Hydrogen

LEVERAGING HYDROGEN TECHNOLOGY – BRIEFING MATERIAL

Summary

- Hydrogen has a number of attractive features; but also some important drawbacks.
- Its future will rest largely with ‘green’ hydrogen, produced from renewable energy sources.
- It could become the mainstay of the chemicals industry, displacing fossil-based chemical feedstocks.
- It may also find widespread use importantly as a fuel or in the manufacture of fuels.
- Policy will be crucial – ranging from an appropriate carbon tax, to R&D, to establishing regulatory frameworks.
- Financing requirements are large, but much will be forthcoming from the private sector if the economics are right.

Introduction

Hydrogen could potentially play an important role in reducing greenhouse gas emissions, in a variety of ways in a number of sectors. The future role for hydrogen is however a complex, uncertain, and times contentious issue.

What hydrogen is

Hydrogen (H_2) is an odourless, colourless, tasteless, combustible gas. While it occurs naturally, to be useable it has to be manufactured, in either of three principal ways:

1. **Electrolysis,** which splits water (H_2O) into its constituent atoms, hydrogen and oxygen.[1] When carried out using electricity generated from renewable sources, the result is termed 'green' hydrogen;[2,3] Currently green hydrogen represents only about 1% of total world production of hydrogen.

2. **Conversion of fossil fuels,** (hydrocarbons) by coal gasification and (mainly) methane reformation[4], into H_2 and CO_2. The resulting hydrogen is dubbed 'grey', unless the resulting CO_2 is captured and stored, in which it is called 'blue'. Nearly all (around 99%) of global hydrogen production (some 70m tonnes) is currently by this method.

3. **Pyrolysis,** whereby natural gas is passed through a molten alkali or metal, producing carbon black as a by-product. This 'turquoise hydrogen' process can be powered by clean energy.

Advantages

a. On burning it forms simply water (H_20) – no CO_2.
b. It can generate either heat or electricity.
c. It can be produced, stored, and transported.
d. Its energy/weight density is 3x that of hydrocarbon fuels.
e. It burns at a similar temperature to natural gas.

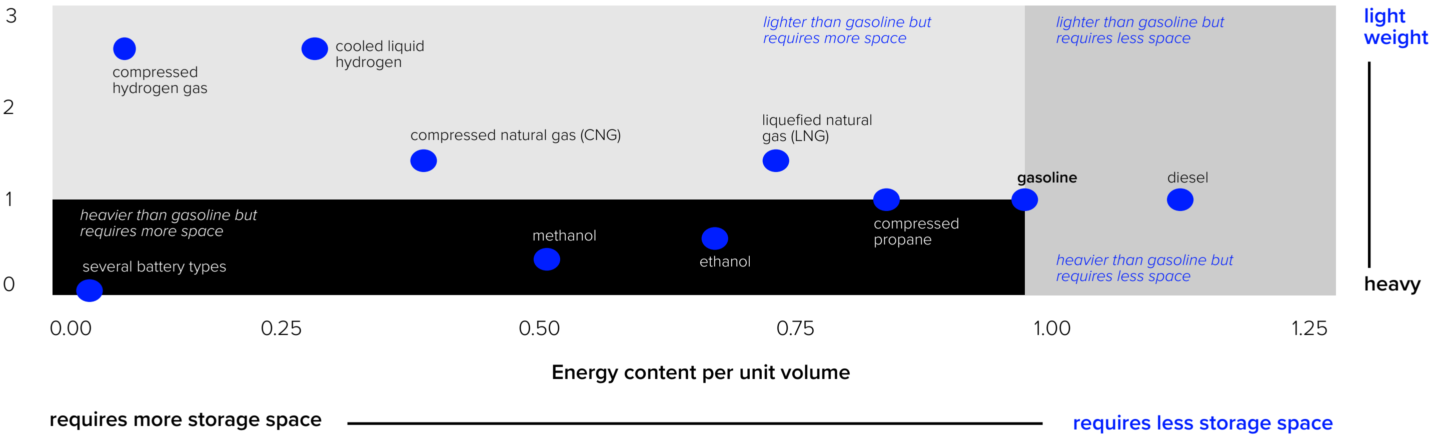
Disadvantages

a. Energy is required to produce it.
b. Its storage requires compression to 700x atmospheric pressure; refrigeration to -253^{0}C or combining with an organic chemical or metal hydride.
c. Its energy/volume density, even when liquefied is only one-quarter that of hydrocarbons (see figure 1).
d. It can embrittle metal - metals exposed to hydrogen can develop cracks.[5]
e. It leaks through the tiniest of holes.
f. It requires careful handling – it is explosive.
g. It cannot in general just be plugged into an existing infrastructure.

Figure 1: Energy density comparison

Energy density comparison of several transportation fuels (indexed to gasoline - 1)

Energy content per unit weight



Source: EIA

Full link: https://www.eia.gov/todayinenergy/detail.php?id=9991

Applications

Hydrogen can enter production processes as an input in various ways; and it can also be consumed directly by end-users. Thus hydrogen can be used as:

1. **A fuel,** including to generate electricity, whether by combustion in gas turbines, or electrochemical conversion in a fuel cell.
2. **A feedstock** for chemical processes**.**
3. **An energy carrier.**

Currently over

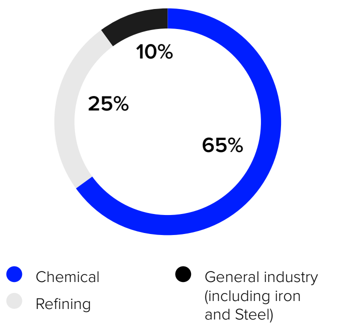
95%

of hydrogen is produced for use in fertilisers, as ammonia (NH_3), and in fossil fuel refining.[6]

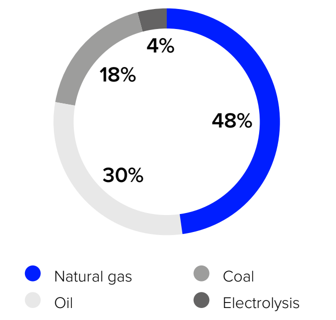
Figure 2: Global hydrogen demand and production sources

Industry Sector	Key Applications
Chemical	• Ammonia • Polymers • Resins
Refining	• Hydrocracking • Hydrotreating
Iron & Steel	• Annealing • Blanketing gas • Forming gas
General Industry	• Semiconductor • Propellant fuel • Glass production • Hydrogenation of fats • Cooling of generators

% of Global H_2 Demand



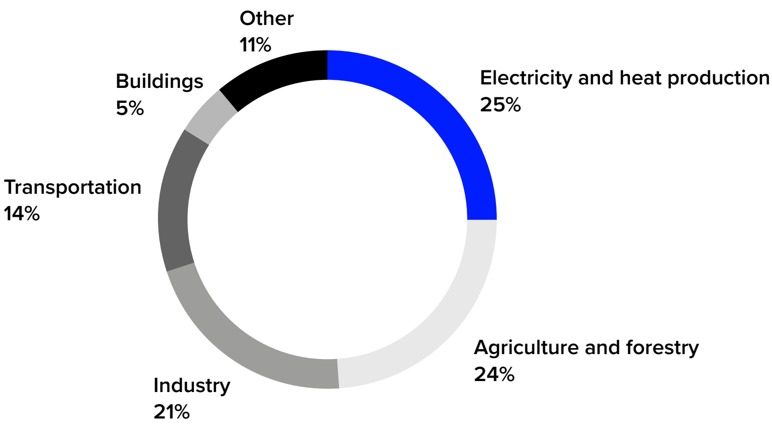
Hydrogen Sources



Source: IRENA (2018)
Full link: https://irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable power_2018.pdf

Hydrogen has many actual and potential applications, including in the transport, heavy industry, energy, and buildings sectors, all of which are currently major emitters of greenhouse gases.

Figure 3: Main emitters by sector



Source: EPA
Full link: https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data

- **Transport.** The applicability of hydrogen to particular transport sectors varies, but those which require rapid refuelling, long distances, heavy loads, and low down-time stand to benefit most.
  - **Cars.** Registrations for fuel cell vehicles has increased significantly in recent years, but they remain significantly more expensive than other vehicles, including battery powered electric.[7]
  - **Mass-transit.** From buses,[8] to trams, to trains,[9] and ferries,[10] hydrogen fuel cell vehicles are well-placed to fuel.
  - **Shipping.** Much of the existing hydrogen infrastructure is concentrated around ports, potentially lowering the barriers to entry for hydrogen-fuelled shipping and hydrogen transport. Energy density remains an issue[11].
  - **Aviation.** Hydrogen's involvement is likely to be focused on shorter distances and liquid fuels rather than fuel cells, and that only in on the medium to long term (2030-2050).[12]

- **Forklifts.** Not technically transport, but forklifts are already a large market for hydrogen fuel cells, 25,000 are currently in use in the US. Fuel cells are cost competitive with battery power here.[13]
- **Heavy Industry.** Hydrogen is seen as a way to decarbonise sectors with difficult-to-decrease emissions such as heavy industry. These industries are already the main users of hydrogen, but it is grey hydrogen. Replacing this with green hydrogen could be an easy win.
  - **Chemical industry.** The primary use for hydrogen currently is the production of ammonia (NH_3) and the hydrocracking of hydrocarbons Methane (CH_4) for use in fertilisers and fuel respectively.
  - **Steel.** A difficult to decarbonise sector due to the high heat required (>500°C). Hydrogen is thought to be a most promising solution in the medium to long term (2030-2050).[14]
- **Energy.** The rapid expansion of renewables has brought costs for green hydrogen generation down: however there are few sectors in which it is price competitive with renewables or fossil fuels.
  - **Grid Balancing/Energy Storage.** Renewables introduce greater variability into electricity supply, hydrogen produced during excess production could help smooth, or balance the grid. It could also enable exporting of renewable energy, extending its reach and avoiding limits to electrification, which the already-overloaded electricity grid faces in light of ever-growing renewable input, by using the existing gas grid.
  - **Off-grid power.** Hydrogen fuel cells can replace diesel generators, with greater reliability and longer storage possible. These can be used for remote locations such as military bases, telecom sites, and data centres.
  - **Building Heating.** In the US ~50% buildings are heated by natural gas; in the UK ~85%. Hydrogen may be able to supplement natural gas in the short term and possibly in the longer term replace it.

The economics and related issues

Although momentum is increasing, due to increased governmental support, the hydrogen economy faces numerous obstacles to its widespread adoption.

Costs

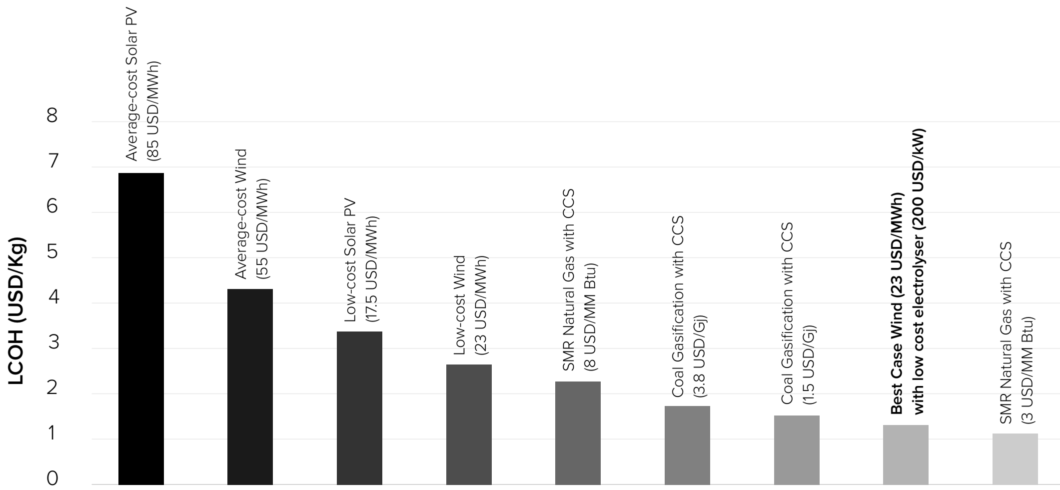
Future costs are uncertain; and perhaps even more importantly, future *relative* costs uncertain. Much will depend on policy, and in particular the pricing of carbon emissions.

Today, neither renewable (green) hydrogen nor low-carbon hydrogen, notably fossil-based hydrogen with carbon capture (CCS) (grey hydrogen), are cost-competitive with fossil-based hydrogen, fossil fuels, and some renewables. Representative costs:

- Renewable (green) hydrogen: 2.5-5.5 €/kg.[15]
- Fossil-based hydrogen: around 1.5 €/kg for the EU, although this figure is highly dependent on the prices of natural gas, and disregards the cost of sequestering the CO_2 produced in the process
- Fossil-based hydrogen with CCS: around 2 €/kg.

Figure 5 below shows the average and best-case supply costs of renewable electricity today, compared with the supply from fossil fuels with CCS. The best case considers a low-cost electrolyser of USD 200/kW, which at a broader scale is expected to be achieved only from 2040.

Figure 5: Costs of producing hydrogen from renewables and fossil fuels today



Notes: Electrolyser capex: USD 840/kW; Efficiency: 65%; Electrolyser load factor equals to either solar or wind reference capacity factors. For sake of simlicity, all reference capacity factors are set at 48% for wind farms and 26% for solar PV systems.
Source: IRENA analysis

A key driver for hydrogen cost competitiveness, if not the key driver, stands to be the size of the tax on emissions of carbon, together with the evolution of renewable energy and electrolyser costs.

- **Carbon pricing.** Pricing CO_2 appropriately would speed up the energy transition and make a more compelling case for green hydrogen. Hydrogen is currently too expensive to compete with fossil fuels unless CO_2 is priced, governments subsidise, or economies of scale are reached.[16,17]
- **Future costs** are perforce highly difficult to project, as they are also affected by the price of both renewable power and fossil fuels.
  - That said, the costs for renewable hydrogen are falling quickly. Electrolyser costs have already come down by 60% in the past ten years, and are expected to halve by 2030 compared with today, due largely to economies of scale.
  - In regions where renewable electricity is cheap, electrolysers are expected to be able to compete with fossil-based hydrogen by 2030.

Lack of infrastructure

In addition to production costs, the requisite infrastructure investment, costs of logistics, as well as of maintenance have to be taken into account.

The most immediate obstacle facing a hydrogen economy is a lack of infrastructure, from fuelling stations to electrolysers,[18] to access to renewable power and storage and transport facilities.[19] Provision is dependent to some extent on research, development, and innovation.[20] The number of charging points is a distinct limitation of consumer uptake around the world of hydrogen fuel cell vehicles.

However, hydrogen can use existing gas infrastructure to a certain extent, although it is important that standards be synchronised to ensure everyone can use the gas.[21]

Shipping would require global buy-in to facilitate refuelling around the world. That said, much of the existing production of hydrogen is concentrated around ports, and nearby industrial facilities.

Such developments would serve to mitigate somewhat the stress to the electricity networks that a massive expansion of renewables would provide, by using existing gas networks to broaden the reach of renewables. However, this is costly.[22] For example, hydrogen pipelines cost three times as much as power lines, and transportation by ships and trucks is even more expensive.

Supportive regulatory framework

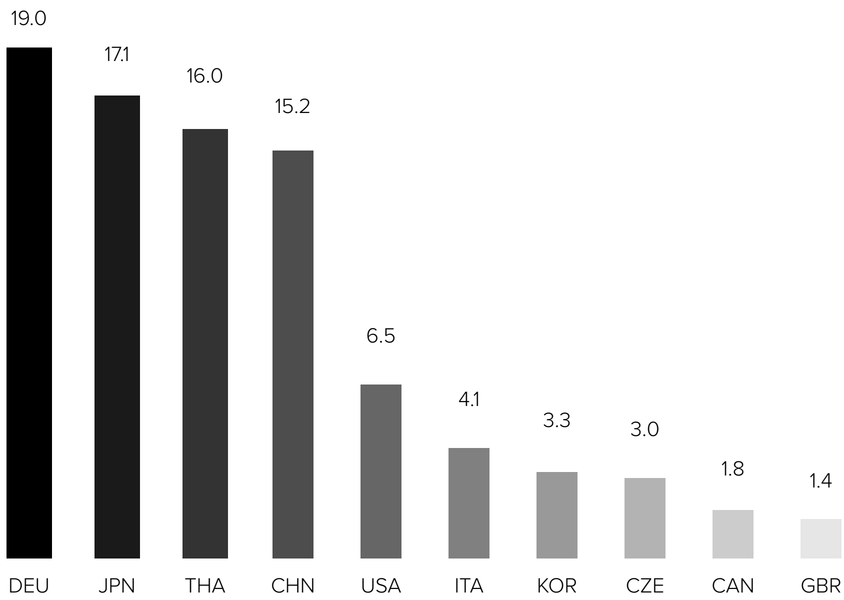
The scaling up of hydrogen, as with the introduction of any new technology, inevitably requires a new supportive policy framework.

- **Grid Access.** The energy sector is heavily regulated to ensure safe and reliable operation. Policies to integrate hydrogen into energy networks and to manage supply are required. If connected to the grid, hydrogen can be produced subject to short-timescale variations in the power market or under flat rates through power purchase agreement (PPA) contracts
- **Standardisation.** The industry requires standardisation of parts and materials to grow, such as charging points and engines.
- **Certification.** Given that hydrogen can be generated from fossil fuels and easily exported, in order to encourage use of green hydrogen, certification is needed to encourage the use of green hydrogen.[23]

Policy

Much basic research and development remains to be done: often this is undertaken, in whole or in part, by governments and indeed a number of major country initiatives are well underway. Competition between some countries is intense – for example between Europe and China in respect of electrolysers. See figure 4.

Figure 4: Global electrolyser market share, by country



Global electrolyser market share in 2016. Germany's share remained around 20 percent in 2020. Source frontier economics/IW
https://www.cleanenergywire.org/news/europe-vies-china-clean-hydrogen-superpower-status

18 countries, accounting for some 70% of the world's economy, include hydrogen as an important part of their decarbonisation strategies. Ten countries have come together in a Clean Energy Ministerial Hydrogen Initiative (CEM H_2I)[24] and several have published hydrogen strategies:

1. **The EU** has announced that cumulative investments in renewable hydrogen in Europe could be up to €180-470 billion by 2050, and in the range of €3-18 billion for low-carbon fossil-based hydrogen. The EU is focused on green hydrogen, delivering 40 GW electrolyser capacity by 2030 and 10 million tonnes of hydrogen.

2. **Germany** is focussed on remaining an exporter in electrolysers, currently comprising 20% of the market, having learned from solar PV. Germany also faces pressure to decarbonise by means of its *Energiewende* transition program, as well as to close its nuclear plants. Germany has by many accounts defined the EU programme for hydrogen. Germany plans to establish up to 5 GW of generation capacity by 2030 and potentially another G 5 GW of generation capacity by 2035. Germany will import a significant amount of its hydrogen. Domestic hydrogen consumption currently amounts to roughly 55 TWh, with only 7% produced as Green hydrogen. Germany's investment includes $110 million annually to fund research laboratories to test new hydrogen technologies for industrial-scale applications.[25]

3. **The US.** Department of Energy funding for hydrogen and fuel cells has ranged from approximately $100 million to $280 million per year over the past decade, with approximately $150 million per year since 2017.[26]

4. **China** primarily produces hydrogen from coal gasification.[27]

5. **Japan.** The Ministry of Economy, Trade, and Industry has announced hydrogen funding of approximately $560 million for 2019.[28] Japan has the world-largest renewable-powered hydrogen project, with 10 gigawatts of capacity, and is the leader in hydrogen refuelling stations – Japan had 113 refuelling stations as of 2019. Hydrogen production from renewable electricity is gaining momentum worldwide. Australia exported for the first time a small amount of green hydrogen produced from renewable energy to a large energy company in Japan in 2019 (Nagashima, 2018). Japan is one of the main hydrogen destinations, and countries have included the country in their own roadmaps. Japan has engaged with Australia, Chile, Norway and Saudi Arabia, among others, to import hydrogen.

6. **Canada.** Air Liquide will build the largest PEM electrolyser in the world, with 20 MW capacity to produce low-carbon hydrogen using hydropower.[29]

7. **California.** State-funded refuelling stations, some 40 of them, marked the rollout of consumer fuel cell vehicles. To help lower emissions from the transportation sector, the state is calling for 250,000 charging stations and 200 hydrogen stations to be in retail operation by 2025, and 5 million ZEVs on the road by 2030, all this to be promoted through a mix of direct financial incentives and credits for low carbon fuels.

8. **The Netherlands** published a Climate Agreement containing a package of measures having broad societal support, including targets for hydrogen production (500 MW of installed electrolysis capacity by 2025 and 3 GW to 4 GW by 2030) and mobility (15,000 FCEVs, 3,000 FC heavy-duty trucks and 50 HRSs by 2025, and 300,000 FCEVs by 2030). From the Climate Budget, the government is making additional funding available to the indicative sum of €40 million per year for pilots and demonstrations in relation to green hydrogen.[30]

9. **Chile.** Chile is also developing a strategy aimed at exporting hydrogen to countries including Japan and the Republic of Korea. The Chilean hydrogen case leverages one of the best solar resources in the world in regions such as the Atacama Desert, with more than 3,000 sun hours and less than 2 millimetres of rainfall per year, which results in the low-cost, high-capacity renewables essential for low-cost hydrogen production (Ministry of Energy, Chile, 2018).

10. **Australia.** the Government has already committed over $146 million to hydrogen projects.[31] Investing in hydrogen power could enable Australia to export its ample solar resources to Asia. The Hydrogen Energy Supply Chain (HESC) Pilot Project is demonstrating a full supply chain, starting with hydrogen production from brown coal in the Latrobe Valley and ending with its transportation to Japan.

11. **Spain**[32] **and Saudi Arabia**[33] also have significant programmes.

Useful sources

European Commission, 2020. A hydrogen strategy for a climate-neutral Europe. Available at https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf [Accessed 3 November 2020]

Global CCS Institute: https://www.globalccsinstitute.com

Hydrogen Council, 2020. Path to hydrogen competitiveness: a cost perceptive. 20 January. Available at https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf [Accessed 3 November 2020]

Imperial College London: https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/briefing-papers/BECCS-deployment---a-reality-check.pdf

International Renewable Energy Agency, 2019. Hydrogen: a renewable energy perspective. (Report prepared for the 2nd Hydrogen Energy Ministerial Meeting, in Tokyo, Japan.) Available at https://irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf [Accessed 3 November 2020]

International Renewable Energy Agency, 2020. Hydrogen from renewable power: technology outlook for the energy transition. Available at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf [Accessed 3 November 2020]

Liebreich, M., Separating Hype from Hydrogen – Part One: The Supply Side. Bloomberg NEF. Available at https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-one-the-supply-side/ [Accessed 2 November 2020];

Liebreich, M., Separating Hype from Hydrogen – Part Two: The Demand Side. Available at https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-two-the-demand-side/

[1] Less than 0.1% of global dedicated hydrogen production today comes from water electrolysis. However, with declining costs for renewable electricity, in particular from solar PV and wind, there is growing interest in electrolytic hydrogen

[2] Electrolytic production is still in its early stages. Europe, the world leader, has a manufacturing capacity of 1.2 gigawatts (GW) per year, enough capacity in theory to power more than half a million fuel cell passenger cars with hydrogen from water. The next two years could set new records, for electrolyser deployment: announced projects stand to bring the global installation of electrolyser capacity from 170 MW in 2019 to 730 MW in 2021. In recent years, the number of projects and installed electrolyser capacity have expanded considerably, from less than 1 MW in 2010 to more than 25 MW in 2019. Furthermore, project size has increased significantly: most projects in the early 2010s were below 0.5 MW, while the largest in 2017-19 were 6 MW and others fell into the 1 MW to 5 MW range. See https://www.iea.org/articles/batteries-and-hydrogen-technology-keys-for-a-clean-energy-future

[3] Companies can perform water electrolysis with either alkaline or proton exchange membrane (PEM) technologies. If the electricity source is low-carbon or renewable, these technologies will produce low-carbon hydrogen. Historically, water electrolysis has been more expensive than SMR largely due to the cost of power, which is why it is not deployed at scale today

[4] Natural gas is currently the primary source of hydrogen production, accounting for around three quarters of the annual global dedicated hydrogen production of around 70 million tonnes. This accounts for about 6% of global natural gas use. This means that the production and use of hydrogen is associated with more than 800 million tons of carbon dioxide (CO2) emissions today – a staggering amount that is equivalent to the emissions of the United Kingdom and Indonesia combined

https://www.iea.org/articles/batteries-and-hydrogen-technology-keys-for-a-clean-energy-future

[5] Known as Hydrogen Embrittlement: only an issue at over 50% H2 in a mix

[6] Around 95% of the hydrogen production currently goes towards the production of ammonia (NH3) for use in fertilisers, and hydrocarbons produced through the use of hydrogen in a process known as hydrocracking. Less than 4% of global dedicated hydrogen production today comes from water electrolysis, with declining costs for renewable electricity, in particular from solar PV and wind, there is growing interest in electrolytic hydrogen. 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] Hydrogen's impact on transport is still minimal and constrained by the number of refuelling stations, currently standing at 470 and primarily concentrated in Japan, the US and Germany. However, it is expanding quickly with the registrations of Fuel Cell Electric Vehicles (FHEVs) more than doubling from 2018-2019 with a total of 25 212 vehicles worldwide. This still only accounts for just 0.5% of new low-carbon vehicles sales. The U.S. dominates in passenger vehicles, China for 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]

[8] In Europe, the H2Bus consortium announced their aim for 1000 commercially competitive buses fuelled with hydrogen from renewable power, the first 600 of which are due on the road by 2023, supported by €40 million from the EU's Connecting Europe Facility. See, H2Bus, 2020. About Us. H2Bus [online] Available at: <https://h2bus.eu/about> [Accessed 2 November 2020]. Both China and South Korea have massively expanded their bus fleets in recent years from only a few sold in 2017 to ~4 400 and ~4 100 respectively in 2019. See, International Energy Association, 2020. Hydrogen. IEA [online] Available at: <https://www.iea.org/reports/hydrogen> [Accessed 2 November]

[9] Alstom, one of the world's largest rolling stock manufacturers have begun rolling out hydrogen trains in European locations and testing in many more.
https://www.alstom.com/press-releases-news/2018/9/world-premiere-alstoms-hydrogen-trains-enter-passenger-service-lower
https://www.cnbc.com/2020/06/04/hydrogen-trains-could-be-on-way-to-italy-after-firms-seal-agreement.html
The UK could also get involved since 24% of their rolling stock is still fuelled by diesel. https://www.bbc.com/news/business-48698532

[10] https://www.dnvgl.com/expert-story/maritime-impact/Power-ahead-with-hydrogen-ferries.html

[11] Much of the infrastructure for refining fossil fuels and producing fertilisers is concentrated around ports, https://www.iea.org/reports/the-future-of-hydrogen

[12] 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]. 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]

[13] See, California Fuel Cell Partnership, 2020. Road Map to a US Hydrogen Economy. CAFCP [online] Available at: <https://cafcp.org/sites/default/files/Road%2BMap%2Bto%2Ba%2BUS%2BHydrogen%2BEconomy%2BFull%2BReport.pdf> [Accessed 2 November 2020]

[14] Industrial processes define three grades of heat required, low (<100oC), medium (100-500oC), and high (>500oC). At the highest temperatures required by the steel industry H2 is more likely to become economical, depending upon the cost of carbon and the length of existing plants lifespans/investments. See, 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]. 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]

[15] https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

[16] https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf
https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-Scaling-up_Hydrogen-Council_2017.compressed.pdf

[17] Requires €3/kg H2 to be competitive with fossil fuelled engines This relies on cost of electricity, loading factor of electrolysing plant, cap-ex and operational costs. This means that tax breaks and incentives are currently required. There is potential for clashes with renewable electricity production in certain areas. Fuel cell vehicles are 70% more expensive than BEVs

[18] Dramatic increases in capacity required: The global capacity of electrolysers, which produce hydrogen from water and electricity, expands to 3 300 GW in the Sustainable Development Scenario, from 0.2 GW today. https://www.iea.org/reports/energy-technology-perspectives-2020

[19] Dramatic increase in innovation required: Just over one-third of the cumulative emissions reductions in the Sustainable Development Scenario stem from technologies that are not commercially available today. In the Faster Innovation Case, this share rises to half https://www.iea.org/reports/energy-technology-perspectives-2020

[20] Dramatic increase in innovation required: Just over one-third of the cumulative emissions reductions in the Sustainable Development Scenario stem from technologies that are not commercially available today. In the Faster Innovation Case, this share rises to half https://www.iea.org/reports/energy-technology-perspectives-2020

[21] This could also be used to new demand could be created directly, for instance, by requiring hydrogen blending in natural gas pipelines. 5% has been demonstrated, 20% should be possible with minor upgrades, and is happening at Keele University. <2% in New South Wales (AU) https://hydeploy.co.uk/
https://www.hydrogen.energy.gov/pdfs/htac_nov12_3_melaina.pdf

[22] Early adoption of the assets installed in the "natural" renewing cycles towards hydrogen-tolerant products will reduce the costs greatly. Postponing the starting point for installing tolerant products by five years will lead to additional transition costs of around EUR 12 billion (USD13.4 billion) for the German gas infrastructure, including gas grids and underground storage (Müller-Syring et al., 2018)

[23] The German designed, EU-backed certification scheme for hydrogen production to ensure that it was generated using renewable energy can be found here. https://www.certifhy.eu/

[24] https://www.cleanenergyministerial.org/initiative-clean-energy-ministerial/hydrogen-initiative

[25] A committee of state secretaries of affected ministries will ensure implementation of the strategy. In addition, the government will establish a national hydrogen council made up of [25] representatives from business, science, and civil society that will support the state secretary committee. https://www.bmwi.de/Redaktion/DE/Downloads/M-O/mitglieder-nationaler-wasserstoffrat.pdf?__blob=publicationFile&v=18
Germany's hydrogen strategy is outlined here https://www.bmbf.de/files/bmwi_Nationale%20Wasserstoffstrategie_Eng_s01.pdf
Germany's 20% share of electrolysers sales stat is from https://www.cleanenergywire.org/news/europe-vies-china-clean-hydrogen-superpower-status

[26] The US dept of Energy has outlined their national strategy in the following https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf
A recent report compiled by McKinsey has outlined a US Road to a Hydrogen Economy. Of note is the inclusion of a disreputable/fraudulent electric vehicle company "Nikola Motors" now partnered with GM, This aside they conclude their report with a call for a carbon credit or cap and trade scheme to generate the investment in infrastructure in addition to tax credits https://cafcp.org/sites/default/files/Road%2BMap%2Bto%2Ba%2BUS%2BHydrogen%2BEconomy%2BFull%2BReport.pdf

[27] Chinas hydrogen strategy reporting.https://www.cleantech.com/hydrogen-in-china/
https://www.spglobal.com/platts/en/market-insights/latest-news/metals/061120-n-china-hydrogen-push-led-by-hydrogen-as-by-product-renewables
https://www.energy.gov/sites/prod/files/2018/10/f56/fcto-infrastructure-workshop-2018-4-li.pdf
https://energyiceberg.com/china-hydrogen-policy-provincial-summary/

[28] https://www.iphe.net/japan
Japan's hydrogen strategy https://www.energy.gov/articles/joint-statement-future-cooperation-hydrogen-and-fuel-cell-technologies-among-ministry

[29] https://www.nrcan.gc.ca/energy-efficiency/energy-efficiency-transportation/resource-library/2019-hydrogen-pathways-enabling-clean-growth-future-canadians/21961

[30] Netherlands hydrogen strategy https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/national-climate-agreement-the-netherlands

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For follow up information, please contact:
Patrick Meyer
Data & Analytics
LSEG
patrick.meyer@lseg.com

London Stock Exchange Group
10 Paternoster Square
London
EC4M 7LS

+44 (0)20 7797 1000

LSEG