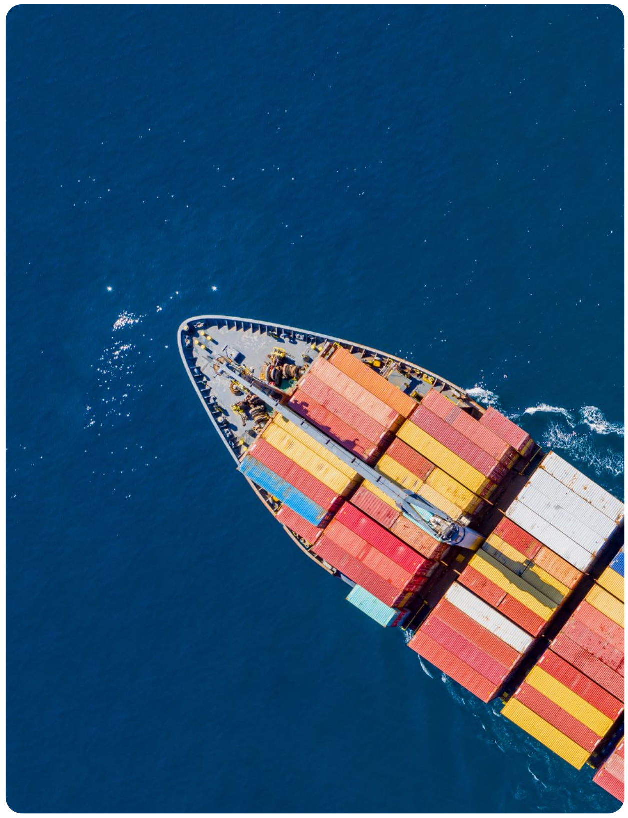
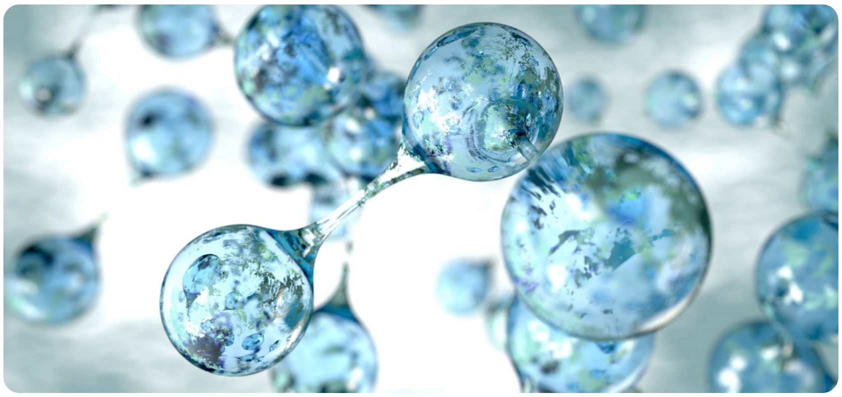
2ND EDITION

# GREEN HYDROGEN GUIDEBOOK





GREEN HYDROGEN COALITION

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# 01 EXECUTIVE SUMMARY

Economy-wide decarbonization is urgently needed to mitigate climate change and protect our communities' public health, infrastructure, and biodiversity. Green hydrogen is a game changer in this transition – it is a portable, energy-dense, scalable fuel that can decarbonize energy systems and economic sectors that are difficult to electrify.

For example, green hydrogen and its derivatives are the only viable, scalable solution to address hard-to-abate mobility sectors such as long-haul trucking, maritime shipping, and air travel. It can also serve as a zero-carbon fuel for high-heat industrial processes, such as steel and cement making. In addition, green hydrogen can safely store large commercial quantities of renewable energy for use when the sun is not shining, or the wind is not blowing – serving as a clean, firm power source for the electricity sector.

By leveraging green hydrogen created from renewable sources to fuel a multitude of sectors, we can transform how we power our world while creating vibrant, clean energy economies with family-sustaining jobs.

Hydrogen is already an internationally traded commodity, with the global demand for hydrogen totaling more than 90 million tons (Mt) annually. Today, it is primarily used as an industrial feedstock for oil refining and ammonia production. More than 70 Mt are used globally as pure hydrogen, and the remaining 20 Mt is mixed with carbon-containing gases in methanol production and steel manufacturing. The vast majority (>99%) of hydrogen sold today is produced from fossil fuel-derived hydrocarbons – namely natural gas and coal – resulting in close to 900 Mt of carbon dioxide ($CO_2$) emissions per year. This carbon impact is greater than the annual carbon emissions equivalent of Germany, the world's fourth-largest economy.[1]

**GHC defines green hydrogen as hydrogen produced from non-fossil fuel resources and has climate integrity, i.e., emits zero or de minimis greenhouse gases on a life cycle basis.**

The Green Hydrogen Coalition (GHC) defines green hydrogen as hydrogen that is not produced from fossil fuels and has climate integrity – meaning that the production pathway achieves zero or de minimis greenhouse gas emissions on a life cycle basis. Some commercially viable pathways to produce green hydrogen include electrolysis of water using renewable electricity, thermal conversion/gasification of biomass and organic waste, and steam methane reformation (SMR) of biogas.

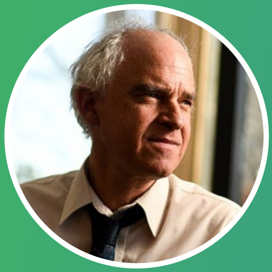
While hydrogen production from fossil fuels is currently more cost-competitive (2 – 3x cheaper), hydrogen produced from renewables is anticipated to be the lowest-cost option in the long-term. According to experts at the International Energy Agency, green hydrogen produced via electrolysis of water using renewable electricity is anticipated to cost as little as $1.30/kilogram (kg) by 2030 – outcompeting hydrogen produced from fossil fuels.[2] Factors that will help bring down green hydrogen production costs in the coming years include, but are not limited to manufacturing economies of scale, technology efficiencies, access to low-cost renewable electricity, and government-led decarbonization mandates.

**"Low-carbon hydrogen is a necessary solution for reducing GHG emissions in hard-to-decarbonize sectors and for getting to net-zero by 2050. Hydrogen is also extremely dynamic as a solution across the energy value chain, and is therefore well-suited for the many different types of clean energy solutions that are required by various jurisdictions."**

**Dr. Guy Gensey**
Director, Energy and Industry Decarbonization,
British Columbia Ministry of Energy, Mines and Low Carbon Innovation

Hydrogen is becoming foundational to international climate efforts. Governmental support for green or low-carbon hydrogen around the globe has accelerated substantially since 2020, with over ten countries and the European Union publishing national hydrogen strategies. These strategies include a wide range of hydrogen market drivers, including procurement targets, legislative and regulatory measures, research and development initiatives, sectoral priorities, and other economic and financial mechanisms.

The United States has achieved notable progress due to the bipartisan Infrastructure Investment and Jobs Act ("IIJA") signed into law by President Biden on November 15, 2021. The IIJA includes $8 billion for Regional Clean Hydrogen Hubs, catalyzing the use of clean hydrogen in the industrial sector and beyond; $1 billion for a Clean Hydrogen Electrolysis Program to reduce costs of hydrogen produced from clean electricity; and $500 million for Clean Hydrogen Manufacturing and Recycling Initiatives to support equipment manufacturing and strong domestic supply chains.[3] The IIJA also requires the development of a national clean hydrogen roadmap and strategy. These provisions will undoubtedly help accelerate progress, reduce technology costs, and ramp up the use of hydrogen as a clean energy carrier throughout the United States.



**"In Colorado, we see green hydrogen as playing an important role in helping to achieve 100% carbon free electricity, providing long duration storage and load following services to complement a primarily renewable grid."**

**Will Toor**
Executive Director, Colorado Energy Office

*The Green Hydrogen Guidebook* is designed to increase understanding of green hydrogen production, transportation, storage, safety, applications and use cases, value proposition, and policy drivers and barriers. The Guidebook offers a vision of an affordable, just, and inclusive clean energy future and catalogs inspiring global examples of green hydrogen projects and practices already underway.

# 02 WHAT IS HYDROGEN?

## Hydrogen is the most abundant element in the universe. It is a globally produced energy carrier that can be used to store, transport, and deliver energy produced from various sources.

Hydrogen (H) is the simplest and most abundant element in the universe. Naturally occurring as two bonded H atoms ($H_2$), hydrogen is the lightest of all molecules. It is a colorless, odorless, and tasteless gas under standard conditions. On Earth, hydrogen is primarily bound within molecules of water or hydrocarbons. Most are familiar with hydrogen as paired with oxygen, forming $H_2O$, or water.

Hydrogen gas is a well-established and globally traded commodity. It is primarily used as an industrial feedstock or as an intermediate chemical feedstock in many industrial processes, such as oil refining, methanol production, and ammonia production for fertilizer.

In addition, hydrogen can be used as a fuel or energy source. Hydrogen has the highest energy density of today's most-used fuels, including diesel, natural gas, and gasoline. Since hydrogen has a very low density at ambient temperature, hydrogen energy is typically measured by weight in kilograms (kg) instead of by volume (as with natural gas). For example, 1 kg of hydrogen contains approximately the same energy as 1 gallon (2.8 kg) of gasoline.

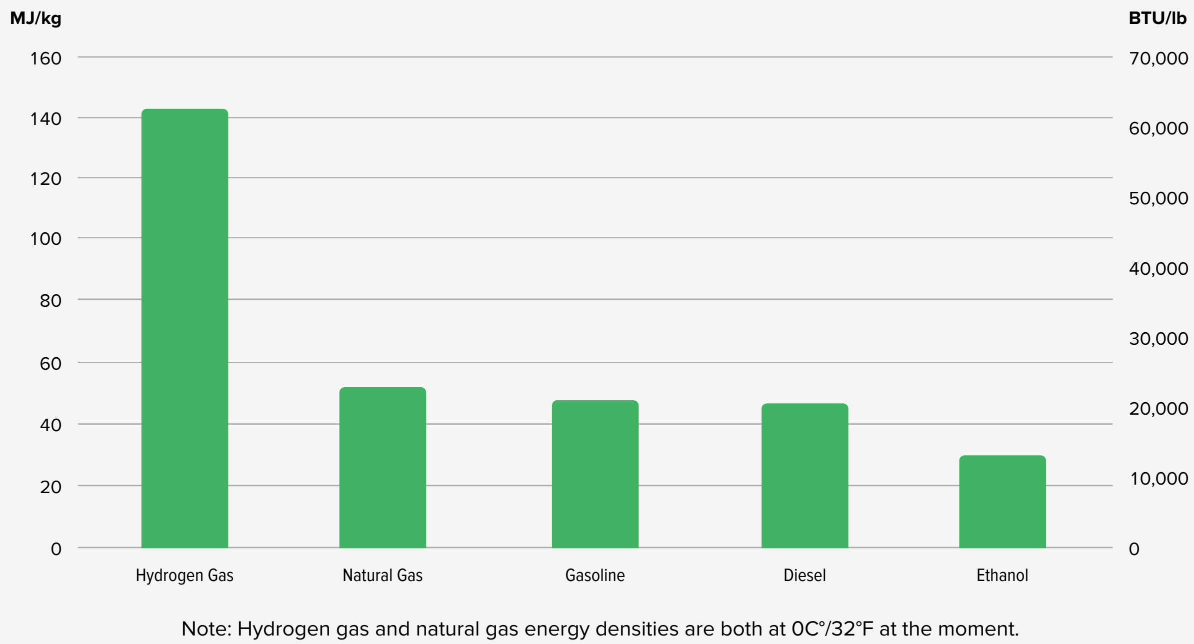



**Figure 1** | Comparative Energy Density of Common Fuels[4]

The annual global demand for hydrogen in 2017 was approximately 90 million tonnes, with about 10 million tonnes being produced annually in the United States.[5] Decarbonizing today's global hydrogen supply would result in a reduction of 900 million tonnes of carbon dioxide emissions per year, more than the annual carbon equivalent of Germany, the world's fourth-largest economy.[6]

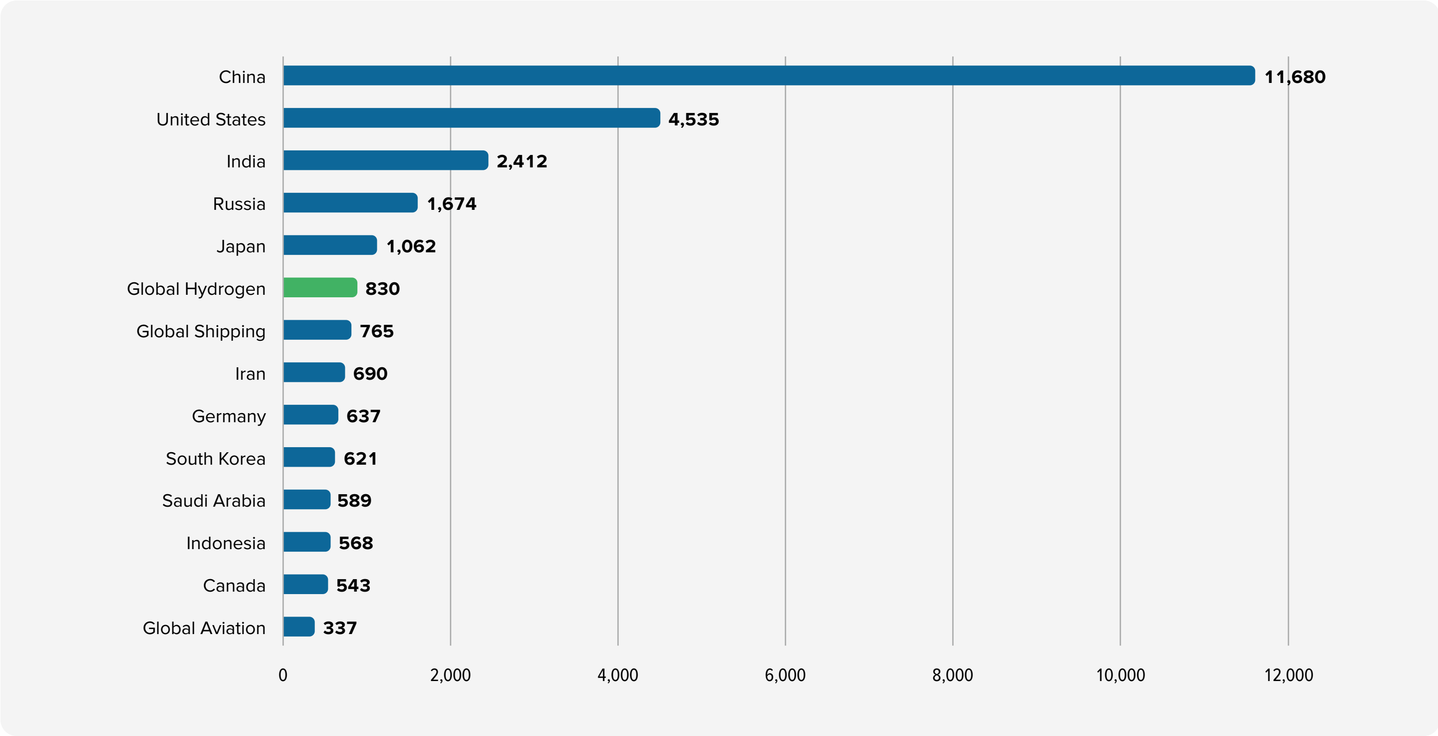
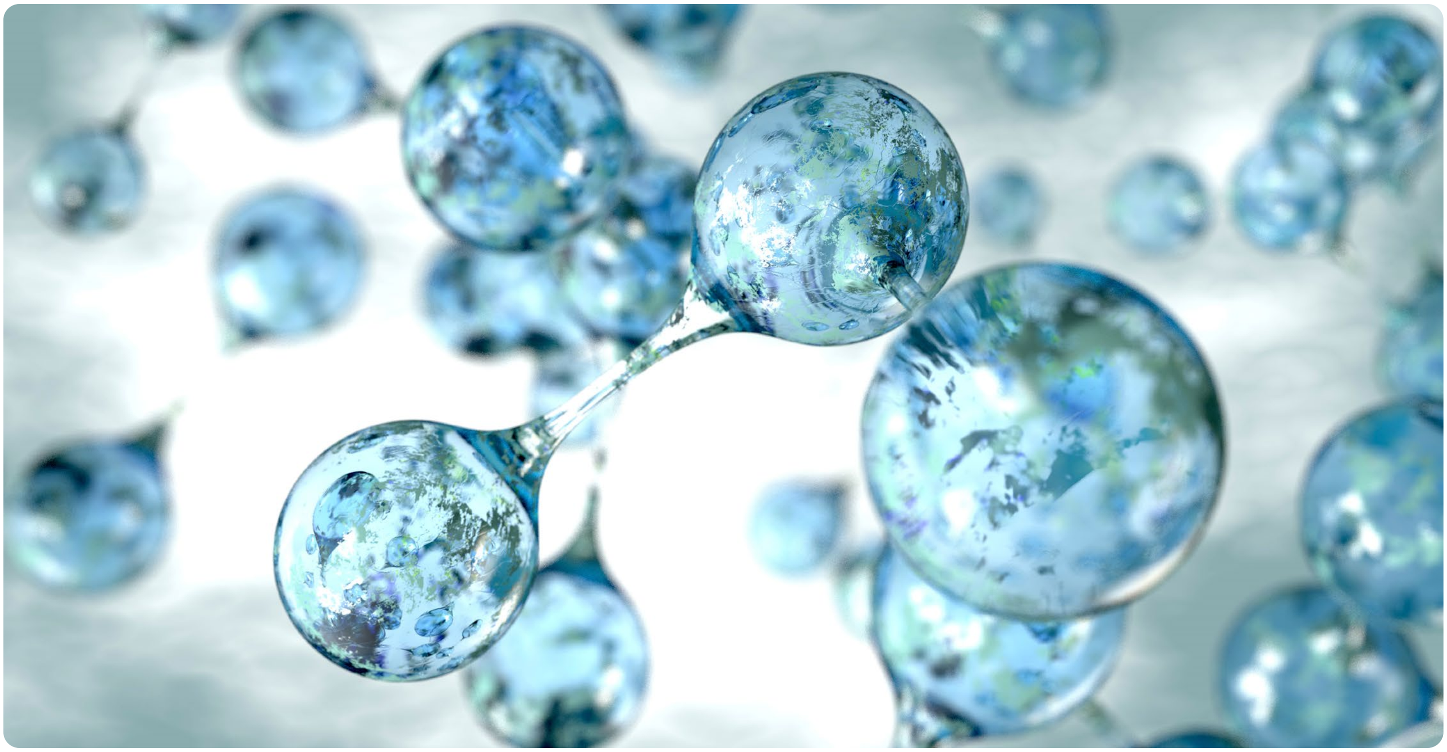



**Figure 2** | 2020 $CO_2$ Emissions by Country & Sector in Megatons of $CO_2$ Per Year[7]



# 03 DEFINING HYDROGEN

### 3.1 | COLOR-CODING

While hydrogen is a colorless gas, it has been given color codes such as green hydrogen, pink hydrogen, blue hydrogen, and so on. The energy industry uses these color codes to indicate the primary feedstocks, energy sources, and production processes used to produce the hydrogen. Below is an illustrative example of a hydrogen color spectrum:

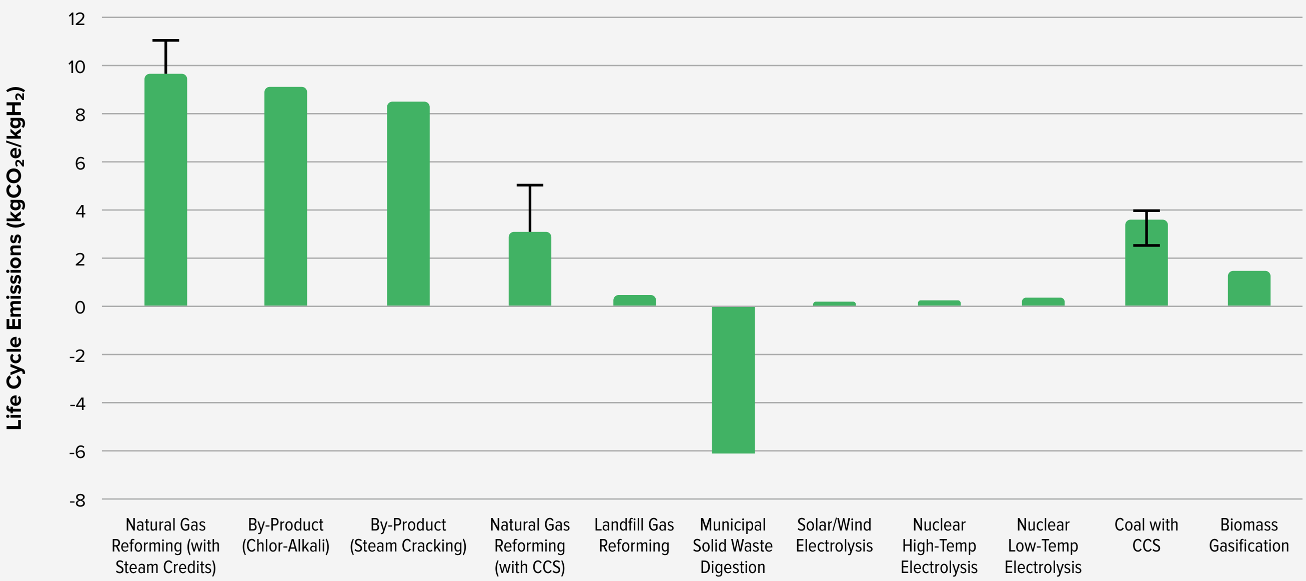
| Color | Primary Feedstock | Primary Energy Source | Primary Production Process | Carbon Intensity $kgCO_2e/kgH_2$ |
|---|---|---|---|---|
| Brown | Coal or Lignite | Chemical Energy in Feedstock | Gasification & Reformation | |
| Gray | Natural Gas | Chemical Energy in Feedstock | Gasification & Reformation | |
| Blue | Coal, Lignite, or Natural Gas | Chemical Energy in Feedstock | Gasification with Carbon Capture and Sequestration | |
| Pink | Water | Nuclear Power | Electrolysis | |
| Green | Water | Renewable Electricity | Electrolysis | |
| | Biomass or Biogas | Chemical Energy in Feedstock | Gasification, Reformation, & Thermal Conversion | |

**Figure 3** | The Colors of Hydrogen

As seen above, there are many ways to create hydrogen gas. The color-coding approach helps simplify and makes common-sense associations for these different pathways. However, due to its simplification, it has led to variance in color definitions and coding worldwide. As a result, there is growing interest in moving from color-coding to something more quantifiable. One such alternative is evaluating hydrogen based on its carbon intensity.

## 3.2 | CARBON INTENSITY METHODOLOGY

Carbon intensity is defined as a fuel's life cycle greenhouse gas emissions per unit of fuel or energy delivered. This accounts for life cycle emissions (well-to-gate), not just those that are emitted when the fuel is consumed. Hydrogen's carbon intensity can be measured in kilograms of $CO_2$ equivalent ($CO_2e$) per kilogram of hydrogen. For any quantity and type of greenhouse gas, $CO_2e$ signifies the amount of $CO_2$ that would have the equivalent global warming impact.[8] The graph below shows the associated life cycle emissions produced from multiple hydrogen production pathways.




Note: Ranges shown reflect potential variability in upstream leak rates, carbon capture and storage (CCS) efficiency, and capture rates. Baseline assumes 90% capture.

**Figure 4** | Life Cycle $CO_2e$ Emissions From Multiple Hydrogen Production Pathways[9]

Unlike coloring-coding hydrogen, carbon intensity provides a quantitative categorizing method. This method is a technology-agnostic approach, as it only considers the life cycle emissions from the hydrogen source. As a result, the door is open for competition to flourish so long as the hydrogen production pathway in question can meet the desired life cycle emissions threshold. A carbon intensity approach is already taking shape in places like the United States, Canada, and the European Union (EU). For example, the U.S. Infrastructure Investment and Jobs Act defines qualified "clean hydrogen" as hydrogen produced with a carbon intensity equal to or less than 2 kilograms of $CO_2e$ per kilogram of hydrogen.[10]

Government agencies worldwide could adopt a similar approach and develop a common carbon intensity framework that meets their specific decarbonization and energy goals. This quantitative approach can provide the following benefits:

- Removes ambiguity when developing hydrogen eligibility guidelines
- Allows flexibility to create specific life cycle emissions thresholds
- Supports easy development of incentive and tariff design
- Increases project finance certainty for developers
- Spurs competition between technology players
- Provides a pathway for emerging technologies to compete
- Allows for a common framework for regional and national collaboration

## 04 HYDROGEN SAFETY

Hydrogen is a safe, nontoxic, and reliable fuel, with 70 million tonnes produced and consumed each year around the world.[11] From a safety perspective, a molecule of green hydrogen is indistinguishable from gray hydrogen and can be treated simply as hydrogen gas ($H_2$).

Hydrogen gas has suffered from a misguided negative reputation associated with an early technical failure. In 1937, the Hindenburg, a lighter-than-air airship held aloft by hydrogen, tragically caught fire and exploded during a lightning storm.[12] Information indicates that hydrogen actually leaked and escaped quickly from the Hindenburg and that what really caught fire was the airship's flammable coating that was intended to be waterproof, as well as the magnesium struts, which burned very brightly. More than 80 years have passed since this tragic event and, like many technologies, hydrogen safeguards have come a very long way.

The U.S. Department of Energy website states, "a number of hydrogen's properties make it safer to handle and use than the fuels commonly used today."[13] Like all fuels, hydrogen should be treated with care. However, compared to the fuels we rely on today, such as gasoline, natural gas, uranium, jet fuel, and diesel, hydrogen is a safer, nontoxic, and—if produced from renewable energy sources—greenhouse gas (GHG)-free fuel source.

The safety benefits of hydrogen as a fuel source are:[14]

- Hydrogen is a **nontoxic**, colorless, and odorless gas that does not threaten human or environmental health if leaked or released into the environment.
- Hydrogen is much lighter than air (14x lighter) and about 57x lighter than gasoline vapor, so it **dissipates rapidly when it is released**. This allows for rapid dispersal of the fuel in the case of a leak.
- Hydrogen rises in the surrounding air, so it is unlikely to remain near the ground where people are in case of fire.
- Hydrogen combustion is more rapid than the combustion of other fuels. A hydrogen cloud will burn within seconds, and all the energy of the cloud will be released.
- Safety features are designed and engineered into hydrogen systems, managed by governments, and are also regulated in accordance with expert third-party international hydrogen safety standards.

For additional safety information regarding hydrogen blending in natural gas pipelines, see Section 5.3.2.

## 05 GREEN HYDROGEN TECHNOLOGIES

Hydrogen has been a globally traded commodity for decades, and a robust hydrogen industry already exists. The components of hydrogen production, storage, and distribution are safe, well-understood, and commercially available today.

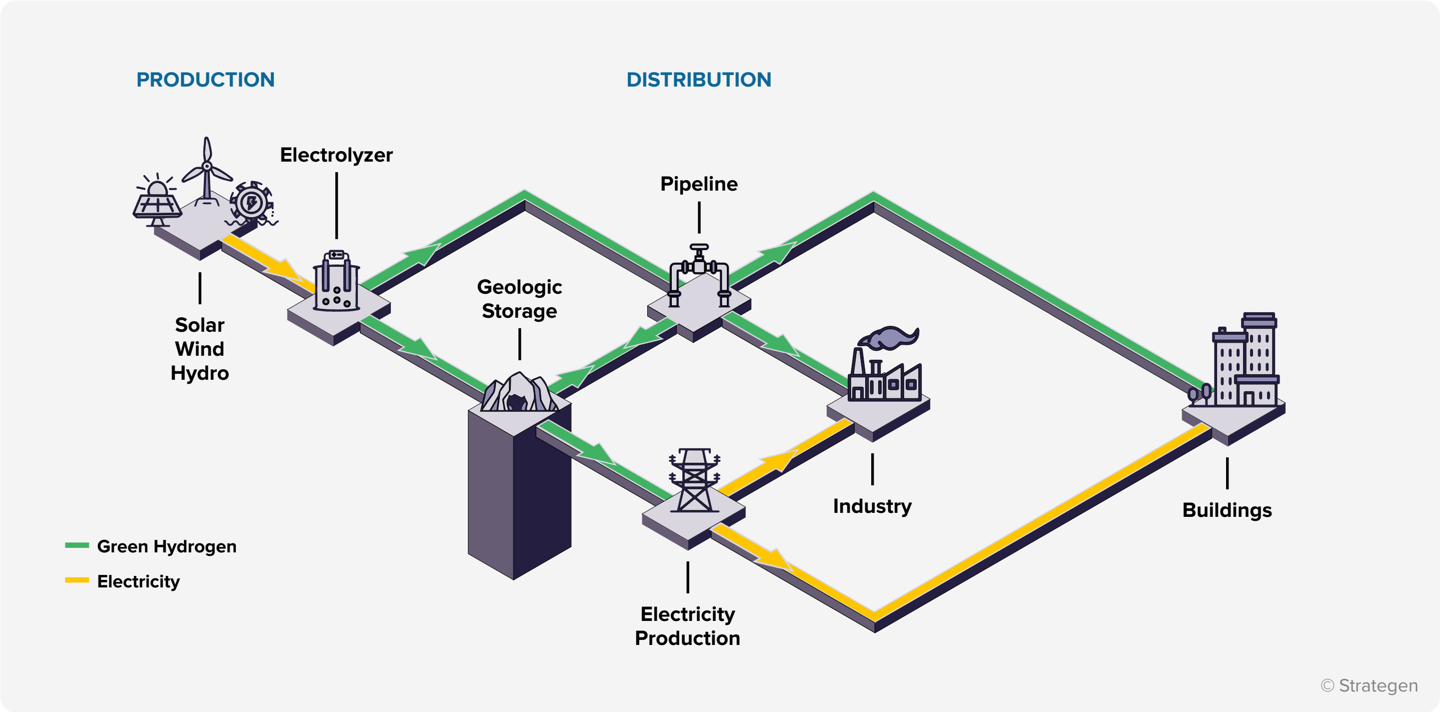



**Figure 5** | Production and Distribution Pathway for Green Hydrogen – Electrolysis Example

### 5.1 | GREEN HYDROGEN PRODUCTION

The GHC's definition of green hydrogen is technology agnostic. To qualify as green hydrogen, the only requirement is that the hydrogen be produced from non-fossil fuel resources, and the life cycle carbon intensity of the hydrogen production pathway be zero, de minimis, or, in some cases, even negative. The following sections discuss some of the most common methods of green hydrogen production—electrolysis of water, steam methane reforming (SMR) of biogas, and thermal conversion of biomass—but, as mentioned, green hydrogen is not limited to only these pathways as many more are likely to be developed and commercialized in the coming years.

#### 5.1.1 | Electrolysis

The green hydrogen technology that has gained the most attention recently is electrolysis of water. The EU's Hydrogen Roadmap focuses almost entirely on electrolysis for the continent's $H_2$ strategy. Electrolysis is an established technology that has been utilized for nearly a century and is a proven and scalable method for green hydrogen production.

Electrolysis is a method of using energy from an electric current to split a molecule into simpler components. In the case of green hydrogen, the feedstock is water ($H_2O$), which gets split into the components oxygen ($O_2$) and hydrogen ($H_2$). Electrolysis is accomplished using a commercially available device called an electrolyzer. When an electrolyzer is powered by renewable or zero-carbon electricity, the **process emits no greenhouse gases**. Hydrogen produced from this methodology is sometimes referred to as "green electrolytic hydrogen" or simply as green hydrogen. Because renewable energy from solar and wind is the lowest-cost, most globally abundant, and most widely available clean energy resource, green hydrogen produced from electrolysis is a very compelling decarbonization opportunity.

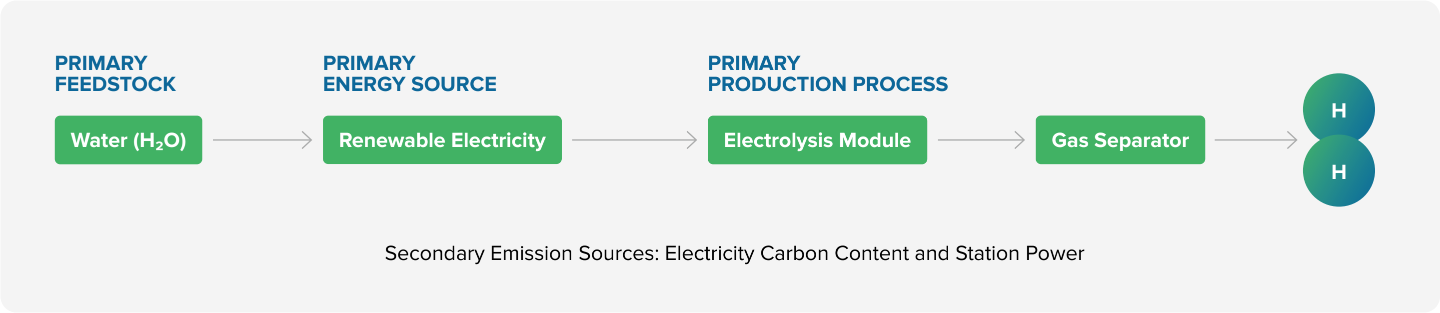



**Figure 6** | Electrolytic Green Hydrogen Production Process Flow Diagram

Electrolyzers range in size from small-scale, appliance-sized devices to large-scale equipment that can be directly connected to utility-scale electricity generation sources. The largest electrolysis cells can be stacked and used for commercial green hydrogen production when connected to wind farms, solar plants, or other renewable electricity sources. Electrolyzer systems can be modular, with the ability for additional units to be added over time.

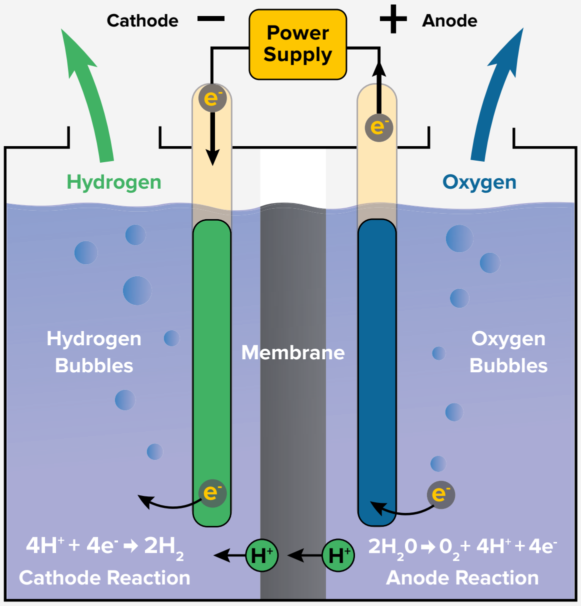



**Figure 7** | Diagram of an Electrolyzer

Electrolyzers can provide important grid services since they operate with fast response times and can provide a flexible load to the grid to address multiday and seasonal needs. For example, deploying fleets of electrolyzers can consistently and reliably reduce critical peak loads within a defined region or location on the grid. They can consume energy when prices are low and defer consumption when prices are high. Electrolyzers can offer ancillary grid services such as voltage support and frequency regulation.[15] Green electrolytic hydrogen is a vital tool for electrification since the resource begins as renewable electricity and can end as renewable electricity.

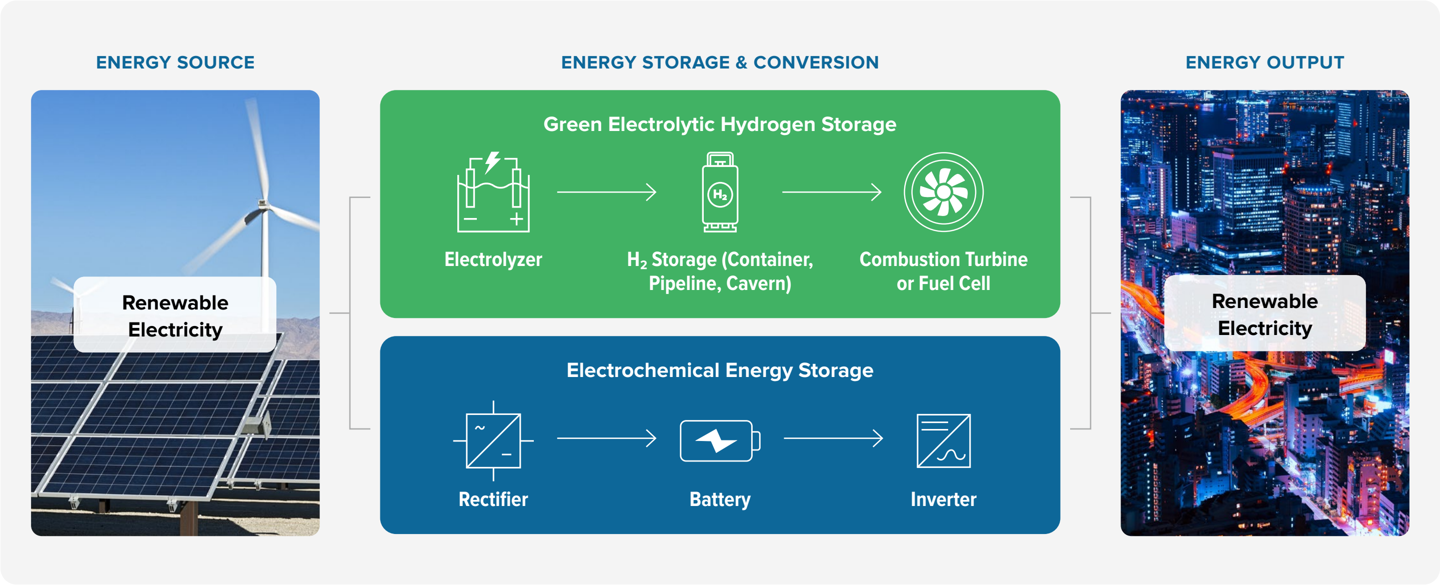



**Figure 8** | Electrolytic Green Hydrogen Energy Storage Compared to Electrochemical Energy Storage

The most mature electrolysis technology is the alkaline (ALK) electrolyzer, which has been in commercial use since the mid-twentieth century. An ALK electrolyzer uses a cell with a cathode, an anode, and an electrolyte based on a solution of caustic salts (e.g., NaOH). ALK technology is mature and has a relatively low capital cost compared to other types of electrolyzers.[16] Other advantages of ALK electrolyzers include virtually instant operation and resistance to humidity and salt air. ALK fuel cells are mostly used in backup generators or long-duration uninterruptible power supplies, as well as for powering telecom towers.[17]

Proton exchange membrane (PEM) electrolyzers utilize an ionically conductive solid polymer rather than a liquid to drive hydrogen production. PEM electrolyzers can react quickly to the fluctuations in power generation typical of renewable power and produce higher-purity hydrogen gas. PEM electrolyzers can be used for renewable power-to-gas applications.

High-temperature solid oxide electrolyzer cells (SOEC) utilize ceramic membranes that conduct ions at very high temperatures and pressures to separate superheated steam into oxygen and hydrogen. The efficiency offered by a SOEC electrolyzer is much higher than other technologies, but this technology is in early commercialization.

| Electrolyzer Technology | Maturity | Stack Efficiency (Lower Heating Value) | Electrical Efficiency ($kWh/kgH_2$) | Capital Cost ($/kW) |
|---|---|---|---|---|
| Alkaline (ALK) | Mature | 50-68% | 50-78 | 500-1,000 |
| Proton Exchange Membrane (PEM) | Mature | 50-68% | 50-83 | 700-1,400 |
| Anion Exchange Membrane (AEM) | Early Market | 52-67% | 57-69 | Unknown |
| Solid Oxide Electrolyzer Cells (SOEC) | Early Market | 75-85% | 40-50 | Unknown |

**Table 1** | System Cost and Efficiency of Available Electrolyzer Technologies[18]

About 2% of today's global hydrogen is produced via electrolysis.[3] Primary costs that contribute to the price of electrolytic green hydrogen include the cost of renewable or grid electricity, the capital costs of the electrolysis equipment, and the capacity factor of the electrolyzer.

Today, electrolyzer system capacities range from tens of kilowatts to tens of megawatts in size. Current research and development is focused on improving power density, lifetime, technology scale-up, cost reductions, and efficiency of electrolysis cells. Several startups are working on pathways to directly electrolyze sea water because electrolyzers today require freshwater for green hydrogen production.[19]

#### 5.1.2 | SMR of Biogas

Biogases can be used as a feedstock for SMR, the same process used to create gray hydrogen. Unlike fossil fuel-derived natural gas, the biogas input is produced from biomass through the process of anaerobic decomposition, a naturally occurring process where bacteria break down biomass and expel biogas. The composition of biogas varies from 40%–60% methane to 60%–40% $CO_2$, alongside small amounts of water vapor and other gases.[20]

When methane from biogas is steam-reformed, the resulting green hydrogen is considered a renewable carbon-neutral fuel because, although the process includes carbon, the carbon used is already active in the earth's carbon cycle. By contrast, when fossil fuels are used, carbon once trapped deep in the earth is released, adding additional, net-positive, carbon to the environment. SMR-generated biogas can displace fossil fuels as the input feedstock, and significantly reduce the carbon impact of hydrogen production.

Biogas can be sourced from landfills, wastewater treatment facilities, and animal and plant waste. Re-using biomass as a fuel feedstock can help municipalities and farmers generate new sources of income by upcycling a low-value product into a valuable product that can be sold. This process also creates an environmentally friendly alternative to flaring biogas waste products.

#### 5.1.3 | Thermal Conversion/Gasification of Biomass and Organic Waste

Thermal conversion, or gasification of organic matter, works by applying high heat and/or pressure on organic matter to transform the material from a solid state to a gaseous state. The resulting components of the process are mainly hydrogen, carbon monoxide, and carbon dioxide, which are further purified to produce hydrogen or methane that can be used for fuel.

**Simplified Thermal Conversion Reaction of Plant Matter:**

$$C_6H_{12}O_6 + O_2 + H_2O \rightarrow CO + CO_2 + H_2 + \text{other}$$

Organic matter can come from forestry waste, agricultural waste, organic municipal solid waste, or animal waste. This method of creating green hydrogen is in the early stages of commercialization. The U.S. Department of Energy estimates that, as of 2005, 1 billion dry tons of biomass could be sustainably produced and available for energy use annually in the United States.[21]

Similar to biogas produced by SMR, the gas produced by this system can displace the traditional fossil fuel inputs in hydrogen processes. Further, as a carbon-neutral fuel creating value from waste, this system encourages the recycling of biomass and other organic material into useful fuels.

Other green hydrogen production processes are also being researched and developed for commercial purposes. These include thermochemical water splitting, photocatalysis, and anaerobic digestion.

#### 5.1.4 | Water Consumption

Water usage is an important environmental consideration when comparing green hydrogen production pathways such as those explained above. From a life cycle perspective, electrolytic hydrogen requires about 9 kg of water per kg of hydrogen produced. Water demand for bio-based pathways is considerably higher and ranges from 18 kg to 7,400 kg of water per kg of hydrogen, but the exact water demand depends on the source of the biomass or biogas (i.e., waste is at the low end for water demand and energy crops are at the high end).[22]

Site-specific resource availability is important in assessing which green hydrogen production method is most appropriate in a given region. For large-scale green hydrogen production in areas with scarce freshwater supplies but abundant, low-cost renewable energy, seawater desalination may be an option.

### 5.2 | HYDROGEN STORAGE

Once hydrogen gas is produced, it must be stored. Hydrogen can be stored using different methods, with each having trade-offs related to application, location, scale, and cost.[23]

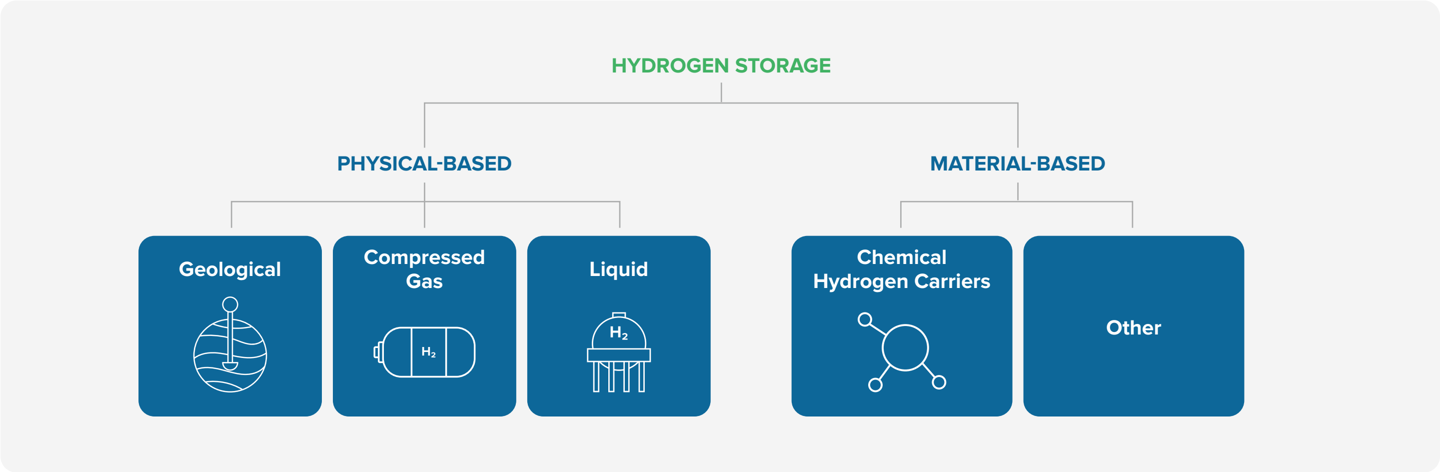



**Figure 9** | Hydrogen Storage

### 5.2.1 | Physical Storage

Physical storage is the most common form of hydrogen storage. Hydrogen is most often stored as a gas or liquid in tanks of various sizes or, on a larger scale, within geologic formations.

### 5.2.2 | Compressed Gas

Compressed gas is the most well-established hydrogen storage technology. State-of-the-art compressed gaseous hydrogen storage includes carbon fiber-reinforced 5,000 and 10,000 pounds per square inch (psi) compressed gas tanks for onboard hydrogen storage. Research regarding compressed hydrogen gas tanks is focused on identifying a lower-cost material that can replace the necessary carbon fibers, while still meeting pressure and safety specifications and not compromising weight and volume.

### 5.2.3 | Liquid

Hydrogen can be stored as a cryogenic liquid at temperatures at or below −253°C in high-grade insulated tanks. Insulated tanks keep heat transfer to a minimum to ensure the hydrogen remains in a liquid state. Heat transfer to the tank increases the internal pressure, which is rectified using a relief valve through which hydrogen can escape in a process known as "boil-off." Because liquid hydrogen has a higher energy density than its gaseous form, liquid storage requires less on-site space. However, liquefaction is required to convert hydrogen to liquid form, which increases the cost and energy inputs.

Further, compression and cooling processes can be combined to yield cryo-compressed hydrogen with an even higher energy density than either liquid hydrogen or compressed hydrogen gas. Cryo-compressed storage systems maintain hydrogen at very high pressures of around 5,000 psi and low temperatures of below −253°C. Insulation is normally achieved via vacuum, and the cryo-compressed storage tanks are carbon-fiber-reinforced, just like compressed hydrogen gas tanks, to withstand high internal pressures. Cryo-compression reduces boil-off as compared to liquid storage. Cooling and compression both require significant energy inputs and result in higher costs.

### 5.2.4 | Geological Storage

Due to economies of scale, high efficiency, and low operational cost, the most cost-effective option for bulk, long-term hydrogen storage is geological storage. Geologic storage includes subsurface options such as naturally occurring salt caverns, depleted natural gas or oil wells, and aquifers, all of which are currently used for natural gas storage. The United States has a total installed underground storage capacity of more than 4 trillion cubic feet of natural gas.[24] Bulk underground hydrogen storage in salt caverns has been demonstrated as a safe and effective process; salt caverns have been used for hydrogen storage in the United Kingdom since the 1970s and in the United States since the 1980s. Other geologic options such as wells and aquifers are much less mature hydrogen storage options; the feasibility and cost still need to be investigated.

The United States has the world's largest operational salt cavern hydrogen storage system, the Air Liquide Spindletop facility in Texas, commissioned in 2017.[25] The subsurface facility has a storage capacity of over 580,000 cubic meters of hydrogen, equivalent to about 2,520 tons. [26,27] This facility is able to store approximately 30 days of hydrogen output from a nearby SMR facility and is intended to help manage supply and demand for refining and chemicals.

Additionally, there is a plan to store green hydrogen in a salt cavern at the Intermountain Power Project in Delta, Utah, the United States' largest green hydrogen project. At this facility, hydrogen gas can be stored for days, weeks, months, and even seasons to be dispatched on-demand as a clean fuel for carbon-free combustion turbine power generation. The potential hydrogen storage capacity of the naturally occurring salt formation in this location is tremendous. One cavern can hold 5,512 tons of hydrogen gas, equivalent to filling 200,000 hydrogen-powered buses. More than 100 caverns can be built at this location.[28]

Lastly, hydrogen can be stored in depleted natural gas fields if the residual gas has low $CO_2$ concentration, and the reservoir rocks are low in carbonate and sulfate-bearing minerals but high in reactive iron-bearing minerals. The reservoirs must also have low temperature and pressure conditions.[29]

#### 5.2.5 | Material-Based

Material-based hydrogen storage can be divided into three subsets: chemical hydrogen carriers, metal hydrides, and adsorbents.

The most common material-based hydrogen storage methods are chemical hydrogen carriers, which usually have high densities of hydrogen and can store the molecule as a solid or liquid rather than as a gas. Hydrogen can be stored in one form and then stripped and reconstituted into its pure form ($H_2$). Examples of hydrogen carriers include ethanol ($C_2H_6O$), natural gas ($CH_4$), and ammonia ($NH_3$), all of which contain hydrogen atoms. Ammonia is a particularly promising, carbon-free chemical energy storage medium, although the process to make ammonia is very energy-intensive.

Additional opportunities for material-based hydrogen storage include metal hydrides and adsorbents. These methods are primarily still in the research and development phase as the storage densities achieved so far are low, and system costs are high. In metal hydride storage systems, hydrogen forms interstitial compounds with metals as it is adsorbed on the metal surface. Hydrogen can then be released again with heat input. Metal hydrides utilize elements such palladium, magnesium, lanthanum, aluminum, intermetallic compounds, and alloys.[30] Hydrogen can also be stored on the surface of solids through adsorption. Such materials include metal-organic frameworks, microporous crystalline aluminosilicates (zeolites), or microscopically small carbon nanotubes. In theory, adsorbent hydrogen storage can make it possible to store large quantities of the molecule at room temperature and pressure, with densities greater than that of liquid hydrogen, because the hydrogen molecules are dissociated into atomic hydrogen within a metal hydride lattice structure.[31] Research, development, and demonstration of materials-based storage is ongoing.

### 5.3 | HYDROGEN DISTRIBUTION

There are many ways to distribute hydrogen, including by pipelines, road transport, and marine shipping.

#### 5.3.1 | Dedicated Hydrogen Pipelines

Like natural gas, compressed hydrogen can be transported and stored in dedicated pipelines. The United States has about 1,600 miles (2,575 kilometers) of dedicated hydrogen pipelines.[32] Most of these pipelines are concentrated near large industrial users in Louisiana and Texas, such as petroleum refineries and chemical plants. Major cities also have dedicated hydrogen pipelines. For example, Air Products operates 17 miles of hydrogen pipeline in Los Angeles.[33]

Dedicated hydrogen pipelines move hydrogen molecules at constant, relatively low pressure. Hydrogen pipelines are typically operated at pressures like those of natural gas pipelines, between 500–1200 psi.[34] In the United States, hydrogen pipeline safety is regulated by the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration.

Recent studies demonstrated the feasibility of repurposing existing natural gas pipelines for pure hydrogen gas transport.[35] While, in principle, hydrogen can embrittle steel pipes and fittings and reduce equipment lifespans, this is only likely if the pipeline already has fractures, is subjected to fluctuating internal pressure, and is exposed to atomic hydrogen. Normal operating conditions include little load alternation and, if only molecular hydrogen is in contact with pipes, pipeline embrittlement is unlikely. Thus, the existing pipeline infrastructure itself is feasible to repurpose. One key modification that should be considered is the need for compressor stations along the pipeline length, as hydrogen has three times higher flow velocity than natural gas. Existing compressors can be used for lower volumes of hydrogen, but the delivery of pure hydrogen will necessitate the installation of new, additional turbines or motors and more powerful compressors.

Repurposing existing natural gas pipelines to transmit and distribute green hydrogen is an effective way of using valuable existing infrastructure and avoiding stranded costs. For example, 69% of the pipelines needed to build a European Hydrogen Backbone could come from repurposing existing natural gas pipelines.[36]

### 5.3.2 | Blended Hydrogen in Pipelines

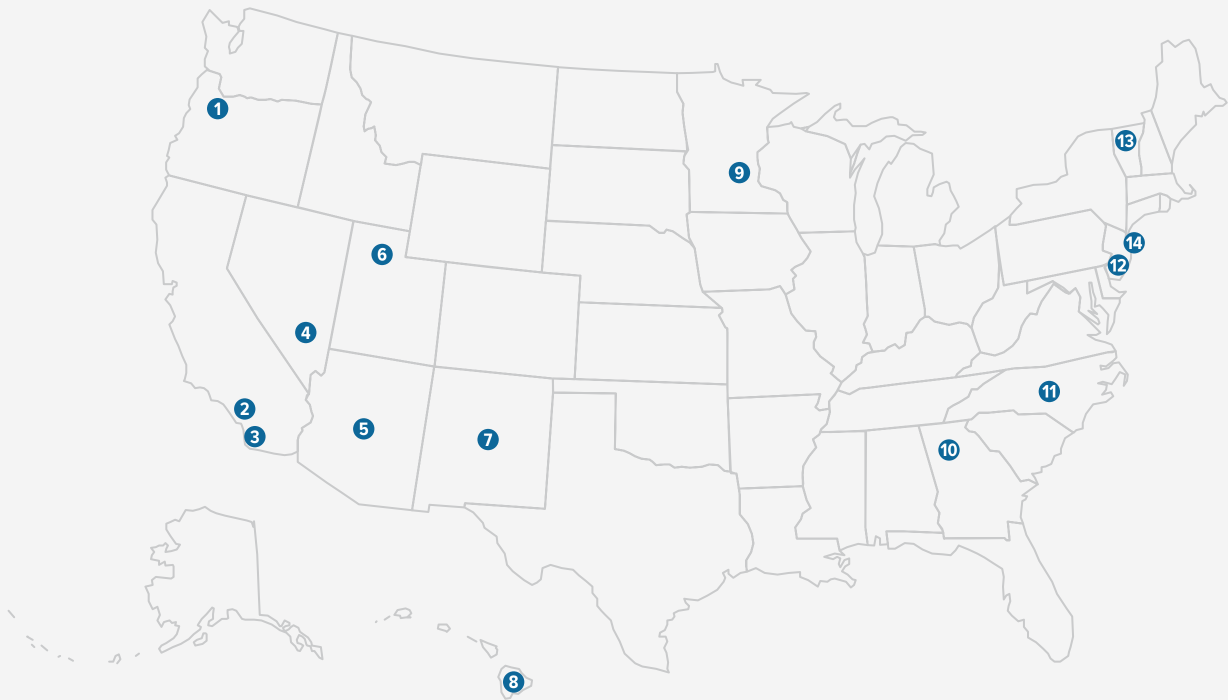
Blending green hydrogen with natural gas in pipelines can help decarbonize gas networks while preserving existing jobs and infrastructure. Blends vary by the percentage of natural gas to hydrogen by volume. Typical hydrogen blends in natural gas pipelines range from 3% to 15% hydrogen by volume.

The highest concentration of hydrogen reported by any U.S. gas utility is in Oahu, Hawaii, where Hawaii Gas's natural gas pipeline contains approximately 12% hydrogen gas.[37] Several other gas utilities are piloting hydrogen-natural gas blending in pipelines, including Southern California Gas (SoCalGas) and Dominion Energy. Other countries, including Canada, Germany, and Austria, are also considering natural gas decarbonization strategies that involve hydrogen blending.

**The highest concentration of hydrogen reported by any gas utility in the U.S. is in Oahu, where Hawaii Gas' natural gas pipeline contains approximately 12% hydrogen gas.**

Ongoing research and development efforts explore the safety, feasibility, maintenance requirements, and costs of expanding hydrogen gas blending across natural gas networks. Notably, a recent University of California Irvine study (UCI) demonstrated that hydrogen leaks from pipes at the same rate as 100% natural gas at any volumetric blend from a typical low-pressure natural gas distribution pipeline (45 psi gauge pressure).[38]

Another research effort focuses on embrittlement due to hydrogen blending in natural gas pipelines. As discussed in the Dedicated Hydrogen Pipeline section, metals can become brittle with the introduction and diffusion of hydrogen into the material. Hydrogen embrittlement becomes significant when it leads to metal weakening or cracking. Embrittlement is an important phenomenon that must be understood for the entire pipeline and all component materials present in any given natural gas service territory. UCI researchers have also studied embrittlement effects on a variety of pipeline materials under the most extreme pressure dynamics and found that, under regular pipeline maintenance, even the worst possible damage is manageable. While this finding is encouraging, further embrittlement studies are required to investigate the effects of hydrogen gas on additional natural gas network components and materials, including wells, fittings, and valves.




**1 Northwest Natural**
Testing how different blends of hydrogen and natural gas work in their equipment and various types of appliances.

**2 3 SoCalGas and SDG&E**
Planning multiple hydrogen blending projects throughout their respective service territories, starting with an isolated section of a plastic distribution system in SoCalGas' service territory. The initial hydrogen blend level is planned at 1% and may increase to as much as 20%.

**4 5 Southwest Gas**
Studying how hydrogen-blended natural gas can further reduce carbon emissions while providing clean, reliable energy.

**6 Dominion**
Analyzed and confirmed via a pilot project that 5% of hydrogen could be blended into the gas distribution network without impairing either the distribution network or appliance performance.

**7 New Mexico Gas**
Conducting a pilot project that will test the blend in appliances in a closed system, then move to small segments of the distribution system that serves customers.

**8 Hawaii Gas**
Existing pipeline network is currently accommodating a mix of synthetic natural gas, renewable natural gas, and up to 15% hydrogen.

**9 CenterPoint**
Evaluating use of a less than 5% blend into existing natural gas system.

**10 Southern Company Gas**
Conducting an R&D initiative, HyBlend, which will address the technical barriers to blending hydrogen in natural gas infrastructure and study life cycle emissions of hydrogen blends.

**11 Dominion**
Piloting a 5% hydrogen blend with gas lines and appliances at a test facility. Plans are currently under review by the North Carolina Public Utilities Commission.

**12 South Jersey Industries**
Piloting a feasibility study to produce hydrogen and blend into natural gas delivery systems.

**13 Vermont Gas Systems**
Piloting a green hydrogen blend in the natural gas pipeline for heating at a GlobalFoundries' semiconductor fabrication plant.

**14 National Grid**
Plans to blend green hydrogen into the existing distribution system to heat approximately 800 homes and fuel 10 municipal vehicles.

**Figure 10** | Projects and Pilots for Hydrogen Blending in Natural Gas Pipeline Infrastructure in the U.S.

### 5.3.3 | Road Transport

Hydrogen can be transported on roads using hydrogen trailers or liquid tankers. Hydrogen trailers carry compressed gas cylinders containing hydrogen at above 180 bar. These trailers are currently limited to pressures of 250 bar by U.S. Department of Transportation regulations, but exemptions have been granted to enable operation at higher pressures (e.g., 500 bar or higher). Recently, composite storage vessels have been developed that have capacities of 560–900 kg of hydrogen per trailer; these are currently being used to deliver compressed natural gas in other countries.[39] This option is used primarily to move modest amounts of hydrogen over relatively short distances. It tends to become cost-prohibitive when these distances are greater than approximately 200 miles from the point of production.[40]

Hydrogen also can be transported and delivered as a liquid in tanker trucks when high-volume transport is needed in the absence of pipelines, because liquid hydrogen is denser and contains greater energy content than gaseous hydrogen. However, liquefaction of hydrogen is costly, as it requires a substantial amount of energy input.

### 5.3.4 | Maritime Transport

Currently, hydrogen can be shipped overseas in tube skids or in high-efficiency liquid storage containers similar in size to that of a road trailer. Liquid hydrogen tanker ships, which are very similar to liquefied natural gas tanker ships, are being developed to transport larger volumes. Kawasaki Heavy Industries, a Japanese company, has constructed a 116 m-long test vessel with a hydrogen capacity of 2,500 cubic meters. The company envisions that this ship will eventually both transport hydrogen and be fueled by it.[41] Green hydrogen can also be shipped long distances on marine vessels as ammonia. Because ammonia molecules contain hydrogen atoms, the hydrogen can be transported in liquid ammonia and then stripped and reconstituted into its pure gaseous form once it reaches its destination. Ammonia is liquid at standard temperature and pressure, has high volumetric and gravimetric energy density, and is considered safe to transport and store in plastic containers. Ammonia also enables the delivery of greater amounts of hydrogen due to its higher energy density and ease of transport.

Although there is an efficiency penalty from using intermediary ammonia to transport hydrogen, shipping hydrogen in the form of ammonia is cheaper than shipping liquefied hydrogen over long distances. Japan, a visionary global leader in developing a hydrogen economy, is developing its hydrogen system with ammonia as the intended hydrogen carrier for consumer fuel cell applications.[42] Australia and Saudi Arabia are also envisioning the use of ammonia as a means for large-scale marine export of green hydrogen.

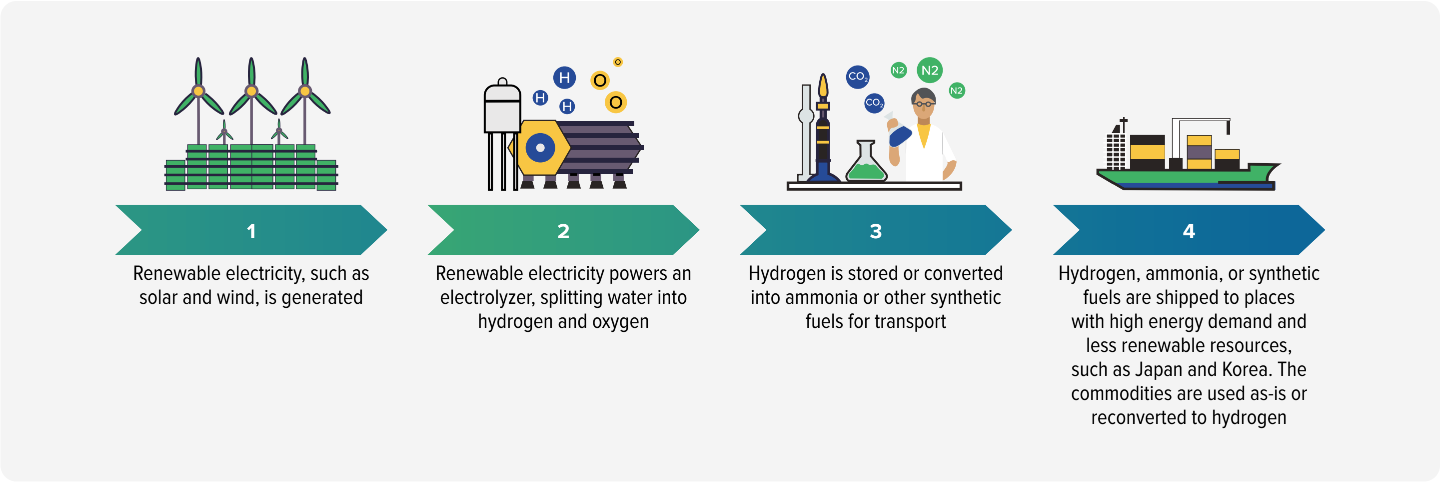



**Figure 11** | Green Hydrogen Export Pathway[43]

# 06 USES ACROSS THE ECONOMY

Green hydrogen can play a major role in eliminating harmful GHG emissions across the global economy as a carbon-free form of fuel and energy storage. Its versatility to provide heat, fuel, and power system services can be leveraged to decarbonize multiple vital economic sectors.

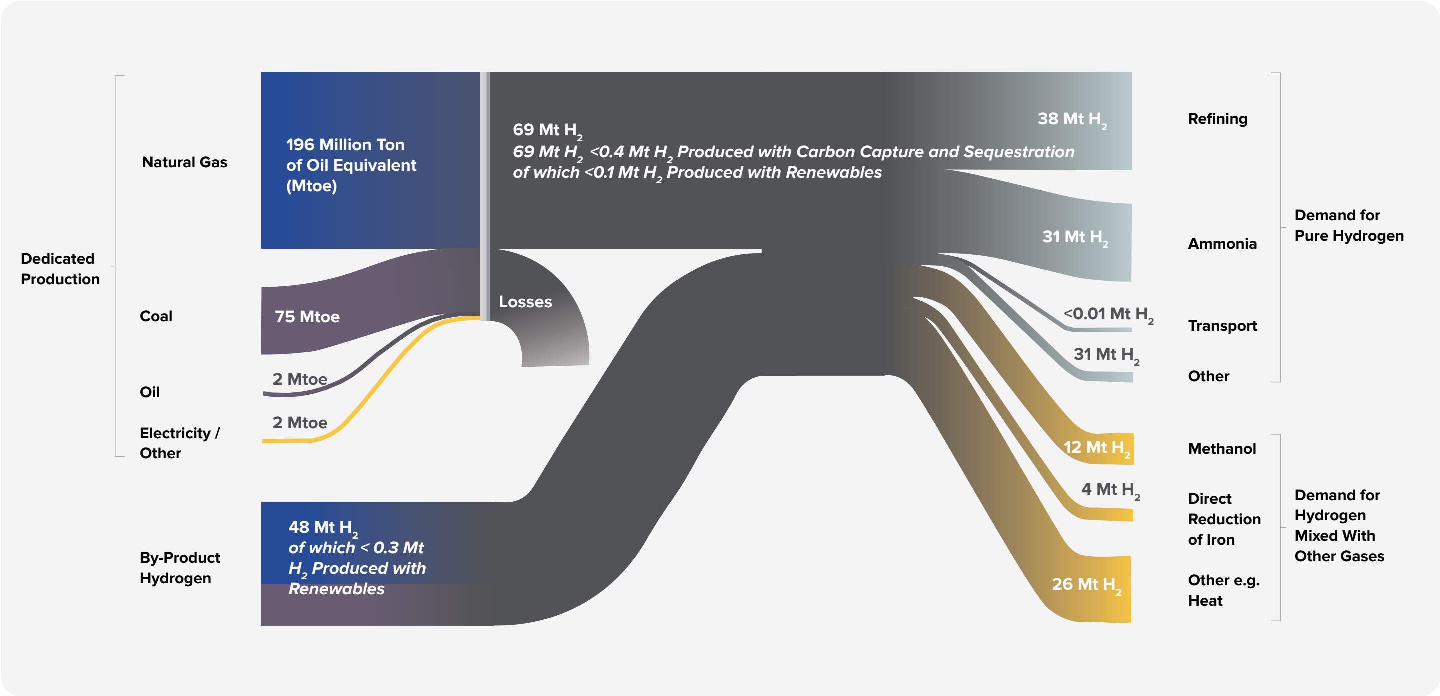
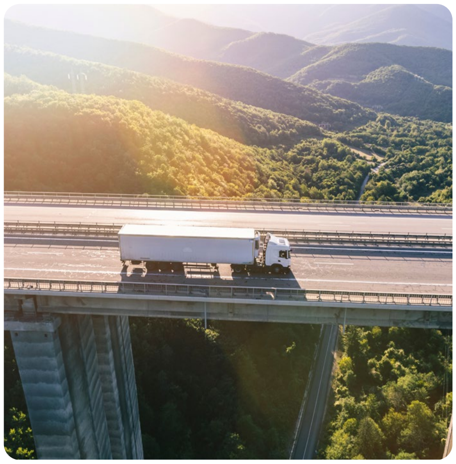


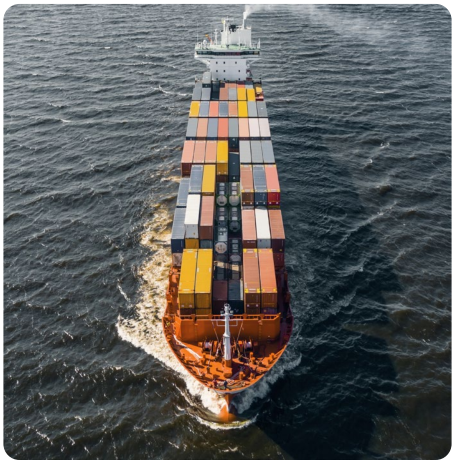

**Figure 12** | Hydrogen Production Sources and End Users[44]

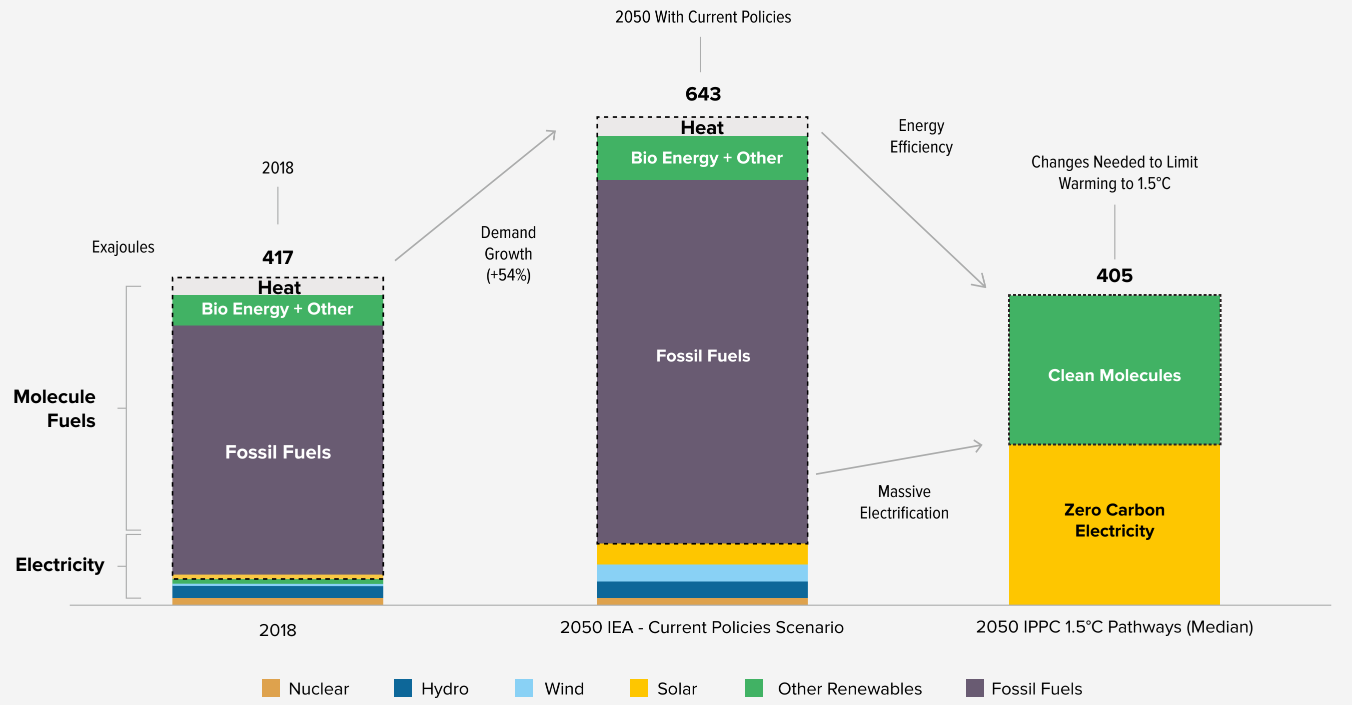
Replacing existing uses of hydrogen across the globe with green hydrogen would have a significant decarbonization impact.[4]

Once green hydrogen is less expensive to produce than gray hydrogen, it opens the possibility of decarbonizing many more sectors by providing carbon-free clean molecules.

To achieve the United Nations Intergovernmental Panel on Climate Change (IPCC) goal of limiting global warming to no more than 1.5°C by 2050, global economies will need to engage in aggressive energy efficiency, massive electrification, and the development of clean molecules for fossil fuel applications that cannot be reduced or electrified. This chapter details economic sectors where green hydrogen can play a major decarbonization role.








Note: The International Energy Agency's (IEA's) Current Policies Scenario is extrapolated using data from 2030 and 2040 to approximate final energy consumption in 2050. The 1.5°C compatible pathway is the median value for the 53 pathways analyzed by the IPCC limiting global warming below 1.5°C, or 1.5°C with limited overshoot.

**Figure 13** | Policy Scenarios Estimating Total Energy Consumption in 2050

### 6.1 | POWER GENERATION

Green hydrogen can be used to dispatch renewable electricity on demand. There are two primary mechanisms for this service: combustion-free electricity production using a fuel cell, and combusting hydrogen fuel in a turbine (power-gas-power).

As more low-cost renewable wind and solar energy is connected to the grid, green hydrogen for power generation will become increasingly economic. When renewable energy is being curtailed, it can be used to produce green hydrogen, which can then be used as a clean energy source during times of high energy demand. In a high-renewable future, dispatchable hydrogen power generation can play a central role in reliably balancing the grid.

### 6.1.1 | Fuel Cell Electricity

Fuel cells are the most energy-efficient devices for extracting power from fuels.[45] Fuel cells produce electricity without combustion, requiring only a constant source of fuel and oxygen. Because there are no moving parts, fuel cells operate silently and with extremely high reliability. Fuel cells using green hydrogen are completely carbon-free, producing only electricity, heat, and water.

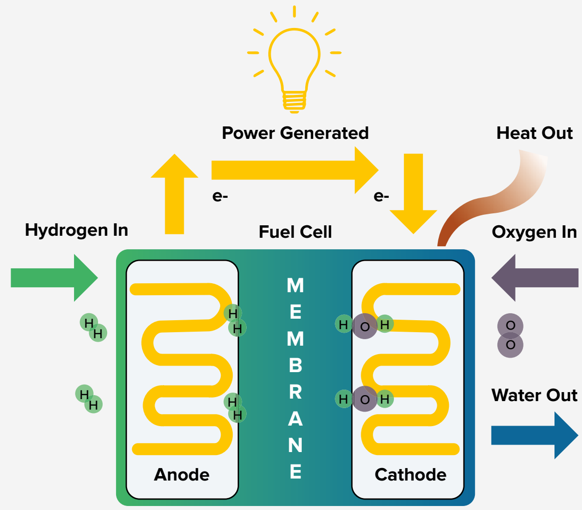



Figure 14 | Diagram of a Fuel Cell

A typical fuel cell is composed of an anode, a cathode, and an electrolyte membrane and functions like an electrolyzer in reverse. A fuel cell works by passing hydrogen through the anode and oxygen through the cathode. While hydrogen protons pass through the membrane in between, the electrons are forced to take another path, forming an external circuit that creates an electrical current. The electrons then rejoin the hydrogen on the other side of the membrane, where they bond with oxygen in the cathode to form its only emission: water. The electrical current generated can power a lightbulb or a motor, or can be fed into the electric grid.

Fuel cells are modular and can be designed in arrays that accommodate a wide range of applications.

Fuel cells fall into three main categories:

1. **Portable fuel cells** are used for recharging batteries, directly powering consumer electronics, and supplying off-grid backup power
2. **Stationary fuel cells** are used for combined heat and power, uninterruptible power supplies, backup power, and baseload distributed primary power.
3. **Motive fuel cells** are used in transport applications, such as power for buses, boats, cars, scooters, forklift trucks, and even aircraft.

The global fuel cell market was valued at $264.2 million in 2020. The fuel cell market is expected to grow at an average rate of 26.2% between 2020 and 2027, earning revenue of approximately $1.34 billion by the end of 2027.[46]

### 6.1.2 | Power-to-Gas-to-Power

Power plants provide centralized energy generation through both baseload and peaking load power. In 2019, 40.5% of U.S. electricity generation need was met with natural gas-powered plants, and 19.3% was met with coal.[47] Many of these existing thermal assets can be updated, repowered, and converted to use green hydrogen. Costly infrastructure to service these plants can be repurposed, avoiding costs for new infrastructure, such as transmission interconnection. Additionally, repurposing thermal assets keeps well-paying jobs in the host communities and takes advantage of local expertise and skills.

Green hydrogen as a replacement for natural gas and coal for centralized electricity production can achieve overall pollution reduction. Green hydrogen can cut emissions factors to zero for carbon monoxide (CO), sulfur oxides, volatile organic compounds (VOC), and particulate matter (PM) (the latter includes most hazardous air pollutants, otherwise known as local toxics). With appropriate treatment, it is possible to maintain emissions of nitrogen oxides (NOx) resulting from green hydrogen combustion at or below levels from the combustion of fossil-derived fuels on a kilowatt-hour (kWh) basis.

**"There is no way to get to 100% renewable energy that I can see right now without hydrogen in the mix. It doesn't exist."**

**Martin Adams**
Chief Engineer and General Manager,
Los Angeles Department of Water and Power (LADWP)

A major power-gas-power project currently underway is the conversion of the Intermountain Power Project (IPP), an 1,800 megawatt (MW) coal-fired generator located in Delta, Utah, to a hydrogen-burning combined-cycle gas turbine. Owned by Intermountain Power Agency, this project will convert and replace existing coal generation assets with an 840 MW combined-cycle gas turbine produced by Mitsubishi Power. IPP will be capable of using a blend of 70% natural gas and 30% green hydrogen in 2025, ultimately increasing that percentage to 100% in or before 2045. The green hydrogen used by the new power plant will be produced exclusively by electrolysis using renewable energy. The primary offtaker of the resulting dispatchable renewable electricity will be the Los Angeles Department of Water and Power, which is in a transmission-constrained basin and has a 100% clean energy mandate.[48] The conversion at IPP will achieve significant reductions in $CO_2$ emissions and other pollutants when fully implemented.

### 6.2 | MULTIDAY AND SEASONAL (BULK) ENERGY STORAGE

Green hydrogen is an ideal resource for bulk, multiday, and seasonal energy storage. Hydrogen can be stored in bulk for long periods and used on-demand for balancing load on the grid.[49] With increasingly high penetrations of variable renewable energy resources on the electric grid, long-duration and seasonal energy storage will be required to stabilize the load and maintain electric reliability. For example, models show that California alone may require as much as to 55 GW of long-duration energy storage (LDES) by 2045 to support a 100% clean energy grid.[50]

When 10 hours or more of energy storage is required to provide power, it is significantly more cost-effective to store energy via green hydrogen than via electrochemical batteries. In fact, a 2019 study by the National Renewable Energy Laboratory (NREL) found that using green hydrogen for energy storage applications of 13 hours or more would make financial sense using today's technology.[51]

This is because hydrogen offers separate power (kilowatt) and energy (kWh) scaling. For example, the size of the electrolyzer can be determined independently of the size of the hydrogen storage tank. During a long, cloudy winter, stored energy may have to last for weeks. In that scenario, only a renewable fuel like green hydrogen would provide the appropriate scale at a reasonable cost to maintain grid reliability.

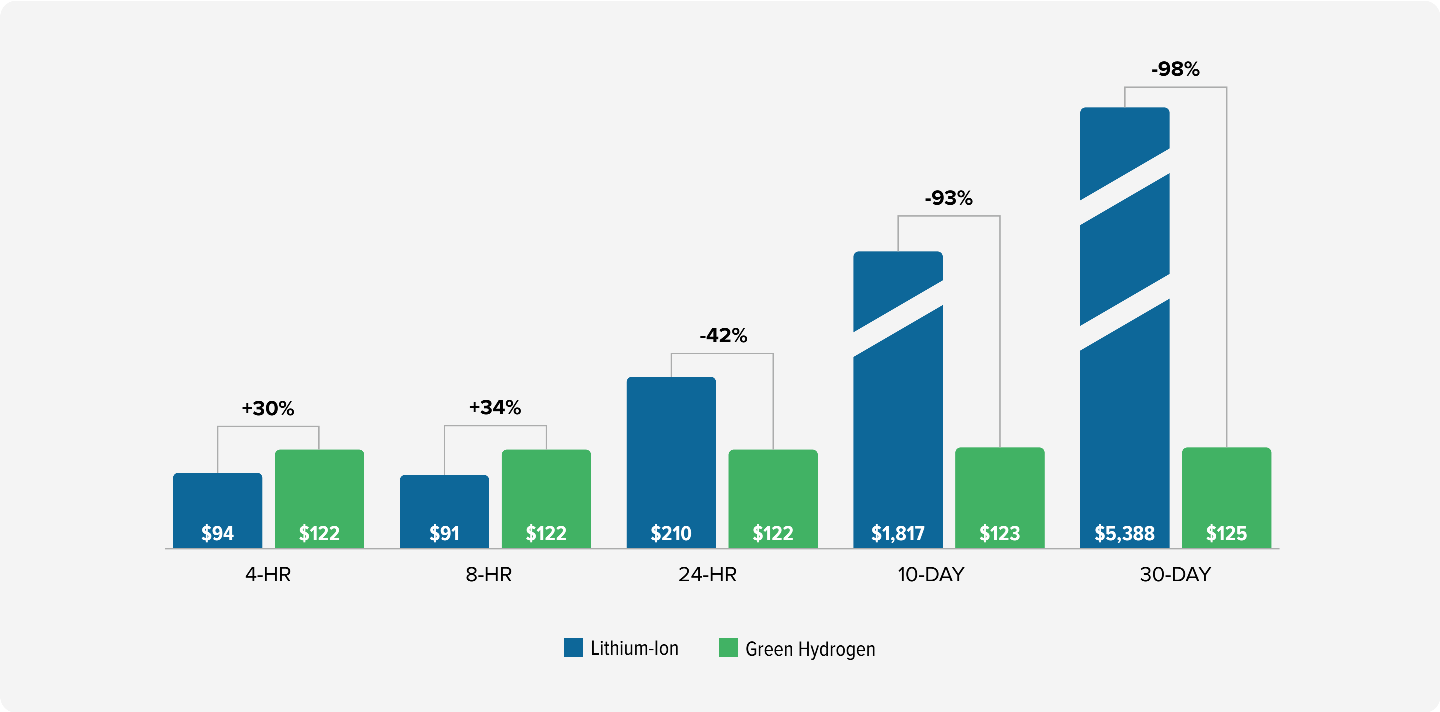



**Figure 15** | Levelized Cost of Energy ($/megawatt-hour) of Energy Storage by Discharge Time[52]

Hydrogen is the only molecule that is sufficiently abundant to store the amount of energy that will be required to achieve a global 100% renewable energy system.

A recent simulation completed by UCI showed that global solar and wind dynamic production to meet total world annual energy demand would require nearly 20,000 terawatt-hours of energy storage.[53] Sufficient quantities of metals needed for battery production, such as lithium and cobalt, simply do not exist on the planet to store that much energy, underscoring the need for alternative bulk storage solutions. Meeting this level of storage with only batteries is simply cost- and technology-prohibitive.

Hydrogen used as a multiday storage resource can provide carbon-free grid support during worst-case scenario grid-disconnection events, such as those increasingly arising because of natural disasters like hurricanes and wildfires. Green hydrogen can deliver carbon-free grid support either by replacing natural gas in existing thermal electric generating facilities, or by providing local distributed backup power to essential buildings such as hospitals and fire stations.

For example, the large salt dome formation in Utah near the IPP plant can be used for long-term storage of green hydrogen and provide a strategic renewable energy reliability reserve for the electric system. Moreover, this reserve would also be available as a backup fuel source for transportation, industrial, mining, and other activities.

### 6.3 | DECARBONIZING THE NATURAL GAS PIPELINE

Of the 55 parent investor-owned utilities in the United States, a majority have meaningful emissions reduction targets, with about half being net-zero or carbon-free electricity goals.[54] Green hydrogen can enable utilities to achieve these targets. This clean molecule can be used to power diverse end uses as a natural gas substitute, but doing so would have to happen gradually due to pipeline infrastructure limitations. See Sections 5.3.1 and 5.3.2 for details.

As of 2020, Americans consumed 30.5 trillion cubic feet of natural gas annually, resulting in emissions of about 1,670 million tonnes of $CO_2$. By blending even small amounts of hydrogen into our natural gas infrastructure, significant reductions in $CO_2$ emissions can be achieved.[55,56]

| Percentage by Volume of Green Hydrogen in U.S. Natural Gas Pipeline | Million Tons of $CO_2$ Saved/Year | Equivalent Millions of Cars Driven for a Full Year |
|---|---|---|
| 3% | 50.1 | 10.9 |
| 10% | 167 | 36.3 |
| 15% | 250 | 54.3 |

**Table 2** | $CO_2$ Reductions from Blending Green Hydrogen in the U.S. Natural Gas Pipeline[57]

This application will help all gas pipeline end users decrease their carbon footprints, including from residential and commercial needs such as cooking and heating.[58] Decarbonizing the natural gas pipeline would also support emissions reductions in sectors that are difficult to electrify and depend on high-temperature processes powered by natural gas, such as steelmaking, cement mixing, glass making, and smelting.

## 6.4 | HIGH-TEMPERATURE INDUSTRIAL PROCESSES

Many industrial processes, including the production of steel, cement, glass, and chemicals, depend on high temperatures produced by coal to manipulate raw inputs into useful outputs. Because high temperatures are required for these operations, they are difficult to electrify. Green hydrogen offers an electrification solution because it takes clean electricity and converts it to fuel for supplying high heat. In fact, it is estimated that almost 12% of industrial heating energy could come from hydrogen by 2050.[59] A transition to clean-burning and renewably generated green hydrogen for these applications would be a game changer in reducing pollutants at industrial sites around the world. It would also provide significant environmental and monetary benefits for participating industrial sites in regions with established carbon markets, such as California and the European Union.

### 6.4.1 | Steel Production

Producing 1 ton of crude steel creates nearly 1.4 tons of $CO_2$ emissions, making it a very carbon-intensive process. Traditional steelmaking relies on a chemical reaction between iron oxide and carbon monoxide to reduce iron ore and produce steel. The carbon monoxide is formed by heating coke fuel in a blast furnace; the coke acts as both a fuel and reducing agent in the blast furnace as it produces carbon monoxide when burned, and reacts with the iron oxide to produce molten pig iron and carbon dioxide. New production processes are exploring the use of hydrogen gas as both a reactant and fuel instead of coke. Hydrogen reacts with iron oxide in a similar fashion to carbon monoxide, but instead of producing carbon dioxide, the only byproduct is water vapor. In addition, hydrogen can also reach the high temperatures required for industrial processes when burned. Pilot projects in Sweden, Germany, and Austria are exploring the use of hydrogen to reduce iron ore in the steelmaking process.[60]

### 6.4.2 | Cement Manufacturing

Cement is a crucial construction material, but its production accounts for about 8% of global $CO_2$ emissions.[61] Hydrogen combustion can reach the high temperatures required in the cement manufacturing process, but the use of hydrogen as a fuel source is only in the early testing stages. In the United Kingdom, the Department for Business, Energy, and Industrial Strategy (BEIS) has awarded around $8 million to the Mineral Products Association for an innovative demonstration of the potential of hydrogen to reduce carbon emissions in cement and lime production.[62]

Additionally, carbon capture and synthetic fuel production is an important pathway for cement decarbonization, as up to 70% of the $CO_2$ emissions in the sector come from the production of a key input to the cement manufacturing process, calcium carbonate. These emissions cannot be reduced with other methods as there is no viable replacement for calcium carbonate currently. Synthetic fuels can be produced from green hydrogen and captured $CO_2$ from cement manufacturing; this process would both decarbonize the cement manufacturing process and produce green fuel for alternative uses.

## 6.5 | TRANSPORTATION

Green hydrogen is an excellent option for low-carbon transport where rapid fueling, long range, and a large payload are required.

### 6.5.1 | Road Vehicles

The transportation sector is responsible for 24% of direct $CO_2$ emissions from fuel combustion globally. Road vehicles—cars, trucks, buses, and two- and three-wheelers—account for nearly three-quarters of transport $CO_2$ emissions.[63] In the United States, the transportation sector is the largest source of GHG emissions and derives over 90% of its energy from fossil fuels.[64] By replacing fossil-fueled vehicles with green hydrogen-fueled vehicles, the sector could reduce emissions to zero.

Hydrogen-fueled vehicles are an important complement to battery electric vehicles for decarbonizing transportation. Hydrogen vehicles can alleviate pressure on the electric grid, smartly utilize gas pipeline infrastructure to decarbonize transportation, and create fuel diversity and resilience for land transport applications.

Hydrogen-fueled transport is ideally suited for high-utilization, heavy-duty transport applications such as buses and trucks. These are significant categories, accounting for more than one quarter of transport energy usage.[65] These vehicles can be powered by fuel cells or even modified internal combustion engines that are able to combust hydrogen. It is also possible to blend hydrogen with natural gas or diesel in dual-fuel vehicles, or to switch between both in bi-fuel powertrains.

Hydrogen vehicles can be refueled quickly, like gasoline-powered vehicles, taking about 5 minutes to fill a light-duty vehicle. Additionally, fuel cell vehicles have a range similar to that of gas vehicles: 250–400 miles.[66] Service stations that provide electric charging of battery electric vehicles and supply green hydrogen, both along the highways and within cities, can help decarbonize road transportation. If, in addition, a service station is powered by a solar-plus-battery system to direct-charge electric vehicles and to produce on-site green hydrogen using electrolyzers, then it will ensure the additional needed energy is coming from renewable sources—both for charging and for the supply of hydrogen to fuel cell vehicles. Doing so will reduce needs for expanding the electric grid and for the long-distance transport and supply of hydrogen.[67]

In June 2020, the California Air Resources Board passed a rule requiring half of all commercial trucks and vans sold in the state to be zero-emissions by 2035.[68] This represents a major opportunity for the development of hydrogen fuel cell vehicles powered with green hydrogen. Over 10,000 fuel cell cars have been sold and leased in the United States to date. In addition, there are already 48 fuel cell buses in operation in California.[69] Currently, the Alameda-Contra Costa Transit District ("AC Transit") in San Francisco is collaborating with Stanford University's Precourt Institute for Energy on the world's first extensive comparison study of different bus propulsion technologies. Titled "Zero Emission Transit Bus Technology Analysis", the two-year test will analyze five bus technologies– fuel cell dominate hydrogen fuel cell electric, battery dominate fuel cell electric, battery electric, diesel electric (hybrid), and diesel.[70]

### 6.5.2 | Maritime

Global shipping accounted for about 2% of global energy-related $CO_2$ emissions in 2019.[71] Most marine transport is powered by fuel oil from fossil fuels, with some more modern fleets transitioning to liquid natural gas. As marine shipping falls under increasing environmental scrutiny and faces tougher international emission standards, alternative marine fuels, including hydrogen and ammonia, are increasingly attractive.

Propulsion on a hydrogen-fueled ship can be powered by an electric motor that is receiving electricity from a fuel cell, or the ship can use hydrogen fuel in a gas-powered engine. Today, a few hydrogen-powered ferries and boats operate in the United States and Europe. Fueling locations for ships are conveniently located at ports, which are also centers for truck and rail operations that could be converted from fossil fuels to hydrogen fuels, considerably reducing air pollution in these areas. Alternatively, green hydrogen can be used to produce green ammonia that can also be used as a marine shipping fuel. Viridis Bulk Carriers has begun to offer ammonia-powered marine vessels.[72]

### 6.5.3 | Aviation

Aviation is the most carbon-intensive form of transport, responsible for about 2% of global greenhouse gas emissions.[73] Biofuels are one clean alternative to today's fossil-based jet fuel; however, green hydrogen offers another zero-emission pathway. Green hydrogen can also be used as an ingredient in making cleaner synthetic jet fuels that can be used by existing long-haul jet turbines. Synthetic jet fuel could potentially utilize existing fueling infrastructure at airports.

Hydrogen-powered fuel-cell airplanes, also known as hydrogen-electric airplanes, are beginning to gain popularity in the aviation sector due to emissions reductions and ease of scalability. Hydrogen-electric airplanes only emit water and tend to be much quieter than traditional aircraft. In order to engineer and build commercial green hydrogen-electric aircraft, several technological areas must still be developed, including safe on-board hydrogen storage and lighter fuel cell equipment.[74] In addition to technology development, hydrogen fueling infrastructure at airports will need to be built and uniform safety codes and standards created.

Small hydrogen aircraft have already shown proof-of-concept, and industry analysts believe hydrogen-powered fuel cell airplanes could enter the market as soon as 2035.[75] In September 2020, ZeroAvia completed the first hydrogen-fueled commercial-grade aircraft flight on a six-seater commercial Piper aircraft retrofitted to be supported by hydrogen fuel cells. This trip was a 20-minute flight in England.[76]

### 6.5.4 | Rail

Hydrogen fuel cells can be used to power rail cars and are a good alternative for replacing diesel-powered trains. Compared to diesel trains, hydrogen fuel cell trains emit zero emissions, are quieter, and have lower vibrations, helping to address criticisms of rail operations in urban areas.

Fuel cell trains are being deployed globally. The first hydrogen-powered train developed by iLINT entered service in Germany in 2018, and the company has since sold 41 additional units to two German commuter rail operators.[77] A Chinese company, CRCC, has built hydrogen-powered trams, which entered service in 2019. Hyundai Rotem is developing a hydrogen-powered train in South Korea. And in Japan, JR East, Hitachi, and Toyota are planning to build a hydrogen fuel cell-powered train. Siemens is also planning to debut a hydrogen fuel cell-powered version of its new Mireo commuter rail electrical unit, the Mireo Plus, in 2024. In the United States, Stadler has signed the first contract to supply a hydrogen-powered train for the San Bernardino County Transportation Authority in California. The train is expected to be introduced in 2024 as part of the Redlands Passenger Rail Project.[78]

## 6.6 | HEATING FOR BUILDINGS

Heating demand for buildings rarely aligns with the timing of renewable generation, which is driven by the availability of sun and wind. Heating is the largest energy demand in residential and commercial buildings in areas with cold winters.

Hydrogen can be considered as one of many complementary low-carbon technologies, along with electrification, on-site renewables, demand reduction, heat networks, and other green gases as an alternative to heating with oil or natural gas. Green hydrogen can either supply 100% of the heating fuel or can be blended into existing natural gas networks, as described above.

On-site hydrogen fuel cells can provide building heat, electricity, and resilience to buildings such as single-/multifamily and commercial buildings. On-site fuel cells can provide energy diversity and can be operated in island mode or as part of a microgrid, ensuring resilience and continued, uninterrupted service when the electric grid is down.

The Australian company LAVO has developed a hydrogen residential battery system that has solar panels that charge a 40 kWh lithium ion battery. When the battery is fully charged, the solar and battery system operates a small electrolyzer, and the produced hydrogen is stored in metal hydrides (the metal part of which is a fibrous sponge) in canisters. When needed, the metal hydride from the canisters emits hydrogen for a fuel cell that generates electricity for supply to the house or to the grid.[79]

## 6.7 | INDUSTRIAL FEEDSTOCK

More than 70% of the hydrogen consumed today is used as an industrial feedstock. Processes such as the production of ammonia for fertilizers, production of methanol, and oil refining all require hydrogen.

Industrial applications for hydrogen are well positioned to take advantage of switching from gray hydrogen to green hydrogen. Gray hydrogen users are good offtaker candidates for large-scale green hydrogen projects: They have large existing hydrogen demand and related infrastructure in place, and refineries and ammonia plants are often located in geographic clusters, making them convenient offtakers of large green hydrogen projects. Thus, converting the existing demand for gray hydrogen to green hydrogen is a relatively straightforward pathway to help lower the carbon footprint of numerous industrial processes.

### 6.8 | AGRICULTURE

Fertilizers provide vital nutrients to plants and play a critical role in achieving high crop yields needed to feed a world population approaching 8 billion people. As world population grows, so does fertilizer demand. Fertilizer manufacturing is responsible for about 2% of global GHG emissions annually.[80]

The most common form of fertilizer is ammonia-based nitrogen fertilizer. Manufacturing this fertilizer requires a very energy-intensive process, called Haber-Bosch, that combines hydrogen gas with nitrogen to create ammonia. About half of the GHG emissions associated with nitrogen fertilizers are attributable to the production process, due to the high energy requirements. The process also normally includes the use of reformed fossil fuels as hydrogen feedstock.[81]

There are exciting new developments in the future of fertilizer production with green hydrogen. For example, green hydrogen created from electrolysis or biomass gasification can be used in place of gray or brown hydrogen, as both the feedstock for the fertilizer production process and as the fuel to power the reaction. Local fertilizer production can be achieved via a closed-loop system, using local agricultural waste as an input.

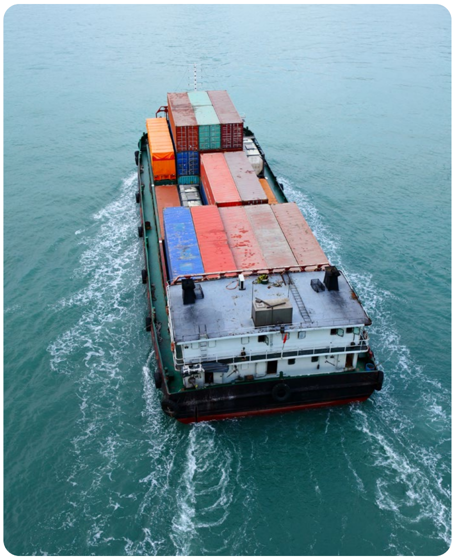
As of 2019, fertilizer producers on five continents had begun feasibility studies, launched pilot demonstrations, or already reengineered their ammonia plants to replace fossil fuel inputs with renewable hydrogen.[82] In Spain, fertilizer producer Fertiberia and energy company Iberdrola have teamed up to construct a 20 MW electrolysis facility paired with a 100 MW photovoltaic (PV) plant to produce green hydrogen. The green hydrogen supply will allow Fertiberia to reduce its natural gas consumption by 39,000 tons per year. Considering the current price of carbon on the European Union's Emissions Trading Scheme, this project could also save Fertiberia about $1 million annually.

### 6.9 | MINING

Minerals and metals mining is responsible for between 4–7% of global GHG emissions. This industry is challenging to decarbonize, both because of its energy-intensive nature and because of the remoteness of most mineral deposits.[83]

Remote mining sites operate far from high-quality energy infrastructure connections. Remote Area Power Systems (RAPS) often rely on diesel fuel for their varied energy needs, from generating power to operating mining equipment such as drills, shovels, loaders, and material handling trucks.[84] RAPS face economic, operational, and environmental challenges. Economically, it is expensive to transport fuel via truck to remote communities, resulting in on-site mining energy costs as high as $440/megawatt-hour (MWh).[85] Operationally, trucking in diesel adds costs and risks to mining sites. Environmentally, diesel produces harmful emissions. Diesel exhaust conditions are exacerbated in enclosed underground mines, so companies must install proper ventilation to protect workers. Running these ventilation systems can represent as much as 30–40% of a mine's total energy operating costs.[86]

Green hydrogen provides a promising opportunity to reduce mining operational costs, reduce health risks to workers, and decarbonize their operations. Green hydrogen has the value of being usable in a variety of different operational processes at a mine, including as fuel for trucks and other heavy equipment, as energy for heating and cooling systems, and as a primary fuel stock for electricity generation. Green hydrogen is particularly well-suited for local production at mine sites with high solar penetration, such as in central Australia and the high desert plains of Chile and Bolivia.



# 07 VALUE PROPOSITION

Green hydrogen is becoming cost-competitive with gray hydrogen as the price of renewable inputs and electrolyzers decrease. However, fully valuing and capturing all of green hydrogen's diverse and beneficial attributes—not just lowering costs—will be critical in accelerating market development for green hydrogen.

The IEA found that "clean hydrogen is currently enjoying unprecedented political and business momentum, with the number of policies and projects around the world expanding rapidly." Rapid deployment and scaling of green hydrogen technologies will drive down costs enough to allow green hydrogen to become widely used in the near future. This will also increase the demand for clean energy generation, and along with it, the cost-reduction benefits of scaling green hydrogen production will expand to other industries. Going forward, it will be critical to value green hydrogen beyond simply comparing it to the cost of gray hydrogen or natural gas as a drop-in fuel replacement.

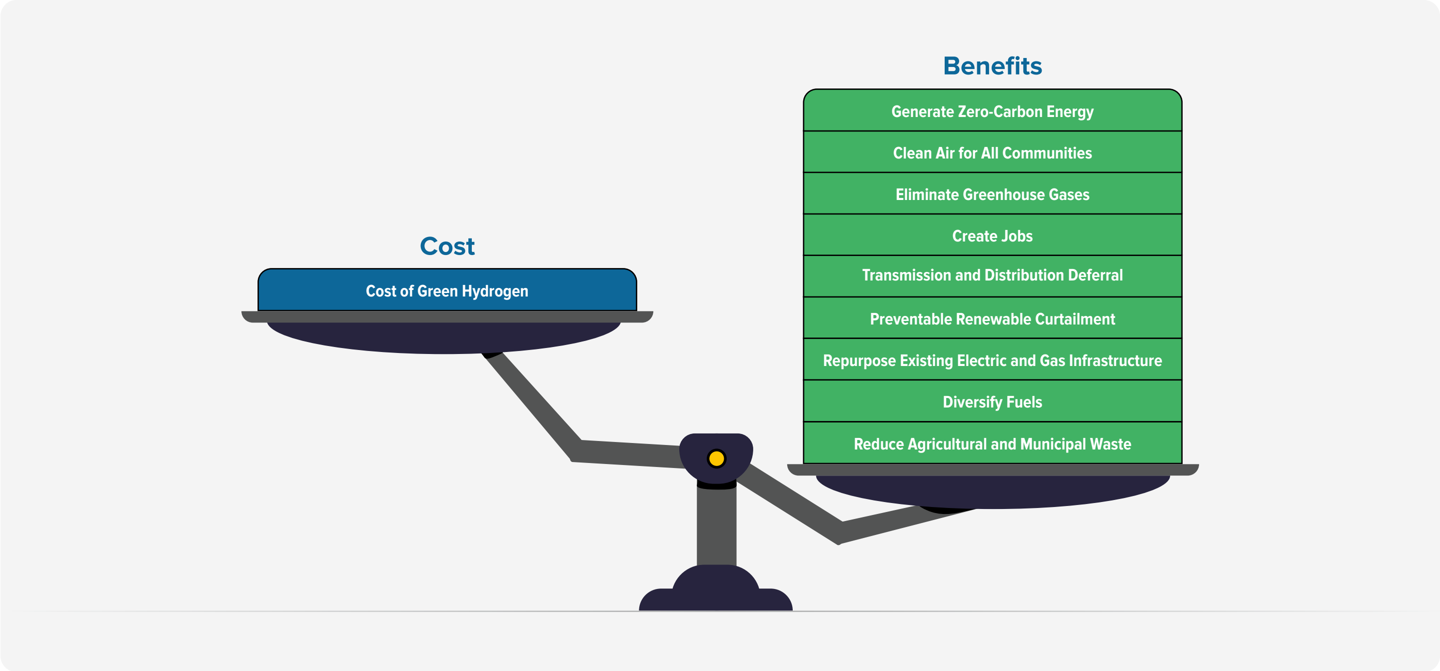



**Figure 16** | Valuing Stacked Benefits of Green Hydrogen

## 7.1 | BENEFITS OF GREEN HYDROGEN

Much like conventional energy storage on the grid, green hydrogen delivers value that exceed its costs as a drop-in replacement for gray hydrogen or natural gas. Green hydrogen can provide fuel diversity, energy security, generation capacity, flexibility, and ancillary services, as well as take advantage of low-cost power during peak production to eliminate renewable curtailment and alleviate congestion and mitigate expensive build-out of the electric grid.

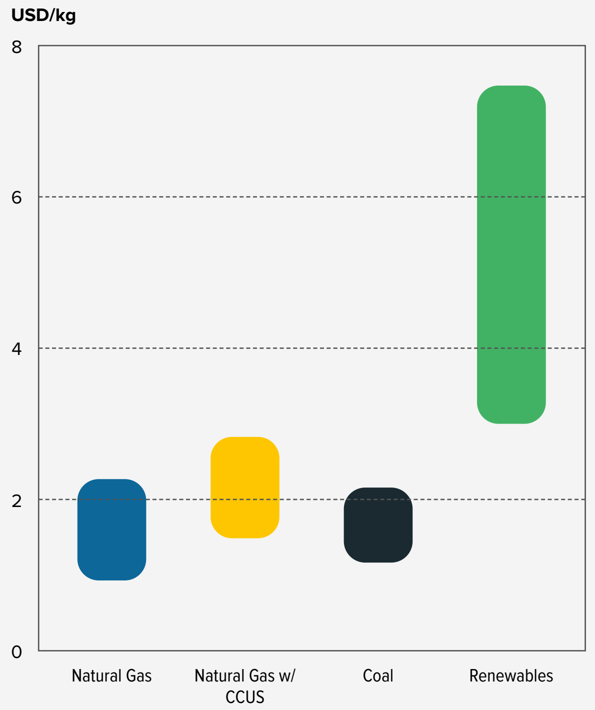



**Figure 17** | Hydrogen Production Costs by Energy Source, 2018[87]

### 7.1.1 | Generate Zero-Carbon Energy

Green hydrogen can play a major role in decarbonizing energy systems by providing carbon-free fuel flexibility and energy storage. Its versatility to provide heat, fuel, and power system services can be leveraged to reduce the carbon intensity of multiple economic sectors.

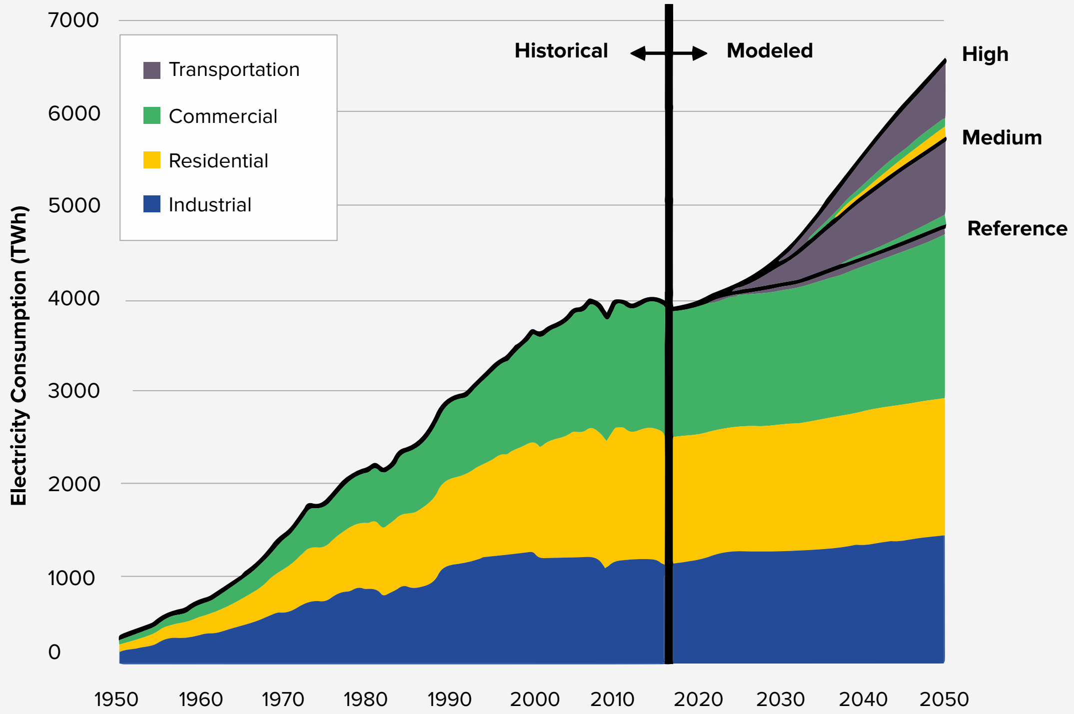



**Figure 18** | Historical and Projected Annual Electricity Consumption by Sector in the U.S.[88]

### 7.1.2 | Clean Air for All Communities

Nearly one-half of all Americans—an estimated 150 million—live in areas that do not meet federal air quality standards.[89] Poor air quality directly results from emissions produced by the burning of fossil fuels for energy, especially diesel and coal, which release gases and chemicals into the air with serious adverse health effects. Passenger vehicles and heavy-duty trucks are a major source of air pollution, producing about 10% of VOC emissions and 10% of PM emissions.[90]

Unfortunately, too often the burden of poor air quality is concentrated in lower-income neighborhoods and communities of color. Replacing diesel use for heavy duty trucking with green hydrogen, replacing natural gas peaker plants with green hydrogen, and prioritizing the safety of communities that do not meet federal air quality standards can tremendously reduce local air quality issues and protect the health of the most vulnerable communities.

### 7.1.3 | Eliminate GHGs

Green hydrogen has a transformative role to play in decarbonizing the global economy. Renewable electricity is not a practical substitute for several hard-to-decarbonize sectors, including heavy industry, heating, and transportation fuel, but the versatility of green hydrogen provides a promising solution to delivering clean molecules.

Production of large quantities of green hydrogen will play a major role in global decarbonization by providing a zero-carbon alternative to fossil fuels. The rollout of green hydrogen technologies could offset up to one-third of global greenhouse gas emissions produced by fossil fuels and industry by 2050, resulting in $148 billion to $765 billion in benefits based on the United States' current range for the social cost of carbon.[91]

#### 7.1.4 | Create Jobs

Growth in the hydrogen economy will lead to a multitude of new employment opportunities and can support local high-paying jobs to support a transitioning energy system. Many of these jobs will take advantage of technical and manufacturing skills to support well-paying careers. Skills utilized in today's fossil fuel industry are transferable to roles supporting the green hydrogen industry. The Fuel Cell and Hydrogen Energy Association, a national industry group, estimates that the hydrogen economy in the United States could generate an estimated $140 billion per year in revenue and support 700,000 jobs by 2030.[92]

#### 7.1.5 | Defer Transmission and Distribution

Historically, addressing grid issues such as load growth, rising peak demand, network congestion, and system reliability was accomplished by building out additional fossil-based thermal electric generation and transmission and distribution (T&D) infrastructure. However, permitting and building new transmission pathways is a long, risky, and difficult process, and this infrastructure is expensive to construct. As load grows on the grid due to increasing electrification of industrial processes and electric vehicle growth, it will cost billions of dollars to electrify everything. Local, on-site hydrogen generation can serve as a fuel to produce local, dispatchable, resilient clean electricity; reduce the need to build costly T&D infrastructure; and can be deployed rapidly.

#### 7.1.6 | Prevent Renewable Curtailment

Curtailment is the reduction of output of a renewable resource below what it could have otherwise produced. Curtailment occurs when there is insufficient concurrent energy demand for the clean energy being produced. A classic example is at noon on a temperate day when solar production is at its peak, but grid demand is not. Production of green hydrogen with electrolysis can make use of excess renewable energy on the system, which will help address the challenge of renewable energy curtailment on a highly renewable grid. Matching the creation of electrolytic hydrogen production to peak clean energy generation can enable 100% utilization of solar and wind energy.

Managing renewable energy curtailment is a win-win for customers, developers, and the grid. Sourcing renewable energy to produce green hydrogen creates another revenue stream for wind and solar projects and can lower customer costs, given that less of the investment in renewable energy projects would need to be recovered through electricity customer rates.

#### 7.1.7 | Repurpose Existing Infrastructure

Repurposing existing energy infrastructure reduces the cost of green hydrogen project development.

##### 7.1.7.1 | Repurpose Gas Infrastructure

To transport green hydrogen, blending with natural gas would allow for the use of the existing natural gas pipeline network with minimum infrastructure investment. Utilizing this infrastructure provides a low-cost pathway that promotes the transition toward a green hydrogen economy by significantly scaling up hydrogen storage and use. Longer term, as demand for green hydrogen grows, existing natural gas pipelines can be converted to 100% green hydrogen pipelines. This is a fundamental part of the European Hydrogen Backbone initiative, in which Europe's natural gas transmission network is being converted to a green hydrogen network.

##### 7.1.7.2 | Repurpose Electricity Infrastructure

Power plants are very expensive to build, and they are collocated with other expensive infrastructure assets, such as transmission interconnection. Cost savings in hydrogen project development can be achieved by repowering existing natural gas and coal-fired power plants with green hydrogen turbines.

Repowering power plants with green hydrogen is feasible today, with major turbine manufacturers, including as Mitsubishi Hitachi Power Systems (MHPS), General Electric, and Wartsila, offering high-power (800 MW+) hydrogen-ready gas turbines. GE's 9F.03 combustion turbines can routinely run on 50% hydrogen and, in some specific cases, have run on as much as 70–90% green hydrogen blend.[93] GE has 70 of these plants installed around the world. Additionally, MHPS has been developing high-efficiency, low-NOx combustion systems, which can use as rich a mix as a 30% hydrogen/70% natural gas fuel mixture for its largest and most advanced gas turbines, and has also announced the capability to use 100% hydrogen in its turbines by 2025.

The Long Ridge Energy Terminal in Hannibal, Ohio, is a repowering model that is retrofitting its 485 MW combined-cycle power plant to run on a blend of natural gas and renewable hydrogen, making it the first large U.S. gas turbine plant to transition to hydrogen fuel. The site initially will burn 5% hydrogen by volume in the natural gas stream. The program is outlining the changes necessary to transition entirely to using 100% green hydrogen over the next decade.

### 7.1.8 | Diversify Fuels

A diverse energy system provides resilience and protects customers against grid failures and energy price volatility. Currently, the electric grid faces reliability and resilience challenges, from extreme weather events to cyberattacks and planned public safety power shutoff events to reduce wildfire risk.

As the frequency and severity of climate events increase, so too does the demand for flexible fuels that can provide backup resiliency and safely power critical infrastructure sites during an emergency. Distributed, behind-the-meter hydrogen fuel cells for emergency backup are combustion-free options to support microgrids, homes, or schools. Unlike diesel or gasoline generators, hydrogen fuel cells do not release carbon monoxide or other harmful emissions, making them safer, lower-fire risk options. Because hydrogen fuel cells can support distributed grids, they can reduce hardships associated with public safety power shutoffs and support fire risk mitigation.

Additionally, when the grid fails, fuel diversity and local generation will be necessary to support everything from critical infrastructure to residences. On-site hydrogen fuel cells can provide heat and power to facilities that last for days; most customer-sited behind-the-meter battery-based energy storage applications can provide no more than 8 hours of back-up energy and do not have the ability to provide building heat. Especially in areas with cold winters, independent heating and power systems protect the most vulnerable customers when the grid is off-line.

Utilizing green hydrogen as an alternative to gasoline and diesel for transport will also mitigate price shocks that occur in the global fossil fuel supply chain. Further, because green hydrogen can be produced domestically from a variety of abundant primary sources, its ultimate price will be fairly stable in the long run.

Green hydrogen produced on-site can have a big advantage for remote locations that may be far from the grid, or where it may be too expensive to transport fossil fuels or connect to an electrical grid.

### 7.1.9 | Reduce Agricultural and Municipal Waste

Each year, the United States produces more than 70 million tons of organic waste: livestock manure, agriculture wastes, wastewater, and food waste. Improperly managed waste poses a risk to environmental and public health as chemicals present in waste can contaminate surface and ground waters through runoff or by leaching into soil. Additionally, as they decompose, organic wastes generate large amounts of methane, a powerful greenhouse gas that traps heat more efficiently than $CO_2$.

Fortunately, agricultural, and municipal waste can be transformed from a source of pollution to a useful clean energy source. Waste can be converted into carbon-neutral biogas using well-understood technology such as biodigesters. Purified biogas can be treated as a carbon-neutral natural gas substitute to produce green hydrogen via SMR. Solid organic waste can be converted to green hydrogen through thermal gasification. Additionally, the $CO_2$ produced from this process can be efficiently captured and permanently sequestered in depleted oil/gas wells or naturally occurring rock formations, providing opportunities to be carbon negative, or reducing the amount of total existing carbon in the atmosphere.

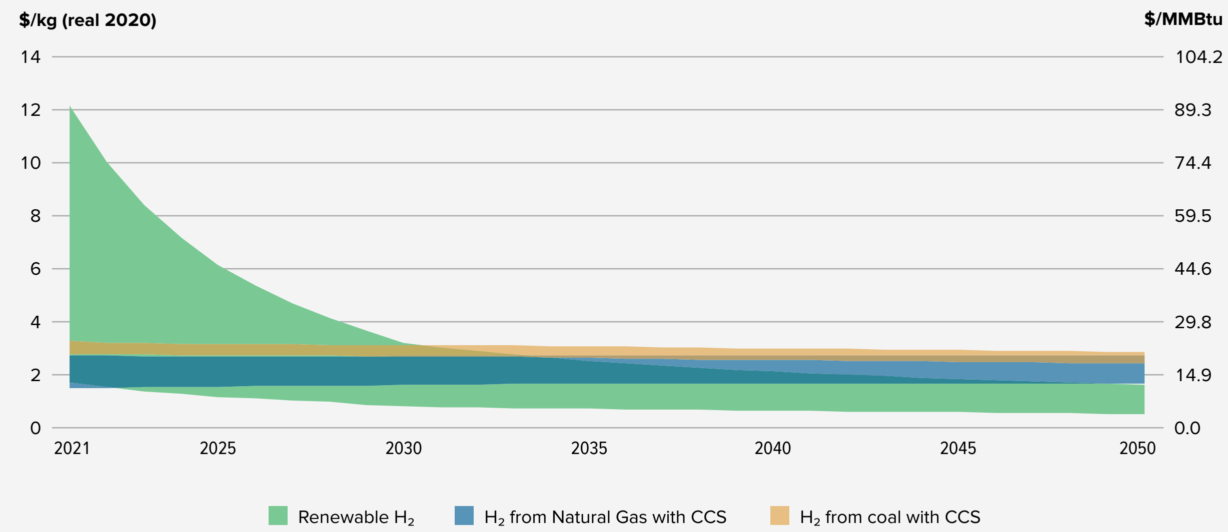
The United States has about 2,200 operating biogas facilities. Expanding biogas production could lead to the installation of over 13,500 new systems which would result in more than 335,000 temporary construction jobs and 23,000 permanent jobs.[94]

Green hydrogen produced from biogas systems can help turn waste management costs into a revenue opportunity for America's farms, dairies, and industries. For example, New York City spends roughly $400 million annually to transport 14 million tons of waste to incinerators and landfills.[95] Diverting that waste to anaerobic digestion or thermal gasification facilities would turn this municipal waste cost into a revenue-generating opportunity for the city. For green hydrogen developers, payments for accepting waste materials (tipping fees) could be an attractive revenue stream to help make projects bankable.

## 7.2 | ADDRESSING COSTS

The specific timing of green hydrogen cost competitiveness varies by end use and by region, based on energy prices, infrastructure readiness, and policy to support scale-up. Experts at Bloomberg and the IEA agree that, by 2030, the levelized cost of hydrogen (LCOH) will be at or below $1.30/kg. Wood Mackenzie predicts green hydrogen will be competitive in markets with the highest utilization rates and lowest renewable electricity prices by 2030 and will double in adoption by 2050.

Low-cost green hydrogen is necessary to achieve meaningful scale. The LCOH, measured in $/kg of hydrogen, is the metric commonly used to evaluate the cost of hydrogen, but this value only accounts for the capital and operating costs of producing hydrogen and doesn't include storage and transport costs. Instead, we need to be referring to the delivered cost of hydrogen, which incorporates all of the key inputs contributing to overall green hydrogen cost: (1) production, (2) transportation, and (3) storage.




Note: Renewable $LCOH_2$ range reflects a diversity of electrolyzer type, Chinese alkaline (low) to PEM (high). The electricity powering the electrolyzer is either PV or onshore wind, whichever is cheaper. Assumes equal CCS costs in all countries.

**Figure 19** | Global Range of 'Green' and 'Blue' Levelized Cost of Hydrogen in 30 Countries[96]

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### 7.2.1 | Production Costs

Scale and technology are the most important contributors to hydrogen production costs. Clean energy technology costs have proven to decrease over time with increased adoption and deployment. A doubling of cumulative production for solar photovoltaic technology and wind turbines led to related cost reductions of 19–35% and, over the last decade, lithium-ion battery prices fell 87% due to increased demand for electric vehicles, grid storage, and personal electronic devices.[97] Green hydrogen technologies are still in the early days, so significant cost reductions should be expected.

For electrolytic green hydrogen specifically, production costs include electricity, asset utilization and lifespan, discount rate, capital, and operating costs, and are influenced by electrolyzer efficiency and performance. A 60% to 80% reduction in electrolyzer system capital expenditure is expected to result from large-scale manufacturing by 2030.[98] Considering the attention that green hydrogen is getting globally, it is expected that there will be innovations in technologies and new production pathways for which costs will differ.

### 7.2.2 | Transportation Costs

Large-scale offtakers like ammonia plants or refineries typically produce hydrogen either on-site or in close proximity to their operations, and then distribute it via pipelines. Since this infrastructure already exists today, the cost contribution is minor and there is limited cost-reduction potential. For smaller-scale hydrogen offtakers, distribution is a major cost driver and can add more than 50% of the total delivered hydrogen cost.

The lowest-cost delivery mode for green hydrogen depends upon geographic and market characteristics that differ by area. Generally, compressed gas trucks, cryogenic liquid trucks, and gas pipelines are the most viable transport methods for hydrogen today, but overseas shipping is also emerging.

Compressed gas truck transportation costs are relatively independent of hydrogen flow rate. However, the hydrogen transport distance, which affects the number of trucks, operations and maintenance costs, and fuel costs, has a large effect on transmission costs and scales linearly with distance. For liquid hydrogen truck delivery, the majority of the delivered cost is due to liquefaction, so the overall costs for liquid hydrogen trucking depend strongly on hydrogen flow, due to the economies of scale associated with the liquefaction equipment. For pipeline transport, costs depend on both hydrogen flow and transport distance; the largest contributor is capital costs. In general, pipelines are the most cost-effective method for high volumes of hydrogen transport; compressed gas trucks are best for low quantities of hydrogen transported over short distances, and liquid hydrogen trucks are best for low quantities of hydrogen transported over long distances.[99]

### 7.2.3 | Storage Costs

Hydrogen storage can be physical or materials-based—see Section 5.2 for details. For bulk green hydrogen storage, such as the kind required to provide seasonal reserve storage, salt caverns offer the lowest cost of storage, between $0.11 and $0.38 per kilogram. The costs and durations of hydrogen storage methods are displayed in the following figure.

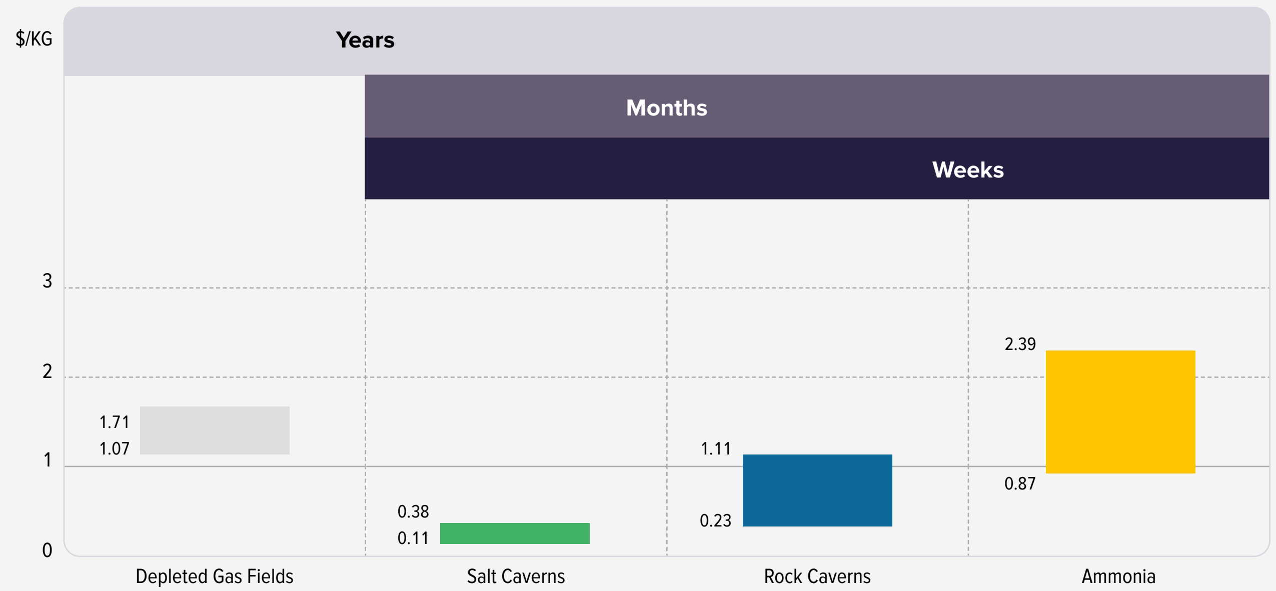


**Figure 20** | Cost of Hydrogen Storage Based on Method[100]

### 7.2.4 | Cost Reductions from Hydrogen Hubs: HyDeal Los Angeles Example

Hydrogen hubs create a full value chain of colocated and combined hydrogen production, infrastructure, and utilization to achieve the scale and investment necessary to produce low-cost delivered green hydrogen in a specific region.

HyDeal Los Angeles (LA) is an initiative to create the first scaled hub for green hydrogen in North America, delivering green hydrogen at less than $2 per kilogram by 2030, consistent with the $1/kg U.S. Department of Energy Hydrogen Earthshot production goal. The initiative brings together the entire value chain across the LA Basin, including production, transport, storage, and multi-sectoral aggregated offtake. HyDeal LA takes into account the drivers of low delivered costs - production, transportation, and storage - and seeks to optimize them to drive adoption.

**The HyDeal LA hub connects multi-sectoral offtakers and low-cost renewable electrolytic production and storage, spanning four U.S. states**

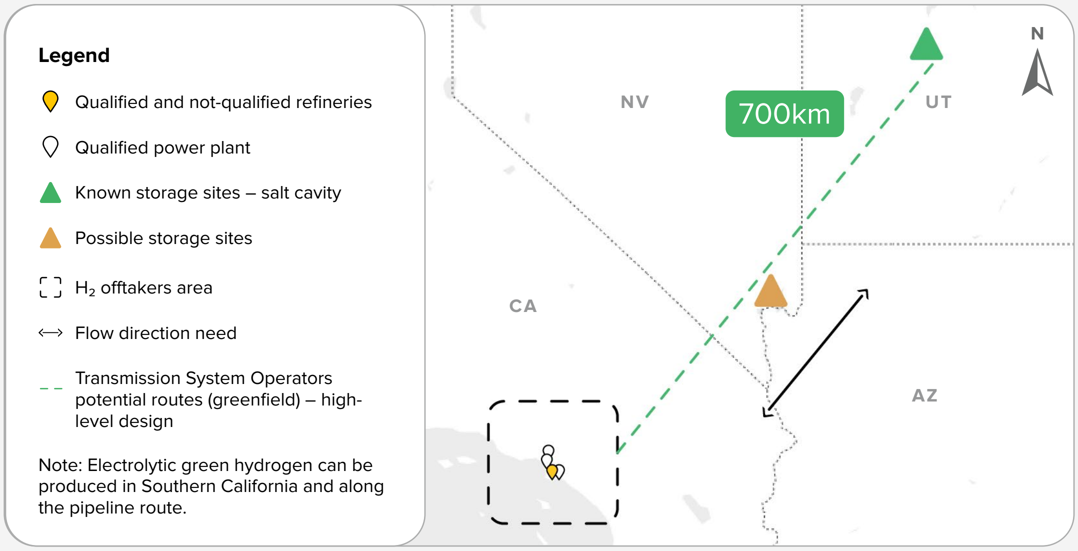


**Figure 21** | HyDeal Los Angeles System Map

The HyDeal LA initiative identified that the best scenario to reach under $2/kg delivered green hydrogen in the LA Basin will require: electrolytic green hydrogen production from low-cost renewables, transportation via a dedicated 100% hydrogen pipeline that connects LA with Central Utah, and underground geologic storage in salt domes in central Utah.

Green hydrogen production and use can be rapidly scaled by displacing natural gas in the power plants around the Ports of LA and Long Beach, helping LA achieve 100% renewable energy affordably and reliably. Demand at this scale will drive down the delivered cost of green hydrogen, enabling adoption by other heavily polluting sectors in the area, such as heavy-duty trucks and maritime shipping. Mass-scale, low-cost green hydrogen will accelerate the transition away from diesel, reducing carbon emissions and local pollutants.

# 08 BARRIERS AND CHALLENGES

The greatest barriers and challenges to the rapid deployment of green hydrogen lie not with the technology but with its related market design. Barriers like dependence on the least-cost paradigm, decoupled gas and electricity sector planning, and the need for leadership, focus, and alignment must be addressed to successfully scale green hydrogen.

**"As a fundamental building block in the energy systems of many sectors, green hydrogen is a super game changer in our fight against climate change. Accelerating adoption is fundamentally a market design challenge: how to achieve production and use at scale."**

**Janice Lin**
Founder and President of the Green Hydrogen Coalition and CEO of Strategen

### 8.1 | HIGH COSTS

As discussed in Section 6.2, green hydrogen is not yet cost-competitive with fossil fuel-based hydrogen due to higher production costs. Green hydrogen produced via electrolysis today is two to three times more expensive than fossil fuel-based hydrogen on average.[101] This makes green hydrogen adoption for end uses expensive and creates a barrier for market penetration. Cost parity of green hydrogen and hydrogen-based end uses with conventional technology will allow green hydrogen to play a larger role in system-wide decarbonization.

### 8.2 | THE LEAST-COST ENERGY SECTOR PARADIGM

Historically, power and gas sector planning has relied on least-cost models to evaluate and prioritize infrastructure investment decisions. For decades, this system worked well as demand was relatively easy to forecast and fossil-fueled capacity easy to procure. However, this system limits innovation and no longer serves the interests of consumers and our clean energy policy goals.

The way we generate and use energy is changing rapidly. Trends such as very low-cost renewable energy, moving from centralized to decentralized energy systems, smart digital controls, bidirectional energy storage, and the urgent need to decarbonize energy systems is challenging this old least-cost paradigm. When making infrastructure planning decisions, a more prudent approach for our energy systems would be to award such decisions based on a comparison of net benefits instead of the traditional least cost approach.

Bidirectional energy storage was the first significant technology addition to grid planning that challenged the traditional least cost procurement approach. Jurisdictions that recognize the benefit-stacking potential of bidirectional energy storage assets—including recognizing benefits that a single asset can provide, such as energy arbitrage, capacity, ancillary services, and distribution deferral, are now procuring and deploying energy storage to achieve more flexible, resilient, stable, and affordable grid operations. Realizing the benefits of bidirectional energy storage for the power system was a direct result of regulatory innovation that enabled stacked benefits to be recognized and compensated.

Similarly, planning and procurement for green hydrogen must be considered under a **net benefits** paradigm. Like energy storage, green hydrogen has the ability to deliver many stacked benefits (see Section 7.1). To attract investment, the benefits provided from these projects must be recognized and compensated.

Enabling compensation pathways for all the benefits provided by a green hydrogen project is exceptionally challenging because the benefits not only span the silos inherent in the power sector (transmission, distribution, generation, load), but can also span multiple sectors: power, gas, transportation, water, and waste management. Further, these sectors and their related jurisdictional governing bodies were organized many decades ago and did not envision the use of a flexible resource like green hydrogen that has many pathways for production and use.

Because green hydrogen solutions are commercially available today, the best pathway to accelerate progress is smart market design that allows aggregation of green hydrogen applications (demand), scalability, and recognition and compensation for all the benefits provided. This will create a virtuous cycle that ensures ongoing investment and sustainability.

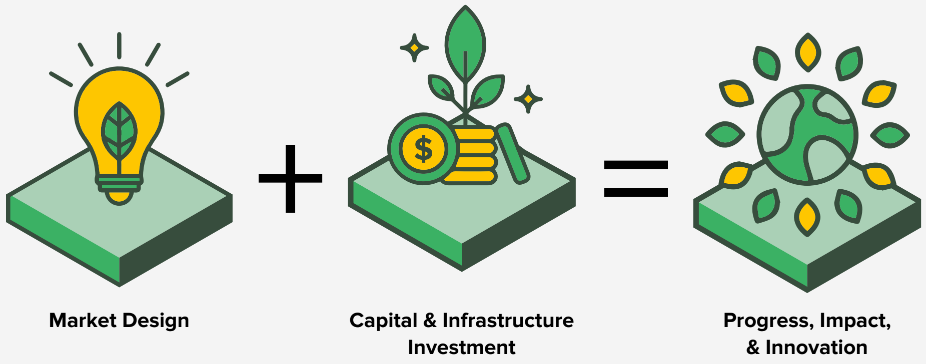


**Figure 22** | Market Design with Capital and Infrastructure Investment Will Lead to Progress

### 8.3 | DECOUPLED GAS AND ELECTRICITY SECTOR PLANNING

Today, we lack modeling tools that can help inform energy planners of the possible trade-offs between gas and power infrastructure investments using green hydrogen. This absence of appropriate modeling prevents green hydrogen infrastructure development and limits widespread adoption, including, but not limited to, pipeline access, large-scale physical storage, and the ability to utilize electric sector capacity to produce green electrolytic hydrogen.

Current electric system capacity expansion and production cost modeling tools for electric power sector optimization and planning need to be modified to include the use of green hydrogen, both as a potential new modifiable load (e.g., electrolysis) as well as a clean, bulk, long-term energy storage solution. Unlocking the ability of grid-connected electrolysis equipment to intelligently utilize existing capacity in the electric system will require not only new planning tools, but also new rate design for this potentially large and flexible new load that can decarbonize many end uses.

A key barrier to green hydrogen infrastructure development is the exclusion of multi-sectoral green hydrogen production and opportunities in existing regulated infrastructure planning at the local, state, regional, and national levels. For example, a hydrogen fueling station may be much more cost effective if the hydrogen used there could come from a larger project that also provides green hydrogen as a clean alternate fuel for thermal electric gas generation. Today, there is no procurement pathway for the thermal electric gas generation option, much less one that also considers the benefits of scaling green hydrogen production and use to also accelerate its use for zero-carbon transportation applications.

### 8.4 | NEED FOR LEADERSHIP, FOCUS, AND ALIGNMENT

Transformational, multi-sectoral, systemic changes to established industries and regimes requires visionary leadership, focus, and alignment. Green hydrogen's ability to decarbonize multiple sectors is its greatest asset and its greatest challenge—primarily because the decisions that govern how green hydrogen benefits are to be compensated are disparate and fall under multiple jurisdictions, bodies, and regions.

The first step to accelerate progress is to unite local, state, and regional stakeholders around a common goal. This is already happening for green hydrogen, with governments and forward-thinking environmental groups, such as the Natural Resources Defense Council, calling for the use of green hydrogen to transition away from fossil fuels.

Governments around the world are launching roadmaps and programs for green hydrogen development and export. Australia published its national hydrogen roadmap as early as 2018. In June 2020, two major commitments came out of Europe: Germany published its national energy roadmap and awarded hydrogen its largest share of green stimulus funds: a total of €9 billion ($10.3 billion) to support the country's goal of 5 GW of electrolysis capacity by 2030 and 10 GW by 2040.[102] Also in June 2020, the EU announced its regional hydrogen strategy to achieve a climate-neutral Europe, including specific targets for green hydrogen production via electrolysis and the decarbonization of hard-to-abate sectors in the 2030–2050 timeframe.[103]

In the United States, the City of Los Angeles, along with its municipal electric utility, the Los Angeles Department of Water and Power, is leading the way to establish the United States' first significant green hydrogen project: the renewal of Intermountain Power Project in Delta, Utah, from a coal fired plant to a 100% green hydrogen-powered combined-cycle gas turbine plant. This landmark project is helping set the stage for an ambitious, integrated, Western regional green hydrogen system that can serve multiple states and utilities.

# 09 POLICY AND REGULATORY RECOMMENDATIONS

Policy and regulatory innovation are essential to accelerate the deployment of green hydrogen at scale. With a diverse set of use cases for green hydrogen, the GHC recommends prioritizing policies and regulations that support the accelerated deployment of near-term, large-scale infrastructure projects.

## ESTABLISH NECESSARY LEADERSHIP AND GOVERNANCE

Leadership drives policy and regulatory innovation. Several countries, regions, states, and cities around the world are moving green hydrogen policies forward, often by establishing decarbonization or green hydrogen production and use targets that provide important market signals to investors, developers, and consumers. Similar to the important role renewable energy targets have played in the maturation of renewable electricity over the last 30 years, green hydrogen production and multi-sectoral use targets communicate a jurisdiction's commitment to progress, a foundational requirement needed to attract investment.

### 9.1.1 | Establish State and Local Leadership

States can establish multi-agency groups to organize and focus relevant agencies on delivering the crosscutting and multi-sectoral decarbonization benefits of green hydrogen. These groups should incorporate leadership from utilities and municipalities in the energy, waste, water, and transport sectors to align on specific initiatives that commercialize green hydrogen production and use at scale. The scope of work for this effort could include:

- Develop a state-level green hydrogen roadmap that identifies and prioritizes technology-neutral production pathways and multi-sectoral green hydrogen applications and related decarbonization targets
- Identify policy and regulatory barriers and needed actions by relevant agencies and prioritize resolution of these barriers
- Develop new legislation as needed
- Develop procurement targets and pathways that leverage aggregated demand for green hydrogen across sectors and include compensation mechanisms for all provided benefits
- Establish a common carbon-intensity framework and mechanisms for quantifying, tracking, and compensating the full range of benefits green hydrogen provides
- Create stakeholder alignment by facilitating diverse stakeholder support and input from green hydrogen offtakers, consumer advocates, and environmental groups

### 9.1.2 | Develop Sector-Specific Targets and Roadmaps

Transformational change requires effective alignment of a broad group of stakeholders across multiple industries. To take full take advantage of the massive potential of green hydrogen as a locally produced, carbon-free, versatile energy resource, multi-sectoral decarbonization roadmaps can be developed to achieve the necessary stakeholder alignment and impact. Below are several sector-specific roadmap and target recommendation examples:

| Sector | Area of Focus | Recommendation |
|---|---|---|
| Natural gas | Pipelines | • Establish a decarbonized fuel mandate or standard for natural gas pipelines that includes green hydrogen as part of a broader renewable gas portfolio.<br>• Set green hydrogen injection targets for natural gas pipelines and develop market incentives that assure green hydrogen storage access for every kilogram of green hydrogen produced. |
| Natural gas | Electric generation | • Establish emissions reduction targets for generation plants that require 100% renewable fuel compliance by a date certain, and encourage retrofitting assets to use green hydrogen as a zero-carbon fuel. |
| Electric | Critical power supplies | • Incorporate resource planning for service interruption events that encourages procurement of green hydrogen with fuel cells for emergency distributed critical backup power. |
| Electric | Grid support | • Set electrolyzer procurement targets and market adoption incentives such as a dispatchable load tariffs (retail or wholesale) that compensate electrolyzers for providing grid support.<br>• Ensure that green hydrogen is eligible as a LDES resource pursuant to any storage or LDES targets to support renewable integration. |
| Transportation | On-road | • Set technology-neutral zero-emission vehicle mandates for transportation applications (e.g., light, medium, and heavy-duty on-road transportation) and ensure incentives for accelerating green hydrogen infrastructure deployment. |
| Transportation | Maritime shipping | • Develop a seaport decarbonization roadmap to shift from fossil fuels to green hydrogen and its derivative liquid fuels to power medium-and heavy-duty vehicles, including heavy equipment such as forklifts, drayage trucks, and cranes. The roadmap should also aim to scale up infrastructure and storage, ultimately to not only decarbonize port operations, but also maritime shipping fuels. |
| Transportation | Aviation | • Develop an airport decarbonization roadmap to shift from fossil fuels to green hydrogen and its derivative fuels to displace fossil fuels for airport operations, as well as aviation fuels. The roadmap should also aim to scale up needed green hydrogen airport infrastructure and storage. |
| Industrial | Oil refining | • Set decarbonization targets to require oil refining operations to utilize increasing percentages of green hydrogen, increasing to 100% green hydrogen by 2050. |
| Industrial | Green ammonia | • Set targets to prohibit agricultural producers from doing open-field burning of agricultural waste and instead utilize the waste as a valuable resource to produce local green hydrogen (for fertilizer and transport uses to create a more local, circular economy).<br>• Expand access to carbon markets and incent development of local green hydrogen and ammonia and fertilizer production. |

Table 3 | Policy Recommendations to Enable Green Hydrogen Development by Sector

### 9.1.3 | Create a Regional Taskforce

Creation and support for collaborative regional green hydrogen task forces can accelerate green hydrogen deployment at scale and provide a platform for advancing innovation. An excellent example of a regional task force is the Western Green Hydrogen Initiative (WGHI). WGHI is a public-private partnership developed to assist 14 states and 2 Canadian provinces in advancing the deployment of green hydrogen infrastructure to benefit the region's economy and environment. This regional task force structure is replicable; a scope of work for any region could include:

- Coordinate and leverage state, federal, and industry investments in green hydrogen research, development, and demonstrations to guide priorities and scale commercial technology options
- Assist states and provinces in developing renewable hydrogen storage and utilization roadmaps to advance innovation and expand opportunities for low-cost green energy to produce, use, and store green hydrogen
- Address regulatory, policy, and commercial barriers associated with the scaled production and use of green hydrogen
- Establish a common regulatory framework, such as a common carbon accounting/tracking system, to foster regional collaboration and harmonized market rules for increased project investment
- Support electric-, gas-, transportation-, water-, and waste-sector modeling efforts at the regional level to inform coordinated state policy actions and investment for green hydrogen production and use at scale, utilizing existing infrastructure as much as possible to increase affordability
- Identify education and workforce opportunities that support the transition to a localized and resilient green hydrogen energy system

### 9.1.4 | Define Eligible Hydrogen Based on a Carbon Intensity Framework that uses well-to-gate life cycle emissions accounting

Currently, there is no universally established definition for renewable or green hydrogen. Creating this definition is key to supporting future mandates, incentive programs, and producer and offtaker investment decisions. Given the diversity and complexity associated with the myriad of possible feedstocks and energy sources to produce green hydrogen, a common framework based on life cycle carbon intensity is preferred. The GHC specifically recommends a carbon intensity framework that uses well-to-gate life cycle emissions accounting to ensure a level playing field across hydrogen production pathways and appropriate tracking of all carbon emissions and benefits to ensure decarbonization progress. This framework is a technology-agnostic approach, as it only considers the GHG emissions associated with hydrogen production based on a common and appropriately inclusive methodology. As a result, it opens a pathway for competition to flourish if the hydrogen can meet the desired life cycle emissions threshold, regardless of production technology.

**A well-to-gate carbon intensity approach tracks all emissions associated with feedstock production, transportation, losses, flaring, hydrogen production, and carbon capture and storage (if applicable).**

In addition to implementing this framework for definition and market development purposes, this framework is also crucial to ensuring reductions in greenhouse gas emissions since it quantifies and tracks the carbon intensity of all hydrogen pathways based on on-site and upstream production emissions. This helps reduce market misrepresentations and facilitates the development of a credible renewable hydrogen market. Additionally, evaluating emissions associated with hydrogen production through this framework will help reduce subjectivity and support a scientific approach focused on decarbonizing systems, not individual value chains.

### 9.2 | ESTABLISH AN EMISSIONS CERTIFICATION AND ELECTRONIC TRACKING FRAMEWORK

Developing an emissions certification and electronic tracking framework enables cross-sector accounting for the emissions benefits of green hydrogen, and eligibility toward meeting specific local, state, and national carbon reduction and green energy targets. The emissions attributes from green hydrogen represent a large, tradeable new certificate market.

Just as certification organizations helped grow the renewable electricity market in the 1990s, baseline rules and standards will do the same for today's green hydrogen market. Standards work to unify the market, ensure consistency, establish a set of baseline criteria, and reward those who surpass that baseline. Certification is fundamental in new markets to establish an accepted foundation of guidelines and rules to operate. This shared understanding leads to increased trust and stability in the market, high consumer confidence, and overall market growth. Electronic tracking of the production and use of green hydrogen is another essential policy tool to expand and support the green hydrogen market. Many electronic tracking systems have developed similar rules and operating procedures, but variance exists both within countries and worldwide. Global best practices include:

- Standardized certificate information (resource/fuel type, production location, the producer's name, issuance date, etc.)
- Registration of generation or production facility
- Defined geographical footprint
- Independence and transparency

A green hydrogen certification and tracking system should follow the hydrogen life cycle, which includes direct emissions from the end use of hydrogen and indirect emissions, such as those from land-use changes, feedstock, and production methods. Having such a system in place will provide the following benefits:

- Market-based pricing for the environmental attributes (carbon intensity) of the hydrogen
- Disclosure of origin to an end user to provide guarantees about its sustainability
- Reporting and verification tools for renewable and/or emission reduction targets
- Green and low-carbon hydrogen can become a tradable commodity across regional markets

### 9.3 | DEVELOP GREEN ELECTRICITY TARIFFS FOR ELECTROLYZERS

The current leading green hydrogen production technology, electrolysis, faces barriers to mass-scale adoption, with the most significant being production cost. One way to reduce production costs is to develop compensation pathways that properly value the full range of benefits available from electrolytic hydrogen. One critical compensation pathway for electrolyzers is to value their ability to provide such benefits as capacity, curtailment, frequency-support, voltage-support, and ramping services. Load serving entities (LSEs) can play a crucial role in developing this compensation pathway through tariff development. For example, an LSE could develop an electrolyzer real-time rate schedule or a fixed dispatchability adder on top of a feed-in tariff rate. LSEs could also develop a direct access tariff that allows electrolyzer owners to interact directly with the wholesale market. This tariff could permit electrolyzer owners to procure their power, pay transmission access charges, and provide grid services directly in the wholesale market.

Overall, putting electrolyzer tariffs in place would offer electrolyzer owners a single bankable revenue stream and a fully dispatchable and flexible resource for LSEs and grid operators. This is an important consideration even for electrolyzers colocated with renewable electricity generators, as it would enable grid-supplied renewable electricity to increase the electrolyzer utilization, reducing the resulting green hydrogen production cost. Therefore, it is recommended that LSEs begin developing tariffs for electrolyzers to support market development and LSE resource diversity to support grid needs.

### 9.4 | FUND GREEN HYDROGEN RD&D

Many innovative green hydrogen technologies are commercially available today. However, additional research, development, and demonstration (RD&D) are needed. Research and development in material sciences, controls, and system platforms will transform green hydrogen performance, diversity, and cost profiles. State, federal, and LSE RD&D funding has played a critical role for all energy resources to date, but green hydrogen needs dedicated funds for project development, storage, and deployment. Areas for advanced research, demonstration, and deployment should include:

- Planning and infrastructure incentive funding to advance green hydrogen hubs as strategic starting points for accelerated progress, beginning with regions of concentrated potential offtakers and significant fossil fuel use, such as seaports
- Improving local stakeholder outreach and inclusion toward co-creating the green hydrogen hub vision and roadmap to get there, with a focus on restoring communities that have been negatively impacted by fossil fuel use
- Repurposing existing fossil assets such as existing natural gas pipelines and depleted oil and gas fields for hydrogen storage, as well as developing a workforce development and transition strategy
- Demonstrating and advancing NOx reduction solutions for hydrogen combustion turbines
- Developing water alternatives for electrolytic production, such as desalinated seawater
- Demonstrating and advancing synthetic liquid fuel production from green hydrogen and waste $CO_2$ sources
- Developing planning software that can model integrated power- and gas-sector resource planning
- Improving commercial readiness for photolytic and biological production pathways and solid oxide fuel cells and electrolyzers

These investments will increase innovation, attract private capital, and accelerate the adoption and realization of a clean and just energy transition.

### 9.5 | CLARIFY JURISDICTIONAL AUTHORITY FOR INTERSTATE HYDROGEN PIPELINES

Mass-scale adoption of green hydrogen requires the development of a substantial interstate pipeline network like the natural gas and oil pipelines we have in place today. However, unlike the authority of the known regulatory governing bodies overseeing natural gas and oil pipelines, ambiguity exists regarding interstate regulatory authority for the economic regulation of blended and 100% hydrogen pipelines. If left unresolved, this ambiguity will impede project development and capital formation, and will stall the development of a mass-scale hydrogen market.

Thus, clarity is needed through administrative and potentially legislative pathways to confirm the appropriate regulatory authority to approve and regulate interstate blended and 100% hydrogen pipelines. Therefore, state, and federal policymakers should work together to establish clear regulatory authority to ensure the certainty needed to support investment in a hydrogen pipeline network, while keeping infrastructure open and accessible to encourage market development.

### 9.6 | EXECUTE AUTHENTIC ENVIRONMENTAL JUSTICE ENGAGEMENT

Green hydrogen can offer many benefits to environmental justice and disadvantaged communities by creating and retaining sustainable family jobs and reducing local air pollution by displacing fossil fuels that disproportionately impact these communities. However, without proper inclusion of these communities during the transition, concerns may arise about cost, usage, and tangible benefits, with particular focus on green hydrogen's ability to restore these communities.

Therefore, it is imperative to include these communities from the beginning to ensure they can voice their positions, concerns, and preferences. Consequently, regulators and policymakers should work together with these communities to help design the architecture of the clean energy transition roadmap through a transparent and inclusive process built on shared principles and goals.

# 10 CONCLUSION

Green hydrogen will play an essential role in combatting climate change, increasing renewable penetration, providing power system flexibility, and reducing dependence on fossil fuels across multiple sectors. In recognition of this potential, many governments and global corporations have opted to include green hydrogen in their decarbonization strategies, jumpstarting significant market momentum.

GHC expects to see continued proactive policy approaches that contribute further to green hydrogen market growth. These policy approaches may consist of a wide range of hydrogen market enablers, including, but not limited to, procurement targets, legislative and regulatory measures, research and development initiatives, sectoral priorities, and other economic and financial mechanisms. To create the value proposition for green hydrogen, stakeholders must work together to ensure green hydrogen is included, recognized, and compensated for its benefits as a critical solution in our clean energy transition.

Strategic implementation of these policy approaches will be critical to continuing to scale the green hydrogen economy. This will require engaging the entire set of ecosystem stakeholders, including government, manufacturers, hydrogen producers, offtakers, investors, labor groups, tribal communities, and energy and environmental justice groups. The next few years will be critical for this ecosystem to develop, build trust, collaborate, and establish a roadmap for a just green hydrogen future.

While green hydrogen is still more expensive to produce than other kinds of hydrogen today, GHC anticipates costs to decline dramatically as policy approaches are implemented, additional projects are deployed at scale, and technologies continue to advance.

## The stakes are high, and the opportunity is immense. Green hydrogen is a game changer for our economy and for our planet.

**Funding and support matter in the fight for our climate and a clean energy future. Visit our website to access free educational resources, sign up for news, and donate.**

Visit ghcoalition.org ›

# 11 APPENDIX A

This section provides an update on key U.S. green hydrogen market activities and projects as of the date of publication. For additional news and updates, please visit the GHC website: ghcoalition.org.

### 11.1 | U.S. GREEN HYDROGEN MARKET ACTIVITY

**Federal:**
The U.S. Department of Energy's (DOE) released a "Hydrogen Program Plan" in late 2020, with application-specific cost targets for hydrogen production, storage, and use to guide R&D efforts.

Secretary of Energy Jennifer M. Granholm launched the DOE's Energy Earthshots Initiative to accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade. The first Energy Earthshot, Hydrogen Shot, seeks to reduce the cost of clean hydrogen by 80%, to $1 per kilogram, in a decade.[104]

The Clean Hydrogen Deployment Act, introduced by New York Representative Paul Tonko, establishes a pilot program—authorized at $370 million for fiscal year 2022 and $250 million annually for fiscal years 2023 through 2026—at the DOE that uses a contract-for-difference model to offset increased costs and support clean hydrogen users. The program focuses on difficult-to-decarbonize sectors by requiring at least one project each in the power sector, in the transportation sector, an industrial feedstock, and as an industrial fuel, while promoting innovative high-impact projects by using hydrogen produced with 80% less GHG.[105]

**California:**
California has been focused on hydrogen for more than a decade as part of its zero-emission vehicles goals and low-carbon fuel standard program. Recently, legislation was enacted to qualify electrolytic hydrogen as a form of energy storage (SB 1369), and new legislation has been proposed to create a needed legal and regulatory framework for green hydrogen and its multi-sectoral applications (SB 18, SB 67).

**Washington:**
Washington State Bill WA SB 5588 authorizes public utility districts to produce and distribute renewable hydrogen for use in internal operations and for sale and distribution, and requires renewable resources, both for the feedstock and the energy input.

**Oregon:**
Oregon's SB 98 provides a definition of renewable natural gas, sets a target of 30% of gas purchased by the utility that will be delivered to retail customers to be renewable natural gas by 2050, and allows utilities to invest in and own the facilities to connect to the local gas distribution system. Notably, Oregon has also created an interruptible load tariff for electrolyzers.

**Utah:**
In Utah, SB 109 allows for a post-production tax credit of 30% for 20 years, up to 50% of the cost of the project. Eligible infrastructure includes "plant or facility that stores, produces or distributes hydrogen for use as a fuel in zero-emission motor vehicles, for electrical generation, or for industrial use."

**Regional:**
To drive top-down momentum for further regional project and infrastructure development, the GHC launched the WGHI in partnership with the National Association of State Energy Officials and the Western Interstate Energy Board. This is a public-private partnership that will enable focused attention and leadership on green hydrogen infrastructure and market development. The WGHI will serve as the steering committee to assist in the development of a regional green hydrogen strategy, including the development of large-scale, long-duration green hydrogen-based renewable energy storage.

### 11.2 | U.S. GREEN HYDROGEN PROJECTS AT SCALE

**California:**
SGH2, a global energy company, is building a green hydrogen production facility in Lancaster, California able to produce as much as 11,000 kilograms of green hydrogen per day, and 3.8 million kilograms per year. The plant will use 42,000 tons of recycled waste annually to produce green hydrogen.[106]

Microsoft has plans to demonstrate the feasibility of using a 3 MW hydrogen fuel cell for backup power at one of its data centers, and hopes to expand these deployments to help meet the company's carbon-neutral goals.[107]

SoCalGas has partnered with startup H2U Technologies to reduce the cost of green hydrogen production in commercial settings by replacing rare-earth metals used in conventional electrolysis with more readily available materials. H2U aims to have a pilot electrolyzer deployed within 18 months.[108]

**Florida:**
Through its Florida Power & Light utility, NextEra Energy is proposing construction of a $65 million, 20 MW green hydrogen pilot plant where an electrolyzer will be powered by solar power that would otherwise have gone unused. The green hydrogen produced will be used to replace some of the natural gas that is currently consumed by the utility's 1.75 GW Okeechobee gas-fired plant. If approved by state regulators, the project could be online by 2030.[109]

**Louisiana:**
The United States' largest producer of ammonia, CF Industries Holdings, signed a contract with thyssenkrupp for a 20 MW green hydrogen project at its factory in Louisiana. When complete in 2023, the Donaldsonville green ammonia project will be the largest of its kind in North America. The complex will produce 20,000 tonnes of green ammonia annually.[110]

**Minnesota:**
The passage of the Natural Gas Innovation Act will establish a regulatory framework for flowing renewable natural gas and green hydrogen to Minnesota gas customers.

**Montana:**
Oriden LLC, a venture of MHPS, has been approved to purchase 160 acres of land in Butte, Montana, to construct hydrogen production facilities. The project is still in development, but plans include conversion of treated and polished water from the Berkeley Pit into green hydrogen through electrolysis, which would then be transferred via a to-be-constructed 450-mile gas pipeline to be stored in vast salt domes in Delta, Utah.[111]

**Ohio:**
Long Ridge Energy Terminal, in collaboration with New Fortress Energy, has announced plans to transition its 485 MW combined-cycle power plant in Ohio to run on carbon-free hydrogen. Commercial operations were planned for November 2021, utilizing a GE 7HA.02 combustion turbine, which can burn 15–20% hydrogen initially, with the capability to eventually transition to 100% hydrogen.[112]

**New Jersey:**
Atlantic Shores Offshore Wind has committed to supporting the development of a 5–10 MW green hydrogen pilot project in New Jersey.[113]

New Jersey Natural Gas awarded a contract to McDermott International for the engineering, procurement, and construction of a green hydrogen power-to-gas facility in Howell, New Jersey. Solar power will be used to produce green hydrogen, which will be used for injection into the natural gas distribution network for residential and commercial use.

**Nebraska:**
Two SGT6-5000F turbines will be installed to power Omaha Public Power District's new Turtle Creek Station Peaking Plant in Papillion, Nebraska. The turbines offer the ability to run on as much as 30% hydrogen and biodiesel in support of future technology advancements.[114]

**New York:**
In November 2021, Plug Power officially opened its new, $125 million Innovation Center in Henrietta, New York. With this facility's opening, Plug Power has established the world's first ever gigafactory for PEM technology where it will manufacture hydrogen fuel cell stacks and electrolyzers. The opening created 377 new jobs at the John Street facility due to the support of Empire State Development, which is providing up to $13 million in Excelsior Tax Credits, and the New York Power Authority, which is providing 5.1 megawatts of low-cost ReCharge NY power.[115]

New York Gov. Andrew Cuomo announced, in July 2021, that New York would spend $8.5 million on a green hydrogen demonstration project at the New York Power Authority's Brentwood power plant on Long Island, substituting renewable hydrogen for a portion of the natural gas used there.[116]

**Texas:**
Frontier Energy launched a project in Texas called H2@Scale in Texas and Beyond with two initiatives, one at the University of Texas (UT) at Austin, and one at the Port of Houston. The $10.8 million project has been funded by the DOE's Hydrogen and Fuel Cell Technologies Office and the Office of Energy Efficiency and Renewable Energy. At the UT Austin campus, green hydrogen will be produced on-site via electrolysis with solar and wind power, and through reformation of renewable natural gas from a Texas landfill. The hydrogen will be used to provide power for the Texas Advanced Computing Center at UT Austin and will supply a hydrogen station with fuel for a fleet of Toyota Mirai fuel cell electric vehicles.[117]

Plug Power and Apex Clean Energy have announced a 345 MW wind power purchase agreement and a development services agreement for a green hydrogen production facility that will produce more than 30 tonnes per day of clean liquid hydrogen. The facility doesn't yet have a location, but the wind power will come from Texas.[118]

**Utah:**
The IPP in Delta, Utah is a coal plant that is being converted to 100% green hydrogen by 2045. The power purchaser, Los Angeles Department of Water and Power, plans to store the hydrogen in natural underground salt caverns and provide California residents with power through the existing interconnection of IPP to the Los Angeles Basin. The conversion process requires first converting the coal plant be use natural gas, then gradually blending that fuel with increasing proportions of green hydrogen. There is a planned conversion to a 30% hydrogen blend by 2025, with the goal of reaching 100% green hydrogen by 2045. The goal is to leverage curtailed and low-cost wind and solar energy to produce green hydrogen, store it on-site, and use it in place of natural gas at IPP, ultimately enabling carbon-free, dispatchable electric generation.[119]

**Washington:**
The Douglas County Public Utility District in Washington will utilize a 5 MW PEM Cummins electrolyzer to produce hydrogen from renewable energy. This project is expected to be operational in 2021. It is the first of its kind to be led by a public utility in the United States.[120] This project emerged from energy storage legislation in Washington that authorized public utilities in the state to create and sell gas for hydrogen vehicles.

# 12 APPENDIX B

## 12.3 | GLOBAL GREEN HYDROGEN AT SCALE

**Australia**

The National Hydrogen Strategy unifies the hydrogen frameworks and targets released by state and territory governments, and emphasizes the production of renewable-based hydrogen and realizing the country's export potential.[121]

The government has dedicated substantial funding to support hydrogen-powered projects. For renewable hydrogen, the Clean Energy Finance Corporation has administered an Aus$300 million (about US$215 million) Advancing Hydrogen Fund, and the Australian Renewable Energy Agency opened an Aus$70 million funding round.[122]

H2-Hub is a proposed multi-billion dollar chemical complex for the production of green hydrogen and ammonia at industrial scale. The project will be built in stages to integrate a 3 GW electrolysis plant, and an ammonia production capacity of up to 5,000 tons per day. The site has been secured under contract and the project is now moving into the planning phase. The project is targeting approvals by 2023 and operation in 2025.[123]

The Port Lincoln Green Hydrogen Project under construction includes a 30 MW electrolyzer plant and an ammonia production facility, as well as a 10 MW hydrogen-fired gas turbine and a 5 MW hydrogen fuel cell. The facility will also support two new solar farms, as well as a nearby microgrid that will be utilized by local aquaculturists who have been affected by aging back-up power generation.[124]

Infinite Blue Energy is planning a Aus$350-million green hydrogen production facility, known as the Arrowsmith project, which includes a 160 MW wind and solar project and the ability to produce as much as 25 tonnes of zero-emissions hydrogen each day.[125]

In Western Australia, Norway's Yara International SA and France's Engie SA won government support for a project to produce ammonia from green hydrogen. They plan to start producing up to 625 tonnes of green hydrogen and 3,700 tonnes of green ammonia a year in 2023 with a 10 MW electrolyzer. By 2028, they aim to scale up to 1 GW of electrolyzer capacity.[126]

**Austria**

A 6 MW green hydrogen pilot production facility began operations in November 2019. The pilot is funded by the European Fuel Cell Hydrogen Joint Undertaking (FCH JU) as part of the H2Future project, which aims to help European electrolyzer original equipment manufacturers (OEMs) develop products with the quality and capacity required by European industry to reduce $CO_2$ emissions.[127]

**Belgium**

A green hydrogen project called HYPORT Oostende was launched in 2020 to take advantage of excess wind generation. Although the feasibility study and the development plan are still being defined, the project aims to produce green hydrogen from about 4 GW of offshore wind capacity by 2025. A demonstration project with a 50 MW electrolyzer is already scheduled.[128]

**Brazil**

Enegix Energy plans to build a facility in northeast Brazil that could produce more than 600 million kilograms of green hydrogen per year. The hydrogen production would be powered by 3.4 GW of combined wind and solar power through a partnership with Enerwind, an Italian wind turbine manufacturer. The project is expected to take 3 or 4 years to build.[129]

**Canada**

Natural Resources Canada has released a Hydrogen Strategy for Canada, which calls for the use of the country's hydroelectric capacity to make green hydrogen through electrolysis.[130]

Macquarie Capital is financing a plant producing 60 tonnes/day of green hydrogen. A dedicated wind project will supply the energy for the plant, and the waste heat from the electrolyzer will be used in greenhouses. The green hydrogen produced is to be injected into the natural gas pipeline at 3% by volume.[131]

Renewable Hydrogen Canada, FortisBC, and Macquarie Capital have partnered for the Sundance Hydrogen project to produce hydrogen from electrolysis using renewable electricity.

**Chile**

Chile has released a green hydrogen strategy with the goal of reaching 5 GW of electrolysis capacity by 2025, producing the world's least-expensive green hydrogen by 2030, and making the country one of the top three fuel exporters by 2040.[132]

Chile's state petroleum company, ENAP, along with Enel Green Power, Siemens, and Porsche, have partnered to develop a green hydrogen pilot project in Chile. Green hydrogen will be produced from wind, alongside carbon capture from the atmosphere, via a synthesis process to produce green methanol and fuel for transport. The initial goal is to produce 350 tons of green methanol and 250 tons of carbon neutral fuel annually. The pilot will be commissioned in 2022, subject to local approval.[133]

Engie and Enaex's HyEx project will use a 2 GW solar farm to power a 1.6 GW hydrogen electrolysis plant to produce 124,000 tonnes of green hydrogen per year. The green hydrogen will be used to produce 700,000 tonnes of green ammonia annually. A pilot of this project, consisting of a 36 MW solar plant and a 26 MW hydrogen electrolyzer producing 18,000 tonnes per year of ammonia, will be operational by 2024, with full project operation targeted for 2030.

**Denmark**
A 2 MW electrolysis plant was awarded $5 million in funding from Denmark's Energy Technology Development and Demonstration Program. The plant will use electricity from two 3.6 MW offshore wind turbines to produce renewable hydrogen for buses, trucks, and potentially taxis.[134]

**European Union**
HyDeal Ambition is a 20-member collaborative project that brings together renewable energy developers, investors, gas transmission system operators, electrolyzer OEMs, and major offtakers with the shared goal of delivering 10,000 tons of hydrogen by 2023, 500,000 tons by 2025, and 4.2 million tons by 2030. Starting in 2025, their goal is a €1.5 euro/ton delivered price, not including subsidies. Land in Spain to build 10 GW of electrolysis production has already been secured to enable this goal.

The European Union's Hydrogen Strategy includes significant goals: 6 GW of electrolyzers installed by 2024, and 40 GW by 2030.

The European Commission has established the Clean Hydrogen Alliance, which expects a cumulative investment in green hydrogen of €180–470 billion by 2050.[135]

**France**
The association for European grid companies is planning to commission a €1 billion plan in 2022 to install 11 GWh of hydrogen storage capacity around Paris by 2030, which will be used to power a 50,000 fuel cell-powered taxi fleet using electrolysis and green or decarbonized electricity sources. Ten locations in Paris will have 20–50 MW of grid-connected electrolyzer capacity installed, with a storage capacity of 100–500 MWh.[136]

**Germany**
By 2030, Germany aims to have 5 GW of installed electrolysis capacity, with another 5 GW by 2040, to produce green hydrogen. An action plan to achieve these ambitious goals is laid out in the government's National Hydrogen Strategy. This plan is supported by a recent commitment of €9 billion from the government.

The Westküste 100 project initially has plans for the installation of a 30 MW electrolysis plant. Information gathered from this small-scale plant will inform the installation and operation of a 700 MW electrolysis plant fed with electricity from an offshore wind farm. Future plans include a hydrogen grid built between the refinery, the municipal utilities, a cavern storage system, and the existing natural gas grid using newly developed pipeline technology. The hydrogen storage cavern system will provide a continuous stream of green hydrogen for industrial use.[137]

Linde plans to build, own, and operate the world's largest PEM electrolyzer plant at the Leuna Chemical Complex. This 24 MW electrolyzer, which will begin producing hydrogen in 2022, could support as many as 600 fuel cell buses driving 40 million kilometers, and save up to 40,000 tons of carbon dioxide tailpipe emissions per year.[138]

The AquaSector project, German's first large-scale offshore hydrogen park, intends to install an approximately 300 MW electrolyzer to produce as much as 20,000 tons per year of green hydrogen offshore.[139]

**Japan**
The government's Green Growth Strategy calls for as much as 3 million tons of hydrogen production capacity to be introduced in 2030, rising to about 20 million tons in 2050. This plan requires Japan to develop its own hydrogen industry without relying on imports.[140]

Targets in Japan focus on the growth of the fuel cell electric vehicle (FCEV) market. The government aims to have 800,000 FCEVs operating by 2030 and 320 refueling stations by 2025. So far, the government has dedicated more than $1 billion to technology R&D and subsidies.[141]

The Fukushima Hydrogen Energy Research Field (FH2R) was completed in 2020 and claims to be the world's largest facility yet for green hydrogen production. Partners including Toshiba, Tohoku Electric Power, and New Energy and Industrial Technology Development Organization state that the system can produce as much as 100 kg of hydrogen an hour. A 20 MW solar array is backed up by renewable power from the grid to run a 10 MW electrolyzer and produce green hydrogen. The project is to be used as a pilot for the mass production of green hydrogen, with initial output directed to fuel hydrogen cars and buses.[142]

In Hokkaido, a consortium of four developers, Hokkaido Electric Power, Green Power Investment, Nippon Steel Engineering, and Air Water Inc, will create a hydrogen plant powered by offshore wind. The 110 MW wind farm and the hydrogen facility will be built in the coastal city of Ishikari. The new plant is expected to increase local hydrogen production to 2,500 tons.[143]

**Netherlands**
The Government's Vision on Hydrogen sends a clear signal emphasizing the importance of zero-carbon hydrogen and introduces a goal of 500 MW of installed electrolysis capacity by 2025. The government plans to allocate €35 million per year to support green hydrogen development.[144]

An existing 440 MW combined-cycle gas-turbine, part of a 1.3 GW plant built by Mitsubishi, is being converted from natural gas to hydrogen by 2023. Ammonia is being considered for long-term hydrogen storage, which would be reconverted into hydrogen and nitrogen before combustion in the retrofitted turbine. Although the first phase of the project will use blue hydrogen, the goal is to ultimately only use green hydrogen. This project is part of a national effort to transition toward a green hydrogen economy.[145]

Shell and Gasunie are partnering to build NorthH2, a green hydrogen project powered by as much as 10 GW of installed offshore wind in the North Sea. The plan aims to produce hydrogen by 2027, and produce 800,000 tons of green hydrogen annually by 2040.[146]

A consortium, including DEME Offshore and Eneco, will develop the world's first offshore green hydrogen pilot, having secured a grant of €3.6m from the Dutch government. Electricity generated by offshore wind will be used to power the hydrogen plant on the Q13a-A platform, converting seawater into demineralized water, then into hydrogen via electrolysis.[147]

**Portugal**

The H2 Seines green hydrogen facility, planned to have a capacity of 1 GW by the end of this decade, is being planned in Sines, Portugal. The project will begin with a 10 MW pilot electrolysis installation and be expanded gradually to 1 GW, backed by around 1.5 GW of renewables capacity. Feasibility studies are currently being conducted by utility EDP, Lisbon-based energy company Galp, industrial conglomerate Martifer, national grid operator REN, and the Danish wind turbine manufacturer Vestas.[148]

H2Evora, a new utility-scale solar-to-hydrogen plant, is set to produce nearly 15 tonnes of green hydrogen annually.[149]

**Saudi Arabia**

In July 2020, Saudi Arabia announced plans to build a green hydrogen facility to power Neom, a new Saudi city planned near its borders with Egypt and Jordan. The 4 GW facility, powered by wind and solar, will be capable of producing 650 tons of green hydrogen per day—enough to power 20,000 green hydrogen buses. The project is a collaboration between Air Products, Saudi Arabia's ACWA Power, and Neom, with fuel cells provided by thyssenkrupp. Production is expected to begin in 2025.[150]

**Scotland**

Peel NRE has signed a collaboration agreement with Powerhouse Energy Group to develop 11 waste plastic-to-hydrogen facilities across the United Kingdom over the next few years, with the option of exclusive rights for a total of 70 facilities. The 13,500-tonne facility in Clyde, Scotland, will use pioneering technology developed by Powerhouse Energy Group that makes sustainable hydrogen from nonrecyclable plastics. They welcome plans to colocate a refueling station at the site that will help increase uptake of hydrogen fuel in the region and add to Scotland's growing hydrogen economy.[151]

**Singapore**

The CleanTech One building, built in 2011 by JTC Corporation, has a 1 MW power plant that generates green hydrogen for the building's power needs. When fed wood chips, plant waste, and other biological material, the fuel cell plant produces about 20% of the building's power needs from green hydrogen.[152]

**Spain**

Two Spanish companies, the fertilizer producer Fertiberia and the energy firm Iberdrola, plan to build a facility with the capacity to produce 720 tonnes of green hydrogen annually for ammonia production. The project will feature a 100 MW PV plant to generate electricity to power the electrolyzers. Fertiberia estimates that the project will reduce the fertilizer plant's natural gas consumption by 39,000 tons annually.[153]

Iberdrola will use a €6 million loan secured from the Instituto de Crédito Oficial and a €3.7 million grant from the EU's Connecting Europe Facility to build and operate a hydrogen station to supply renewable energy to vehicles in the Transports Metropolitans de Barcelona fleet. The 5,000-square meter green hydrogen production facility, being developed as part of a collaboration with the Spanish Ministry of Transport, Mobility, and the Urban Agenda, will enable the creation of a low-carbon hydrogen hub.[154]

Repsol and Talgo will jointly develop projects to support the creation of renewable hydrogen-powered trains, as well as promote emissions-free rail transport in the Iberian Peninsula. Talgo is developing hydrogen-powered trains to support the decarbonization of railway lines. Two electrolyzers, with a capacity of 100 MW, will supply its complexes with renewable hydrogen.[155]

**Sweden**

HYBRIT is a Swedish project attempting to decarbonize the steel industry by replacing coal with green hydrogen. A pre-feasibility study was conducted in 2016 and 2017, and construction began in 2018. The pilot phase will end in 2024, after which the demonstration phase will begin. The cost for the pilot will be funded by Swedish Energy Agency, along with the companies that own the project, including SSAB, LKAB, and Vattenfall. Today, the steel industry produces 10% of Sweden's $CO_2$ emissions, and this pilot aims to reduce the carbon footprint of steel production by 12% per finished tonne by 2021.[156]

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Strategen advises and empowers leading organizations — utilities, government agencies, NGOs, and industry clients — to design innovative, practical solutions that capture the promise of a clean energy future, strengthen resilience and adaptability, and are equitable, collaborative, and impactful.

Headquartered in Northern California, and with offices across the western U.S. and in Australia, Strategen's mission-driven experts leverage a global perspective and market-leading capabilities to deliver novel, high-impact, stakeholder-aligned approaches across the policy, regulatory, and market design spheres that sustainably accelerate the deployment of low-carbon energy systems.

Strategen's expertise spans corporate strategy, energy system planning, policy and regulatory innovation, and multi-stakeholder engagement. We take an integrated, multidisciplinary approach, informed by our core values of intellectual honesty, humility, sustainability, diversity, and inclusion.

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