The Future Uses of Hydrogen

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Executive Summary

Hydrogen

In the urgent drive to decarbonize the UK economy hydrogen is being proposed as a zero-carbon alternative to replace fossil fuels for some applications – especially where electricity is seen as less viable. Like fossil fuels, hydrogen has a high energy density and can be stored for long periods. Hydrogen is already used today, primarily in industrial applications.

Today most hydrogen is produced either from natural gas (98%), usually using steam methane reforming (SMR) when it is called **grey hydrogen**, or from the electrolysis of water using electricity - referred to as **green hydrogen** provided green electricity is used. Converting gas/electricity to hydrogen fuel rather than using them directly consumes significantly more gas/electricity (see Table 1).

Capturing and storing the CO_2 produced during production (CCS) partially decarbonizes grey hydrogen, producing **blue hydrogen**. However, CCS is expensive, does not capture all the CO_2 produced, has yet to prove itself at scale, and there are leaks of methane (a powerful greenhouse gas) associated with extraction and transport of natural gas.

At present grey hydrogen is much cheaper to produce than green hydrogen; with blue somewhere in between.

Energy is recovered from hydrogen either by burning it, or (at room temperature) using a hydrogen fuel cell which can be more efficient – especially for smaller-scale applications.

Conversions to and from hydrogen are currently only moderately energy efficient (see Table 1) and despite its high energy density, hydrogen's low physical density creates extra handling and storage costs. Thus, each application must be evaluated carefully.

Hydrogen applications

Three significant areas where hydrogen is being considered in the UK are energy storage, transport, and heating.

Energy storage. Using electrolysis, electrical energy can be conveniently and flexibly stored or transported as hydrogen - for example when local renewable electricity production is too high to be used. Because electrolysis equipment is expensive, and the round-trip efficiencies are quite low, each application must be considered on its merits.

Transport. Hydrogen's high energy density and (currently) faster refuelling competes with the much higher energy efficiency of electric batteries (Table 1).

For cars batteries generally outcompete hydrogen except when hydrogen is locally abundant.

Hydrogen lorries can be more practical; but without a refuelling network they may not be viable except in niche applications; and it is likely that battery technology will continue to improve.

Progress has been slow in the effort to decarbonize shipping with the International Maritime Organization targeting only a 50% reduction in emissions by 2050. Hydrogen-derived ammonia and methanol, which are easier to store and handle than hydrogen, are being considered.

Where aviation is concerned the additional weight and volume of the hydrogen storage and handling systems means that bulk-carrier hydrogen-powered aircraft are probably not viable in the near term.

For trains and buses hydrogen generally struggles to compete with electric unless there is a local supply of hydrogen.

Heating. Heating and hot water in buildings account for around 20% of today's UK GHG emissions with around 80% supplied from natural gas. The large, variable, and highly seasonal demand make this a hard area to serve with green electricity.

Repurposing the gas grid to carry hydrogen, as proposed by many including industry groups and the UK government, promises a relatively simple 'like for like' transition. Furthermore hydrogen, like natural gas, can potentially be stored to address variable demand. However, for the foreseeable future most green electricity in the UK will be needed for more energy efficient decarbonization applications such as existing electricity users and electric cars, leaving only blue hydrogen for heating. This will mean that alongside costly infrastructure changes, heating using hydrogen will result in significant extra gas imports and blue hydrogen's associated emissions.

The leading low carbon alternative to hydrogen for heating are electric heat pumps, which are more efficient than electric heaters and green hydrogen. But it may be hard (and expensive) to convert much existing housing stock and the problems of variable supply and winter demand remain to be solved.

Thus, it seems likely that a mixture of approaches may be used for decarbonizing heating, but the potential downsides of the current options demonstrate the overriding importance of efficiency savings.

What next for hydrogen?

Hydrogen is being advanced as a like for like replacement for natural gas and other fossil fuels. However, it is expensive and costs significant energy to produce, and it will only truly be a fossil free fuel when it is green.

Several countries have developed hydrogen strategies including Japan, the EU and most recently the UK.

In the medium term it may be more effective for the UK to use blue and green hydrogen in existing industrial processes and favourable niche applications, rather than for decarbonization of the energy supply.

There are important decisions to be made, either by, or with a steer from, government.

1 Introduction

As the world gradually comes to terms with the impacts on the climate of burning fossil fuels, alternative fuels are being considered and researched. In many more developed economies, including China, the production of electricity using wind turbines and solar panels is rapidly increasing and the cost of such energy is falling quickly.

However, there is still a long way to go. In 2019 the UK obtained 19.8% of its total energy from low carbon sources, and 23.9% of electricity was supplied by wind and solar power, but electricity represented only about 17.9% of the UK's final energy consumption[1]. Furthermore, these sources have the obvious limitation that they only produce when the wind is blowing, and the sun is shining. In contrast, fossil fuels are cheaply available, easily stored until they are needed, and have a high energy content to provide heating and power most transport at present.

While renewable energy production is increasing and progress is being made to improve batteries, many are proposing hydrogen as a low carbon or carbon-free substitute for some fossil-fuel uses and hydrogen has a prominent role in the UK government's ten-point green plan[2].

Hydrogen can be burnt to provide heat much like natural gas and can also be compressed or liquefied for storage or to provide portable energy for transport. Fuel cells also provide an efficient way to extract electricity from hydrogen. In all these applications the main emissions are carbon-free - consisting solely of water.

One measure of how much energy can be obtained from a fuel is its Specific Energy - the energy released as heat by burning it in air - expressed as megajoules per kilogram (MJ/kg). Examples for various fuels are[3]:

Coal (anthracite)	35 MJ/kg
Wood	20 MJ/kg
Petrol	47 MJ/kg
Diesel	46 MJ/kg
Natural gas/liquefied natural gas (LNG)	54 MJ/kg
Methane	55.5 MJ/kg
Hydrogen	142 MJ/kg

So, one can see another reason why hydrogen is seen as a valuable potential fuel.

This all sounds promising. However, the catch is that hydrogen, though a common chemical element, occurs almost exclusively in combination with other elements, principally combined with oxygen in water or with carbon and other elements either in fossil fuels or in plants and animals. Pure hydrogen therefore must be manufactured through chemical processes; and this is the problem. Energy and infrastructure are required, and when hydrogen is recovered from carbon compounds the remaining carbon must be prevented from escaping into the atmosphere as carbon dioxide (CO_2) if carbon emissions are to be avoided.

In 2019 the International Energy Agency (IEA) wrote:

"Supplying hydrogen to industrial users is now a major business around the world. Demand for hydrogen, which has grown more than threefold since 1975, continues to rise – almost entirely supplied from fossil fuels, with 6% of global natural gas and 2% of global coal going to hydrogen production.

As a consequence, production of hydrogen is responsible for CO_2 emissions of around 830 million tonnes of carbon dioxide per year, equivalent to the CO_2 emissions of the United Kingdom and Indonesia combined."[4].

So, even today, when hydrogen is used primarily for industrial processes, emissions from its production are significant.

There are always losses in the transfer of energy from one form to another, whether from gas to electricity or petrol to motive energy, or simply compressing or liquefying hydrogen. So, producing and using hydrogen consumes valuable energy. There are also financial costs and EROEI (energy return over energy invested) to consider.

Some see a need to create a complete 'hydrogen economy' so that capital expenditure (CapEx) costs can be shared, while others see hydrogen as a useful niche option. So, when is using hydrogen worth it? This note tries to help judge this.

There are many possible uses of hydrogen which might help to reduce those emissions that are currently due primarily to the extraction and burning of fossil fuels; and these will be discussed in this document.

Hydrogen presents some significant handling challenges compared with traditional fossil fuels. Hydrogen's low density also means it must be compressed, often around 700 times, or even liquefied, to be stored or piped. These require significant amounts of energy and even after liquefying LNG typically has around twice the amount of energy per litre as hydrogen, so storing hydrogen also takes more space. Containers must also have thick walls or be made of specialist materials to prevent leakage of the small hydrogen molecules by diffusion.

The major issues regarding the use of hydrogen relate to its production and transport, since its use produces minimal greenhouse gas emissions.

2 Hydrogen production

There are several methods of producing hydrogen (H_2), but currently there are two that are the most important for the hydrogen debate as described below.

Steam methane reforming (SMR) is the most used method, also known as steam reforming or natural gas reforming. It produces hydrogen from natural gas, which is predominantly methane (CH_4) and water. The process consists of heating methane to between 700–1100 °C in the presence of steam and a nickel catalyst. The resulting reaction produces carbon monoxide and hydrogen. The carbon monoxide is then passed with steam over iron oxide or other oxides to obtain more hydrogen and carbon dioxide (CO_2). The overall reaction is:

$$CH_4 + 2H_2O = CO_2 + 4H_2$$

A major by-product of the reaction is CO_2. Further methane is burnt to produce heat and steam. Depending on the quality of the natural gas about nine tonnes of CO_2 is produced for every tonne of hydrogen in large production plants[5]. By comparison, burning natural gas to produce the same amount of energy will produce somewhat over seven tonnes of CO_2. Thus, although the use of the resulting hydrogen as a fuel will produce no greenhouse gas emissions, more CO_2 is produced overall.

By separating the CO_2 produced by the SMR process and storing it underground – a process termed carbon capture and storage (CCS[a]), much of the CO_2 can be prevented from entering the atmosphere. However, it is thought that only some 80 – 90% of CO_2 can realistically be captured in this way[6].

Even though many experts believe that CCS is vital if the world's emissions are to be reduced sufficiently to avoid a 2° temperature rise, it is a technology that is not fully proven at the large scales required. It is also expensive. Monitoring of the stored CO_2 for leaks adds further cost[7].

Research is being carried out into the use of CO_2 to manufacture animal feeds, plastics, and methanol, among others. If these can be undertaken at a large scale, then this will help use this CO_2 by-product.

A related process, autothermal reforming (ATR), pre-mixes natural gas with oxygen obtained using an air separation unit (ASU). Though more complex and only suitable for large plants, ATR makes it easier to capture the CO_2[8].

Both processes require steam which consumes energy. SMR requires fuel to create the high temperature needed for the reaction to proceed. ATR avoids this by starting the reaction by partially burning methane in oxygen, but the ASU consumes energy. Other efficiency losses result because natural gas is not pure methane, additional unwanted chemical reactions occur, the main reaction does not go to completion, and energy is consumed by plant operations.

An overall energy efficiency for SMR of around 70% is often reported, although this can vary between 60% and 90%. ATR, although making it easier to capture more CO_2, is generally estimated to be slightly less efficient than SMR[9].

Hydrogen produced using SMR or ATR without CCS is termed **grey hydrogen**. If CCS is used the hydrogen produced is generally known as **blue hydrogen**.

Electrolysis of water. The second method of production is by electrolysis. It comprises simply connecting a DC current source of electricity to two electrodes (metal plates typically made from some inert metal such as platinum or iridium) which are placed in the water. Hydrogen appears at the cathode and oxygen appears at the anode.

There are two main technologies used for electrolysis of water – polymer exchange membrane (PEM) and alkaline water electrolysis. A third more experimental method, solid oxide electrolysis cell (SOEC) has currently fallen out of favour but has the potential for higher efficiency[10]. Alkaline water electrolysis equipment is generally cheaper than PEM equipment and does not require rare metals as catalysts but is less compact and produces lower purity hydrogen.

[a] CCS is also proposed for fossil-fuel power stations.

Electrolysis efficiency has improved and is currently around 65- 75% efficient (Table 1), but electrolysis equipment is expensive and so it is generally uneconomic to produce hydrogen in small quantities or intermittently, as may be the case when energy might be stored during brief periods of renewable over-production.

Electrolysis is used commercially to a small extent only at present, because SMR is currently a lot cheaper. The huge advantage of this method is that if electricity from renewable sources is used, the hydrogen is produced without producing greenhouse gases. Hydrogen produced by this method is commonly known as **green hydrogen**.

There are other methods of production, including using SMR on methane produced from biomass (biomethane), and by using electricity generated by nuclear power or the high temperatures involved in the nuclear process.

According to the IEA, 2019, again:

"76% of hydrogen comes from gas and 23% from coal – the latter mostly in China – with just 2% coming from electrolysis. Less than 0.7% of current hydrogen production is from low-carbon green or blue supplies."

In 2020, approximate average prices of hydrogen were:

Grey	€1.50 / kg
Blue	€2–€3 / kg
Green	€3.5–€6 / kg

It is estimated that a €50–60 per tonne carbon price could make blue hydrogen competitive in Europe [11].

The reason why green hydrogen is more expensive than others at present appears to be primarily due to the cost of the electrolysis equipment, as well as the cost of renewable energy in many parts of the world. However, there is an expectation that both these elements will become cheaper. Electrolysis equipment manufacture is now the subject of intense international competition[12] and prices are likely to continue to decrease.

Fuel cells (described below) require hydrogen with 99.999% purity to protect the, usually platinum, catalysts. Electrolysis produces hydrogen of this purity, whereas the hydrogen produced by SMR requires further purification[13].

Energy Efficiencies/Losses in Hydrogen Production

The production of hydrogen, which always converts energy from another source – generally either from fossil fuels or electricity - incurs losses of useful energy along the way. Unfortunately, these estimates have large ranges making it hard to evaluate different production systems.

The energy cost (or loss) of compression is generally estimated at around 10% of the hydrogen energy although there is scope for reducing it. Liquefying hydrogen costs about 30% to 35% of the hydrogen energy[14]. For practical reasons, the energy is not normally recovered when the hydrogen is used.

Table 1 Summarizes the (energy) efficiency estimates for some of the processes discussed in this document.

Table 1. Estimates of the efficiency of some energy transformations. Note. Because some of these figures come from different sources, combining them may not always produce an answer consistent with other figures in the table.

	Operation	**Efficiency (%)**
A	Combustion of natural gas or hydrogen to electricity (eg a power station)	50 - 60
B	Electricity to hydrogen (electrolysis) (Green hydrogen)	65 – 75 (Say 70)
C	Hydrogen from methane (natural gas) by steam methane reforming (Grey hydrogen)[9]	60 – 90 (Say 70)
D	Grey hydrogen with CCS (Blue hydrogen)[9]	50 – 80 (Say 60)
E	Hydrogen to fuel cell (PEM) to electricity[9]	50
F	Electricity to battery storage to electricity[15]	82
G	Natural gas to heat (eg of building)	90
H	Electricity (Air source heat pump) for heating (eg of building) [13]	250 - 450
J	Green hydrogen to heat (eg of building)[13]	62
K	Blue hydrogen to heat (eg of building) (Based on J and D)	53
L	Grey hydrogen to heat (eg of building) (Based on J and C)	62
M	Hydrogen compression	90
N	Hydrogen liquification	65 - 70
P	Fossil fuel car	15 - 35
Q	Battery car (renewable electricity)[16]	77
R	Fuel cell car (Green hydrogen)[16]	33
S	Renewable electricity to hydrogen to fuel cell to electricity[17]	30
T	Renewable electricity to hydrogen to combustion for electricity[18]	35 - 40

Carbon capture and storage

Separating the CO_2 for sequestration, often by reaction with organic amines, has a theoretical minimum energy cost of just under 1% of the energy of the methane consumed, although practically it costs about three times that amount[19]. Further costs come from compressing or liquefying the CO_2 for transport and storage. Overall Balcombe et al[20] report the energy cost of CCS as being between 5% and 14% and a working figure of 10% is often used.

Additional carbon emissions occur in the natural gas supply, where methane leaks from gas fields and gas supply pipelines can be significant[21, 22] and hard to detect[23]. This is especially important since a molecule of methane has approximately 25 times the global warming effect as a molecule of CO_2 over a period of 100 years[24] meaning that, for example, a level of 1% leakage (the lower end of many estimates) is approximately equivalent to a release of 25% of the CO_2 after burning. Because significant amounts of extra natural gas are needed to drive SMR/ATR and CCS blue hydrogen associated methane leaks may be higher than generating the same amount of energy from natural gas directly.

Some have suggested using SMR with CCS using methane produced from biological sources such as anaerobic digestion (biomethane) to create 'negative emissions' to balance out emissions from SMR.

One significant issue is how to assure that hydrogen is blue rather than grey[25, 26], since any use of CCS is a financial cost without any benefit for producer and consumer.

3 Hydrogen applications

As mentioned earlier, most hydrogen currently produced is for industrial processes, the major ones being:

- Ammonia production, primarily for making fertilisers.
- In oil refineries to remove sulphur from fuels.
- To hydrogenate vegetable oils to produce margarine, for instance.

It is difficult to replace hydrogen usage in most of these processes. Therefore, until the need for hydrogen is removed, the use of green or blue hydrogen may be more usefully used in these situations than for those listed below.

The focus of this paper is the potential ways of decarbonising the world energy supply using hydrogen in areas where it has not generally been used in the past such as:

- Energy storage, particularly from intermittent renewable electricity production methods, when they are "over producing" and long-term storage such as needed for winter fuel supplies.
- Fuel for cars, heavy goods vehicles, buses, trains, ships, and even aircraft.
- A replacement for natural gas for domestic heating.
- Industrial applications – mainly heating based, although hydrogen is also proposed as a replacement for fossil-fuel-based chemical feedstock. The most 'hard to decarbonize' include steel and cement production, and many assume these must switch to using hydrogen. CarbonBrief[27] discusses some experimental alternatives that use electricity. These are not discussed further here.

There are essentially two ways to re-extract the energy from hydrogen – either by simply burning it when all the embodied energy is recovered as heat, or by using a fuel cell to generate electricity as described next.

Hydrogen fuel cells

Hydrogen fuel cells operate rather like a battery. Hydrogen is supplied at an anode where a catalyst splits hydrogen into an electron and a (positively charged) proton. In a PEM fuel cell (PEMFC) the electrons then pass through a circuit creating an electric current while the protons pass through a polymer electrolyte membrane (PEM) which only allows positively charged ions through, and on to a cathode where they combine with oxygen and electrons to create water. Other types of fuel cell work on a similar principle.

Essentially this is the same chemical reaction as burning hydrogen, but electricity rather than heat is produced, and the reaction occurs at room temperature. Some heat, about one seventh

of the available energy, is still produced and usually discarded. Currently PEM fuel cells only convert about 50% of the energy to electricity.

The big advantage of using a fuel cell can be seen when comparing the efficiency of petrol and diesel engine cars – between 15% and 35% - with hydrogen using a fuel cell at around 30% or battery at around 80%. Much of this is essentially down to the thermodynamic advantage of chemical energy or electricity vs heat as a power source.

What is generally known as a fuel cell is a stack of multiple single fuel cells. This is because a single fuel cell produces one volt or less. So, these individual cells are linked in series in large numbers so that they can power, say, a computer (50-100 watts), a home (5 kw) or virtually any central power generation requirement.

The technology was invented in the 1840s by Sir William Grove but has only recently been exploited on a large scale. It is already used today in several applications:-

- Buses and cars.
- Reliable remote power requirements, such as weather stations, construction site lighting, wildlife filming.
- Backup power supply to data centres.

Hydrogen is not the only fuel that can benefit from fuel cells – solid oxide fuel cells (SOFCs) can use methane, ammonia, and other fuels but must run at high temperature.

PEMFCs are generally considered to be around 50% efficient while SOFCs may be up to around 70% efficient[28].

Energy storage

The variability of wind and solar power will become more problematic if, as anticipated, the proportion of energy supplied by wind and solar increases. Even today wind farms can overwhelm the network's capacity in windy conditions – in 2020 6% of wind-powered electricity generated in the UK had to be 'curtailed' (thrown away)[29].

Although load balancing, even across countries, can help, there is clearly potential value in storing energy – for example sometimes near the site of over-generation. Although batteries offer a high round-trip (electricity-battery-electricity) efficiency of around 82%[30], battery storage can be expensive, and batteries leak power over time.

Pellow et al modelled a hypothetical wind farm storage solution using alkaline water electrolysers to produce and store hydrogen from overproduction of energy, and fuel cells to generate electricity from the stored hydrogen when needed[31]. Despite the relatively low overall electricity-hydrogen-electricity round-trip efficiency of 30%, the hydrogen solution was estimated to store significantly more energy per unit cost than batteries over the installation's lifetime.

Although in this study both pumped energy storage and compressed air energy storage performed even better than hydrogen, hydrogen can offer a more flexible option, for example for a small community not connected to a large grid. On Orkney the excess energy produced by wind and tidal power is used to produce hydrogen. This is stored and then used as a fuel for land and sea transport, possibly air transport in the future, and to power a fuel cell to produce electricity on other islands[32].

For large-scale storage of 'surplus electricity' Welder et al[33] suggest storing it as hydrogen, with the most efficient method of regenerating electricity being combustion in combined cycle gas turbine (CCGT) power stations which can reach 60% efficiency. The resulting round-trip efficiency is 35 -40%[18].

The above gives a flavour of the complications of choosing methods of storing renewable energy. The obvious sounding system of storing curtailed energy from renewables by making hydrogen is not necessarily a sensible option. It depends on the relative locations of electricity production and demand, and the size and capacity of the grid on which both these elements are sited. It is a complex calculation, but there is likely to be a place for the use of hydrogen in some instances.

Transport

In 2019 38% of the UK's energy consumption was in the form of (mainly oil-based) transport fuels[34] divided up as:

Road transport	72%
Railways	2% including 0.4% from electricity
Shipping	2%
Aviation	24%

Hydrogen fuel is being proposed to decarbonize the transport sector with the main competitor being rechargeable batteries.

Vehicles powered by hydrogen – hydrogen electric vehicles (HEVs) - are being commercially produced today. These are essentially electric vehicles (EVs) where the electricity is supplied by a hydrogen fuel cell rather than a battery, although a small battery is needed to store braking energy and smooth electricity demand. The hydrogen is compressed, usually about 700 times (70 MPa) taking about four times the space of the equivalent petrol or diesel fuel[35].

For decarbonizing road transport, the main competitors to HEVs are battery electric vehicles (BEVs). Even today, energy-efficiency-wise, batteries compete well with internal combustion engines (ICEs) because burning fossil fuels at a power station to generate electricity is more efficient than burning fossil fuel in an ICE (up to 50% vs 15% to 35% in an ICE, due to economies of scale and burning at a higher temperature), making up for the energy cost of transmission and the battery round-trip for electricity.

Refuelling an HEV is like filling up with petrol, much faster than recharging a BEV. HEVs can also generally drive further between refuelling. These advantages make longer journeys and high vehicle utilization easier – often important, for example, for fleet cars, HGVs, and buses. Hydrogen fuel cells also last much longer than batteries[27] and do not require as many relatively scarce materials such as lithium and cobalt needed for battery production.

Although hydrogen has a high specific energy density of 142 MJ kg^{-1} compared with around 47 MJ kg^{-1} for petrol and around 46 MJ kg^{-1} for diesel, the heavy fuel tank system required brings this down to around an effective 5.4 MJ kg^{-1} for compressed hydrogen and 8.99 MJ kg^{-1} for liquefied hydrogen[36] . This still compares well with today's batteries which store around 0.9 MJ kg^{-1} [37]. Consequently, HEVs can be lighter and have potentially longer range than BEVs. For example, the Tesla Model S battery stores 306 MJ (85 kWh) giving a range of under 300 miles, but weighs 540 kg[38] – over half a tonne.

Despite the potential advantages of HEVs, van Renssen states[39] that 'Few believe that private cars will run on hydrogen in future'. CarbonBrief[40] estimates that in 2019 while worldwide there were 11,200 passenger vehicles running on hydrogen, there were over 7 million electric cars, and initial enthusiasm for HEVs in the Far East seems to be waning. Sales of electric cars and hybrids continues to grow in the UK[41].

Much of the case against HEVs is related to energy use efficiency. Using green hydrogen rather than batteries reduces the overall efficiency starting with renewable energy by about two thirds, from around 70% for BEVs down to around 23% for HEVs[42]. This includes the cumulative energy costs of electrolysis (25%), compression to 700 bar (10%), and fuel cell efficiency (50%). This figure for HEVs is far lower than that in Table 1, above, from a different reference, but includes the transport/transfer costs mentioned below. This demonstrates the difficulty of obtaining accurate, consistent information.

Hydrogen can suffer a further fuel transport energy cost of 20% vs a 10% cost for electricity transmission, although the relative cost can depend on the scenario – for example bulk transport from remote offshore locations may be cheaper using hydrogen.

Transport & Environment[43] estimates that having a greater reliance on hydrogen when decarbonizing transport in 2050 would increase annual renewable electricity demand for transport by 15% from 369 TWh to 426 TWh.

So, there are pros and cons for the use of hydrogen as a fuel for cars, but the relatively low efficiency of the energy conversions involved is likely to mitigate against it for general use.

Heavy Goods Vehicles

For long-distance transport and heavy goods vehicles many argue that the battery weight, which can be a significant proportion of the vehicle payload, and logistical costs of using batteries, including long refuelling times, make hydrogen electric trucks (HETs) attractive. For example, teslari.com estimates that the much-discussed Tesla Semi truck's battery would weigh between five and six tonnes, which must be arranged as four separate battery packs for faster charging. The greater weight of battery electric trucks (BETs) causes more road damage and can bring trucks up against legal axle limits, reducing the load they can carry.

HETs are currently relatively expensive due to the complexity of refuelling, the cost of fuel cells and hydrogen tanks, which must withstand high pressures and hydrogen diffusion, but there is plenty of scope for innovation in these areas[35].

Developing a hydrogen refuelling network would be expensive, so seems unlikely to happen if it is not needed for cars[44] [27]. Analysis by Earl et al[44] concluded that BETs could be competitive depending on the electricity price. The specific energy density of batteries increased by a factor of five between 2009 and 2017[35], and as this continues to improve, along possibly with other innovations such as overhead charging catenaries on major routes for BETs[27], so there is a risk that investment in HETs and the hydrogen distribution network may be wasted.

The IEA[45] sees a significant role for HETs. However, Cebon and Ainalis[46] estimate that powering the UK's lorry fleet using blue hydrogen would increase the UK's gas imports by a quarter, and sufficient quantities of green hydrogen will not be available in any useful timeframe in the UK.

Perhaps lateral thinking is required here. If the fundamental question we must ask is “how do we decarbonise freight transport” rather than “how do we decarbonise HGVs” there may be a much simpler answer with fewer technical or infrastructure problems, namely transfer heavy freight to an electrified railway system. It would be far more efficient from an energy point of view, but there would be capacity issues to overcome.

Overall, depending on technology developments, it appears there may be a niche role for HETs, hydrogen buses and possibly hydrogen fleet cars, possibly based near hydrogen production facilities, but a comprehensive hydrogen refuelling network seems unlikely to be developed.

Trains and buses

Trains

To meet the deadline for the phasing out of diesel trains **t**here is active interest in developing blue hydrogen-fuelled passenger trains for long lightly-used lines to complement electrification of busier lines. A small fleet of trains is being converted for experimental use in the Middlesborough area.[47] They would make use of experimental CCS facilities being developed in the area. However, a study by the German federal transport ministry found that battery-electric trains would have about 35% lower whole-life costs than the iLint hydrogen trains now running, even assuming a future reduction in the cost of green hydrogen[48].

Buses

London has had a few hydrogen fuel cell buses for about twenty years, but rapid expansion is taking place this year in Aberdeen[49], London, Birmingham and Belfast. The latest double-deckers lose accommodation for 20 passengers to make room for the fuel storage and extra equipment.

Thus, there are local pilots with hydrogen trains and buses, often associated with local hydrogen production. But in general hydrogen struggles to compete with electric.[50,51]

Shipping

Shipping is one of the hardest areas to decarbonize and is responsible for around 3.1% of worldwide GHG emissions[20]. A particular difficulty is the life of a ship which is a large investment and is likely to be at sea for some 20 to 30 years.

The International Maritime Organization has a target of only a 50% reduction in shipping emissions by 2050[52]. Economics, long lead times, and lack of supportive legislation means current decarbonisation efforts are effectively in ‘deadlock’[53]. Current efforts are centred around the introduction of liquefied natural gas (LNG) by 2030, which is expected to make a 20-25% saving in GHG emissions as a ‘transition’ fuel[40], although as noted above doubts remain about the carbon footprint of natural gas due to methane leakage during use (‘slippage’) and upstream leaks.

Hydrogen as a fuel has been trialled in some projects, although the additional storage and handling needed for liquid hydrogen create additional costs[40]. Ideally deployment would use fuel cells, as burning hydrogen would be less efficient, although there may be industry resistance to moving away from combustion. Green ammonia[54] and green methanol[55] which can be derived from green hydrogen and can also be used in fuel cells, are possible alternatives, as they take less space and are cheaper to store than hydrogen[40]. However, they are not expected to be adopted

by other industries, so the associated infrastructure costs may be borne solely by the shipping industry.

An interesting recent development is the use of solid oxide fuel cell (SOFC) technology[56] which can be fuelled by LNG, releasing the energy with up to 44% greater efficiency than burning[20]. This reduces emissions and prevents NOx formation. SOFC fuel cells can also accept hydrogen as a fuel for zero carbon emissions, providing a possible path to hydrogen. But, as discussed above, much infrastructure would still have to change to accommodate hydrogen or ammonia. As well as higher efficiency and elimination of NOx generation[57], fuel cells are much quieter, causing less damage to marine ecosystems[20] .

Aviation

The climate impact of aviation is generally reported as around 2% of total emissions but may account for as much as 3.5% of warming impact[58]. The high specific energy density of hydrogen (142 MJ kg^{-1}) makes it an obvious carbon-free alternative for aviation. However, hydrogen needs around four times as much storage space as conventional fuel[40] and the weight of existing hydrogen storage systems can bring down the effective energy density down to around 5.4 MJ kg^{-1} [59] – far lower than conventional aviation fuel (43 to 48 MJ kg^{-1}). Another concern is the greenhouse gas effect of water vapour produced, although using the hydrogen in fuel cells would produce water cold enough to capture within the aircraft[27].

These technical limitations probably mean that full commercial aviation using hydrogen is not an immediate prospect. Instead, as with shipping, aviation companies are investigating various synthetic fuels, some of which may be based on hydrogen.

Although fuel decarbonization seems a long way off for shipping and aviation both sectors are looking at the use of fuel cells for auxiliary on-board functions[60].

Heating

In 2019 domestic gas cons - emption was 18.7% of the UK's total energy consumption and this was mainly used for heating. CCC (2016)[61] reported that heating and hot water provision for buildings accounted for 20% of the UK's greenhouse gas emissions. Around 80% of building heating in the UK is provided by burning natural gas[27].

Decarbonizing heating is technically, economically, and politically challenging, due to the scale and variability of the demand, the relative efficiency of, and high investment in, the existing network, the state of the UK housing stock and the long lead times and high costs of making changes[62]. For example, in contrast to transport, where fossil fuel vehicles are only 15% - 35% efficient, a typical condensing gas boiler is over 90% efficient (if correctly set up[63]).

Meeting the UK winter peak heating demand using electricity would be another challenge. This is often quoted as around 300 GW or five to six times the total current maximum electricity demand, based on Sansom[64], although Watson et al[65] suggests this is closer to 170 GW.

The most important and cost-effective decarbonization step is to reduce heating demand by improving insulation and draught-proofing of new and existing homes. In fact, the UK CCC[13] expects a

> "*15% reduction in energy used for heating existing buildings by 2030 through efficiency improvements, requiring insulation of about 7 million walls and lofts in homes, and heating controls and other insulation measures in homes and non-residential buildings"*

However, progress has been slow to non-existent with, for example, the abandoning of new home efficiency standards[66] and the scrapping of the green homes grant[67]. Beyond efficiency measures, the UK government has identified three main options – (electric) heat pumps, using hydrogen as a fuel, and local heat networks where heat is distributed from a variety of local heat sources[68, 61, 69].

Heat pumps are more efficient than electric heaters because they exchange heat with the outside like a reverse fridge. The UK Climate Change Committee[13] says that using a source of low carbon electricity to heat a house using a heat pump would be 250-450% efficient, since they are transferring heat, rather than producing it. Using the same electricity to produce green hydrogen and heat the house with a boiler would be 62% efficient. This does not consider financial costs.

However, heat pumps are relatively expensive – around £9,000-£11,000 to buy and install an air source heat pump[70]. To perform well they need a well-insulated house, work better with underfloor heating, and can struggle with very cold conditions[71]. Also, it may be that additional radiators are required when a house is being retrofitted, because the temperature of the water produced is lower than that produced using gas heating. Consequently, heat pumps are expected to be adopted more for new build homes, which will not then need connecting to the gas grid, and for existing properties not on the gas grid, where heating costs a lot more today anyway.

Providing heating via hydrogen can help reduce the anticipated burden on the electricity network, especially during peak periods, and arguably reduce the cost of retrofitting homes down to the cost of a new boiler. One prominent boiler manufacturer suggests this would address the needs of the 85% of UK homes heated by natural gas with minimal disruption, compared to the main competing technology of (electric) heat pumps[27].

The UK's gas network is already being made 'hydrogen ready'[72] and the UK government has sponsored projects to look at converting the gas network to 100% hydrogen, including the industry backed H21 project and the Hy4Heat programme[73]. The industry group Hydrogen Taskforce has urged that all new gas boilers should be 'hydrogen ready boilers' by 2025[74]. This is also included in the UK Climate Change Committee (CCC)'s 'balanced pathway'[75]. The UK government proposes a whole town trial as part of its '10-point plan'[76]. Frazer-Nash Consultancy reported[77] to the UK government on some of the issues still to be resolved of this proposed switch to hydrogen boilers including leak detection, limiting NOx emissions, fire risks, gas flame visibility and odourising.

Unsurprisingly, the main issue many have with plans to heat homes using hydrogen - apart from the obvious continuing complexity of the continued need to maintain two energy supplies and fittings for each house - is with hydrogen cost and supply. Even using grey hydrogen, since SMR is not cost-free, using hydrogen will be more expensive than natural gas.

H21[78] asserts that converting to a hydrogen gas grid is economically viable, and forecasts a maximum increase in gas bills over 30 years of 2.9%, saying this will be achieved by using 'regulated business plans'. However, the CCC[13] suggests reusing the gas grid *'does not give the hydrogen scenario a decisive advantage'*, partly because of the anticipated costs of upgrading the

network and storage facilities. A detailed study by Sunny et al[8] (looking at moving existing consumers to blue hydrogen and biomethane with CCS to generate balancing negative emissions) concluded that the price for consumers could be three times today's prices. Much of the additional cost is attributed to the necessary infrastructure investment. This approach would likely require an increase in gas usage to make up for the conversion energy losses and CCS[13].

Most advocates of hydrogen for heating anticipate an eventual transition to green hydrogen which would essentially utilise the same assets. although this would obviously require a significant reduction in the cost of electricity.

A risk of the hydrogen investment is that it may only be of short-term value, as all-electric solutions are likely to be more efficient. However, if hydrogen is used as the backup for variable supply and winter peaks some hydrogen infrastructure will be needed anyway.

Stafell et al[79] suggest the capital cost of wholesale introduction of heat pumps in all homes at between £50-100 billion with an extra 75 TWh per year demand from the network. The CCC[13] estimates that the cost of moving to hydrogen is similar to that of using heat pumps; but suggest a subsidiary role for hydrogen because of the energy losses in producing hydrogen.

Heat networks (using a single large scale and efficient heat generation and distribution system over multiple homes/other users) can work with a wide range of heat generation technologies (including both heat pumps, and gas/hydrogen boilers) and potentially bring significant reductions in both carbon emissions and costs, generally for high density environments.

Thus, heating policy in the UK may face a crossroads. Are existing gas heating customers to be offered a relatively non-disruptive, but possibly expensive, transition to mainly blue hydrogen in the near term? Should the current emphasis be on more insulation and draught-proofing, with a longer-term move to heat pumps possibly combined with hydrogen pilot projects close to centres of spare green hydrogen production?

4 What next for hydrogen?

So, where are we now? Hydrogen is being seen by many as a like for like replacement for natural gas and other fossil fuels in many situations. Hydrogen, as well as being an important industrial input, is already a proven low-emission flexible energy storage option, especially where it can be produced cheaply. Green hydrogen offers a way to store green energy and smooth supply. Blue hydrogen opens an opportunity to continue using fossil fuels but with lower emissions, although simply using CCS in gas-fired power stations also offers this. However, hydrogen is expensive to produce, and it will only truly emissions-free when it is green hydrogen.

A huge increase in renewable electricity production would be needed before there is any 'spare' to produce large quantities of green hydrogen. Therefore, in the short term, grey and then blue hydrogen are likely to be used; the former not reducing emissions at all, and the latter still resulting in significant emissions. E3G recommends against near-term large investments in hydrogen which could divert resources from more effective emission reduction approaches and innovation[80].

For example – consider improving energy efficiency measures coupled with continuing the move to condensing gas boilers along with retraining fitters to tune them correctly[81], taxing gas (while exempting poorer uses) to reduce demand and incentivising heat pumps and adding any cheaply available blue (or green) hydrogen to the existing gas supply[82]. Compared with a switch to hydrogen boilers these measures would start making emissions savings much sooner, be undoubtedly cheaper and less disruptive for consumers and in the long run, may overall rival emissions savings of switching to blue hydrogen, would reduce the UK's balance of payments deficit and reliance on overseas gas supplies (which would increase significantly if heating was switched to blue hydrogen) and buy time for introducing more heat pumps and for further innovation.

Many consider that when blue and green hydrogen come on stream in significant quantities priority should be given to existing industrial processes, rather than using it as a green energy source.

A number of countries have developed hydrogen strategies[83], particularly in the Far East and Europe. The EU has one. The UK has just published its hydrogen strategy document which appears to leave important questions unanswered[84].

On the ground most projects are either small-scale, or at the prototype/planning stage.

As North Sea oil and gas production is reducing, both because of lack of resource and necessary greening of energy, there is the opportunity to utilise some of the infrastructure that is already in place. That, together with technology of offshore wind energy production that now exists, means that there is the opportunity to produce green hydrogen at large scale, and pipe it ashore.

There are several plans to produce blue hydrogen from gas produced in the North Sea. Some of the existing infrastructure could be used; but this requires the carbon dioxide emissions to be captured and stored. There is storage capacity in locations that gas has been removed from; but the CCS technology has yet to be demonstrated at the scale that would be required[85].

The Danish renewable energy company Orsted have recently (March 2021) announced plans to develop an offshore wind farm and adjacent hydrogen plant at the North Sea Port straddling the Dutch-Belgian border. The wind farm would have capacity to produce two gigawatts of electricity and would power a one- gigawatt electrolysis plant, which would be able to produce about 116,000 tonnes of hydrogen a year by 2030 for use as energy. This would supply about 20% of the hydrogen currently used in industry in the immediate area[86].

There are important decisions to be made, either by, or with a steer from, government. The economies of scale are such that it will be important for the various sectors that might use hydrogen to know whether others will also require it[87, 88].

Robin Speed and Brian Shorter, September 2021

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