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

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

Past
- Energy Efficiency
- Cleaner Electricity

Today
- Efficient Electrification
- Low-Carbon Resources

2030++
- Ubiquitous clean electricity
- Efficient electrification

2050
- Negative-emission technologies
- Low-carbon resources

~10-15 years
~15-30 years
Reducing Economy-Wide CO₂ Emissions

Source: EPRI Report 3002020700
Reducing Economy-Wide CO₂ Emissions

U.S. Economy-Wide CO₂ Emissions

1 Gt = 1000 MMT

Potential Role of Low-Carbon Fuels

Source: EPRI Report 3002020700
Today’s Energy System

Primary Energy

- Renewables
- Nuclear
- Natural Gas
- Petroleum & Coal
- Bioenergy & Waste

Conversion

- Electricity Generation
- Hydrogen Production

Storage and Delivery

- Electricity Storage
- Gas Storage

Energy End-Use

- Distributed Resources
- BUILDINGS
  - Co-Gen/CHP
- INDUSTRY
- TRANSPORTATION
  - On-Road
  - Non-Road
  - Re-Fueling Infrastructure
  - Liquid Fuels
  - Biofuel

Today's Energy System includes primary energy sources such as renewables, nuclear, natural gas, petroleum & coal, and bioenergy & waste. These primary energy sources are converted into electricity, which is then stored and delivered to various end-use sectors such as buildings, industry, and transportation. Transportation sectors include on-road and off-road vehicles, as well as re-fueling infrastructure for biofuels and liquid fuels.
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**

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**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

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Source: US Government Accountability Office (GAO-21-327)  
Source: EPRI 3002025872
And...there is a **cost**

**United States Billion-Dollar Disaster Events 1980-2021 (CPI-Adjusted)**

- **Drought Count**
- **Flooding Count**
- **Freeze Count**
- **Severe Storm Count**
- **Tropical Cyclone Count**
- **Wildfire Count**
- **Winter Storm Count**
- **Combined Disaster Cost**
- **Costs 95% CI**
- **5-Year Avg Costs**

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:

<table>
<thead>
<tr>
<th>Combines with:</th>
<th>To form:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>Water ((H_2O))</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>Ammonia ((NH_3))</td>
</tr>
<tr>
<td>Carbon</td>
<td>Methane ((CH_4))</td>
</tr>
</tbody>
</table>
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 embrittlem 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

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**Photo by CEphoto, Uwe Aranas or alternatively © CEphoto, Uwe Aranas CC BY-SA 4.0**

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: H₂ generates incremental NOₓ when it is combusted alone or blended with natural gas |
| Detection: H₂ 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) |

**Source:** h2tools [https://h2tools.org/bestpractices/hydrogen-flames](https://h2tools.org/bestpractices/hydrogen-flames)

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**Source:** LCRI Report 3002019994

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**Proper design and procedures must be used to avoid potential fire or explosion**
### Environmental health and safety mitigations

<table>
<thead>
<tr>
<th>Hazards</th>
<th>Mitigations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Very small molecule</strong>: need proper materials to contain and detect</td>
<td>Welded connections and hydrogen-compatible materials. Consult industry standard for hydrogen-specific component requirements</td>
</tr>
<tr>
<td><strong>Material compatibility</strong>: can embrittle some metals, causing cracks and leaks</td>
<td>Codes &amp; standards (ASME B31.12) outline material requirements for leak protection as well as to minimize embrittlement and corrosion</td>
</tr>
<tr>
<td><strong>Fire</strong>: highly flammable, potential flame jetting. Pale blue flame when burning is difficult to see in daylight</td>
<td>Utilize leak and flame detectors, proper design and system shutdown planning per NFPA 2, industry best practices, control ignition sources, and regular maintenance</td>
</tr>
<tr>
<td><strong>Explosive</strong>: high explosive energy</td>
<td></td>
</tr>
<tr>
<td><strong>Pollutants</strong>: $\text{H}_2$ generates incremental NO$_x$ when it is combusted alone or blended with natural gas</td>
<td>NOx emissions can be reduced by employing new burner designs &amp; selective catalytic reduction systems for post-combustion control</td>
</tr>
<tr>
<td><strong>Detection</strong>: $\text{H}_2$ gas is colorless and odorless. Burns with pale blue flame which is difficult to see in daylight.</td>
<td>$\text{H}_2$ gas and flame detectors commercially available, with newer leak detection methods being explored (e.g., wide-area leak detection)</td>
</tr>
<tr>
<td><strong>Storage</strong>: Typically transported and stored at high pressure (gas) and very low temperature (liquid)</td>
<td>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</td>
</tr>
<tr>
<td><strong>Asphyxiation</strong>: can occur in enclosed areas (unlikely)</td>
<td>Hydrogen sensors should be placed in enclosed spaces where hydrogen could collect</td>
</tr>
</tbody>
</table>

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

Source: LCRI Report [3007019994](https://h2tools.org/bestpractices/best-practices-overview)
Analysis of H₂ Incidents in Industry

- 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 H₂ 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
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 will the costs and benefits be 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 potential?
- 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?
- Does this distract from improving economic outcomes?

**Community Concerns of Hydrogen**
- 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

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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 CO₂/year

- SMR: emits ~10 metric tons of CO₂ for every metric ton of hydrogen produced
- Coal gasification: almost twice as CO₂-intensive as SMR
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 charged cathode electrode generating hydrogen, which are separated by a membrane or separator.

Types of Electrolyzers:

1. Alkaline
2. Proton Exchange Membrane (PEM)
3. Solid Oxide Electrolyzer Cell (SOEC)
4. Anion Exchange Membrane (AEM)

Source: LCRI Report 3002021864
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: NREL

Typical Cryogenic Tank Construction

[https://h2tools.org/bestpractices/liquid-storage-vessels#-text=liquid%20hydrogen%20(LH2)%20is%20usually%20precaution%20to%20prevent%20over%20pressurization](https://h2tools.org/bestpractices/liquid-storage-vessels#-text=liquid%20hydrogen%20(LH2)%20is%20usually%20precaution%20to%20prevent%20over%20pressurization)
Moving & Storing = Energy

Energy Requirements for H₂ Compression

- **Liquefaction of H₂** requires ~11 kWh/kg
- **Underground storage** ~45 to 200 bar
- **Gaseous tube trailers** ~200 to 500 bar*
- **Transmission Pipeline Transport** ~70 to 140 bar
- **Typical H₂ fuel cell vehicle dispensing pressure**

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

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

- Geologic storage of H₂ 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
U.S. existing natural gas & H₂ potential storage capacity, TWh

Legend (% vol. blend)

100% Natural Gas 5% H₂ | 95% NG 20% H₂ | 80% NG 80% H₂ | 20% NG 100% Hydrogen

100% H₂ storage would be approximately ~25% relative to natural gas on an energy basis.

To equal current natural gas energy storage capacity utilizing H₂, a 4X expansion of underground storage resources would be required.
Where is hydrogen used today?
Current Production Scale and Use

Worldwide Production
~94 million metric tons (MMT)

- Natural gas: 18%
- Coal: 19%
- By-product: 62%
- Fossil fuels with CCUS: 0.7%
- Electricity: 0.04%

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

- Refining: 55%
- Ammonia and Methanol: 35%
- Metals: 8%
- Other: 2%

Other includes:
- Food Processing
- Electronics

~60% Captive
~40% Merchant


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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

**SECTOR**
- TRANSPORT
  - On-road Vehicles
  - Non-road Vehicles
  - Residential Buildings
  - Commercial Buildings
- BUILDINGS
- INDUSTRY
  - Primary Industry

**TECHNOLOGY**
- Reciprocating IC Engine
- Gas Turbine Engine
- Hydrogen Fuel Cell
- Electric Motor
- Electric Heat
- Steam
- Direct Combustion
- Electro-Chemical Synthesis

**TASK**
- Propulsion
- Mechanical Work
- Cooking & Drying
- Space Conditioning
- Water Heating
- Process Heating
- Smelting & Reduction
- Cracking, Catalysis & Electrolysis
Opportunities for low-carbon fuels in the power sector

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

5-year Comparison of Operational Demands: CAISO

- 10 GW/hr Ramp

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

California 2022 Monthly Generation & Curtailment

- Solar
- Curtailled Solar
- Wind
- Curtailled Wind

Resource
- Solar
- Curtailled Solar
- Wind
- Curtailled Wind
- Nuclear
- Hydro
- Thermal
- Imports
Emerging markets

Potential export opportunities

Low-carbon fuels: leveraging new and existing markets

2019 U.S. Ammonia Exports

Data Source: World Bank

Green Methanol Makes a Splash in Quest for Net-Zero Shipping

August 17, 2023
By Bernardo Burga, Renewable Fuels, BloombergNEF

A Massive E-Fuel Plant Is Coming To Texas

E-fuels are a fledgling energy source, but the production of a reliable well could enhance their potential.

Porsche’s $100 Million Crusade to Future-Proof Internal Combustion

ConocoPhillips and JERA Americas sign ammonia off-take deal with Uniper

Iberdrola steps up green ammonia plans with 750 million euro project

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International & domestic opportunities

Emerging Domestic Energy Economy

Transportation
- On-road: Light-duty vehicles
- Non-road: Marine, Rail, Aviation

Industry
- Primary metals
- Petroleum and chemicals
- Cement and glass
- Food and beverage
- Other Manufacturing

Buildings
- Commercial: Space heating, Water heating
- Residential: Space heating, Water heating, Cooking

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
- [Flag]
- [Flag]
- [Flag]

Major Exporters
- [Flag]
- [Flag]
- [Flag]
Hydrogen is key to the power-to-fuels value chain.
Economic Considerations
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?

New Market Development

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

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

Change is never easy
Market headwinds & growing pains

Key Market Producer Price Indexes Relative to 2019 Prices

Industry-wide challenges

Emerging market challenges

Electrolyzer manufacturers struggle to turn growing order books into profits

Wednesday, September 6, 2023 4:04 AM ET

By Camilla Naschert
Markit Intelligence

Electrolyzer Market Growth

Data Source: US BLS

Large potential = large impacts

Diverse range of end-use applications with large markets

Pathways to Net-Zero

**LCRI U.S. NET-ZERO 2050**

**Reference** with no new carbon policy, continued technology improvements

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

- **All Options**
  - Geologic Storage of CO₂: Lower Costs
  - Natural Gas Supply Costs: Lower Costs
  - Bioenergy Feedstock Supply: Full

- **Higher Fuel Cost**
  - Geologic Storage of CO₂: Higher Costs
  - Natural Gas Supply Costs: Higher Costs
  - Bioenergy Feedstock Supply: Supply Limited

- **Limited Options**
  - Geologic Storage of CO₂: Not Available
  - Natural Gas Supply Costs: Lower Costs
  - Bioenergy Feedstock Supply: Supply Limited

Source: LCRI Report 3002024882

Full report available at lowcarbonlcri.com/netzero
Primary and Final Energy in Net-Zero 2050 Scenarios

**Primary Energy**
- **2020:**
  - Fossil: 92%
  - Fossil + CC*: 1%
  - Bioenergy: 1%
  - Bioenergy + CC*: 1%
  - Nuclear: 1%
  - Renewables: 2%

- **2050:***
  - All Options: 77%
  - Higher Fuel Cost: 60%
  - Limited Options: 68%

**Final Energy**
- **2020:**
  - Fossil Fuels: 60%
  - Low-Carbon Fuels**: 3%
  - Electricity: 37%

- **2050:**
  - Fossil Fuels: 42%
  - Low-Carbon Fuels**: 38%
  - Electricity: 36%

*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

2020

2050 Reference (No CO₂ Target)

2050 Net-Zero

All Options

Higher Fuel Cost

Limited Options

$19-$22

$13-16

$12

$9

$8

US average commodity price in $/mmBtu (including carbon penalty for Net-Zero cases)

NG

Ammonia Non-Energy Refining

NG+CC

Transport Industry (including non-road vehicles)

Bio+CC

Blend in NG Pipeline

Supply

Demand

Electrolysis (high-temp)

Electrolysis (PEM)

Power

Fuel synthesis (Syn-JF, SNG)

Source: LCRI Report 3002024882
Electrolytic Hydrogen Cost Sensitivities
LCOH = Levelized Cost of Hydrogen

Electrolysis Cost and Capacity Factor may have the largest influence on electrolytic hydrogen production costs.
Electrolysis LCOH Comparisons: 45V Impacts ($3/kg)

Potential to have significant impacts on H₂ 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
Benefits of Low-Carbon Hydrogen

Reduced emissions and environmental impact
- No direct CO₂ 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

Creating a Market for Low-Carbon Hydrogen
Government Support through the Infrastructure Bill

Total Funding: $21B

- Carbon Storage Validation & Testing: $2.5B
- Low-to-No Emissions Buses & Ferries ($2.5B each): $2.5B
- Electrolysis RD&D: $1B
- H₂ Recycling & Manufacturing ($0.5B): $0.5B
- CO₂ Capture Demo and Pilot Program: $3.4B
- Clean Direct Air Capture Hubs: $3.5B
- Clean H₂ Hubs: $8B

Carbon Dioxide Transportation Infrastructure Finance and Innovation (CIFIA)
Public resources

- The Center for Hydrogen Safety (CHS) and the Hydrogen Safety Panel (HSP). “Hydrogen Tool (H₂Tools),” https://h2tools.org/
Together...Shaping the Future of Energy™