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Sustainable Futures

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The Hydrogen Economy Pipedream Or Panacea?

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Introduction

As concern regarding a rapidly changing climate mounts, momentum has been growing to explore whether hydrogen can provide a solution to many of the challenges we face in decarbonising the economy.

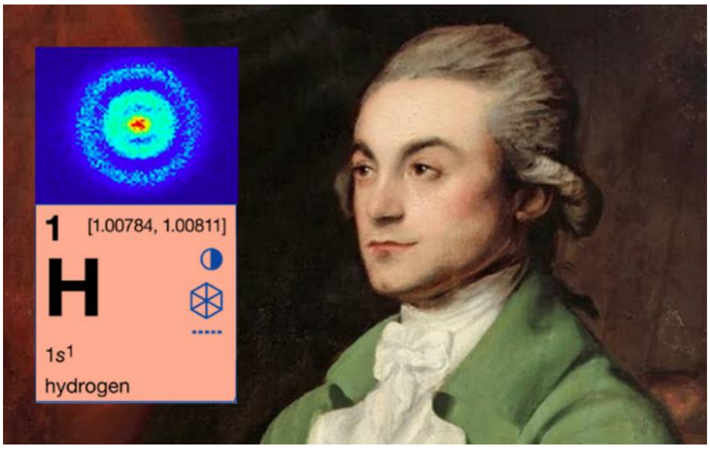
Hydrogen has had a long history of use in human activity from powering the first internal combustion engines over 200 years ago[1], to providing the source of the fertilizers that sustain our current population levels. Hydrogen is energy-dense, and its use produces no direct emissions other than water. But for hydrogen to make a significant meaningful contribution to the net zero transition its use needs to be adopted in sectors where, until now it has been completely absent.

This short report provides an overview of the state of play in the hydrogen economy and examines some of the major barriers and opportunities it faces.

Hydrogen

Hydrogen, with an atomic number of 1 is the lightest and most abundant element in the universe. As the basic fuel source of stars, it comprises around 75% of all matter by mass[2]. At room temperature hydrogen is a colourless, odourless gas, and although the means of its artificial production (through the reaction of metals with acids) were discovered by Paracelsus in the 1500's[3], it was only identified as a distinct element by Henry Cavendish in the 18th century, who described its property of producing water when burned (hence its Greek etymology "water maker").

Figure 1 | Henry Cavendish With A Quantum Microscope Image Of A Hydrogen Atom[4]



Uses

Hydrogen has a long history of being utilized in a wide variety of industries, and the majority of hydrogen today is used in fields such as oil refining, methanol production and ammonia production.

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[1] *The first internal combustion engine was invented by Swiss engineer Francois Isaac de Rivaz in 1806and was powered by a mix of hydrogen and oxygen.*

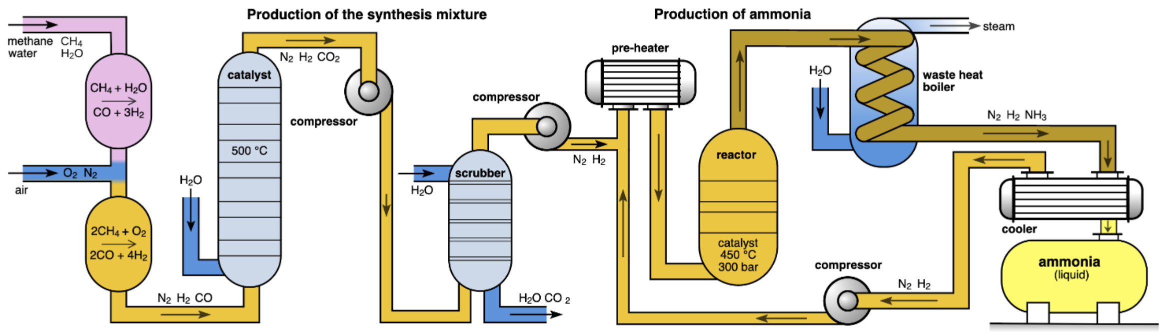
[2] Harvard & Smithsonian Centre For Astrophysics (accessed 25.03.24) ***Before the Dark Ages*** https://www.cfa.harvard.edu/news/dark-ages

[3] Royal Society of Chemistry (accessed 25.03.24) ***Periodic Table- Hydrogen*** https://www.rsc.org/periodic-table/element/1/hydrogen

[4] Stodolna A. S. et al ***Hydrogen Atoms under Magnification: Direct Observation of the Nodal Structure of Stark States***, Phys. Rev. Lett. 110, 213001 – Published 20 May 2013

It is worth lingering on the last of these for a moment, as the Haber-Bosch process for ammonia production is credited with averting mass starvation[5] and fuelling the population boom of the 20th century (as well as earning Fritz Haber and Carl Bosch two Nobel prizes). It is estimated that nearly 50% of the nitrogen found in human tissues originates from the Haber-Bosch Process[6].

Figure 2 | The Haber-Bosch Process



(source Wikimedia Commons)

More recently, hydrogen has attracted attention as a potential energy storage mechanism for use in transport and as a stepping stone in the transition to net-zero.

The Hydrogen Economy

The hydrogen economy is catch-all term used to refer to an energy delivery infrastructure based on hydrogen as a carbon-free energy carrier. In other words, using hydrogen to replace fossil fuels particularly for use in transport and heavy industry.

There are three areas where hydrogen could play a role in the transition to net zero.

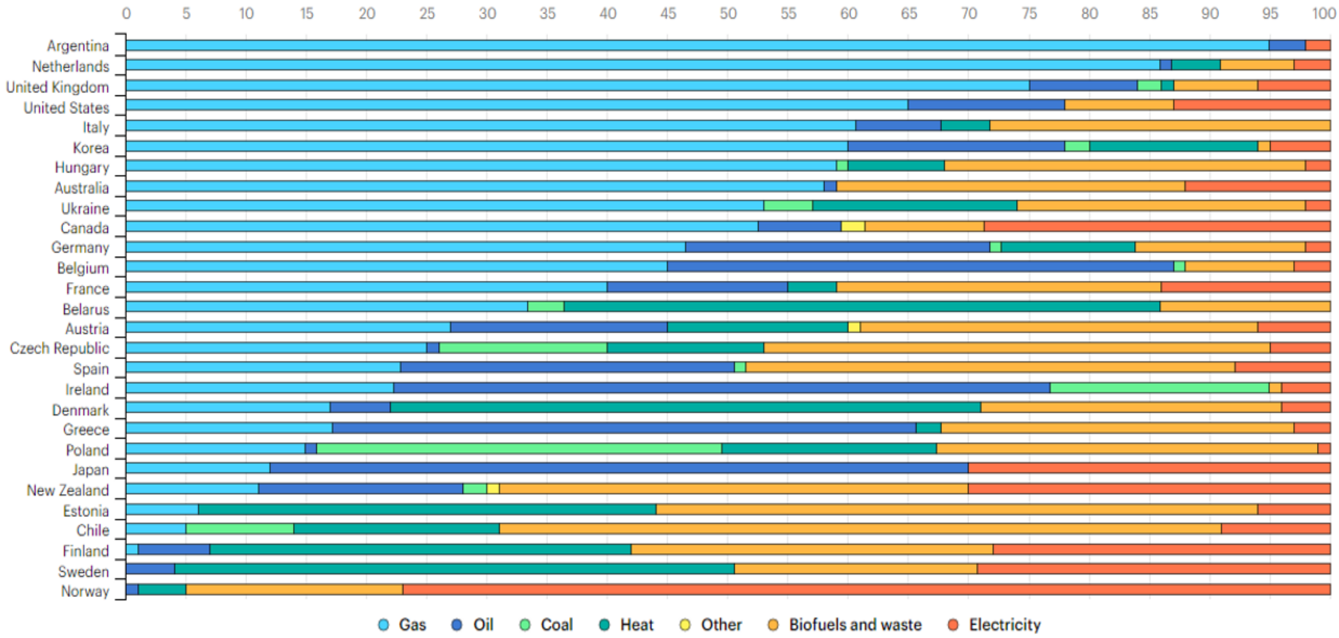
- The use of hydrogen as a replacement for fossil fuels in domestic heating and cooking (see figure 5)
- The use of hydrogen as a replacement for coal or natural gas in high temperature industrial processes such as steel making
- The use of hydrogen as a replacement for fossil fuels in transport

Domestic Use

With respect to using hydrogen to replace natural gas in a domestic context, whilst this appears at first glance to be an attractive proposition (indeed in the UK, the Department for Energy and Net Zero in collaboration with OFGEM initiated a trail with gas distribution network companies[7] since discontinued), practical considerations have prevented any progress.

[5] Quraishi M (2020) ***The Haber Process: A Simple Discovery that Changed the World The Oxford Scientist*** https://oxsci.org/the-haber-process-a-simple-discovery-that-changed-the-world/
[6] Solomon C *et al* ***2004 Role of urea in microbial metabolism in aquatic systems: a biochemical and molecular review*** AME Vol. 59, No. 1. https://www.int-res.com/abstracts/ame/v59/n1/p67-88/
[7] OFGEM 2022 (accessed 26.03.04) https://www.ofgem.gov.uk/publications/hydrogen-village-trial-detailed-design-studies-decision

Figure 5 | Residential Energy Consumption By Fuel Source In Selected Countries



Source IEA[8]

These considerations have included the safety of using hydrogen in a domestic setting, the cost of converting domestic boilers and cookers to run on hydrogen , the availability of a low-cost hydrogen supply and the need to prioritise the decarbonisation of hydrogen supplies. A recent meta-analysis of 34 independent studies into the viability of hydrogen as a domestic energy source concluded that, despite significant lobbying from gas suppliers and boiler makers, at present the domestic use of hydrogen is not a viable option[9].

Industrial Use

The most promising area for using hydrogen is iron and steel refining. The industry is currently responsible for around 4% of all CO_2 emissions in Europe, and 7% worldwide[10], primarily due to the use of coal in production. Replacing coal by hydrogen would make it possible to significantly reduce emissions from this sector – providing the hydrogen was generated from renewable sources.

The technology to manufacture iron and steel using hydrogen is well understood and a number of pilot plants have been constructed, which are further refining the process. Production has already started at H2 Green Steel, first green steel plant in Boden, northern Sweden[11].

[8] IEA 2022 ***Energy Efficiency 2022*** https://www.iea.org/reports/energy-efficiency-2022
[9] Rosenow J 2022 ***Is heating homes with hydrogen all but a pipe dream? An evidence review*** | Volume 6, Issue 10, P2225-2228 https://www.cell.com/joule/fulltext/S2542-4351(22)00416-0?_returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS2542435122004160%3Fshowall%3Dtrue
[10] IEA 2020 ***Iron and Steel Technology Roadmap*** https://www.iea.org/reports/iron-and-steel-technology-roadmap
[11] Mining Technology 2023 ***Europe's first commercial green steel plant to open in Sweden*** https://www.mining-technology.com/news/green-steel-hydrogen/

However, hydrogen prices vary:

Hydrogen produced from fossil fuel sources costs from US$5 to 7 per kg in the US, and $7 to 11 in Europe and Australia. Whilst green hydrogen produced through electrolysis using renewable power costs US$10-15 per kg , depending on availability.

Currently replacing coal with hydrogen using currently available infrastructure and technology would drive up the price of a ton of steel by about one third[12], although this gap is likely to narrow as carbon carbon-emission pricing will drive up the cost of using coal, the costs of renewable electricity will fall and efficiency gains resulting from larger-scale production of hydrogen (and advances in hydrogen-based steel-making processes progress). More significantly, scaling up hydrogen production for a full decarbonisation of the steel industry will require an increase in renewable electricity production of around 20 % over current targets.

Transport Use

Up until the eighteenth century, mankind relied primarily on animal power for transport.

All of this changed with the industrial revolution. Initially horsepower was used on canals, but as the revolution gathered pace, coal, which was relatively cheap and eminently portable took over to fuel ships and trains. **Coal contains approximately 29 MJ/kg of energy.**

As the twentieth century dawned and technology advanced coal was replaced for use in transport by oil. **Petrol contains 47 MJ/kg of energy.**

Coal and oil are both energy sources – they are dug out of the ground and burnt to release energy. However, they can also be considered to be energy storage media – they are compact and portable and the energy that they are storing is chemical energy created by biological processes as a result of sunlight falling on earth hundreds of millions of years ago. The energy density and portability of fossil fuels makes them perfect for use in transport. Unfortunately, fossil fuels release carbon dioxide when they are used which is the primary driver of global warming.

In the twenty first century two further energy storage media have emerged. Batteries and hydrogen.

Battery technology has advanced enormously over the last decade. However, batteries are still heavy and expensive and require charging. They also have poor energy density compared with fossil fuels - **a lithium-ion battery pack has an energy density of around 0.3MJ/kg.**

By contrast hydrogen packs a significant punch with an **energy density of approximately 120MJ/kg.**

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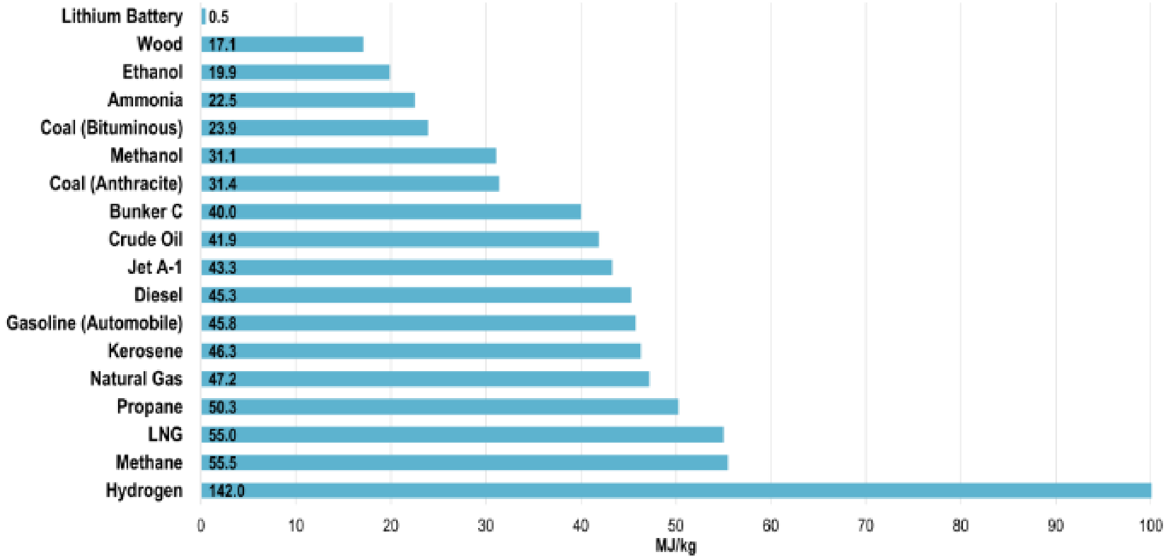
[12] European Parliament 2020 ***The potential of hydrogen for decarbonising steel production*** https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS_BRI(2020)641552_EN.pdf

Figure 4 | Energy Density



Source: The Geography of Transport Systems[13]

Although, hydrogen is an energy dense storage medium, a note of caution must be inserted. energy density is not the sole consideration when it comes to fuel sources in transport as energy density is not the same as molar density. That is to say, a kilogramme of petrol does not occupy the same volume as a kilogramme of hydrogen:

1kg Petrol (@18°C at 1 atmosphere) = ~2 litres

1kg Hydrogen (@-239.95 C at 13 atmospheres) = ~14 litres

A small car will achieve a fuel efficiency of around 6 litres per 100km[14]. A hydrogen fuel cell car will achieve a fuel efficiency of 10 litres per 100km[15]. Due to the size and weight of hydrogen storage tanks, this reduces the range available to smaller vehicles, although this is not a major impediment when it comes to road vehicles - the Toyota MIRAI II fuel cell car has a range of up to 650 km - and cars can refill their tanks rapidly at fuel stations much the way ICE vehicles can.

Fuel cell cars and ships are already a reality, their potential only limited by a lack of investment in refuelling infrastructure and risk aversion by major car manufacturers. At the time of writing, there are only two mainstream hydrogen-powered cars on sale: the Toyota Mirai and Hyundai Nexo. However, there are more hydrogen-powered cars in the pipeline, with firms such as BMW, Land Rover and Vauxhall all planning new models within the next five years[16].

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[13] Rodrigue J 2020 ***The Geography of Transport Systems (Fifth Edition)*** New York: Routledge, ISBN 978-0-367-36463-2

[14] What Car? (accessed 16.03.24) https://www.whatcar.com/news/real-mpg-most-efficient-cars-with-10-litre-engines/n19440

[15] Toyota (accessed 16.03.24) https://www.toyota.co.uk/new-cars/mirai

[16] Auto Express 2023 ***Hydrogen cars: do hydrogen fuel cell or combustion cars have a future?*** https://www.autoexpress.co.uk/electric-cars/93180/hydrogen-cars-do-hydrogen-fuel-cell-or-combustion-cars-have-future#:~:text=At%20the%20time%20of%20writing,within%20the%20next%20five%20years.

However, the molar density of hydrogen does present some difficulties when it comes to air transport, where, range and infrastructure considerations, as well as the economics of fleet renewal present a complex picture.

Airbus is currently working on ZEROe, a project which aims to bring to market the world's first hydrogen-powered commercial aircraft by 2035[17]. To Airbus must surmount significant technical challenges, including aircraft design and technologies, as well as preparing the ecosystem that will produce and supply the hydrogen.

Box 1 The Hydrogen Fuel Cell

A fuel cell uses the chemical energy of hydrogen or other fuels to cleanly and efficiently produce electricity. If hydrogen is the fuel, the only products are electricity, water, and heat.

The first fuel cells were invented by Sir William Grove in 1838. The technology was refined by Francis Thomas Bacon in 1932 who invented the hydrogen–oxygen fuel cell (or alkaline fuel cell), which has been used in NASA space programs since the mid-1960s to generate power for satellites and space capsules.

Fuel cells are unique in terms of the variety of their potential applications; they can use a wide range of fuels and feedstocks and can provide power for systems that range in scale from a utility power stations, through aircraft and cars, to laptop computers.

In recent years significant advances have been made in the efficiency of fuel cells, solid-state electrolysers, proton exchange membrane and fuel cell systems integration have resulted from major investment in R&D from firms such as Toyota, Daimler, Shell, BMW, Air Liquide and Hyundai.

E.ON's1.4-MW Fuel Cell Power Plant at Mannheim, Germany

[17] Airbus (accessed 26.03.24) https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe

Hydrogen Production

There has recently been some discussion in scientific journals of the existence of lithospheric hydrogen reserves. Energy companies such as Shell, BP and Chevron are joining a consortium created by the U.S. Geological Survey and Colorado School of Mines to study geologic hydrogen[18], but some smaller firms are already joining what may become a new gold rush. HyTerra (hyterra.com)and Natural Hydrogen Energy (nh2e.com) are preparing to drill for it in Nebraska and Kansas, and Gold Hydrogen (goldhydrogen.com.au) is searching for it in Australia.

However, until these firms strike paydirt, hydrogen remains an energy transfer medium rather than an energy source. As a result, hydrogen is made at industrial scale either through the use of fossil fuels or by the application of large amounts of energy. Currently there is a spectrum for hydrogen production (see figure 3):

Grey (or brown) hydrogen, which is still used for the bulk of hydrogen production uses fossil fuels as feedstock and involves combining methane (derived from natural gas or coal) with steam, at high temperatures and pressures to produce syngas, a mixture of hydrogen and carbon monoxide, from which the carbon monoxide is extracted to leave pure hydrogen. The carbon monoxide is then burnt to produce CO_2 which is released to the atmosphere.

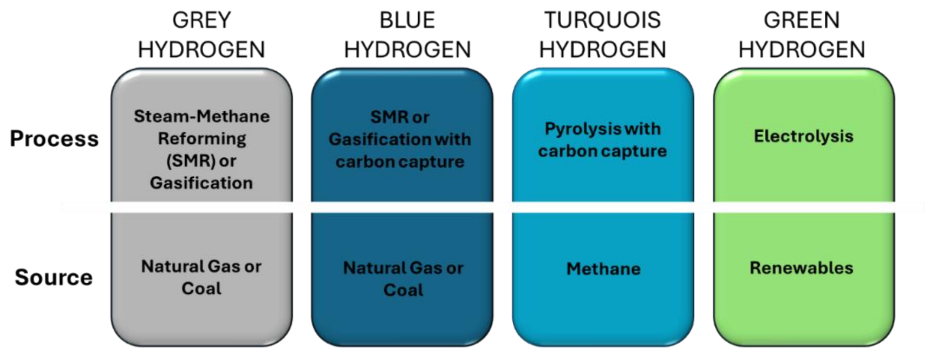
Blue hydrogen uses a similar process and feedstock to grey hydrogen, but the CO_2 is captured and securely stored.

Turquois hydrogen is a developing technology that uses a process called methane pyrolysis to produce hydrogen and solid carbon. The main technical challenge with turquoise hydrogen is the handling of the solid carbon. If the reaction occurs over a conventional solid catalyst, carbon rapidly deposits on the catalyst surface, deactivating it, so trials are being conducted which form the reaction in a liquid bath of molten metal or salt. Needless to say, the process is energy intensive and has yet to be scaled up to commercial viability.

Green hydrogen is hydrogen produced by splitting water into hydrogen and oxygen using renewable electricity (primarily from hydroelectric sources). Unfortunately, the process of hydrogen production by electrolysis is very energy intensive.

Hydrogen is also produced through electrolysis as by-product of chlorine manufacture (purple hydrogen), from nuclear power (pink or red hydrogen) and from solar power (yellow hydrogen).

Figure 3 | The Hydrogen Rainbow



[18] Forbes 2024 Forget Oil. New Wildcatters Are Drilling For Limitless 'Geologic' Hydrogen https://www.forbes.com/sites/alanohnsman/2023/06/26/forget-oil-new-wildcatters-are-drilling-for-limitless-geologic-hydrogen/

Currently 47% of global hydrogen production is from natural gas, 27% from coal, 22% from oil (as a by-product) and only around 4% comes from renewables[19] and other sources.

Global hydrogen production is at present about 120 million tons per year[20], of which two-thirds is pure hydrogen and one-third is mixed with other gases. The global hydrogen generation market size was estimated at USD 170.14 billion in 2023 and is expected to grow at a compound annual growth rate (CAGR) of 9.3% from 2024 to 2030[21].

China is the largest producer and consumer of hydrogen in the world it currently has an annual production capacity of around 33 million tons[22], by comparison the US produces 10 million tons and the EU, EFTA and UK 11.3 Mt in total. China is currently investing heavily in production capacity and technology in anticipation of a rapid expansion in the demand for hydrogen.

Challenges

For hydrogen to takes its' place in the armoury of tools mankind must have at its disposal to tackle climate change a number of significant factors need to align.

Hydrogen production must increase exponentially, costs per kilogramme must decline and new infrastructure must be developed. This will require unprecedented levels of investment. In February of this year the EU announced that it has committed US$7.4bn in state aid to kick start the hydrogen economy[23], but in a recent interview a senior executive at Mitsubishi Heavy Industries estimated that $1 trillion is required for building infrastructure to enable widespread use of hydrogen fuel in the US and Europe[24].

Because of the level of investment required and the current scarcity of green hydrogen, careful consideration must be given to prioritising the uses that green hydrogen is put to. As discussed above, domestic uses are not currently feasible, with the money better spent on enhancing energy efficiency. Instead, priority should be given to the decarbonisation of iron and steel production as this is where the greatest carbon efficiency gains can be made, transport uses come a close second, although

[19] IRENA (accessed 23.03.24) ***Hydrogen*** https://www.irena.org/Energy-Transition/Technology/Hydrogen#:~:text=As%20at%20the%20end%20of,around%204%25%20comes%20from%20electrolysis.

[20] Allianz 2021 ***The Hydrogen Economy: Opportunities And Risks In The Energy Transition*** https://commercial.allianz.com/news-and-insights/reports/hydrogen-energy.html#:~:text=The%20vast%20majority%20of%20hydrogen,is%20mixed%20with%20other%20gases.

[21] Grand View Research (accessed 20.03.24) ***Hydrogen Generation Market Size & Trends*** https://www.grandviewresearch.com/industry-analysis/hydrogen-generation-market#:~:text=b.-,The%20global%20hydrogen%20generation%20market%20size%20was%20estimated%20at%20USD,the%20hydrogen%20generation%20market%20growth%3F

[22] PtX Hub (accessed 20.03.24) ***Hydrogen Factsheet – China*** https://ptx-hub.org/factsheet-on-china-the-worlds-largest-hydrogen-producer-and-consumer/#:~:text=Hydrogen%20Factsheet%20%E2%80%93%20China&text=China%20is%20the%20largest%20producer%20and%20consumer%20of%20hydrogen%20in%20the%20world.

[23] Reuters 2024 ***EU approves $7.4 bln in state aid to boost renewable hydrogen*** https://www.reuters.com/sustainability/climate-energy/eu-approves-74-bln-state-aid-boost-renewable-hydrogen-2024-02-15/

[24] Hydrogen Central 2024 ***Hydrogen Economy – Hydrogen adoption will cost Europe, US more than $1 trillion*** https://hydrogen-central.com/hydrogen-economy-hydrogen-adoption-will-cost-europe-us-more-than-1-trillion/

refuelling infrastructure will require cooperation from a reluctant oil industry - Shell is currently closing its hydrogen refuelling stations in California[25].

A critical factor in driving the investment required to overcome the inertia generated by organisations who have heavily invested in legacy infrastructure, is a conducive and stable policy environment.

Beleaguered politicians, already beset by disgruntled populations reeling from the 'cost of living crisis' are reluctant to add to inflationary pressure by increasing energy costs. Without public investment, the reduction of fossil fuel subsidies and the ramping up of mechanisms such as emissions trading, carbon taxes and carbon accounting, the case for the hydrogen economy is on shaky ground.

However, the financial services sector can help. Green products such as green loans, green bonds and sustainability bonds can drive investment into this sector, whilst financial centres can prepare the way by developing market infrastructure for hydrogen.

Functioning markets will greatly assist the successful development of a hydrogen industry. Access to hydrogen as a commodity and the development of secondary markets in derivatives and futures will allow enhanced liquidity and increasing volumes of trade. The European Energy Exchange, located in Leipzig, Germany established HYDRIX – the first market-based hydrogen price index worldwide, in May 2023 and expects cleared trading to begin by 2029[26]. Other financial centres look set to follow.

Conclusions

There is still a mountain to climb before the promise of the hydrogen economy can be fully realised. The technology is ready to go, but massive investment in production and infrastructure is required which in turn is reliant on nerves of steel by policy makers.

What is certain is that hydrogen will play a critical role in the path to net zero, and that global production of hydrogen will expand exponentially as the century progresses – potentially growing to rival oil as a traded commodity.

Financial centres can assist with progress by developing infrastructure for hydrogen trading and ensuring that the right investment products are available to organisations seeking to push the pace of progress forwards.

[25] Autoweek 2024 Shell Closes Its Hydrogen Stations In California https://www.autoweek.com/news/a46791348/shell-closes-hydrogen-stations-california/

[26] EEX (accessed 26.03.04) https://www.eex.com/en/markets/hydrogen#29899

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