Hydrogen Handbook

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CALIFORNIA HYDROGEN BUSINESS COUNCIL

Table of Contents

01 Introduction

CHBC is invested in commercializing hydrogen as a climate-friendly energy carrier.

1.1 About CHBC

California Hydrogen Business Council (CHBC) is a trade association working to commercialize hydrogen and fuel cell technology to meet California's climate, air quality, and decarbonization goals. We work with a wide array of organizations across the industry — in California and beyond — advocating for the use of hydrogen and fuel cell technology in the energy and transportation sectors.

1.2 About the Handbook

CHBC believes that hydrogen is essential to achieving a clean and sustainable energy future. This guide will provide details, explaining why hydrogen is so necessary in our energy transition from using fossil fuels, for energy services.

California is setting bold climate goals, with Los Angeles hoping to reach 100% renewable power by 2045, and other cities in the state following closely behind. Hydrogen will be a key component of this transition, as a method of storing and distributing renewable and low-carbon intensity power.

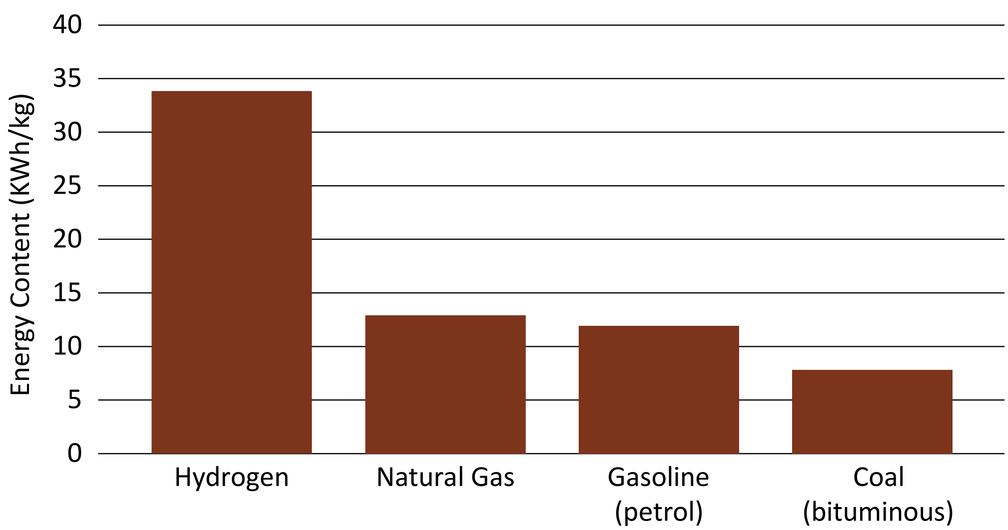
1.3 What is Hydrogen?

Hydrogen is the most abundant element in the universe, largely present in molecules like water and methane. By breaking the chemical bonds in these molecules, molecular hydrogen (H_2) can be produced, and subsequently used as a fuel.

Hydrogen can be produced in several different ways, including low-carbon pathways. The global implementation of hydrogen and fuel cell technology would allow every region of the world to have the potential to produce its own zero-emission fuel, ultimately benefiting the environment and local economies.

Hydrogen gas contains more energy per mass than traditional fuels, with twice that of methane (natural gas) and nearly three times as much energy as gasoline.[1] (Figure 01)

Figure 01: Energy Content of Fuels[2]

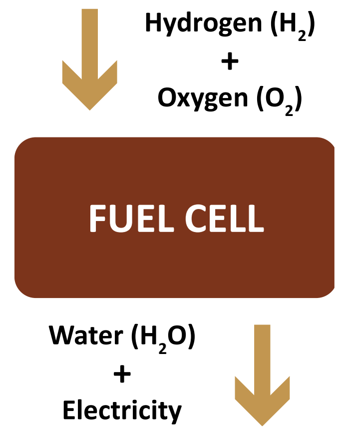


Historically, hydrogen gas has been used as an industrial feedstock in refining or chemical processes. These markets are fairly well established, with over to 70 million tons of hydrogen produced globally every year.[3] Producing this hydrogen emits 830 million tons of carbon dioxide annually — as much CO_2 as the entire country of Germany.[4] As hydrogen markets expand, low-carbon intensity hydrogen will become cheaper and these emissions, along with those in other sectors, will be reduced and eventually eliminated.

Today, with developing technology, hydrogen can be used for a variety of applications: vehicles, stationary power, renewable energy storage and battery-like portable power. Hydrogen has the potential to decarbonize these sectors at a competitive price as the technology to produce, store and distribute low carbon-intensity hydrogen scales up.

Simply put, hydrogen is an abundant, safe, potentially zero-emission energy carrier that will be essential in reducing carbon emissions. Along with decarbonization, developing hydrogen and fuel cell technology will create green jobs, support a sustainable energy economy and improve the resilience of our electricity grid.

1.4 What is a Fuel Cell?



Hydrogen generates electricity when used in a fuel cell: an electrochemical device that converts hydrogen (fed into the cell as a fuel) and oxygen (taken from the air) into water and electricity. This is done through a series of oxidation-reduction reactions.

A single fuel cell, running less than 1 V DC, does not provide a significant amount of electricity. To power a vehicle or to produce large amounts of power, multiple cells are connected in series to form a fuel cell stack.

Three of the most common fuel cells are: proton exchange membrane (PEM), used to power fuel cell electric vehicles (FCEVs); alkaline fuel cells; and solid oxide exchange fuel cells. Each of these cells consist of two electrodes separated by an electrolytic membrane. The primary difference in types of fuel cells is in the electrolyte separating the electrodes — different electrolytes transport different ions, facilitating distinct oxidation-reduction reactions.

PEM Fuel Cells

1. A Polymer Electrolyte Membrane (PEM) fuel cell, also known as a proton exchange membrane fuel cell (PEM), makes use of a proton-conducting polymer electrolyte membrane to generate electricity. PEM fuel cells operate at relatively low temperature, typically less than 80°C. Hydrogen is fed into one electrode, the anode, where it is split by the catalyst into a proton (H^+) and an electron.
   $H_2 \longrightarrow 2e^- + 2H^+$
2. Oxygen gas is held in the other electrode, the cathode; the two are separated by the polymer electrolytic membrane, which can only conduct positively charged molecules. The protons move through the membrane, reaching oxygen at the cathode. When the electrons reach the cathode, they recombine with the protons and oxygen to form water.
   $O_2 + 4H^+ + 4e^- \longrightarrow H_2O$
3. A wire is placed connecting the two electrodes closes the circuit, creating an electric current.

Alkaline Fuel Cells

Alkaline fuel cells use a relatively high pH solution of potassium hydroxide in water as their electrolyte. They can operate over a wide temperature range, typically 0 - 90°C, and can achieve efficiencies of 70%, higher than other fuel cells.

1. Hydrogen is fed into the cell at the anode, where it is oxidized with hydroxyl ions from the electrolytic membrane.
   $H_2 + 2OH^- \longrightarrow 2H_2O + 2e^-$
2. Water exits at the anode, and the electrons travel through an external circuit (wire) to the cathode, creating electricity. At the cathode, oxygen enters the cell. It reacts with water and is reduced with the electric current.
   $O_2 + 4e^- + 2H_2O \longrightarrow 4OH^-$
3. Hydroxide ions travel through the electrolyte to the anode, closing the circuit.

Molten Carbonate Fuel Cell

A molten carbonate fuel cell (MCFC) uses an alkali carbonate melt (sodium, potassium, or lithium salts, Na_2CO_3, K_2CO_2, or Li_2CO_3), or a combination of alkali carbonates that is retained in a ceramic matrix as electrolyte. An MCFC operates at between 550 - 650°C where the alkali carbonates form a highly conductive molten salt with carbonate ions (CO_3=) providing ionic conduction through the electrolyte matrix.

1. At the anode, hydrogen is fed into the cell and is oxidized with the carbonate ions as follows:
   $CO_3^{2-} + H_2 \longrightarrow H_20 + CO_2 + 2e^-$
2. Water exits and some of the CO_2 is recycled to the cathode compartment, while the electrons contribute to the external flow of electric current.
3. At the cathode, air is fed into the cell and the oxygen in air is reduced with the CO_2 as follows:
   $\frac{1}{2} O_2 + CO_2 + 2e^- \longrightarrow CO_3^{2-}$

   Molten carbonate fuel cells can also produce electricity from hydrocarbon fuels, like natural gas and biogas. This process, however, is not zero-emission — it produces carbon dioxide in proportion to efficiency and fuel renewable content.

Phosphoric Acid Fuel Cell

A phosphoric acid fuel cell (PAFC) uses a liquid phosphoric acid (H_3PO_4) electrolyte. A PAFC operates at between 150 - 250°C.

1. At the anode, hydrogen is fed into the cell and is oxidized to produce hydrogen ions (H^+) as follows:
   $H_2 \longrightarrow 2e^- + 2H^+$
2. The electrons contribute to the external flow of electric current.
3. At the cathode, air is fed into the cell and the oxygen in air react with the hydrogen ions and electrons to produce water as follows:
   $O_2 + 4H^+ + 4e^- \longrightarrow H_2O$

Phosphoric acid fuel cells can also produce electricity from hydrocarbon fuels, like natural gas and biogas. This process, however, is not zero-emission — it produces carbon dioxide in proportion to efficiency and fuel renewable content.

Solid Oxide Fuel Cell

A solid oxide fuel cell (SOFC) uses a solid ceramic electrolyte instead of liquid electrolyte and operates at high temperatures, typically between 500 - 1,000°C.

1. At the anode, hydrogen is fed into the cell. It oxidizes with O^{2-} ions from the electrolyte.
   $O^{2-} + H_2 \longrightarrow H_2O + 2e^-$ —
2. Water exits, electrons travel through the external circuit to the cathode, creating electric work. Oxygen is fed into the cell at the cathode, where it is reduced by the electrons
   $\frac{1}{2} O_2 + 2e^- \longrightarrow O^{2-}$
3. O^{2-} ions travel back through the electrolyte to the anode, continuing the process.

Solid oxide fuel cells can also produce electricity from hydrocarbon fuels, like natural gas and biogas. This process, however, is not zero-emission — it produces small amounts of carbon dioxide in proportion to efficiency and fuel renewable content.

1.5 Why Hydrogen?

Hydrogen is a sustainable replacement for conventional fuels for several reasons. As a fuel, it is as versatile and scalable as fossil fuels, can be produced from almost any energy resource, and can be used in practically any energy service application. Producing electricity from hydrogen in a fuel cell is a zero-emission process.

Hydrogen-based synthetic fuels, hydrogen combustion engines, and blending hydrogen into existing fuels can also reduce or eliminate emissions from across a variety of applications.

Hydrogen also addresses several other environmental concerns. Fuel cells are much quieter than traditional engines, and don't contribute to noise pollution. Since fuel cells are zero-emission (excluding water), using them also reduces particulate pollutants and harmful NO_x emissions. This is particularly important in California, where air quality is a serious concern.

Bulk storage of hydrogen is simple, relatively inexpensive, and is a means of capturing energy from solar and wind power. One of the primary challenges with wind and solar is finding a means to harness and store this power, in order to balance the energy variances occurring on a daily and seasonal basis. Storing hydrogen in bulk could solve this problem.

Using hydrogen also reduces dependance on petroleum imports, since it can be produced from indigenous resources.

02 Hydrogen Production

H_2 can be produced in a multitude of ways, which vary in carbon intensity.

2.1 Electrolysis

Electrolysis uses electricity to split water into oxygen and hydrogen, essentially reversing the process that occurs in a fuel cell. This electricity input can range from burning fossil fuels to solar or wind power, wherein electrolysis can produce hydrogen with zero emissions. In electrolysis, an electric current passing through the cell generates oxygen at the anode (positive electrode) and hydrogen at the cathode (negative cathode). The two gasses, kept separate by a membrane, are then collected.

There are three primary types of electrolyzers, corresponding to the three types of fuel cells: alkaline, PEM, and solid oxide. (Figure 02) The difference between these types largely lies in the use of different electrolytes, which facilitate different redox reactions.

Alkaline Electrolyzers

Alkaline electrolyzers are the most mature electrolyzer technology, with the highest efficiencies of current technology and lowest capital costs.[5] Alkaline electrolyzers use a liquid alkaline electrolyte, typically potassium hydroxide, that allows for the transport of hydroxyl ions (OH^-) from cathode to anode. At the cathode, water is fed in and oxidized using an electric current, producing hydrogen and hydroxyl ions:

$$2H_2O + 2e^- \longrightarrow H_2 + 2OH^-$$

The hydroxyl ions flow through the electrolyte to the anode. At the anode, these ions are oxidized via the following reaction:

$$2OH^- \longrightarrow \frac{1}{2} O_2 + 2e^- + H_2O$$

The electrons then travel via external circuit through the external power source to the cathode, closing the circuit.

PEM Electrolyzers

PEM electrolyzers are currently in early commercial adoption, have higher capital costs than alkaline electrolyzers and lower efficiencies[6]. In these cells, water is fed in at the anode, where it is oxidized in the following reaction:

$H_2O \longrightarrow O_2 + 4H^+ + 4e^-$

Oxygen exits, electrons travel along external path, protons travel through membrane to cathode. At the cathode, protons and electrons recombine to form molecular hydrogen, which exits:

$2H^+ + 2e^- \longrightarrow H_2$

Solid Oxide Electrolyzers

Solid oxide electrolyzers are the newest electrolyzer technology, still in the research and development stage. Capital costs for these electrolyzers are currently much higher than alkaline or PEM electrolyzers, but solid oxide electrolyzers have the capacity for higher efficiencies when combined with a high temperature heat source such as a high temperature thermal power plant[7]. At the cathode, water is fed into the cell, where it is reduced:

$H_2O + 2e^- \longrightarrow O^{2-} + H_2$

O^{2-} ions travel through solid oxide from cathode to anode where hydrogen is produced and molecular hydrogen exits. At the anode, O^{2-} ions from solid oxide membrane are oxidized and oxygen is generated:

$O_2 \longrightarrow \frac{1}{2} O_2 + 2e^-$

Oxygen exits and electrons travel along the external path, to the cathode.

Figure 02: Electrolyzer Comparison[8]

	Alkaline	Proton Exchange Membrane	Solid Oxide Exchange
System Efficiency (kWh/kg H_2)	50 - 78	50 - 83	45 - 55
Capex ($/kW)	500 - 1,000	700 - 1,400	2,000+
Market Stage	Mature	Early Market	R&D

Electrolysis in Action

In January of 2017, Hydrogenics and StratosFuel began construction of a facility that will store wind and solar power as compressed hydrogen. Using Hydrogenics' (now Cummins') PEM electrolyzers, it will be the largest zero-emission hydrogen production facility in North America.[9]

Air Products announced plans to build a green hydrogen facility to support California net-zero goal by 2023, with 10 metric tons by day production.[10]

In 2021, Plug Power announced plans to build a production facility in Fresno County, CA, which will produce 30 metric tons of liquid green hydrogen daily.[11]

Arches, a collaboration of University California, equipment suppliers, and community stakeholders has been created to respond to the Regional Clean Hydrogen Hub solicitation issued by US DOE, which will award up to $2 billion in funding for creation of a hydrogen hub which includes a minimum of 50 Mt/d hydrogen supply capacity.

These activities lead the way for larger green hydrogen projects, making it a key facilitator of California's sustainability goals, particularly SB 100 and SB 1505, which mandate that 33% of hydrogen used in fuel cell vehicles be produced by using renewables.

2.2 Steam Methane Reforming

Steam Methane Reforming (SMR) is a means of producing hydrogen from natural gas. Methane, found in natural gas, is reacted with steam to produce carbon dioxide and hydrogen. The carbon dioxide produced in this reaction can be sequestered, limiting emissions.

Non-sequestered SMR produces roughly 10 - 12 kg CO_2/kg H_2, while sequestered SMR produces about 1 - 6.[12] 95% of all hydrogen today is produced using SMR, primarily because it is currently the most cost-effective method.[13]

How It Works

First, high pressure and high temperature steam is reacted with methane.

$H_2O + CH_4 + \text{heat} \rightarrow CO + 3H_2$

Then, carbon monoxide is reacted with water in a water-gas shift reaction.

$CO + H_2O \rightarrow CO_2 + H_2 + \text{heat}$

The carbon dioxide is then removed using pressure swing adsorption, or by amine extraction, leaving pure H_2. Giving the net reaction

$2H_2O + CH_4 + \text{heat} \rightarrow CO_2 + 4H_2$

Pressure swing adsorption (PSA) is a gas separation technique. At high pressures, different gases are attracted to solid surfaces with different intensities. PSA uses this fact, passing a high-pressure gaseous mixture through a bed of solid adsorbent. One of the gases is adsorbed more strongly, remaining on the surface of the solid, and the mixture leaving the bed is enriched in the other gas, hydrogen. The bed is then regenerated, CO_2 is released, by lowering the pressure.

2.3 Thermochemical Conversion

2.3.1 Methane Pyrolysis

Methane pyrolysis is a relatively new technology that uses the thermal decomposition of methane to produce hydrogen in a low emission process. Pyrolysis involves heating methane in a reactor until it decomposes into solid carbon, which is then sequestered, and hydrogen.

$$CH_4 + \text{heat} \rightarrow C\,(s) + 2\,H_2$$

This process can be zero emission, depending on the source of the energy used to heat the reactor. This heat can come from burning natural gas, renewable electricity, or using some of the hydrogen that the reactor produces. Depending on the source of this energy, methane pyrolysis can range from zero emission to a roughly 75% decrease in emissions compared to SMR.[14] This process is still being commercialized and will require more development to be cost-competitive with other, more mature technologies.

2.3.2 Gasification

Gasification is the process of breaking down organic materials (coal, biomass, etc.) into hydrogen and other products. This occurs by reacting the feedstock at high temperatures — above 700°C — with a controlled amount of oxygen and steam.

Organic/biogenic feedstock for gasification is practically unlimited, and even waste products can be used to produce hydrogen in this process. Gasification emissions vary depending on the material broken down: for example, biomass growth is carbon negative in nature, so breaking it down naturally produces less carbon than breaking down a material like coal, which emits 50 - 100% more carbon dioxide as non-sequestered SMR.[15]

Gasification typically begins with dehydration: all water is removed from the feedstock, which is then heated to high temperatures in the gasifier. This breaks down the organic material's weaker bonds, releasing gases like hydrogen and methane, and leaving behind a solid called char, primarily composed of solid carbon. The gases and some of the char then react with a limited amount of oxygen to form carbon dioxide and carbon monoxide in the following exothermic reactions:

$$C + \frac{1}{2} O_2 \rightarrow CO$$

$$CO + \frac{1}{2} O_2 \rightarrow CO_2$$

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$$

The remaining char then reacts with carbon dioxide and steam:

$$C + CO_2 \leftrightarrow 2CO$$

$$C + H_2O \leftrightarrow CO + H_2$$

The reversible reaction from methane pyrolysis also occurs:

$C + 2H_2 \rightarrow CH_4$

A mixture of carbon dioxide, methane, carbon monoxide and steam then remains. The same methane water-gas shift reactions from SMR occurs simultaneously, in both directions. The conditions of the gasifier determine the composition of the final gas, known as syngas.

$CO + H_2O \leftrightarrow CO_2 + H_2 + heat$

$H_2O + CH_4 + heat \leftrightarrow CO + 3H_2$

The net reaction for hydrogen production is:

C + 2H 2O $\rightarrow$ CO_2 + 2H_2

Other side reactions occur due to the compounds other than carbon contained in the char, like sulfur and nitrogen. The concentrations of these elements are small enough that they have practically no effect on the final syngas composition.

2.3.3 Anaerobic Fermentation

This process also generates hydrogen from waste biomass, such as food waste and agricultural waste by using bacteria.

2.3.4 Production Costs

Currently, clean hydrogen costs roughly $5 per kilogram at the point of production. For this to be cost competitive with gasoline (from a $/mile perspective) it should be around $1/kg. The DOE has a goal of reaching this by 2030.[16] The price of hydrogen is determined by three factors: operations and maintenance; capital costs and feedstock costs, which are electricity costs; and/or biomaterials. For electrolysis, this means access to low-cost electricity, particularly renewable electricity.

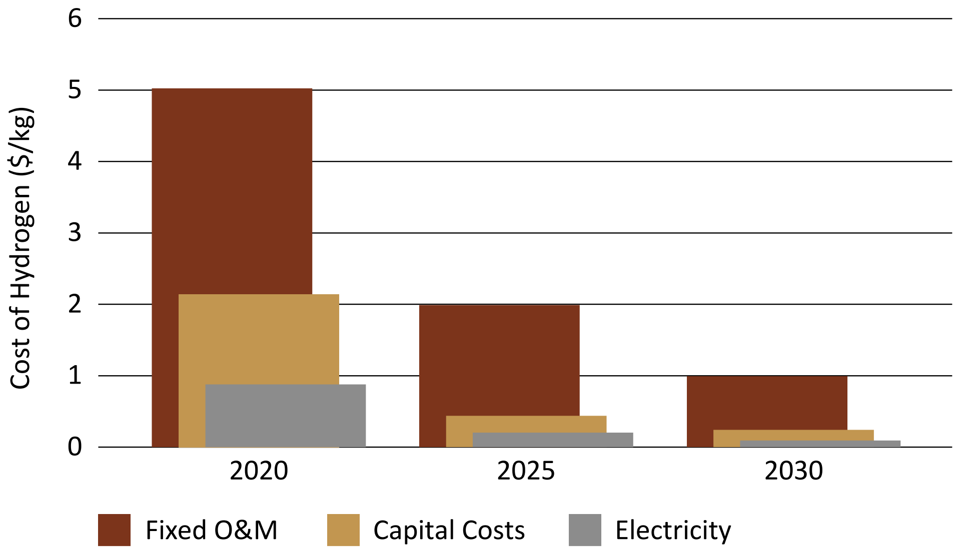
Alongside this, electrolysis technology and production facilities must become more cost effective. In part, this will come from scaling to industrial manufacturing levels: For PEM electrolyzers, scaling up to even 1,000 MW per year can reduce stack manufacturing costs by half.

Hydrogen produced with electrolysis could be cost-competitive with fossil fuels as soon as 2030.[17] The United States Department of Energy (DOE) estimates that the costs for PEM electrolyzers will be nearer to $400/kW in 10 - 15 years.[18]

As this happens, markets will expand for hydrogen in newer end-uses, accelerating decarbonization and driving new investments. Operations and maintenance costs, like capital expenditures, will decrease with time and technological development, as shown in Figure 03.

But getting to this $1/kg goal will be a challenge — this is an 80% reduction in roughly ten years. However, hydrogen has significant momentum behind it. Currently, there are 200+ ongoing hydrogen projects across the globe, and over $300 billion USD will be invested in hydrogen by 2030.[19] Alongside this investment, state and federal regulations and incentives will also be essential for reducing the price of hydrogen.

Figure 03: Projected Cost of Hydrogen Over Time[20]



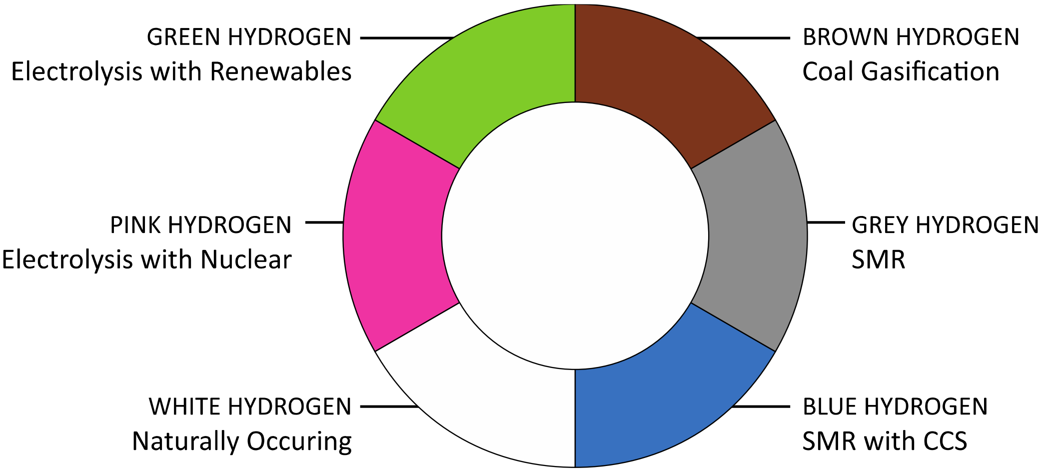
03 Classifying Hydrogen

Hydrogen production processes can be grouped and compared in several different ways. The two primary methods of doing this are by 1) energy feedstock and 2) output carbon emissions.

3.1 Hydrogen Color Wheel

The hydrogen color wheel (Figure 04) assigns a color to hydrogen according to the means in which it was produced.

Figure 04: Hydrogen Color Wheel



Green hydrogen, which makes up about 0.1% of global hydrogen today, is hydrogen produced via electrolysis powered by renewable electricity.[21] Grey hydrogen, comprising about 71% of global hydrogen, is produced via methane SMR with no carbon capture or sequestration. Blue hydrogen is produced via Steam Methane Reforming with Carbon Capture and Storage. Brown hydrogen is produced with coal gasification.[22]

Several other, much less common, types of hydrogen are also classified using this system: electrolysis performed with electricity from nuclear power is known as pink hydrogen, and molecular hydrogen occurring naturally in underground deposits (which are largely inaccessible) is known as white hydrogen. Additionally, hydrogen produced with methane pyrolysis is sometimes referred to as turquoise.

3.1 Carbon Intensity Score

CHBC prefers using Carbon Intensity (CI) Score to evaluate hydrogen. This is a metric that gives a numerical value to the relative GHG emissions produced in making the fuel (kg CO_2/ kg H_2).

This system is more transparent and allows for the relative carbon impact of different types of hydrogen to be evaluated and compared. Additionally, this allows different types of hydrogen to be directly compared to conventional fuels.

When it comes to carbon intensity, coal gasification (brown hydrogen) emits the most carbon dioxide per kg of fuel produced. Of the primary methods of production natural gas SMR is the next highest in emissions, followed by SMR with carbon capture. Green hydrogen — hydrogen produced via electrolysis with renewable energy — is the lowest of all, with a CI score closest to zero.

04 Storage & Distribution

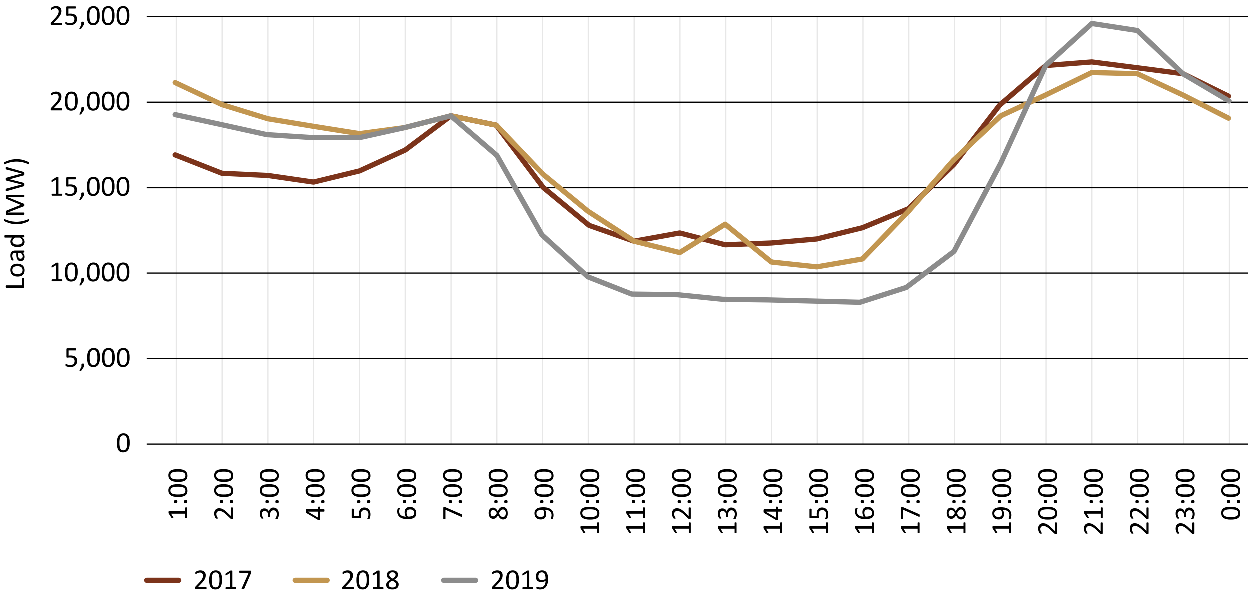
4.1 Storage

Like electricity, hydrogen is an energy carrier, rather than a source of energy. Unlike electricity, hydrogen can be stored on a large scale when applications demand it.

Production of hydrogen by electrolysis can deal with the daily and seasonal imbalances of solar and wind energy by providing large scale energy storage in the form of transportation fuels, heating fuels, and using fuel cells or gas turbines for electricity storage.

Hydrogen can help solve California's duck curve electricity supply problem. The duck curve is a bimodal curve that shows electricity demand throughout the day.[23] (Figure 05)

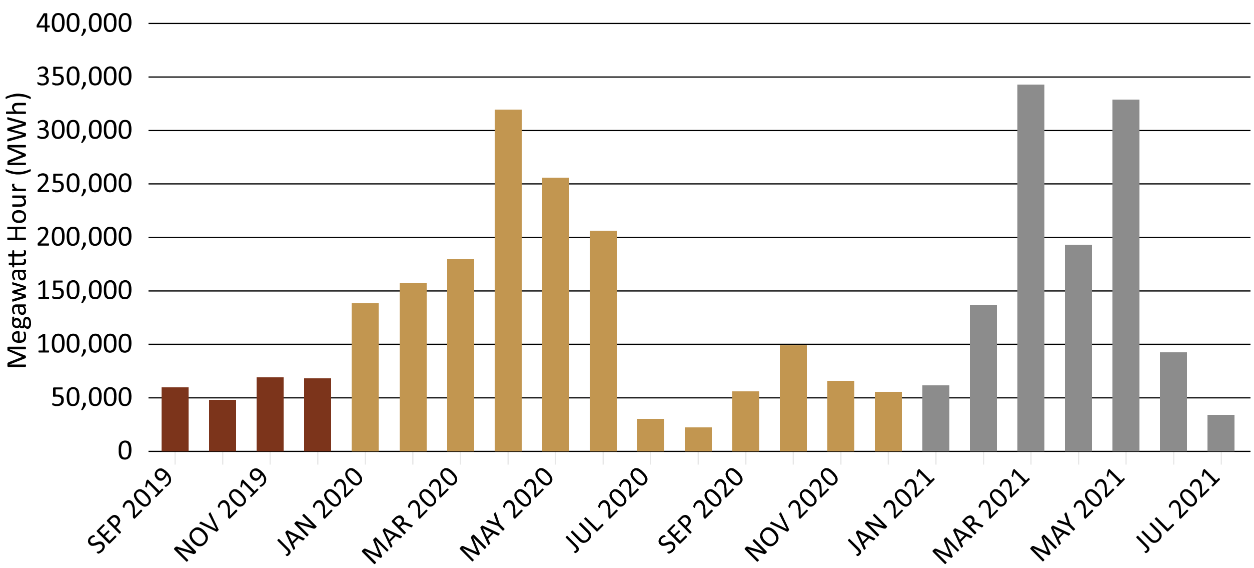
Figure 05: The Duck Curve[24]



The demand peaks at around 8 pm, after increasing steadily all day, then sharply declines. This contrasts sharply with solar production, which peaks around 2 pm, and is practically zero between 8 pm and 7 am. It's this disparity that makes renewables unreliable for constant, firm grid power. Hydrogen energy storage along with batteries can solve this problem – excess electricity can be used to produce hydrogen which can then be stored and used for power when solar and wind production can't meet energy demand.

This also occurs on a seasonal basis. In the peak of summer, solar may exceed grid needs. In this case – when grid demands are too low to require the forecasted amount of renewable energy production – production is curtailed. (Figure 06)

Figure 06: Monthly Wind and Solar Curtailments[25]



This means that the output is reduced, creating missed revenue for the operators, and lowering the useable capacity of renewable production facilities.

The main advantage of hydrogen as a renewable alternative is the ability to produce it abundantly. In order for global solar and wind dynamic production to meet the total world annual energy demand, it's estimated that 20,000 TWh of energy storage would be required. Pumped storage and compressed air energy systems are examples of potential storage systems that can meet some of the needs, but they require specific geographic conditions.

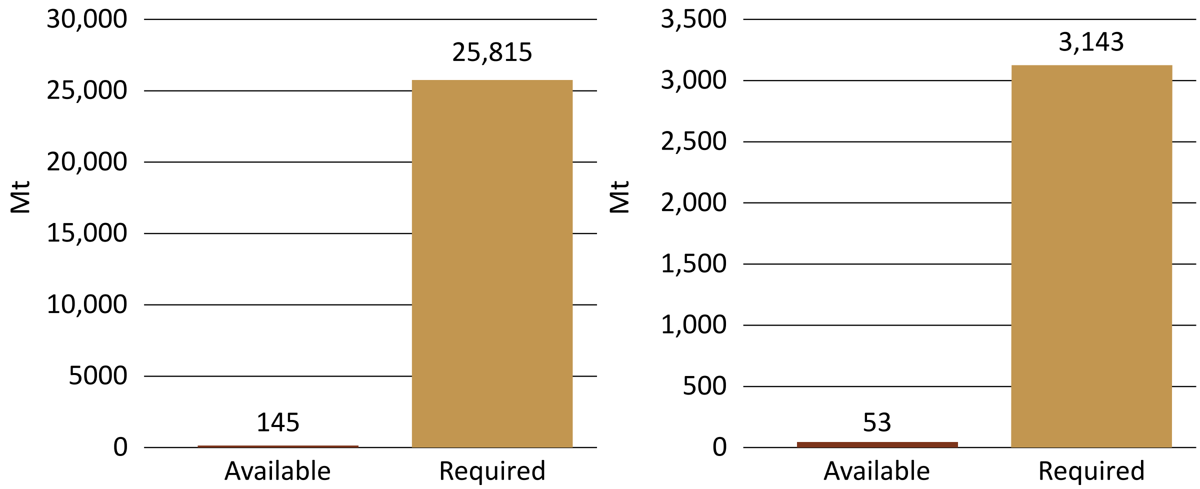
Battery storage does not depend on such geological conditions, but requires rarer metals like lithium and cobalt, which is not realistic given the scale of storage needed. Given this, hydrogen storage is crucial to harnessing intermittent renewable power and increasing its market penetration (see Figure 07).[26]

Geological Storage

Underground geological storage is one method of bulk storage. Hydrogen can be successfully stored in salt caverns, which, as done with natural gas, can store large volumes of electricity able to be stored in some caverns. One major development in geographical hydrogen storage is the intermountain Power Project, funded by the LA Department of Water and Power. This is a power plant in Utah with salt caverns that can store up to 5,512 tons of hydrogen — the power equivalent to filling 200,000 hydrogen buses, one million fuel cell cars or 14,000 delivery tankers. The plant can house up to 100 caverns.[27]

Figure 07: Global Availability of Metals for Battery Storage to Meet Annual Demand

Metal reserves are not nearly enough to power a perfectly efficient battery capable of meeting global energy storage demand in a 100% renewable energy economy.



New methods of storing hydrogen in depleted oil and gas reservoirs, mines and aquifers are being developed. These methods are being tested to determine potential for contamination, which is not an issue in salt caverns.

Physical Storage

Since hydrogen naturally occurs as a gas, it is typically compressed to be stored in larger energetic quantities for a given volume. This means it is either pressurized and stored as a compressed gas or condensed into the liquid state. As a gas, hydrogen is typically compressed to 10 - 900 bar for storage. Liquid hydrogen must be kept at -253 °C, which requires cryogenic tanks and additional infrastructure, increasing costs.[28]

Material Storage

Material storage is a newer technology for storing hydrogen. This includes adsorption, absorption and hydrogen carriers.

Hydrogen can be stored within solids. This can be done via surface adsorption, where hydrogen attaches to the surface of a material as molecular hydrogen (H_2) or atomic hydrogen (H). Absorption, or hydriding, is another method of material storage, in which hydrogen molecules dissociate and become incorporated into the lattice framework of the solid.

Hydrogen can also be stored within hydrogen carriers — essentially a means of storing hydrogen using the bonds of another molecule, a reaction called hydrogenation. When H_2 needs to be stored, the carrier is hydrogenated. When that hydrogen needs to be used, the molecule can be dehydrogenated, recovering the H_2. Liquid-organic compounds (LOHCs) and ammonia are gaining the most traction as hydrogen carriers.[29]

4.2 Distribution

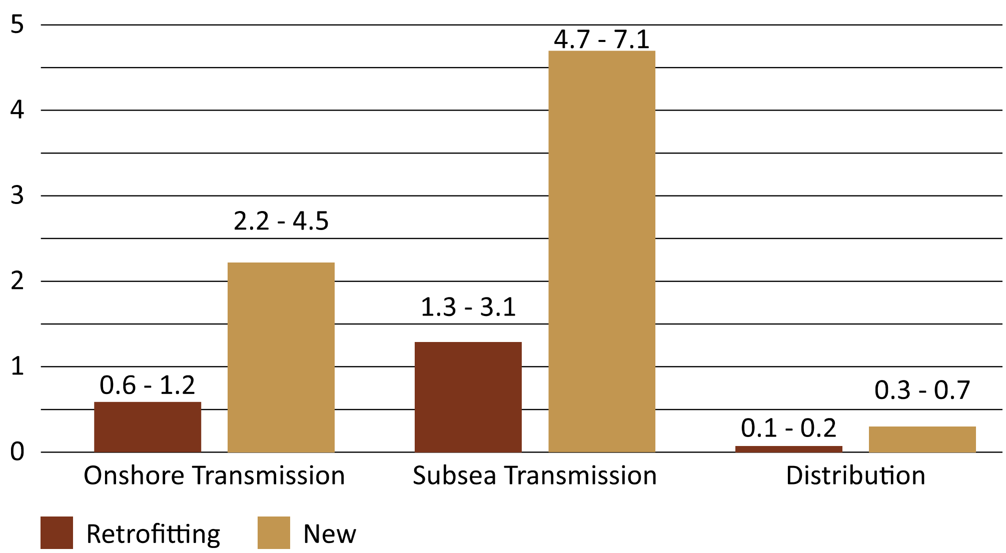
Although hydrogen has an extremely high energy density by weight, its energy density by volume is lower than any other common fuels.

Generally speaking, over short distances less than 100 miles and small quantities less than 250 kg, hydrogen is delivered as a compressed gas. Over longer distances, liquid hydrogen is more cost effective. For requirements greater than a couple of tonnes per day, on-site generation becomes practical.

Large quantities of hydrogen, such as hydrogen required by a refinery, can also be delivered by pipeline. Dedicated hydrogen pipelines operate currently – over 1,600 miles of dedicated hydrogen transmission pipelines run in the US.

These are primarily located near petroleum refineries and chemical plants where production is highest, near the Gulf of Mexico. These pure hydrogen pipelines are installed when demand is sufficient and is expected to remain stable for 15 - 30 years.[30] (Figure 08)

Figure 08: Capital Expenditures for Hydrogen Pipelines (million USD/km)[31]



Along with pure hydrogen pipelines, hydrogen can be injected into existing natural gas pipelines to reduce carbon content of the gas. For some gas grids, this blend can be up to 20% hydrogen by volume or 7% by weight, with few infrastructural modifications necessary.[32] This could become an inexpensive way to distribute large quantities of hydrogen as various companies are looking at how to separate the hydrogen from the natural gas pipeline.

Renewable hydrogen and carbon dioxide can also be converted to renewable methane, which can then be transmitted via pipeline and used as a decarbonized alternative to fossil sourced natural gas.

05 End Uses

Hydrogen is capable of meeting energy demand in practically every sector.

5.1 Power Generation

There are two ways to get power from hydrogen: fuel cells and turbines. Stationary hydrogen fuel cells, described above, generate electricity through an electrochemical reaction, producing no emissions. If supplied with electrolytic hydrogen, fuel cells are a near 100% carbon-free source of power.

Gas turbines generate electricity through a combustion process. Typically, natural gas is used as fuel for combustion, but this can be replaced by hydrogen for a zero-emission option. Existing fuels can also be injected with hydrogen for use in turbines, reducing emissions with minimal infrastructural changes.

Power-to-X is a concept commonly used to describe the pathway from renewable sources (like solar or wind) to end use applications. Fuel cells and turbines are essential to this pathway.

5.2 Electric Grid Services

Stored hydrogen from solar and wind can be used to firm grid power. Grid firming is the use of stored hydrogen to help balance seasonal and daily imbalances caused by intermittent renewable power.

Hydrogen can also be used in microgrids, localized groups of electricity sources that can operate independently (known as islanding) or in conjunction with the central electric grid. Fuel cells in a microgrid provide a zero-emission electricity solution that can be used during an electric grid outage.

Renewable Microgrid Powers Connecticut Town in Woodbridge, CT, a fuel cell microgrid supplies power during outages for six critical town buildings: the high school; library; fire department; town hall; senior center; and police department and public works. The 2.8 MW system has black start capabilities and also provides heat to the high school. Critical loads are sequenced by the microgrid controller and the inverter follows the microgrid load.[33]

Hydrogen can also be used as backup power, meaning it can provide electricity in remote locations or in the event of an electric grid outage. For example, using hydrogen as emergency power during California's Public Safety Power Shutoffs (PSPS) could mitigate the risk of wildfires.

Fuel cell generators are cost-effective in the long term, as well. Battery generators are up to 193% more expensive over ten years, while diesel generators are up to 143% more costly.[34] Fuel cells are flexible, scalable and low maintenance. They can be used in low and high-power situations and can operate under extreme weather conditions.

5.3 Decarbonizing the Gas Grid[35]

The existing natural gas grid, with a few alterations, can be used to transport and store hydrogen. This is done by blending hydrogen and natural gas, up to 20% H_2 by volume. This blend then fuels the furnaces, boilers and stoves traditionally powered solely by fossil natural gas. This lowers the carbon emissions of these appliances, all while distributing hydrogen in a simple and relatively inexpensive way.

One barrier in increasing hydrogen concentrations in pipeline injection is hydrogen embrittlement. Under certain concentrations, temperatures and pressures, hydrogen gas weakens metal and polyethylene pipes, leading to leaks. This is currently the limiting factor in using the natural gas infrastructure to distribute and store larger quantities of hydrogen. In order to distribute hydrogen in high concentrations and pressures in existing pipelines, more significant modifications would be necessary.

Though hydrogen pipeline injections may only decrease carbon emissions minimally compared to simply using hydrogen instead of natural gas, this strategy increases the market for hydrogen, and may ultimately help drive costs down.

5.4 Industrial and Chemical Processes

Many industrial and chemical processes (refining, steel, ammonia and methanol production) can be carried out with hydrogen and currently make up the bulk of hydrogen usage.

95% of hydrogen in the US is used for ammonia, methanol production and chemical refining.[36] (Figure 09) These industrial processes use the lion's share of hydrogen, very little of which is green. Nearly 28% of global greenhouse emissions come from industry.[37] Despite significant cost and technology barriers, established processes — including ammonia, methanol, and refining — present an opportunity to scale up the use of green and low-carbon hydrogen while new applications — such as steel and heating — could be long-term solutions for hard-to-abate industrial sectors.

Ammonia production currently accounts for 2% of global energy use and makes up a major portion of hydrogen consumption. Most ammonia is used to produce fertilizer, meaning that commercializing green hydrogen also promotes to sustainable agriculture.[38] Since ammonia is easier to transport than hydrogen — it liquefies at -10°C, rather than -253°C — there is mounting interest in its application as an energy vector. Ammonia is produced in the following reaction:

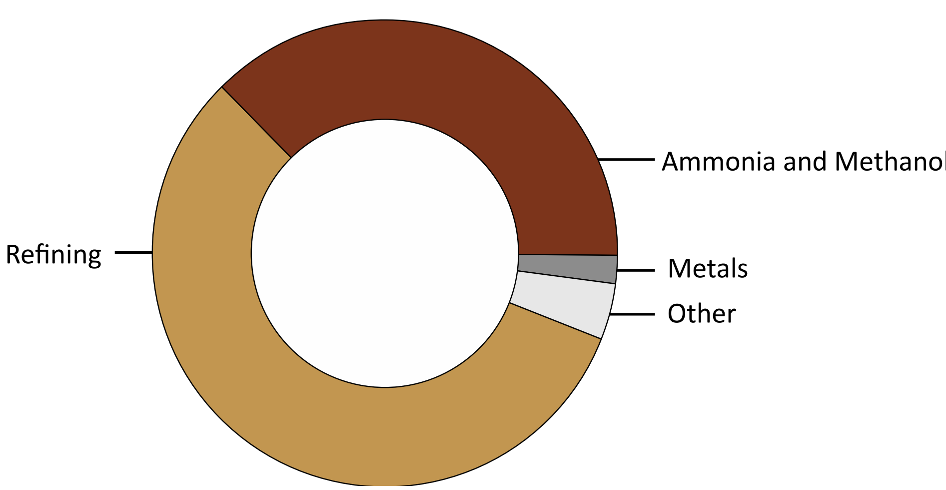
$3\ H_2 + N_2 \longrightarrow 2\ NH_3$ $3\ H_2 + N_2 \longrightarrow 2\ NH_3$

and so, the process can be decarbonized by using low carbon emission hydrogen sources.

Accounting for 8% of global emissions, steel production is another carbon-intensive industrial process. Steel making using hydrogen, rather than coal, known as direct reduction iron by hydrogen "H_2-DRI", is considered the only viable avenue for producing decarbonized steel. Because of this, countries like Germany consider hydrogen steel production a critical avenue in decarbonizing the industrial sector. Low-carbon steel produced with the H_2-DRI process will likely be competitive in certain places by 2030.[39]

Figure 09: Hydrogen Markets in the US[40]

March 2021



Cement production is a large source of emissions globally and has also been historically difficult to decarbonize. Alongside lowering emissions, using hydrogen to produce cement improves energy efficiency. Decarbonizing cement production by 2050 would prevent the emission of 3.2 gigatons of carbon dioxide.[41] Renewable hydrogen would be able to replace natural gas or coal-fired high-temperature processes. Biproduct oxygen from the electrolysis could also help deal with process emissions.

5.5 Industrial Heating

Hydrogen combustion (using hydrogen as fuel for boilers) and fuel cell heat capture can be used to replace current heating systems. Currently, heating contributes up to 40% of energy-related carbon emissions globally.[42] The first hydrogen boiler was successfully demonstrated in the Netherlands. The groundbreaking system burns green hydrogen in a zero-emission process.

Decarbonizing heating can also be done via the existing natural gas infrastructure, as was done in the H21 Leeds City Gate project. H21 is a suite of gas industry projects designed to support conversion of the UK gas networks to carry 100% hydrogen. Currently, 83% of domestic UK homes use natural gas for heating and cooking, with that number higher in cities. H21 has proved conversion of the existing gas grid to carry 100% hydrogen is technically possible and economically viable. In Leeds, high-concentration hydrogen is distributed via pipeline at low pressures (below 7 bar), to avoid embrittlement. This has the potential to reduce carbon emissions (including embodied CO_2 from the production and importation of natural gas) by 59%.[43]

5.4 Transportation

Transportation is the largest source of US emissions, accounting for nearly 29% annually.[44] Using hydrogen and fuel cells alongside battery technology to decarbonize this sector will be critical to achieving this country's climate goals. Hydrogen and fuel cells have zero tailpipe emissions, are fast to refuel and have long-range, multi-shift operations. This means that FCEVs can offer a one-to-one replacement for traditional engines in light, medium and heavy-duty applications.

5.6.1 Road Vehicles

Light-Duty

Fuel cells can easily be used for light duty transportation and have similar mileage ranges to typical car engines.

Light-duty FCEVs are available and relatively cost-competitive in California with rebates from the Clean Vehicle Rebate Project. The Mirai, Toyota's fuel cell car, is available from $49,500 with incentives from $4,500 - $7,000.[45] Light-duty fuel cell vehicles are becoming more common, which will also help drive costs down. As of July 2021, there are 10,803 fuel cell electric vehicles leased in the US, almost all in California, with 48 retail hydrogen fueling stations in operation and 72 stations funded and in development. By executive order of the Governor, there will be 200 refueling stations in California by 2025, and the California Fuel Cell Partnership is calling for 1,000 by 2030.[46]

Public Transit

Fuel cell buses are a lower-emission alternative to traditional diesel transit buses. Currently, 48 FCEBs are active in California, with 42 more in development. By 2029, California has aims to purchase only zero-emission transit buses. By 2040, the entire transit fleet should be transitioned to zero-emission[47] power systems.

Medium & Heavy-Duty Trucking

Currently, a number of heavy-duty fuel cell trucks are in development, with models from Toyota, Kenworth, Nikola, and Hyzon Motors.

One significant advantage of fuel cell trucks in comparison to battery-powered is the weight of the fuel itself. Assuming a maximum weight of 80,000 pounds, a fuel cell for long-haul truck loses about 1,000 pounds of cargo capacity compared to a diesel engine. A battery to power a long-haul truck (even with an ideal battery density of 4 kg/kWh, which has yet to be achieved for heavy-du-ty applications) would lose around 5,000 pounds of capacity. Given current battery densities, the capacity loss would be closer to 10,000 or 15,000 pounds.[48] This means that hydrogen fuel cell trucks can hold anywhere from 4,000 - 14,000 more pounds of cargo than current battery powered trucks.

In addition to this cargo advantage, it's estimated that, under ideal efficiency conditions, hydrogen heavy-duty trucks will reach cost-parity with BEVs by 2025, and with diesel trucks before 2030.[49] (Figure 10)

Transitioning heavy-duty trucking to hydrogen will also have major impacts in air quality equity. High-emissions trucking, particularly near the Port of Long Beach, is concentrated in low-income neighborhoods. This has resulted in substandard air quality and severe health consequences, which is emblematic of a larger trend.

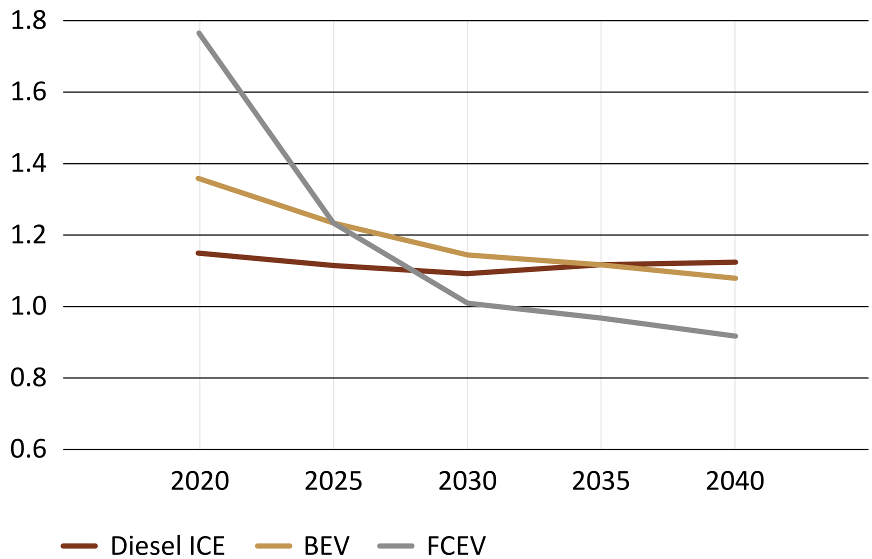
With a current goal of making all drayage trucks zero-emission by 2035, CARB aims to mitigate these air quality concerns raised by trucking.[50]

Fuel cell trucks could play a significant role in improving environmental equity in this region.

5.6.2 Off-Road Vehicles

Hydrogen can also be used to power off-road vehicles such as forklifts, warehouse vehicles and top lifters. According to California's Air and Resources Board, off-road vehicles are the largest single source of mobile emissions in California, making up 29% of statewide diesel PM emissions and 11% of statewide NO_x emissions.[51] Transitioning these vehicles to hydrogen could significantly improve air quality across California, particularly in low-income communities that are disproportionately affected by these emissions.

Figure 10: Cost of Ownership of Heavy-Duty Trucks Over Time[52]

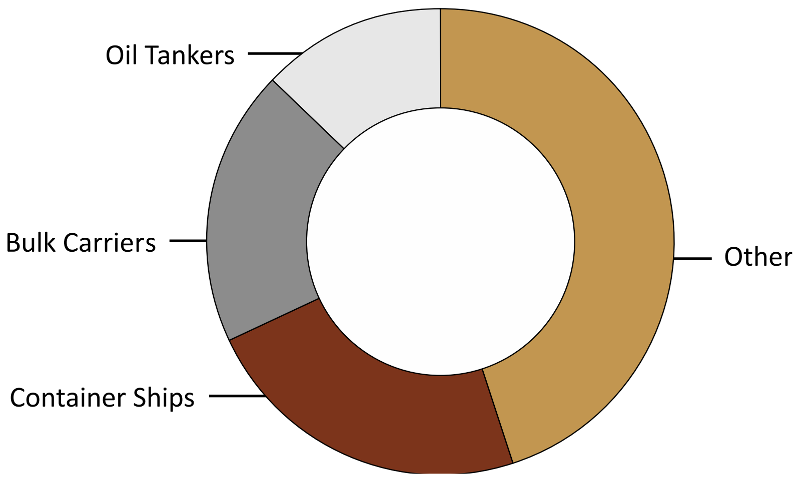


5.6.3 Maritime

Hydrogen could be key to decarbonizing shipping — an industry both reliant on diesel and rapidly expanding. Fuel cells and hydrogen-based fuels have a broad range of maritime applications and can be scaled to serve many use-cases, including passenger vessels, ferries, cruises, and commercial shipping, which dominates maritime traffic and emissions. In the long-term, hydrogen fuel cells and hydrogen-based fuels could be used to replace dirty diesel combustion engines, reducing GHG emissions and contributing to a cleaner energy economy.

Figure 11: Global Shares of Maritime CO_2 Emissions by Ship Class[53]

2013 - 2015



A March 2020 study by the International Council of Clean Transport (ICCT) found that 99% of shipping voyages connecting the US and China's busiest port clusters can be powered by hydrogen with only minor changes to fuel capacity or operations. 43% of these journeys were found to require no such changes.[54] Achieving this will require further technological development, but these results demonstrate that hydrogen is a serious contender for decarbonizing commercial shipping in the long term.

Maritime hydrogen projects, especially in commercial applications, are taking off — pilot projects for large hydrogen vessels have tripled over the past two years. Future projects, most notably Norway's 3.2 MW fuel cell ferry planned for 2023, will expand the size and scope of proven maritime applications, while demonstrating the short and mid-term commercial viability of using fuel cells and hydrogen-based fuels to decarbonize smaller vessels.[55]

SWITCH Maritime will launch its first hydrogen-electric vessel, an 84-passenger ferry, later this year in the San Francisco Bay.[56] With a $3 million grant from the California Air Resources Board (CARB), they hope their flagship demonstration will lead to North America's first zero-emission fleet, positioning California as a leader in hydrogen-electric maritime use.

5.6.4 Rail (Hydrail)

Passenger hydrail is being seriously explored across the globe. Despite the challenges brought on by cost and infrastructure development, several companies have plans to scale up commercial projects over the next several years. Fuel and production costs will decrease in the long term, and technological developments may unlock freight applications, expanding the hydrail market further. Hydrogen rail has the potential to replace fossil-powered train seamlessly — it only takes roughly 20 minutes to refuel a hydrogen train supporting 18 hours of operation.[57] Currently, less than 1% of US rail is electric, meaning there is substantial opportunity to decarbonize through hydrogen.[58]

Hydrogen rail is already popular in Europe — Germany has been operating two hydrail commuter trains since 2018. After a successful pilot period, German officials ordered 43 more of Alstom Coradia iLint trains to incrementally begin service by 2022. Starting in 2021, the UK, also in partnership with Alstom, will retrofit 100 commuter trains with hydrogen. This project coincides the UK Department of Transportation's ambitious goal to completely phase out diesel-only trains by 2040.[59]

Siemens is also developing a hydrogen train in partnership with Deutsche Bahn. The Mireo Plus H uses fuel cell drive alongside a lithium-ion battery. Powered by green hydrogen from electrolysis, the train can be refueled in less than 15 minutes. The German train is scheduled to begin trial operations in 2024 and could prevent up to 330 tons of carbon dioxide emissions[60] per year. Other hydrail projects have been announced in France, China, Russia, Japan, and Korea.

5.6.5 Aviation

Aviation is the largest and fastest growing source of individual emissions in the US, according to the Environmental and Energy Study Institute (EESI). Globally, aviation makes up 3% of annual emissions. In the past five years, aviation emissions have increased by 34%. Hydrogen has the capability to be a major part of the aviation mix and could significantly reduce climate impact, with hydrogen planes potentially accounting for 40% of global aviation by 2050.[61]

Achieving this will require significant research, investment, and regulatory innovation. California is home to ZeroAvia, the leading hydrogen plane company. ZeroAvia is one of several companies and government research groups exploring hydrogen aviation. These projects build on decades of hydrogen applications in the space and military sectors.

It's estimated that a short-range hydrogen powered aircraft could be debuted as soon as 2035. Medium-range aircraft, powered by H_2 turbines, could enter service in 20 years, with long-range planes following five years later.[62] This would significantly reduce the climate impact of air travel.

06 Financeability, Funding & Incentives

There are several pathways for hydrogen to reach cost-competitiveness.

6.1 Financing Hydrogen[63]

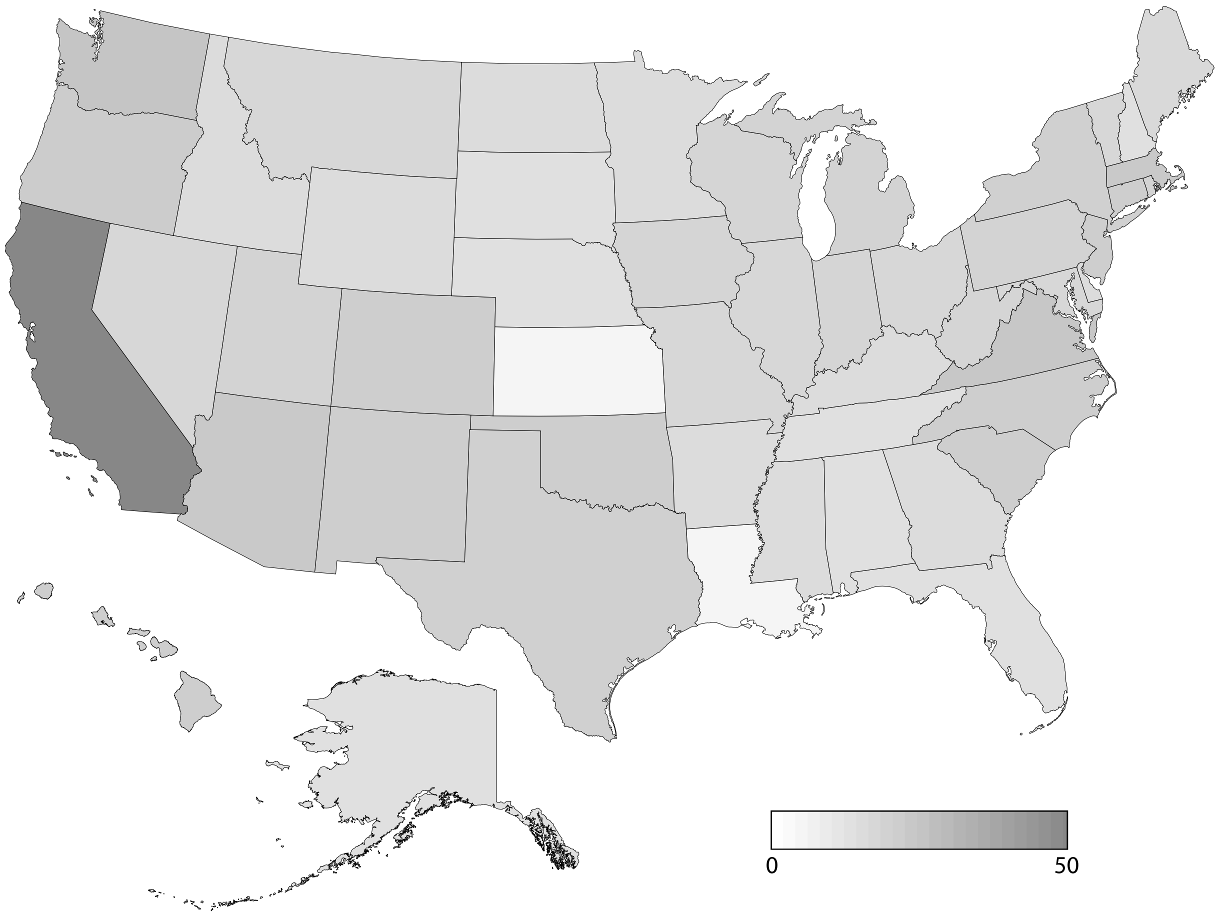
The main challenge in establishing a stable hydrogen economy is developing reliable offtake agreements for currently nascent markets. Zero and low carbon hydrogen is more expensive and will require investment and a well-developed regulatory framework to replace fossil fuels on a global stage. This is particularly true in sectors where hydrogen is still a relatively new alternative, including heating and electricity generation. Use cases like transportation are a little further along, with hydrogen considered a necessary counterpart to BEVs. Markets where non-renewable hydrogen is already widely used, such as industrial processes and chemical refining, are likely to take off first for low carbon-intensity hydrogen.

Ideally, hydrogen projects would be financed via long-term, fixed-price offtake contracts with utilities or other public purchasers, like public transit agencies. First-mover projects will require major maintenance reserves, and warranties may need to be backed by insurance, which will be expensive. This will likely be a challenge, as several of the major players in supplying hydrogen technology today are somewhat limited in budget.

Government support on a federal level is critical to facing these challenges. Along with state and local incentives, federal technology incentive programs and carbon pricing will be necessary to develop a self-sustaining hydrogen economy.

Figure 12: Hydrogen Laws and Incentives by State[64]

July 2021



6.2 Incentives & Funding Programs

California has several pieces of legislation that support the commercialization of hydrogen and fuel cell technology. These are some of the main players.

State Incentives (August 2021)[65]

California Clean Vehicle Rebate Program

CARB offers rebates for purchasing or leasing select BEVs, FCEVs or hybrids. These grants range up to $4,500 for FCEVs, and less for other vehicles, depending on gross annual income.

Clean Transportation Program

California Energy Commission began this program to provide financial incentives for businesses, consumers and academic institutions who are developing and deploying renewable transportation technologies. This includes electric, hydrogen and natural gas vehicles and charging, biofuels and workforce development.

Tax Exemptions

Zero-emission transit buses are exempt from state sales and use taxes. There are also sales and use tax exclusions for manufacturers of transportation that reduce pollution and energy use while promoting economic development.

Volkswagen Environmental Mitigation Trust

Bus Replacement Grant

CARB offers grants for the purchase of new zero-emission buses to replace old gasoline, diesel, compressed natural gas, or propane buses. This grant doesn't apply to non-compliant school buses. Grants range in value from $160,000 to $400,000.

Heavy Duty ZEV Replacement

South Coast Air Quality Management District (SCAQMD) offers grants to replace eligible heavy-duty vehicles with ZEVs, up to 75% for non-government and 100% for government (up to $2,700,000).

Clean Cars for All

This is a Bay Area program that provides grants in amount up to $9,500 — for income-eligible residents to replace select older vehicles with FCEVs or BEVs.

Zero-Emission Transit Funding

The California Clean Mobility Options Voucher Pilot Program, designed for low-income communities, offers up to $50,000 for purchasing zero-emission vehicles and projects involving ZEV infrastructure, planning, outreach, and operations.

Clean Air Grants – Santa Barbara

Heavy-Duty ZEV Grant

This grant offsets the cost of transitioning heavy duty vehicles to ZEVs, including replacing commercial buses and trucks, transit, some emergency vehicles, and more.

Alternative Fuel Infrastructure Grants

These grants aim to reduce the costs of installing alternative fuel infrastructure by covering 80% of project cost (up to $150,000).

South Coast

Air Quality Investment Program

This program allows employers in the South Coast to make annual investments into an administered restricted fund. The revenues collected from this fund are used on projects aiming to reduce emissions, including alternative fuel vehicle projects.

Clean Fuels Program

This program funds research, development, demonstration, and deployment projects helping commercialize low-emission transportation technologies.

This includes powertrains and energy storage or conversion devices, such as fuel cells and batteries, and the necessary infrastructure to implement these clean fuels.

Support for hydrogen is also available at the federal level, with several programs funding research and development of hydrogen and fuel cell technology.

San Joaquin Valley

Alternative Fuel Vehicle Technical Training

This is a mechanic training program with incentives up to $15,000 for workforce development on the operations, safety and maintenance of alternative fuel vehicles and fueling stations.

Heavy-Duty Truck Emission Reduction Grants

This program funds the replacement of older vehicles within fleets with newer, low-emission technology. This includes zero-emission, hybrid or low NO_x vehicles.

Alternative Fuel and Advanced Vehicle Rebate

This program provides rebates for purchasing or leasing select natural gas, fuel cell, propane, electric and plug-in vehicles. Rebates are up to $4,000 dollars, available for residents and businesses in San Joaquin Valley Air Pollution Control District.

Federal Programs (August 2021)

H2@Scale[66]

H2@Scale is a Department of Energy led initiative that focuses on commercializing hydrogen in order to expedite decarbonization. This initiative brings stakeholders together and funds hydrogen projects, including the advancement of hydrogen storage, infrastructure and production.

Advanced Research Projects Agency — Energy[67] ARPA-E is another federal agency that funds research and development for alternative energy technologies, including hydrogen.

Energy Earthshots — Hydrogen[68]

The DOE’s Energy Earthshots Hydrogen initiative aims to reduce the price of clean hydrogen by nearly 80%, to $1/kg, by 2030. This would position hydrogen as a cost-competitive option for new market, allowing for a drastic reduction in carbon emissions.

Fuel Tariffs under the “Inflation Reduction Act” (2022) support low carbon hydrogen production based on carbon intensity, paying up to $3.00/kg for green hydrogen production.

07 Hydrogen Safety

Hydrogen is just as safe — if not safer — than traditional fuels.

7.1 Vehicles & Refueling Stations[69]

One common concern with hydrogen is with regard to its safety as a transportation fuel. Light-duty vehicles (passenger cars) use high pressure systems to store the hydrogen on board the vehicle, to extend the driving range, while buses and larger-duty vehicles use slightly lower pressure tanks. These tanks are wrapped in carbon-fiber, making them extraordinarily robust, and were originally developed for the space program and later improved for commercial applications. The tanks are put through rigorous testing including crash tests, gunfire and performance requirements, including being subjected to more than twice the maximum pressure they should experience.

In a vehicle, hydrogen is transferred from the high-pressure storage tank to a low-pressure delivery system and then to the fuel cell. If the low-pressure system is compromised, the entire fuel system immediately shuts down, preventing any high-pressure hydrogen from escaping and leaving behind a very small quantity of low-pressure H_2 that could escape. Since hydrogen is 14 times lighter than air, it quickly diffuses to concentrations below the low flammability limit (LFL). If ignition were to occur, such a small quantity of hydrogen would escape that damage would be limited.

Additionally, hydrogen fuel stations have redundant protection systems in place, so it's virtually impossible to over-pressurize a vehicle's fuel system. Hydrogen codes and standards at the national level (and those adopted at the local and regional levels) ensure that hydrogen fueling stations are as safe as their gasoline counterparts. All FCEVs have to meet the same rigorous federal safety standards that apply to all consumer vehicles. In short, FCEVs and the fueling stations are just as safe as conventional systems today.

7.2 Production & Storage Safety

Hydrogen has been safely produced and used in the US industrial sector for more than 50 years. As with every fuel, safe handling practices are required. Hydrogen is non-toxic and does not pose a threat to human or environmental health if released. Hydrogen (just like natural gas and gasoline) is a volatile substance. When combined with an oxidizer in the right proportions, it can ignite and give off energy in the form of heat. Industry has learned to design systems that use these energetic substances safely; hydrogen systems are designed to be no riskier than their conventional fueled counterparts.

Stored hydrogen is designed to handle leaks safely. When stored as a liquid, hydrogen requires well insulated tanks, which are double-walled, vacuum sealed and kept at low pressures. The handling of liquid hydrogen is, and will be in the foreseeable future, handled only by trained professionals. At a stationary storage facility, hydrogen can be stored under high pressure. Following NFPA 2, the facility is engineered in such a way that should a leak occur, it will be directed away from any other hazards where it can be safely mitigated. While these leaks are unlikely, they have happened, and the safety systems responded exactly as intended with no serious consequences.[70]

08 Policy Recommendations

These are CHBC's top policy priorities in 2021.

8.1 Key Market Enablers

As of 2021, California Hydrogen Business Council has three primary policy priorities. We believe these to be the key market enablers — what will grow hydrogen markets the fastest while reducing greenhouse gas emissions.

Fueling Station Development

First, CHBC wants to push for 1,000 light-duty hydrogen refueling stations in California by 2030. Developing the necessary fueling infrastructure is essential to promoting hydrogen as a viable transportation fuel option. Doing so will help develop markets for hydrogen in other sectors, as well. As more stations are developed, costs at the pump go down.

Currently, there are 48 hydrogen refueling stations open and functioning in California, with 127 more stations in development.[71] This is well on track to meet the plan for 200 light-duty stations by 2025, which will lead into CHBC's goal of 1,000 in the next nine years.

Renewable Gas Injection Standard

Secondly, CHBC supports a renewable gas injection standard for gas utilities. This means establishing supportive regulations to allow hydrogen blending in the natural gas system and ensure optimal use of the gas grid for long-term and seasonal energy storage.

Additionally, this will involve integrating pipeline and electric grids in order to maximize both thermal and electric renewable and decarbonized energy options, including fuel cells. The renewable gas injection standard will help increase demand for hydrogen while decarbonizing the gas grid without significant modifications.

Wholesale Market Access for Electrolyzers

Finally, CHBC wants to focus on improving wholesale electricity market access for electrolytic hydrogen producers. In California, the best way for these facilities to access wholesale electricity prices currently is by working with either a load-serving entity or electricity service provider.

Expanding this market access will help lower the cost of the green hydrogen produced by these assets. This also will help diversify the grid, increasing reliability and flexibility in the long-term.

09 Conclusion

Hydrogen is an essential component in meeting our climate goals.

We are in a critical period of transition as a state, a nation, and a planet. California Hydrogen Business Council believes that hydrogen and fuel cell technology will prove invaluable in reaching the clean energy future we need to achieve.

In both its application and production, hydrogen is incredibly versatile. Hydrogen is capable of decarbonizing practically every sector, from transportation fuels to power generation, to chemical feedstocks.

Currently, hydrogen is used in chemical and industrial processes. Expanding these markets and making low carbon intensity hydrogen cost-competitive has the potential to drastically reduce our fossil fuel usage and associated GHG emissions. Hydrogen fuel cell technology also has a multitude of environmental benefits, addressing environmental concerns such as noise pollution and cleaner air.

Existing problems with wind and solar power — most notably, the need for long-duration, large scale storage — could be solved with hydrogen. As more material and geological hydrogen storage options are developed, we will be able to build a more reliable and resilient grid, powered by renewables. Since hydrogen supply is practically unlimited, hydrogen can store massive amounts of energy at a relatively low cost.

Hydrogen today is safely distributed by road, rail, ship, and pipeline. Depending on shipping costs, on-site production is also an option.

The development of hydrogen and fuel cell technology also brings energy security. Domestic hydrogen production will reduce reliance on foreign petroleum imports and strengthen local economies. Hydrogen and fuel cell technology is also a step towards environmental equity: zero-emission fuel cells will improve air quality in communities that have been disproportionately affected by particulate pollutants.

Making hydrogen a viable option from a cost perspective is the primary challenge. Low-carbon H_2 production technology is new and will require investment to reach cost parity with fossil fuels and gray hydrogen.

California has positioned itself at the forefront of adoption of hydrogen energy in the United States, having invested considerable capital into commercializing hydrogen and fuel cell technology. Based on these investments, forecasts for hydrogen costs are encouraging — especially at industrial scale, prices are decreasing rapidly. Cost parity could be reached as soon as 2030, several years faster than previous estimates.

But hydrogen and fuel cell technology needs continued and dedicated local, state and federal support. Beyond that, private investment is crucial in commercializing this industry and expediting the pathway to cost competitiveness.

As we move forward, CHBC is optimistic about the future of hydrogen. We are confident that this technology will be essential as we continue to set — and meet — ambitious air quality and climate goals.

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