RI EMERGING ISSUES | MAY 2019

HYDROGEN'S ROLE IN A ZERO-CARBON ECONOMY

The concept of a "hydrogen economy" came into prominence in the early-2000s, when US economist and social theorist Jeremy Rifkin envisioned the replacement of an oil-based economy with one centred on hydrogen, in his aptly-named book *The Hydrogen Economy.* Rifkin's ideas met with much opposition at the time, but, with technological advances in the intervening twenty years, the release of the IPCC's (2018) 1.5°C report, and the welcome declaration of a "climate emergency" by the UK Parliament, we now revisit hydrogen's potential role in a zero-carbon economy.

WHAT IS HYDROGEN?

Hydrogen – a single electron circling a single proton – is the most abundant element in the Universe, accounting for some 75% of all normal matter. It is essential to life as we know it, but pure hydrogen gas (H_2) is quite scarce in Earth's atmosphere – hydrogen mostly occurs in combination with oxygen, as well as in organic matter (including plants, and fossil fuels).

Hydrogen has a number of applications: it is reacted with nitrogen to make ammonia for fertilizer, added to fats and oils through hydrogenation, and used in rocket fuel. However, we are focussing here on hydrogen's role in a low-carbon future by looking at the potential of the hydrogen fuel cell in the transport sector.

HOW IS HYDROGEN PRODUCED?

Because hydrogen does not exist in nature in a readily-usable form, it has to be separated from the compounds which contain it (e.g. H_2O) before it can be used as a transport fuel. Hydrogen's "green" credentials therefore rest heavily on how it is produced.

The two principal methods in use today are (i) steam methane reforming, and (ii) electrolysis. The former uses a source of methane, most often natural gas, to produce carbon monoxide and hydrogen under presence of a catalyst. Then, the carbon monoxide and steam are reacted to produce yet more hydrogen and carbon dioxide. So unless you can capture and store the CO_2 in the process of producing hydrogen, this is not a truly low-carbon solution.

Electrolysis using renewable energy is, therefore, the more promising method to produce hydrogen. This involves running an electric current through water (H_2O) to produce hydrogen and oxygen, as in the opposite diagram.

It's also possible to use bacteria to convert biodegradable organic matter into hydrogen gas, and Japan in particular is looking to adopt this technology at scale. Even more intriguing is the recent development of a new catalyst (Mo_6S_4), based on molybdenum sulphide, which may "revolutionize industrial use of the hydrogen evolution reaction (HER), which generates hydrogen gas by splitting water molecules". The HER process has hitherto relied on expensive noble metals, such as platinum; by contrast, the crystalline form of molybdenum sulphide, discovered by researchers at A*STAR Institute of Materials Research and Engineering, is both stable and cheap.[1]

Once the hydrogen has been produced, it requires an infrastructure network – such as that for natural gas – to transport it to local distribution centres. From a filling station, hydrogen is pumped into a vehicle (be that a car, a bus, train, ship, or aeroplane) where the hydrogen is then put to work to create electricity and drive electric motors.

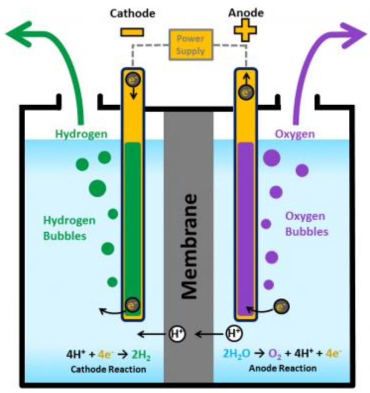


Figure 1. Diagram showing hydrogen production through electrolysis. Source: *US Office of Energy Efficiency and Renewable Energy*

HOW DOES A HYDROGEN FUEL CELL WORK?

A fuel cell is a device – composed of an anode, a cathode, and an electrolyte membrane – that generates electrical power through a chemical reaction by converting a fuel (hydrogen) into electricity. In the case of a hydrogen fuel cell, hydrogen is passed through the anode and oxygen through the cathode. At the anode site, the hydrogen molecules are split into electrons and protons. The protons pass through the electrolyte membrane, while the electrons are channelled

[1] https://phys.org/news/2018-12-newly-catalyst-cheaper-hydrogen-production.html

through a circuit, generating an electric current and excess heat. At the cathode, the protons, electrons, and oxygen combine to produce water molecules (the only waste product from the electricity generation process).[2]

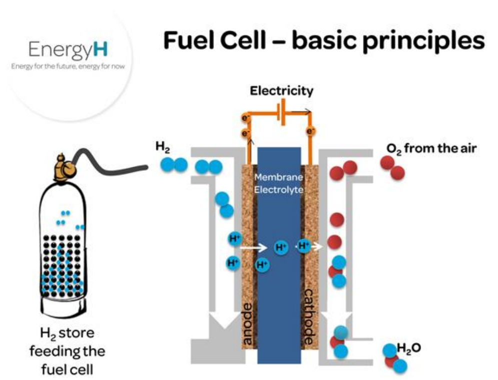
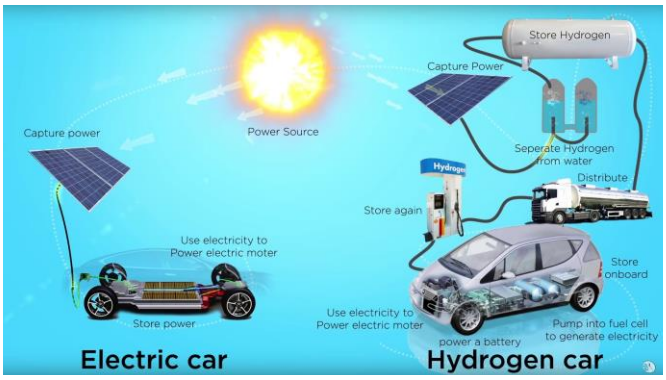


Figure 2. "Fuel cell basic principles". Source: *Materials Energy Research Laboratory in Nanoscale* (MERLIN), 'Hydrogen FAQs'.

HYDROGEN ON THE ROAD

For the purposes of this section, battery electric vehicles (BEVs) will be distinguished from [hydrogen] fuel-cell electric vehicles (FCEVs). The key difference between BEVs and FCEVs in terms of how electricity for the electric motor is generated, stored, and transported are shown below:



Even to the untrained eye, it's clear that the overall process for getting a FCEV moving is more complicated than for a BEV. This – alongside under-developed refuelling infrastructure (there are only a handful of hydrogen refuelling stations in the whole of the UK) – is one of the main drawbacks to FCEVs at present. Because of the complexity of the process (to use clean power to separate hydrogen from water, store it, distribute it, pump it into a car's fuel cells to generate electricity and then use that electricity to run an electric motor), the energy efficiency of hydrogen cars is very poor compared to electric vehicles. The former typically achieve energy efficiencies of 25-35%, while the latter can achieve closer to 80-85%.[3]

The one benefit of hydrogen-powered cars as opposed to electric vehicles is that, once you've found yourself a hydrogen refuelling station (an easy task in some countries, and a near-impossible one in others), it only takes a few minutes to refill your car. That does not appear to be enough to persuade car makers, however, which are almost universally pursuing the BEV model, despite the practical and ethical challenges that this presents in terms of lithium, nickel, and cobalt sourcing.

A more promising application may be in the mining sector, where trucks operate in a highly localised context (the vicinity of the mine site). This cuts out the problem of hydrogen transportation infrastructure, as the fuel can be produced on-site from renewable energy and electrolysing water. Diversified mining company Anglo American, for instance, has recently announced its intention to trial a hydrogen-powered truck within the next 12 months.

Hydrogen-powered articulated trucks are also capturing the imagination of proponents of zero-carbon transport/logistics. Following the unveiling of the *Nikola Tre* in November 2018 (aimed primarily at European markets), pioneering Utah-based

[2] US Fuel Cell and Hydrogen Energy Association

[3] Lajunen, A. & Lipman, T. 'Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses.' *Energy* 106, 329–342 (2016); as cited in Cano, Z.P. 'Batteries and fuel cells for emerging electric vehicle markets', *Nature Energy* Review Article, April 2018.

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Nikola Motor Company now offers three hydrogen-powered truck models, with impressive range figures of up to 1,200km. The company is also working with partners to roll out hydrogen refuelling infrastructure – hitherto one of the most significant hurdles to face hydrogen-powered road vehicles.

Elsewhere, in the public transport arena, hydrogen-fuel-cell bus fleets have proved viable in the Scottish city of Aberdeen. The Aberdeen Hydrogen Bus Project, which comprises two European-funded initiatives, has grown to encompass a fleet of 10 vehicles, which just recently racked up their 1 millionth mile, collectively. Yet in the bus world, as with cars, BEVs are in the ascendancy. Chinese megacity Shenzhen now has 16,000 electric buses; Santiago de Chile doubled its electric bus fleet in January 2019, adding a further 100 vehicles; and scores of cities globally are adopting the zero-emission technology.[4] Bloomberg's New Energy Finance has suggested that, globally, electric buses are currently reducing diesel demand by 275,000 boe *per day,* and will cut demand by over 6m boe/day by 2040.[5]

HYDROGEN ON THE TRACKS

In September 2018, the world's first hydrogen-powered passenger train powered by hydrogen fuel cells began operation on a 62-mile stretch of line between Cuxhaven and Buxtehude, in northern Germany. The trains – which emit only water, and store excess energy produced by the fuel cells in on-board lithium-ion batteries – are built by French TGV-maker Alstom. The company intends to deliver 14 more zero-emission trains to Lower Saxony by 2021. Hydrogen trains are more expensive than their diesel counterparts which currently run on the Cuxhaven-Buxtehude line in terms of capex, but their running costs are significantly lower.

HYDROGEN IN THE AIR

Hydrogen as an aviation fuel has a somewhat chequered past, but as experience has led to a more complete understanding of how to handle, store, and transport hydrogen safely, scientists and engineers are increasingly optimistic about hydrogen's potential to 'green' aviation.

This optimism is, in part, owing to pessimism about the practicality of battery-powered aircraft, since batteries – at least in their current form – are too heavy and not sufficiently energy-dense to be a practical solution to cutting the aviation industry's carbon emissions. Although solutions such as HES Energy System's *Element One* are in their infancy, they may yet prove both viable and scalable.

Figure 4. *A digital rendering of a hydrogen-powered concept aeroplane. Known as Element One and proposed by Singaporean company HES Energy System, the plane – expected to be completed by 2025 – will be able to carry four passengers between 500 and 5,000km.* Source: https://impakter.com/element-one-hes/

HYDROGEN ON THE WATER

Hydrogen fuel cells have also been put forward as a zero-carbon solution to greenhouse gas emissions from marine vessels – everything from small passenger ferries and vessels operating exclusively in ports to cruise ships and container vessels.

Hydrogen fuel cells' benefits in a marine context are much the same as in the aviation industry – principally, they are lighter and more energy-dense than batteries, and allow for longer distances to be travelled between refuelling. An additional benefit is that they reduce engine and propeller noise, which has been shown to significantly impact marine animals, particularly larger species.[6] Research has demonstrated that shipping noise can alter the behaviour of marine giants (whales, dolphins, and large sharks), including avoidance, foraging and movement patterns, habituation, and disrupted

[4] https://www.theguardian.com/cities/2018/dec/12/silence-shenzhen-world-first-electric-bus-fleet; https://santiagotimes.cl/2019/01/22/chile-adds-another-100-electric-buses-to-its-fleet/

[5] https://www.bloomberg.com/news/videos/2019-03-21/electric-buses-are-wiping-out-oil-demand-in-a-hurry-video

[6] De Jong, K., et al. 'Noise can affect acoustic communication and subsequent spawning success in fish', *Environmental Pollution*, Vol. 237, June 2018, pp. 814-823; Rako-Gospić, N. & Picciulin, M. 'Underwater Noise: Sources and Effects on Marine Life', in *World Seas: an Environmental Evaluation (Second Edition), Volume III: Ecological Issues and Environmental Impacts*, 2019, pp. 367-389.

communication.[7] Yet hydrogen as a fuel source for marine vessels also has a familiar drawback at present: a lack of refuelling infrastructure.

CONCLUSION

In a zero-carbon future, there is clearly room for both battery-electric and hydrogen-electric modes of transport. Practicality and cost will likely determine which is used in specific contexts. Battery-electric cars, for instance, seem to make more sense than hydrogen-electric cars, but battery-electric planes are impractical, and hydrogen-electric trucks may be more viable in highly localised settings.

Investment opportunities in a hydrogen economy remain thin on the ground for all but governments and private equity/venture capital firms, and the uncertainty around the relative importance of clean-energy sources in the transition to a low carbon economy is undeniable.

[7] Pirotta, V., et al. 'Consequences of global shipping traffic for marine giants', *Frontiers in Ecology and the Environment*, Vol. 17, 2019, pp. 39–47.

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