Technologies series

Hydrogen (H_2)

A potentially vital part of the low carbon economy, decarbonising the hard-to tame-sectors.

Lightening the load of decarbonisation

What it is

Hydrogen (H_2) has three principal functions: a fuel; a chemical feedstock; and an energy carrier. It thereby has many applications in industry, and the power, transport, and heating sectors.

How it works

Hydrogen occurs naturally, but not in usable form. It is generated in two principal ways:[1]

1. **Conversion of fossil fuels** into H_2 and CO_2 via coal gasification and (primarily) methane reformation.[2] Termed 'grey hydrogen' this represents ~96% of global H_2 production of ~70m tonnes. If the CO_2 produced is captured and stored the hydrogen is termed 'blue hydrogen'.[3]
2. **Electrolysis**, whereby electricity is passed through water, splitting it into its two constituents, H_2 and O_2.[4] If the electricity is generated from a renewable source, the hydrogen is termed 'green hydrogen'.[5] So far this represents only ~4% of global production.

Applications

Hydrogen is used principally in the chemical industry and fossil fuel refining.[6] However, it has potential applications in decarbonsing other industries,[7] primarily due to its energy density,[8] application in high temperature processes, and relative ease of transportation.[9]

- **Heavy Industry.** H_2 could be used to decarbonise sectors with difficult-to reduce-emissions, notably the chemical and steel industries,[10] the main users of H_2 and high temperatures. Switching to green H_2 would reduce emissions significantly.[11]
- **Energy.** The cost of green hydrogen is tied to that of renewables. It could play a complementary role in grid balancing and energy storage particularly where renewable electricity is abundant.[12] It may also have a role in decarbonising the existing gas infrastructure.[13]
- **Transport.** The applicability of H_2 differs by sector, but those that involve long distances, heavy loads, and require low down-time and rapid refuelling, such as logistics and mass-transit, stand to benefit particularly.[14] Shipping[15] and aviation[16] may be others.

Implications and issues

Many countries, accounting for ~70% of the world's economy, have published hydrogen strategies.[17] Although momentum is increasing given increased governmental support, the hydrogen economy faces numerous obstacles to widespread adoption:

a. **Cost.** Green hydrogen is presently too expensive to compete with fossil fuels in most contexts, unless: CO_2 emissions are priced appropriately; governments subsidise; or scale economies prove substantial. Improvements in technology and decreasing renewable costs will likely help, but whether that will suffice to achieve competitiveness is debatable.[18]

b. **Lack of Infrastructure.** The most immediate obstacle facing an H_2 economy is a lack of infrastructure, from fuelling stations[19] to electrolysers,[20] access to renewable power, and storage and transport facilities. These will also require standardisation and certification.[21]

c. **Safety.** H_2 is highly flammable, and when pressurised needs very careful handling.[22] As the smallest atom, it leaks through the tiniest holes, and metals exposed to H_2 can develop cracks.[23]

d. **Storage.** This requires compression; refrigeration; or combination with an organic chemical or metal hydride. This is expensive in terms of energy used but enables renewable energy to be transported without the need for a shared electric grid.[24]

e. **Policy.** Rigorous policies and stringent regulations would be needed to integrate H_2 into energy networks and manage supply at an acceptable level of safety.

f. **Pollution.** The creation and use of green hydrogen produces no harmful emissions. The same can be true of blue hydrogen, but fugitive CO_2 emissions are an issue.[25]

Green hydrogen is recognised in most of the world's major economies as an important part of their future energy mix. That said, its precise contribution will depend on a ready supply of renewable electricity, early support for infrastructure, and a constructive policy environment. ■

[1] A third method of hydrogen manufacture, *Pyrolysis*, is currently carried out only at very small scale. It involves passing natural gas through a molten alkali or metal, producing carbon black as a by-product. This is sometimes referred to as 'turquoise hydrogen', closer to green than blue, because the process can be powered by renewable energy, although associated CO_2 emissions do have to be captured. See, Schneider, S., et al., 2020. *State of the Art of Hydrogen Production via Pyrolysis of Natural Gas*. ChemBioEng Reviews [e-journal] https://doi.org/10.1002/cite.202000021.

[2] Natural gas reformation accounts for around half of the hydrogen produced, with much of the rest coming from coal and oil. Most of China's hydrogen comes from coal, given its low cost. This accounts for approximately 5% of its total coal consumption. See, International Renewable Energy Agency, 2018. *Hydrogen From Renewable Power Technology Outlook For The Energy Transition*. IRENA, [online] Available at: <https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf> [Accessed 2 November 2020] & Brasington, L., 2019. Hydrogen in China. Cleantech Group [online] Available at: <https://www.cleantech.com/hydrogen-in-china> [Accessed 16 November 2020]. US national hydrogen strategy is outlined in the following Office of Fossil Energy, 2020. Hydrogen Strategy. United States Department of Energy [online] Available at: <https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf> [Accessed 1 December 2020].

[3] For a simplified, graphical, illustration of the colours corresponding to different hydrogen production processes, see: CertifHy Canada Inc., 2018. *Hydrogen An Elemental Shift in How We Use Energy*, CertifHy Canada Inc., [online] Available at: <https://certifhy.ca/About.html> [Accessed 2 November 2020].

[4] There are currently 3 main technologies used for this electrolytic process. In order of technological maturity, these are; Alkaline Electrolysers; Polymer Electrolyte Membrane Electrolysers; and Solid Oxide Electrolysers. See, United States Department of Energy, 2020. *Hydrogen Production: Electrolysis*. Available at: <https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis> [Accessed 2 November 2020].

[5] A brief definition of Green Hydrogen can be found in: Cleanenergypartnership, 2018. *Positioning 'Green hydrogen'*, Clean Energy Partnership [online] Available at: <https://cleanenergypartnership.de/fileadmin/Assets/sidebar/CEP-GreenH2_28.08.2018_ENG.pdf> [Accessed 2 November 2020]. For a more detailed definition of "Green Hydrogen" see, CertifHy, 2018. *CertifHy– Developing a European Framework for the generation of guarantees of origin for green hydrogen*, CertifHy [online] Available at: <https://ec.europa.eu/jrc/sites/jrcsh/files/Vanhoudt%20Definition%20of%20Green%20Hydrogen%20SFEM.pdf> [Accessed 2 November 2020].

[6] Currently the biggest end-use of hydrogen is as a chemical feedstock for ammonia (NH_3) in fertilisers, with the remainder used in the rest of the chemical industry, and in the refining of hydrocarbons produced in a process known as hydrocracking. See, International Renewable Energy Agency, 2018. *Hydrogen From Renewable Power Technology Outlook For The Energy Transition*. IRENA, [online] Available at: <https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf> [Accessed 2 November 2020].

[7] For an overview of the various applications, see, Liebreich, M., 2020. *Liebreich: Separating Hype from Hydrogen – Part Two: The Demand Side*. BloomberNEF [online] Available at: <https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-two-the-demand-side> [Accessed 16 November 2020].

For a comprehensive detailed look at hydrogen's potential as an alternative to fossil fuels and for tackling climate change, including how it could help different sectors, see CarbonBrief, 2020, *In-depth Q&A: Does the world need hydrogen to solve climate change?* Multiple Authors, 30 November. [online] Available at https://www.carbonbrief.org/in-depth-qa-does-the-world-need-hydrogen-to-solve-climate-change?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20201130&utm_medium=email&utm_source=Revue%20Daily [Accessed 2 December 2020]

[8] Hydrogen has a lower energy density by volume than gasoline and diesel, but in cooled form it surpasses that of batteries. See: U.S. Energy Information Administration, 2013. *Few transportation fuels surpass the energy densities of gasoline and diesel*. EIA [online] Available at: <https://www.eia.gov/todayinenergy/detail.php?id=9991> [Accessed 15 November 2020].

[9] This 'relative ease of transport' applies in comparison with batteries. In areas or countries particularly well endowed with wind or sunshine the production of green hydrogen can be one way whereby they can export this renewable energy. This strategy is already being pursued by Australia, and Chile and Saudi Arabia are actively investigating the possibilities. See, COAG Energy Council, 2019. *Australia's National Hydrogen Strategy*. Commonwealth of Australia [online] Available at: <https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf> [Accessed 16 November 2020], Lee, A., 2020. *Saudi Arabia plans $5bn 'world's largest' green hydrogen plant to fuel global bus and truck fleets.* RechargeNews [online] Available at: <https://www.rechargenews.com/transition/saudi-arabia-plans-5bn-worlds-largest-green-hydrogen-plant-to-fuel-global-bus-and-truck-fleets/2-1-839532> [Accessed 16 November 2020], & ChileReports, 2020. *The Chilean Government presents a national strategy to convert Chile into a global leader in green hydrogen*. ChileReports [online] Available at: <https://chilereports.cl/en/news/2020/11/04/the-chilean-government-presents-a-national-strategy-to-convert-chile-into-a-global-leader-in-green-hydrogen> [Accessed 16 November 2020].

[10] Industrial processes define three grades of heat required: low (<100°C); medium (100-500°C); and high (>500°C). At the highest temperatures, H_2 is more likely to become economical. Such temperatures are required by the steel industry: for the production of

primary steel, hydrogen is currently considered to be the most promising solution for replacing hard-coal coke, where it can help substitute high-emission blast furnace processes with the direct reduction of iron ore. See: Homann, Q., 2019. *Hydrogen as a Clean Alternative in the Iron and Steel Industry*. Fuel Cell & Hydrogen Energy Association [online] Available at: <https://www.fchea.org/in-transition/2019/11/25/hydrogen-in-the-iron-and-steel-industry> [Accessed 15 November 2020], Hydrogen Council, 2020. *Path to hydrogen competitiveness A cost perspective*. Hydrogen Council, [online] Available at: <https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf> [Accessed 2 November 2020].

[11] Although this is generally seen as a longer term vision based on the time taken to implement and investments/lifespans of older plants coming to an end by 2030-2040, the possibility of using hydrogen in steel production has already been demonstrated in a Swedish steel mill. See: Collins, L., 2020. *'World first' as hydrogen used to power commercial steel production*. ReCharge [online] Available at: <https://www.rechargenews.com/transition/-world-first-as-hydrogen-used-to-power-commercial-steel-production/2-1-799308> [Accessed 2 November 2020].

[12] This would allow green hydrogen production to take advantage of the lowest possible prices of energy. See: International Renewable Energy Agency, 2019. *Hydrogen: A Renewable Energy Perspective*. IRENA [online] Available at: <https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf> [Accessed 16 November 2020] and Liebreich, M., 2020. Liebreich: Separating Hype from Hydrogen – Part One: The Supply Side. BloombergNEF [online] Available at: <https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-one-the-supply-side> [Accessed 16 November 2020].

[13] Mixes of 10-20% hydrogen with natural gas have been demonstrated to be possible with minor upgrades, as is planned for the UK's Keele University gas network. It could also be used to generate demand for hydrogen, by requiring hydrogen blending in natural gas pipelines. See: HyDeploy, 2020. *Why HyDeploy?* HyDeploy [online] Available at: <https://hydeploy.co.uk> [Accessed 16 November 2020] and International Renewable Energy Agency, 2019. *Hydrogen: A Renewable Energy Perspective*. IRENA [online] Available at: <https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf> [Accessed 16 November 2020].

[14] Registrations for Fuel Cell Electric Vehicles (FHEVs) has increased significantly in recent years, but they remain significantly more expensive than other vehicles, including battery powered electric, and hence account for just 0.5% of new low-carbon vehicles sales. Hydrogen's impact is constrained by the number of refuelling stations (currently 470 worldwide) and concentrated primarily in Japan, the US, and Germany. However, registrations are expanding quickly, those of FHEVs more than doubling from 2018 to 2019, with a total of 25,212 vehicles worldwide. The U.S. dominates in passenger vehicles, China in buses and light- and medium-duty trucks. See, Samsun, R.C., Antoni, L., & Rex M., 2020. Mobile Fuel Cell Application: Tracking Market Trends. Advanced Fuel Cells Technology Collaboration Programme [online] Available at: <https://www.ieafuelcell.com/fileadmin/publications/2020_AFCTCP_Mobile_FC_Application_Tracking_Market_Trends_2020.pdf> [Accessed 2 November 2020].

[15] With regard to shipping it requires global buy-in for refuelling around the world. However, much of the existing infrastructure for the production of hydrogen for refining fossil fuels and producing fertilisers is concentrated around ports, and nearby industrial facilities. See, International Energy Agency, 2019. *The Future of Hydrogen*. IEA [online] Available at: <https://www.iea.org/reports/the-future-of-hydrogen> [Accessed 15 November 2020].

[16] The future of hydrogen powered flight is generally seen as utilising hydrogen in liquid fuels. However, smaller aircraft have demonstrated the possibility of hydrogen fuel cell powered flight. See, ZeroAvia, 2020. *ZeroAvia Completes World First Hydrogen-Electric Passenger Plane Flight*. Zero Avia [online] Available at: <https://www.zeroavia.com/press-release-25-09-2020> [Accessed 2 November 2020]. For a detailed report on the impact of hydrogen on the aviation industry see: McKinsey & Company for the Clean Sky 2 JU, and Fuel Cells and Hydrogen 2 JU, 2020. *Hydrogen-powered aviation*. European Commission, [online] Available at: <https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_Hydrogen%20Powered%20Aviation%20report_FINAL%20web%20%28ID%208706035%29.pdf> [Accessed 2 November 2020].

[17] The EU's plan focuses on the production of both green hydrogen and electrolysers, with specific targets for 2024, 2030, and 2050, and providing cumulative investments of almost €500 billion. Many European countries have their own hydrogen strategies, focussing on targets for installed electrolyser capacity, hydrogen fuel cell vehicles on the road, and produced green hydrogen. Germany and Spain are proposing notably high levels of investment. See: European Commission, 2020. *A hydrogen strategy for a climate-neutral Europe*. European Commission [online] Available at: <https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf> [Accessed 16 November 2020]. Other ambitious hydrogen strategies include that of Japan and China. See, Hydrogen and Fuel Cell Strategy Council, 2019. *The Strategic Road Map for Hydrogen and Fuel Cells*. Hydrogen and Fuel Cell Strategy Council [online] Available at: <https://www.meti.go.jp/english/press/2019/pdf/0312_002b.pdf> [Accessed 16 November 2020],

Lewis, S., 2020. *N China hydrogen push led by hydrogen as by-product, renewables*. SPGlobal [online] Available at: <https://www.spglobal.com/platts/en/market-insights/latest-news/metals/061120-n-china-hydrogen-push-led-by-hydrogen-as-by-product-renewables> [Accessed 16 November 2020], & Brasington, L., 2019. Hydrogen in China. Cleantech Group [online] Available at: <https://www.cleantech.com/hydrogen-in-china/> [Accessed 16 November 2020]. The current US national hydrogen strategy is outlined in the following, Office of Fossil Energy, 2020. *Hydrogen Strategy*. The United States Department of Energy [online] Available at: <https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf> [Accessed 16 November 2020]. However, the incoming Biden administration has highlighted green hydrogen as a focus, aiming to bring its price down to that of grey hydrogen within a decade. See, Biden For President, 2020. *The Biden Plan To Build A Modern, Sustainable Infrastructure And An Equitable Clean Energy Future*. Biden For President [online] Available at: <https://joebiden.com/clean-energy> [Accessed 16 November 2020].

[18] At present green hydrogen costs 2.5 to 5.5 €/kg, blue (fossil-fuel powered with CO_2 capture) costs approximately €2/kg, and grey (fossil fuel powered) hydrogen around €1.5/kg. These figures all depend on the price of cost of electricity or fossil fuels to power the process, the price of CO_2, and the capital expenditure and operational costs. It is suggested that the cost of green hydrogen must fall below ~€2/kg to become competitive with fossil fuels, which means that present tax breaks and other incentives are currently required. However, it is expected that improvements in electrolyser technology and the continued fall of the costs of renewable energy will bring this price down. See, Hydrogen Council, 2020. *Path to Hydrogen Competitiveness: A Cost Perspective*. Hydrogen Council [online] Available at: <https://hydrogencouncil.com/en/path-to-hydrogen-competitiveness-a-cost-perspective> [Accessed 16 November 2020], Hydrogen Council, 2020. *Hydrogen, Scaling Up*. Hydrogen Council [online] Available at: <https://hydrogencouncil.com/en/study-hydrogen-scaling-up> [Accessed 16 November 2020], Mathis, W., & Thornhill, J., 2019. Hydrogen's Plunging Price Boosts Role as Climate Solution. BloombergNEF [online] Available at: <https://www.bloomberg.com/news/articles/2019-08-21/cost-of-hydrogen-from-renewables-to-plummet-next-decade-bnef > (paywall) [Accessed 16 November 2020], & Glenk, G., Reichelstein, S., 2019. Economics of converting renewable power to hydrogen. *Nature Energy* [e-journal] https://doi.org/10.1038/s41560-019-0326-1.

[19] Hydrogen's impact is constrained by the number of refuelling stations (currently 470 worldwide), and concentrated primarily in Japan, the US and Germany. See, Samsun, R.C., Antoni, L., & Rex M., 2020. Mobile Fuel Cell Application: Tracking Market Trends. Advanced Fuel Cells Technology Collaboration Programme [online] Available at: <https://www.ieafuelcell.com/fileadmin/publications/2020_AFCTCP_Mobile_FC_Application_Tracking_Market_Trends_2020.pdf> [Accessed 2 November 2020].

[20] Dramatic increases in capacity are required. The global capacity of electrolysers, which produce hydrogen from water and electricity, needs to expand to 3300 GW in the International Energy Agency's Sustainable Development Scenario, from 0.2 GW today. See, International Energy Agency, 2020. *Energy Technology Perspectives 2020*. IEA [online] Available at: <https://www.iea.org/reports/energy-technology-perspectives-2020> [Accessed 1 November 2020]. The costs of electrolysers depend greatly on their country of manufacture and the type of technology used. China is able to manufacture alkaline electrolysers at a fraction of the cost at which the EU manufactures solid oxide and proton exchange membrane (PEM) electrolysers. Alkaline electrolysers are a more established technology, and China benefits from economies of scale and cheaper labour and materials. However, they are regarded as less able to cope with the realities of variable renewable energy and associated peaks and troughs in electricity demand and supply. Whether costs of manufacturing other electrolyser technologies decrease enough to become economical or alkaline electrolysers are able to improve their load following remains to be seen. See: Ridjan, I., 2016. *The role of electrolysers in energy system*. Aalborg Universitet [online] Available at: <https://vbn.aau.dk/ws/portalfiles/portal/239060666/The_role_of_electrolysers_in_energy_system_WP5.pdf> [Accessed 16 November 2020] and Liebreich, M., 2020. *Liebreich: Separating Hype from Hydrogen – Part One: The Supply Side*. BloombergNEF [online] Available at: <https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-one-the-supply-side> [Accessed 16 November 2020].

[21] Information on the German-designed, EU-backed certification scheme for hydrogen production to ensure that it was generated using renewable energy can be found here: CertifHy, 2020. *What is a Guarantee of Origin?*. CertifHy [online] Available at: <https://www.certifhy.eu/79-slideshow/118-what-is-a-guarantee-of-origin.html> [Accessed 16 November 2020]

[22] Explosions at hydrogen refuelling stations have led directly to injuries, although there have been no recorded deaths. See: Garza, V., 2019. *Cause of explosion in Sandvika: leak in hydrogen tank*. NorwayToday [online] Available at: <https://norwaytoday.info/news/explosion-sandvika-hydrogen-tank> [Accessed 17 November 2020] &

Hyunjoo Jin, Jane Chung, 2019. Hydrogen hurdles: a deadly blast hampers South Korea's big fuel cell car bet. Reuters [online] Available at: <https://www.reuters.com/article/us-autos-hydrogen-southkorea-insight-idUSKBN1W936A> [Accessed 17 November 2020].

[23] At proportions higher than 50% in a given mixture, hydrogen has been shown to cause small cracks in metals. This 'Hydrogen Embrittlement' poses an issue for safely storing and piping hydrogen. At lower proportions (<10-20%), hydrogen can be blended into natural gas without significant technical challenges or dramatic changes to infrastructure. See: International Renewable Energy Agency, 2019. *Hydrogen: A Renewable Energy Perspective*. IRENA [online] Available at: <https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf> [Accessed 16 November 2020] and San Marchi, C., 2013. *Hydrogen Compatibility of Materials*. Sandia National Laboratories [online] Available at: <https://www.energy.gov/sites/prod/files/2014/03/f12/webinarslides_h2_compatibility_materials_081313.pdf> [Accessed 16 November 2020].

[24] Although this requires energy it increases H_2's energy density, enabling it to be shipped or piped more efficiently. However, its energy density may mean that it is more economical to produce it locally. Converting to ammonia (NH3) is an even denser form but cannot be used directly. In the case of shipping, significant losses occur in the logistics chain (for example, in pressurisation and liquefaction), which can increase the demand for hydrogen supply. See, Wijayanta, A. T., 2019. Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: Comparison review, *International Journal of Hydrogen Energy* [e-journal] https://doi.org/10.1016/j.ijhydene.2019.04.112

[25] Fugitive CO_2 emissions are those which escape due to leaks or inefficiencies of carbon capture.