Hydrogen

Hydrogen is a feedstock and energy carrier used in multiple sectors.[1] Globally 95 Mt of hydrogen were produced and used in 2022[1] with 10 Mt in the U.S.[2] Hydrogen is the most abundant element in the universe, but is present in limited amounts in elemental form on Earth. The primary method of producing hydrogen is steam methane reforming (SMR) of natural gas (NG). SMR results in CO_2 emissions, which is problematic from a climate change perspective. Electrolysis is a hydrogen production process that uses electricity to split water into hydrogen and oxygen. This production process can provide a pathway for decarbonizing some sectors of the economy if the electricity is generated from zero- or low-carbon sources such as renewables and nuclear power. Hydrogen can play a key role in decarbonizing end-use applications where other alternatives such as electrification are problematic.[2]

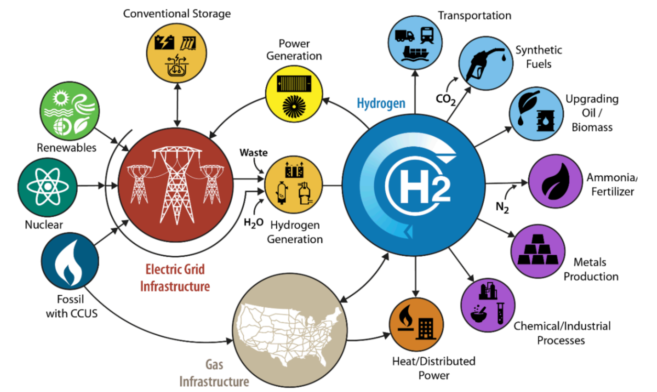
- Hydrogen has the highest energy per mass of any fuel at 120 MJ/kgH_2 on a lower heating value basis.[3]
- Hydrogen has a very low volumetric energy density of 8 MJ/L for liquid hydrogen[3], 5.6 MJ/L for compressed hydrogen gas at 700 bar pressure[4], compared to 32 MJ/L for gasoline at ambient conditions[3].
- Hydrogen can be stored as either a high-pressure gas, or low-temperature liquid.[3]
- Global demand for hydrogen could reach 150 Mt by 2030.[1]

Hydrogen Technologies

Production

- Hydrogen can be produced via several pathways including SMR, electrolysis of water, and gasification of coal or biomass.[6]
- Color codes have been used to describe hydrogen production pathways. Commonly used colors include grey for SMR, blue for SMR with carbon capture and sequestration (CCS), and green for electrolysis using renewable electricity.[7]
- In SMR, NG is reacted with high temperature steam to produce hydrogen. The resulting synthesis gas also contains CO and CO_2. Using the “water-gas shift reaction”, the CO and steam are reacted together over a catalyst producing more hydrogen and CO_2.[8]
- SMR is the least expensive (\$1-2/kgH_2) and most widely used method of producing hydrogen[6], accounting for 95% of hydrogen production at large central plants in the U.S.[9] Hydrogen produced with SMR emits about 7-10 kgCO_2/kgH_2.[10]
- Alkaline and proton exchange membrane (PEM) electrolyzers are commercially available, while solid oxide electrolyzer cell (SOEC) and anion exchange membrane (AEM) electrolyzers are maturing.[11]

DOE H2@Scale Diagram[5]



- The production cost for green hydrogen was about \$7.5/kgH_2 in 2020. The U.S. Department of Energy (DOE) targets are to lower this to \$2/kgH_2 by 2026 and \$1/kgH_2 by 2031.[12]
- The current grid mix is not ideal for electrolysis as around 60% of U.S. electricity is still produced using fossil fuels.[13] The CO_2 intensity of hydrogen produced by electrolysis is approximately 20-25 kgCO_2/kgH_2 in the U.S.[5]

Distribution and Storage

- Hydrogen in the U.S. is produced at, or near, where it will be used, reflecting difficulties with transportation.[6]
- Hydrogen can be transported to point of use via pipeline, or over the road using liquid tanker, or tube trailer trucks.[14]
- Pipelines have the lowest cost to deliver hydrogen at \$0.2-0.5/kgH_2. There are ~1,600 mi in the U.S.[6,15] Tube trailers transport compressed hydrogen, typically 200 miles or less, but are expensive at \$0.9-1.9/kgH_2. [6,15]
- Liquid tankers are better suited than tube trailers for transporting larger amounts of hydrogen over longer distances, but are more expensive at \$2.7-3.2/kgH_2 due to energy and equipment requirements for the liquefaction process. [6,15]
- Storage of hydrogen as a compressed gas typically requires high-pressure tanks at 350-700 bar (atmopheric pressure is 1.013 bar).[3]
- Liquid storage can achieve greater densities than compressed gas, but is more energy intensive and requires extremely low temperatures since its boiling point is −253°C (-423°F). [3,16]
- Underground hydrogen storage may be possible. Conventional options include salt caverns, while proposed sites include abandoned coal mines and refrigerated mined caverns.[17]

End-Uses

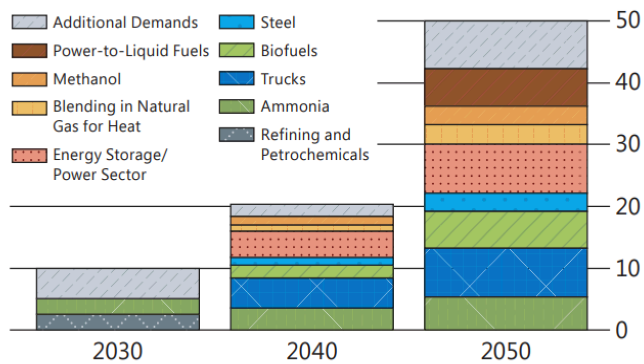
- Refining is the largest end use of hydrogen in the U.S., at about 5.5 Mt in 2021, followed by ammonia synthesis with around 3.5 Mt. Other uses include methanol production, and the direct reduction of iron (DRI) in steelmaking.[5] Producing DRI requires 47-68 kg H_2/ton.[9]

- A potential demand for hydrogen is synfuel production through reacting hydrogen with CO_2. When CO_2 captured from the air is used for hydrocarbon synfuel production, the carbon in the fuel can be considered net zero in emissions, though emissions from the CO_2 capture process may still occur.[19]
- Blending hydrogen with NG could result in rapid demand increase. Preliminary estimates say hydrogen can be injected into NG pipelines up to concentrations of 20% by volume, but co-firing with NG reduces GHG emissions only 6-7%. [19, 20]
- Hydrogen burners are currently under development to replace NG and other fossil fuels in high-temperature heat applications, including cement clinker kilns, glass furnaces, aluminum remelting furnaces, metal rolling, and heat treatment furnaces.
- Hydrogen can be used in residential buildings to power fuel cell combined heat and power (CHP) systems, direct flame combustion boilers, catalytic boilers, and gas-powered heat pumps. Larger district heat and CHP devices using NG could be redesigned for hydrogen.[21]
- Hydrogen can be used in conventional and synfuels in all forms of transportation (road, rail, water, air). Global refining used over 41 Mt H_2 in 2022, which was more than 1,000 times the direct use of hydrogen as a transportation fuel.[1]
- Hydrogen transportation uses in the U.S. include more than 50k fuel cell forklifts, nearly 50 retail hydrogen fueling stations, over 80 fuel cell buses, and more than 15k fuel cell vehicles.[5]
- Electric-powered transport is currently 3-8 times more energy efficient than hydrogen alternatives.[22]
- Hydrogen is not well suited for light-duty vehicles, but is expected to decarbonize heavy-duty transport where storing large amounts of energy and rapid refueling are challenging for electric vehicles.[1,2]

Environmental Impacts

- Concerns around hydrogen include NOx emissions from high-temperature combustion[23], methane leakage from blue hydrogen production[24, 25, 26], and atmospheric reactions with greenhouse gases (e.g., CH_4, O_3, H_20) leading to positive radiative forcing.[27]
- However, in general climate benefits for hydrogen depend on the specific use case, the production method, hydrogen and methane emission rates, the availability of renewable electricity, and the time scale of interest.[24,]
- Global warming potential for hydrogen reported in the literature ranges from 4.3 to 12.8.[27]
- Green hydrogen production using renewable electricity is estimated to result in a 66-95% reduction in warming relative to the displaced fossil fuel technologies.[24]
- Electrolysis represents less than 5% of worldwide hydrogen production now, but is a pathway to zero-carbon emissions.[28]

U.S. Projected Growth in Hydrogen End-Uses (Mt/yr)[5]



- On a stoichiometric basis, the water consumption required for electrolysis is 9 kgH_2O/kgH_2.[29] When accounting for electricity generation, water use increases to 15-20 kgH_2O/kgH_2.[30]
- The water required to produce 800 Mt of hydrogen for a net zero economy in 2050 is much less than what is needed for the extraction and processing of fossil fuels today. Hydrogen production on this scale would account for 0.7% of global freshwater use. [30] Desalination would add approximately $0.02/kg to the price of hydrogen made from salt water.[30]

U.S. Hydrogen Strategy and Policy

- The Infrastructure Investment and Jobs Act provided $9.5B for hydrogen[31], including $7B to the Regional Clean Hydrogen Hubs Program (H2Hubs) to form the foundation of a national clean hydrogen network[32]. Seven hydrogen hubs have been selected by DOE, including the Midwest Alliance for Clean Hydrogen (MachH2).[33]
- The U.S. National Clean Hydrogen Strategy and Roadmap from the DOE explores pathways for clean hydrogen to aid in decarbonization goals across the economy.[5]
- The Inflation Reduction Act (IRA) offers up to a 30% Investment Tax Credit and a $3/kg$H_2$ (2022 value) Production Tax Credit for clean hydrogen production.[31]
- The U.S. Federal Highway Administration designated a national network of electric vehicle charging and hydrogen, propane, and NG fueling infrastructure along interstate highway corridors.[34]

IRA Tax Credits for Hydrogen[31]

Life Cycle Emissions ($kgCO_2e/kgH_2$)	Investment Tax Credit (%)	Production Tax Credit (2022$/$kgH_2$)
2.5-4	6%	0.60
1.5-2.5	7.5%	0.75
0.45-1.5	10%	1.00
0-0.45	30%	3.00