GREEN HYDROGEN

GUIDEBOOK

GREEN
HYDROGEN
COALITION

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GREEN HYDROGEN COALITION

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GREEN HYDROGEN COALITION

Founded in 2019, the Green Hydrogen Coalition (GHC) is an educational non-profit organization. The GHC focuses on building top-down momentum for scalable green hydrogen projects that leverage multi-sector opportunities to simultaneously scale supply and demand. The work of the GHC is supported by annual charitable donations.
www.gh coalition.org

STRATEGEN

Strategen is a mission-driven professional services company specializing in impactful market development for decarbonized energy systems. Strategen works across the power sector ecosystem with public sector leaders, global technology corporations, utilities, and project developers to help them achieve their clean energy goals.
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EXECUTIVE SUMMARY

Green hydrogen is a gamechanger for our economy and our planet. Plants make zero-carbon emission energy from water and the sun, and so can we- with green hydrogen. Green hydrogen is the only solution we have today to power energy, transportation, agriculture, mining, industrial systems, and beyond with 100% clean energy.

Hydrogen is the most abundant element in the universe and a safe and proven energy carrier for the storage and transport of energy. Leveraging hydrogen created from renewable sources to replace fossil fuels in a multitude of sectors gives us the ability to transform every aspect of how we power our world while creating a vibrant, local, clean energy economy with sustainable jobs.

Hydrogen has been a global commodity for decades and a robust hydrogen industry already exists. Used primarily as an input into oil refining and as an industrial feedstock, global demand for hydrogen reaches 70 million metric tons annually.

The vast majority (99%) of hydrogen sold today is produced from fossil-fuel derived hydrocarbons, namely natural gas and coal. Less than 0.1% is green hydrogen produced from the conversion of renewable energy resources, such as wind, solar, and biomass, into a renewable fuel and feedstock. The components of green hydrogen production and utilization are well understood and are largely available "off-the-shelf"; they include electrolysis, steam methane reformation, gasification, storage, pipeline and on road transportation, fuel cells, and hydrogen compatible gas turbines.

Green hydrogen produced via electrolysis with low cost renewable electricity is anticipated to be lower cost than hydrogen made from fossil fuels within ten years.[1] The low cost of green hydrogen will not only displace fossil fuels for current hydrogen production and related applications, but also open pathways for utilizing green hydrogen to displace fossil fuels in many other applications, thus accelerating decarbonization and driving new investment and jobs.

"There is no way to get to 100% renewable energy that I can see right now without hydrogen in the mix. It doesnt exist."

– MARTIN ADAMS

GENERAL MANAGER & CHIEF ENGINEER
LOS ANGELES DEPT. OF WATER & POWER

To support the clean energy transition, many countries and communities are setting bold decarbonization and renewable energy targets that limit the use of greenhouse gas emitting energy resources. New policies are accelerating the multi-sectoral adoption of green hydrogen as a preferred fuel source. Governments and utilities are realizing that for the power sector, achieving 100% renewable energy and maintaining reliability will require a dispatchable, renewable fuel. For example, the City of Los Angeles has set a 100% renewable energy goal by 2045 and its municipal utility, the Los Angeles Department of Water and Power, is actively pursuing green hydrogen as a key strategy to achieve that goal.

Strong scientific evidence suggests a massive clean electrification effort will be required to limit the warming effect of climate change to 1.5 degrees Celsius. A key component of this clean electrification effort will require the full conversion of existing fossil fuel demand to 'clean molecules.' Green hydrogen is a strategic resource that will enable the unbounded availability and supply of such clean molecules to power a cleaner energy future.

At this critical juncture for the transition of our energy system, green hydrogen is the ultimate gamechanger to assure energy system reliability, affordability, and security. Development of this resource supports repurposing existing infrastructure and creates economic development, local jobs, greater fuel diversity, and system resilience. Ultimately, green hydrogen will support a sustainable energy economy for all.

This guide is designed to increase understanding of green hydrogen production and distribution, safety, applications and use cases, value proposition, policy and regulatory drivers, and barriers and challenges. Most importantly, the guide offers a vision of a green hydrogen future and catalogues inspiring global examples of large-scale green hydrogen projects already underway.

01: WHAT IS HYDROGEN

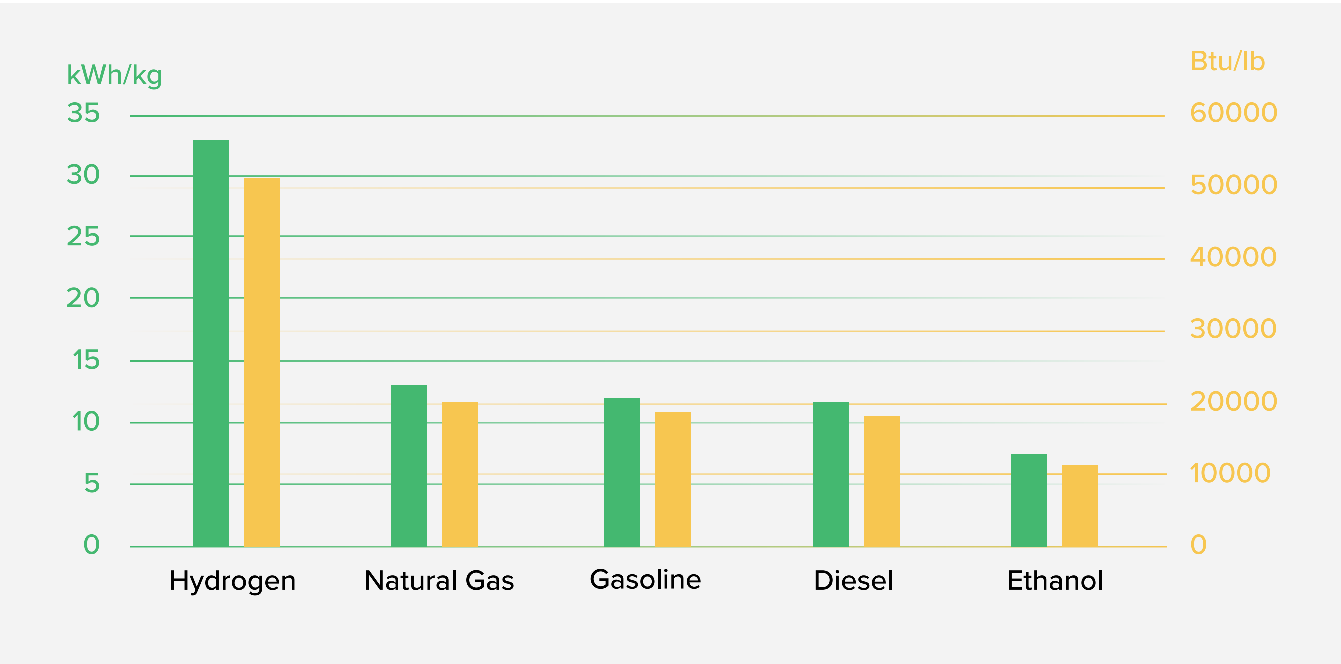
Hydrogen is the most abundant element in the universe. It is a globally produced energy carrier that can be used to store, transport, and deliver energy produced from various sources.

Hydrogen (H_2) is the simplest and most abundant element in the universe. Naturally occurring as H_2, hydrogen is the lightest of all molecules. It is a colorless, odorless, and tasteless gas at standard conditions. On Earth, hydrogen is primarily bound in 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. Hydrogen gas 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 to its use as an industrial feedstock, hydrogen can also be used as a fuel or energy source. Hydrogen gas has an energy density roughly twice that of the common fuel methane (natural gas) and three times that of gasoline. Hydrogen energy is typically measured by weight in kilograms (kg) instead of volume because as a gas, it has a low volumetric energy density. In electrical terms, one kilogram of hydrogen holds an impressive 33.3 kWh of usable energy versus diesel which only holds 11.83 kWh per kg.[2]

FIGURE 01:
COMPARATIVE ENERGY CONTENT OF FUELS[2]

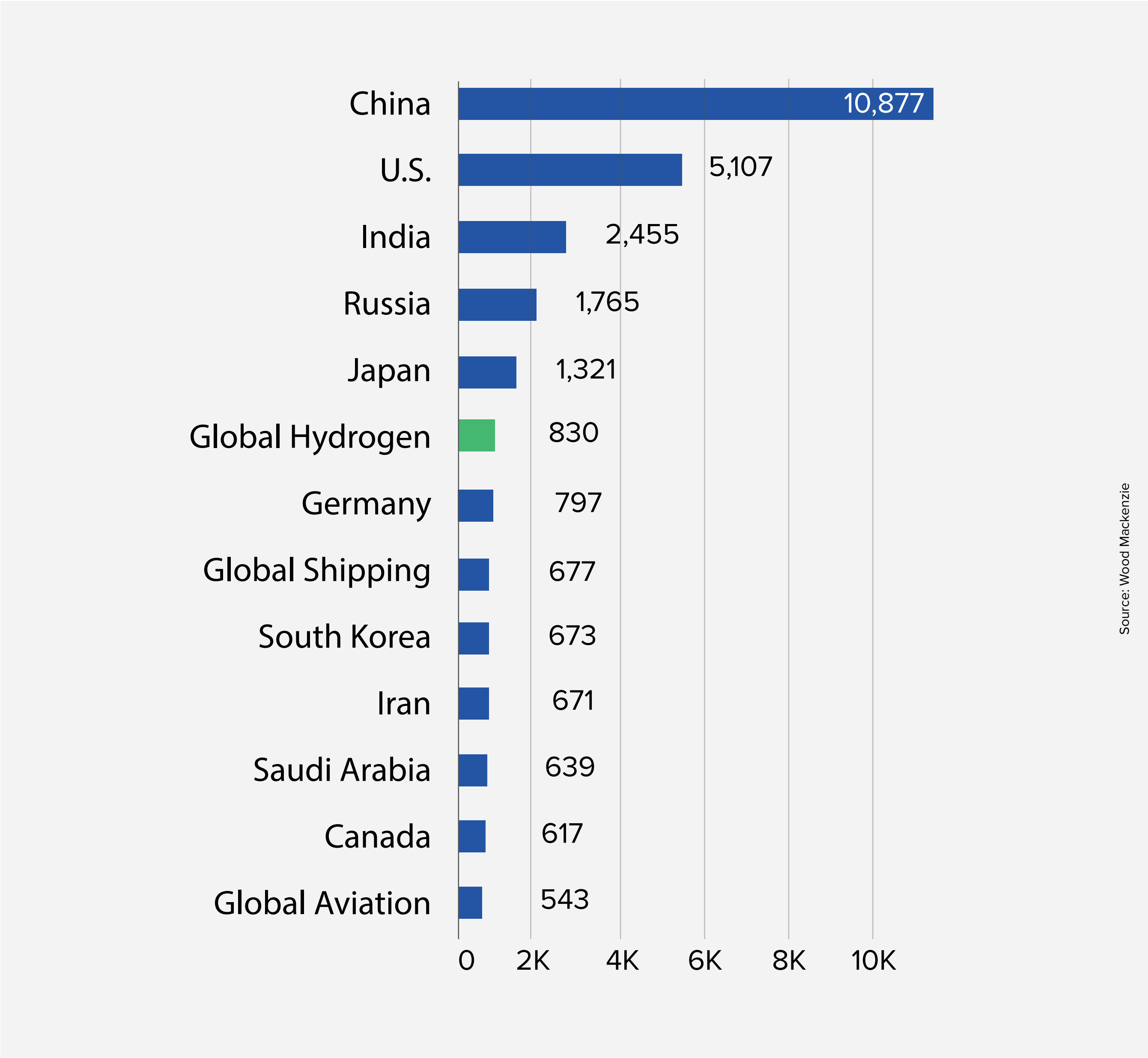


01: WHAT IS HYDROGEN (CONT.)

Used in a fuel cell or to power an electric motor, 1 kg of hydrogen contains approximately the same energy as a gallon (2.8 kg) of gasoline. Replacing fossil fuels with green hydrogen has the potential to eliminate global energy-related carbon dioxide (CO_2) emissions, removing an astounding 33 gigatons of CO_2 from the environment each year.[3]

Annual global demand for hydrogen is approximately 70 million metric tons with 9 million tons being produced annually in the U.S. Decarbonizing today's hydrogen supply alone would result in a reduction of 830 million tons of CO_2 per year which is roughly the annual carbon equivalent of Germany, the world's fourth largest economy.[4]

FIGURE 02:
2017 CO_2 EMMISSIONS BY COUNTRY & SECTOR IN MEGATONS OF CO_2 PER YEAR[5]



02: THE COLORS OF HYDROGEN

There are many ways to create hydrogen gas, but the carbon footprint of these processes varies significantly. Green hydrogen production converts renewable energy resources like wind, solar, and biomass into a clean, renewable fuel. Today, only about 0.1% of hydrogen production is "green."

To determine the type of hydrogen production, we consider:

1. The hydrogen feedstock
2. The energy input into the production process
3. The treatment of carbon emissions that may arise

TABLE 01: CARBON IMPACT OF KEY HYDROGEN PRODUCTION METHODOLOGIES[6]

	Hydrogen Production Methodology	Carbon Impact (kg CO_2/kg H_2)
CARBON IMPACT OF HYDROGEN PRODUCTION	Gray: Natual gas SMR	8-12
	Brown: Coal Gasification + SMR	18 -20
	Blue: Natural Gas SMR + Carbon Capture	0.6 - 3.5
	Green: Electrolysis with Renewable Electricitys	0

2.1 GRAY HYDROGEN

Approximately 71% of the hydrogen produced today is considered "gray."[7] Gray hydrogen results from using fossil fuels such as natural gas, ethanol, or propane as the feedstock for hydrogen production, as well as using fossil fuels as the energy source for the hydrogen separation process.

Gray hydrogen is made via process known as steam methane reformation (SMR). During SMR, methane (CH_4) reacts with high-pressure steam to produce hydrogen, carbon monoxide, and carbon dioxide. Subsequently, a water-gas shift reaction produces more carbon dioxide and hydrogen from the reaction of carbon monoxide and additional steam. Impurities are then removed from the gas stream, leaving pure hydrogen gas. Steam reforming is endothermic, so heat must be supplied to the process for this reaction to occur.[8]

2.2 BROWN HYDROGEN

Brown hydrogen accounts for approximately 23% of all hydrogen generation today.[7] Brown hydrogen is produced by gasifying solid fossil fuels such as coal or lignite, then collecting hydrogen from the resulting gas via SMR. Fossil fuels are used as the energy input to heat up and gasify the solid fuel feedstock.

2.3 BLUE HYDROGEN

Blue hydrogen is a lower-carbon hydrogen production method because it uses carbon capture and sequestration (CCS) technology to reduce carbon emissions. Like gray and brown hydrogen, fossil fuels are used as the feedstock and the energy source for the hydrogen separation process, SMR, but a portion of the resulting emissions are captured. Carbon capture technologies can reduce carbon emissions by 71-92%, but this technology is not yet widely commercial.[9]

2.4 GREEN HYDROGEN

The Green Hydrogen Coalition defines green hydrogen as hydrogen created from renewable energy sources such as solar, wind, hydro power, biomass, biogas, or municipal waste.

2.4 GREEN HYDROGEN

Green hydrogen can be created by the following methods:

1. Electrolysis of water with renewable energy
2. Steam methane reformation (SMR) of biogas
3. Thermal conversion or gasification of organic matter and other waste streams

DEFINITION:

GREEN HYDROGEN [grēn hahy-dr*uh*-j*uh*n]
noun

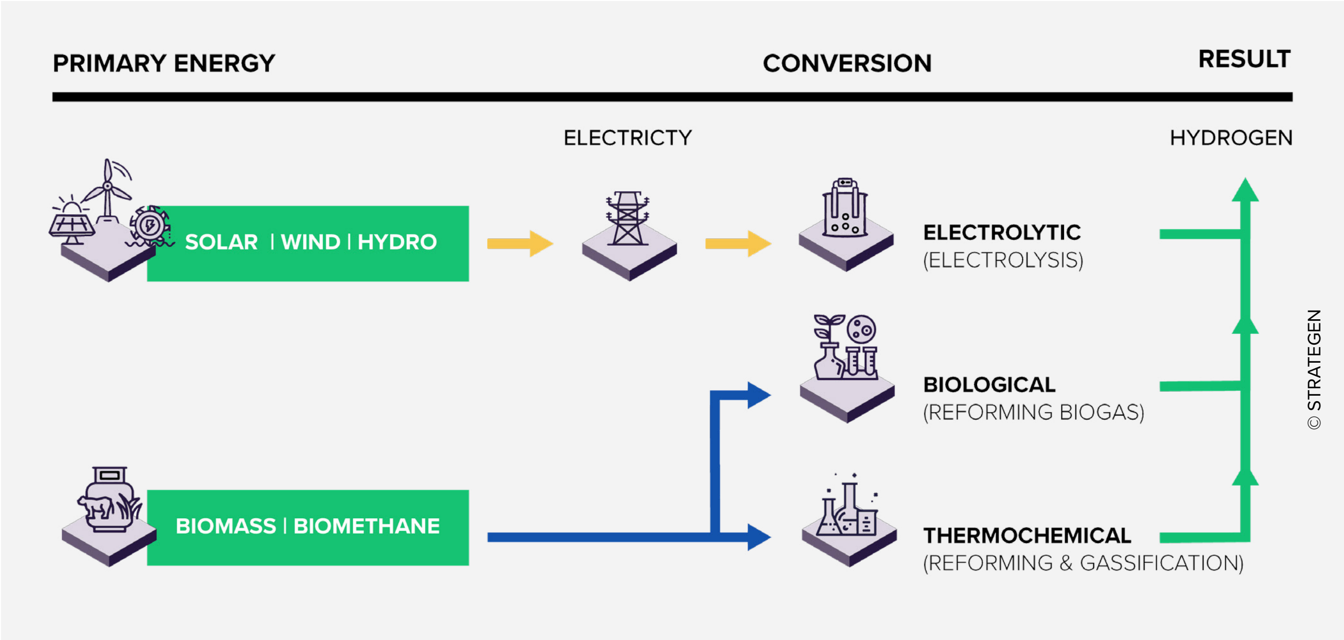
[1] hydrogen created from renewable energy sources such as solar, wind, hydro power, biomass, biogas, or municipal waste.

These methods are all commercially available today and have the potential to make large-scale green hydrogen production a competitive, and potentially lower cost alternative to fossil fuel based hydrogen. In the case of electrolysis, hydrogen production can take advantage of very low cost wind and solar electricity. Today, solar and wind power is the lowest cost source of electricity in many countries around the world and unlike fossil fuels, it is unlimited. In the other two production cases, green hydrogen production can help solve waste issues by transforming waste products into a value stream.

The use and storage of green hydrogen is quite similar to existing processes for storing and transporting gray and brown hydrogen. Incumbent players in the oil and gas industry are well positioned to have a competitive advantage in the inevitable scaling up of green hydrogen production and use. Green hydrogen thus represents an opportunity for oil and gas interests to innovate and expand their business models while becoming important investors and leaders in the clean energy transition.

Currently, green hydrogen production accounts for only 0.1% of global production with only $365 million invested in 94 megawatts (MW) of capacity.[7,10] However, the global pipeline of new projects constitutes many gigawatts (GW) and is growing.[11]

FIGURE 03:
ILLUSTRATION OF THE OFFICIAL GHC DEFINITION OF GREEN HYDROGEN



03: GREEN HYDROGEN SAFTEY

Hydrogen is a safe, non-toxic, and reliable fuel with 70 million tons produced and consumed each year around the world.[7] *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] Over 80 years have passed since this event, and like most 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, green hydrogen is a safer, non-toxic, and GHG-free fuel source.

Safety benefits of hydrogen as a fuel source:[14]

- Hydrogen is a non-toxic, colorless, and odorless gas that does not threaten human or environmental health if 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 surrounding air, so it is unlikely to remain near the ground where people are in the case of a fire.
- Hydrogen combustion is more rapid than 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 and managed by governments as well as regulated in accordance with expert third-party international hydrogen safety standards.

AIChe Center for Hydrogen Safety: American Institute of Chemical Engineers (AIChE) is a nonprofit organization providing leadership to the chemical engineering profession representing more than 60,000 members in industry, academia, and government.[15]

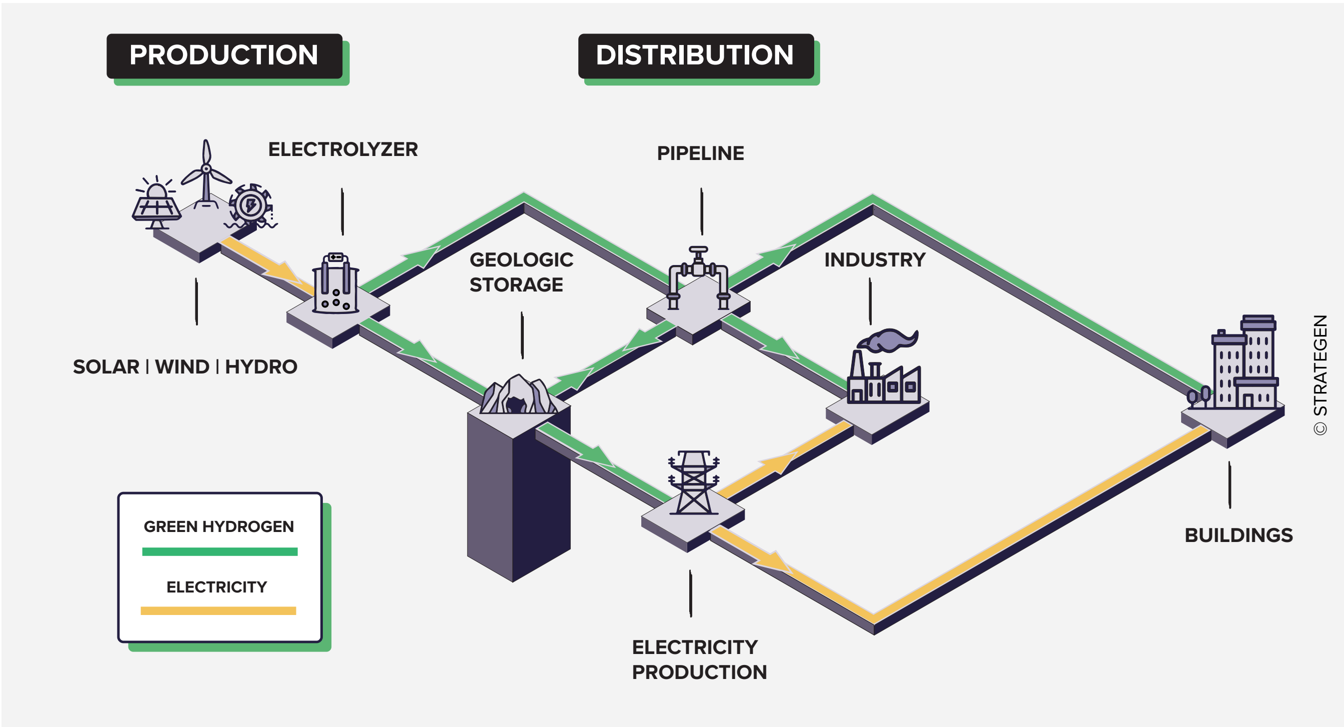
Hydrogen Fuel Cell Codes and Standards: This resource, provided by the Fuel Cell and Hydrogen Energy Association, tracks over 400 codes and safety regulations around the world.[16]

U.S. Department of Transportation Office (DOT) of Pipeline and Hazardous Materials Safety Administration (PHMSA): The DOT has regulated hydrogen pipelines since 1970 via 49 CFR Part 192, Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards. PHMSA's mission is to protect people and the environment by advancing the safe transportation of energy and other hazardous materials that are essential to our daily lives. To do this, the agency establishes national policy, sets and enforces standards, educates, and conducts research to prevent incidents. PHMSA also prepares the public and first responders to reduce consequences if an incident does occur.[17]

04: GREEN HYDROGEN PRODUCTION, STORAGE, & DISTRIBUTION

Hydrogen has been a global 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 04:
PRODUCTION AND DISTRIBUTION PATHWAYS OF GREEN HYDROGEN - ELECTROLYSIS EXAMPLE



4.1 GREEN HYDROGEN PRODUCTION

Three commercially available methods of green hydrogen production are described in this chapter.

4.1.1 ELECTROLYSIS WITH RENEWABLE ENERGY

A promising and scalable method for green hydrogen production is electrolysis powered by renewable electricity sourced from zero carbon resources including solar, wind, hydropower and geothermal energy. Renewable primary energy from solar and wind is the most globally abundant and geographically available clean energy resource. Hydrogen produced from this methodology is sometimes referred to as "electrolytic hydrogen."

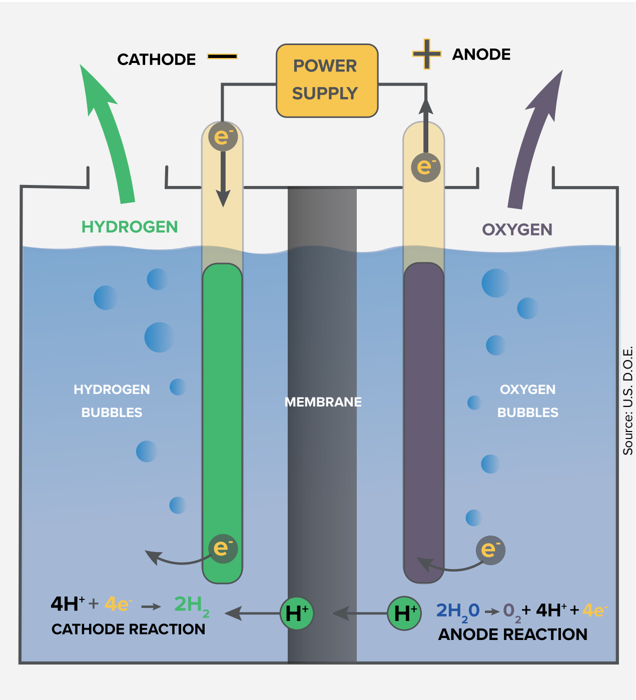
Electrolysis is a method of using the energy from an electric current to split water into its elemental components: oxygen and hydrogen. This is accomplished using an off-the-shelf device called an electrolyzer. When an electrolyzer is powered by renewable energy, green hydrogen is produced by using water as a feedstock (rather than hydrocarbons). This process emits no greenhouse gases.

4.1 GH_2 PRODUCTION (CONT.)

ELECTROLYSIS:

- Reaction: $2H_2O$ + Electricity ⟶ $2H_2 + O_2$
- Yield: 9L of H_2O = 1kg of Green H_2
- Typical Efficiency: 45-78 kWh/kg (60-90%)

FIGURE 05:
ELECTROLYSIS REACTION, YIELD, AND EFFICIENCY [18, 19]



4.1.1 ELECTROLYSIS WITH RENEWABLE ENERGY

Electrolyzers can range from small-scale, appliance sized devices to large-scale equipment that can be directly connected to central utility-scale electricity generation sources. The main application of electrolysis is for paired power-to-hydrogen production. 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. Electrolyzers interconnect to the grid similarly to solar or energy storage systems, with inverters. They operate with a fast response time and can provide flexible load to the grid, as well as ancillary services including voltage support and frequency regulation.

The most mature electrolysis technology is the alkaline electrolyzer, primarily used for large-scale commercial hydrogen production. Other electrolyzer technologies include proton exchange membrane electrolysis and solid oxide electrolyzer cells.

About 4% of today's global hydrogen is produced via electrolysis powered by fossil fuels.[21] (Recall electrolytic hydrogen is only "green" if the electricity to produce it is carbon-free). Primary costs that contribute to the price of electrolytic hydrogen include the cost of electricity and the capital costs of the electrolysis equipment.

TABLE 02:
COST AND EFFICIENCY OF AVAILABLE ELECTROLYZER TECHNOLOGIES[20]

	Electrolyzer Techonolgy	Nominal Stack Efficiency (LHV)	CAPEX ($/kW)	Maturity
Cost and Efficiency of Available Electrolyzer Technologies	Alkaline	63-71%	950-1,750	Mature
	Proton exchange membrane	60-68%	1,650-2,500	Early Market
	Solid oxide electrolyzer cells	100%	N/A	R & D

GREEN HYDROGEN COALITION

4.1 GH_2 PRODUCTION (CONT.)

4.1.1 ELECTROLYSIS WITH RENEWABLE ENERGY

Today, modular electrolyzer system capacities range from kilowatts to megawatts. Current research and development is focused on improving power density, lifetime, and efficiency of electrolysis cells in addition to technology scale-up and cost reductions. Several startups are working on pathways to directly electrolyze seawater.[22]

4.1.2 STEAM METHANE REFORMATION OF BIOGAS

Biogases can also be used as a feedstock for steam methane reformation (SMR), the same process as 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 as waste. The composition of biogas varies from 40%–60% methane to 60%–40% carbon dioxide (CO_2), with small amounts of water vapor and other gases.[23]

When methane from biogas is steam reformed, the green hydrogen that results is considered a renewable carbon-neutral fuel because the carbon used is already active in the earth's carbon cycle. This is different from fossil fuels, where carbon once trapped deep under the earth is released adding net carbon to the environment.

Biogas can be sourced from landfills, wastewater treatment facilities, and animal or plant waste. Reusing biomass as a fuel feedstock can help municipalities and farmers generate 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.

4.1.3 THERMAL CONVERSION/GASIFICATION OF ORGANIC MATTER AND/OR WASTE

Thermal conversion or gasification of organic matter (biomass or municipal and other organic waste streams) works by applying high heat and/or pressure to the organic matter to transform the material from a solid state to a gaseous state. Once gasified, the resulting components of the gas are mainly hydrogen, carbon monoxide, and carbon dioxide, which is further purified to produce hydrogen or methane that can be used for fuel.

Organic matter can come from forestry waste, agricultural waste, organic municipal solid waste, or animal waste. This method of creating green hydrogen is in early commercialization. The U.S. Department of Energy estimates that one billion dry tons of biomass could be available for energy use annually in the U.S.[24] Similar to SMR of biogas, this system is carbon-neutral and can help create value for wastes, encouraging the recycling of biomass and other organic material into useful fuels.

4.2 HYDROGEN STORAGE

Once hydrogen is produced it must be stored.

Gases hold large amounts of energy, but their molecules expand to fill a given space. Gas compression or liquefication, a commonly used strategy for the storage of all industrial gases, allows higher gas density to be achieved for a given volume. To transport large quantities of hydrogen, the gas must be either pressurized and delivered as a compressed gas or cooled and liquefied.

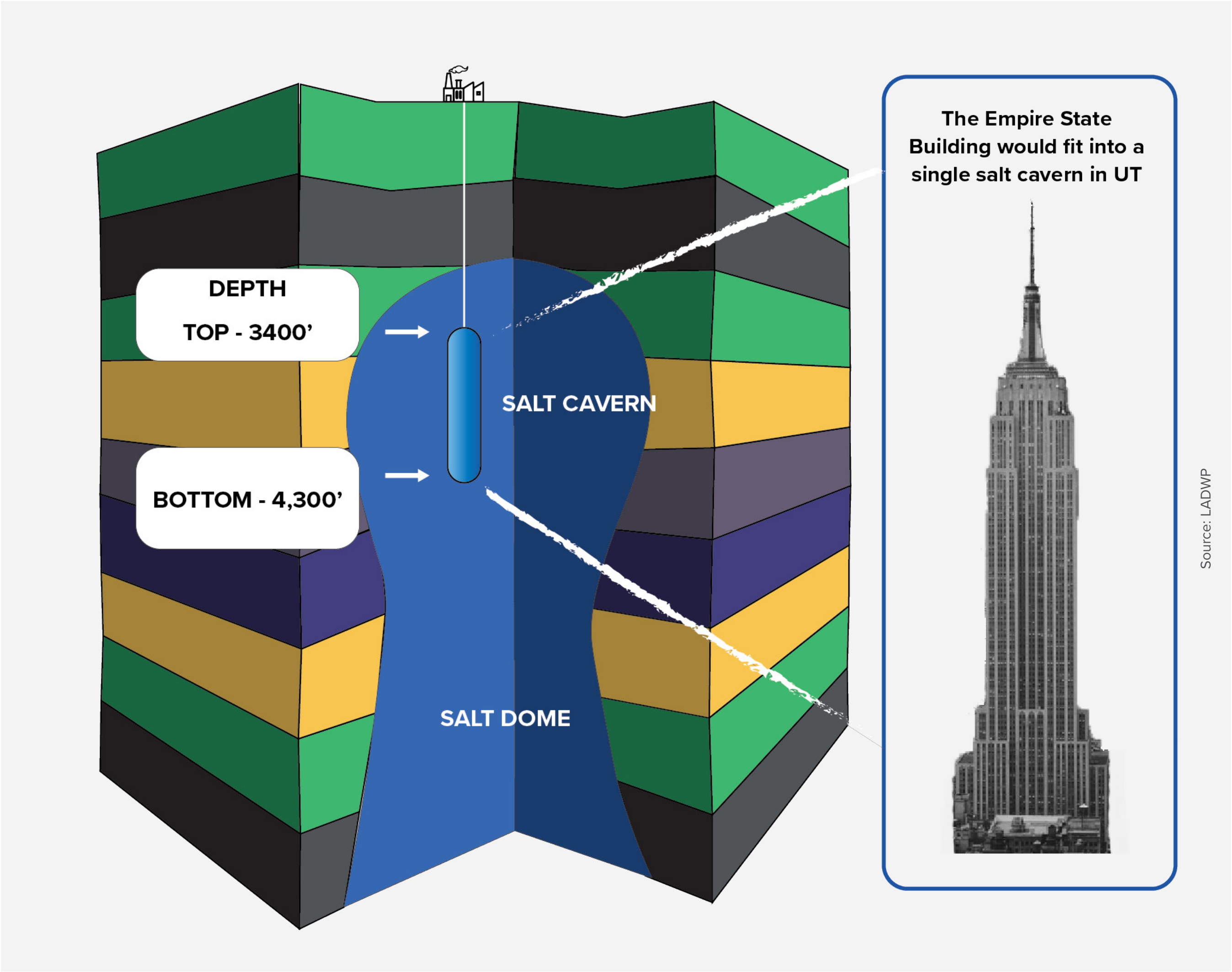
Hydrogen can be stored via different methods and at different temperatures and pressures depending on the application; each storage method has tradeoffs related to location, scale, duration, and cost.[25] In smaller volumes, hydrogen is usually stored in compression or in cryogenic tanks. In large volumes, it is more cost-effective to use bulk-storage facilities. Bulk storage can take advantage of natural geological formations such as salt caverns and depleted oil wells. This is a geographically limited opportunity but could bring great financial savings to storing large quantities of hydrogen.

4.2 HYDROGEN STORAGE (CONT.)

Bulk underground hydrogen storage in salt caverns has been demonstrated as a safe and effective process in the U.S. Since 2016, Liberty County Texas has been home to a very large Praxair underground hydrogen storage cavern. The subsurface Texas facility has a storage capacity of 20 MMCF (566,000 m^3) of hydrogen. Hydrogen is injected into the cavern at pressures over 1,000 psi.[26] The facility is integrated into a 310 mile 100% hydrogen pipeline that serves over 50 refineries and chemical plants.

At the Intermountain Power Project in Delta Utah, green hydrogen will likely be stored in an adjacent salt cavern with a storage capacity of 150,000 MWh of electricity. Here hydrogen gas can be stored for days, weeks, months, and even seasons to be dispatched on demand as a clean fuel for carbon-free gas turbine power generation. The storage capacity of the salt caverns in this location are tremendous-one cavern can hold 5,512 tons of hydrogen gas, equivalent to the hydrogen needed to fill 200,000 hydrogen powered buses, and over 100 such caverns can be built at this location.[27, 28]

FIGURE 06:
HYDROGEN STORAGE CAPACITY AT THE SALT CAVERNS IN DELTA, UTAH



4.3 HYDROGEN DISTRIBUTION

There are many ways to distribute hydrogen, including via pipeline, road transport, rail, and marine shipping.

4.3.1 PIPELINES

Similar to natural gas, once compressed, hydrogen can be transported and stored in pipelines. Existing pipeline infrastructure can store hydrogen either in its pure form or in a blend with natural gas.

4.3.2 DEDICATED HYDROGEN PIPELINES

The U.S. has about 1,600 miles of dedicated hydrogen pipelines.[29] These are mainly concentrated near large hydrogen users in Louisiana and Texas, such as petroleum refineries and chemical plants, and serve industrial demand. Major cites also have dedicated hydrogen pipelines. For example, Air Products operates 15 miles of hydrogen pipelines in Los Angeles, CA. In these pipes, hydrogen is transported at constant, relatively low pressure. In the US, hydrogen pipeline safety is regulated by the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA). Natural gas transmission pipelines in the U.S. typically operate at pressures of 200–1500 psi. Existing hydrogen pipelines, which are associated with industrial facilities such as oil refineries and chemical plants, operate at similar pressures around 500–1200 psi.[30]

4.3.3 BLENDED HYDROGEN IN PIPELINES

Hydrogen can be transported through natural gas pipelines as a blend with natural gas, then either separated in facilities close to the point of consumption or delivered as a blend to end users. The presence of up to 15% hydrogen by volume in natural gas pipelines allows for delivery without significantly increasing risks from use of the gas blend in end-use devices or the integrity of the natural gas pipeline network, however, the appropriate blend may vary significantly between various pipeline network systems.[31] Repurposing existing natural gas pipelines to transmit and distribute green hydrogen is an effective way of using valuable existing infrastructure and avoiding stranded cost.

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

The DOT has regulated hydrogen pipelines since 1970 via 49 CFR Part 192, Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards. PHMSA's mission is to protect people and the environment by advancing the safe transportation of energy and other hazardous materials that are essential to our daily lives. To do this, the agency establishes national policy, sets and enforces standards, educates, and conducts research to prevent incidents. PHMSA also prepares the public and first responders to reduce consequences if an incident does occur.[32]

The highest concentration of hydrogen reported by any gas utility in the U.S. is in Oahu, Hawaii, where Hawaii Gas's natural gas pipeline contains approximately 12% hydrogen gas.[33] Canada, Germany, Austria, and other countries are currently adding hydrogen to their natural gas pipelines. Adding green hydrogen to natural gas can significantly reduce greenhouse gas emissions by partially decarbonizing the multitude of end uses that depend on natural gas as a fuel (See Table 3, Section 5.3).

4.3 HYDROGEN DISTRIBUTION (CONT.)

4.3.4 ALTERNATIVE HYDROGEN CARRIERS

Hydrogen can be distributed in alternative chemical forms such as ethanol (C_2H_6O), natural gas (CH_4), or ammonia (NH_3). Because each of these molecules contain hydrogen atoms, the hydrogen can be transported in one form, and then stripped and reconstituted into its pure form (H_2) once it reaches its destination. Alternative hydrogen carriers can enable easier and less expensive transport. For example, ammonia is a liquid at room temperature, has high volumetric and gravimetric energy density, and is considered safe to transport and store. 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.[34] Australia and Saudi Arabia are also envisioning the use of ammonia as a means for large scale export of green hydrogen.

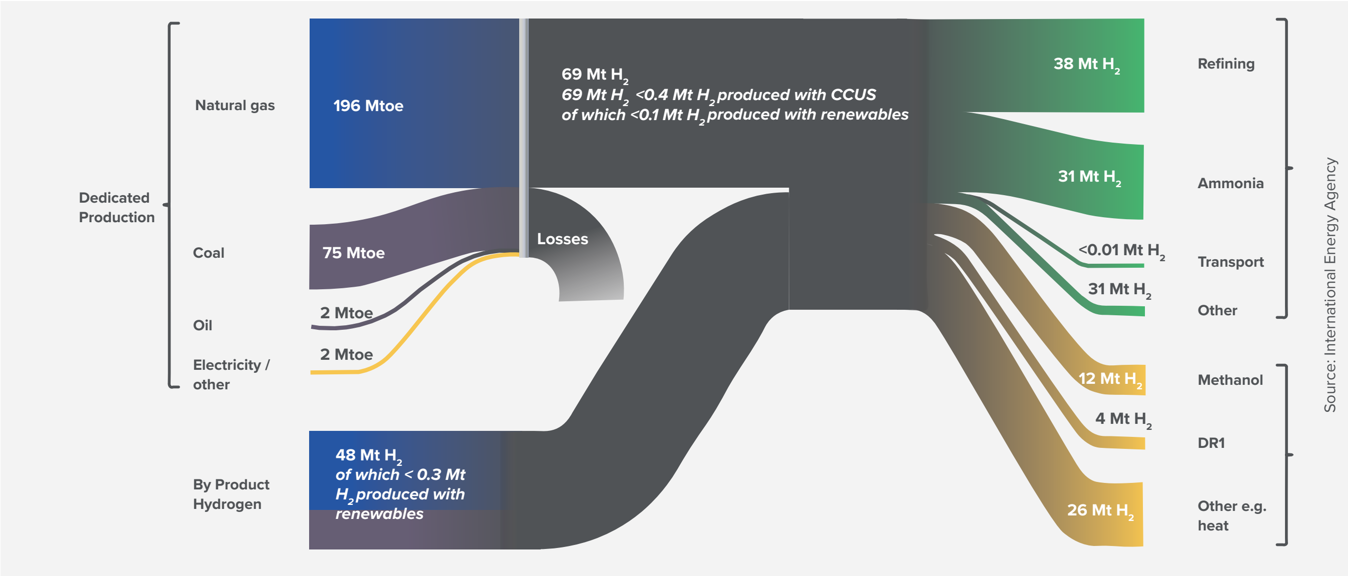
FIGURE 07:
OUR NEXT GREAT EXPORT (AUSTRALIA) [35]

Source: Australian Renewable Energy Agency

05: USES ACROSS THE ECONOMY

Green hydrogen could play a major role in cleaning 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 decarbonize multiple sectors.

FIGURE 08:
HYDROGEN AS A COMMODITY: PRODUCTION SOURCES AND END USES[7]



Replacing existing uses of gray and brown hydrogen with green hydrogen would have a significant decarbonization impact- similar in size to removing the carbon emissions of all of Germany.[4] Once green hydrogen is cheaper to produce than gray hydrogen, it will open 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 degrees Celsius 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 sectors across the economy where green hydrogen can play a major role in decarbonization.

5.1 POWER GENERATION

Green hydrogen can be used as a fuel source to produce dispatchable renewable electricity on demand. There are two primary mechanisms for this: combusting hydrogen fuel in a gas turbine (Power-Gas-Power) and combustion-free electricity production using a fuel cell.

As more low-cost renewable wind and solar energy is interconnected to the grid, green hydrogen for power generation will become increasingly economic. In a high-renewable penetration future, hydrogen power generation will play a central role in reliability applications. Its ability to be stored as a fuel will help avoid wasteful and uneconomic curtailment of renewable electricity sources resources.

5.1 POWER GENERATION (CONT.)

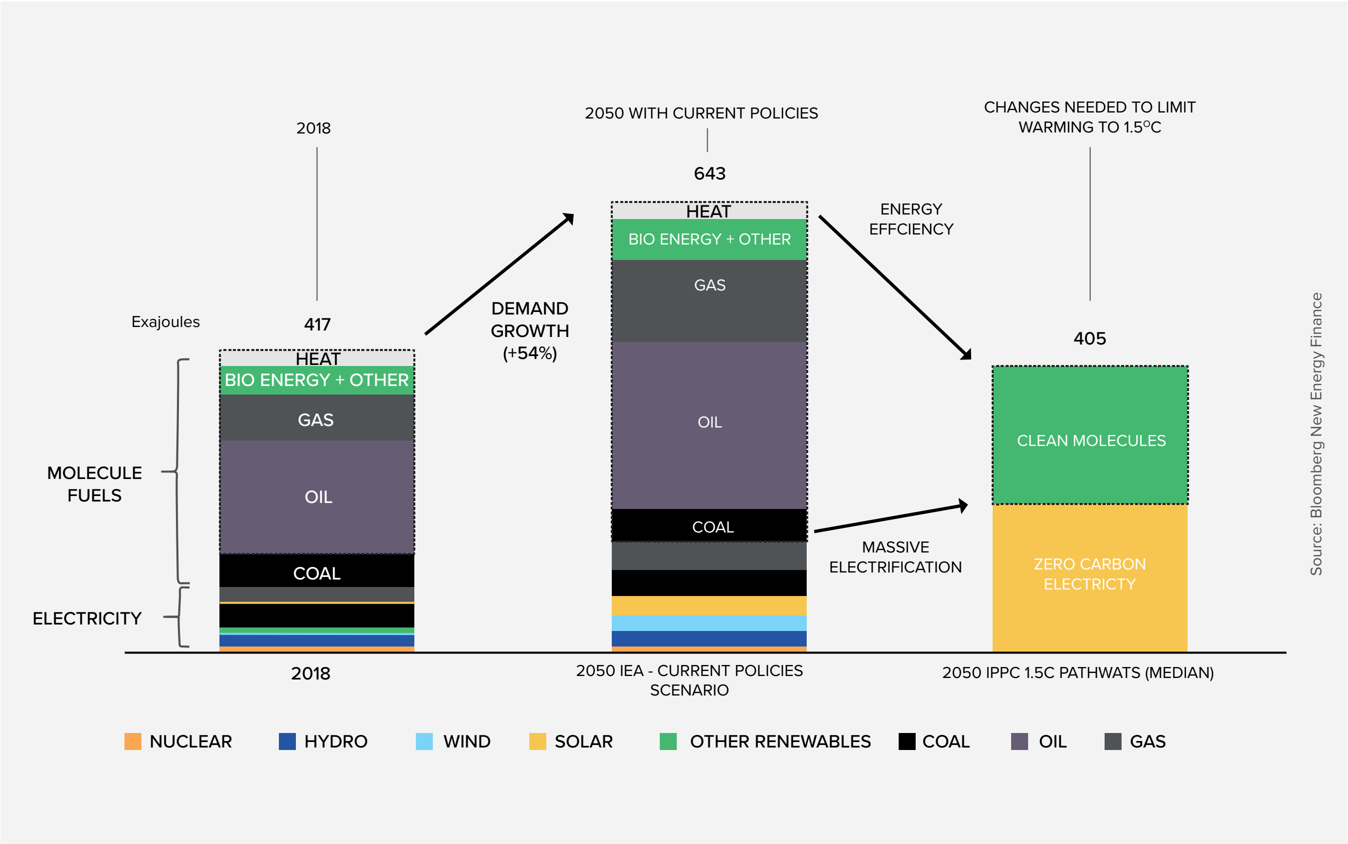
5.1.1 POWER TO GAS TO POWER

Power plants provide centralized energy generation and are important parts of our electrical system, providing both baseload and peaking load power. In 2019, 38% of U.S. electricity generation was met with natural gas powered plants, and another 23.5% was met with coal.[36] Many of these existing thermal assets can be updated, repowered, and converted to use green hydrogen.

All gas turbines work by converting the chemical energy in fuel (natural gas, hydrogen, methanol) to heat, and then converting that heat to work, in this case in the form of electrical power. Many of the world's largest turbine technology providers are continuously developing their hydrogen turbine technology, including Mitsubishi Hitachi Power Systems (MHPS), GE, and Wartsila. MHPS has publicly announced that their hydrogen turbines will be able to combust 100% hydrogen by 2025.

Hydrogen can be safely combusted in a gas turbine and has environmental benefits over other fuels. Hydrogen has a wide range of flame stability in a fuel-air mixture, which means it is very stable from an operational standpoint. Hydrogen combustion can be temperature controlled and is ten times faster than natural gas. These factors help reduce NOx production in the combustion process, bringing NOx emissions down to 2 ppm or less.[37] Hydrogen gas also eliminates particulate, sulfur, carbon dioxide and carbon monoxide emissions, as there is no carbon or other impurities in the fuel.

FIGURE 09:
PROJECTIONS FOR GLOBAL FINAL ENERGY CONSUMPTION IN 2050



5.1 POWER GENERATION (CONT.)

5.1.1 POWER TO GAS TO POWER (CONT.)

A major example of a Power-Gas-Power project is the conversion of Intermountain Power Project (IPP), an 1,800 MW coal-fired generator located in Delta, Utah to a hydrogen burning combined cycle gas turbine. Owned by Intermountain Power Agency (IPA), this project will convert existing assets to a 840 MW combined cycle gas turbine capable of using a blend of natural gas and 30% green hydrogen in 2025, ultimately increasing that percentage to 100% on 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 Los Angeles Department of Water & Power, which is in a transmission constrained basin and has a 100% clean energy mandate.[38]

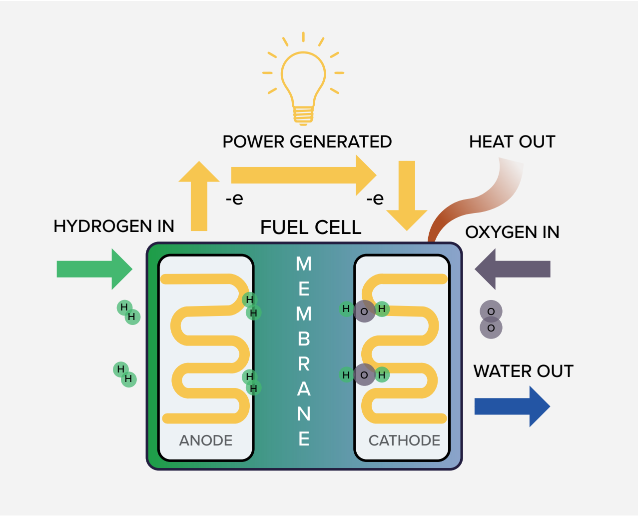
5.1.2 FUEL CELL ELECTRICITY

Fuel cells are the most energy efficient devices for extracting power from fuels.[39] Fuel cells produce electricity without combustion requiring only a constant source of fuel and oxygen. As there are no moving parts, fuel cells operate silently and with extremely high reliability. Fuel cells that use green hydrogen are completely carbon-free, only producing electricity, heat, and water.

A typical fuel cell, composed of an anode, cathode, and an electrolyte membrane, is like an electrolyzer in reverse. A fuel cell works by passing hydrogen gas through the anode and oxygen through the cathode. While hydrogen protons pass through the membrane in between, the electrons are forced 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 the oxygen in the cathode to form water- its only emission source. The electrical current that is created can power a lightbulb, a motor, or be fed into the electric grid.

Fuel cells can provide clean, silent power for applications that vary greatly in size and power, from combustion engine replacements for electric vehicles to large-scale, multi-megawatt installations providing electricity directly to the utility grid or microgrid. Because fuel cells are modular, they can be combined to meet the needs of a wide range of customers and uses.

FIGURE 10:
FUEL CELL



Fuel cells have three main applications:

1. Portable uses including recharging batteries, directly powering consumer electronics and also supplying off-the-grid backup power.

2. Stationary installations for combined heat and power (CHP), uninterruptible power supplies (UPS), backup power, and baseload distributed primary power supply.

3. Motive power for buses, trains, boats, cars, scooters, forklifts, trucks, and even aircraft.

The global fuel cell market size was estimated at $10.48 billion in 2019 with stationary fuel cells accounting for 70% of the market. The fuel cell market is expected grow over 15% per year from 2020-2027 and has unlimited potential to help decarbonize a variety of industries and applications.[40]

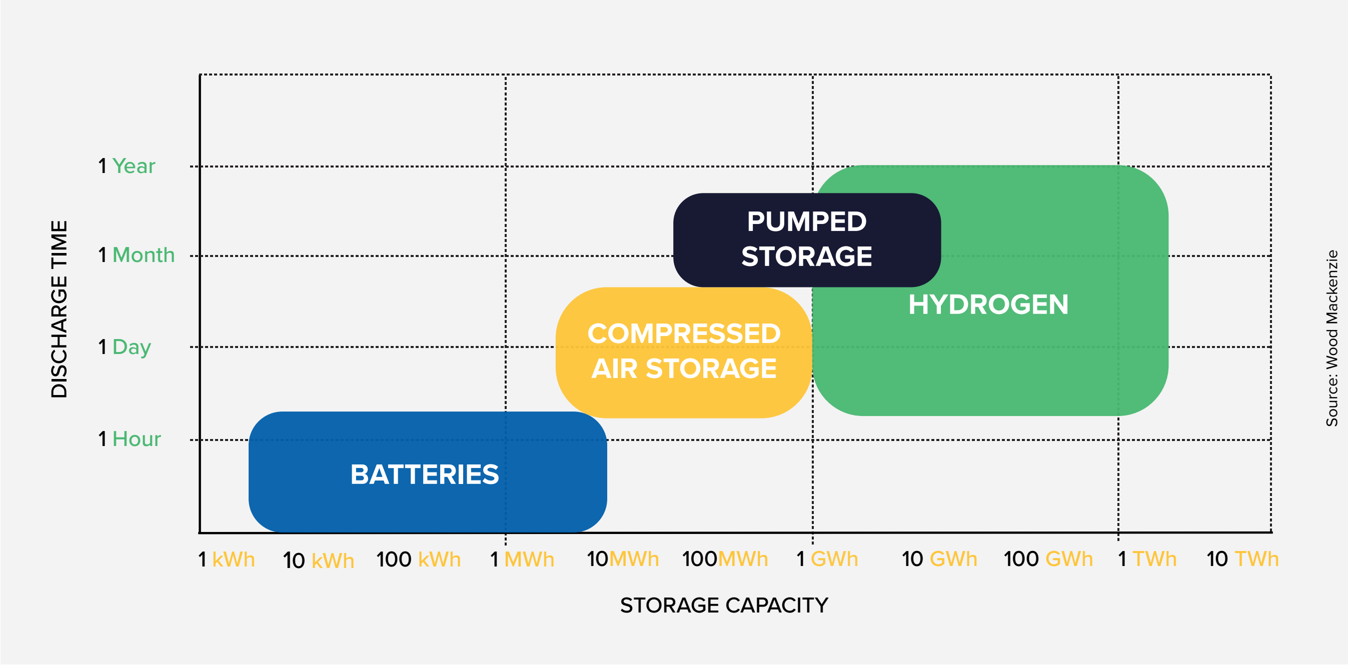
5.2 MULTI-DAY & SEASONAL (BULK) ENERGY STORAGE

Green hydrogen is an ideal energy storage carrier for bulk, multi-day and seasonal energy storage. Hydrogen can be stored in bulk for long periods and used on demand for balancing load on the grid.[41] With increasingly high penetrations of intermittent renewable energy resources on the electric grid, long duration and seasonal energy storage will be required to stabilize load and maintain electric reliability.

Hydrogen storage is unique from other storage technologies in that it has separate power (kW) and energy (kWh) scaling. For example, the size of the fuel cell can be determined independently of the size of the hydrogen storage tank. There may be times when storage helps correct short load mismatches, like meeting the evening peak load. When green hydrogen is used as a drop-in fuel replacement for natural gas, it can utilize existing natural gas generation infrastructure to meet daily demand fluctuations, similar to how daily cycling electrochemical batteries are used.

However, when a long period of storage, ten hours or more, is required to provide power, it may be significantly more cost effective to store energy via hydrogen instead electrochemical batteries. For example, during a long cloudy winter, stored energy may have to last for weeks. In this case, only a renewable fuel like green hydrogen would provide the appropriate scale at a reasonable cost to maintain grid reliability.

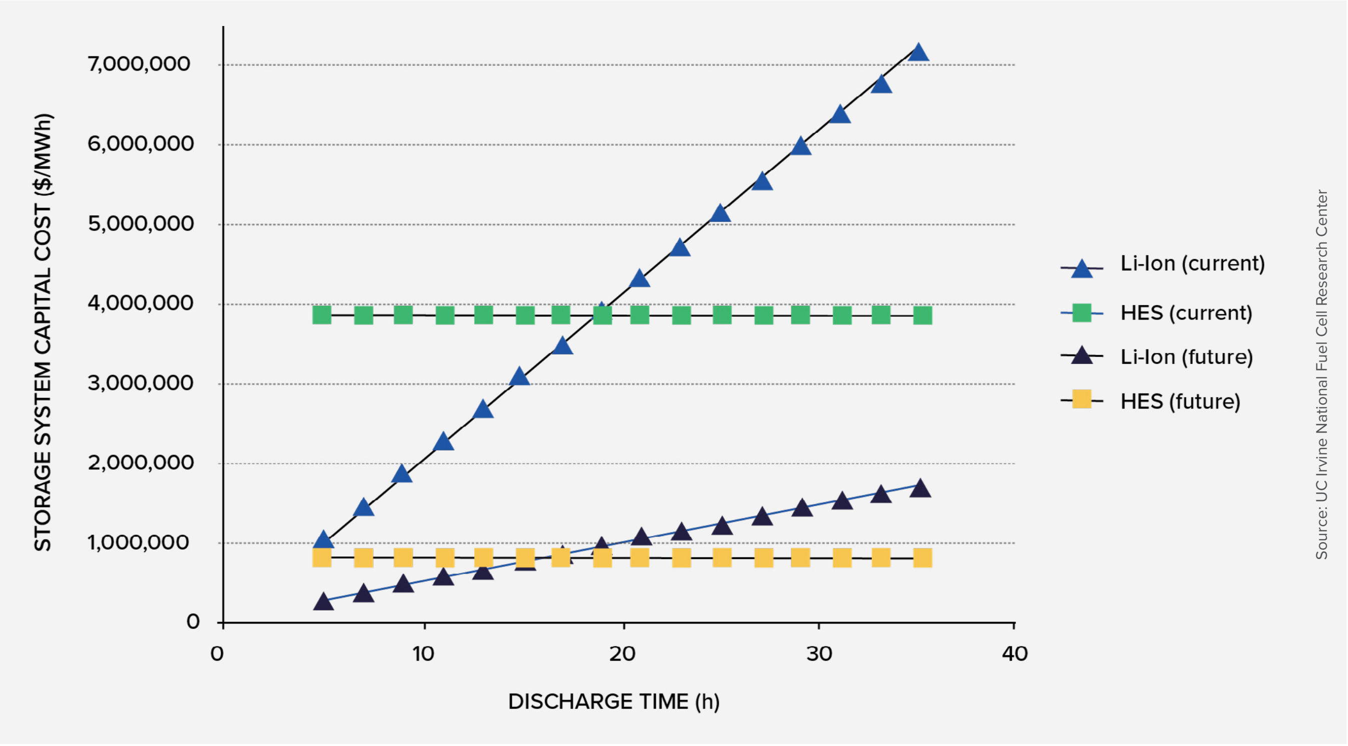
FIGURE 11:
STORAGE CAPACITY VS. DISCHARGE TIME FOR COMMERCIALLY AVAILABLE STORAGE SOLUTIONS



5.2 MULTI-DAY & SEASONAL (BULK) ENERGY STORAGE (CONT.)

A study by the U.S. National Renewable Laboratory (NREL) published in 2019 found that using green hydrogen for energy storage applications of 13 hours or more makes financial sense with today's technology.[42]

FIGURE 12:
HYDROGEN ENERGY STORAGE: SEPARATE POWER & ENERGY SCALING[43]



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 scenario. A recent simulation completed by the University of California, Irvine showed that global solar and wind dynamic production to meet total world annual energy demand would require nearly 20,000 TWh of energy storage.[44] Sufficient quantities of metals such as lithium and cobalt simply do not exist on the planet to store that energy, underscoring the need for alternative bulk energy storage solutions to batteries.

Hydrogen used as a multi-day storage resource can provide carbon-free grid support during worst case scenario grid disconnection events such as those that are increasingly arising from natural disasters such as hurricanes and wildfire. Green hydrogen can accomplish this 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 central west Utah nearby the Intermountain Power Project (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, the reserve would also be available as an emergency, back-up fuel source for transportation, industrial, mining and other applications.

5.3 DECARBONIZING THE NATURAL GAS PIPELINE

Renewable hydrogen can be blended with natural gas for use in everything from home appliances to power plants. The presence of up to 15% hydrogen by volume in natural gas pipelines can safely allow for delivery of the gas blend without affecting the integrity of the natural gas pipeline network or many end use devices.[31] The transition to partially decarbonized pipeline gas would enable continued use of the existing natural gas pipeline distribution networks, valuable pre-existing energy infrastructure.

Hawaii, Canada, Germany, Austria, and other countries are already adding hydrogen to their natural gas pipelines, significantly reducing greenhouse gas emissions from gas end uses.

As of 2019, Americans consumed 31 trillion cubic feet of natural gas annually, resulting in emissions of about 1,650 million metric tons of CO_2. By blending even small amounts of hydrogen into our natural gas infrastructure, significant reductions in CO^2 emissions can be achieved.[45,46]

TABLE 03:
CO_2 REDUCTIONS FROM DECARBONIZING THE U.S.NATURAL GAS PIPELINE

	Volume % of H_2 in Natural Gas Pipeline	Million Tons of CO_2 Saved/Year	Equivalent CO_2 Emissions/Year
CO_2 REDUCTIONS FROM DECARBONIZING NATURAL GAS PIPELINE	3%	49.4	City of Toronto
	10%	165	Singapore
	15%	247	New York City

This application will help all gas pipeline end users decrease their carbon footprint, including from residential and commercial end uses, such as cooking, and heating.[47] Decarbonizing the natural gas pipeline can also help reduce emissions in sectors that depend on high temperature processes powered by natural gas such as steelmaking, cement mixing, glass making, and smelting.

5.4 HIGH TEMPERATURE INDUSTRIAL PROCESSES

Industrial processes, including production of steel, cement, glass, and chemicals, depend upon high temperatures to manipulate raw inputs into useful outputs. Because such high temperatures required for these operations, often in the hundreds to thousands of degrees Fahrenheit, it is very difficult to electrify these operations. Green hydrogen, however, offers a solution by acting as a fuel to supply high heat for these processes. In fact, it is estimated that almost 12% of this heating energy could come from hydrogen by 2050.[48]

Many high temperature industrial processes depend on coal as a heat source. Coal contributes to air pollution with particulate matter, sulfur dioxide emissions, mercury, lead, and other heavy metals, as well as carbon dioxide. A transition to clean-burning and renewably generated green hydrogen for these applications would be a gamechanger in reducing point-source pollutants at industrial sites around the world.

Pilot projects are underway to replace traditional coal with hydrogen as an industrial heat source in steel manufacturing and chemical synthesis. The conversion to hydrogen fuel provides large carbon and other air pollution emission reductions, providing significant environmental benefits, as well as potential monetary benefits for participating industrial sites in the in regions with established carbon markets, such as California and the European Union.

5.5 TRANSPORTATION

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

5.5.1 LAND TRANSPORTATION

Since 2016, transportation has been the largest source of U.S. greenhouse gas emissions. The subsector producing the greatest emissions is on-road transportation, including passenger cars, light-duty trucks, medium- and heavy-duty trucks, buses, and motorcycles. Road transportation derives over 90% of its energy from fossil fuels. By replacing fossil-fueled vehicles with green hydrogen fueled vehicles, the sector could reduce emissions to zero.[49]

Hydrogen 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 resiliency for land transport applications.

> *GREEN H_2 ON THE GO: LAND, AIR, AND SEA*
>
> *Green hydrogen is an excellent option for low carbon transport involving anything that requires rapid fueling, long range, and a large payload.*
>
> *Using hydrogen as an alternative to electric vehicles - especially for trucks and buses - can alleviate pressure on the electric grid. It can also power marine shipping and aviation, which are poor canidates for electrification.*

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 a quarter of transport energy usage.[50] These vehicles can be powered by fuel cells or even modified internal combustion engines. 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, similar to gasoline pumping, taking about five to seven minutes to fill a light duty vehicle. Additionally, fuel cell vehicles have a similar range to gas vehicles: 250-400 miles.[51] Because hydrogen is more energy dense and lighter than gasoline or diesel, using hydrogen fuel increases the vehicles payload capacity.

In June 2020, the California Air Resources Board (CARB) passed a rule requiring half of all commercial trucks and vans sold in the state to be zero-emissions by 2035.[52] This represents a major opportunity for development of hydrogen fuel cell vehicles powered with renewable green hydrogen.

5.5.2 MARINE TRANSPORTATION

Global shipping accounted for ~ 2% of global energy-related CO_2 emissions in 2019. 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 gas powered engine. Today, a few hydrogen-powered ferries and boats operate in the U.S. 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.

5.5 TRANSPORTATION (CONT.)

5.5.3 AVIATION

Aviation is the most carbon-intensive form of transport, globally responsible for about 2% of global greenhouse gas emissions.[54] Biofuels are one clean alternative to today's fossil-based jet fuel; however green hydrogen offers another zero-emission pathway. Hydrogen-powered fuel cell airplanes emit only water and tend to be much quieter than traditional aircraft. 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.[55]

A hydrogen plane requires a storage system to safely store liquid hydrogen, fuel cells to convert hydrogen to electricity, a device to control the power of the cells, and a motor to turn a propeller. In order to engineer and build commercial green hydrogen powered aircraft, these four areas must be developed.[56] In addition to technology development, efforts will also be required to build hydrogen fueling infrastructure at airports and create uniform safety codes and standards.

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. A synthetic jet fuel could potentially utilize existing fueling infrastructure at airports.

Europe is leading the development of hydrogen aviation. In the future, passengers will be able to fly from San Francisco to Singapore on a green hydrogen powered plane with zero emissions.

5.6 HEATING FOR BUILDINGS

Heating demand for buildings rarely aligns with the timing of renewable generation driven by 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 one of many complementary low carbon technologies, along with electrification, onsite renewables, demand reduction, heat networks, and other green gases, to provide 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 in Section 5.3.

Onsite hydrogen fuel cells can provide heat and electricity to buildings. Onsite fuel cells provide energy diversity and can be operated in "island" mode or as part of a microgrid, ensuring resiliency and continued, uninterrupted service, even when the electric grid is down.

5.7 INDUSTRIAL FEEDSTOCK

Over 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.[7]

Industrial applications for hydrogen are poised to take advantage 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 existing demand for gray hydrogen to green hydrogen is relatively straightforward pathway to lower the carbon footprint of numerous industrial processes.

5.8 AGRICULTURE

Fertilizers provide vital nutrients to plants and play a critical role in achieving high crop yields needed to feed the growing world population, soon approaching eight billion people. As the world population grows, so does demand for fertilizer. Fertilizer manufacturing is responsible for ~1% of global GHG emissions annually.[57]

The most common form of fertilizer is ammonia-based nitrogen fertilizer. Manufacturing this fertilizer requires a very energy-intensive process that combines hydrogen gas with nitrogen to create ammonia (NH3). 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 the hydrogen feedstock.[58]

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 of using local agricultural waste as an input.

As of 2019, fertilizer producers on five continents had begun feasibility studies, launched pilot demonstrations, or already re-engineered their ammonia plants to replace fossil fuel inputs with renewable hydrogen.[59] Europe's largest plant making green hydrogen for use as ammonia is currently under development in Spain and on target to be operational in 2021. The 1 GW electrolysis facility paired with a 100 MW photovoltaic (PV) plant is a partnership between fertilizer producer Fertiberia and energy company Iberdrola. The green hydrogen supply will allow Fertiberia to reduce its natural gas consumption by 39,000 tons per year. Taking into account the current price of carbon on the European Union's Emissions Trading Scheme, this project could also save Fertiberia about $1 million per year.[60]

5.9 MINING

Minerals and metals mining is responsible for 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.[61]

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.[62] RAPS face economic, operational, and environmental challenges. Economically, it is expensive to transport fuel via truck to remote communities, causing onsite mining energy costs to be as high as $440/MWh.[63] Operationally, trucking in diesel adds costs and risk 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 up to 30-40% of a mine's total energy operating costs.[64]

Green hydrogen provides a promising opportunity for mines to reduce operational costs, reduce health risks to workers, and to decarbonize their operations. 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 central Australia and the high desert plans of Chile and Bolivia.

06: VALUE PROPOSITION

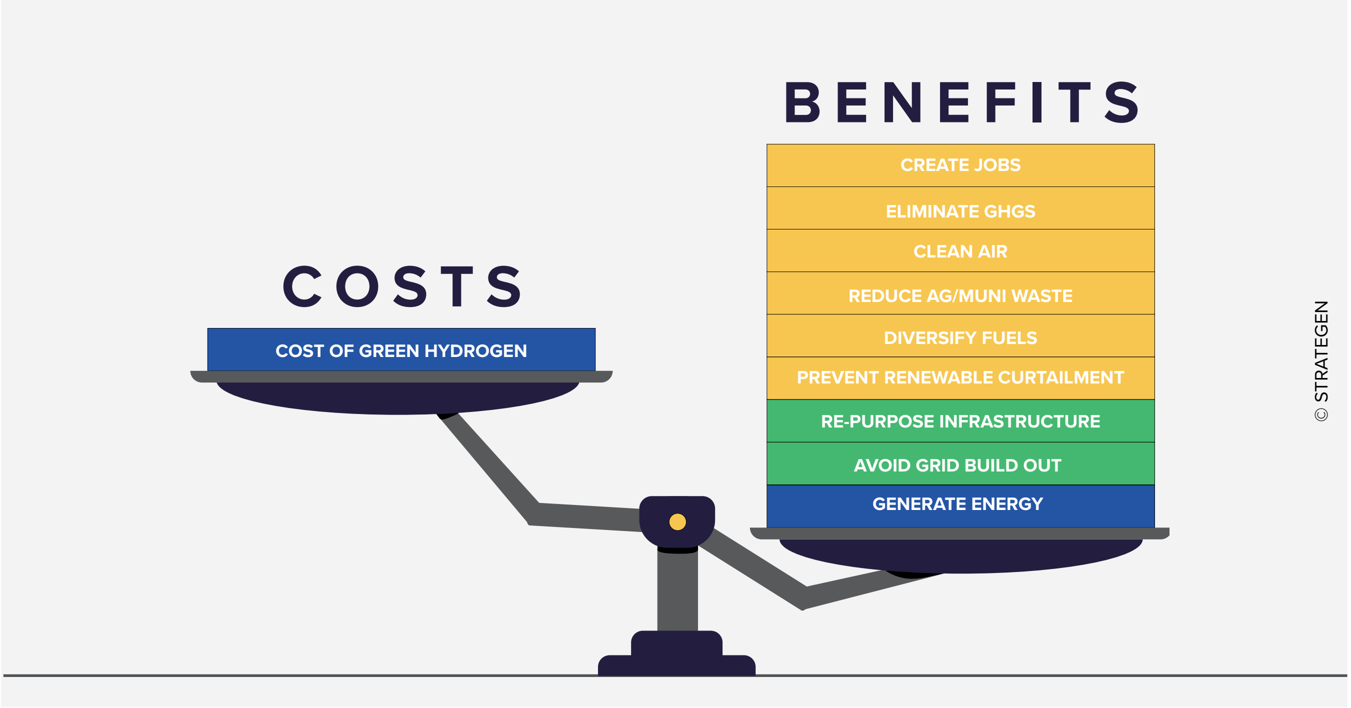
Green hydrogen is becoming cost competitive with gray hydrogen as the price of renewable inputs, fuel cells, and electrolyzers decrease. However, fully valuing and capturing all of green hydrogen's diverse and beneficial attributes will be critical in accelerating green hydrogen market development.

The International Energy Agency found that "clean hydrogen is currently enjoying unprecedented political and business momentum, with the number of policies and projects around the world expanding rapidly."[7] Rapid deployment and scale-up of green hydrogen technologies will drive down costs, allowing green hydrogen to become widely used in the near future. Going forward, it will be critical to value green hydrogen beyond simply comparing it to natural gas as a drop-in fuel replacement.

6.1 BENEFITS OF GREEN HYDROGEN

Much like conventional energy storage on the grid, green hydrogen has values 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 which would prevent expensive build out of the electric grid.

FIGURE 13:
VALUING STACKED BENEFITS OF GREEN HYDROGEN

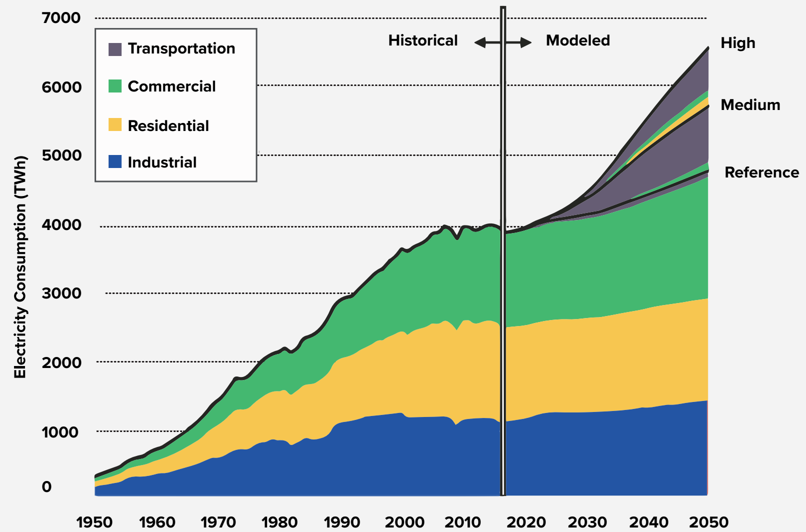


6.1 BENEFITS OF GREEN H_2 (CONT.)

6.1.1 AVOID GRID BUILD OUT

Historically, addressing grid issues such as load growth, rising peak demand, network congestion, and system reliability has been 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 such infrastructure is extremely expensive to construct. As load grows on the grid due to increasing electrification of industry and the vehicle fleet, it will cost billions of dollars to fully electrify everything. Local, onsite hydrogen generation to serve as a fuel to produce local dispatchable resilient clean electricity can reduce the need to build out costly T&D infrastructure and can be deployed more rapidly.

FIGURE 14:
HISTORICAL AND PROJECTED ANNUAL ELECTRICITY CONSUMPTION[65]



Source: National Renewable Energy Laboratory

6.1.2 REPURPOSE EXISTING INFRASTRUCTURE

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

6.1.2.1 Repurposing Gas Infastructure

To transport hydrogen, blending with natural gas would allow for the use of the existing natural gas pipeline network with minimum infrastructure investment. Using existing natural gas infrastructure offers a low-cost pathway that would promote the transition towards a green hydrogen economy by significantly scaling up hydrogen storage and use.

6.1.2.2 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 for hydrogen project development can be achieved by repowering existing natural gas and coal fired power plants with green hydrogen.

Repowering power plants with green hydrogen is feasible today, with major turbine manufacturers such as MHPS, GE, and Wartsila offering high power (800 MW+) hydrogen-ready gas turbines.

6.1 BENEFITS OF GREEN H_2 (CONT.)

GE's 9F.03 gas turbines can routinely run on 50% hydrogen and, in some specific cases, have run on up to 70-90% fuel-blend.[66] GE has 70 of these plants installed around the world that currently provide flexible energy. Additionally, MHPS has been developing high efficiency, low NOx combustion systems, which are capable of using up to a 30% hydrogen/70% natural gas fuel mixture, and has announced the capability to use 100% hydrogen in its turbines by 2025.

The Intermountain Power Project (IPP) in Delta, Utah, is demonstrating such a repowering by replacing a coal-fired power plant with a combined cycle gas powered turbine powered in part by green hydrogen. The project at IPP utilizes an MHPS gas turbine. Initially the repowered plant will run on a blend of green hydrogen and natural gas. Over time, it will increase the proportion of green hydrogen such that on or before 2045, IPP will combust 100% green hydrogen. This project is enabling carbon-free, dispatchable, renewable, utility-scale power generation to meet the needs of Los Angeles basin off-takers.[67]

6.1.3 PREVENT RENEWABLE CURTAILMENT

Curtailment is the reduction of output of a renewable resource below what it could have otherwise produced. Curtailment happens when there is insufficient energy demand for the clean energy being produced. An example of this is noontime on a temperate day, when solar production is at its peak but grid demand is not. Currently, curtailed clean energy is valued at $850/MWh in PJM[68], $9,000/MWh in ERCOT[69], and $15 to $300/MWh in CAISO.[70]

Green hydrogen production could address the uneconomic curtailment of renewables. Instead of wasting the clean energy, demand could be bolstered by electrolyzers creating green hydrogen with lowest cost energy. Matching the creation of electrolytic hydrogen production to peak clean energy generation can enable 100% utilization of solar and wind energy.

6.1.4 CREATE JOBS

Growth in the hydrogen economy will lead to a multitude of new employment opportunities. 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, from upstream, to midstream, to downstream, 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 U.S. could generate an estimated $140 billion per year in revenue and support 700,000 jobs by 2030.[71]

6.1.5 ELIMINATE GREENHOUSE GASES

Green hydrogen has a huge 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 deliver "clean molecules."

Production of large quantities of green hydrogen will play a major role in global decarbonization by providing a zero-carbon and emission-free alternative to fossil fuels. Rollout of green hydrogen technologies could offset up to one third of global greenhouse gas emissions produced by fossil fuels and industry by 2050, which would result in $148 to $765 billion in benefits based on the U.S.'s current range for the social cost of carbon.[72]

6.1.6 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.[73] Declining 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.

6.1 BENEFITS OF GREEN H_2 (CONT.)

6.1.6 CLEAN AIR FOR ALL COMMUNITIES

Passenger vehicles and heavy-duty trucks are a major source of air pollution, producing over 55% of total NOx emissions in the U.S., about 10% of VOC emissions, and 10% of particulate matter (PM) emissions.[74]

Unfortunately, too often the burden of poor air quality is concentrated in low income neighborhoods and communities of color. Replacing fossil fuels with green hydrogen and prioritizing 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.

6.1.7 REDUCE AGRICULTURAL+MUNICIPAL WASTE

Every year the U.S. produces more than 70 million tons of organic waste: livestock manure, agriculture wastes, wastewater, and food waste.[75] Improperly managed waste poses a risk to environmental and public health as chemicals present in wastes can contaminate surface and ground waters through runoff or by leaching into soils. Additionally, as they decompose, organic wastes generate large amounts of methane, a powerful greenhouse gas with a heat trapping potential 28 times greater than that of than CO_2.[76]

Fortunately, agricultural and municipal waste can be transformed from a polluting nuisance to a useful clean energy source to produce green hydrogen. Waste can be converted into carbon-neutral biogas using well understood technology such as bio-digesters. Purified biogas can be treated as 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 U.S. currently only has 2,200 operating biogas facilities. Expanding biogas production could lead to the installation of over 13,500 new systems which would result in over 335,000 temporary construction jobs and 23,000 permanent jobs.[75]

Green hydrogen produced from biogas systems can help turn the cost of waste management 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.[77] 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) provide an attractive bankable project revenue stream.

6.1.8 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 cyber attacks to planned public safety power shutoff (PSPS) events to reduce wildfire risk.

When the grid fails, fuel diversity and local generation will be necessary to support everything from critical infrastructure to residences. Onsite hydrogen fuel cells can provide heat and power to facilities that lasts for days; most customer-sited behind the meter battery-based energy storage applications can provide no more than eight hours of backup 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 down.

6.1 BENEFITS OF GREEN H_2 (CONT.)

Utilizing green hydrogen as an alternative to gasoline and diesel for mobile 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 energy sources its ultimate price will be fairly stable in the long run.

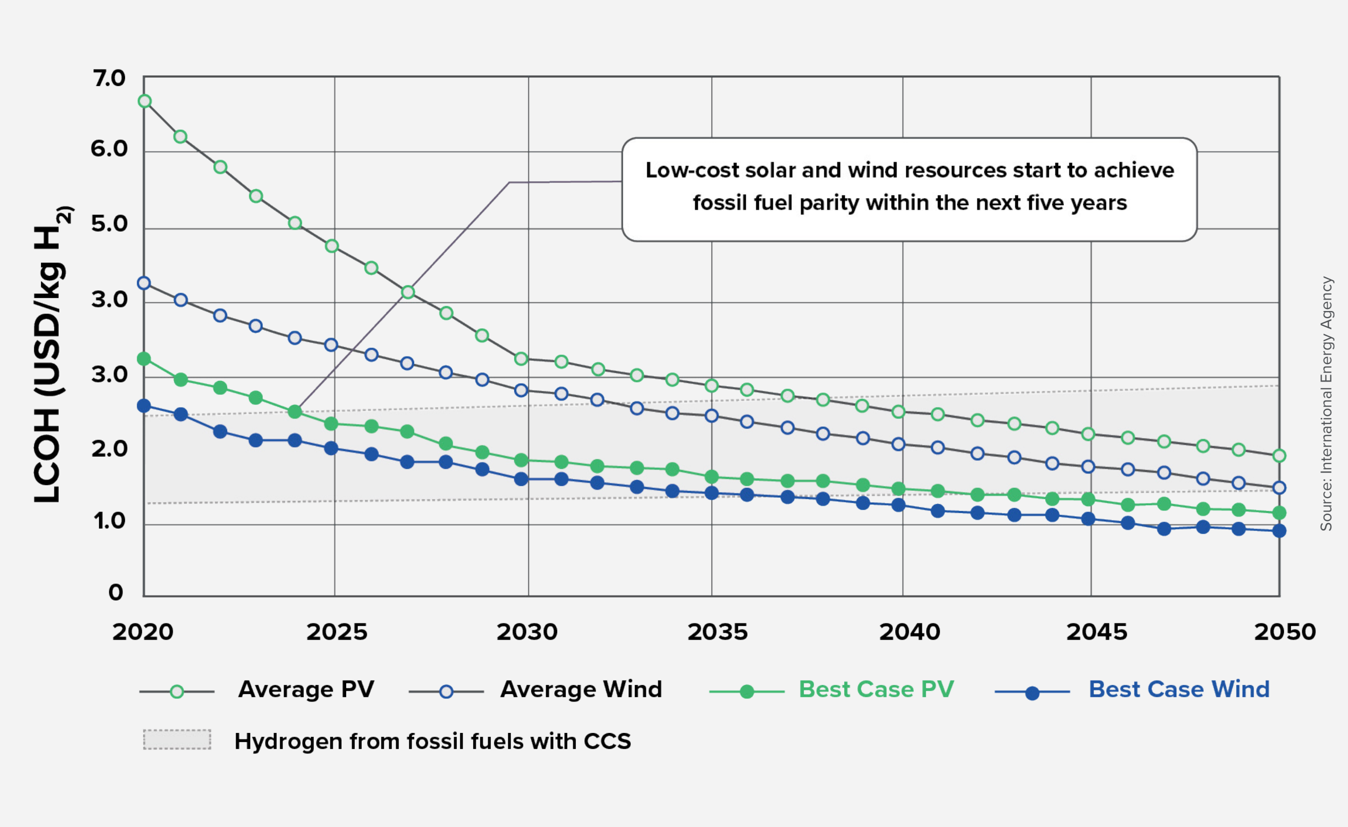
6.2 ADDRESSING COST

6.2.1 RENEWABLE ENERGY

Global cumulative installed capacity of solar photovoltaic energy and wind generation is predicted to double from 2019 to 2024.[5] As renewables proliferate their costs continue to decline which is great news for electrolytic green hydrogen production.

Growth in renewable capacity is leading to increasing mismatch between electricity supply and demand which has led to curtailment and negative power prices in some cases. Green hydrogen can help mitigate and even solve these intermittency issues while benefitting from wind and solar cost decreases. The cost of producing green hydrogen is expected to decline and begin to reach parity with blue hydrogen within the next five years.

FIGURE 15:
LEVELIZED COST OF HYDROGEN FORECAST[78]



6.2 ADDRESSING COST

6.2.2 FUEL CELLS

Fuel cells convert hydrogen gas into electricity without emitting any greenhouse gases. The fuel cell market is forecast to grow from 220 MW in 2018 to 612 MW in 2030, and in the same time period increase in value from $3.2 billion to $5.08 billion. As installed capacity increases, costs continue to fall. Costs for fuel cell systems are expected to drop 50% by 2030.[79]

FIGURE 16:
PROJECTED FUEL CELL INSTALLED CAPACITY[80]

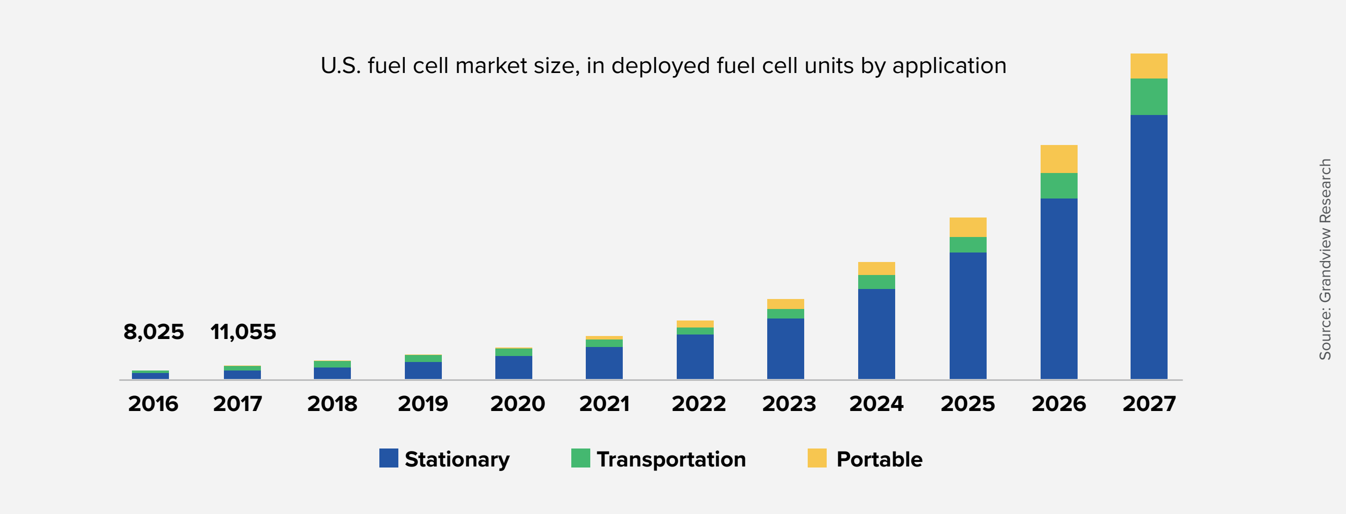
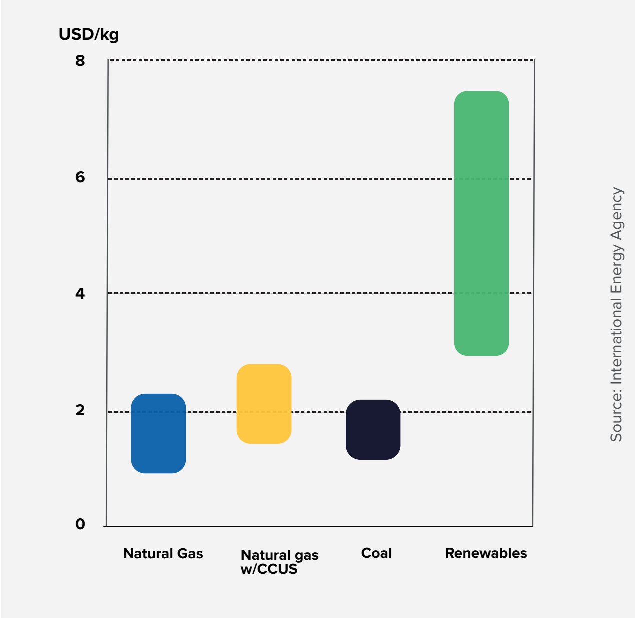


FIGURE 17:
HYDROGEN PRODUCTION COSTS BY PRODUCTION SOURCE, 2018[81]



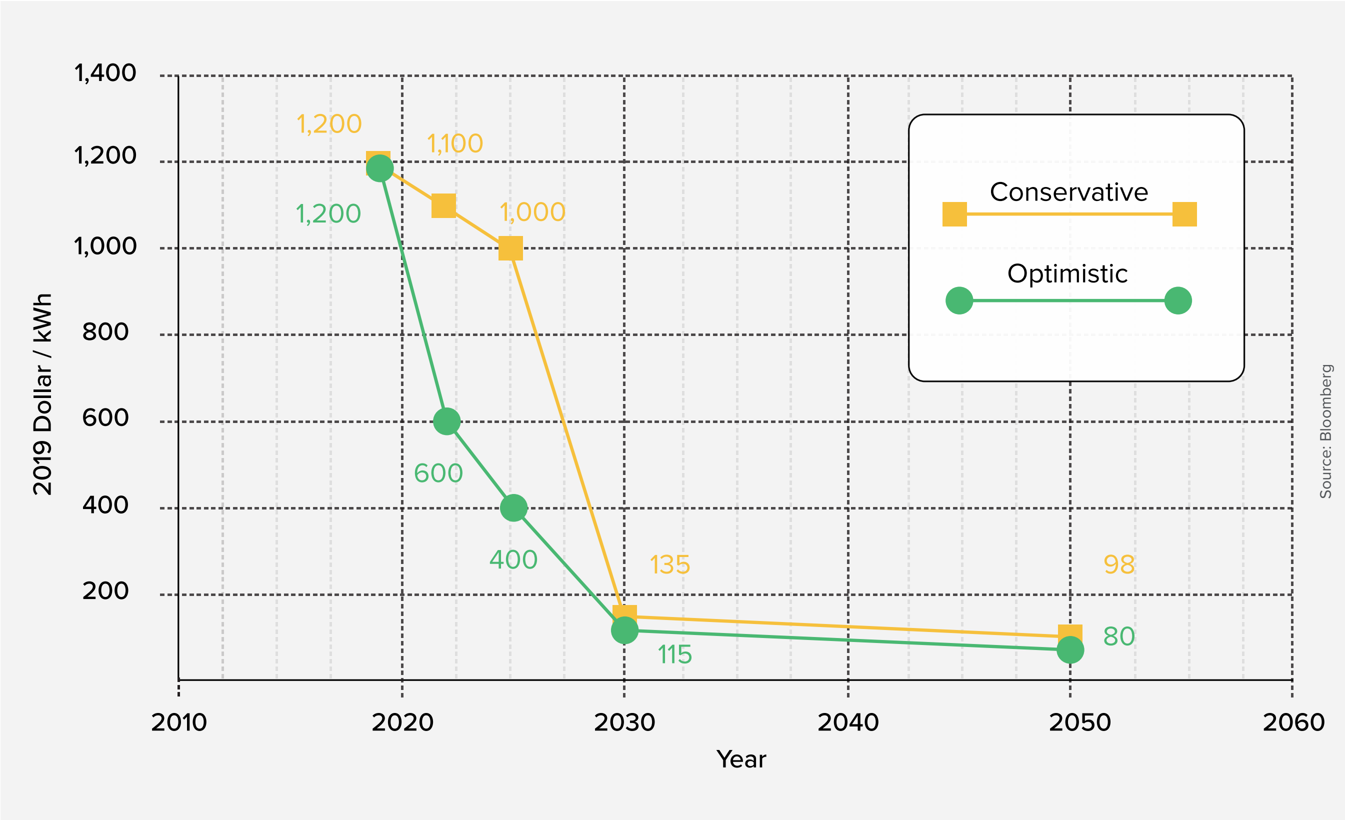
Green hydrogen is still more expensive to produce than gray, brown, and blue hydrogen, but the declining costs of renewables and value of the additional benefits that green hydrogen offers are making it cost-competitive. In the future green hydrogen has the potential to become the low-carbon and low cost source of energy.

6.2 ADDRESSING COST (CONT.)

6.2.3 ELECTROLYZERS

Electrolyzers are the devices required to produce hydrogen from water and oxygen through electrolysis. Electrolyzer costs will also come down in the near future. Costs of electrolyzers are already rapidly falling with the plethora of recently announced GW scale projects around the world and are expected to fall by an additional 50% by 2050.[78]

FIGURE 18:
PROJECED CONSERVATIVE & OPTIMISIC DECREASES IN ELECTROLYSIS COSTS[82]



07: BARRIERS AND CHALLENGES

The greatest barriers and challenges to the rapid deployment of green hydrogen lie not with the technology but with 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 gamechanger in our fight against climate change. Accelerating adoption is fundementally a market design challenge: how to achieve production and use at scale."

- JANICE LIN

FOUNDER & PRESIDENT, GREEN HYDROGEN COALITION | CEO, STRATEGEN

7.1 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 ratepayers and 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, bi-directional energy storage, and the urgent need to decarbonize energy systems is challenging this old "least cost" paradigm.

We need to change the "least cost" paradigm with a "Benefit Stacking and Compensation" approach to energy.

To explain Benefit Stacking and Compensation, a simple consumer analogy is the word processor. Thirty years ago, the dominant word processing platform was an electric typewriter, retailing for a couple hundred dollars. Today, consumers are willing to spend a more than $1,000 dollars on a laptop for their word processing needs. This is because the laptop performs word processing better than a typewriter, and provides many more benefits in addition. For example, a laptop can serve as a budget analysis tool, a platform for entertainment, and enables global connectivity via the internet. In short, today, consumers evaluate their purchasing decision for word processing on a ***net benefit*** basis, not ***least cost***.

When making infrastructure planning decisions, a more prudent approach for our energy systems would be to similarly award such decisions based on a comparison of "net benefits" instead of the traditional "least cost."

7.1 THE "LEAST COST" ENERGY SECTOR PARADIGM (CONT.)

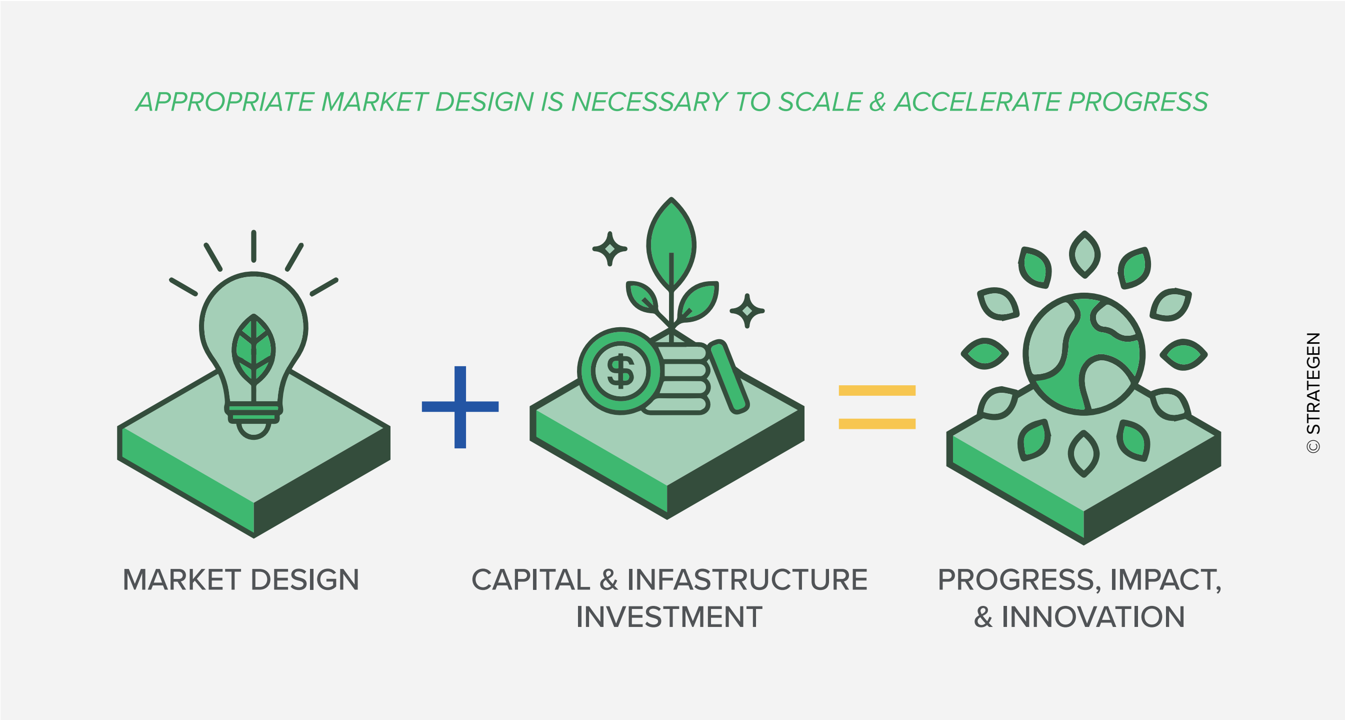
Bi-directional energy storage was the first significant technology addition to grid planning that challenged the traditional "least cost" procurement approach. Jurisdictions that recognize the benefit stacking potential of bi-directional energy storage assets- including recognizing benefits that a single asset can provide, energy arbitrage, capacity, ancillary services, and distribution deferral- are now actively procuring and deploying energy storage to achieve more flexible, resilient, stable, and affordable grid operations. Realizing the benefits of bi-directional 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 6.1). To attract investment, the benefits provided from these projects must be recognized and compensated.

Enabling compensationpathways 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 and transportation. Further, these silos were organized many decades ago and did not envision the use of such a flexible resource such as green hydrogen.

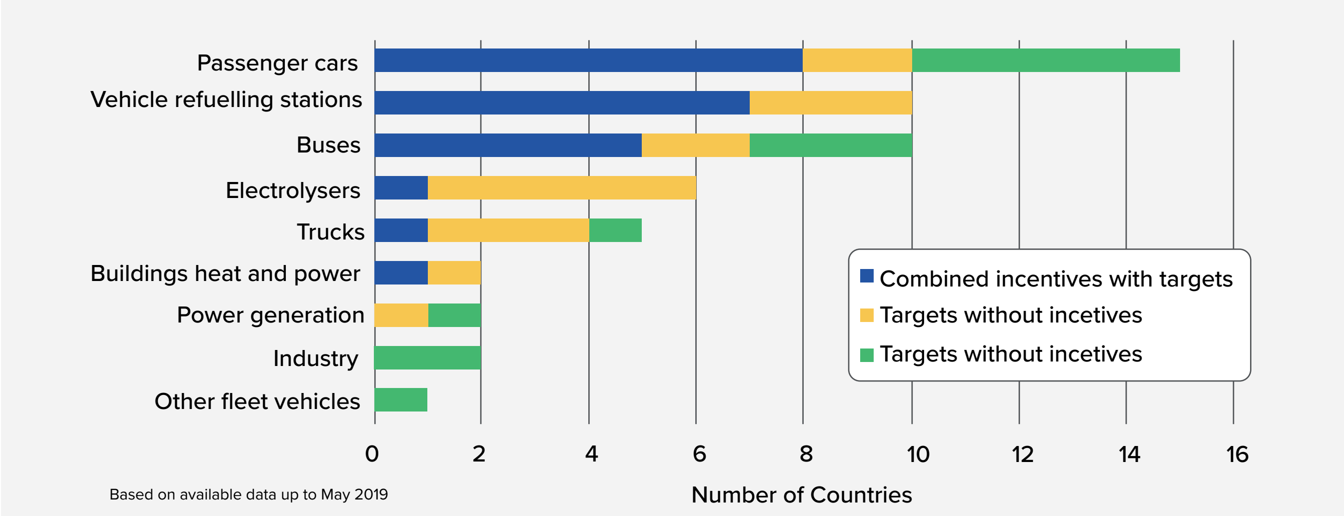
Because green hydrogen solutions are commercially available now, the best pathway to accelerate progress is smart market design. This entails aggregation of green hydrogen demand, scalability, and recognition and compensation for all the benefits provided to create a virtuous cycle that ensures ongoing investment and further cost reduction.

FIGURE 19:
THE FORMULA FOR PROGRESS



7.2 DECOUPLED GAS & ELECTRICITY SECTOR PLANNING

FIGURE 20: GLOBAL POLICIES FOR HYDROGEN DEVELOPMENT[83]



Source: IEA Analysis & Government in collaboration with IEA Hydrogen Technology Collaboration

Today, we lack the modeling tools that can help inform energy planners of the possible tradeoffs between gas and power infrastructure investments using green hydrogen. The absence of appropriate modeling and planning tools to support the consideration of green hydrogen in the electric and gas sector prevents green hydrogen infrastructure development and limits widespread adoption, including, but not limited to, pipeline access and large-scale physical storage.

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.

A key barrier to green hydrogen infrastructure development is the exclusion of multi-sectoral green hydrogen production and use opportunities in existing regulated infrastructure planning at the local, state, regional and national level.

7.3 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, falling 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 starting to happen for green hydrogen, with governments and forward thinking environmental groups, such as the Natural Resources Defense Council (NRDC), calling for the use of green hydrogen to transition away from fossil fuels.

7.3 NEED FOR LEADERSHIP, FOCUS, AND ALIGNMENT (CONT.)

"To stave off the worst effects of the climate crisis, we must urgently transition from polluting fossil fuels to emissions-free energy. "Green" hydrogen is quickly emerging as a potential solution for the sectors most difficult to electrify from clean resources –– such as aviation, marine shipping, and heavy industry –– and could help us resolve some of the biggest challenges to a fully renewable electricity system."

NRDC EXPERT BLOG POST | AUGUST 6, 2020 | RACHEL FAKHRY & ROBERT HARDING

Governments around the world are aggressively launching roadmaps and programs for green hydrogen development and export. Australia published its national hydrogen roadmap as early as 2018.[84] 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 totaling €9 billion to support the country's goal of 5GW of electrolysis capacity by 2030 and 10GW by 2040.[85] Also in June 2020, the European Union 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.[86]

Accelerating progress in the U.S. will require local, state, regional and national leadership. 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 U.S.' first significant green hydrogen project: the renewal of IPP 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.

08: POLICY AND REGULATORY RECOMMENDATIONS

Policy and regulatory innovation is essential to accelerate the deployment of green hydrogen at scale. Because the use cases for green hydrogen are so varied, the GHC recommends prioritizing policies and regulations that support near-term, large-scale infrastructure projects.

8.1 ESTABLISH NECESSARY LEADERSHIP & GOVERNANCE

Policy and regulatory innovation begins with leadership. A number of countries around the world are moving green hydrogen policies forward, often by establishing key targets that help provide important market signals to investors, developers, and utilities to pursue and accelerate the deployment of green hydrogen at scale.

8.1.1 ESTABLISH STATE AND LOCAL LEADERSHIP

In the U.S., many energy planning decisions fall under the jurisdiction of states and cities. States and cities have shown tremendous clean energy leadership in the last decade encouraging the adoption of renewable resources such as wind and solar, energy storage and low emission vehicles. U.S. states and cities have the proven ability to also lead in developing green hydrogen as a resource to decarbonize multiple sectors.

States can establish multi-agency taskforces led by an appointed agency to organize and focus relevant bodies to realize the benefits of green hydrogen as a cross cutting, multi-sectoral resource for decarbonization. Cities can similarly organize, bringing necessary leadership from municipal services in the energy, waste and transport sectors to align on specific initiatives that commercialize green hydrogen production and use at scale to displace fossil fuels.

The scope of work for state and municipal efforts could include:

- Establish and develop a legal and regulatory framework for a multi-agency taskforce that coordinates across local and state level jurisdictions and provide linkages to key ongoing and upcoming proceedings. The taskforce can lead the development of a state-level green hydrogen roadmap that identifies and prioritizes green hydrogen applications and related decarbonization targets.

- Identify and prioritize policy and regulatory barriers and relevant agencies that need to be involved to resolve these barriers. Identify new legislation as needed.

- Develop procurement targets and procurement pathways that leverage aggregated demand for green hydrogen across sectors and include compensation mechanisms for all benefits provided.

- Establish mechanisms for quantifying, tracking and compensating the full range of benefits green hydrogen can offer (See Section 6.1).

- Create stakeholder alignment by facilitating diverse stakeholder support and input from green hydrogen offtakers, ratepayer advocates, and environmental groups.

8.1 ESTABLISH NECESSARY LEADERSHIP & GOVERNANCE (CONT.)

8.1.2 CREATE A REGIONAL TASK FORCE

A collaborative regional green hydrogen task force composed of state and local leadership can provide momentum for accelerated deployment of green hydrogen at scale and provide a platform for advancing new technology innovation. It also supports creating a regional green hydrogen roadmap that identifies broad opportunities to re-purpose existing infrastructure, develop storage, enhance reliability, and realize the development of new markets and products to drive investment, jobs and decarbonization.

8.1.3 ESTABLISH AND SHARE GLOBAL BEST PRACTICES

Green hydrogen is a global phenomenon (See Appendix). Accelerated progress is possible by sharing global best practices in market and policy development, technology innovation and applications, and business models. Local, state, regional, and federal green hydrogen policy and regulatory leaders can join an informal global network of country-level government leaders.

8.2 KEY POLICY RECOMMENDATIONS

The GHC has identified specific policy recommendations that could immediately build momentum and accelerate progress for multi-sectoral production and use of green hydrogen at scale and establish pathways for deep decarbonization over the next 15-30 years.

8.2.1 DEFINE GREEN HYDROGEN BROADLY

Define green hydrogen broadly to include all pathways to produce green hydrogen (technology neutral). This broad definition will enable robust innovation and competition for supply contracts.

8.2.2 ESTABLISH EMISSIONS CERTIFICATION & TRACKING PROGRAMS

Develop emissions certification and tracking programs that enable cross-sector accounting for the emissions benefits of green hydrogen and eligibility toward meeting specific local, state and national carbon reduction and renewable energy targets.

The emissions attributes from green hydrogen represents a large, tradeable potential new certificate market, and there are entities today working to establish these types of standards. In Europe, the CertifHy organization has set the first standard for renewable hydrogen Guarantees of Origin (GO). This certificate documents both zero-emissions hydrogen (green hydrogen) and low-carbon hydrogen (blue hydrogen) and ensures that these commodities meet specific criteria in order to be traded in different European markets. In the U.S., the Green-e certification program, administered by the nonprofit Center for Resource Solutions, has announced the development of a new certification program for producers and consumers of renewable hydrogen in the voluntary renewable energy market.

As certification and standard organizations helped grow the renewable electricity market in the 1990s, baseline rules and standards will do the same for the green hydrogen market today. Standards work to unify the market, ensure consistency, establish a set of baseline criteria, and reward those who surpass that baseline. Certification is especially important in new markets to establish an accepted foundation of guidelines and rules from which to operate. This common understanding leads to increased trust and stability of the market, elevated consumer confidence, and overall market growth.

8.2 KEY POLICY RECOMMENDATIONS (CONT.)

8.2.2 ESTABLISH EMISSIONS CERTIFICATION & TRACKING PROGRAMS

Tracking the production and uses of green hydrogen is another essential policy tool that can be used to expand and support the green hydrogen market. Renewable energy in the US is either tracked by (1) electronic tracking systems, or (2) contract-path tracking, which documents the chain-of-custody from production to final consumption through the use of one or more legally enforceable contract(s). Many electronic tracking systems have developed similar rules and operating procedures, but variance exists both within countries and around the world. Global best practices include:

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

It is recommended that regulators and policymakers support electronic tracking systems in order to simplify facility registration and validation, document the production, trade, and end use of green hydrogen in one place, ensure transparency and consistency, prevent double counting, and boost integrity of the market.

8.2.3 INCORPORATE GREEN HYDROGEN INTO ENERGY SYSTEM PLANNING MODELS

A key advantage of green hydrogen is its ability to decarbonize multiple sectors. Energy system planning models can consider its use accordingly and reflect the cost advantages of aggregating demand across sectors. Procurement processes can also account for the unique advantages of green hydrogen use in meeting current system needs. A single large project with a number of contracts and a variety of offtakers will be lower cost and easier to finance.

Consider an example in the power sector: green hydrogen can be used to accelerate the retirement of natural gas for thermal electric generation. Capacity expansion and production cost modeling tools can consider green hydrogen's bulk (multi-day and seasonal) energy storage capacity and its ability to be sited and stored in congested load pockets to increase electric reliability. The modeling strategy can also account for the ability of the existing gas pipeline and other large underground and above ground storage facilities to store energy capacity. Finally, the power sector can anticipate increased load (from the electrolysis of water) and the benefits of being able to utilize and store low cost renewable energy even when there is not electric demand (i.e. prevent uneconomic curtailment).

Similarly, gas sector modeling and planning can reflect the ability of hydrogen to decarbonize the contents of the existing gas pipeline system over time and consider its use as a bulk renewable energy storage resource. Where gas system upgrades are needed, modifications to ensure safe storage and transmission of hydrogen can be routinely considered. Finally, where there are sufficient large offtake opportunities (i.e. multi-sectoral aggregated demand) concentrated in a specific geography, such as for industrial applications, power generation or decarbonizing port operations, investments in new 100% hydrogen pipeline can be considered.

The decarbonization potential of green hydrogen at scale must be part of all ongoing integrated resources energy infrastructure planning as the key to accelerate energy system decarbonization.

8.2 KEY POLICY RECOMMENDATIONS (CONT.)

8.2.4 REFORM WHOLESALE MARKETS TO INCLUDE GREEN HYDROGEN

To various degrees, wholesale electricity markets are gradually evolving to support energy storage participation models. These models should also allow the participation of electrolytic hydrogen as both a modifiable wholesale load or as a generation source (if converted to electricity). Such reforms are essential to enabling green hydrogen to access excess, low-cost renewable electricity which might otherwise be curtailed. Electricity market access also enables electrolytic hydrogen to provide valuable grid services such as ancillary services, e.g. spinning reserves, or perhaps also voltage/VAR support functions.

To illustrate, electrolysis equipment can be explicitly allowed to participate in all wholesale markets similarly to batteries- as a non-generator resource with modifiable load. In this configuration, the electrolysis can occur during period of very low power prices when renewable generation is abundant. Grid operators can also optimally schedule the loads for any electrolysis and green hydrogen energy storage assets, just as they do for the thermal fleet. In this manner, the timing of these loads is managed to best support grid reliability and efficient (low-cost) use of the electric system.

Wholesale markets can also place value on key attributes of green hydrogen, including its 'long hold' capabilities, its zero-carbon footprint, or its capacity value for helping with reliability. Many current capacity products in the 4-10-hour range are designed to reflect current grid needs, but these needs are predicted to quickly evolve as the electric system adopts more renewables. This in turn will create the need for 'very long-duration' services which would compensate green hydrogen's ability to provide multi-day and, where necessary, seasonal clean energy storage and reliability. Such compensation pathways will properly value the full range of benefits available from electrolytic hydrogen.
To enable efficient and smart power-gas sector integration, wholesale market reforms are also needed in the gas sector. Examples could include new gas standards for green hydrogen interconnection, procurement pathways and tariffs that enable the use of curtailed and purpose-built renewables for electrolytic hydrogen production, and storage in the natural gas pipeline.

8.2.5 FUND GREEN HYDROGEN RD&D

Many innovative green hydrogen technologies are commercially available today. However, additional research, development and demonstration (RD&D) is needed. Research and development in material sciences, controls, and system platforms will transform the performance, diversity, and cost profiles of green hydrogen solutions. State and national RD&D funding has played a critical role for all energy resources to date, and dedicated focus is also needed for green hydrogen.

State and federal RD&D dollars can be invested into green hydrogen project development, storage, and deployment. Areas for research include feasibility studies for the repurposing of existing natural gas pipelines and depleted oil and gas fields for hydrogen storage; advanced research on electrolysis for seawater; and software development to study the use of green hydrogen in support of ongoing integrated power and gas sector resources planning and modeling efforts.

The U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office (HFTO) currently supports hydrogen project development. Sixty-four million dollars of its $150 million 2020 budget is dedicated to providing funding for projects that demonstrate ways to scale up affordable hydrogen and fuel cell technology options and support the H2@Scale vision.

8.2 KEY POLICY RECOMMENDATIONS (CONT.)

8.2.5 FUND GREEN HYDROGEN RD&D

While funding for hydrogen is available, funding for dedicated green hydrogen research is limited.[87] For comparison, the 2020 DOE budget allocated $750M for the Office of Fossil Energy Research & Development.[88]

8.2.6 DEVELOP SECTOR-SPECIFIC TARGETS AND ROADMAPS

Transformational change requires effective alignment of broad 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.

Decarbonize the Gas Sector

Actions should be taken to proactively decarbonize the existing natural gas sector.

Recommendations to support decarbonization of the gas sector via dedicated hydrogen pipelines:

- Repurpose retired gas pipelines, where appropriate, to 100% hydrogen pipelines that can connect low cost sources of green hydrogen production at scale with high volume demand centers.
- Alternatively, find ways to leverage right of ways of existing gas pipelines to build new 100% green hydrogen pipelines adjacent to existing gas pipelines where possible.

Recommendations to support decarbonization of the gas sector by blending green hydrogen into the gas pipeline:

- Determine safe and appropriate green hydrogen blending and injection limits.
- Establish a decarbonized fuel mandate or standard for the natural gas pipeline that includes green hydrogen as part of a broader renewable gas portfolio.
- Create tariffs for gas pipeline injection and market incentives that assure green hydrogen storage access for every kilogram of green hydrogen produced.
- Consider modifications to enable increased green hydrogen pipeline content when performing scheduled pipeline upgrades and maintenance.

Decarbonize Critical Power Supplies

In the U.S., multi-day electric power outages are increasingly common. In the West, public safety power shutoffs are increasingly used to reduce the risk of wildfires from power lines damaged in windstorms. On the East and Gulf Coasts, hurricanes and severe storms cause grid damage that can take days or even weeks to address. As a result, sales of polluting backup diesel and gas generators have reached all-time highs. However, locally stored green hydrogen and onsite fuel cells can provide an alternative, zero-emission, multi-day critical backup power solution.

Utility resource planning for service interruption events should consider the use of green hydrogen with fuel cells for emergency critical backup power. Programs for consumer education and incentives for purchasing clean alternatives to diesel and gas should be developed. This solution is already being deployed at telecom stations, traffic signals and other remote power applications. With appropriate market design, green hydrogen powered fuel cells could also be routinely used to provide safe, clean emergency backup for grid tied applications.

8.2 KEY POLICY RECOMMENDATIONS (CONT.)

Decarbonize Transportation

Leadership and focus will be critical to accelerating the use of green hydrogen for a wide section of transportation applications including trucking, marine shipping, and aviation. Zero-emission vehicle mandates have been particularly effective in aligning stakeholders around a common achievable goal.

Roadmaps to decarbonize transportation applications with green hydrogen should consider opportunities to concurrently decarbonize multiple sectors (e.g. light, medium, and heavy-duty transportation) as well as consider multiple pathways to produce the green hydrogen to supply this network. Attention should be paid to not only the adoption of hydrogen-fueled vehicles but also the investment and support for green hydrogen fueling infrastructure.

Coastal shipping port regions and cities are excellent candidates to aggregate demand for green hydrogen. They are epicenters of concentrated fossil fuel use, as they must fuel thousands of diesel-fueled trucks, port operation vehicles, rail traffic, and ships, and are often closely located with airports. For example, Belgium's HYPORT of Oostende takes advantage of offshore wind and a variety of port-related offtakers to demonstrate electrolytic hydrogen production and consumption at GW scale.

Decarbonize Industrial Applications

Hydrogen is a globally traded commodity that is currently used in large volumes in several key industrial applications; namely, oil refining and manufacturing ammonia. These applications are excellent targets to decarbonize with green hydrogen, as they represent very large off-take opportunities. Special focus on these sectors, and ideally specific decarbonization targets, is needed to encourage rapid transition to green hydrogen to displace current gray hydrogen use. New industrial applications of green hydrogen are also possible, such as displacing fossil fuels for mining operations.

Decarbonize Oil Refining

Oil refining represents the single largest use of gray hydrogen today. Setting targets to require oil refining operations to utilize increasing percentages of green hydrogen increasing to 100% green hydrogen by 2050 would establish a clear decarbonization pathway to this large industrial application.

Decarbonize Green Ammonia and Green Fertilizer

After oil refining, the second largest industrial use of gray hydrogen as commodity feedstock is for the production of ammonia.[7] The majority of the ammonia manufactured today is used to make fertilizer. Agricultural regions in California and the Midwest U.S. can decarbonize their agricultural sector and create local jobs by requiring that an increasing percentage of fertilizer be made from green ammonia, gradually increasing this target to 100% by 2050.

A focused effort involving a variety of ecosystem stakeholders can accelerate this progress through work with:

- Municipal recycling entities to produce green hydrogen and reduce organic waste in landfills.
- State level agricultural agencies to develop low carbon food branding for consumers.
- Agricultural producers to stop open field burning of agricultural waste and instead utilize it as a valuable resource to produce local green hydrogen (for fertilizer and transport) to create local skilled jobs and establish a sustainable circular economy.
- Ammonia and fertilizer supply chain stakeholders to facilitate access to carbon markets and the development of local green hydrogen and ammonia and fertilizer production.

8.2 KEY POLICY RECOMMENDATIONS (CONT.)

8.2.6 DEVELOP SECTOR-SPECIFIC TARGETS AND ROADMAPS

- Ammonia and fertilizer supply chain stakeholders to facilitate access to carbon markets and the development of local green hydrogen and ammonia and fertilizer production.

Decarbonize Mining

Remote mining sites are excellent candidates for green hydrogen, as are other Remote Area Power Systems (RAPS) which often rely on diesel fuel for their varied energy needs.

Green hydrogen provides a promising opportunity for mines to reduce operational costs, reduce health risks to workers, and to decarbonize their operations. 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 central Australia and the high desert plans of Utah, Chile and Bolivia.

Setting targets to decarbonize mining operations and RAPS with green hydrogen can be an effective mechanism to rally the necessary ecosystem partners to commercialize effective solutions at scale and at a competitive price to status quo fossil alternatives.

09: CONCLUSION

Green hydrogen is a gamechanger in the fight against climate change.

The versatility of green hydrogen as a carbon-free renewable fuel can be leveraged across multiple energy intensive sectors. Green hydrogen offers decarbonization pathways for power generation, high temperature industrial processes, transportation, agriculture, mining, heat for buildings, seasonal energy storage, and beyond.

In particular, green hydrogen is uniquely suited to provide seasonal, grid-scale, low-cost bulk energy storage. A 100% clean energy future will rely on intermittent and variable renewable resources balanced by energy storage technologies, including dispatchable, clean, green hydrogen to support year-round grid reliability and resiliency.

The expansive use cases for green hydrogen can provide immense value to local communities through reducing waste and pollutants, repurposing existing infrastructure, and creating well-paying, skilled, and sustainable clean energy jobs.

Hydrogen is a proven, safe, and globally traded commodity that is ready to serve diverse sectors today. Countries such as Australia, Germany, Japan, and South Korea already have explicit targets for the use of hydrogen or hydrogen-based fuels in their power sectors. Ambitious clean energy and greenhouse gas reduction targets aimed to limit the use of fossil fuels could accelerate the deployment of green hydrogen all over the world.

Currently, green hydrogen is more expensive to produce than other colors of hydrogen. However, costs are expected to decline dramatically, and quickly as large projects are deployed at scale. Very favorable cost projections are attracting the interest of governments and investors who understand the value proposition and stacked benefits green hydrogen offers, including its ability to avoid grid buildout, repurpose infrastructure, reduce greenhouse gases and air pollution, and diversify fuels.

Proactive policies can significantly contribute to the growth of the green hydrogen market. Helpful policies can include support for regional collaboration, funding for pilots and RD&D, eliminating regulatory barriers, scaling up the hydrogen value chain to reduce costs, and setting explicit targets for the use of hydrogen as an alternative to existing energy services across multiple sectors. Shifting the energy planning paradigm from a "least cost" approach to a "benefit stacking and compensation" approach can further make green hydrogen an attractive investment, particularly if demand can be aggregated across applications and sectors.

Green hydrogen is truly a gamechanger for our economy and our planet. The pathways to produce and use green hydrogen are commercially ready today. Green hydrogen's ability to displace fossil fuels and fight climate change is only limited by ourselves. We must focus and work together to build the momentum that will ultimately allow green hydrogen to participate, be recognized, and compensated for all its benefits. The opportunity is immense, and the stakes are high.

FUNDING AND SUPPORT MATTER IN THE FIGHT FOR OUR CLIMATE AND A CLEAN ENERGY FUTURE. SIGN UP FOR NEWS FROM THE GREEN HYDROGEN COALITION (GHC) AND DONATE.

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APPENDIX: GLOBAL GREEN HYDROGEN AT SCALE PROJECT LIST

There are many use cases around the world that exemplify the qualities and impact of hydrogen technologies in the power sector.

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 the country's export potential.[1]

The government has dedicated substantial funding to support hydrogen-powered projects. Both for renewable hydrogen, the Clean Energy Finance Corporation (CEFC) is administering a AUS-$300m "Advancing Hydrogen Fund," and ARENA has recently opened a AUS$70m funding round.[2]

H2-Hub is a proposed multi-billion 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 project is now moving into the planning phase. The project is targeting approvals by 2023 and operation in 2025.[3]

The Port Lincoln Green Hydrogen Project under construction in Australia 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 micro-grid which will be utilized by local aqua agriculturists who have been affected by ageing back-up power generation.[4]

Austria

A 6 MW green hydrogen pilot production facility began operations 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 its CO_2 emissions.[5]

Belgium

In Belgium, a green hydrogen project called HYPORT Oostende was lunched 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 off-shore wind capacity by 2025. A demonstration project with a 50 MW electrolyzer is already scheduled.[6]

Canada

Macquarie Capital is financing a plant producing 60 tons/day of green hydrogen in Canada. A dedicated wind project will supply the energy for the plant and the waste heat from the electrolyzer will be used in greenhouses. The produced green hydrogen is to be injected into the natural gas pipeline at 3% by volume.[7]

Denmark

A 2 MW electrolysis plant yet to be built was awarded $5 million in funding from Denmark's Energy Technology Development and Demonstration Program (EUDP). The plant will use electricity from two 3.6 MW offshore wind turbines to produce renewable hydrogen for buses, trucks and potentially taxis.[8]

APPENDIX (CONT.)

Germany

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

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 a newly developed pipeline technology. The hydrogen storage cavern system would provide a continuous stream of green hydrogen for industrial use.[10]

Japan

Targets in Japan focus on the growth of the FCEV market. The government aims to have 800,000 FCEVs in the country by 2030 and 320 refueling stations by 2025. So far, the government has dedicated over $1 billion to technology R&D and subsidies.[11]

The Fukushima Hydrogen Energy Research Field (FH2R) was completed in early 2020 and is claimed to be the world's largest facility yet for green hydrogen production. Partners including Toshiba, Tohoku Electric Power and Japan's New Energy and Industrial Technology Development Organization (NEDO) state that the system can produce up to 100kg of hydrogen an hour. A 20MW solar array is backed up by renewable power from the grid to run a 10MW electrolyser and produce green hydrogen. The project is to be used as a pilot for mass production of green hydrogen, with initial output directed to fuel hydrogen cars and buses in Japan.[12]

Netherlands

The "Government's Vision on Hydrogen" sends a clear signal emphasizing the importance of zero-carbon hydrogen and introduces the goal of 500 MW of installed electrolysis capacity by 2025. The government plans to allocate €35 million/year to support green hydrogen development.[13]

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 use only green hydrogen in the long-term. This is part of a large national effort to transition towards a green hydrogen economy.[14]

Shell and Gasunie are partnering to build NorthH2, a green hydrogen project powered by up to 10GW 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.[15]

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.[16]

APPENDIX (CONT.)

Saudi Arabia

In July 2020, Saudi Arabia announced plans to build a massive green hydrogen facility to power Neom, a new Saudi mega-city planned near Saudi Arabia's 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-around 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. The hydrogen produced can be shipped globally as ammonia and then converted back to hydrogen. Production is expected to begin in 2025.[17]

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.[18]

Spain

Two Spanish companies, the fertilizer producer Fertiberia and the energy firm Iberdrola, a fertilizer producer and energy firm, respectively, plan to build a facility with the capacity to produce 720 metric tons of green hydrogen annually for ammonia production. The project will feature a 100MW 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.[19]

Sweden

HYBRIT is a long-term Swedish project attempting to decarbonize the steel industry by replacing coal with green H_2. A pre-feasibility study was conducted 2016-2017 and construction began in 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 who 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.[20]

United States

The Intermountain Power Plant (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 (LADWP) plans to store the hydrogen in natural underground salt caverns and provide California residents power through the existing interconnection of IPP to the Los Angeles basin. The conversion process requires the coal plant first be converted to natural gas, then gradually blend with increasing proportions of green hydrogen. There is a planned conversion to a 30% hydrogen blend by 2025, with the ultimate goal of reaching 100% green hydrogen by 2045. The goal is to leverage curtailed and low-cost purpose-built wind and solar energy to produce green hydrogen, store it onsite and use it in place of natural gas at IPP; ultimately enabling carbon-free, dispatchable electric generation.[21]

Through its Florida Power & Light utility, NextEra is proposing construction of a $65 million, 20MW green hydrogen pilot plant in Florida where electrolyzer will be powered by solar 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-gigawatt Okeechobee gas-fired plant. If approved by state regulators, the project could be online by 2030.[22]

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