Hydrogen

Hydrogen is a not an energy source but an "energy carrier." Hydrogen is produced using *other* energy, but once produced, hydrogen is transportable, storable, and usable in a variety of formats in a way that other forms of energy are not. Hydrogen is clean burning, and the only byproduct is water vapor.

There are various ways of producing hydrogen, some more proven than others:

- Steam-methane reforming separates hydrogen atoms from the carbon atoms in methane (CH_4) by reacting methane with high-pressure steam. The source of methane in this application can be from natural gas, landfill gas/biogas, petroleum, or biofuels. Hydrogen produced through steam-methane reforming releases CO_2.[1] When this CO_2 is captured and stored, the hydrogen produced this way is called "blue" hydrogen.[2] When this CO_2 is released into the atmosphere, the hydrogen produced this way is called "gray" hydrogen.[3] Steam-methane reforming accounts for the majority of current commercial hydrogen production in the U.S.[4]
- Electrolysis splits hydrogen from the oxygen atoms in water by using an electric current. When employed at an industrial scale, electrolysis is known as "power to gas" because it uses power (electricity) to yield gas (hydrogen, which can then be converted back to electricity again by recombining with oxygen whenever electricity is needed). When this electricity is from renewable sources, the hydrogen produced this way is called "green" hydrogen.[5] When this electricity is from nuclear power, the hydrogen produced this way is called "pink" hydrogen.[6] When it is produced by nuclear power combined with heat, it is called "purple" hydrogen.[7] When it is produced by nuclear power through the high-temperature catalytic splitting of water, it is called "red" hydrogen.[8]
- Coal gasification is the incomplete oxidation of coal, a carbohydrate, to produce carbon monoxide, which is then reacted with steam to yield hydrogen and CO_2.[9] Hydrogen produced from gasification of brown (lignite) coal is called "brown" hydrogen and hydrogen produced from gasification of black (bituminous) coal is called "black" hydrogen.[10]

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[1] EIA. "Hydrogen explained." https://www.eia.gov/energyexplained/hydrogen/production-of-hydrogen.php
[2] H2 Bulletin. "Hydrogen colours codes." https://www.h2bulletin.com/knowledge/hydrogen-colours-codes/
[3] H2 Bulletin. "Hydrogen colours codes." https://www.h2bulletin.com/knowledge/hydrogen-colours-codes/
[4] EIA. "Hydrogen explained." https://www.eia.gov/energyexplained/hydrogen/production-of-hydrogen.php
[5] H2 Bulletin. "Hydrogen colours codes." https://www.h2bulletin.com/knowledge/hydrogen-colours-codes/
[6] H2 Bulletin. "Hydrogen colours codes." https://www.h2bulletin.com/knowledge/hydrogen-colours-codes/
[7] H2 Bulletin. "Hydrogen colours codes." https://www.h2bulletin.com/knowledge/hydrogen-colours-codes/
[8] H2 Bulletin. "Hydrogen colours codes." https://www.h2bulletin.com/knowledge/hydrogen-colours-codes/
[9] Allen, Jessica.
[10] H2 Bulletin. "Hydrogen colours codes." https://www.h2bulletin.com/knowledge/hydrogen-colours-codes/

- Pyrolysis produces hydrogen by heating methane (CH_4) to produce hydrogen and CO_2. Hydrogen produced in this way is called "turquoise" hydrogen.[11] This is a newly emerging technology that is considered cleaner than "gray" hydrogen because the CO_2 byproduct is in solid form, rather than in gaseous form that can be emitted into the atmosphere.[12]
- Microbial fermentation uses microorganisms to break down biomass (e.g., refined sugars, corn stover, or wastewater), and the byproducts of fermentation are then combined by enzymes to produce hydrogen.[13]

Once hydrogen is produced, it can be stored until it is needed. This hydrogen can then be used for electricity generation or transportation. Typically, this takes place within a hydrogen fuel cell, in which hydrogen can be reacted with oxygen across an electrochemical cell similar to a battery.[14] The process produces only water and a small amount of heat as byproducts. Fuel calls can range from very small (e.g., to power a laptop computer) to military applications and space ships. Fuel cells can be placed in buildings to provide electricity and in vehicles to provide mobility. It is also possible to burn hydrogen in a power plant by combining it with natural gas.[15]

There are 166 operating fuel cell electric power generators at 113 facilities in the U.S., with a combined capacity of about 260 MW.[16] The major hydrogen-producing states are California, Louisiana, and Texas. Most of the hydrogen produced in the U.S. at present is used for refining petroleum, treating metals, producing fertilizer, and processing foods.[17] Europe is currently pursuing hydrogen energy more zealously than the U.S., in part driven by the European Union's commitment to net zero emissions by 2050.[18]

One challenge facing broader deployment of the so-called "hydrogen economy" is distribution. Hydrogen can be distributed through pipelines, high-pressure tube trailers, and liquefied hydrogen tankers. About 1,600 miles of hydrogen pipeline exist currently near petroleum refineries in Illinois, California, and the Gulf Coast. Natural gas pipeline infrastructure can be converted to carry hydrogen, but requires expensive upgrades due to hydrogen's tendency to "embrittle" pipes and its small molecular size, which makes it more prone to leakage.[19] High-pressure tube trailers containing compressed hydrogen can be loaded onto trucks, railcars, and ships, but this method is expensive and is generally only used to transport hydrogen 200 miles

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[11] H2 Bulletin. "Hydrogen colours codes." https://www.h2bulletin.com/knowledge/hydrogen-colours-codes/
[12] Florence School of Regulation. "Between green and blue: A debate on turquoise hydrogen." https://fsr.eui.eu/between-green-and-blue-a-debate-on-turquoise-hydrogen/
[13] DOE. "Hydrogen production: Microbial biomass conversion." https://www.energy.gov/eere/fuelcells/hydrogen-production-microbial-biomass-conversion
[14] EIA. "Hydrogen explained." https://www.eia.gov/energyexplained/hydrogen/use-of-hydrogen.php
[15] EIA. "Hydrogen explained." https://www.eia.gov/energyexplained/hydrogen/use-of-hydrogen.php
[16] EIA. "Hydrogen explained." https://www.eia.gov/energyexplained/hydrogen/use-of-hydrogen.php
[17] DOE. "Hydrogen production and distribution." https://afdc.energy.gov/fuels/hydrogen_production.html
[18] van Renssen, Sonja. 2020. The hydrogen solution? *Nature Climate Change* 10: 799-801. DOI: 10.1038/s41558-020-0891-0
[19] DOE. "Hydrogen pipelines." https://www.energy.gov/eere/fuelcells/hydrogen-pipelines

or less. Hydrogen is lightweight, but it contains less energy per unit volume than all other fuels. This makes transporting and storing it very expensive. As a result, most hydrogen is currently produced near the sites where it is used, such as large industrial sites. On the positive side, the fact that hydrogen can be produced from so many different sources means that there is high potential to produce it locally or regionally, making long-distance transportation unnecessary.[20]

Hydrogen was first used during World War II, when the Nazis used it to produce synthetic fuels from coal,[21] but despite much talk, it has never taken off as a major component of the energy system. Some experts have dismissed it as "hydrogen hype," saying that hydrogen has lost the race to batteries when it comes to storage and transportation. But others say it can fill some critical gaps in the energy portfolio. First, it can help solve the intermittency problem by storing surplus renewables power when the grid cannot absorb it.[22] Second, it can help decarbonize hard-to-electrify sectors such as long-distance transport and heavy industry. [23] Third, it can replace fossil fuels as a zero-carbon feedstock in chemicals and fuel production.[24]

The use of hydrogen in fuel cells has no environmental impacts itself; all environmental impacts take place during the production and distribution phase. For gray, black, and brown hydrogen, there are impacts associated with fossil fuel extraction and combustion. For green hydrogen, there may be impacts associated with renewable energy generation. For pink, purple, and red hydrogen, there may be impacts associated with nuclear power.

Green hydrogen is currently more expensive than fossil-based hydrogen: on a globally averaged basis, green hydrogen costs $3-$6 per kilogram (kg), compared to $1.5-$2.5/kg for blue hydrogen.[25] Some experts call for short-term subsidies to help close the gap, such as production tax credits, loan guarantees, contract-for-difference schemes (in which the government makes up the difference between an agreed-upon rate and the market price of energy), green procurement policies, and regulatory and supportive standards to encourage widespread use of hydrogen as an energy carrier. [26]

- Fishery friendliness: Since hydrogen is an energy carrier (analogous to energy storage) its impacts to fisheries are determined by the source of energy that is used to produce it, which can be renewable, fossil fuel-based, or nuclear.
- Co-benefits: None

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[20] DOE. "Hydrogen production and distribution." https://afdc.energy.gov/fuels/hydrogen_production.html

[21] van Renssen, Sonja. 2020. The hydrogen solution? *Nature Climate Change* 10: 799-801. DOI: 10.1038/s41558-020-0891-0

[22] van Renssen, Sonja. 2020. The hydrogen solution? *Nature Climate Change* 10: 799-801. DOI:10.1038/s41558-020-0891-0

[23] van Renssen, Sonja. 2020. The hydrogen solution? *Nature Climate Change* 10: 799-801. DOI:10.1038/s41558-020-0891-0

[24] van Renssen, Sonja. 2020. The hydrogen solution? *Nature Climate Change* 10: 799-801. DOI:10.1038/s41558-020-0891-0

[25] IRENA. 2020. *Green hydrogen cost reduction*. https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction

[26] Beagle, Emily (November 22, 2021). "Policy priorities to spur the green hydrogen economy." *Green Biz.* https://www.greenbiz.com/article/these-policies-are-needed-spur-green-hydrogen-economy

- Environmental externalities: Since hydrogen is an energy carrier (analogous to energy storage) its environmental impacts are determined by the source of energy that is used to produce it, which can be renewable, fossil fuel-based, or nuclear.
- Policy catalysts: Production of green or clean hydrogen can be promoted through tax incentives, loan guarantees, contract-for-difference schemes, green procurement policies, renewable/clean energy portfolio standards, carbon pricing, lead-by-example programs, and government-sponsored research and development.
- More information:
  - DOE: "Alternative fuels data center: Hydrogen."
  - EIA: "Hydrogen explained."
  - DOE: "Hydrogen production and distribution."
  - van Renssen, Sonja. 2020. The hydrogen solution? *Nature Climate Change* 10: 799-801.
  - Kakaras, Emmanouil (November 23, 2021). "The 'hydrogen hype' is justified: Here's why." *Forbes.*
  - Alter, Lloyd. "Hydrogen science coalition cuts through the 'hydrogen hype.'" *Treehugger.*

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