Clean hydrogen overview

Not yet economic, but may reach grey hydrogen parity from 2030-2050

Overview

Clean hydrogen, produced by electrolysis of water using renewable power ("green" hydrogen) or from fossil fuels in conjunction with carbon capture and storage ("blue hydrogen") is currently more expensive than "grey" or "brown" hydrogen, produced by steam methane reforming (SMR) of natural gas or gasification of coal. Costs are dropping with reductions in the cost of renewable power, economies of scale and technological changes, and are expected to reach parity with grey hydrogen in advantaged locations by 2050 and earlier with pricing of carbon emissions, assuming government policy support and subsidies. The key variables driving green hydrogen economics are the cost of renewable power and renewables plant utilization. The best locations for green hydrogen production are those with large, high quality renewable resources with access to storage and transport and without competing land use, however, these may not be located near demand centres. Key challenges include development of suitable storage and transportation infrastructure.

Key points

"Coloured" hydrogen: different types of hydrogen are recognized based on the source: "green" from hydrolysis of water using renewable energy, "blue" from fossil or biofuels combined with carbon capture and storage (CCS), "grey" (and "brown") from natural gas and coal without CCS, "pink" from hydrolysis using nuclear energy and various others, listed below.

Current market is 99% grey: The current market for hydrogen is ~70 Mtpa. [2]. Production is almost entirely based on fossil fuels, with 71% from natural gas and 29% from coal, and only 0.1% from renewables.

Wide range of uses: The most important current uses of hydrogen are in ammonia synthesis and petroleum refining (hydrocracking and sulphur reduction). Emerging uses include energy storage for renewables balancing, difficult-to-decarbonize industries such as steel and cement, blending with methane in gas pipelines and fuel cells for electric vehicles.

Green hydrogen is currently expensive, costing €3 to €8/kg, compared with grey hydrogen at €1 to €2/kg (without a price on carbon emissions) [1]. CCS adds $US0.50/kg. [2]. They key cost drivers are power prices and renewables plant availability, followed by capex. The cost of electrolyzers is falling, reducing by 40% between 2014 and 2019. Costs will continue to decrease, due to falling renewable energy costs, economies of scale and technological advances. WoodMac estimates green hydrogen with a carbon price of US$40/t could reach parity with blue hydrogen in 2030.

Parity with grey hydrogen by 2050: BNEF expects costs to reach $US2/kg ($US15/MMBtu) by 2030 and $US1/kg ($US7.40/MMBtu) by 2050, comparable to grey hydrogen without CCS. Costs could be 20-25% lower in countries with the best renewable and hydrogen storage resources, such as the U.S., Brazil, Australia, Scandinavia and the Middle East. However, costs could be 50-70% higher in places like Europe, Japan and Korea that have weaker renewable resources and unfavorable geology for storage, making these markets likely importers of hydrogen. WoodMac estimates with sub-US$30/MWh electricity prices, green hydrogen production can be competitive with grey hydrogen in Australia, Germany and Japan by 2030 [1].

Favoured locations: Hydrogen is likely to be most competitive in large-scale local supply chains in regions with good renewable resources and large-scale geological storage, where clusters of industrial customers can be supplied by dedicated pipeline networks.

Green hydrogen production to grow: demand is expected to grow steadily through niche applications until 2030, before accelerating, with demand in 2050 ranging from 150-500 Mtpa, depending on global climate ambitions and the development of sector-specific activities, energy-efficiency measures, direct electrification and the use of carbon-capture technologies.

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Policy revisions and subsidies required: Use of green hydrogen could cut global greenhouse gases by 34% by 2050 but will require major policy revisions and subsidies of ~$US150b over the next decade (less than what fossil fuels currently receive) to reach parity with grey hydrogen [1]. The subsidies would support development of supply chains and infrastructure.

Existing projects: Existing green hydrogen capability is small, with only ~250 MW of capacity [3]. The pipeline of new projects is growing fast, with 3.2 GW expected by 2025. Rising membership of the Hydrogen Council, formed in 2017, reveals the widespread interest across multiple sectors including automakers (e.g. BMW, GM and Honda), power and gas utilities (Engie and EDF), engineering (Bosch, Alstom), and oil and gas (Aramco, Shell, BP, Total and Equinor). WoodMac expects hydrogen could displace 1400 Mtoe of primary energy demand by 2050 under a 2-degree scenario, 10% of global supply, with green hydrogen the majority of that.

Complements renewables: Green hydrogen electrolyzers require only seconds to operate at maximum capacity and can be paired with renewable assets to store energy for later use.

Hydrogen could meet ~25% of global energy needs by 2050: BNEF estimates that if strong and comprehensive policies are in place 696 Mt of hydrogen could be produced by 2050, supplying 24% of the final energy demand in a 1.5 °C warming scenario. This would take more electricity than the world generates now from all sources and investment of $11 trillion. With supportive but piecemeal policy production is likely to be limited to 187 Mt, equivalent to 7% of final energy needs. If all the unlikely-to-electrify sectors in the economy used hydrogen, demand could be as high as 1,370 Mt.

New markets should target hard-to-abate sectors: Hydrogen is a promising emissions reduction pathway for the hard-to-abate industry sectors that require the physical and chemical properties of molecular fuels. At $US1/kg, a carbon price of $US50/tCO_2$ would be enough to switch to renewable hydrogen in steel making, $60/tCO_2$ for heat in cement production, $US78/tCO_2$ for ammonia synthesis, and $90/tCO_2$ for aluminum and glass manufacturing [1].

Targeted role in transportation: Hydrogen can play a valuable role decarbonizing long-haul, heavy-payload trucks, which could be cheaper to run using hydrogen fuel cells than diesel engines by 2031. However, battery electric drive trains are expected to be cheaper for the bulk of the car, bus and light-truck market. Green ammonia from hydrogen is a potential option for ships and could be competitive with heavy fuel oil with a carbon price of $145/tCO_2$ in 2050.

Significant challenges: China, much of Europe, Japan, Korea and South East Asia may not have enough suitable land to generate the renewable power required for green hydrogen production, requiring international trade and transportation. Blue hydrogen (from fossil fuels with CCS) may still be required to play a significant role, particularly in countries like China and Germany that could be short on land for renewables but are well-endowed with gas and coal.

Storage and transportation issues: Hydrogen's low energy density (on a volumetric basis) makes it harder to store and transport than fossil fuels. Storage options such as salt caverns are geographically limited and the cost of alternative liquid storage technologies is often greater than the cost of producing the hydrogen [1]. Pipeline transportation is possible, and hydrogen can be blended with natural gas at up to 15-20% (and sometimes higher), depending on existing infrastructure. Hydrogen is expensive to transport via road or ship, with liquefaction to increase energy density requiring 700 atmospheres of pressure or -253 °C (c.f. LNG at -161 °C).

Alternative sources of hydrogen: SGH2 Energy Global, LLC, a subsidiary of Solena Group, is focused on the gasification of waste into hydrogen. SGH2 has projects in development in Australia, UK, China, South Korea, Japan and the US, and recently announced it would build a facility to produce "greener than green" hydrogen in southern California. It estimates production costs of $US2/kg [4].

Signposts of a developing hydrogen economy: BNEF lists seven indicators: (1) net-zero climate targets are legislated, (2) standards governing hydrogen use are harmonized and regulatory barriers removed, (3) targets with investment mechanisms are introduced, (4) stringent heavy transport emission standards are set, (5) mandates and markets for low-emission products are formed, (6) industrial decarbonization policies and incentives are put in place and (7) hydrogen ready equipment becomes commonplace.

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1. Types of hydrogen and existing green hydrogen projects

Table 1 Types of hydrogen

Type	Description
Green	Produced by electrolysis of water using renewable energy (e.g. wind and/or solar).
Blue	Produced from natural gas (or coal or biomass) using steam methane reforming (SMR) or autothermal reforming (ATR), combined with carbon capture and storage (CCS)
Grey	Produced from natural gas using SMR or ATR, without CCS. Current dominant technology.
Brown	Produced from coal, without CCS.
Pink	Produced by electrolysis of water using nuclear energy.
Yellow	Produced by electrolysis of water using only solar energy.
Emerald ("Greener than green")	Produced by gasification of waste.
Turquoise	Produced by methane pyrolysis of natural gas using renewable energy. Produces solid carbon. No requirement for CCS. Significantly lower energy consumption than electrolysis (10-20 kWh/kg H_2 vs 60 kWh/kg). First commercial plant online 2022.

Source: Petrofac, https://www.petrofac.com/en-gb/media/our-stories/the-difference-between-green-hydrogen-and-blue-hydrogen/, accessed 19th May 2021; Pure Hydrogen, June 2021 quarterly report, 30th July 2021; Florence School of Regulation, https://fsr.eui.eu/between-green-and-blue-a-debate-on-turquoise-hydrogen/, accessed 6th August 2021.

Table 2 Existing green hydrogen projects

Location	Description
Saudi Arabia	Saudi Arabia is constructing a futuristic city on the Red Sea from scratch, called Neom. The $500 billion city will be home to one million people and uses 4 GW of renewable electricity from wind and solar to produce hydrogen from water.
Europe	Europe, which is saddled with high energy prices and is heavily dependent on Russian natural gas, is providing funding for construction of electrolysis plants and other hydrogen infrastructure. Germany has allocated the largest share of its clean energy stimulus funds to green hydrogen.
USA	Intermountain Power Project in Utah will replace two aging coal-fired plants and produce electricity for southern California, using a salt dome for hydrogen storage. Startup is expected in 2025. In late 2020 a group of heavy-duty vehicle users and energy industry officials formed the Western States Hydrogen Alliance to press for rapid deployment of hydrogen fuel cell technology and infrastructure to replace diesel trucks, buses, locomotives, and aircraft.
Japan	The 1,200 Nm3/hr Fukushima Hydrogen Energy Research Field (FH2R), one of the world's largest green hydrogen plants, opened in March 2020. The hydrogen will be used to power stationary and vehicular fuel cells.
Australia	The proposed "Asian Renewable Energy Hub" in the Pilbara comprises 1,743 wind turbines and ~80 sq km of solar panels to run a 26-gigawatt electrolysis plant to create green hydrogen to send to Singapore. The University of New South Wales, in partnership with global engineering firm, GHD, has created a home-based system called LAVO that uses solar energy to generate and store green hydrogen in home systems, with conversion back into electricity as needed.

Source: Yale School for the Environment [2]

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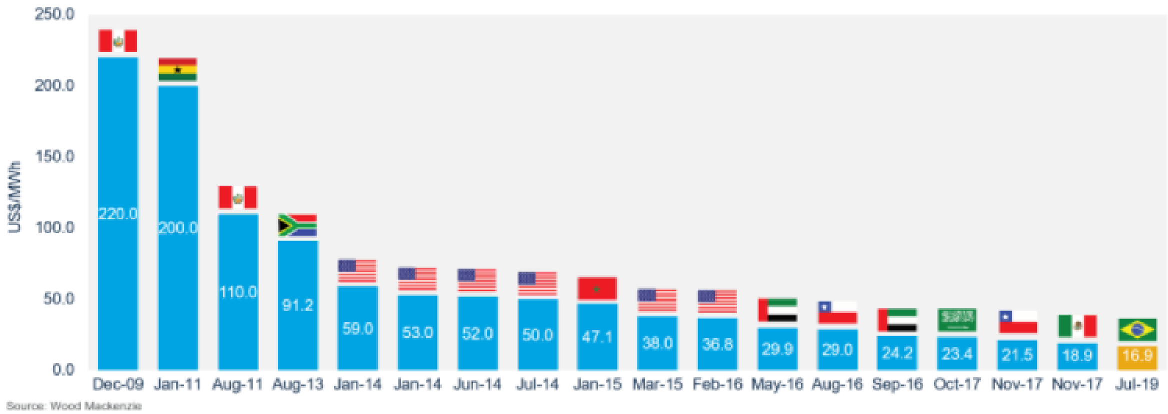
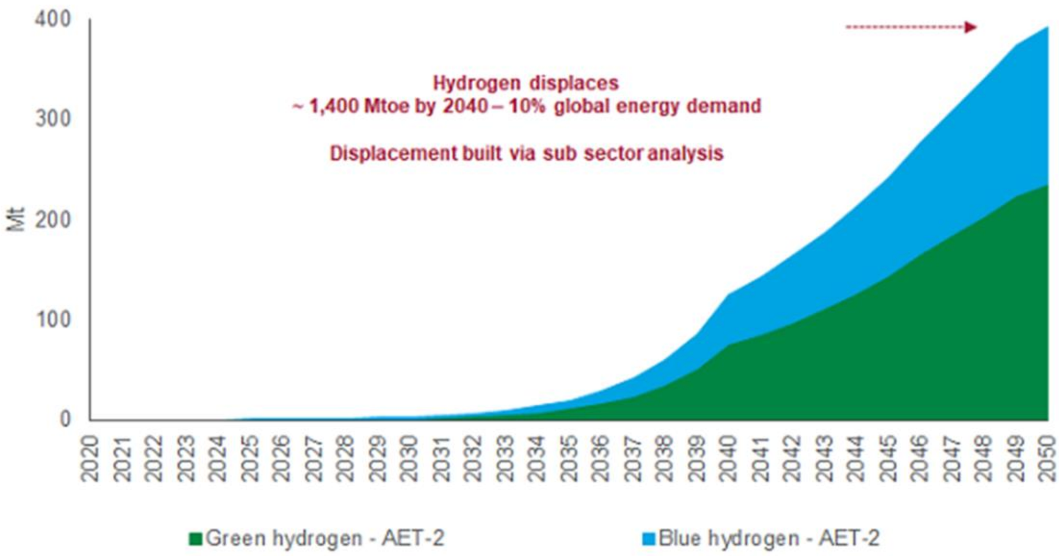
2. Power pricing and hydrogen demand estimates

Figure 1 Renewable power purchase agreement price trajectory



Source: WoodMac, [3]

Figure 2 WoodMac estimate of hydrogen demand under a 2-degree Celsius pathway



Source: WoodMac, [2]

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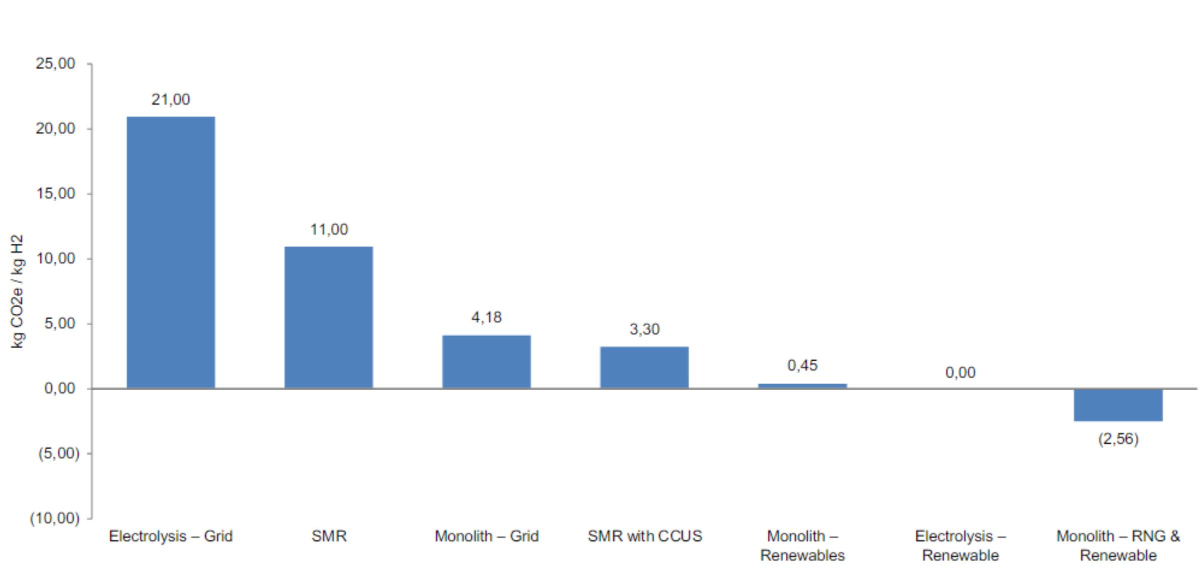
3. Carbon intensity of hydrogen production

Figure 3 Carbon intensity of hydrogen production



Source: Laurent Fulcheri, "Methane Pyrolysis", Florence School of Regulation, 17th March 2021. Original chart from Monolith Materials, USA.

4. Hydrogen properties

Table 3 Hydrogen properties

Property	Units	Value	
Atomic weight	kg/kg mol	1.008	
Molecular weight	kg/kg mol	2.016	
Melting point	°C	-259	
Boiling point	°C	-253	
Density (gas)	kg/m3	0.090	At 20 °C at 1 atm
Density (liq)	kg/m3	0.70	
Explosive limit	%	4-75	
Ignition temp.	°C	585	
HHV	MJ/kg	141.7	=134.3 MMBtu/tonne
LHV	MJ/kg	120.0	=113.7 MMBtu/tonne
Specific volume	Boe/tonne	23.16	HHV @ 5.8 MMBtu/boe

Source:
1) Libretexts [6]
2) Lenntech [1]
3) Engineering toolbox [8]

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