NH_3, etc.)
- **Offtake and End Use**
  - Offtake or end use customer
  - Long term contract potential
  - Price appetite considering production, storage, and delivery

EPRI

Equity and Environmental Justice

EPA's definition

- *Environmental justice is the fair treatment and meaningful involvement of all people, regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies*

Goals

- An energy future that fully and meaningfully involves communities
- Social justice: An equitable distribution of both benefits and costs
- It is a part of decision making throughout the process
- Movement towards a just transition and a just future
- With expertise comes responsibility – present accessible, understandable, and factual information

Helpful resources

- EPRI's Equitable Decarbonization Interest Group (EDIG)
- DOE's energy justice mapping tool: https://energyjustice.egs.anl.gov/
- DOE's disadvantaged communities mapping tool: https://screeningtool.geoplatform.gov/en/#3.74/25.83/-93.2
- DOE's Justice 40 initiative: https://www.energy.gov/diversity/justice40-initiative

Report #: 3002023584
Just Transition: An Overview of the Landscape and Leading Practices
https://www.epri.com/research/products/000000003002023584

Community Concerns of Hydrogen

Economic Impacts

- Will this increase bills?
- How are the costs and benefits being distributed?

Workforce Impacts

- Will jobs be lost?
- How will upskilling or reskilling be handled?

Safety and Health Impacts

- How are leaks, fires, explosions… being prevented?
- How are CO_2, NO_x, or other emissions being prevented?

Environmental Impacts

- Will water and land be used responsibly?
- What is the global warming protentional?
- Are fossil fuels continuing to be combusted?

Diversion or Misuse of Resources

- Will water, land, and energy be used responsibly?
- Will renewable resources be diverted from communities?

Social Impacts

- How will job transition or loss impact a community's or person's sense of self, purpose, or belonging?
- Will large industrial plants or infrastructure projects feel like a deterioration of the community?

Misplaced Efforts or Prioritizations

- Does this distract from electrification and efficiency efforts?
- Does this distract from improving economic outcomes?

The various hydrogen production techniques

Hydrogen Production Methods

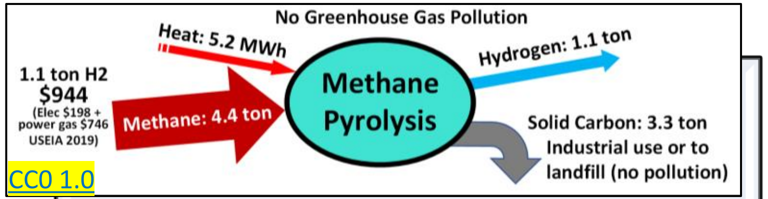
Electrolysis using electricity from renewable energy sources

Steam methane reforming of natural gas

Steam methane reforming, but much of the emissions are captured and stored

Gasification of coal or biomass

Electrolysis using electricity from nuclear energy



Methane pyrolysis

EPRI

Production – Fossil Derived Hydrogen

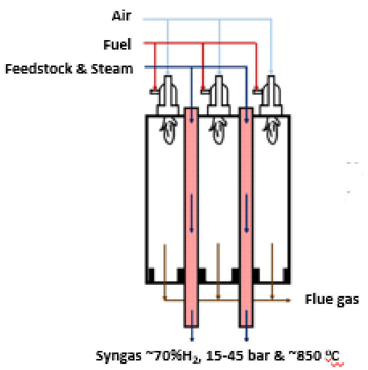
Fossil-derived sources without carbon capture are the most prominent sources of hydrogen

- ~62% of production is from SMR (worldwide)
- ~19% of production is from coal gasification (worldwide)

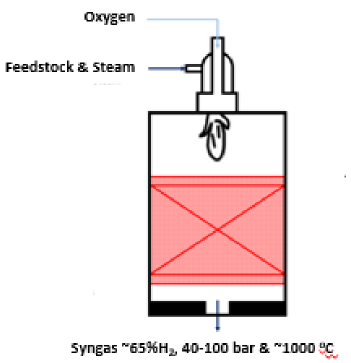
Currently, SMR and gasification accounts for ~900 MMT of CO_2/year

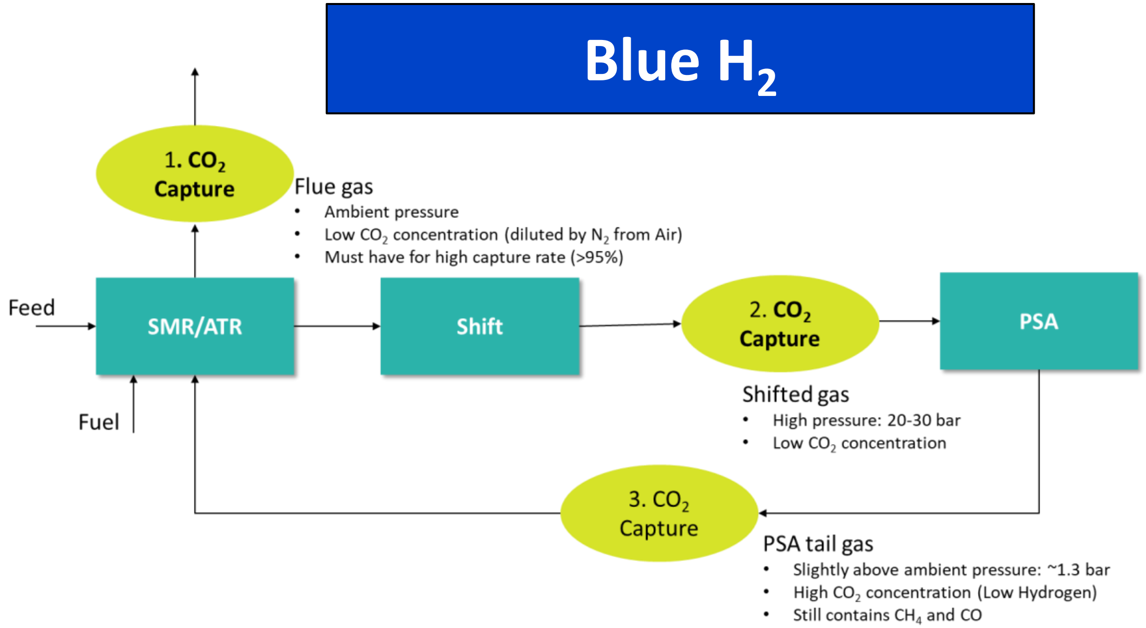
- SMR: emits ~10 metric tons of CO_2 for every metric ton of hydrogen produced
- Coal gasification: almost twice as CO_2-intensive as SMR

Steam Methane Reforming (SMR)

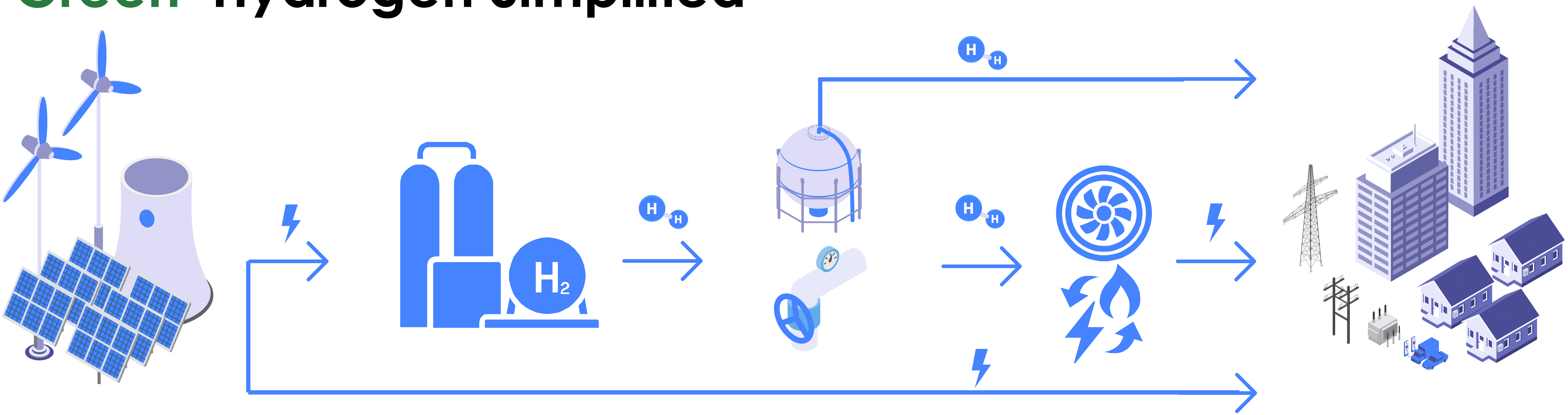


Autothermal Reforming (ATR)





‘Green’ Hydrogen Simplified



Carbon-free generation	Hydrogen production	Transport & storage	Power generation	End use
Renewables and nuclear deliver electricity to the grid and to hydrogen production	Electrolysis can leverage carbon-free energy to produce H_2	Transported by pipelines and stored underground.	Dispatchable carbon-free electricity	Electricity delivered to customer

Hydrogen could decarbonize many end uses in addition to power generation technologies

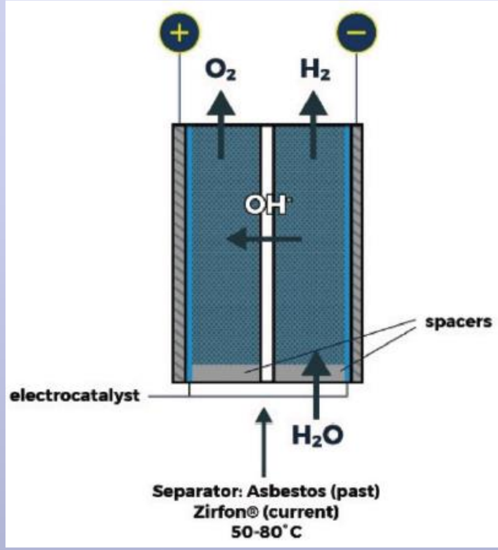
Production – Electrolysis

- Electrochemical process that splits water into hydrogen and oxygen using an electrolyzer powered by electricity
- Electrolyzers have a positively charged anode electrode generating oxygen and a negatively charge cathode electrode generating hydrogen, which are separated by a membrane or separator.

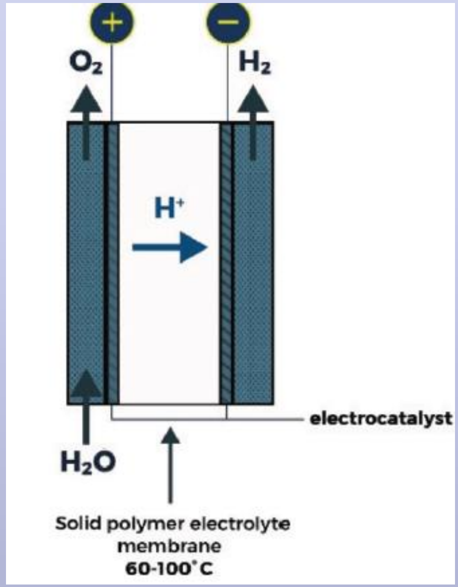
Types of Electrolyzers:

Source: LCRI Report 3002021864

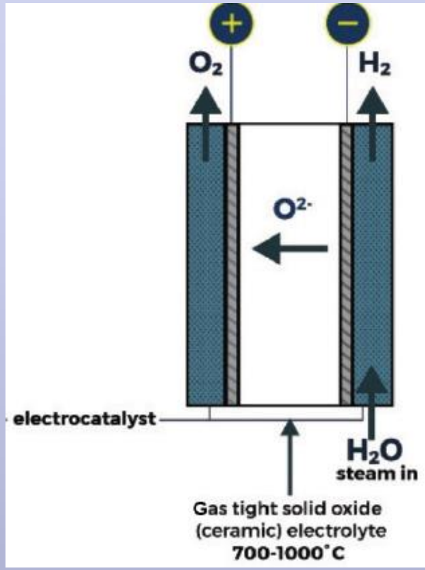
Alkaline



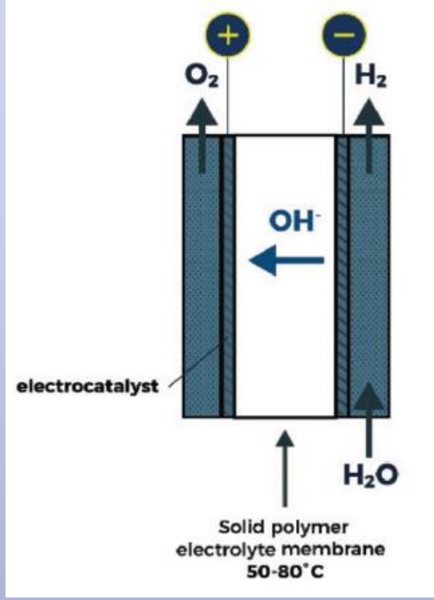
Proton Exchange Membrane (PEM)



Solid Oxide Electrolyzer Cell (SOEC)



Anion Exchange Membrane (AEM)

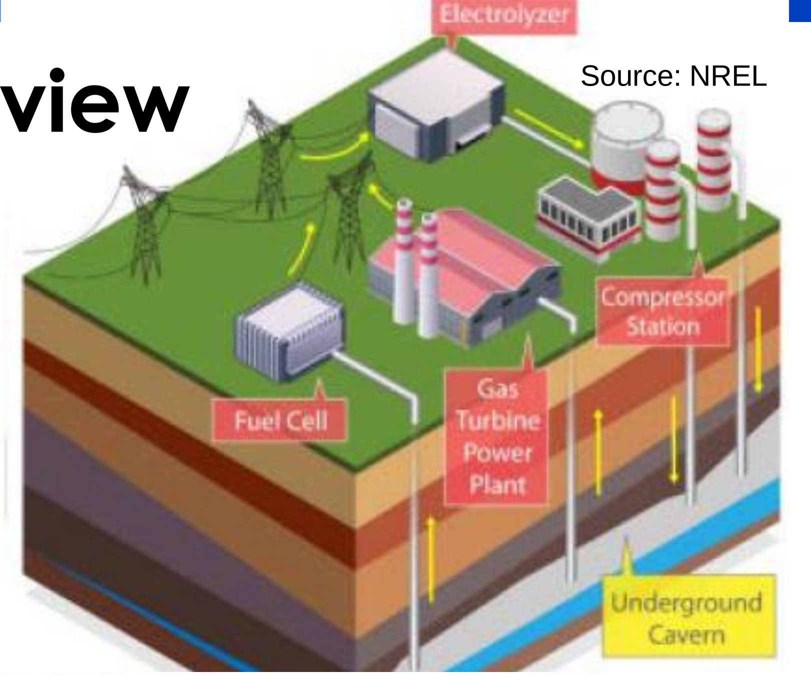


The methods for hydrogen storage and delivery

Transport, Storage, and Distribution Overview

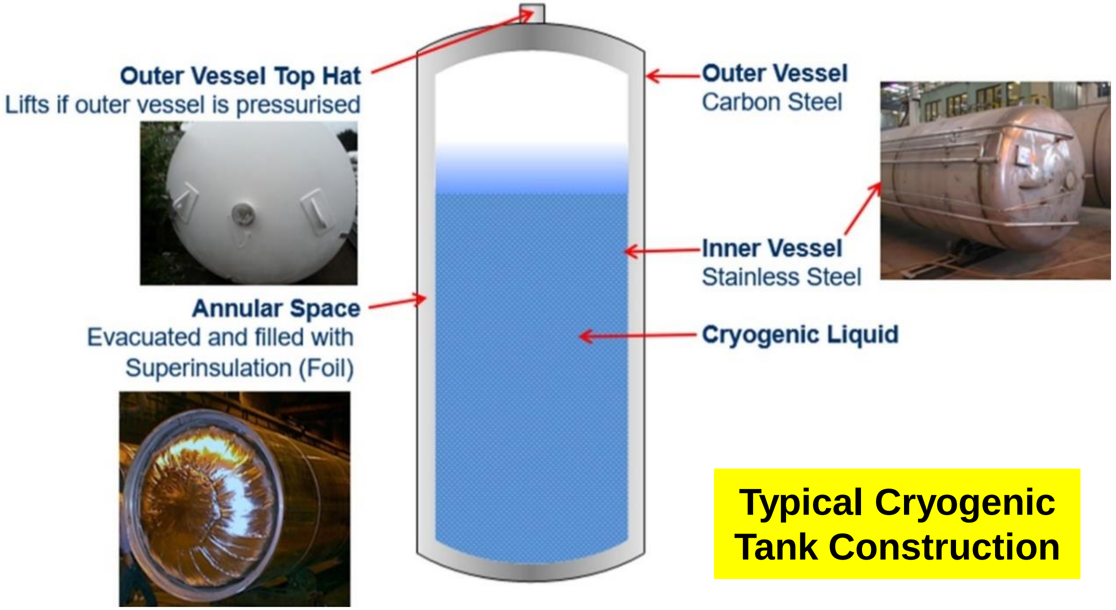
- Transport methods
  - Pipelines
  - On-road vehicles
  - Shipping
- Storage methods
  - Underground (salt caverns, depleted oil and gas reservoirs, saline aquifers)
  - Tanks (compressed gas, liquified)
  - Converted to other energy carriers
- Considerations
  - Conversion costs
  - Compression vs. liquefaction
  - Transmission vs. distribution pipelines
  - Electricity costs

Source: DOE https://www.energy.gov/eere/fuelcells/hydrogen-pipelines



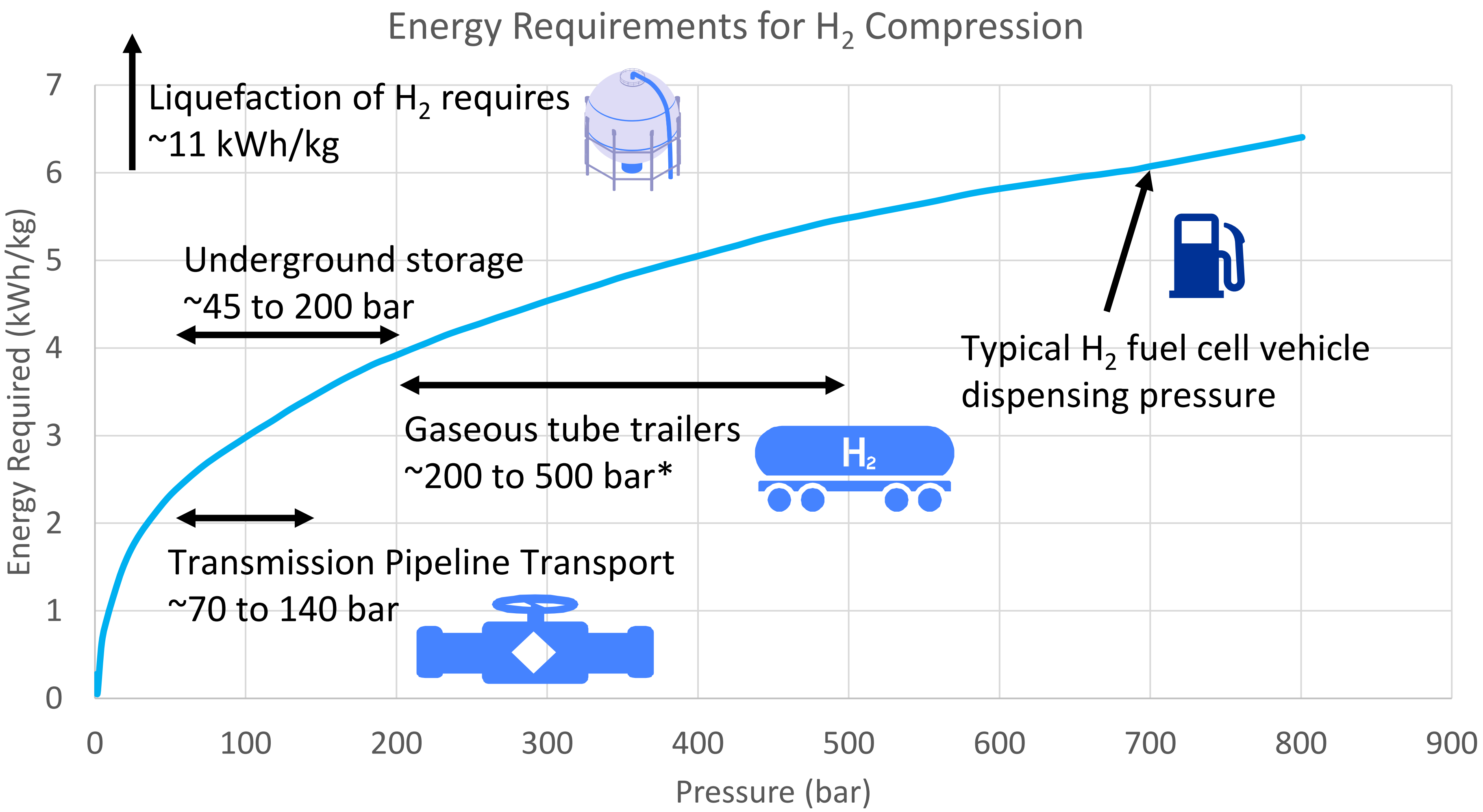
Source: NREL

- Cryogenic tanks are double walled and vacuum insulated



https://h2tools.org/bestpractices/liquid-storage-vessels#:~:text=Liquid%20hydrogen%20(LH2)%20is%20usually,precaution%20to%20prevent%20over%20pressurization.

Moving & Storing = Energy

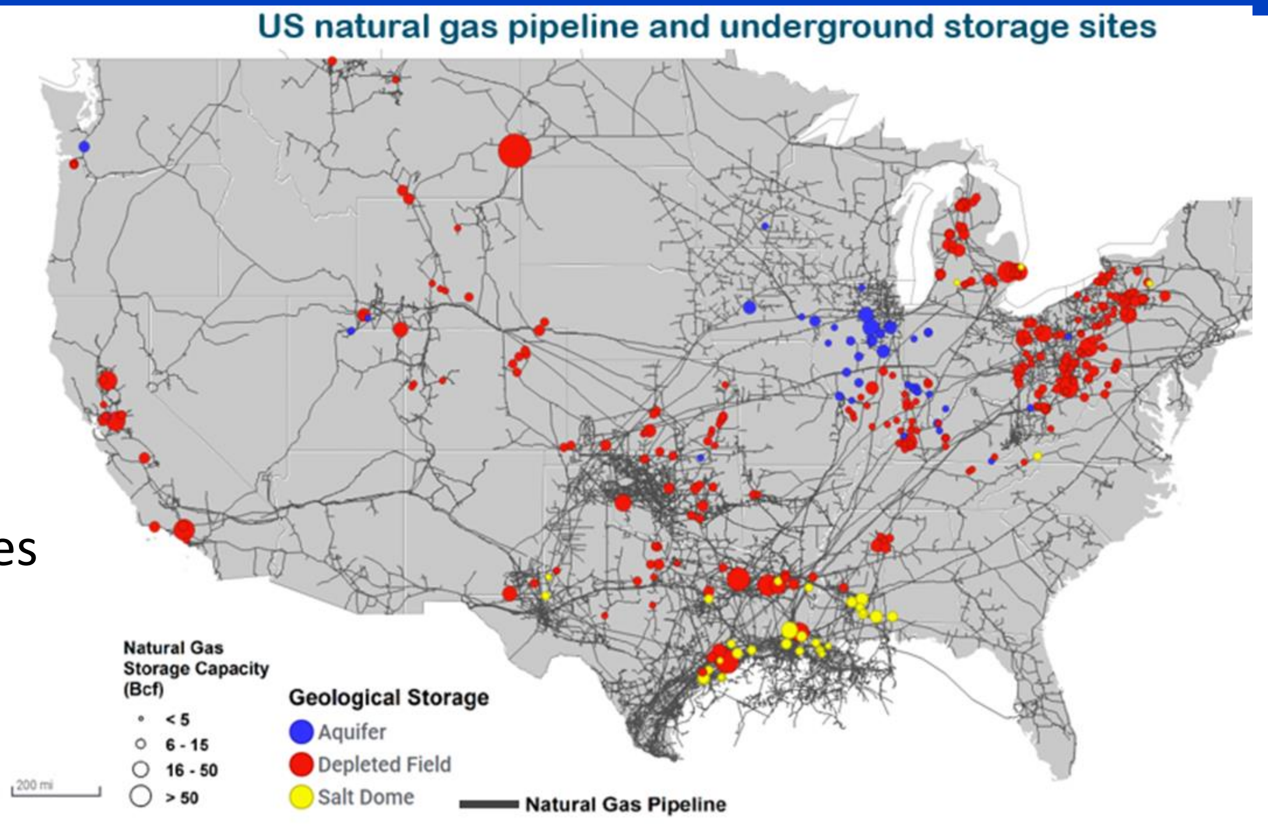


*U.S. Department of Transportation limits tube trailer pressures to 250 bar, higher pressures require special exemptions

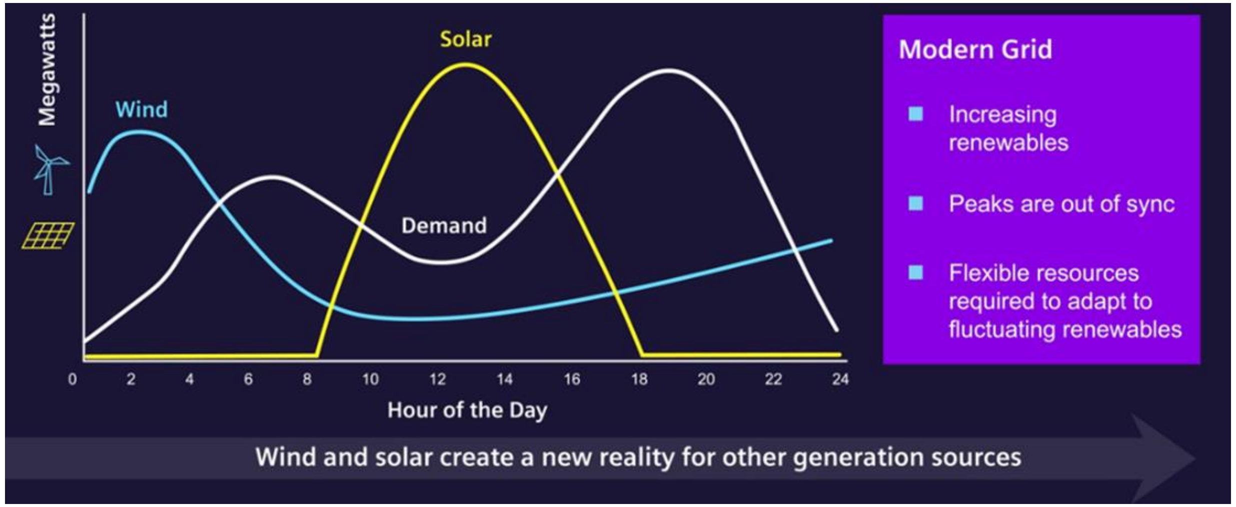
Data source: Elberry et al.
References: US DOE, EPRI

Bulk Storage

- Geologic storage of H_2 can be used to:
  - Meet seasonal energy demand needs
  - Ensure continuity in supply during disruptions
  - Arbitrage low-cost energy to high demand times
  - Helps integration of more intermittent renewables
- A need for large scale, long duration storage
  - The U.S. natural gas infrastructure has immense energy storage capacity
    - Intense demand needs of seasonal space heating
    - Can meet ~16% of total annual natural gas demand
  - U.S. Electricity storage meets ~0.7% of typical annual electricity demand
    - >90% of this is from pumped hydro
    - Battery storage capacity is growing, yet small and lacks seasonal capabilities

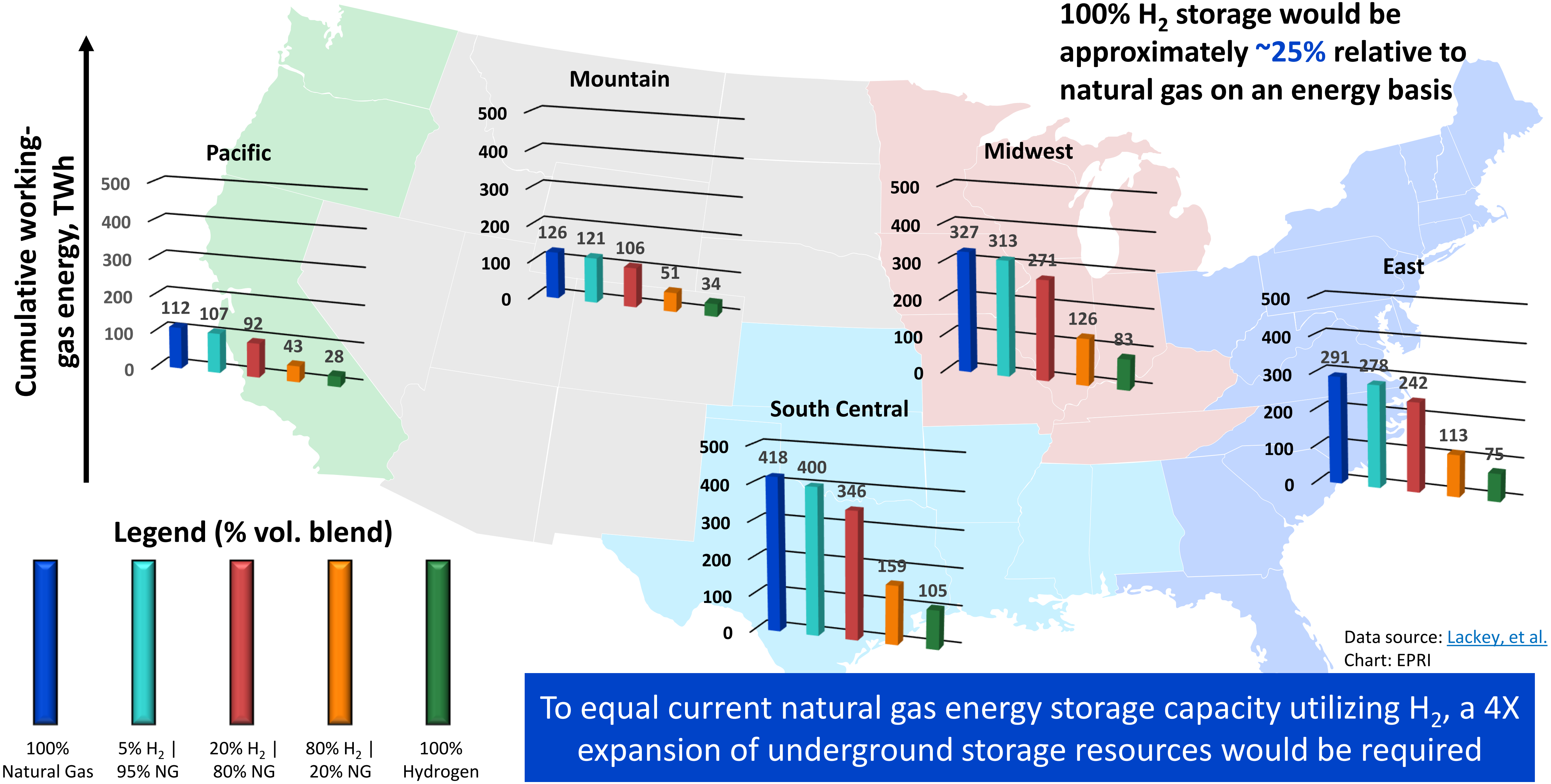


Source: EIA



U.S. existing natural gas & H_2 potential storage capacity, TWh

100% H_2 storage would be approximately ~25% relative to natural gas on an energy basis



Data source: Lackey, et al.
Chart: EPRI

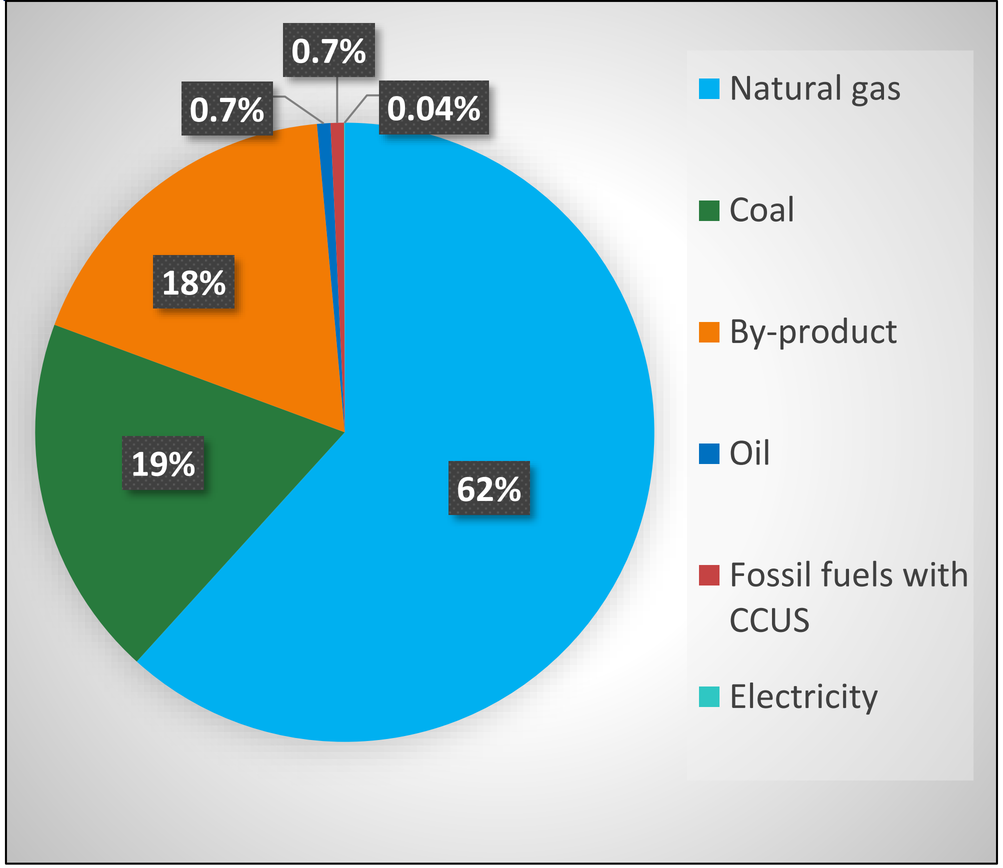
To equal current natural gas energy storage capacity utilizing H_2, a 4X expansion of underground storage resources would be required

EPRI

Where is hydrogen used today?

Current Production Scale and Use

Worldwide Production
~94 million metric tons (MMT)



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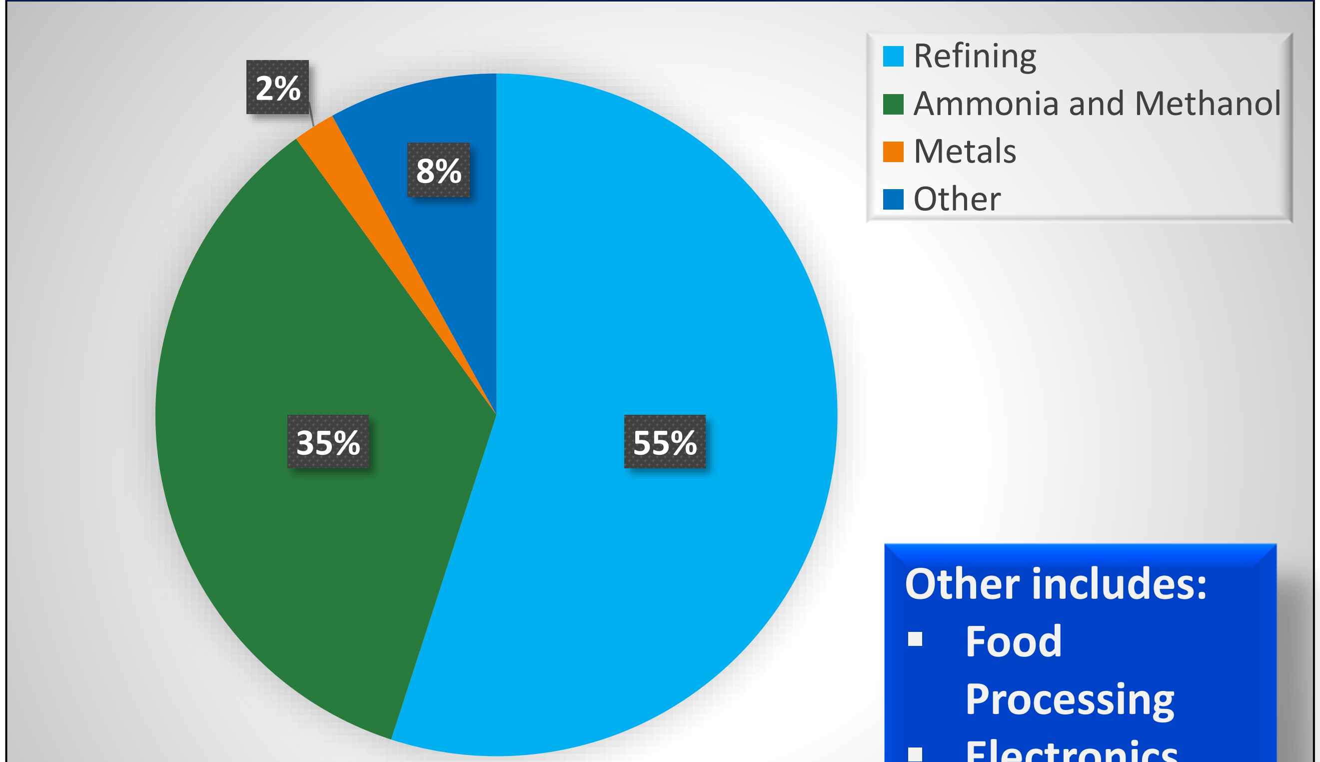
IEA (2022), Global Hydrogen Review 2022, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2022, License: CC BY 4.0

United States Hydrogen Annual Usage
~10 million metric tons (MMT)

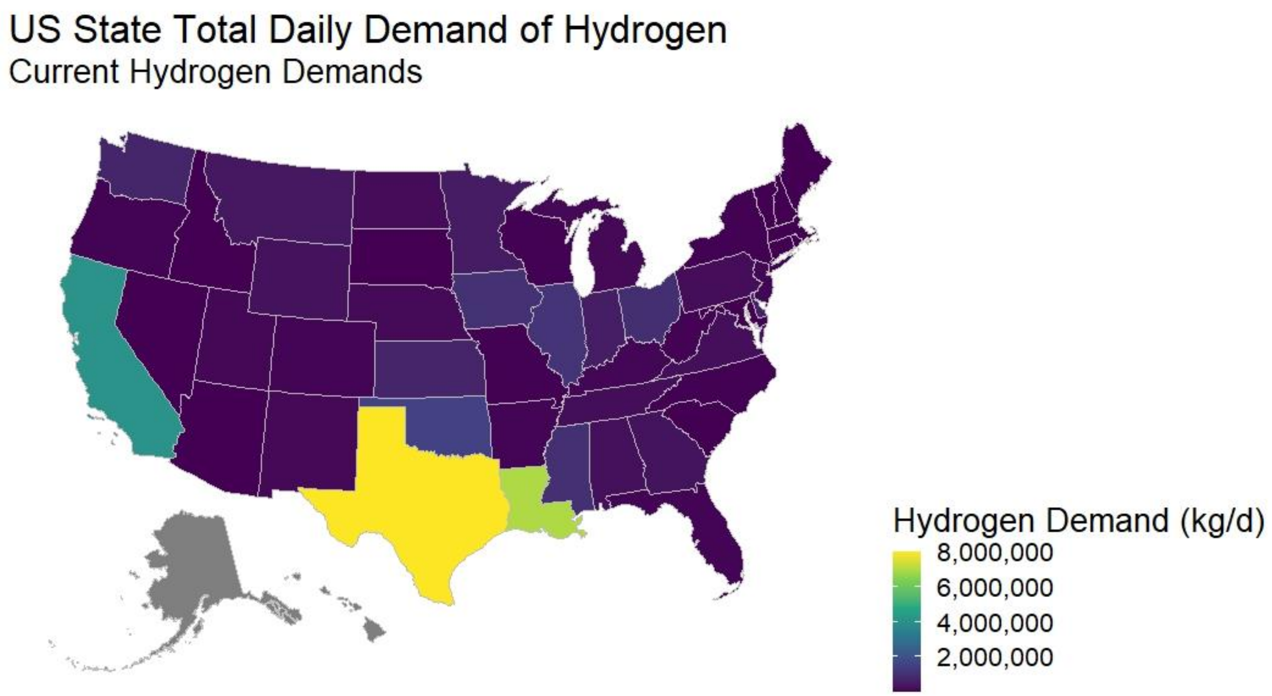


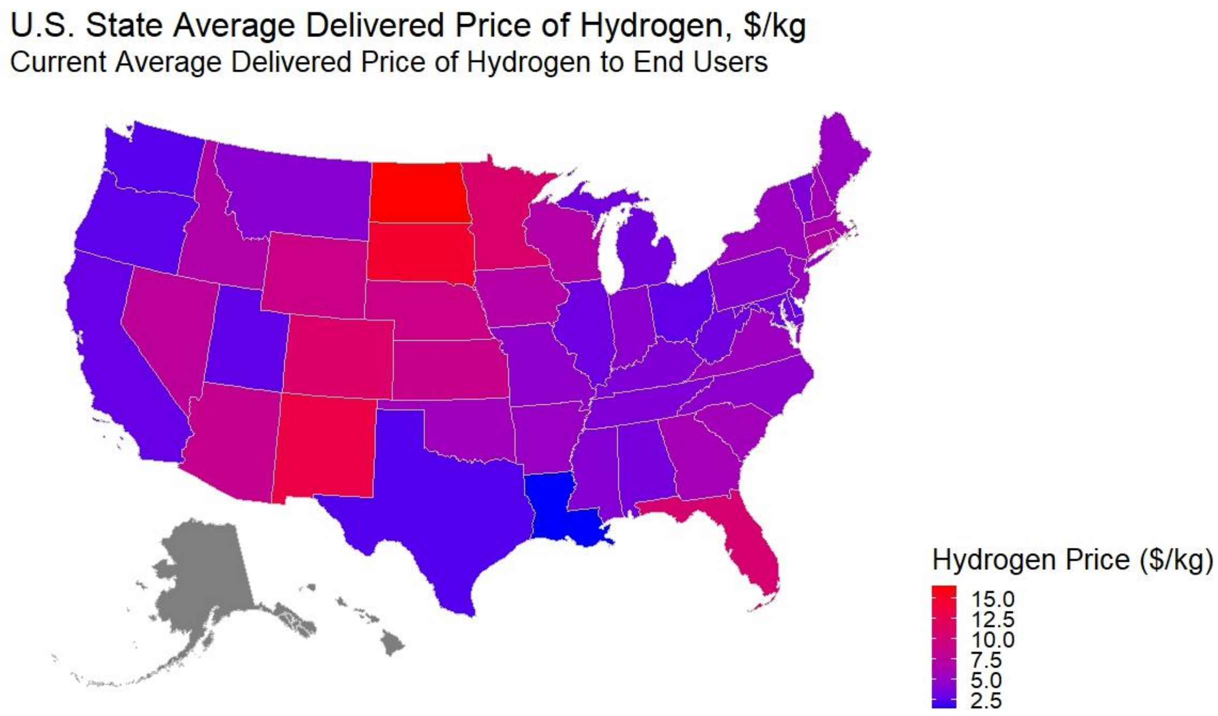
Other includes:
- **Food Processing**
- **Electronics**

~60% Captive
~40% Merchant

U.S. Department of Energy (DOE). "DOE National Clean Hydrogen Strategy and Roadmap," 2023.
https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

A Closer Look at U.S. Hydrogen Supply and Demand





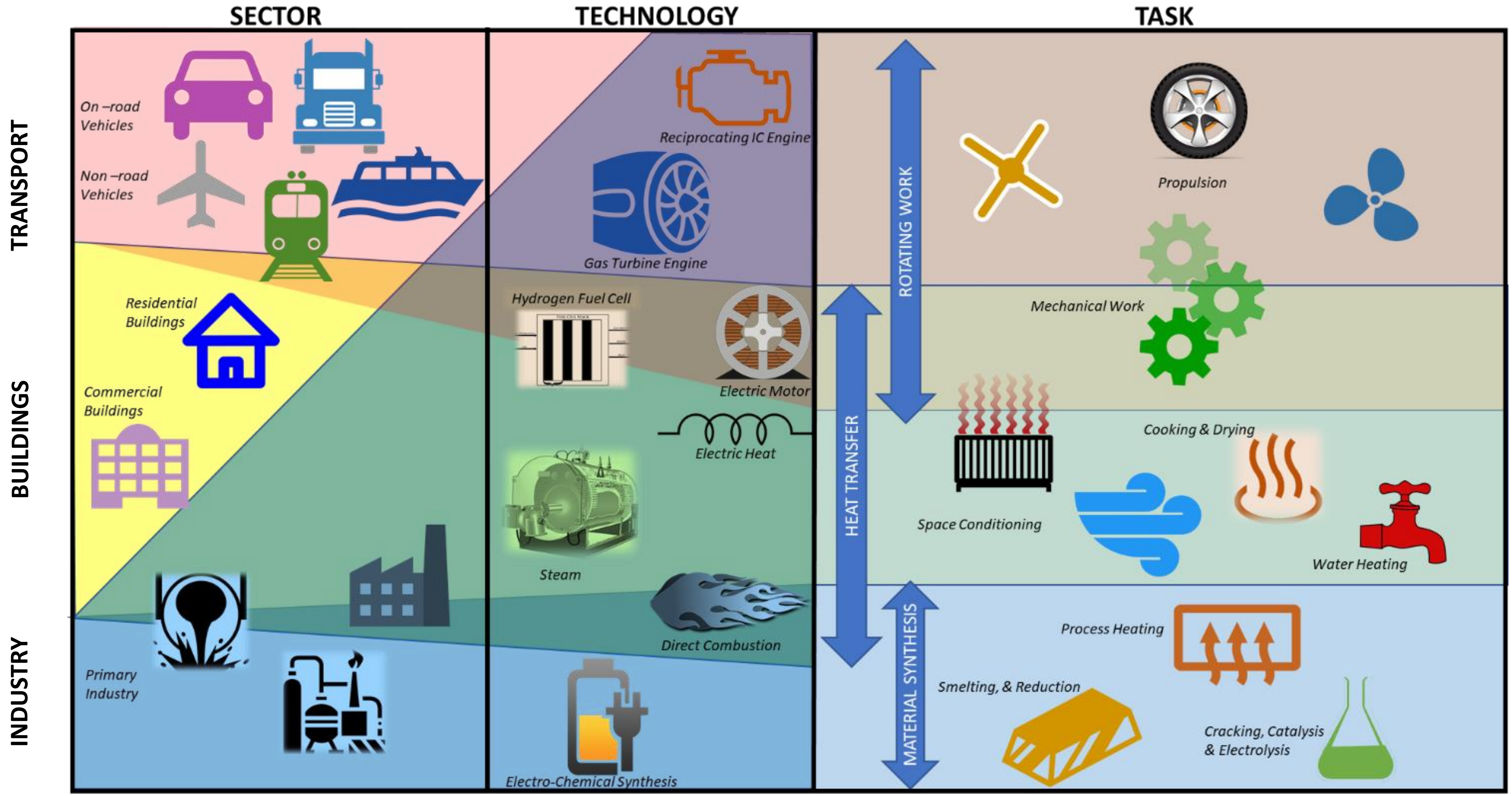
Hydrogen demand varies geographically. Most hydrogen demand is concentrated in Texas, Louisiana, and California due to high concentrations of petroleum refining facilities.

The areas with higher hydrogen demand are typically the areas where hydrogen prices are lower. This is primarily driven by proximity to hydrogen production facilities and demand volumes.

Source: EPRI, SEP North American Hydrogen Market Model

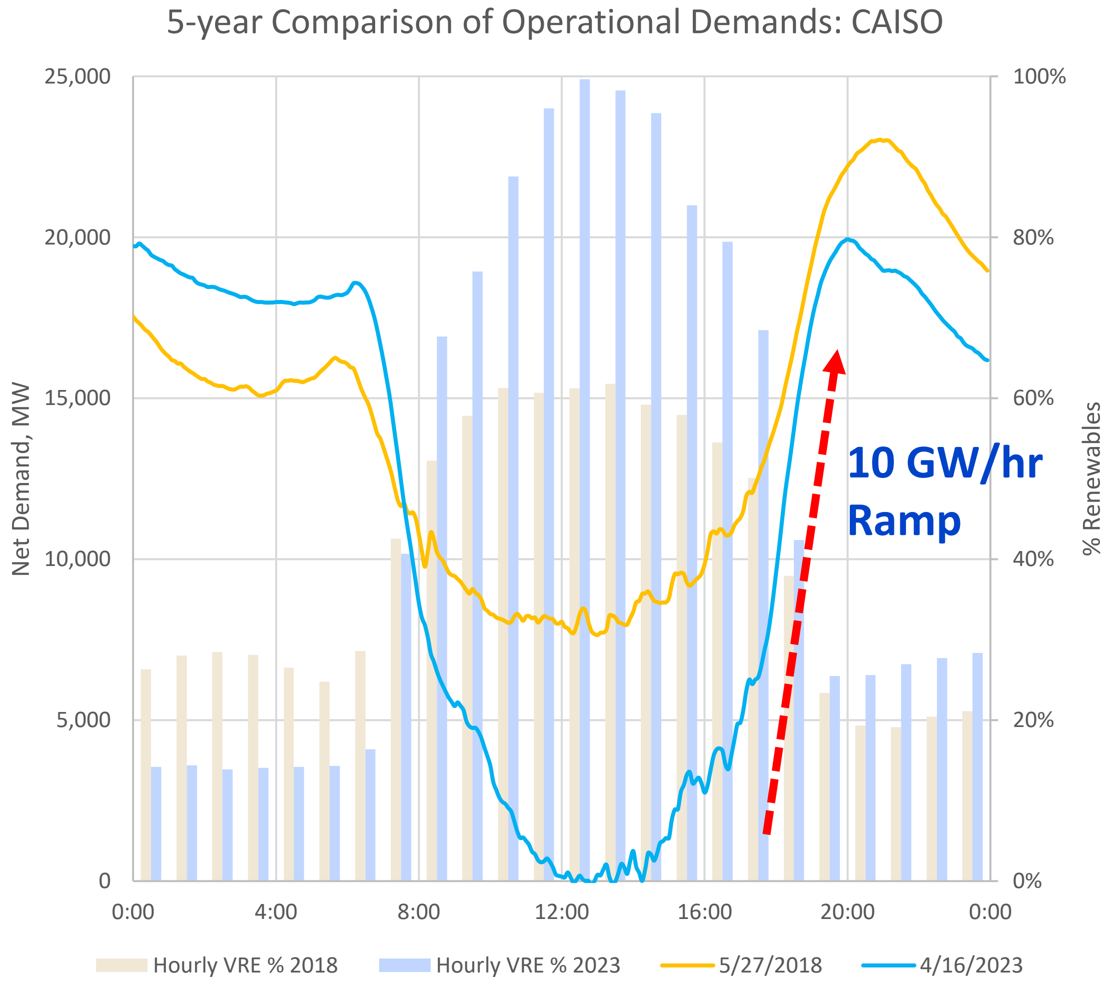
Hydrogen's applications across multiple end use sectors

Use Cases of Hydrogen to Decarbonize Final Energy

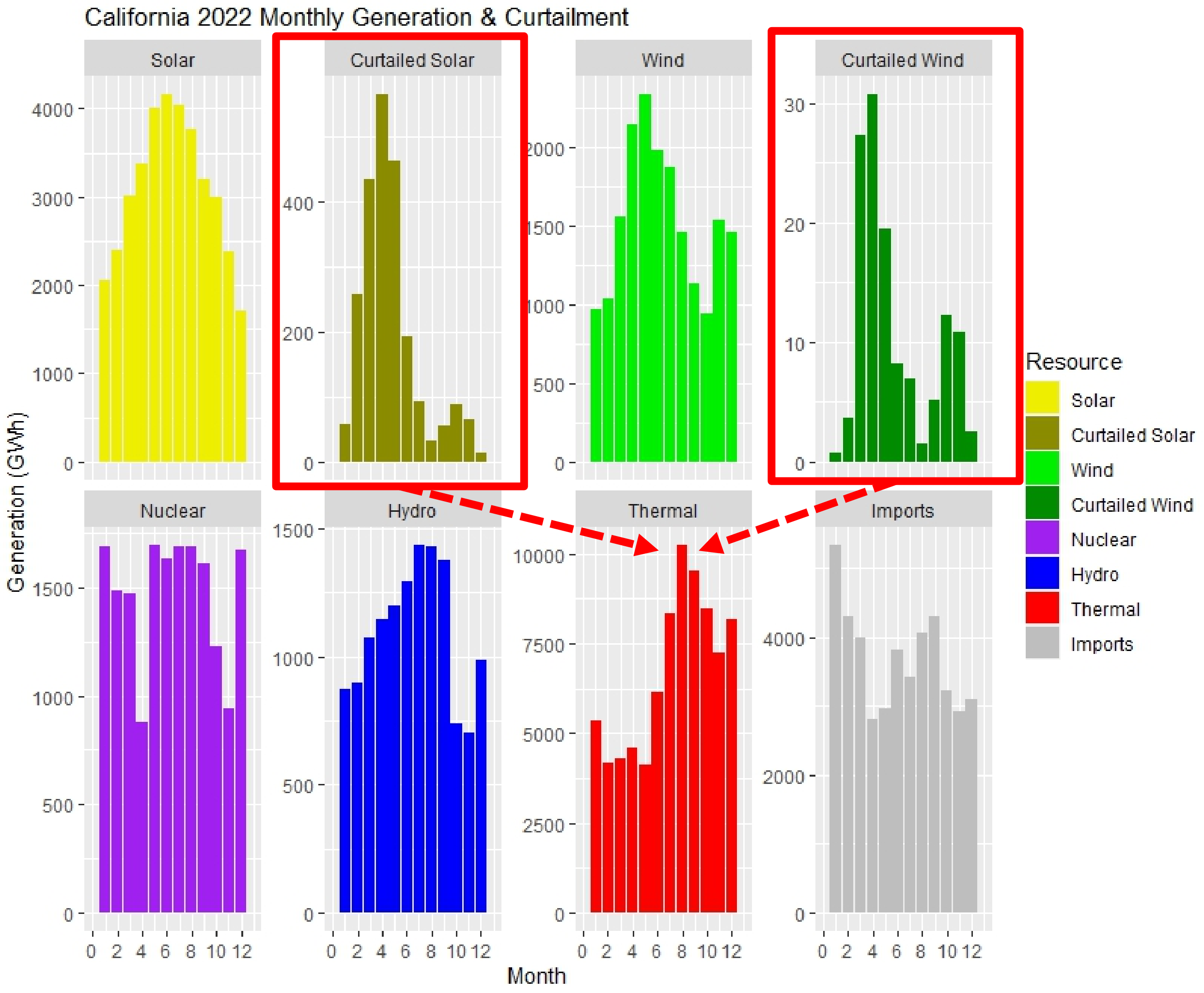


Opportunities for low-carbon fuels in the power sector

How can low-carbon fuels support peaking & reliability needs?

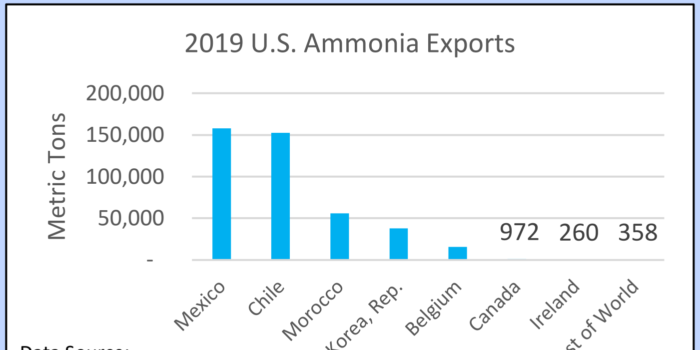


How can low-carbon fuels support the overall energy system?

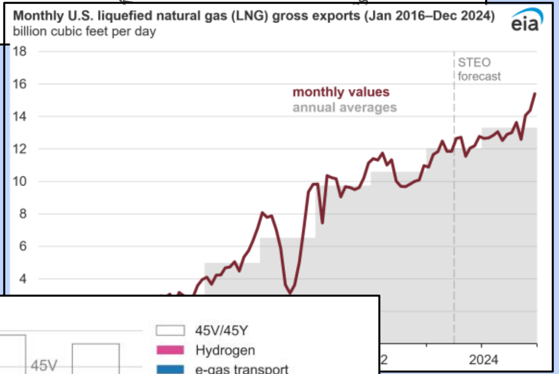


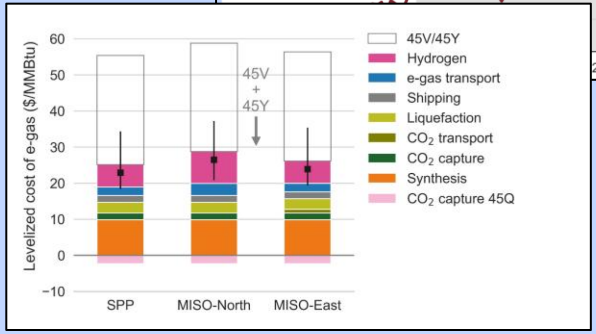
Emerging markets

Potential export opportunities

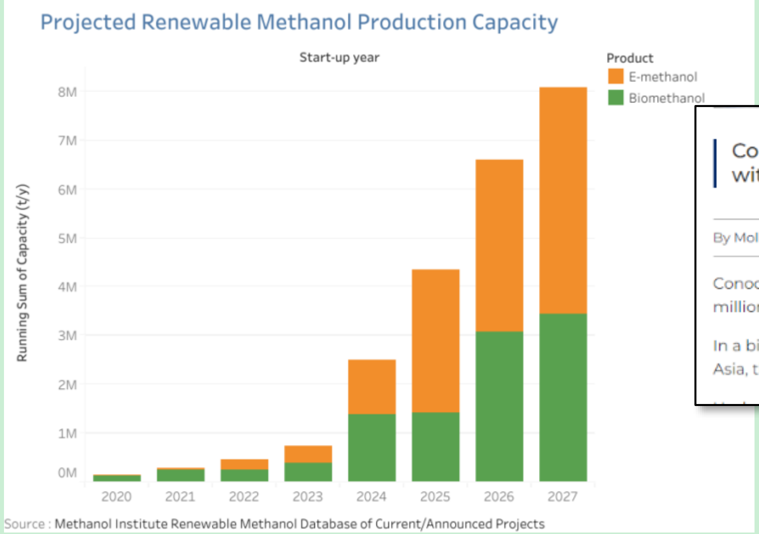


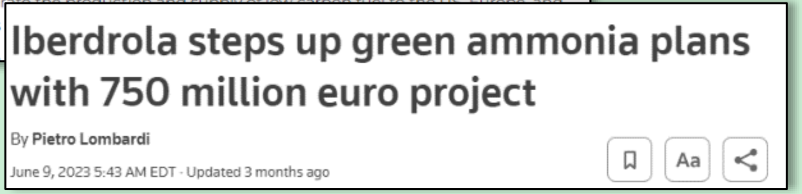
Data Source:
World Bank





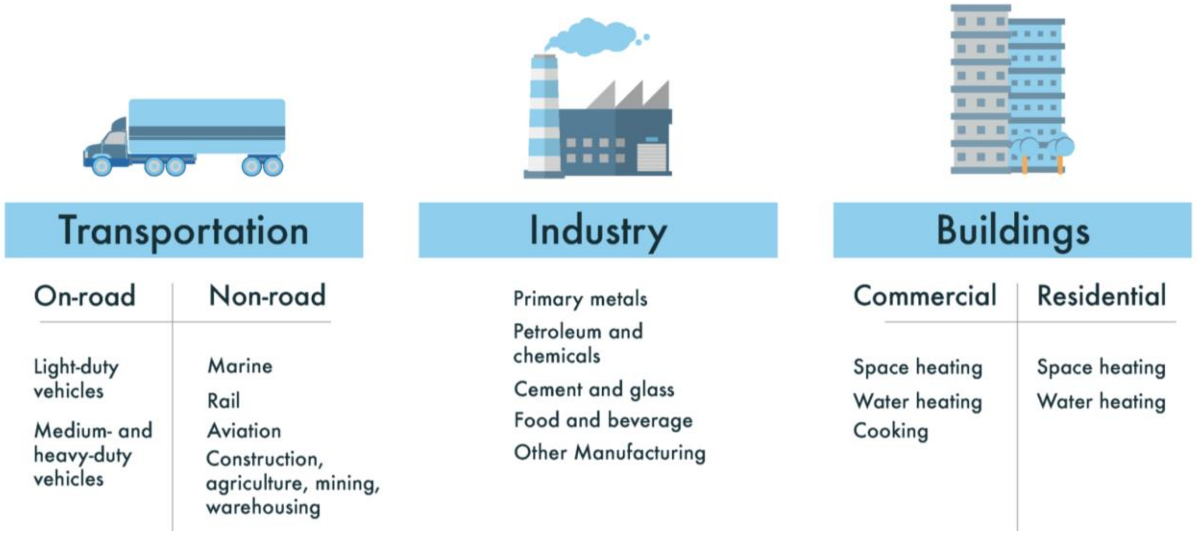
Low-carbon fuels: leveraging new and existing markets



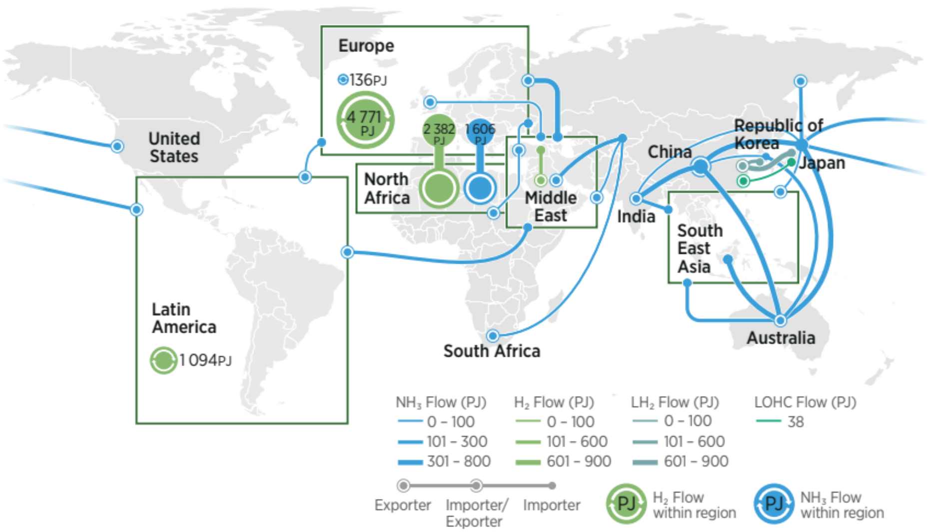


International & domestic opportunities

Emerging Domestic Energy Economy



Emerging International Energy Trade Flows

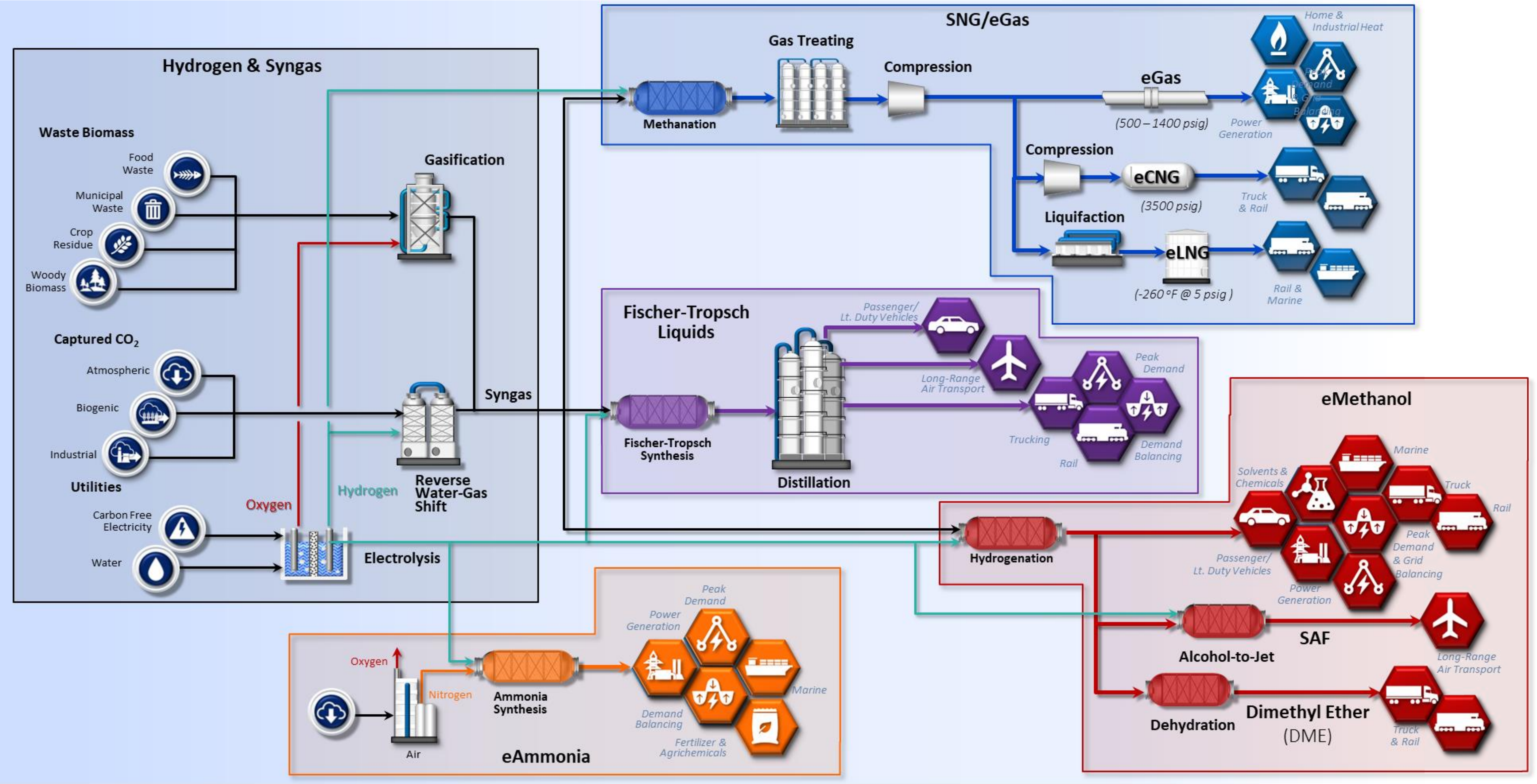


Source: IRENA 2022, "Global hydrogen trade to meet the 1.5°C climate goal: Trade outlook for 2050 and way forward". https://www.irena.org/publications/2022/Jul/Global-Hydrogen-Trade-Outlook

Major Importers

Major Exporters

Hydrogen is key to the power-to-fuels value chain

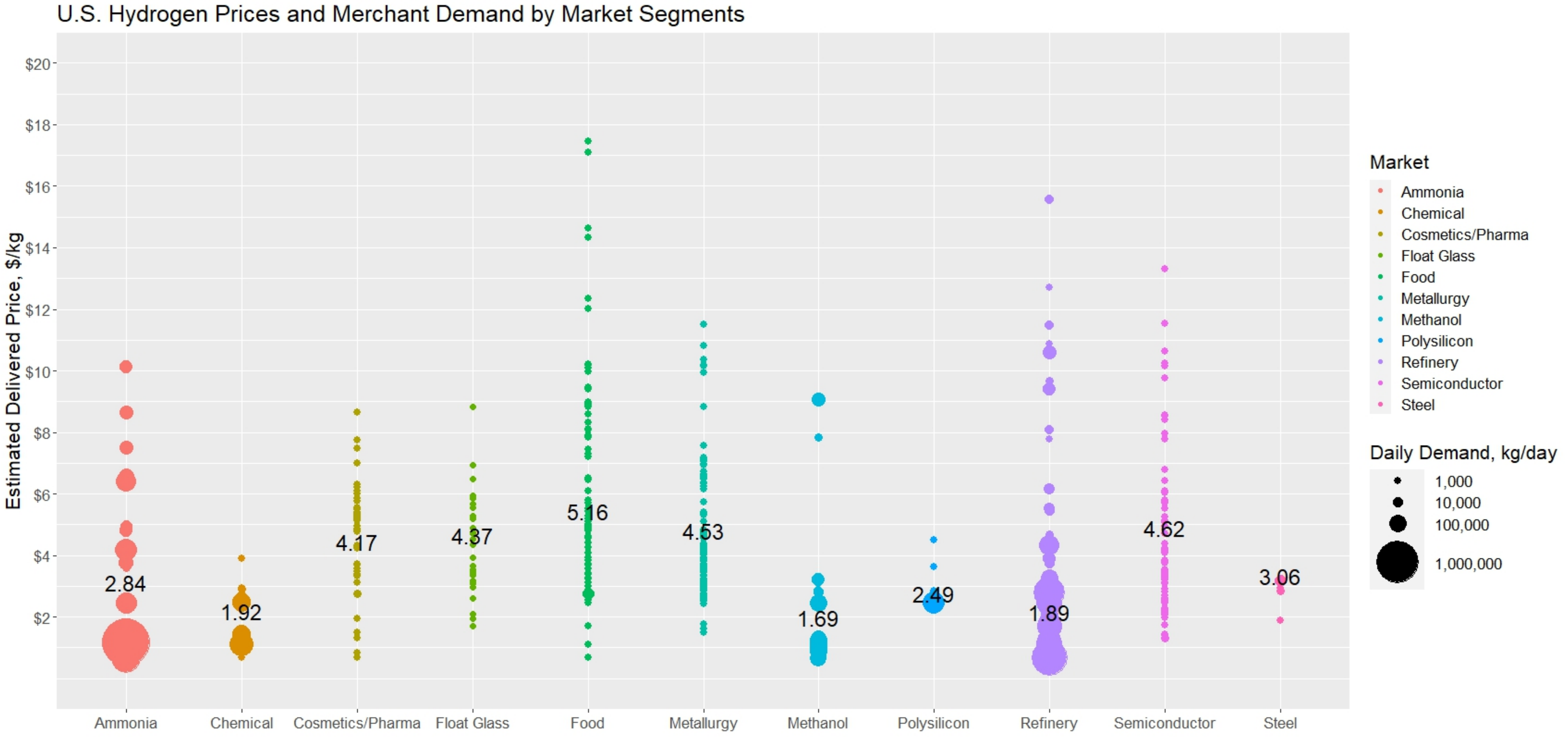


Economic Considerations

Current U.S. Hydrogen Supply and Demand

Delivered price of hydrogen varies widely between and within industries. Processes with larger demands such as refining and ammonia production are able to realize lower costs due to higher volumes and lower purity requirements.

Smaller market segments with higher purity requirements on average, are subject to higher delivered prices of hydrogen. Depending on the specific volume and purity requirement this could range from $2 to $12/kg of hydrogen.

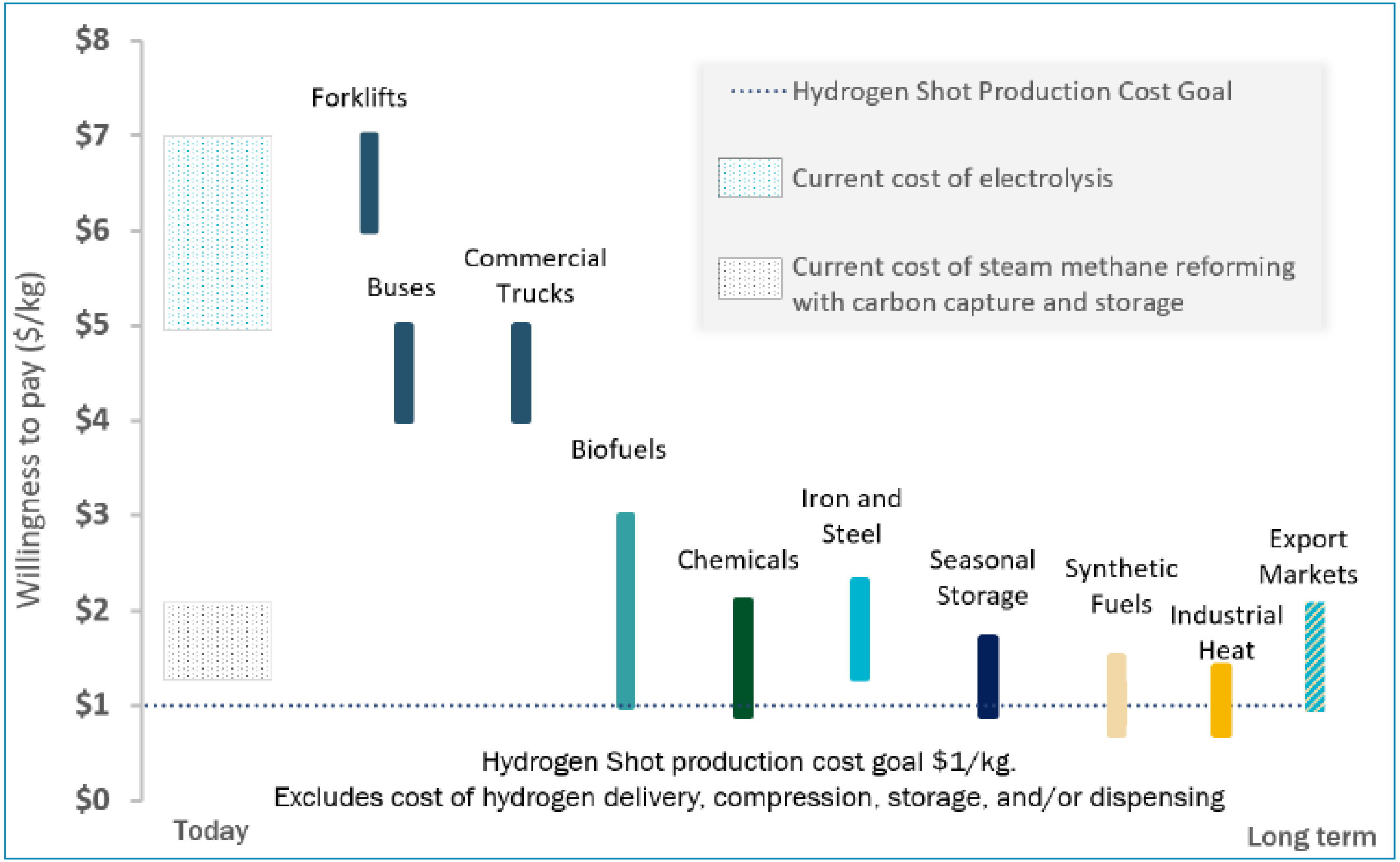


Demand volume weighted price averages by industry are shown on the chart above. Refining, chemical, and methanol industries currently have an average delivered price of hydrogen less than $2/kg. While smaller hydrogen demand industries on average pay over $4/kg.

Source: EPRI, SEP North American Hydrogen Market Model

New Market Development

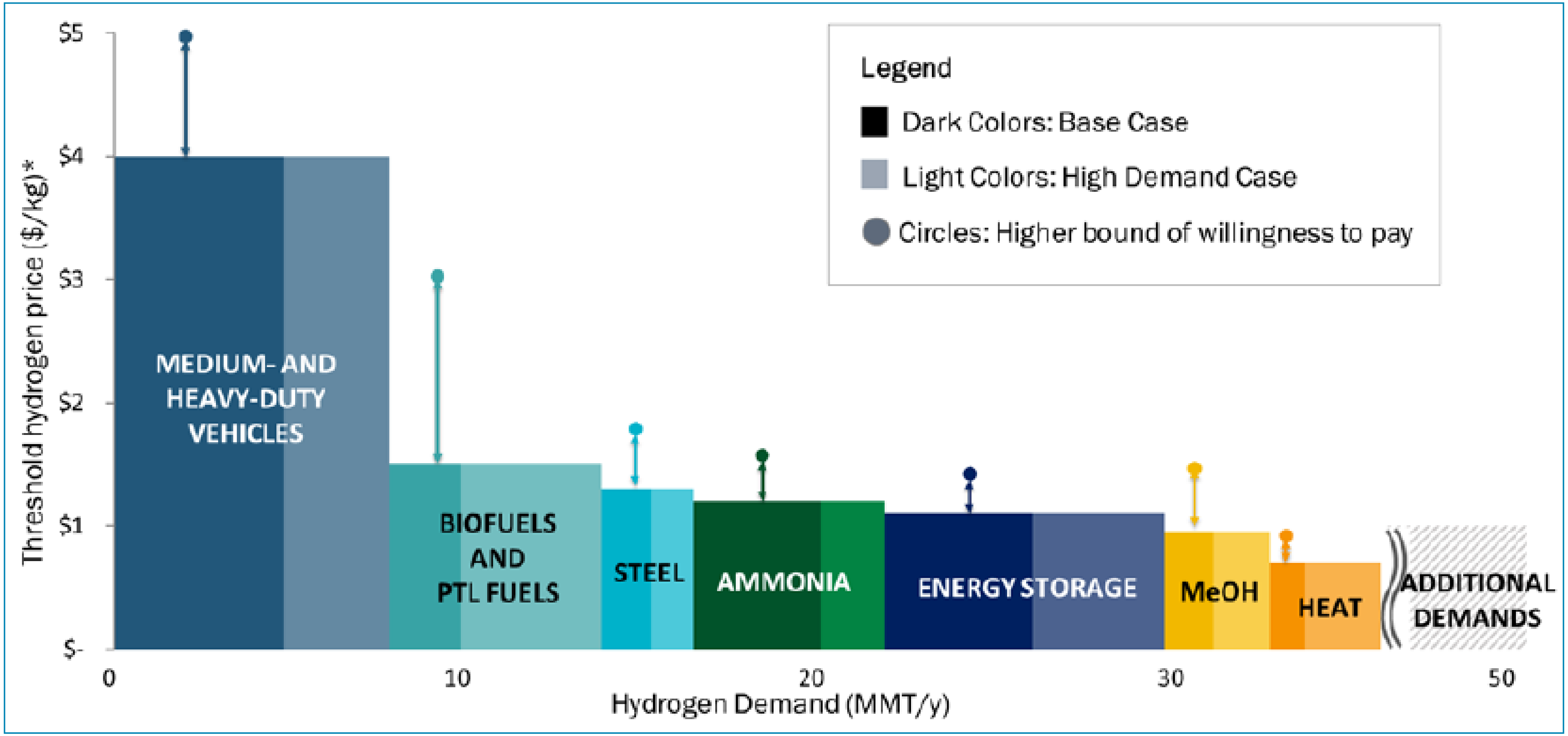
Hydrogen Offtake Applications: What are you willing to pay?



U.S. Department of Energy (DOE). "DOE National Clean Hydrogen Strategy and Roadmap," 2023. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

New Market Development

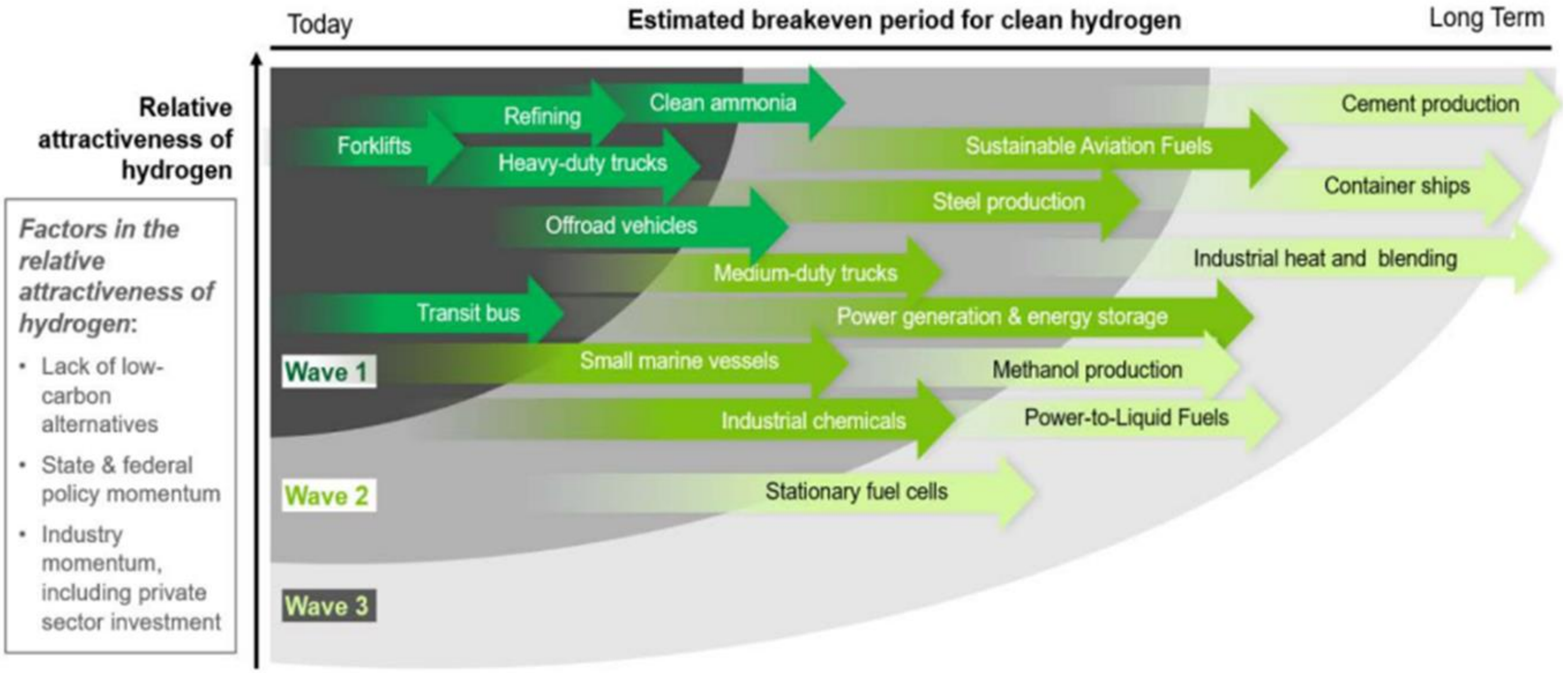
Clean Hydrogen Demand in Key Sectors: How much do you want?



U.S. Department of Energy (DOE). "DOE National Clean Hydrogen Strategy and Roadmap," 2023.
https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

New Market Development

When could adoption occur?

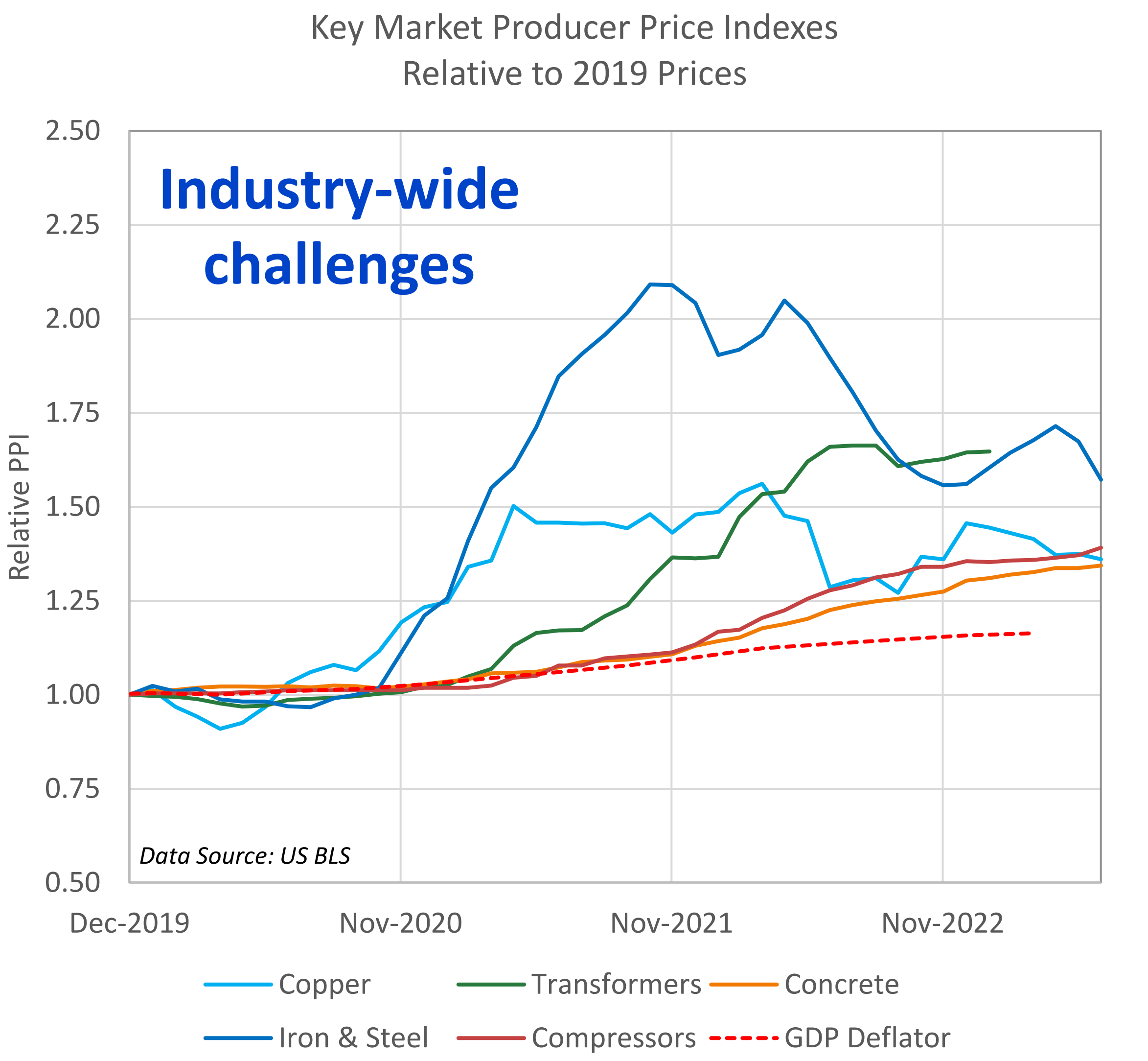


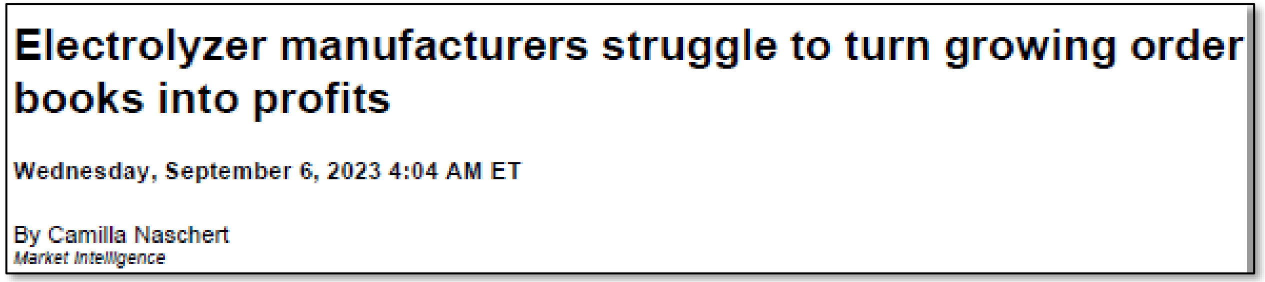
Clean hydrogen will meet demands in waves based on attractiveness in each end-use application

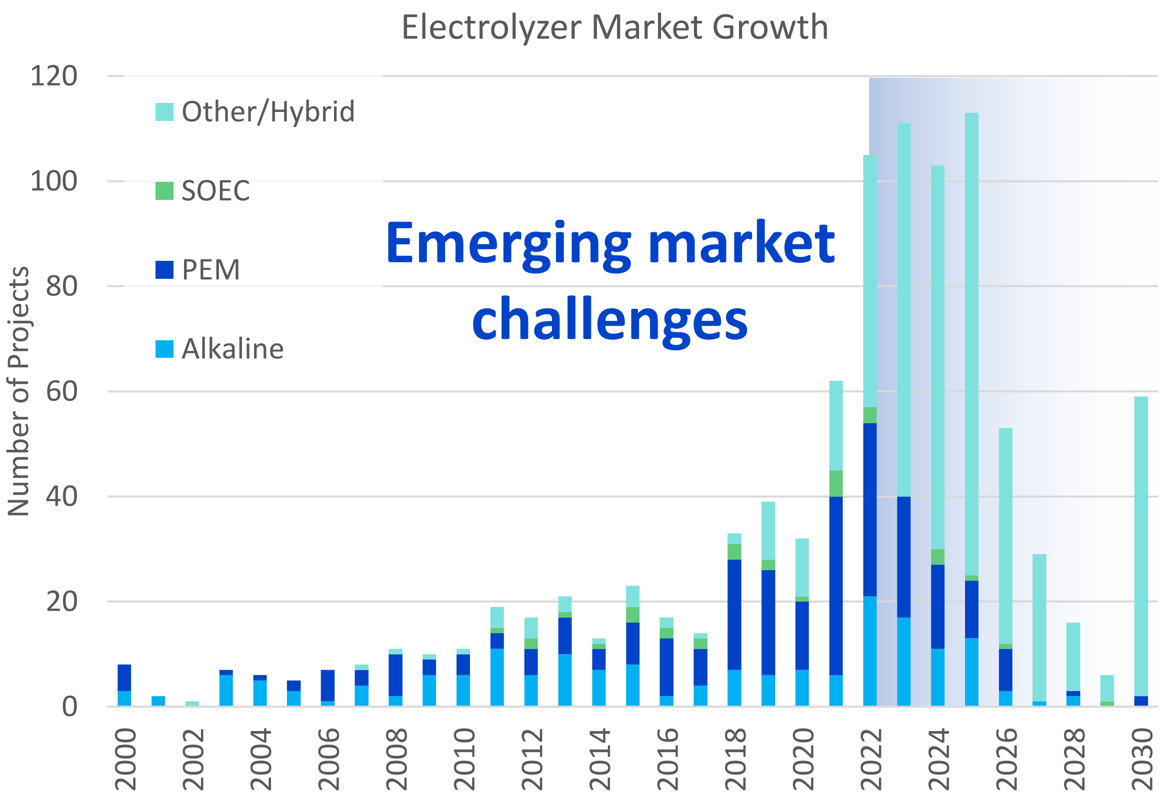
U.S. Department of Energy (DOE). "DOE National Clean Hydrogen Strategy and Roadmap," 2023. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

Change is never easy

Market headwinds & growing pains

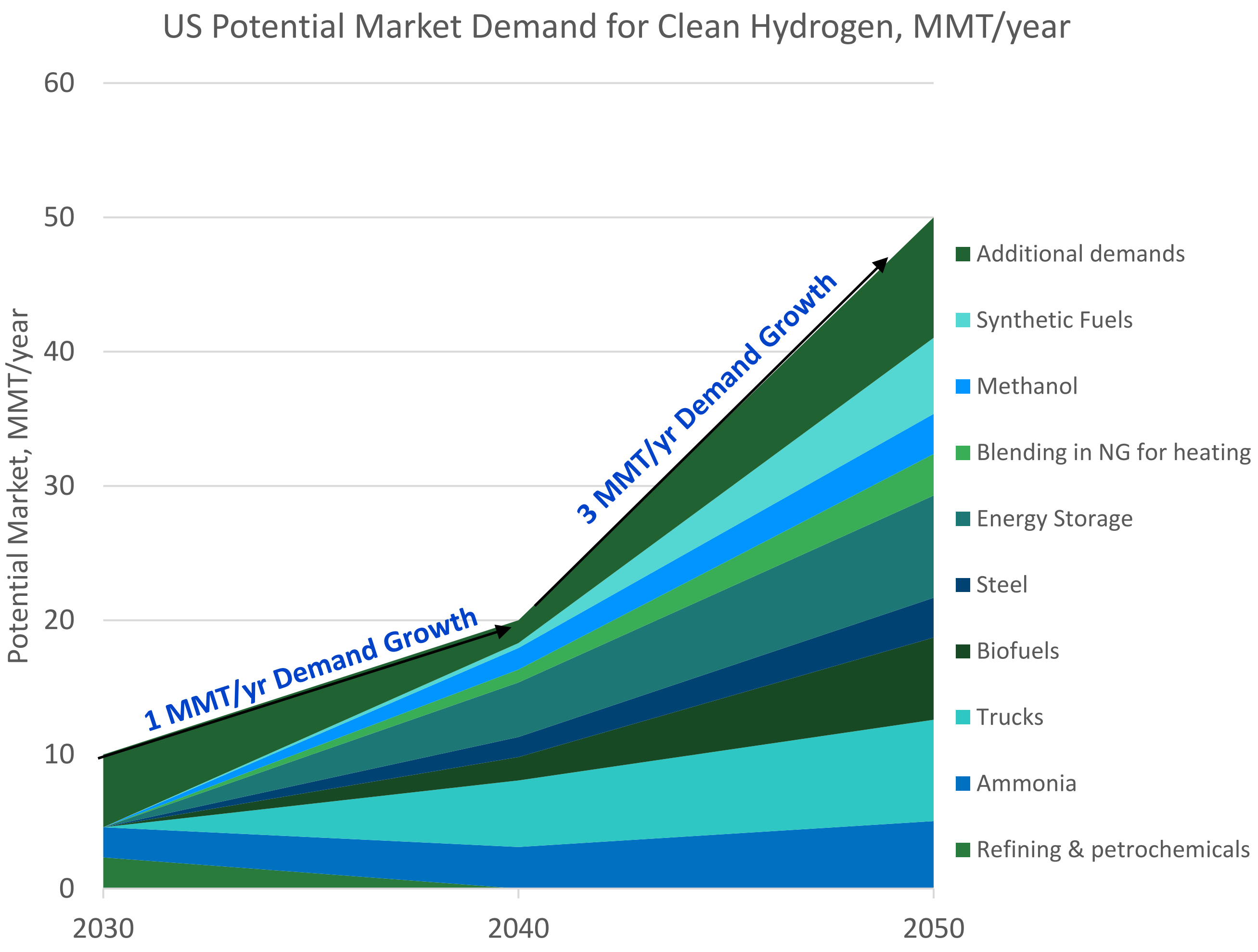


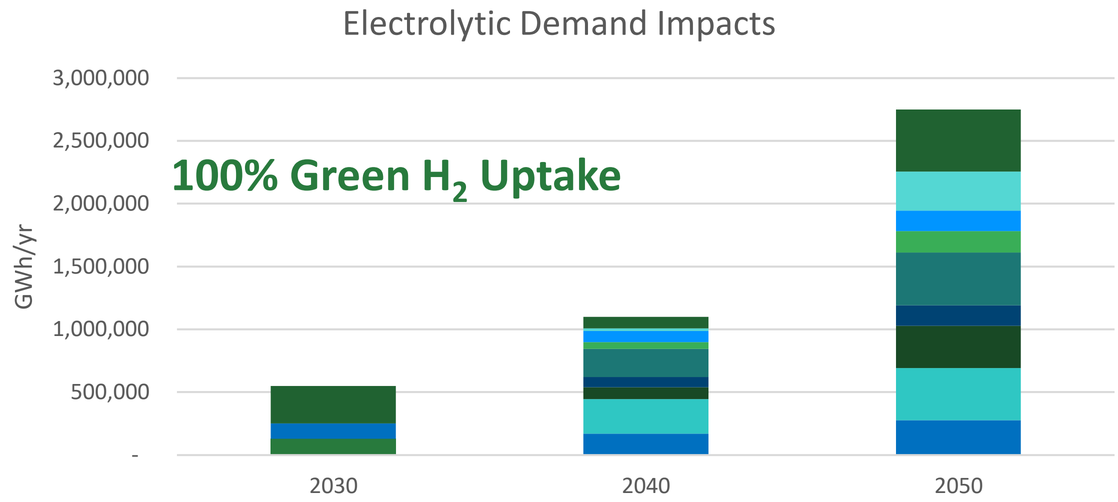


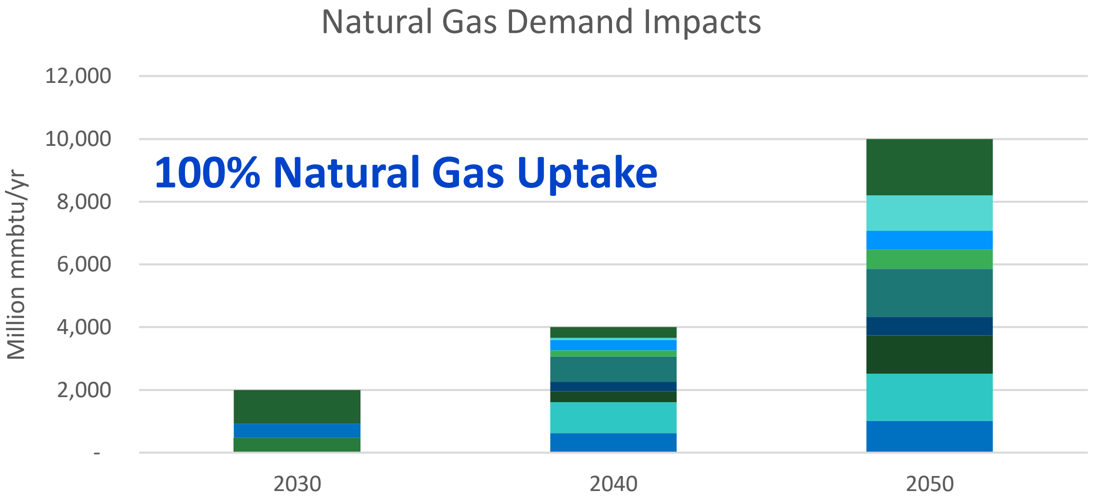


Source: IEA Hydrogen Projects Database. Paris, France: 2022.

Large potential = large impacts







U.S. Department of Energy (DOE). "DOE National Clean Hydrogen Strategy and Roadmap," 2023. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

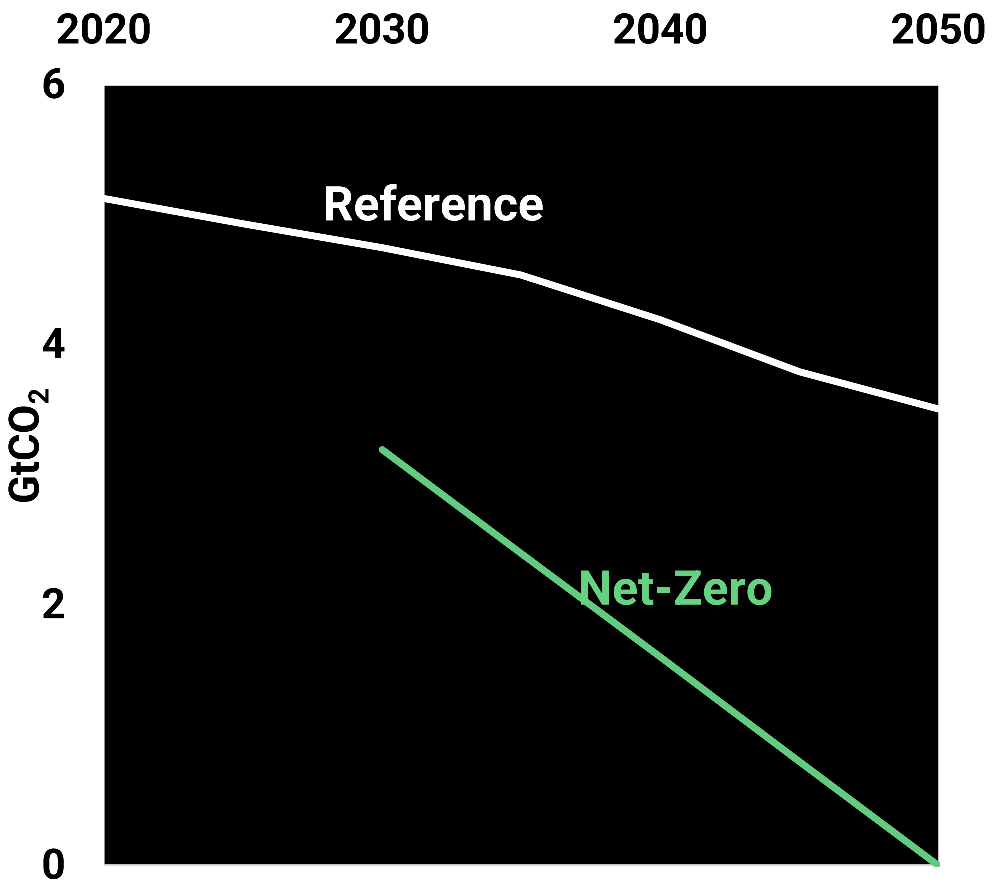
Diverse range of end-use applications with large markets

Pathways to Net-Zero

LCRI U.S. NET-ZERO 2050

Full report available at lowcarbonlcri.com/netzero

Reference with no new carbon policy, continued technology improvements

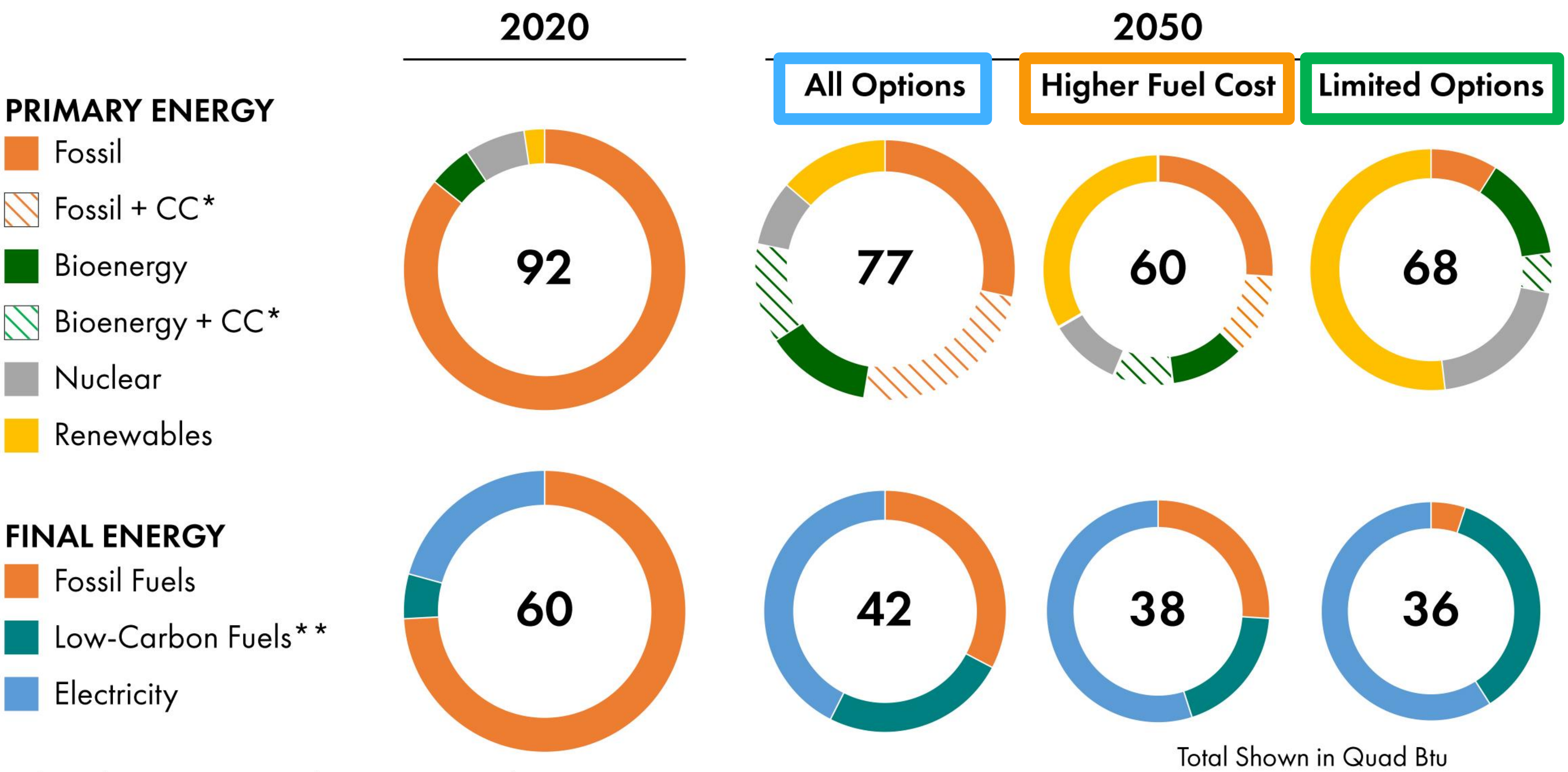


Net-Zero by 2050 with three core sensitivities around CCS, gas, bioenergy

	All Options	Higher Fuel Cost	Limited Options
Geologic Storage of CO_2	Lower Costs	Higher Costs	Not Available
Natural Gas Supply Costs	Lower Costs	Higher Costs	Lower Costs
Bioenergy Feedstock Supply	Full	Supply Limited	Supply Limited

Source: LCRI Report 3002024882

Primary and Final Energy in Net-Zero 2050 Scenarios

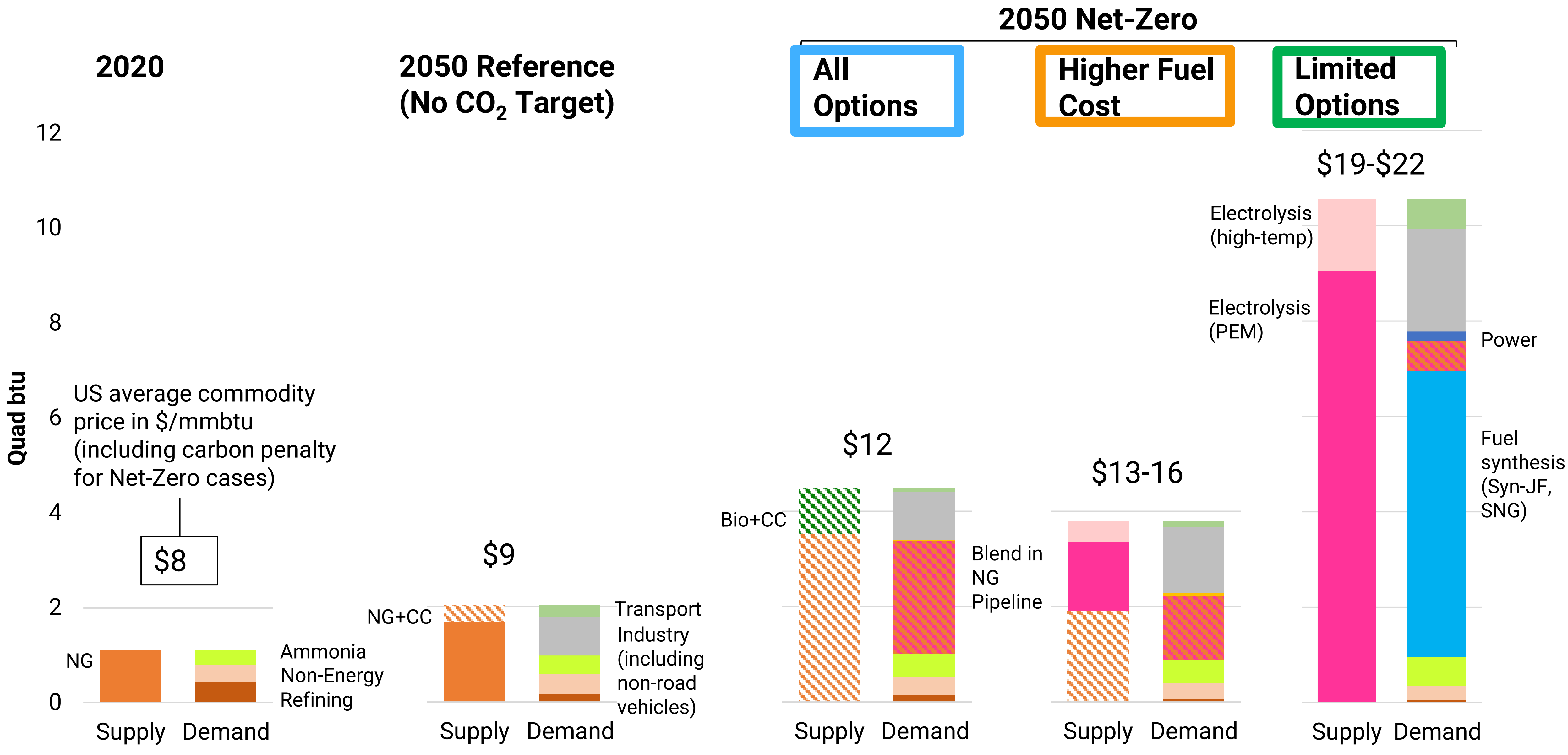


*Carbon capture, with storage or utilization

**Low-carbon fuels include hydrogen, hydrogen-derived fuels (e.g., synthetic fuels and ammonia) and bioenergy.

Source: LCRI Report 3002024882

Hydrogen Supply and Demand

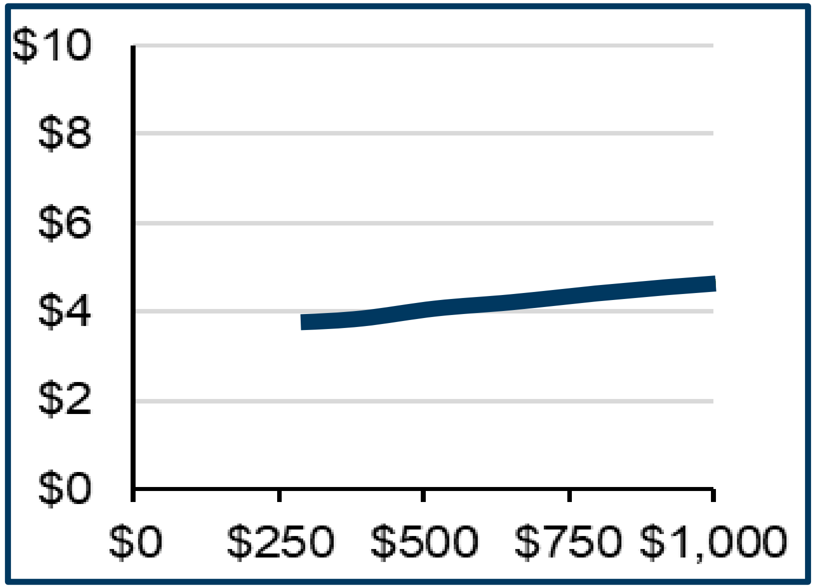


Source: LCRI Report 3002024882

Electrolytic Hydrogen Cost Sensitivities

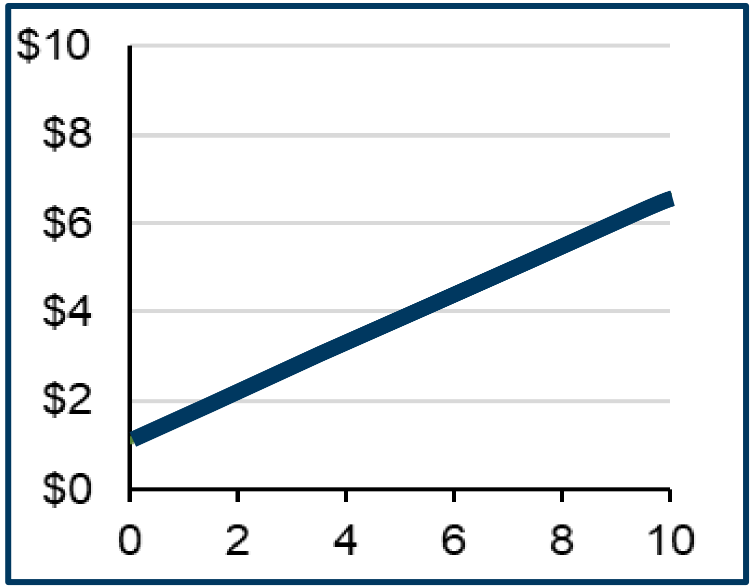
LCOH = Levelized Cost of Hydrogen

$/kg



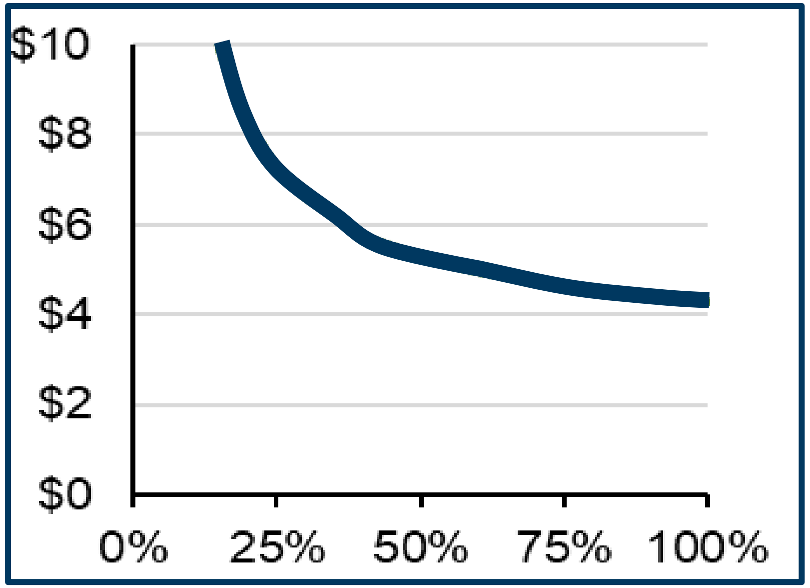
Capital Cost

$/kW



Electricity Price

¢/kWh



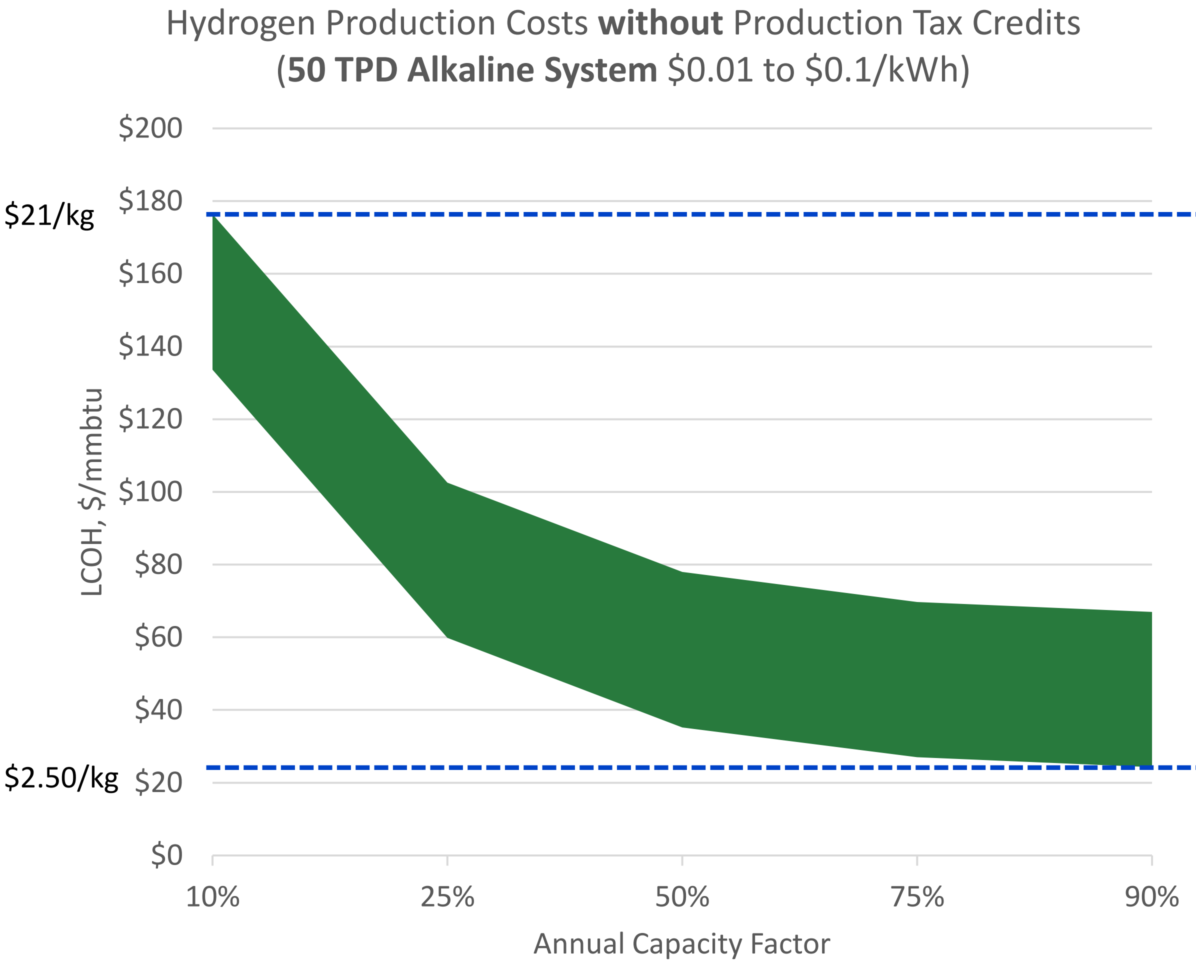
Capacity Factor

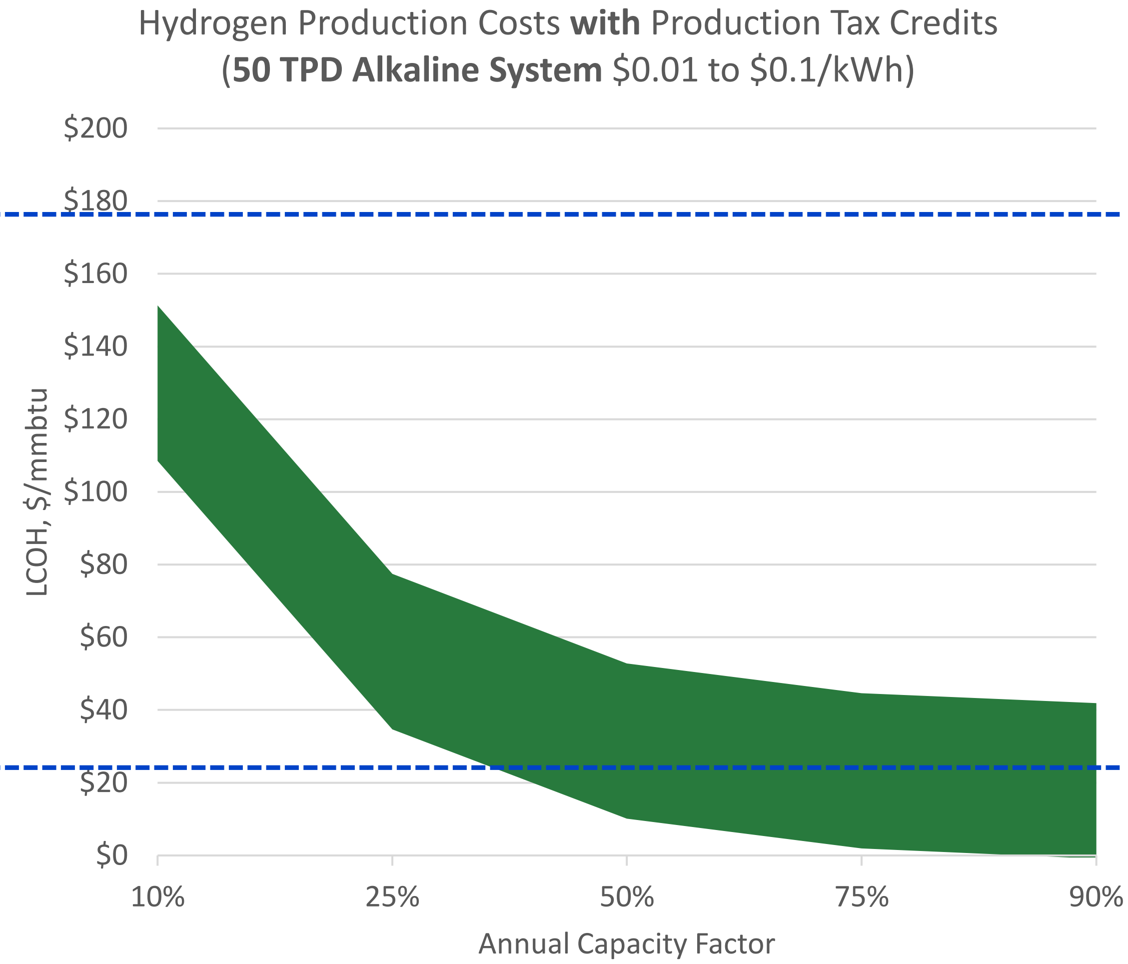
%

ELECTRICITY COST and CAPACITY FACTOR may have the largest influence on electrolytic hydrogen production costs

EPRI

Electrolysis LCOH Comparisons: 45V Impacts ($3/kg)





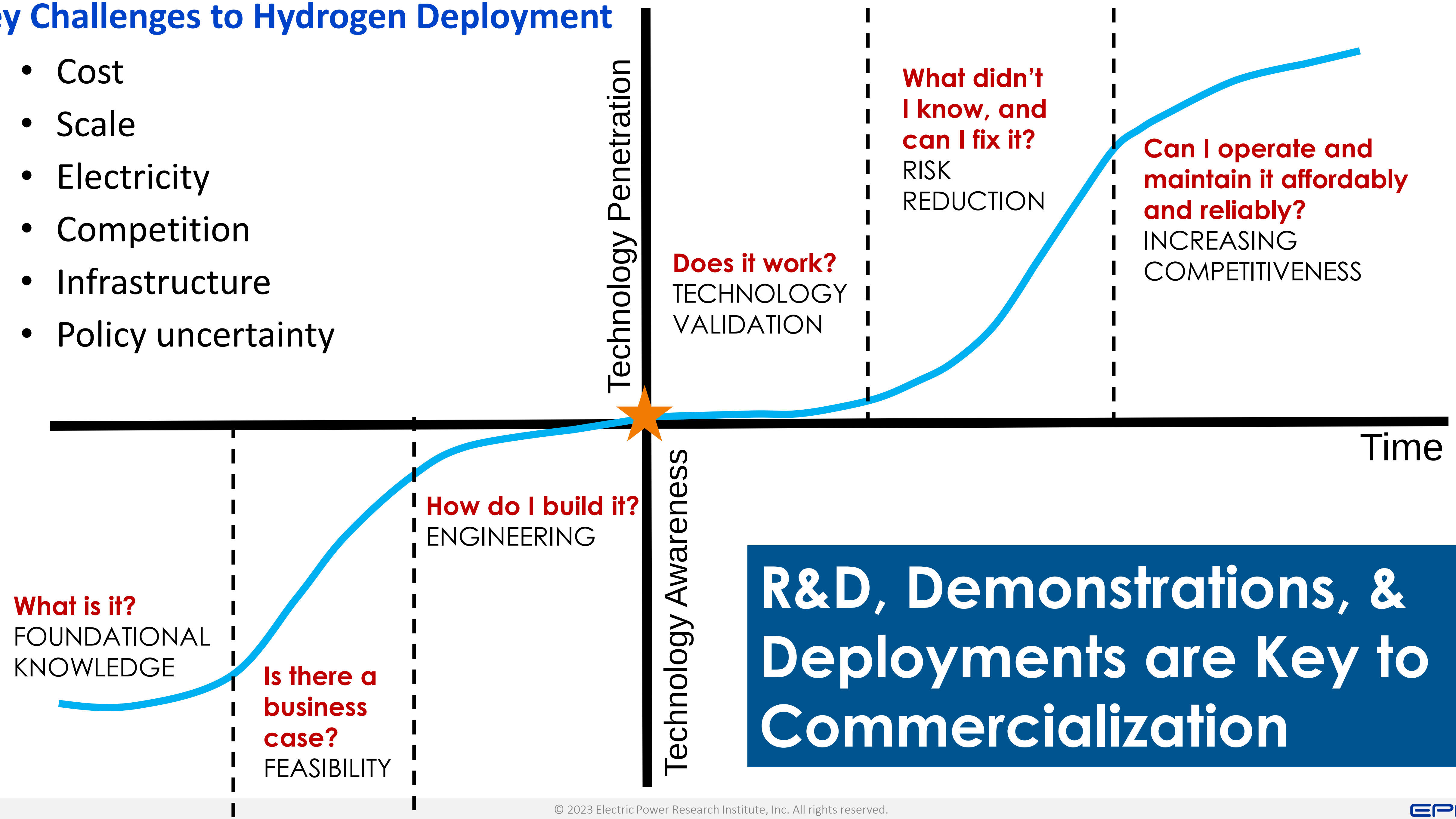
Potential to have significant impacts on H_2 production costs from electrolysis

2% O&M and PTC escalation, 5.4% discount rate, 20-year MACRS, 20-year booklife, 2% degradation

Challenges, benefits, & opportunities

Key Challenges to Hydrogen Deployment

- Cost
- Scale
- Electricity
- Competition
- Infrastructure
- Policy uncertainty



R&D, Demonstrations, & Deployments are Key to Commercialization

EPRI

Benefits of Low-Carbon Hydrogen

Reduced emissions and environmental impact

- No direct CO_2 emissions when combusted
- Decarbonize current sectors that use hydrogen
- Decarbonize hard-to-abate sectors that can be difficult to electrify
- Possibility to positively contribute to equity and environmental justice

Balancing asset

- Increased storage opportunities
- Able to capture peaks in electricity generation from renewables and store as hydrogen molecules for later
- Deliver hydrogen and other hydrogen carriers to areas that need the energy
- Increases reliability and resilience

Economic

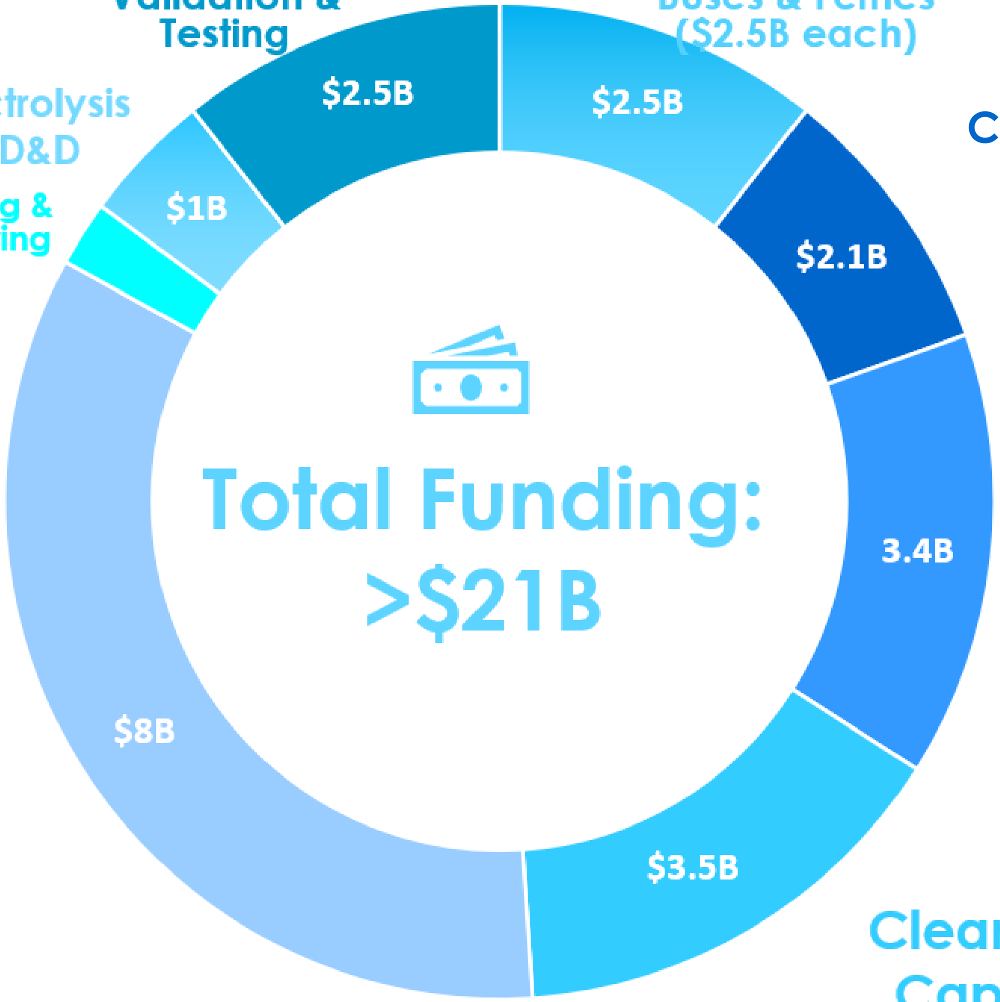
- Spur domestic manufacturing
- Enable energy affordability
- Increase jobs
- Learning by doing and economies of scale
  - Scaling renewable energy can further decrease the cost of renewable energy as well as low-carbon hydrogen

Hydrogen can help make the case for integrating more renewable energy into the grid

U.S. Department of Energy (DOE). "DOE National Clean Hydrogen Strategy and Roadmap," 2023. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

Creating a Market for Low-Carbon Hydrogen

Government Support through the Infrastructure Bill



Clean H_2 Hubs

CO_2 Capture Demo and Pilot Program

Clean Direct Air Capture Hubs

Public resources

- U.S. Department of Energy (DOE). "DOE National Clean Hydrogen Strategy and Roadmap," 2023. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf
- U.S. Department of Energy (DOE). "Pathways to Commercial Liftoff: Clean Hydrogen," 2023. https://liftoff.energy.gov/clean-hydrogen/
- The Center for Hydrogen Safety (CHS) and the Hydrogen Safety Panel (HSP). "Hydrogen Tool (H_2Tools)," https://h2tools.org/
- IEA (2023), Global Hydrogen Review 2023, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2023, License: CC BY 4.0
- IEA (2022), Hydrogen Projects Database, IEA, Paris https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database, License: CC BY 4.0
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- Hydrogen Council. "Hydrogen Insights 2023," https://hydrogencouncil.com/en/hydrogen-insights-2023/
- Pillsbury Law Firm. "The Hydrogen Map," https://www.thehydrogenmap.com/
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- The Low-Carbon Resources Initiative (LCRI). "Net-Zero 2050: U.S. Economy-Wide Deep Decarbonization Scenario Analysis," 2023. https://lcri-netzero.epri.com/


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