Developments in the global hydrogen market: The spectrum of hydrogen colours

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The fundamental reasons for considering the adoption of hydrogen as a fuel, industrial feedstock and energy storage medium are presented. Hydrogen production methods are outlined, with reference to the colour prefixes used to describe different types of hydrogen. The relative greenhouse gas emissions and economics of green and blue hydrogen production are considered for achieving a 'net zero' climate-neutral energy system by 2050. In general, it appears that green hydrogen will soon be cheaper than blue hydrogen due to the falling costs of renewable electricity and electrolysers, then cheaper than grey hydrogen, and in the long term potentially cheaper than natural gas.

Introduction

Hydrogen is the most abundant element in the universe, but it does not occur naturally on Earth. Energy is required to extract it from fossil fuels, biomass or water, with water being the most plentiful source. Energy is also required to manufacture the technologies involved in hydrogen production, purification, storage and utilisation. Therefore, a set of compelling reasons is needed to justify switching to hydrogen in our efforts to decarbonise the energy system and reduce atmospheric pollution [**Table 1**].

Hydrogen is very useful for carrying, storing and utilising renewable energy as and when required by various types of end use. To achieve a climate-neutral energy system by 2050, it is important to ensure 'net zero' hydrogen is produced, and that hydrogen supply and demand are well matched throughout the transition. Consideration should therefore be given to the ultimate capacity of each hydrogen production method, its ability to facilitate a progression in supply and demand, and the greenhouse gas (GHG) footprint of the hydrogen it produces.

The two-carrier approach for renewable energy, the rationale for electrolyser deployment, and the policies required to advance green hydrogen have been outlined in a previous paper.[1] The present paper covers both renewable and non-renewable methods of hydrogen production, the challenge of achieving net-zero hydrogen, and the fundamental points of distinction between green and blue hydrogen.

Hydrogen from fossil fuels

'Grey' hydrogen is produced commercially in large quantities from fossil fuels by a hydrocarbon reformation technique involving steam and/or oxygen; namely steam methane reforming (SMR) or autothermal reforming (ATR) of natural gas, and by partial oxidation (POX) of coal or heavy oil. In each case a mixture of hydrogen and carbon monoxide is produced (syngas), which then requires the carbon monoxide to be removed via the water-gas shift reaction to yield further hydrogen and carbon dioxide:

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (1)$$

In total about 6% of global natural gas production and 2% of global coal production is used to make approximately 70 Mt of hydrogen per annum, and this results in atmospheric emissions of about 830 Mt of carbon dioxide.[2] Most of the existing hydrogen production is by steam methane reforming, because the required plant is of relatively low capital cost and the chemical reaction is easy to control. Reformer capacities lie mainly in the range of 50–1000 MW, they usually operate under steady-state conditions, and globally the current installed capacity is in the region of 300 GW.

SMR is a high-temperature endothermic process that first requires trace sulphur compounds to be removed from the natural gas to avoid catalyst poisoning, and then substantial inputs of heat (at temperatures up to 1000°C) and water in the form of superheated steam:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad (2)$$

ATR combines steam reforming and fuel oxidation into one unit, and operates at a higher temperature than SMR (up to 1150°C). It is more efficient because heat from the exothermic oxidation step can be utilised by the reformation reaction, but ATR also requires an oxygen input:

$$4CH_4 + O_2 + 2H_2O \rightarrow 10H_2 + 4CO \qquad (3)$$

The partial oxidation of heavy hydrocarbons can be undertaken catalytically (at about 950°C) and non-catalytically (at up to 1315°C). The respective POX reactions may be written:

Allows renewable energy to be captured at a scale far beyond that achievable with renewable electricity alone
Enables renewable energy to be transferred in bulk via a hydrogen transmission pipeline network
Permits very large amounts of renewable energy to be stored via the underground storage of hydrogen (or a derived carrier)
Facilitates renewable power generation on-demand via hydrogen fuel cells without emitting COx, SOx, NOx, particulates or noise; or by hydrogen gas turbines without emitting COx, SOx or particulates
Enables various types of fuel cell electric vehicle (FCEV) to be refueled rapidly and travel the desired range without emitting COx, SOx, NOx, particulates or noise
Underpins several major industrial processes by providing an essential chemical feedstock or reducing agent
Permits heat generation by combustion without emitting COx, SOx or particulates
Improves a nation's energy security and balance of payments by establishing indigenous production of a storable fuel from inexhaustible supplies of renewable energy and water

Table 1. The fundamental reasons for adopting hydrogen in the energy system.

$$C_nH_m + 0.5nO_2 \rightarrow nCO + 0.5mH_2 \quad (4)$$
$$C_nH_m + nH_2O \rightarrow nCO + (n + 0.5m)H_2 \quad (5)$$

Ostensibly fossil fuels provide the source of hydrogen for these processes, but it should be noted from the above equations that a large proportion of the hydrogen produced originates from the water input. Some 43%, 50%, 69% and 83% of the hydrogen is derived from water by ATR (methane), SMR (methane), POX (heavy oil) and POX (coal), respectively.[3]

In practice these techniques produce a hydrogen-rich gas mixture, which contains hydrocarbons, CO, CO_2, nitrogen and various other trace contaminants. Hydrogen purities of 87%, 93% and 94% are typical for coal gasification, ATR and SMR, respectively.[4] Therefore further purification is needed to yield grey hydrogen of the required quality (e.g. via pressure swing absorption, membrane separation or liquefaction) depending on the end use. It has been proposed that a minimum hydrogen purity of 98% will suffice for combustion appliances connected to a future hydrogen grid,[5] although the required purity at the injection points is not known.

The production of grey hydrogen at scale is long established and its further expansion is not capacity limited, although fossil fuel reserves are ultimately finite. The CO_2 by-product is usually vented to atmosphere along with the CO_2 emissions from the steam raising and oxygen production processes. Grey hydrogen production therefore makes a significant contribution to global warming.

Hydrogen may also be generated via the pyrolysis of a fossil fuel, where the by-product is carbon. The pyrolysis of natural gas to produce carbon black is well known:

$$CH_4 \rightarrow 2H_2 + C \quad (6)$$

Producing hydrogen by pyrolysis involves the thermal decomposition, catalytic decomposition or plasma decomposition of methane.[6] Each approach is currently at the R&D stage but, unlike SMR/ATR/POX, pyrolysis avoids the need to sequester CO_2 in order to produce hydrogen with a low GHG footprint, provided that the by-product is utilised (e.g. for building and construction materials). Hydrogen production via the pyrolysis of a fossil fuel has been described as 'turquoise' hydrogen.

Greenhouse gas footprints

It has been proposed to capture CO_2 from the water-gas shift stage of SMR/ATR/POX and sequester it via carbon capture and storage (CCS)[7] to reduce the GHG footprint of grey hydrogen, and so earn the prefix 'blue' or 'low-carbon'. Capturing CO_2 from the heat generation, steam raising and oxygen production processes is also desirable in order to minimise the GHG footprint, but this is technically more difficult to achieve. There appears to be no precise definition of the overall CO_2 capture rate required to justify changing the prefix from grey to blue. Maximum capture rates are reported to be up to 70% for SMR (or up to 90% if post-combustion CO_2 capture is included) and over 90% for ATR.[8]

"There is an urgent need to both reduce fugitive methane emissions and avoid designing them into future hydrogen strategies"

Producing grey, turquoise or blue hydrogen from natural gas also causes methane leaks upstream of the production process, due to the exploration and long-distance transportation of natural gas. These so-called 'fugitive' emissions have a substantial global warming impact, which is additional to the CO_2 emissions resulting from converting natural gas to hydrogen. Atmospheric methane concentrations have been rising since 2007, and accelerating in recent years.[9] Satellites and more precise measurement technology have revealed significant methane leaks from the oil & gas infrastructure.[10] It has been estimated that 2.3% of US gas production is emitted to the atmosphere, which when considered on a 20-year time base brings about radiative forcing of a similar magnitude to that caused by all of the CO_2 emissions resulting from US gas combustion.[11] Thus there is an urgent need to both reduce fugitive methane emissions and avoid designing them into future hydrogen strategies (e.g. the European Commission recently set out its plan to reduce anthropogenic and biogenic methane emissions[12]).

The GHG footprint of grey hydrogen is a function of the CO_2 output from the water-gas shift reaction, the GHG footprints of the steam and oxygen inputs, and the fugitive emissions. A datum value of 91 gCO_2e/MJ of hydrogen (328 gCO_2e/kWh) has been identified by the CertifHy initiative to represent the GHG footprint of SMR hydrogen, with a proposed threshold value of 36.4 gCO_2e/MJ, below which hydrogen may be described as 'low carbon'.[13] The latter equates to a 60% reduction in GHG emissions, leaving a further 40% to be achieved if net-zero hydrogen is to be produced. Turquoise and blue hydrogen may thereby be referred to as low-carbon hydrogen.

Blue hydrogen is characterised by upstream methane emissions as well as an imperfect downstream process of capturing and sequestering CO_2. Therefore it has a residual GHG footprint, which means of itself it isn't compatible with achieving the net-zero objective. Most modelling studies appear to have assumed capture rates of 90–98% and overlooked or underestimated the global warming impact of fugitive emissions. In general, there is a lack of data concerning CO_2 capture rates for blue hydrogen production in practice, partly because CCS still requires further technological development, especially for large-scale systems.[14]

To achieve a zero-GHG footprint for blue hydrogen requires so-called 'negative emissions' to be captured in the correct amounts to compensate for its residual emissions. This necessitates implementing extra measures, which serve to increase the cost of blue hydrogen (e.g. afforestation, or CCS combined with biogenic energy conversion or direct air capture). As yet no colour prefix appears to have been attributed to blue hydrogen production when combined with negative emissions production, but clearly this coupling is essential if blue hydrogen is to play a role in the future climate-neutral energy system.

Hydrogen from biogenic sources

Hydrogen may be generated by biomass fermentation, gasification, reforming, pyrolysis and bio-photolysis processes. The potential capacity of biogenic hydrogen is limited, because the amount of indigenous biomass available usually amounts to only a small fraction of a country's energy needs. For the EU it has been estimated that the potential biomass resource amounts to roughly 10% of Europe's final energy consumption.[15] Also, with a rising global population there is an overarching conflict of interest between growing plants to provide fuel and food production.

The CO_2 produced when extracting hydrogen from biogenic sources may enter the atmosphere (which is arguably acceptable, provided the life cycle analyses and auditing processes verify that the production process is carbon-neutral in practice), or captured via CCS. If biogenic hydrogen production is combined with CCS then advantageously it produces negative-carbon hydrogen. Such an approach may be implemented in its own right, in which case the ultimate scale of the biomass resource will dictate the scale of CCS required. Alternatively it may be viewed as a means of netting off the residual emissions of blue hydrogen production (e.g. by reforming streams of biomethane and natural gas in the required proportions).

At present, no significant production of biogenic hydrogen is occurring. No colour prefix appears to have been attributed to biogenic hydrogen, with or without CCS being applied.

Hydrogen from water electrolysis

Hydrogen may be produced from water electrolytically, photo-electrolytically, or thermo-electrolytically. The latter two methods are still R&D topics and hampered by low conversion efficiencies, but water electrolysis is well proven and can convert electricity to hydrogen at an efficiency of 70–80% (higher heating value, HHV).

Electrolysis is a low-temperature single-step process that requires two inputs, namely electricity and water, and produces two outputs: high-purity hydrogen and oxygen. Electrolysers may follow steady-state or transient operating regimes, with proton-exchange membrane (PEM) electrolysers offering particularly rapid response times.

The water electrolysis reaction may be written:

$$2H_2O \rightarrow 2H_2 + O_2 \quad (7)$$

Clearly there is no contamination from hydrocarbons in electrolytic hydrogen production; it produces hydrogen of >99.95% purity. There is no association between electrolytic hydrogen production and CO_2 or methane emissions (and hence requirement for CCS), unless the electrolysers consume electricity generated by a fossil fuel power plant.

Renewable hydrogen is produced when the electrolyser is fed with renewable electricity – this is commonly referred to as 'green' hydrogen. The production of green hydrogen is not capacity-limited. Some 173 000 TW of solar energy strikes the Earth continuously, which is approximately 10 000 times the global energy consumption. Simplistically the latter could be met by covering 8% of the Sahara desert with solar power sources, or 1.5% of the Pacific Ocean with wind power sources.[16] Green hydrogen production of itself produces net-zero hydrogen, without requiring CCS or the capture of negative emissions.

To achieve a zero-GHG footprint for green hydrogen requires the electrolyser to be directly connected to a renewable power source. Alternatively, if the electrolyser only uses renewable electricity purchased via the electricity grid, or operates in a synchronous manner with grid-connected renewables, then arguably it also produces green hydrogen. In some regions (e.g. Norway, Scotland, British Columbia, northeastern Brazil, Uruguay, New Zealand) grid-connected electrolysers will already yield hydrogen of zero, or near-zero, GHG footprint. However, in most industrialised countries the current average GHG footprint of grid electricity prevents this. Therefore policies are needed to facilitate green hydrogen production on-grid, so the synergies between greater renewables integration and electrolyser operation can be realised.

Several definitions of green hydrogen have been proposed and discussed in the literature.[17] The aforementioned CertifHy GHG intensity threshold of 36.4 gCO_2e/MJ enables hydrogen produced predominantly, as opposed to entirely, from renewable electricity to be classified as green.[12] An alternative threshold has been suggested where the green prefix may be used provided the GHG footprint of the electrolytic hydrogen is <25% of that applying to the fuel it displaces.[18] However, at present there is no agreed threshold or auditing methodology to confer the green prefix on hydrogen produced by grid-connected electrolysers, which amounts to both a strategy gap and a policy gap. This issue is currently being addressed by the European Commission in the finalisation of Renewable Energy Directive II.[19]

Because renewable generation is weather-dependent it is often out of time phase with energy demand. Accordingly, green hydrogen production is ultimately constrained by the operating patterns and capacity factors of renewable power sources. Fortunately, hydrogen can be stored cheaply at scale (unlike electricity) and so storage is a central consideration in the wider implementation of green hydrogen solutions. The geological storage of green hydrogen in salt caverns and suitable underground stores can provide a renewable energy 'lung' for the entire energy system. For these reasons there is vast potential in locating green hydrogen production in regions of high renewable resource (e.g. with offshore wind farms in the North Sea and with solar farms in North Africa), interconnecting them with subterranean stores and conveying hydrogen to the points of demand.[1, 16, 20–22]

Hydrogen from water electrolysis using nuclear power

Electrolytic hydrogen can also be produced from nuclear power, and this has been referred to as 'yellow' hydrogen.[23] The electrolysers may be operated to minimise the curtailment of nuclear power stations,[24] and if the technologies are co-located hydrogen can be produced at scale. For countries with significant installed capacities of nuclear power, substantial amounts of yellow hydrogen could be produced at regional level for industrial clusters or a future hydrogen grid.

Combining large electrolysis plants with nuclear power plants allows a relatively high baseload of power generation year-round, by using the electrolysers as a flexible demand-side load. This approach could provide significant operational advantages both for existing nuclear power stations and micro nuclear reactors, which are currently under development by Rolls-Royce and other companies worldwide.

Green and blue hydrogen: cost comparisons

There are choices to be made concerning the amounts and types of hydrogen that will be produced, or imported, to achieve a climate-neutral energy system. Some nations have recently declared that they will focus on green hydrogen (e.g. France, Germany, Portugal, Spain), some may produce yellow hydrogen, and some may wish to produce or import blue hydrogen. The main decision appears to be between blue and green hydrogen, and many believe the choice will be made solely on economic grounds.

There are relatively few independent and detailed comparisons of blue and green hydrogen costs in the literature, but several misconceptions exist such as 'blue is cheaper than green', 'blue is required to enable green', and 'blue should be adopted first, because green will not be economic until later'. In general, this subject warrants careful analysis if effective cost comparisons are to be made. Any economic assessment of hydrogen production methods should foremost ensure that it is comparing like with like. It is fundamentally incorrect to compare blue and green hydrogen unless they are of identical purity, pressure and GHG footprint – analyses should ensure parity values apply for each of these parameters. Clearly any steps involving purification, compression or

GHG footprint adjustment serve to increase hydrogen costs.

In general, there are several areas where potential errors can occur or a lack of transparency can cast doubt over the cost estimates:

- If the points of production and consumption are co-located for some production methods but not for others, comparisons are invalid unless the interconnecting distribution method is accounted for.
- The assumptions concerning leakage rates into the atmosphere and global warming potentials (for methane, carbon dioxide and hydrogen) associated with the production and any implicit distribution of hydrogen.
- The assumptions concerning embodied carbon, CO_2 capture rate, fugitive emissions and negative emissions for netting off residual emissions.
- Comparing the cost of hydrogen produced by MW- versus GW-scale plant, because economies of scale apply.

Observations on the cost of blue hydrogen production

Blue hydrogen costs depend mainly on the price of natural gas, the cost of the reformer, the cost of implementing the required CO_2 recovery, transport and storage/utilisation facilities, and the operating costs for the combined system of natural gas reformation and CCS. Also, if the hydrogen is to be of zero-GHG footprint there are additional costs in generating/capturing the required negative emissions. To produce low-cost hydrogen, CCS must be applied at large scale, and preferably fed with CO_2 from a number of large-scale reformers. It is thus a centralised approach that requires some means of distributing hydrogen in large amounts to the points of use.

SMR and ATR are mature processes, but CCS is not. Accordingly there are several uncertainties and cost implications for blue hydrogen that are associated with CCS:

- Legal responsibilities and liabilities (public or private).
- Insurance arrangements for the high-pressure CO_2 infrastructure.
- The extensiveness of the infrastructure required for transporting CO_2 from inland sites.
- Monitoring arrangements for CO_2 leakage and upstream methane leaks.
- Achieving the targeted CO_2 capture rates in practice.
- An auditing methodology to verify that operators are producing net-zero hydrogen rather than low-carbon hydrogen.
- The government subsidy scheme required to establish a suitable business model.
- Public attitudes towards CCS and blue hydrogen.

In general, there would appear to be three prerequisites for establishing blue hydrogen. First, a large hydrogen demand needs to exist that can consume hydrogen at scale on a reasonably continuous basis. Secondly, some form of hydrogen infrastructure is required to interconnect the points of supply and demand. Thirdly, a carbon dioxide infrastructure is required to pipe or ship the CO_2 to the storage sites, for which an economic value needs to be placed on the CO_2. On the demand side, the two main options for blue hydrogen in the short term are: large industrial clusters that currently use grey hydrogen, or a natural gas grid into which blue hydrogen admixtures can be injected. Advantageously both of these can be achieved with a minimum of hydrogen transmission infrastructure if the reformers are appropriately located. In the longer term, the main outlet for blue hydrogen is an extensive gas grid that enables numerous end-users to combust hydrogen rather than natural gas.[25] However, in all cases there needs to be an income stream or 'customer' for the CO_2. To date this has been solved by using CO_2 for enhanced oil recovery (EOR), to extract crude oil that cannot be extracted otherwise.[26] Unfortunately EOR has limited CO_2 storage capacity and only partially offsets the costs of CCS; and when the oil is used it simply leads to more CO_2 emissions!

Therefore the economic dilemma for blue hydrogen is the need to establish a suitable price for the waste CO_2 stream. If it can be used as a feedstock to synthesise chemicals, then it can have value (as implied by the recent adoption of the term CCUS, to impart that the CO_2 may be utilised rather than just accumulated). However, such an approach invokes a need to establish the production of synthetic fuels and chemicals at a sufficient scale to make use of the CO_2, which amplifies the required capital investment. By comparison, there is no need to provide an income stream for the oxygen that is usually vented to atmosphere from an electrolyser, because oxygen isn't a global warming gas and doesn't need to be sequestered. Any commercial applications of electrolytic oxygen are therefore a genuine economic upside for green hydrogen.

Usually the producer pays to dispose of any waste associated with the production process. If this principle is applied to blue hydrogen production, then its cost will be substantially greater than that of grey hydrogen (which in turn is significantly more expensive than natural gas). Although economies of scale will be realised if blue hydrogen is widely adopted, the handling and storage of the CO_2 by-product will always have a large impact on costs. So the adoption of CCS will require subsidies if the fossil fuel sector is to produce blue hydrogen at low cost.

According to the International Monetary Fund (IMF),[27] fossil fuels receive 85% of all existing subsidies worldwide (amounting to 6.3% of global GDP), so additional subsidies for CCS would appear difficult to justify. The European Academies Science Advisory Council (EASAC) recently recommended that governments should remove subsidies, taxes, levies and other incentives for fossil fuels,[28] because they continue to distort energy markets and limit the potential growth of markets for renewable hydrogen and synthetic fuels. No government has yet introduced a subsidy scheme for blue hydrogen production. Indeed, it appears that blue hydrogen is increasingly being advocated as a temporary measure in order to make use of existing investments in oil & gas assets, rather than as an environmentally sustainable long-term solution for 2050 and beyond.

Observations on the cost of green hydrogen production

Green hydrogen production can be applied via a decentralised approach close to the points of demand and at a greater scale via a more centralised approach (e.g. at the points of power generation, or upstream of bottlenecks in the electricity grid). On the demand-side, the ability to step up the installed electrolyser capacity at a given site is particularly useful for increasing the degree of decarbonisation over time. It enables hydrogen supply and demand to grow in unison and spreads the investment costs for stakeholders, reducing working capital requirements. On the supply-side, electrolysers can offer a firm market for new renewables and a flexible load for grid operators (from whom an income can be earned for providing frequency response and negative reserve services). It also offers renewable power companies the opportunity to create a new product that is storable. Hence the green hydrogen approach

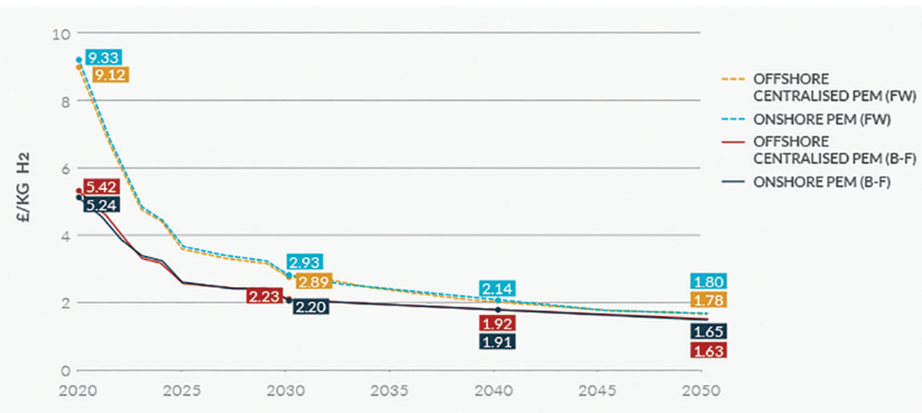

Figure 1. Trend in the levelised cost of hydrogen (LCOH) for hydrogen production from PEM electrolysers based on UK offshore wind power.[21]

provides benefits to several stakeholders, and importantly it does not produce a downstream waste.

Green hydrogen costs depend mainly on the price of the input electricity and the load factor of the electrolyser. As renewable power sources are upscaled and their deployment increases, unit costs decrease and capacity factors increase. This results in improved availability and lower-cost renewable electricity (e.g. new offshore wind farms in the UK currently sell electricity at ~40 £/MWh, but this is expected to fall to ~30 £/MWh by 2030[21]). Furthermore, as the grid integrates more and more renewables, the value of renewable electricity during low demand periods decreases to a very low level, or even becomes negative when supply exceeds demand. The ability of green hydrogen production to coincide with low demand periods therefore provides both a new market for the renewable power providers, which is out of time phase with the conventional electricity demand profile, and a new flexible load for helping the electricity system operator to balance the grid. These synergistic benefits will result in lower-cost green hydrogen as the integration of renewables increases.

Electrolyser costs

Electrolyser technology is currently being upscaled and cost-reduced in preparation for volume production. Ongoing efforts to optimise membrane-electrode assemblies (MEAs), increase the active area per cell, increase the number of cells per stack, increase current density without compromising efficiency, reduce balance of plant (BOP) costs, reduce power conversion costs, modularise system designs, reduce assembly time, semi-automate manufacturing and achieve supply chain efficiencies will culminate in substantial reductions in the unit costs of electrolysers across the next few years. For example, the price of a 100 MW PEM electrolyser system from ITM Power is expected to fall to <400 £/kW by 2024.[29]

This trend in electrolyser cost, in combination with the aforementioned trend in electricity cost, enables green hydrogen production to be characterised by a progressively decreasing unit cost over time. For example, hydrogen production from offshore wind in the UK is expected to result in costs falling to about 2 £/kg (~50 £/MWh) by the mid-2030s [**Figure 1**].[21] For a Europe-wide hydrogen grid in 2050, unit costs as low as 11 €/MWh have been predicted for green hydrogen, which is cheaper than natural gas, while blue hydrogen remains above 40 €/MWh [**Figure 2**].[30] If hydrogen is to be widely employed as a combustion fuel, the ability of green hydrogen to ultimately achieve a similar unit cost to that of natural gas is a key point of distinction.

Clearly the green hydrogen approach circumvents the uncertainties, complexities and costs associated with blue hydrogen production and CCS. Moreover, the characteristic cost down curve for green hydrogen suggests that taxpayer subsidies, which will be required to avoid market failure during the early years, can in time decline to zero. When compared with blue hydrogen, green hydrogen offers several advantages [**Table 2**]. These are important factors for governments to consider in planning the transition to a climate-neutral energy system.

Discussion

The reformation of fossil fuels involves extracting hydrogen from two inputs (a hydrocarbon fuel and water), while electrolysis only requires water. Because it is the hydrocarbon input that is causing the global warming problem that society is trying to solve, it would seem fundamentally wise to focus on hydrogen production processes based on water alone. The electrolysis of water using renewable electricity provides an immediately available pathway for producing high-purity hydrogen without causing global warming or atmospheric pollution. Accordingly, green hydrogen should be viewed as the priority for achieving a climate-neutral energy system.

It is essential that measures are put in place to ensure that hydrogen production has a zero-GHG footprint. For green and yellow hydrogen this is relatively straightforward, but blue hydrogen is characterised by significant residual emissions which need to be netted off with negative emissions (e.g. as implied by the 'net zero' decarbonisation commitment of the UK government). This can be achieved by several methods including afforestation, reforestation and by applying CCS to direct air capture and bioenergy production, but it adds cost.

Blue hydrogen production is both the potential saviour of the existing fossil fuel supply chain and a means for increasing natural gas sales per TWh of final energy consumption (due to the energy losses associated with hydrocarbon reformation and CCS). For several years suppliers of natural gas, gas grid operators and manufacturers of combustion appliances and heat engines have been advocating for blue

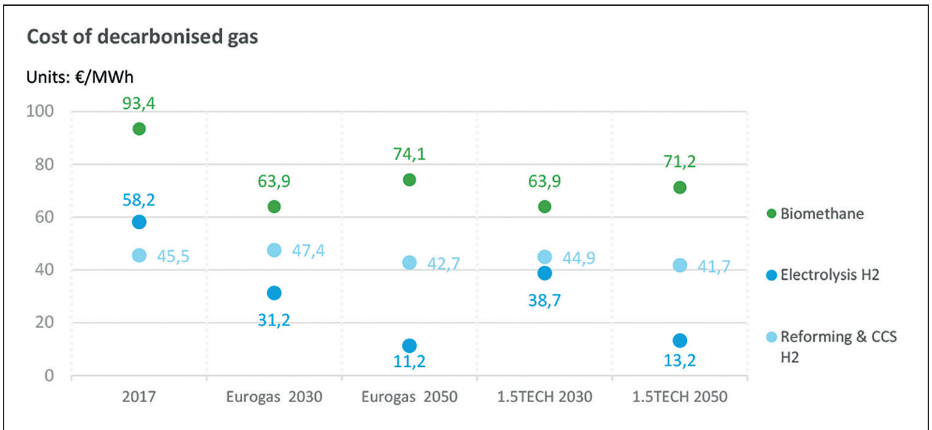

Figure 2. Cost projections for biomethane, blue hydrogen and green hydrogen.[30]

Doesn't require a huge investment to initiate
Can be significantly cheaper than blue hydrogen
Is net-zero compatible
Is based on an inexhaustible energy supply
Can be incrementally deployed to provide a pathway for increasing hydrogen production across multiple sites, so as to establish a stepwise progression in the decarbonisation effect
Can be applied to achieve synergistic economic benefits for renewable power providers, electricity grid operators and hydrogen users
Can commence without requiring a gas grid
Can feed into a future hydrogen grid
Can be implemented off-grid in regions of high renewable resource, to augment local production from grid-connected electrolysers
Results in substantial market growth within the renewables, electrolyser manufacturing and hydrogen utilisation sectors, and hence job creation throughout the supply chain

Table 2. Summary of the advantages of green hydrogen.

hydrogen production.[31] For any nation that is highly dependent on importing natural gas, the blue hydrogen approach helps the overseas gas supplier and stakeholders in the existing supply chain, at the expense of making the country a geological accumulator for the waste CO_2 produced by reforming natural gas. There is also a potential conflict of interest between the country supplying the natural gas (e.g. Norway or Russia) and the country that stores the CO_2 caused by the blue hydrogen production process (e.g. the UK).

Advocating blue hydrogen and the adoption of CCS in order to perpetuate the use of natural gas is a controversial option. Blue hydrogen production needs to be done at scale, requires large investments from the outset, takes time to introduce, requires a substantial sink for the hydrogen, and has a number of uncertainties with respect to CCS and who pays for the CO_2 disposal, which makes it difficult to justify. The choice for the operator of a natural gas reformer in the transition to a climate-neutral energy system is quite stark: either sequester the CO_2 and net off the residual emissions, or shut it down. This applies to existing reformers and any future installations. In essence, blue hydrogen is an end-of-pipe technical fix with dubious economic and environmental credentials; its primary purpose is to protect incumbent organisations in the existing supply chain, so that they can continue to exploit investments in natural gas exploration and infrastructure.

By comparison, green hydrogen is both an economically attractive and environmentally benign option. In the short term, green hydrogen production can be achieved within the electricity grid at a scale appropriate to the demand level by locating electrolysers close to the points of hydrogen consumption. Importantly, rapid-response electrolysers can be operated to assist the integration of renewables into the grid, by providing a new market for electricity at times when generation is high but demand is low. This approach can be engaged immediately, and will enable hydrogen supply and demand to be grown progressively in the early market. In the medium term it can be substantially augmented by off-grid electrolysis, which can produce hydrogen in bulk at low cost in regions of high renewable resource, and feed it into a transcontinental hydrogen grid in a similar manner to that originally proposed in the 1970s for establishing a 'hydrogen economy'.[20] Accordingly, green hydrogen is increasingly being seen as the solution for achieving a climate-neutral energy system by 2050. This was recently expressed succinctly as 'Renewable hydrogen and e-fuels are of critical importance to curb climate change. Without them, it will be impossible to achieve full decarbonisation – and the clock is ticking.'[22]

Studies to date aren't clear about the cost of producing net-zero blue hydrogen. In general, it appears that green hydrogen will soon be cheaper than blue hydrogen, then cheaper than grey hydrogen, and in the long term potentially cheaper than natural gas. For example, it has been predicted that green hydrogen will be cheaper than grey hydrogen by 2030,[32] and that by 2050 green hydrogen will be less than one-third of the cost of blue hydrogen.[30]

At present, governments are taking a rather centralised view of hydrogen; many are giving priority to green hydrogen, while some see green and blue hydrogen as one and the same. In the UK blue hydrogen has dominated thinking to date, and efforts have been focused on trying to make the case for CCS, while the opportunities for green hydrogen have been largely overlooked. No established industry or supply chain has been lobbying for green hydrogen, but awareness of the green hydrogen approach appears to have increased recently, to the extent that it is now probably the preference of the general public.

Those who are uncertain, or believe in 'technology neutrality' as a supreme principle, default to grouping blue and green hydrogen together, and overlook their distinct attributes. This is an unsatisfactory stance, and more detailed assessments of hydrogen derived from fossil fuels versus hydrogen derived from renewable energy are required. In particular, it is important for governments to place a focus on realising the opportunities provided by the green hydrogen pathway, by working with the relevant industry stakeholders to establish effective policies and business models for initiating and growing markets in the industrial process, transport and heat sectors.

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