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The role of hydrogen and ammonia in meeting the net zero challenge

In brief

Hydrogen and ammonia have important potential roles in a net zero economy as they have no carbon emissions at the point of use. Both fuels are versatile, capable of being produced and used in many ways, including production from renewable sources and applications to decarbonise challenging areas, such as heavy transport, industry, and heat, as well as the storage and transport of energy. They are already widely used in industry and agriculture, but their current production carries a high greenhouse gas footprint. Significant greenhouse gas emission reductions could be achieved through decarbonisation of production for both existing and new applications. However, both fuels currently face challenges that require technological advances, including in their generation, storage and use, particularly the costs involved in achieving net zero life cycle emissions. Further research, development, demonstration, and deployment are required to identify the areas where hydrogen and ammonia can make a critical difference in practice.

INSIGHTS

- Hydrogen and ammonia have the potential to be competitive net zero energy sources and energy carriers for a number of applications. Research, development, demonstration, and deployment are required to gauge that potential more accurately.
- Hydrogen and ammonia should be prioritised for demonstration in sectors where they have high potential to be the leading cost-effective low-carbon alternative, such as heavy industry and heavy-duty vehicles, railways, and shipping, as well as energy storage.
- Demonstration at scale can often be most cost-effectively carried out through clusters of industrial partners, with port regions often being particularly suitable, especially for integration with offshore wind.
- International collaboration, including on infrastructure, can help to develop the outcomes presented here, building on current pilot projects, and should be coupled with research to drive further innovation.

1. Hydrogen and ammonia today

1.1 Background

Hydrogen is the most abundant element in the universe and a well-established energy carrier. It has significant potential in a net zero economy as it can be used in transport, heat, power, and energy storage with no greenhouse gas emissions at the point of use. Ammonia, a compound of hydrogen and nitrogen, is also a powerful zero-carbon fuel.

1.2 Conventional production and use of hydrogen and ammonia

The most common current process for producing hydrogen is steam methane reforming (SMR), known as 'grey' hydrogen[1]. Each year, around 6% of the world's natural gas and 2% of its coal is used to make grey hydrogen[2]. Around 51% of the pure hydrogen produced globally is used in refineries, for example to remove impurities such as sulfur from fuels, and around 43% as an input for ammonia synthesis[3]. Other applications use hydrogen as part of a mixture of gases, including the production of methanol used in industrial applications and chemical manufacture, and the reduction of iron to produce steel using electric arc furnaces. Demand for pure hydrogen has reached around 70 million tonnes per year (MtH_2/yr), a threefold growth since the 1970s[3].

As the lightest element, with low volumetric energy density, hydrogen is challenging to store and transport and for many practical uses needs to be compressed or liquefied. These demands mean that today it is typically manufactured close to where it is used. However, there are existing dedicated hydrogen pipeline networks, for example in the US Gulf Coast region, Germany and the Benelux countries[4, 5].

Ammonia is produced in the Haber-Bosch process where hydrogen is mixed with nitrogen and together processed at high temperature and pressure with a catalyst to produce ammonia[6]. The most common uses of ammonia are in the production of fertilisers, as a refrigerant and to make plastics and other products.

Ammonia (NH_3) has higher volumetric energy density than hydrogen and is easier to store and transport. Worldwide production of ammonia is about 175Mt/yr[6].

Both SMR and Haber-Bosch are based today on the use of fossil fuels such as natural gas and coal. Hydrogen production accounts for 830 million tonnes of CO_2 emissions per year ($MtCO_2$/yr), while ammonia production accounts for around 420$MtCO_2$/yr, together around 2% of annual global greenhouse gas (GHG) emissions[7, 8, 9].

1.3 Safety and environmental considerations of hydrogen and ammonia

Both hydrogen and ammonia raise safety concerns that need to be managed. Hydrogen has a very low flashpoint, much lower than gasoline, for example, at -43°C[10]. However, it needs a higher concentration in air to be flammable, 4% compared to 1.6% for gasoline, and its low density and high diffusivity in air reduces risk as it dissipates rapidly[11, 3]. Adequate ventilation and leak detection are important in designing hydrogen systems.

Ammonia is corrosive and toxic, and risks are elevated by high vapour pressure under standard conditions. However, ammonia is readily detectable by smell at concentrations well below those that cause lasting health consequences[6]. While both hydrogen and ammonia have been safely used across several industries for decades, new applications will need to be tested afresh.

From an environmental perspective, new ammonia applications will need to be assessed as ammonia-based fertilisers contribute to GHG emissions via nitrous oxide, to biodiversity decline via excess nitrogen, and to air pollution by reacting with other pollutants to form particulates. Research into hydrogen suggests it has only very small effects on the climate or ozone layer[12].

In both cases there will be challenges of public acceptability, even if some perceptions do not reflect the real risks involved.

2. Low-carbon production and use of hydrogen and ammonia

Hydrogen and ammonia offer opportunities to provide low carbon energy and help reach the target of net-zero emissions by 2050. However, decarbonising their production is fundamental as they are currently produced in heavy industries with a sector-level carbon footprint larger than that of several individual G7 countries – simply for today's applications[13].

2.1 Low-carbon production of hydrogen

There are several ways to produce hydrogen, with varying carbon footprints. In Figure 1 we examine the lower-carbon options of hydrogen production.

Blue hydrogen

'Blue' hydrogen is made from a fossil fuel, typically natural gas, with CO_2 capture and storage (CCS) being applied. Conventional SMR can be used, although new technologies are now being explored, including auto-thermal reforming (ATR) where energy is provided by introducing oxygen to burn part of the feedstock as opposed to separately burning natural gas[14]. While not a fully net-zero technology, it is estimated that up to 95% of the carbon emissions can be captured[15]. This of course depends on the development and deployment of CCS. Many variations are being explored, involving new membranes, solvents, adsorbents, and catalysts[16].

Methane is a potent greenhouse gas, therefore care must be taken to prevent and recoup any upstream methane leakage.

Blue hydrogen is already operating at scale, for example at the Air Products Steam Methane Reformer in Texas, US, the Shell Quest CCS facility in Alberta, Canada[17], and the Air Liquide facility at Port Jerome, France[18].

Green hydrogen

'Green' hydrogen uses renewable electricity to split hydrogen from water through electrolysis and offers a zero-carbon pathway. Alkaline electrolysers are the most mature technology but do not work well with intermittent renewable energy sources. Newer polymer electrolyte membrane (PEM) electrolysers react quicky to the fluctuation of renewable power and are in early deployment. Solid oxide cell electrolysers (SOEC), which work at higher temperatures, are less mature but potentially offer a higher efficiency. Green hydrogen requires renewable electricity and hence could be constrained by the level of renewable capacity. For example, if all of the hydrogen currently used globally was produced through electrolysis it would require 3,600 terawatt hours (TWh) per year, more than the total generation of the EU[3].

Other routes to hydrogen

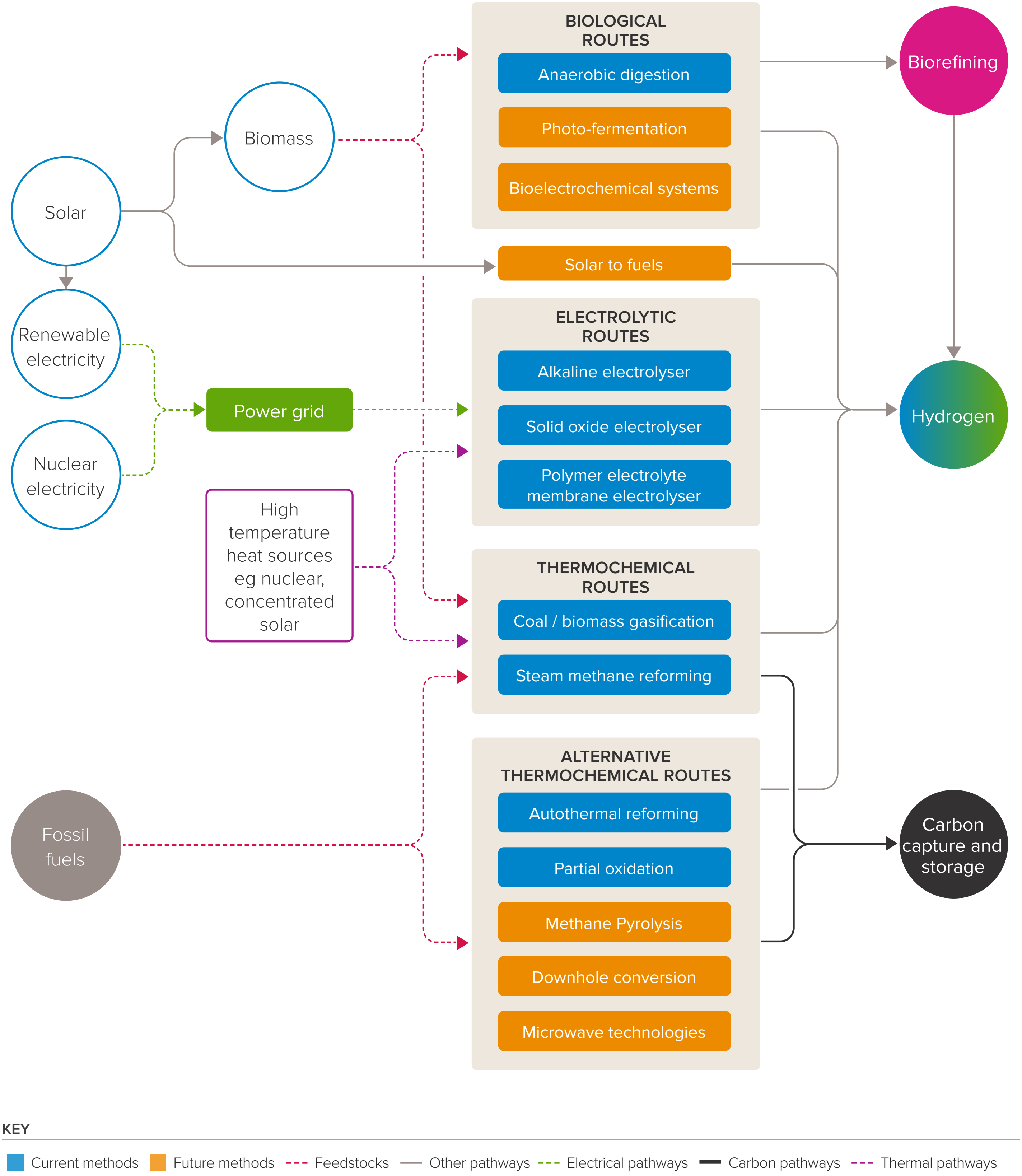
Other possibilities include 'turquoise' hydrogen made by methane thermal pyrolysis – heating in an oxygen-free atmosphere – which produces solid carbon rather than CO_2 as a by-product[19], and 'pink' hydrogen using nuclear energy for electrolysis. Nuclear power could also provide zero-carbon heat to either carry out high-temperature steam electrolysis (higher thermal efficiency) or to meet the high-temperature requirements of SMR with CCS.

Other options include biological methods with lower operating temperatures based on a variation of anaerobic digestion and 'solar to fuels' where water is split into hydrogen and oxygen using solar energy directly.

> 'Green' hydrogen uses renewable electricity to split hydrogen from water through electrolysis and offers a zero-carbon pathway.

FIGURE 1

Schematic of the production options for low-carbon hydrogen[1].



2.2 Low-carbon ammonia production

Ammonia produced through the current Haber-Bosch process is known as 'brown ammonia' if produced using coal or 'grey ammonia' when natural gas is used. Ammonia produced from blue and green hydrogen is known as blue or green ammonia. Renewable electricity is required to power the Haber-Bosch process for both blue and green ammonia if emissions are to be minimised (Figure 2).

2.3 Applications for low-carbon hydrogen and ammonia

Hydrogen and ammonia have considerable potential to help meet net zero goals for power, transport, heat, and energy storage. In practice, however, there are alternative technologies that may be better suited and cheaper for some applications over different timescales, for example, batteries for light-duty vehicles and heat pumps for residential heating.

In the UK, for example, the Climate Change Committee's Sixth Carbon Budget 'balanced pathway' scenario envisages green or blue hydrogen together scaling up by 2035 to a capacity equivalent to nearly one-third of the current power sector, and being used in areas less suited to electrification, particularly parts of industry and shipping[20].

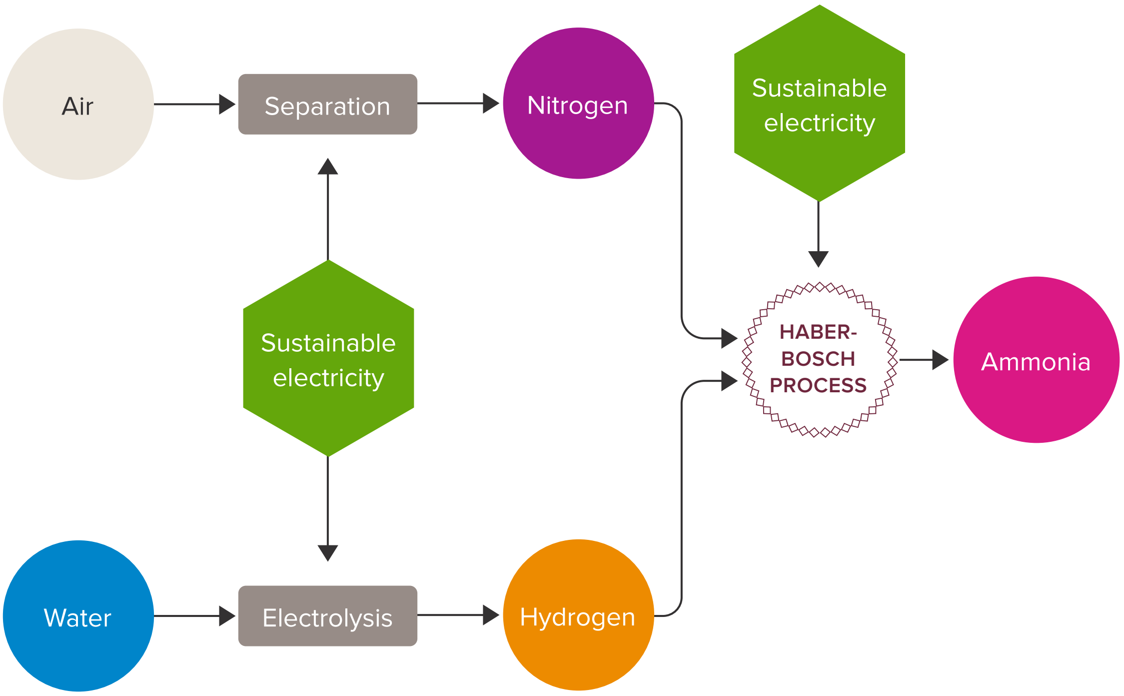
Many applications involve fuel cells that combine hydrogen and oxygen (from air) to generate clean electricity, heat, and water without combustion. Fuel cell production passed the 1-gigawatt (GW) barrier in 2019 and is expected to move to mass production 'giga-factories', like lithium-ion batteries, which will continue to bring down unit costs significantly[21, 22].

Ammonia is being considered for specific applications because it has higher volumetric energy than hydrogen (Figure 3). If needed, ammonia can be 'cracked' back to hydrogen or an ammonia/hydrogen mix after transporting. Alternatively, it can be used directly in high temperature solid oxide fuel cells to produce electricity.

Hydrogen and ammonia have considerable potential to help meet net zero goals for power, transport, heat, and energy storage.

FIGURE 2

Schematic of green ammonia production based upon hydrogen production from water electrolysis and the full decarbonisation of the Haber-Bosch process[6].



Industry

Hydrogen has a range of potential applications in industry. These start with existing uses in refining and production of ammonia, methanol and steel, whose carbon footprint could be reduced or eliminated if green or blue hydrogen is used.

Beyond existing applications, zero-carbon hydrogen could be used a source of high temperature heat as well as in reduction and reaction processes. One UK report indicated that around 40% of fossil fuel used in manufacturing could be replaced with hydrogen by 2040[23]. Hydrogen has been used to produce high-temperature heat for steel making for the first time at a commercial steel mill in Sweden[24]. Ammonia can also be burned for high process temperatures in industry and is already used for sulfur recovery in refining[25].

Heavy-duty road vehicles

Hydrogen fuel cells or hydrogen-derived fuels offer a low-carbon alternative for heavy-duty vehicles, for which batteries do not currently have the energy density to offer a long-range solution. Several initiatives for hydrogen-powered have been proposed by manufactures including Toyota, Cummins, and Nikola[26, 27, 28]. The automaker Hyundai has made a series of hydrogen-powered trucks with a range of around 400km for customers in Switzerland[29].

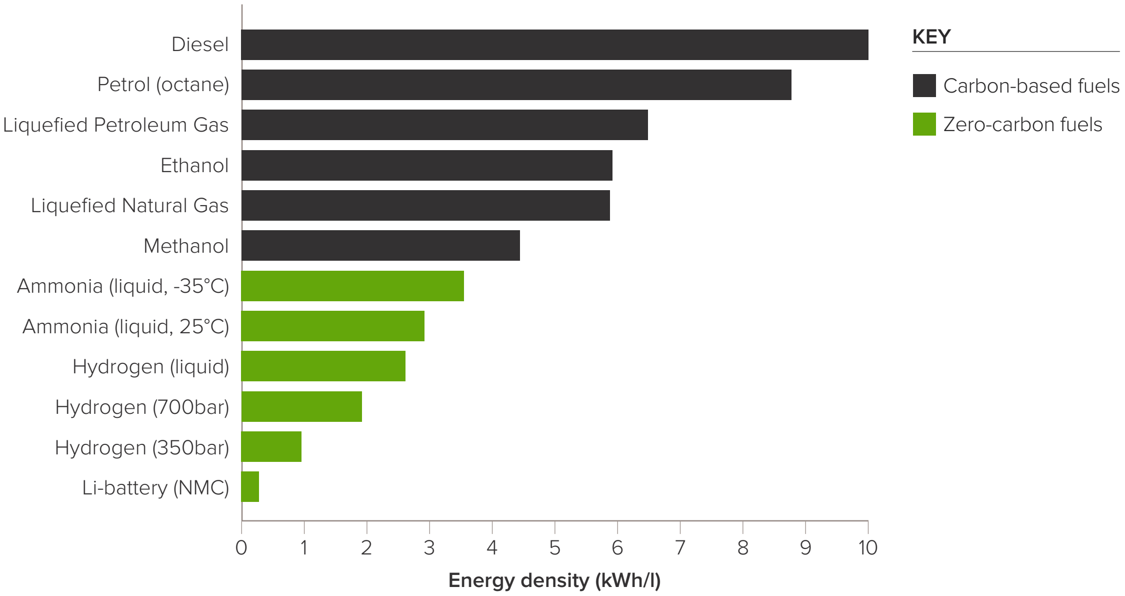
Light-duty road vehicles

The future of hydrogen in the car market is uncertain as battery electric vehicles (BEVs) are currently more economical than fuel cell electric vehicles (FCEVs) and already an established technology. There are estimated to be around 25,000 FCEVs on the world's roads compared to more than seven million BEVs[30, 31]. However, FCEVs may have a viable future in the longer term if their life-cycle emissions are lower than BEVs, if they can deliver long driving ranges, and/or if the use of fuel cells in trucks and buses leads to a large-scale supply chain becoming established.

As of 2020, the US had most hydrogen vehicles, followed by China, South Korea, and Japan[27].

FIGURE 3

The volumetric energy density of a range of fuel options[6].



One niche market for hydrogen fuel cells is forklift trucks. These currently outnumber hydrogen cars, with around 30,000 in use. Fuel cell forklifts are suited to warehouse use because refuelling is simple, and the vehicles emit no air pollutants[32].

Shipping

Low carbon ammonia is of interest to all maritime countries as it is a strong fuel candidate to support the International Maritime Organisation's goal of reducing the carbon intensity of international shipping by at least 40% by 2030[33]. Projects are now underway to ensure that large fuel cells running on ammonia can deliver power to shipboard systems safely and effectively. These include plans to fit a large bulk carrier in Japan with an ammonia fuel system and piloting ammonia in Norway's Color Fantasy, the world's largest roll-on-roll-off cruise liner[34, 35].

Rail

Trains powered by hydrogen fuel cells are in operation in Germany and being trialled in countries such as the Netherlands and UK. Hydrogen trains could provide a zero-carbon option on routes where railways have not been electrified[3]. Challenges include storage, with the volume of fuel needed being around eight times that of diesel, and high demand for renewable power if electrolysed fuel is used[36].

Aviation

The aviation industry is also exploring the use of hydrogen and ammonia fuels. For example, Airbus is planning to develop hybrid-hydrogen aircraft, powered by hydrogen combustion through modified gas turbine engines[37].

Meanwhile, a UK based project is exploring a technology that partially cracks green ammonia to hydrogen, creating a mix that mimics jet fuel by burning stably, making it possible to adapt existing engines and aircraft to use zero-emission fuels[38].

Synthetic fuels

A range of synthetic fuels for multiple uses can be made via the Fischer Tropsch process, reacting captured CO_2 with hydrogen. These could potentially provide a lower carbon drop-in fuel alternative for the aviation fleet as well as an option for trucks or ships[39].

Storage and transport

Hydrogen can be compressed in gaseous form in underground caverns, liquefied or – for small applications such as drones – contained in solid state materials such as metal hydrides. For storage, hydrogen has to be compressed to around 350 to 700 times atmospheric pressure as a gas, or cryogenically cooled to -253°C as a liquid[40]. Ammonia is denser and only requires compression to 10 times atmospheric pressure or chilling to -33°C[6]. Ammonia storage is mature because of its widespread use as a feedstock for mineral fertilisers.

Both hydrogen and ammonia are leading candidates to manage seasonal variations in electricity demand or as short-term back up for intermittent generation from renewables. Hydrogen or ammonia could also potentially be used to carry energy generated from renewables from regions with plentiful solar and wind to centres of demand thousands of kilometres away.

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Power

Hydrogen or ammonia can also be used to generate power, either using fuel cells or driving turbines[41, 42]. Gigawatt-scale power plants using fuel cells are being planned while smaller scale versions have been trialled, for example, in data centres[43].

There is also scope to capture CO_2 from natural gas and burn the remaining hydrogen directly in a turbine to create power. However the process requires changes to equipment and processes, and while manufacturers are developing hydrogen-ready turbines, the technology has not yet been deployed at large scale[44, 39].

Countries with high levels of sunshine and wind, including many low-income countries, could store generated energy in the form of hydrogen or ammonia for multiple applications from industry and transport to power for emergency services and access to energy in remote areas[45].

As of 2021, more than 30 countries have released hydrogen roadmaps and governments have committed more than $70 billion in public funding.

Residential heat

Hydrogen is also a possible route for providing heat to residential buildings as a full or partial replacement for natural gas, although with considerable challenges at scale. Boiler and cooker conversion have costs estimated at £2,000 – 4,000 per household[46]. Hydrogen can also cause embrittlement in steel and iron pipes, although countries such as the UK are now converting their piping from metal to plastic[47]. Trials of pure hydrogen include projects at an apartment block in Rotterdam, Netherlands, and homes in Holzwickede, Germany[48, 49]. Other projects are blending hydrogen with natural gas for home heating, at a 10% level in Salerno, Italy, and 20% in Keele, UK[50, 51]. The UK plans to run larger trials of hydrogen for heating and cooking, from a neighbourhood in 2023 to a village by 2025 and a town by 2030[52]. The main competitive technology for residential heating is heat pumps.

2.4 Current developments

Since the 2015 Paris agreement, there has been a surge of activity in public and private sectors.

Government strategies

As of 2021, more than 30 countries have released hydrogen roadmaps and governments have committed more than $70 billion in public funding[53]. For example, the EU strategy envisages hydrogen meeting around one-quarter of energy demand by 2050[54]. The UK and German governments' plans both include scaling up low-carbon hydrogen production capacity to 5GW by 2030[49].

For transport, China is aiming to produce one million hydrogen fuelled vehicles and 1,000 refuelling stations by 2030, the same goals as California[3, 55]. South Korea's roadmap is aiming to produce six million FCEVs and roll out 1,200 refilling stations by 2040[56].

Private sector investment

Hydrogen has also seen a new wave of interest in business. The Hydrogen Council, which formed in 2017 to bring together relevant companies, now has more than 100 members.

Recent years have seen a surge of private sector deals. As examples, Canada-based Hydrogenics, a fuel cell leader, was bought by Cummins in 2019[57]; UK-based ITM Power, a leading maker of electrolysers, has raised £172million to develop hydrogen from renewable energy[58]; Ceres Power, a UK-based company that develops and manufactures fuel cell stacks, has attracted investment from Bosch and Weichai Power[59, 60].

Large-scale projects

Planned blue hydrogen projects include collaborations between groups of companies with public sector support, often around ports with clusters of industries and access to undersea storage. These include the UK's proposed Net Zero Teesside, Zero Carbon Humber and HyNet projects that together ultimately plan to decarbonise nearly 50% of the UK's industrial emissions with storage under the North Sea and Irish Sea[61 62].

Several gigawatt-scale green hydrogen projects have been announced, including the €88 million Heavenn project in the Netherlands, the UK's Gigastack project, and SeaH2Land project for the Dutch-Flemish North Sea Port Cluster[63, 64, 65].

Other projects plan to convert green hydrogen to ammonia for export. On the West coast of Australia, the $36 billion Asian Renewable Energy Hub project will produce green hydrogen and ammonia for Australia and Asian export markets[66, 67]. The $5 billion project at the Saudi Arabian new city of Neom on the Red Sea will produce hydrogen with a 2GW alkaline electrolyser plant, which will be converted into 1.2Mt/yr of green ammonia to be exported and converted back to hydrogen[68].

3. Opportunities for progress and deployment

Hydrogen and ammonia's potential will increase as costs fall, efficiency grows, and optimal solutions emerge in each sector.

3.1 Costs

Projections suggest that green and blue hydrogen could become competitive in the current decade as CCS and electrolyser technologies advance and industrial learning rates accelerate[69]. The EU estimates current production costs are \$1.80/kg for grey hydrogen, \$2.40/kg for blue hydrogen and \$3.00 – 6.60/kg for green hydrogen. Carbon prices in the range of €55-90 t/CO_2 will be needed to make blue hydrogen competitive with grey hydrogen[65, 70]. Another set of projections estimated that renewable hydrogen production costs could decline to \$1.40 – 2.30/kg by 2030, with green and grey hydrogen reaching cost parity around 2028 in some regions – the cost of renewable electricity being a critical factor[50].

Conventional 'brown' ammonia production remains the cheapest route at under \$280 per tonne, although blue ammonia can nearly compete if process emissions alone are captured. Green ammonia's costs vary widely depending on the local cost of renewable power and in areas with very strong solar and wind resources, it can compete with blue ammonia.

3.2 Strategies for demonstration and deployment

It is widely acknowledged that renewable electricity is best used directly where possible, but that where it has no immediate outlet, conversion to hydrogen may be the most effective approach.

Where hydrogen is produced, it is most usefully used directly, but if it cannot be used immediately or on site, it can be stored for use in power, moved by pipeline, liquefied, and moved by ship or tube trailer. If that is not practicable, it can be converted to ammonia or other carriers and moved, potentially being reconverted to hydrogen afterwards. If not reconverted, ammonia can be used directly for the conventional purposes of fertiliser and refrigeration. Ammonia specialists also stress that its density and 'crackability' make it suitable for direct use as a transport fuel or storage medium.

Low-carbon hydrogen's merit order starts with reducing the carbon footprint of current uses – the production of ammonia, refining and chemicals. The next most likely applications include fuel cells for power generation and heavy-duty transport and direct burning of hydrogen for heat in industry; followed by its use in long term energy storage, residential heating, and production of synthetic liquid fuels.

Where hydrogen or ammonia are thought to be the optimal route, short-term investment could focus on scaling up via demonstration projects and infrastructure trials, which can be incentivised with challenge funding or grants. Demonstrations can be built out rapidly where conditions for growth exist, such as near industrial ports and in truck fleets. Blue hydrogen could offer a way to move forward in the near term, especially when funding is shared between clusters of companies and the public sector. For green hydrogen, there is a need to scale up manufacture and continued development of electrolyser systems.

> Demonstrations can be built out rapidly where conditions for growth exist, such as near industrial ports and in truck fleets.

3.3 Priorities for research and development

To realise the potential of hydrogen and ammonia as major contributors to achieving net zero, a number of research challenges need to be met and then developed and demonstrated at scale. Among the most important are:

- Electrolysers are a critical component for green hydrogen and therefore an important research priority. Developing improved electrodes and new catalysts and membranes will reduce costs.
- Solid oxide electrolysers that work at high temperatures are also a particular focus for research due to their high potential efficiency.
- There is a cluster of interesting technologies for potential direct water splitting without the need for electricity, including solar-to-fuels and CO_2 reduction (to CO) using photons.
- The direct reduction of nitrogen to ammonia, for example electrochemically, presents an alternative to the Haber-Bosch process and represents an important challenge for fundamental research.
- More research and development on fuel cells to reduce costs and develop recyclable technologies.
- Research in all energy conversion pathways is required to maximise efficiency and lifetimes. There is scope for fundamental advances in areas such as catalysis, electrocatalysis, membranes, electrochemistry, and electrochemical engineering.
- Current use of platinum and iridium oxides in some fuel cell and electrolyser technologies raise questions on mineral availability and cost.
- An integrated approach is needed to take whole life cycles into consideration, identify interactions between different parts of the system and take advantage of synergies.
- There will also be a need for technically qualified people at all levels to develop, manufacture, install and safely maintain these technologies. Policy-makers can act now to encourage such capability as part of their 'STEM' agendas.

Conclusion

Hydrogen and ammonia have potential to provide key elements of a net zero energy mix, especially in energy-intensive areas. But they are not the only options and if policy-makers wish to identify their full possibilities vis-à-vis the alternatives, research, development, and demonstration projects need to be accelerated.

This briefing is one of a series looking at how science and technology can support the global effort to achieve net zero emissions and adapt to climate change. The series aims to inform policymakers around the world on 12 issues where science can inform understanding and action as each country creates its own road map to net zero by 2050.

To view the whole series, visit **royalsociety.org/climate-science-solutions**
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