Greenwheel Insights

Hydrogen and Net Zero: An Overview

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> **"Hydrogen is often hailed as the solution to all challenges to decarbonisation of the global economy. This piece from Greenwheel offered me valuable, actionable insights into the most viable use cases for hydrogen, noting the obstacles to adoption for other uses and crucially, the most likely alternative technologies in these instances."**
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> **Amanda O'Toole, Portfolio Manager, Redwheel Biodiversity and Clean Economy Strategies**

Key Takeaways

- Under the IEA's Net Zero Scenario, low-carbon hydrogen accounts for 6% of emission reductions by 2050. However, different hydrogen production processes have different lifecycle GHG emission implications, and the strength of argument for different hydrogen use cases varies significantly.

- Hydrogen production processes can be classified according to the 'Hydrogen Rainbow'. Almost all hydrogen currently produced is 'grey', which means it is extracted from natural gas and produces CO2 emissions that are not captured or stored.

- Less than 1% of hydrogen is currently produced using 'low carbon' processes. This includes extraction of hydrogen from fossil fuels or biomass with resulting emissions captured and subsequently stored or used, or hydrogen from water using electrolysis powered by renewable or nuclear electricity.

- Producing low-carbon hydrogen is currently expensive, but with policy support, could become competitive by 2030. Although more than 40 countries have developed a hydrogen strategy, there is a lack of policy support to stimulate demand for low-carbon hydrogen. There are also different approaches to the definitions and forms of low-carbon hydrogen promoted in different countries and regions.

- There are few or no alternatives to hydrogen in the production of fertiliser, desulphurisation in oil refining and hydrogenation in petrochemical production. Hydrogen also presents the most promising path for decarbonising iron and steel production, and for long-term electricity storage in the power sector - although in both cases, alternatives are possible.

- Low-carbon hydrogen, in the form of ammonia or synthetic fuels, are likely to be competitive in fuelling shipping and medium-to-long-haul aviation. For most land transport modes, along with domestic, commercial and low-to-mid-temperature industrial heating, electrification is very likely to win out – manly due to the implications and cost of producing and using low-carbon hydrogen compared to electrification in these sectors, but supported by a range of wider technical and economic factors.

- The Hydrogen Ladder provides a useful framework for placing key potential use cases for low-carbon hydrogen on a scale according to its likely application. Illustrated below, it also indicates the energy carrier or technology that presents the greatest competition to hydrogen. It is important to note that that mapping of potential hydrogen applications and likely dominant alternatives is based on a global view, obscuring specific circumstances in some end uses where hydrogen could be more or less competitive than indicated.

Why is Hydrogen Important to Net Zero?

Hydrogen emits no CO_2 when used and is a versatile energy carrier. Hydrogen is a key input to the refining and chemicals sectors and can play a crucial role in decarbonising other sectors and processes to which other low-carbon energy carriers, such as electricity generated by renewables, are less suited.

Hydrogen is the most common element in the universe, but on Earth, it is largely bound up in compounds or materials, such as fossil fuels, biomass, or water. Depending on the process applied to extract hydrogen from these resources, lifecycle GHG emissions range from significantly above fossil fuels, to very low or even negative.[1]

Under the IEA's Net Zero Scenario, low-carbon hydrogen accounts for 6% of emission reductions by 2050 (IEA, 2023). However, there is significant discussion around the characteristics and prospects of different forms of hydrogen production, and the sectors and processes in the economy in which it may be used. This brief provides an overview of the different forms of hydrogen production (using the 'Hydrogen Rainbow'), and the broad suitability and prospects for using low-carbon hydrogen to decarbonise key end-uses (using the 'Hydrogen Ladder' concept).

The Hydrogen Rainbow

The Hydrogen Rainbow describes the range of hydrogen production processes and assigns them colours based on their different characteristics. The colours do not relate to the physical characteristics of the resulting hydrogen, which are identical regardless of production process.

Roughly 92% of hydrogen used in 2022 was grey hydrogen while low-emission hydrogen accounted for less that 1%. The development of low-carbon hydrogen, and particularly green hydrogen, will depend significantly on policy support. Although more than 50 countries have developed a hydrogen strategy , there is a lack of policy support to stimulate demand for low-carbon hydrogen (IEA 2023).

There are also different approaches to the definitions and forms of low-carbon hydrogen being promoted in different countries and regions. For example, policy frameworks in the USA and Japan appear to favour blue hydrogen, while those in the EU favour green hydrogen (IEA 2023).

[1] Brown hydrogen has a CO2 intensity of 19 kgCO2/kg, equivalent to 158 gCO2/MJ. Motor gasoline, for example, has a CO2 intensity of 69 gCO2/MJ. Hydrogen production may be negative if extracted from biomass, with subsequent GHG emissions captured and stored.

Although there is no universally agreed naming convention and definitions. Table 1 presents those which are commonly used.[2]

Table 1: The Hydrogen Rainbow

Colour	Definitions	Comments
Grey	Produced by steam methane reformation of fossil hydrocarbons, usually natural gas (CH_4), with resulting GHG emissions not captured	Currently the most common and cheapest production process, used as a feedstock for fertiliser, methanol production, and refining. The price is largely driven by that of natural gas. Generates moderate GHG emissions.
Black/Brown	Produced by the gasification of coal. Black hydrogen is produced from black coal, while brown hydrogen is from brown coal (lignite) or biomass, with resulting GHG emissions not captured	More expensive than grey, but cheaper than blue or green. Price is driven by that of coal. The most GHG intensive hydrogen production process (Gupta, 2022).
Blue	Produced by the same processes as grey, black, and brown hydrogen, but captures and subsequently stores or reuses the emitted GHGs	Slightly more expensive than grey or brown/black hydrogen, but cheaper than green. Requires CCUS technology, which is immature at scale. However, deployment is increasing (IEA, 2023). Price driven by that of feedstock and CCUS process. Key uncertainties include difficulty estimating storage requirements and the risk of CO_2 leakage (Lee *et al*, 2019). May be considered low-carbon hydrogen.
Yellow	Produced by water electrolysis using grid electricity (sometimes used to refer to electricity from solar power, considered under 'green' here)	Price and lifecycle CO_2 emissions is driven primarily by the price and CO_2 intensity of electricity from the grid, alongside the cost of electrolysers (also applies to the two electrolytic processes below) (IRENA, 2020).
Green	Produced by water electrolysis using renewable electricity	Primarily driven by the cost of renewable electricity, green hydrogen is on average the most expensive, but with a significant cost range. However, the falling costs of renewable electricity and electrolysers means that green hydrogen could be cost-competitive with other forms by 2030 (IRENA, 2020). May be considered low-carbon hydrogen.
Pink (or Purple/Red)	Produced via water electrolysis using some combination of heat and electricity from nuclear power	If using existing nuclear capacity, then currently significantly cheaper than green (new nuclear likely produces comparable cost)(Soja *et al*, 2023). However, existing capacity would require upgrades to achieve particularly low costs (Karaca *et al*, 2023). May be considered low-carbon hydrogen.

[2] Other, less material, processes include *'turquoise'* (use of methane pyrolysis to produce hydrogen and solid carbon), and *'white/gold'* hydrogen (geological hydrogen found in underground deposits created through fracking).

The Hydrogen Ladder

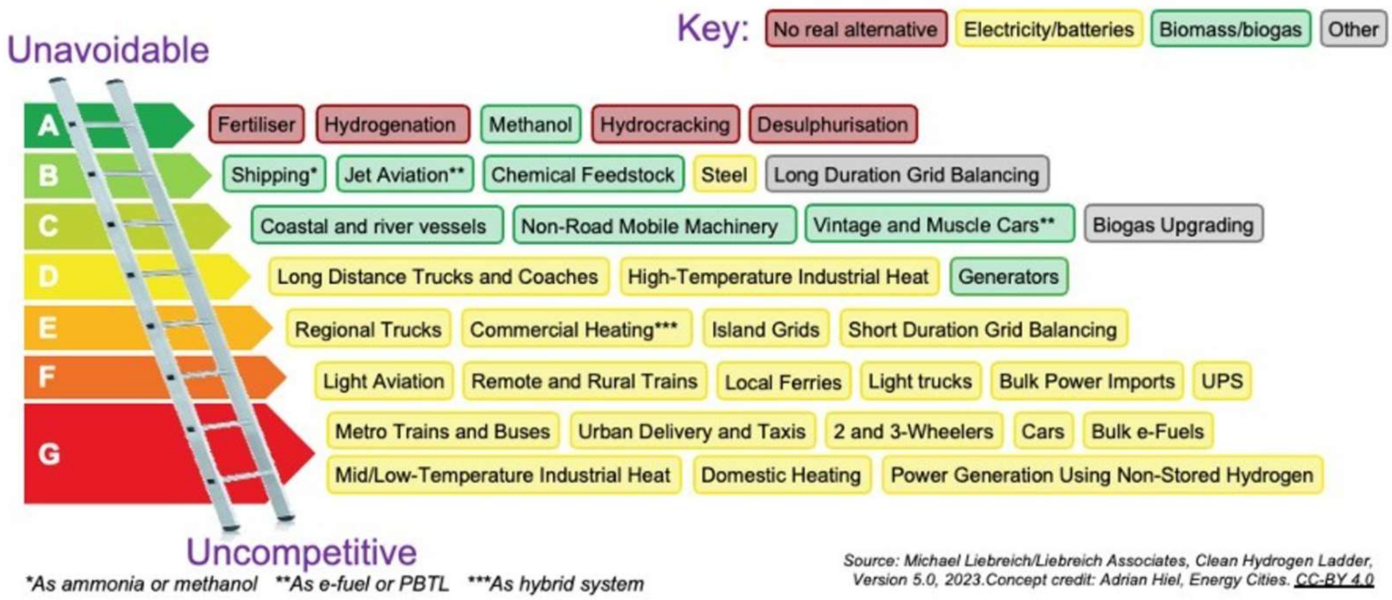
Hydrogen may be used as an energy source for numerous applications across a wide range of sectors, either in its natural form or products derived from it (such as ammonia). However, this does not mean that low-carbon hydrogen is always – or often - the most appropriate low-carbon energy choice. For many applications, other low carbon energy carriers and technologies will have technical or economic advantages.

Developed by Michael Liebreich,[2] the 'Hydrogen Ladder' is a useful concept for placing key potential use cases for low-carbon hydrogen on a scale according to its competitive position, running from applications in which the use of low-carbon hydrogen is unavoidable, to those in which it is highly unlikely to be competitive with other low carbon energy sources and technologies.

The 'Hydrogen Ladder' is a useful concept for placing key potential use cases for low-carbon hydrogen on a scale according to its likely application.

The Ladder is presented below. Also indicated is the energy carrier or technology that presents the greatest competition to hydrogen for the end uses considered. The Ladder is constructed using a combination of factors, including thermodynamics, economics, safety, human behaviour, resilience and geopolitics. It is important to note that that mapping of potential hydrogen applications and likely dominant alternatives is based on a global view, obscuring specific circumstances in some end uses where hydrogen could be more or less competitive than indicated (Liebreich Associates, 2023). It is also not an exhaustive list of uses to which hydrogen may technically be applied. However, we believe the broad rankings presented by the Ladder, including key competing energy carriers and technologies, is a reasonable reflection of the different factors at play.

Figure 1: The Hydrogen Ladder



**As ammonia or methanol **As e-fuel or PBTL ***As hybrid system*

Source: Michael Liebreich/Liebreich Associates, Clean Hydrogen Ladder, Version 5.0, 2023.Concept credit: Adrian Hiel, Energy Cities. CC-BY 4.0

Source: Michael Liebreich/Liebreich Associates, as of 2023

Unavoidable/very likely uses (Row A)

Hydrogen is already used in the production of fertiliser, desulphurisation in oil refining and hydrogenation in petrochemical production. The production of this hydrogen, almost exclusively black, brown or grey, accounts for around 3% of global CO_2 emissions. These are processes in which there a few or no alternatives to hydrogen.

Probable/possible uses (Rows B-D)

Low-carbon hydrogen offers the most promising path for decarbonising iron and steel production, but other options are possible, and may outcompete hydrogen in the longer term (Kim *et al*, 2022). Hydrogen is already used as a feedstock to in a variety of chemical processes. It is also likely to be used to provide high-temperature heat in some industrial sectors, although electric heating (including heat pumps) may prove more attractive in others (Thiel & Stark, 2021).

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[2] Chairman and CEO of Liebreich Associates and co-managing partner of EcoPragma Capital. Michael is a member of the UK Board of Trade, an honorary fellow of the Energy Institute and visiting professor at Imperial College London. He is a former advisor to the UN on Sustainable Energy for All, member of the board of Transport for London and founder of BloombergNEF (Source).

Low-carbon hydrogen is well suited to providing *long-term* energy storage, providing back-up and resilience to the power sector at times when electricity generation from renewables like solar and wind is suppressed for long periods of time, and demand is high. However, other technologies – including pumped hydropower, new battery technologies and network interconnection - are potential alternatives (Lait & Walker, 2022).

Low-carbon hydrogen, in the form of ammonia or synthetic fuels, is likely to be competitive in fuelling shipping and medium-to-long-haul aviation, particularly as electrifying these sectors would be highly challenging. Using hydrogen directly is technically possible, but impractical due to the on-board hydrogen storage space that would be required. Biomass-derived fuels are a significant (and more mature) competitor, although constraints to sustainable biomass supply may arise (Su-ungkavatin *et al*, 2023).

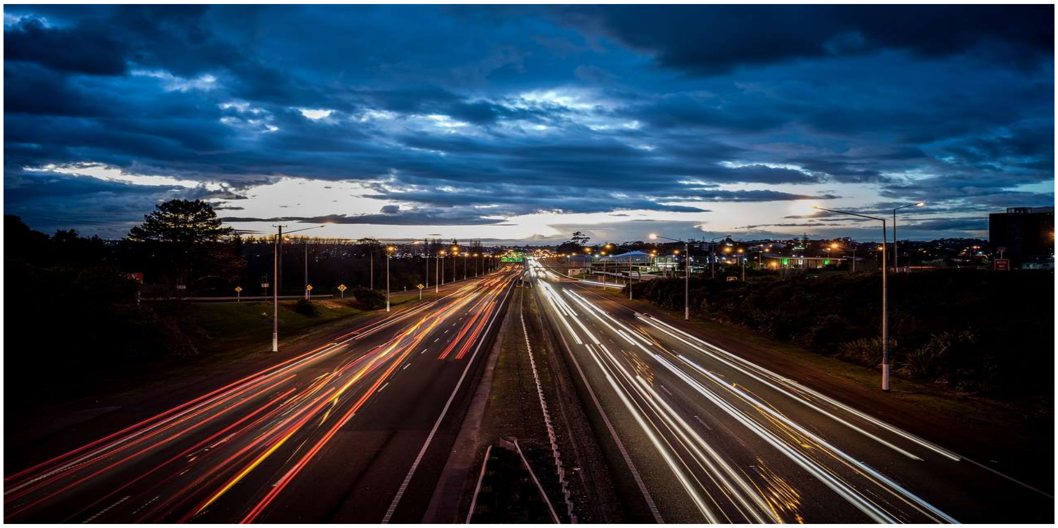
Unlikely/very unlikely uses (Rows E-G)

For short-term support to variable renewable energy in power generation, batteries (and other technologies, including pumped hydropower) are a more efficient and cheaper solution (Egeland-Eriksen et al, 2021). For most land transport modes (with the possible exception of long-distance trucks and coaches, and some off-road vehicles, such as haulers used in the mining industry), along with domestic, commercial and low-to-mid-temperature industrial heating, electrification is very likely to win out.

Although filling a car with hydrogen and using a hydrogen boiler would be very recognisable experiences to the user, technical and economic factors strongly favour electrification. In particular, the hydrogen value chain is inherently energy-inefficient compared to that of electricity. For example, the 'well-to-wheel' efficiency (i.e. energy efficiency of the full energy value chain, from production to useful work delivered) of electric cars is around 80%, compared to less than 40% for fuel cell hydrogen cars (Baxter, 2020). For the electrification of heating using heat pumps, value chain energy efficiency is around 270% (as heat pumps draw more heat energy from the air, earth or water than the electricity used to power them). For hydrogen heating, efficiency is less than 50% (Woollard, 2023). This has significant cost implications.

The hydrogen value chain is inherently energy-inefficient compared to that of electricity.

Other factors include existing and required infrastructure, costs, convenience, policy, and path dependency. Global renewable electricity deployment is growing rapidly, and although the rate of hydrogen electrolyser deployment is also increasing, it is well behind what is required to service even the applications ranked higher on the Ladder (IEA, 2023). Hydrogen is likely to be diverted to sectors in which its use is a greater priority, while its production is relatively limited.



Hydrogen can be produced on-site at a vehicle refuelling station through electrolysis. However, this would require a high-capacity connection to the electricity grid, which would also be required for direct use of this electricity in vehicles. Hydrogen can also be delivered by pipeline or tanker. Delivery by tanker would add significant expense due to the low energy density of hydrogen, and the high cost of liquification (Genovese & Fragiacomo, 2023). Existing natural gas pipelines can be converted to allow the transport of pure hydrogen, and such a process has begun in countries such as the UK (for other reasons), where existing gas networks are extensive. However, for transport refuelling this also requires: (a) enough refuelling stations able to build sufficient connections to these pipelines, and (b) all offtakers of gas from these pipelines able to accept pure or high-volume hydrogen blends. In both cases, this would require significant system-level co-ordination and investment.

Electric vehicles accounted for 14% of global car sales in 2022, and are likely to reach 18% in 2023. Most major car manufacturers have EV manufacturing targets, and an increasing number are committing to all-electric production. Vehicles prices are increasingly competitive with fossil fuel counterparts, and although raw material and battery supply chain constraints may arise with continuing rapid growth, innovation and policy action is likely to mitigate this to some degree. Battery capacity and range is continually increasing. Although EV charging can be slow, chargers can be installed almost anywhere there is an electrical connection, and fast and ultra-fast charging is increasingly available (IEA, 2023). By contrast, **fuel cell cars accounted for just 0.02% of global sales, are likely to remain more expensive to buy, maintain and run than their electric counterparts**, may also face raw material supply constraints if deployed at scale, and must continue to be fuelled at dedicated stations – which would likely only deploy incrementally, inducing a different form of range anxiety (Ajanovic & Haas, 2021).

A similar story plays out for heating. Global heat pump sales are growing rapidly, can be installed in almost any type of home, and are installed in around half of homes in cold climates such as Norway and Sweden (Harris & Walker (2023). By contrast, **full hydrogen boilers are not yet available, and although they are likely to be a similar price to natural gas boilers, they are only potentially useable in buildings with a connection to a gas network**. Although heat pumps are significantly more expensive to retrofit into existing homes, their much lower running costs can largely or potentially more than offset this over time. They can also be disruptive to install, however hydrogen heating is also likely to provide disruptive, including for the installation of appropriate internal piping and additional ventilation for user safety (Harris & Walker (2023). **EVs and heat pumps produce no 'tailpipe' emissions, but hydrogen, as with fossil fuels, can produce nitrogen dioxide (NO_2) when combusted – an air pollutant harmful to health.**

Global public policy is significantly more supportive of electrification for both light duty vehicles and non-industrial heating than it is for hydrogen. Combined with the range of technical and economic benefits highlighted above, this means that **as the switch to electrified light-duty transport and heating gathers pace, barriers to further growth are likely to reduce. At the same time barriers to a significant reorientation toward hydrogen are likely to increase. This means energy systems are likely to become increasingly path dependent on electrification.**

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