The Status of Hydrogen Technologies in the UK: A Multi-Disciplinary Review

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Abstract

Hydrogen has the potential to offer deep decarbonisation across a range of global heavy-emitting sectors. To have an impact on the global energy system, hydrogen technologies must be deployed with greater urgency. This review article facilitates the much needed, multi-disciplinary discussion around hydrogen. In doing so, the paper outlines recent advancements, prevailing challenges and areas of future research concerning hydrogen technologies, policy, regulation and social considerations in a UK setting. Findings suggest that hydrogen will play a significant role in decarbonising several UK sectors whilst simultaneously addressing challenges faced by alternative low-carbon technologies. Optimal production, delivery and storage systems must be developed to accommodate perceived future demand. Whilst this will be largely dictated by scale, efficiency, cost and technological maturity, significant improvements in existing policies and regulation will also be critical. The future role of hydrogen in the UK's decarbonisation strategy is not clearly defined. In comparison to alternative low-carbon technologies, policy and regulatory support for hydrogen has been minimal. Whilst there is growing evidence concerning the public perception of hydrogen in UK homes, additional research is required given its many potential applications. The findings detailed in this article support the urgency for further multi-disciplinary collaborative research.

Key Words: Hydrogen, Decarbonisation, Review, Multi-Disciplinary, Industrial Clusters

Abbreviations[1]

[1] ULEV: Ultra-low emission vehicle, HFC: Hydrogen fuel cell, BEV: Battery electric vehicle, HHV: Higher heating value, LHV: Lower heating value, WI: Wobbe Index, TRL: Technology readiness level, CCS: Carbon capture and storage, SMR: Steam methane reforming, PSA: Pressure swing adsorption, ATR: Auto-thermal reforming, POX: Partial oxidation, LCH: Low-carbon hydrogen, GHR: Gas heated reactor, PEM: Polymer exchange membranes, SOEC: Solid oxide electrolysis cells, LOHC: Liquid organic hydrogen carrier, PtX: Power to X, MOF: Metal organic framework, EU-ETS: EU Emission Trading System, R&D: Research and Development, NIC: Network innovation competition, HRS: Hydrogen refuelling station, LSIP: Large scale integrated projects, MoU: Memorandum of Understanding, FEED: Front-End engineering design, FID: Final investment decision, BEIS: Department for Business, Energy and Industrial Strategy

1. Introduction

In 2018, global CO_2 emissions peaked at 408.52ppm, which was the highest level observed in over 800,000 years [1]. Furthermore, global energy-related CO_2 emissions rose by 1.7% to a historic high of 33.1Gt as a result of greater energy demands [2]. Atmospheric warming attributable to anthropogenic emissions will persist for centuries to millennia and will continue to have long-term effects on the climate system [3]. To strengthen the global response to this issue, the Climate Change Act seeks to maintain a global temperature rise of well below 2°C with efforts to limit this even further to 1.5°C [4]. To align with the 1.5°C target, global emissions must decrease by 7.6% per annum between 2020-2030 [5]. This will require significant transitions in energy, land, infrastructure and industrial systems within a rapid timeframe [3]. Low-carbon hydrogen could play a major role in these decarbonisation efforts.

Hydrogen is a versatile fuel with net-zero end use emissions [6], which can be utilised to decarbonise numerous heavy emitting sectors like transport, industry and electricity and heat generation, which account for approximately 90% of global CO_2 emissions [7]. Other specific roles hydrogen could play in decarbonisation include:

- Enabling large-scale renewable energy integration and power generation
- Distributing energy across sectors and regions
- Acting as a buffer to increase energy system resilience [8].

The concept of using hydrogen as a substitute for conventional fossil-fuels can be tracked back decades. In 1977, Bockris envisioned a “system of industry, transportation, and household energy which depends on piped hydrogen as a fuel” and coined this the ‘hydrogen economy’ [9].

The global demand for hydrogen (74 million tonnes) is now more than triple that observed in 1975 [10]. At present, most hydrogen produced is fossil fuel dependent and carbon intensive. However, by 2050, low-carbon hydrogen could meet 18% of total energy demand, create 30 million new jobs and reduce 6Gt of CO_2 emissions per annum [8]. This equates to an annual demand approximately ten times larger than that observed at present. Therefore, low-carbon hydrogen production needs to proceed with greater urgency [11].

In the UK, there are many projects and initiatives seeking to demonstrate its potential, and subsequently create a market, for hydrogen production, storage, transmission and distribution and end-use technologies. Despite this, the role of hydrogen in the UK’s decarbonisation strategy remains undefined. Challenges faced for hydrogen span beyond those of a technical nature. Policy and regulatory barriers currently prohibit the advancement of hydrogen technologies. The potential social implications must also be understood and addressed.

A collaborative approach across numerous stakeholders and disciplines is pivotal to establishing a market for hydrogen. Despite the ever-increasing body of literature concerning hydrogen, there are few publications that address its wider context by incorporating research from multiple disciplines. Typically, research articles tend to focus on hydrogen technologies from one subject field, whether it be of a technical, social or policy nature. Whilst some articles do touch upon other disciplines, this is not pulled together in a multi-disciplinary manner. To address this existing literature gap, this article aims to review the status of hydrogen technologies in the UK and facilitate the much-needed wider discussion around hydrogen by adopting a multi-disciplinary approach. This article outlines recent advancements, prevailing challenges, and areas of future research in terms of hydrogen technologies, policy, regulation, and social considerations. To provide an overview of the progression of hydrogen technologies to date, a brief outline of the status of on-going hydrogen initiatives is also provided. To summarise, the importance of establishing global hydrogen markets is discussed with reference to international co-ordinated approaches.

2. The Case for Hydrogen in the UK

Since 1990, the UK has successfully reduced its territorial greenhouse gas emissions by 45.2%[2] [12]. This is mainly attributable to the decrease in coal used for power generation coupled with an increased volume of renewable electricity generation. [13]. In 2019, onshore and offshore wind, bioenergy and waste and solar photovoltaics accounted for 19.8%, 11.5% and 4% of total UK electricity generation. Overall, renewable electricity generation accounted for 37.1% of the total UK electricity generation [14]. Despite this, to achieve ambitious net-zero targets, the decarbonisation of heavy emitting sectors must be addressed and confronted urgently [15]. In comparison to other sectors, carbon dioxide emissions from the transport and residential (domestic) sector have shown minor reductions since 1990; see Figure 1. Despite displaying considerable emission reductions over time, the energy supply and business and industrial sector still contribute substantially to overall UK emissions. Hydrogen can act as a substitute for conventional fossil fuels across many sectors including industry, transport, buildings and power [3, 9, 16]. This section provides an overview of the premise and opportunities for hydrogen across various UK sectors.

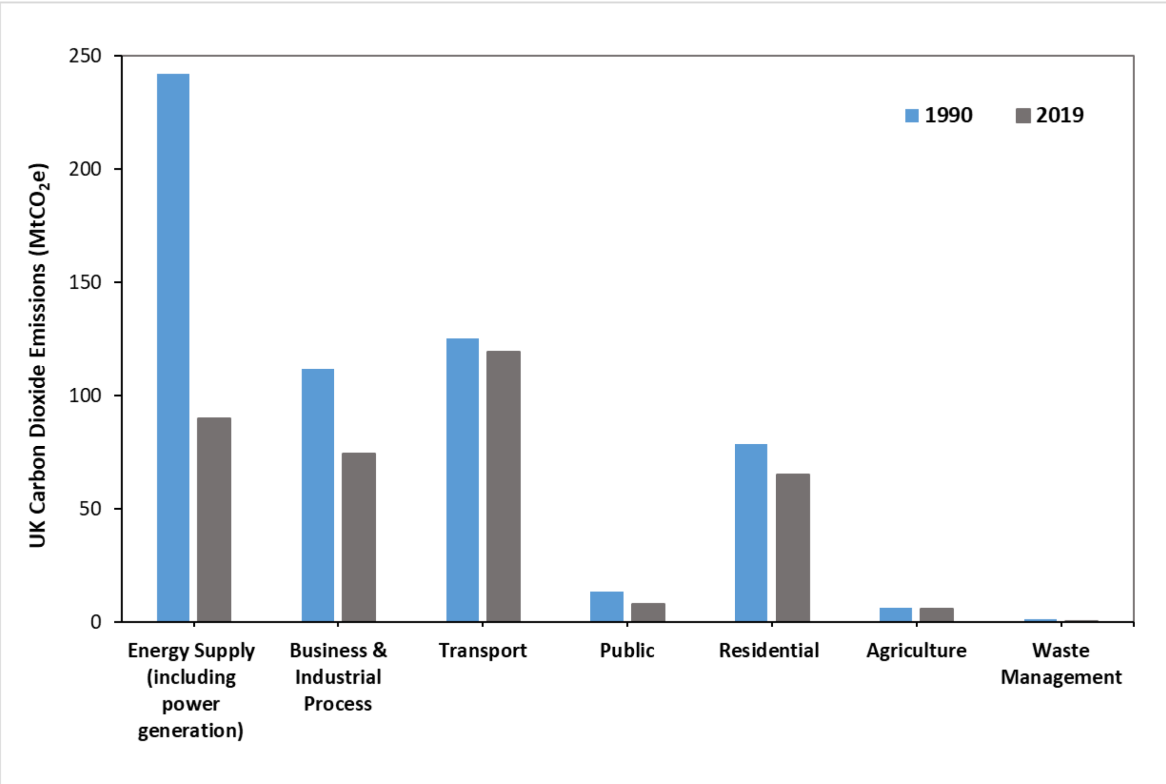


Figure 1 - Comparison of UK Carbon Dioxide Emissions per Sector in 1990 and 2019. Data Retrieved from [12]. [2 COLUMN FITTING IMAGE, COLOUR REQUIRED]. ****Plotted using data from Appendix A: Table A.1***

2.1 Transportation

Accounting for over one quarter of total UK CO_2 emissions [12], the transport sector requires urgent, large-scale decarbonisation. In 2011, UK government announced that conventional car and van sales would end by 2040, with almost every car and van to be zero-emission by 2050 [17]. More recently,

[2] This is a provisional estimate for 2019. Final data for 2018 showed a 43% decrease in emissions from 1990.

a consultation was launched to seek views on whether this should be brought forward to 2035, or earlier, if feasible [18]. To tackle emissions in this sector, ultra-low emission vehicles (ULEVs) could be widely deployed. By definition, ULEVs are vehicles which emit less than 75g CO_2 from the tailpipe, per kilometre travelled. As a result of recent technological advancements, this is expected to be modified to less than 50g CO_2 from 2021 onwards [19].

2.1.1 Applications of Hydrogen Vehicles in the Transport Sector

Hydrogen fuel cell (HFC) vehicles, a type of ULEV, convert chemical energy into electrical energy using hydrogen and oxygen as reactants. The electrical power generated is supplied to the vehicle traction motor which initiates motion [20]. The tail pipe products from this reaction are water vapour and excess heat. Alongside emission reduction advantages, HFC vehicles also have health benefits due to the avoidance of air pollutants like those emitted by conventional petrol and diesel engines [21].

In comparison to alternative modes of low-carbon transport, HFC vehicles can address existing challenges such as land-use, air quality impacts, limited range and driving times [22]. They have received attention due to their long fuel range (approximately 500km) and short refuelling time (approximately 3 minutes) [23]. Furthermore, they can serve niche applications where vehicles are required to return to the same location for refuelling and require minimum refuelling time to avoid loss of earnings [24]. This could encompass vehicles such as buses, trains, forklifts, heavy-goods vehicles, ships and aviation applications.

2.1.1.1 Cars and Light Goods Vehicles

In 2018, the total number of first-time vehicle registrations of ULEVs in the UK was 63,991. In comparison to 2010, this is an increase of over 5000% [25]. Despite HFC vehicles being commercially available in the UK, battery electric vehicles (BEVs) currently dominate the ULEV market. From an economic stance, this is likely because they exhibit a price range similar to conventional petrol or diesel vehicles [26]. Despite providing a longer driving range and significantly shorter refuelling times than BEVs, HFC vehicles currently exhibit significantly higher capital costs [27]. Furthermore, there are only 16 operational hydrogen refuelling stations (HRSs) in the UK with only a further 3 planned [28]. Therefore, there are significant, nation-wide infrastructure requirements to allow HFC market progression.

2.1.1.2 Buses

If public transport usage increases by 2050, there will be a smaller requirement for electric vehicles on the road. This could help decrease transport emissions as well as indirectly mitigate against increases in congestion and accidents [29]. HFC buses have been successfully demonstrated in London since 2003. Initially, these buses had a range of only 125 miles [30]. Studies have shown that BEV buses are most efficient for short range journeys whereas HFC buses are best suited for long ranges [31]. In stage 2 of the UK Hydrogen for Transport Programme, £14m was awarded to numerous projects across the UK. The combined contribution of these projects includes 5 HRSs and 33 fuel cell electric buses [32]. More recently, Wrightbus unveiled plans to convert up to 10% of the UK bus fleet to zero-emission models. This will include up to 3,000 'Metrodecker' hydrogen fuel cell buses, which can carry more than 90 passengers and have a driving range between 200-250 miles [33].

2.1.1.3 Trains

In 2019, the UK's first train to be powered by hydrogen performed a test run. The HFC train, developed by engineers from University of Birmingham and Porterbrook, comprises hydrogen fuel tanks, a fuel cell and lithium batteries. This provides enough power for the train to travel 50-75 miles [34]. In the North West of the UK, Alstom are investigating the potential to convert Class 321 trains to run on hydrogen. This project could see hydrogen powered trains on UK rail infrastructure from 2021 [35]. Alstom have already successfully demonstrated hydrogen trains in Germany with the Coradia iLint.

2.1.1.4 Medium and Heavy-Duty Trucks

In the last 20 years, the freight industry has exhibited considerable economic growth, particularly concerning heavy-duty trucks. Trucks are competitive with other freight power-trains because of their ability to deliver directly to the desired destination in a short time [36]. The majority of medium-heavy duty trucks still run on diesel fuel and have negative environmental impacts in terms of emissions and air quality [37]. BEVs may not offer the required range to complete journeys without stopping and recharging [38]. This makes HFC trucks an attractive low-carbon option. One study found that HFC trucks could reduce well-to-wheel petroleum energy use by 98% and air emissions by 20-45% in comparison to diesel counterparts [37]. Despite being a key area of research, further R&D is required for HFC trucks to become commercially available [36].

In the short-term, dual fuel combustion engines that can operate on both hydrogen and diesel could prove to be a competitive technology. These are already commercially available [39], and could act as an economical bridge solution for sustainable heavy-duty freight with notable emission reductions [36].

2.1.1.5 Maritime Applications

Emissions from international shipping cannot be ignored [15]. In UK territorial emission calculations, international shipping is not included [12]. However, it is estimated that shipping activities contribute to approximately 3-5% of global CO_2 emissions whilst, simultaneously, emitting particulate matter (PM) and other hazardous air pollutants [40]. For the commercial maritime sector, HFC technologies are still at the investigation and demonstration phase [41]. Hydrogen also has the potential to be utilised in the maritime sector as a direct fuel, but this ultimately depends on the capability on producing clean, low-cost hydrogen. One study found that hydrogen fuelled transoceanic tankers emit approximately 0.98g CO_2 per tonne-kilometre in comparison to approximately 5.33g per tonne-kilometre CO_{2e} emitted from conventional heavy fuel oil tankers [42].

2.1.1.6 Aviation

Approximately 2.5-5% of global energy is consumed by the aviation industry [43]. Similar to international shipping, international aviation emissions are exempt from UK territorial emissions [12]. The international aviation sector is expected to grow due to greater demands for air transport [44]. Therefore, CO_2 emissions will continuously increase unless decarbonisation measures are adopted. Many challenges are left to address before hydrogen technologies are commercially deployed within the aviation sector. These include:

- The lack of infrastructure to provide hydrogen fuel for an energy carrier in the aviation industry
- The required alterations to aircraft design and airport operations
- The longer refuelling time of hydrogen in comparison to conventional aircraft fuels

- The specific demand for high quality hydrogen to prevent efficiency reduction and catalyst poisoning within fuel cell systems
- The low power densities of fuel cells [43]
- The requirement for further studies on load, structure and aerodynamics due to the large volumes of hydrogen tanks [45].

2.1.1.7 Material Handling

Material handling equipment is an emerging market for HFC technologies. Examples of machinery include: counterbalanced forklifts, narrow aisle lift trucks, pallet jacks, and stock pickers [46]. Equipment could be deployed in food and retail distribution centres and manufacturing facilities [47]. HFCs can address problems exhibited with battery powered equipment such as the need for frequent battery charging and cool-down [46]. In the United States, more than 20,000 hydrogen fuel cell forklifts are operational [21]. Further information concerning the technical performance of hydrogen fuel cells in material handling equipment can be found at the following sources: [48-50].

2.2 Domestic Sector

In the UK, the domestic sector accounts for approximately 15% of total UK emissions [13]. Of all fuels supplied to this sector, natural gas accounts for approximately 65% of the total share [51]. Primarily, this is used for space and water heating. Continuing to match heating demands with large quantities of natural gas is incompatible with emission reduction targets unless alternative forms of low-carbon heating are adopted [52].

Heat pumps powered by renewable electricity could provide part of this solution. They are thought to be a feasible option for new buildings which are well insulated and where low temperature heating through the floor is possible [53]. However, most buildings are not compatible. Heat pumps face other challenges in terms of the capacity of existing electricity markets and the mismatch of available renewable energy; see Table 4 [54]. To explain further, Figure 2 shows the daily demand for natural gas in comparison to electricity and how much this varies across seasons. Approximately two thirds of this natural gas demand is used for space and water heating [55]. To address this heat demand utilising heat pumps, there would need to be a substantial increase in electricity generation capacity and storage [52]. Furthermore, as is the case for all electric technologies, the electricity utilised must be generated from a low-carbon source to have a carbon benefit.

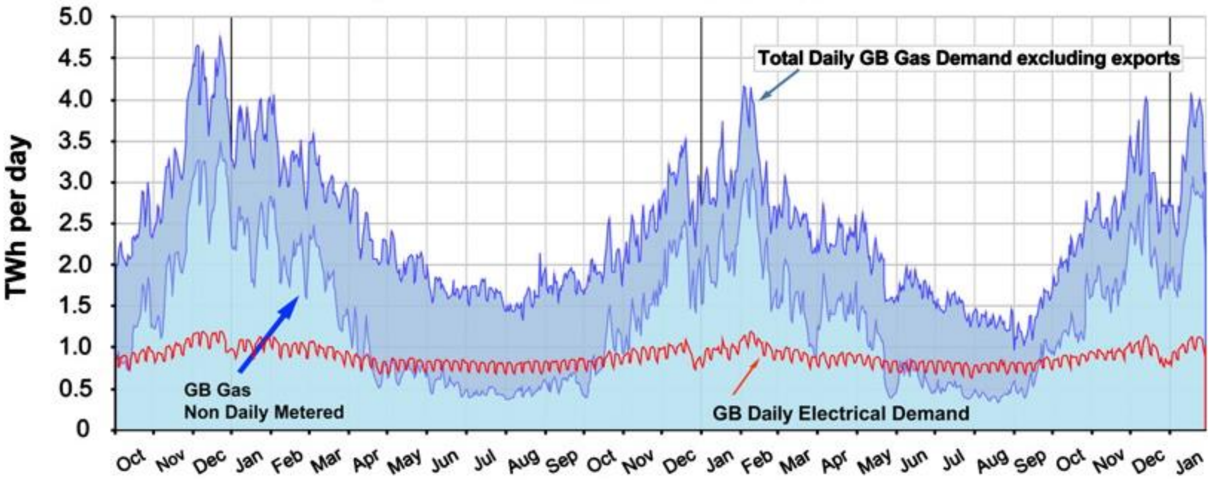


Figure 2 - Daily GB Gas and Electricity Demands (TWh). Retrieved from [55]. [2 COLUMN FITTING IMAGE, COLOUR REQUIRED].

Low-carbon hydrogen could also provide part of this solution, with potential to be produced at volumes sufficient to accommodate future heat demand [16]. A study conducted by KPMG identified that the incremental cost for an electric future (£274-318bn) to meet UK heat and energy demand would be nearly triple that of one with hydrogen as a primary fuel source (£104-122bn) [56]. Please note that since this study was conducted, there have been developments in energy storage, electric vehicles and distributed generation technologies [57]. Furthermore, costs observed for renewable energy technologies have reached record lows [58]. In a modern setting, both factors could have implications on these conclusions drawn. For a brief overview of the advantages and disadvantages of other low-carbon heat options see Table 1.

	Advantages	Disadvantages
Demand Reduction	+ Low regret option + Energy bill reductions + Insulation and more efficient devices to raise customer awareness	- Low turnover rate of building stock - Difficulty retrofitting existing buildings - Lack of concern from customer
Heat Networks	+ Proven and widely used in some countries + Good option for new builds and densely populated regions + Could meet approximately 10-20% of UK heating needs	- High conversion cost and disruption - Low-carbon heat sources required - Heat cannot be transported long distances
Onsite Renewables	+ Utilise local energy sources + Reduces network dependence and therefore minimises upgrade requirements to network	- Limited availability of renewables - Less cost-effective for small schemes

Table 1 - Advantages and Disadvantages of Low-Carbon Heating Technologies. Retrieved from [22].

2.2.1 Further Considerations for Hydrogen

A study was conducted to assess the development of a hydrogen-fired supply chain in the UK [59]. It found that capital equipment costs for hydrogen-fired appliances could be 4x higher than existing natural gas appliances, for the first 1,000 units installed. At 100,000 units, this could reduce 1.5x higher. In addition to economic barriers, other technical and market barriers identified are shown below:

Technical Barriers

- Specific designs for hydrogen appliances are limited in number
- Specific standards for the design of hydrogen appliances do not exist
- Burner technologies may not exhibit the same level of control or flame stability as natural gas alternatives
- Risk of flashback
- NOx emissions may be present at high temperatures without the use of catalysts
- Larger sized appliances may be needed due to hydrogens lower energy density than natural gas
- Suitable odorants have yet to be identified
- Standards for hydrogen purity have yet to be identified
- Currently there are no standards for installation of domestic hydrogen appliances

Market Barriers

- Lack of confidence in safe operation of appliances
- Lack of consumer awareness of the benefits of hydrogen
- Commercial boiler and catering market may be of lower interest to

manufacturers as is a smaller sector compared to the domestic and industrial sector	• Considerable investment in infrastructure is required for product development which requires policy direction.

With regard to suitable hydrogen odourants, the following mixtures are under consideration: 78% tert-Butylthiol (TBM) and 22% dimethyl sulphide (DMS)[3], 34% new blend and 64% hexane, 100% trinitrotoluene (TNT) and, specifically for fuel cell applications, 100% 5-ethylidene-2-norbornene [60]. Concerning hydrogen purity, the draft standard shown in Table 2 has been proposed.

Content or Characteristic	Value
Hydrogen Fuel Index (Minimum Mole Fraction) (%)	98
Carbon Monoxide (ppm)	100
Hydrogen Sulphide Content (ppm)	<3.5
Total Sulphur Content (ppm)	<35
Oxygen Content (%)	<0.2
Hydrocarbon Dewpoint (°C)	-2
Water Dewpoint (°C)	-10
Sum of Methane, Carbon Dioxide and Total Hydrocarbons (%)	<1
Sum of Argon, Nitrogen and Helium (%)	<2
Wobbe Number Range (MJm^{-3})	42-46

Table 2 - Draft Hydrogen Purity Standard Proposed in Work Package 2 of Hy4Heat Programme. Retrieved from [61].

If hydrogen is supplied, preliminarily as a blend with natural gas to UK households, this will change the thermo-physical properties of the existing gas supply, which may affect appliances. The injection of hydrogen into natural gas has been shown to lower the higher heating value (HHV), lower heating value (LHV) and Wobbe Index (WI) of the resultant gas mixture [62], which reduces the thermal energy supplied to end-consumers. Further properties to consider include flame characteristics, appliances performance, combustion noise, burner temperature and emissions [63]. For further technical assessments of hydrogen and natural gas mixtures please refer to the following sources: [63-66].

2.3 Industrial Sector

Natural gas is most commonly consumed within industry as a raw material or heat source and accounts for approximately 49% of the total fuel mix supplied [51]. Hydrogen can be utilised to help decarbonise emissions attributable to natural gas consumption. Evidence suggests that hydrogen could have an important role in decarbonising industrial heat in furnaces and kilns as well as industrial processes where sources of CO_2 emissions are more distributed making carbon capture costly and impractical [67].

One UK study found that up to 30% of fuel consumed in energy-intensive processes could be matched by fuel switching. This could reduce CO_2 emissions by 16Mt per annum [68]. Of the low-carbon fuels analysed, hydrogen exhibited the highest technical potential. This was followed by biomass, waste materials and electricity. Despite this, hydrogen is not a ‘silver bullet’ for all processes, and in some cases, alternative fuels may be more appropriate. Another study assessed the appliance conversion cost of specific hydrogen-fired equipment in addition to its current technology readiness level (TRL) [69]; see Table 3.

[3] Also referred to as new blend.

Hydrogen-Fired Appliance Type	TRL	Example Equipment	Applicable Sector	Appliance Conversion Cost (£m)
Boiler	7	5MW Steam Boiler	Food and Drink	0.45
		10MW Steam Boiler	Chemicals	0.64
		5MW Steam Boiler	Paper and Pulp	0.49
		1.5MW Hot Water Boiler	Elec & Mech Engineering	0.22
Kiln	4	2MW Kiln	Ceramics	0.24
		10 MW Lime Kiln	Lime	0.52
		10MW Furnace	Chemicals	0.84
Furnace	5	20MW Furnace	Metals	1.11
		20MW Glass Furnace	Glass	1.21
		1MW Oven	Food and Drink	0.15
Oven/ Dryer	4	2MW Oven	Vehicles	0.21
		10MW Rotary Dryer	Minerals	0.43

Table 3 - TRL and Appliance Conversion Costs for Various Hydrogen- Fired Equipment – Retrieved from [69].

Under the UK Industrial Fuel Switching Programme, there are several on-going demonstration projects working to test the feasibility of hydrogen in industrial processes such as cement production, glass manufacturing, oil refining, beauty products manufacturing and calcium lime manufacturing [70]. For further information concerning alternative low-carbon fuels for industrial fuel switching, please refer to the following sources: [71-74].

2.4 Power Generation

Low-carbon electricity generation, including nuclear, accounts for nearly 53% of total electricity generation in the UK [75]. From this share, renewable sources account for 62%. Two of the National Grid's Future Energy Scenario's conclude that UK electricity grid capacity must increase by over 100% by 2050. Renewables are expected to account for the largest generation capacity [76]. At present, the intermittent availability of renewables presents problems as it varies significantly across seasons; see Table 4.

Generation (GWh)	1st Quarter 2018	2nd Quarter 2018	3rd Quarter 2018	4th Quarter 2018
Onshore Wind	2370	1320	1291	2298
Offshore Wind	6948	4270	4350	7550
Solar PV	1569	4323	3996	1387

Table 4 - Quarterly Generation of Renewable Electricity in 2018 – Data Retrieved from [14].

Because renewable generation technologies cannot be controlled like thermal and nuclear power generation facilities, fossil-fuel resources are often required as reserve fuels to balance electricity supply and demand [77]. Most commonly, this demand is met by natural gas power generation plants. There is opportunity for hydrogen to cost-effectively replace natural gas back-up measures [67], and complement other low-carbon sources in the UK's ever increasing diversified electricity generation mix. Examples of future hydrogen power generation technologies include gas turbines [78-80] and stationary fuel cell systems [81-83].

3. Hydrogen Technologies

3.1 Hydrogen Production

At present, at least 96% of global hydrogen is produced from fossil fuel processing such as steam methane reforming (48%), coal gasification (18%) and the partial oxidation of oil (30%) [84]. Only 4% is produced through electrolysis. Out of the total global consumption of gas and coal, hydrogen production accounts for 6% and 2% respectively. In terms of emissions, this equates to approximately 830Mt of CO_2 per year [10]. Table 5 depicts the CO_2 emissions associated with various fuel types, which can be utilised in hydrogen production.

Fuel Type	CO_2 Emissions (kg/kWh)	CO_2 Emissions Relative to Natural Gas
Natural Gas	0.20	1.00
Fuel Oil	0.28	1.40
Hard Coal (Anthracite)	0.34	1.70
Brown Coal (Lignite)	0.36	1.80
Wood	0.39	1.95

Table 5 - Comparison of Carbon Dioxide Emissions from Various Fuel Types – Adapted from [85].

Low-carbon hydrogen production from conventional fuels is possible with carbon capture and storage (CCS) technology and is commonly referred to as 'blue' hydrogen. For low-carbon hydrogen production, CCS is critical to avoid an overall net increase of CO_2 emissions [24]. Whilst CCS technologies fall out of scope of this article, further information can be found at the following sources: [86, 87]. Another form of hydrogen is 'green' hydrogen, which utilises renewable energy sources in its generation process.

In the Net-Zero technical report, the Committee on Climate Change (CCC) proposed a hydrogen scenario which claimed that UK hydrogen production must reach 270TWh per year to reach 2050 targets [16]. At present, UK hydrogen production amounts to approximately 27TWh per year from approximately 15 sites [84]. Therefore, to meet the required scale, production must increase by a factor of 10 within the next 30 years. It is envisioned that as much as 63% of future hydrogen could be produced through reforming with the remaining 37% supplied from electrolysis [16]. For this reason, this section focuses mainly on reforming and electrolysis. Biomass gasification and nuclear assisted hydrogen production are briefly highlighted as alternative low carbon technologies which may have a role in future UK hydrogen production. It is important to note that there are a wide range of hydrogen production technologies discussed throughout the literature which are not encompassed within this article. A holistic overview of these technologies can be found in the following articles: [88-92].

3.1.1 Steam Methane Reforming (SMR)

SMR technology has been implemented across industry since 1930 and is the most common hydrogen production process. With approximately 500 plants in operation globally [93], SMR dominates hydrogen production due to its mature status and ability to operate at near maximum theoretical limits [94]. Compared to alternative reforming technologies, like partial oxidation, SMR theoretically possesses the largest mole fraction of hydrogen in its product gas [95]. In this process, methane is mixed with steam and fed into a tubular reactor at temperatures of approximately 700°C and pressures of approximately 35 bar [88]. As a result, syngas (a mixture of CO and H_2) is generated. This reaction is endothermic, and the required external energy input is supplied by natural gas. Following this, the resultant syngas normally undergoes two further water shift reactions: one at approximately 350-475°C and the other at 200-250°C. The shifted syngas undergoes hydrogen purification (normally pressure swing adsorption (PSA)) where purities of up to 99.999% can be obtained [96-98]. To obtain a suitable H_2/CO_2 ratio, the tail gas from the PSA is often recycled to the reforming reactor [99]. On average, the energy requirement for SMR is approximately 46 kWh/kg H_2 which equates to approximately 30-35% of the total natural gas used for the process fuel [22, 88]. The stochiometric equations for steam methane reforming are shown below [96]:

Steam Methane Reforming Reaction:

$$\mathrm{CH_4 + H_2O \leftrightarrow CO + 3H_2} \quad \Delta\mathrm{H}^{\circ} = 198\ \mathrm{kJ\ mol^{-1}} \tag{1}$$

Water Gas Shift Reaction:

$$\mathrm{CO + H_2O \leftrightarrow CO_2 + H_2} \quad \Delta\mathrm{H}^{\circ} = -41\ \mathrm{kJ\ mol^{-1}} \tag{2}$$

3.1.2 Auto-Thermal Reforming (ATR)

Originally, this process was developed to perform partial-oxidation (POX) and SMR in one single reactor. By combining these processes, ATR addresses the issue of low hydrogen yield associated with POX and the slow start-up and response times associated with SMR [100]. In this process, natural gas and steam are mixed with oxygen and/or air. Differing from SMR, the energy required to drive the reaction is supplied from oxygen as opposed to natural gas [101]. Like SMR, the resultant syngas undergoes water gas shift reactions and the hydrogen is separated using PSA. Operating at higher temperatures and pressures than SMR, ATR produces higher pressure syngas at a lower steam to carbon ratio. The reduced steam requirements improve overall process efficiency. Furthermore, high pressure hydrogen, in the syngas, reduces the requirement for additional downstream hydrogen compression [102].

3.1.2.1.1 Low-Carbon Hydrogen (LCH)

The LCH system, coined by Johnson Matthey, differs from the traditional ATR system by coupling the ATR reactor with a gas heated reactor (GHR) [103]. In this process, natural gas undergoes an initial reforming reaction with steam in the GHR prior to entering an ATR unit. This then reacts further with pure O_2 in the ATR unit, where the final reforming reaction takes place. Resultant syngas travels back through the GHR to provide heat for the initial reforming reaction before undergoing water gas shift reactions and PSA for hydrogen separation [101]. Though CCS falls out of scope of this article, it is important to note that LCH technology can capture a greater percentage of carbon than SMR [11]. For further information, please refer to the following source: [104].

3.1.3 Electrolysis

Electrolytic hydrogen production systems consist of two electrodes which are separated and submerged into an electrolyte which allows a current to flow. Water and electricity are used as feedstocks. Water is separated into hydrogen and oxygen as a result of the direct current [105, 106]. Across the literature, alkaline, polymer exchange membranes (PEM) and solid oxide electrolysis cells (SOEC) are analysed most and will therefore be the only electrolytic systems reviewed in this article. To produce 'green' hydrogen from electrolysis, the electricity supplied must have been generated from renewable energy sources.

3.1.3.1 Alkaline Electrolysis

Alkaline electrolysis is the most mature of the three. The largest plant observed a production rate of approximately 1,200kg H_2 per hour however this is currently mothballed [107]. Despite this technology being widely commercialised, it has several drawbacks in comparison to alternative electrolytic systems such as low gas purity, low operational pressures and higher energy consumption [108]. As a result of low operational pressures, additional hydrogen compression is required for downstream applications.

3.1.3.2 Polymer Exchange Membrane Electrolysis

Compared to alkaline electrolysis, PEM systems can operate at higher pressures. Furthermore, they exhibit rapid dispatchability and turn down times and have the capability to operate under a wide range of dynamics, making them better suited for coupling with renewable energy sources for low-carbon hydrogen production [109]. Though still in the early stages of market penetration, PEM systems are expected to achieve hydrogen production in the giga-watt magnitude in coming years [110]. This will be subject to addressing commercial barriers such as high production costs associated with electrode construction materials and efficiency maintenance over the life-cycle of the technology [108]. Further research into catalyst and membrane materials is encouraged to enable the cost-effective, wide-spread application of this technology [111].

3.1.3.3 Solid Oxide Electrolysis Cells

Though still operating at a lab-scale capacity (10kW to 100kW) [107], SOECs have received increased attention due to their capability to operate at higher temperatures than other electrolytic systems. This warrants the opportunity for such systems to be integrated into industrial processes which produce large volumes of waste heat [108]. Other advantageous characteristics include the potential to act in reverse mode (as a fuel cell) and the potential to be utilised in co-electrolysis to produce syngas [112]. Challenges such as poor long-term cell stability and material problems have prohibited the wide-application and commercialisation of these cells [113]. Further information concerning the technical parameters of each electrolytic system is shown in Table 6.

Technical Parameter	Alkaline	PEM	SOEC
Temperature (℃)	60-80	50-80	650-1000
Pressure (bar)	<30	<200	<25
Cell Area (m^2)	<4	<0.3	<0.01
System Energy Consumption (kWh_{el}/Nm^3_{H2})	4.5-6.6	4.2-6.6	>3.7
H_2 Production Rate (Nm^3/h)	<760	<40	<40
H_2 Purity (%)	>99.5	99.99	99.9
Stack Lifetime (h)	60000-90000	20000-60000	<10000

Efficiency (%)	56-79	55-69	88-105% [114]
Cold Start Time (min)	<60	<20	<60

Table 6 - Typical Operating Parameters of Alkaline, PEM and SOEC systems [115, 116].

3.1.3.4 Power to X (PtX) Systems

In future, electrolysis could enable the coupling of the electricity, chemical, mobility and heating sectors through PtX systems [117]. Such systems consist of the conversion of renewable electricity, through electrolysis, into valuable, low-carbon gases, fuels and chemicals. Whilst this falls out of scope of this review article, further information can be found at the following references: [118-121].

3.1.4 Alternative Low-Carbon Hydrogen Production Technologies

This section explores hydrogen production technologies which, in future, could be suitable in a UK setting.

3.1.4.1 Biomass Gasification

Biomass gasification is the thermochemical conversion of biomass into syngas through a gasification medium such as air, oxygen and/ or steam [88]. Typically, gasification reactions occur at temperatures above 700 °C [89], and exhibit efficiencies of approximately 44-48% [22]. Prior to undergoing water gas shift reactions and hydrogen separation, similar to reforming processes, an extra step is often required to reform additional hydrocarbons still present in the syngas [122].

At present, there are many operational facilities which produce heat and/or power using biomass gasification, which could give rise to hydrogen production capabilities [123]. If combined with CCS technology, hydrogen production from biomass gasification has the potential to be carbon negative. This is referred to as bioenergy with carbon capture and storage (BECCS). It is envisioned that by 2050, global deployment of BECCS technology could result in the removal of up to 16Gt CO_2 per year [124]. Though, this is accompanied by a loss in process efficiency and additional CAPEX and OPEX in comparison to alternative reforming technologies [125].

3.1.4.2 Nuclear Assisted Hydrogen Production

Nuclear radiation energy from fission and fusion reactors can provide process steam, sensible heat and/ or electricity required to power various hydrogen production technologies. Radiation energy can be converted into high temperature heat for thermal hydrogen production or used to generate power for electric hydrogen production [126]. Out of the several possible hydrogen production technologies, electrolysis and thermolysis show the most potential [127]. Thermolysis encompasses the thermo-chemical splitting of water and is carried out using thermo-chemical cycles such as sulphur-iodine, hybrid copper-chloride and sodium-manganese.

3.1.5 Economic Considerations of Hydrogen Production Technologies

Figure 3 shows the results of a basic economic analysis performed on the hydrogen production technologies discussed throughout this article. The average cost of hydrogen (£$_{2019}$/kg) and CAPEX (£$_{2019}$/kW) were calculated. All data was collected from sources analysed throughout this section. Further information concerning the methodology, conversion factors and data used can be found in

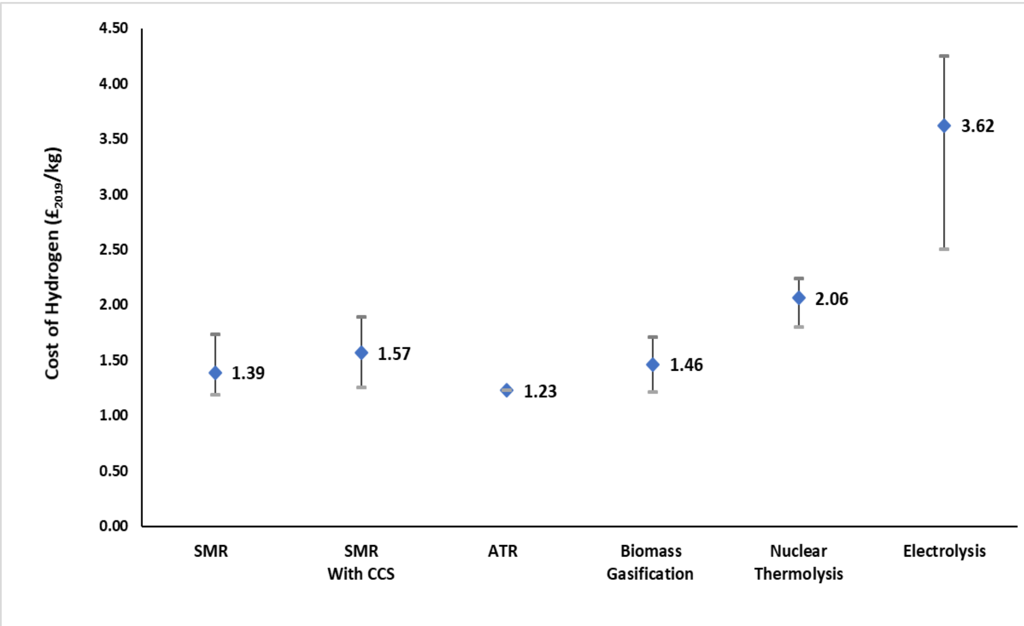
Appendix B as well as an overview of the specific process units incorporated within overall CCS cost assessments.

3.1.5.1 Cost of Hydrogen

The lowest average cost of hydrogen was from ATR, followed by SMR. Electrolysis showed the greatest hydrogen production cost. These results are expected as electricity is the most expensive feedstock [93]. There was insufficient economic data available for biomass gasification with CCS and LCH technologies. For this reason, these technologies were not included in this analysis.

3.1.5.2 CAPEX

With respect to CAPEX, biomass gasification was most expensive, especially with CCS. SMR exhibited the lowest cost. However, this process is not low carbon. To avoid an overall net-increase in CO_2 emissions from future hydrogen production, CCS is critical. Biomass gasification and nuclear assisted hydrogen production showed the greatest variation of data throughout the literature. This is most likely due to the immaturity of these processes in comparison to SMR where accurate values can be obtained. There was insufficient economic data available for LCH and LCH with CCS; with only one value calculated for each. For this reason, these technologies were not included in this analysis. These values are located in **Appendix B: Table B.3.**



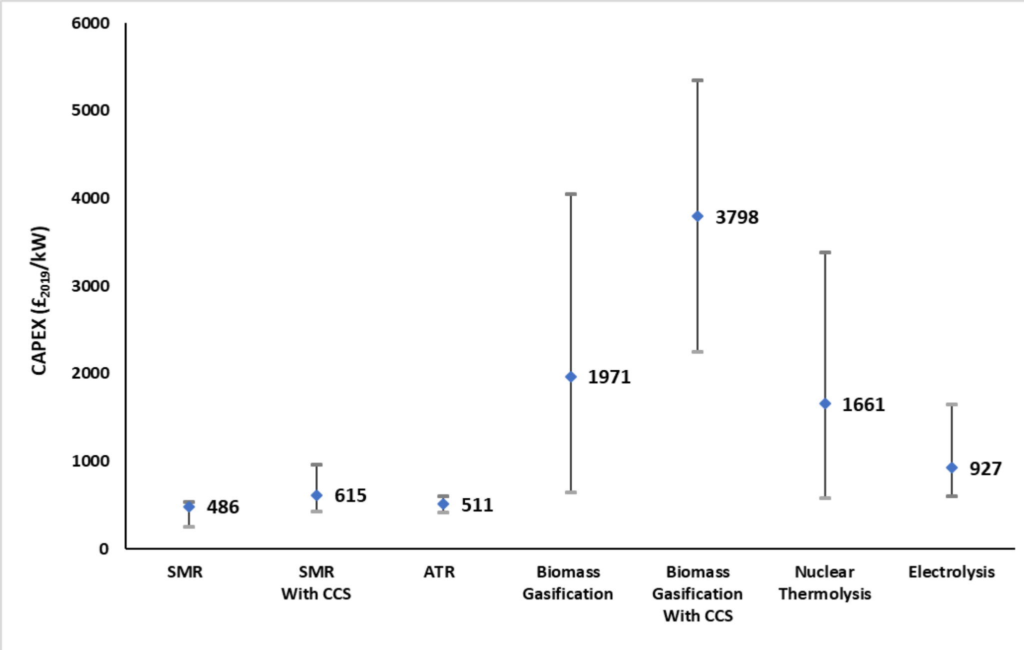


Figure 3 - Average Cost of Hydrogen and CAPEX for Various Hydrogen Production Technologies from Sources Analysed through Article. [2 COLUMN FITTING IMAGE, COLOUR REQUIRED].

3.2 Hydrogen Storage

As demand for hydrogen increases, it is vital that an array of hydrogen storage mechanisms are available to accommodate the volume of hydrogen production [128]. Characteristics such as volumetric density, required energy input and efficiency of operation govern the desirability of storage technologies [129]. This section provides an overview of several hydrogen storage mediums which are discussed most frequently throughout the literature.

3.2.1 Challenges with Hydrogen Storage

Gravimetric energy density refers to the amount of energy stored within a given mass and volumetric energy density refers to the amount of energy stored within a given volume. As shown in Table 7, hydrogen has a considerably greater gravimetric energy density than alternative fuels. However, the mass of hydrogen per given volume is lower than natural gas and gasoline. Because of its low volumetric energy density, hydrogen storage options typically require large volume systems [130].

Characteristic	Hydrogen	Natural Gas	Gasoline
Lower heating value, LHV (MJ/kg)	119.96	47.13	43.44
Higher heating value, HHV (MJ/kg)	141.88	52.21	46.52
Density at 20°C, 1atm (kg/m^3)	0.08	0.65	4.40
Liquid Density (kg/m^3)	70.8	422.8	700.0

Table 7 - Comparison of Characteristics of Conventional Fuels [131, 132]

3.2.2 Physical Hydrogen Storage

To increase the density of hydrogen from that exhibited in standard conditions, there are numerous options such as compression, liquefaction and a combination of the two. The typical conditions of each of these and associated densities are outlined in Table 8. This is referred to as physical storage.

Physical Hydrogen Storage Type	Pressure (bar)	Temperature (℃)	Density (kg/m^3)
CGH_2	300	15	23
CGH_2	700	15	41
LH_2	1	-253	70
CcH_2	300	-23.5	80

Table 8 - Density of Hydrogen for Various Types of Physical Hydrogen Storage Where CGH2 = Compressed Gaseous Hydrogen, LH2 = Liquid Hydrogen and CcH2 = Cryo-compressed Hydrogen [133].

3.2.2.1 Compressed Gaseous Hydrogen (CGH_2)

Hydrogen compression can be achieved using reciprocation compressors which display a maximum operating pressure of approximately 1,000 bar. In theory, rotary displacement machines could also be utilised though this is not common practice [128]. At present, compressed gas is the most well-established hydrogen storage medium [134]. Typically, storage vessels for gaseous hydrogen have a working pressure of 200-300 bar for stationary applications and 700 bar for automotive applications [135]. Compressed storage systems have distinct advantages for the automotive sector as they possess the ability to rapidly refuel vehicles in approximately 3-5 minutes [136]. However, with additional pressure allowances, weight and cost penalties are incurred.

3.2.2.1.1 Salt Caverns

For large scale gaseous hydrogen storage, salt caverns could provide an energy storage capacity within the 100GWh range, geometrical volumes of up to 700,000m^3 and working pressures of approximately 200 bar [137]. Salt cavern storage could be utilised to balance fluctuations in hydrogen demand whilst acting as a power store for the regeneration of electricity from intermittent renewable energy sources [138]. This storage vector is desirable due to low construction costs, low leakage rates, fast withdrawal and injection rates and minimal risks of hydrogen contamination [139].

3.2.2.2 Liquid Hydrogen (LH_2)

Liquid hydrogen is a preferred option for high purity, bulk hydrogen storage due to its higher density than gaseous alternatives [136]. However, the liquefaction process is considerably more energy intensive. This is because of the low boiling point of hydrogen (-253°C at 1 bar) and the requirement for pre-cooling of the liquefaction process [139]. Despite liquefiers being commercially available, this process is only recommended for large-scale systems to limit efficiency losses [128]. Liquid hydrogen also has additional safety challenges. If leakage occurs with gaseous hydrogen, it will rise in air and dissipate quickly due to differences in buoyancy where-as liquid hydrogen will freeze surrounding air and accumulate at ground level [140]. Liquid hydrogen is best suited for circumstances where high-energy density is required and boil-off is less of a concern [134].

3.2.2.3 Cryo-compressed (CcH_2)

CcH_2 systems exhibit higher hydrogen density in comparison to CGH_2 and LH_2 and are recognised as a promising storage vector. Most commonly, the performance of cryo-compressed hydrogen has been assessed for automotive applications [141-143]. The most discussed system throughout the literature is the 'Gen-3 cryo-compressed H_2 storage tank system' for which further information can be found at the following source: [144]. Recent research for CcH_2 systems has shown a 91% improvement in gravimetric capacity and a 21% lower system cost [141]. One advantage of the CcH_2 system is the increased dormancy period within the storage vessel. This means that hydrogen can be stored in cryo-compressed conditions without evaporation losses for longer time periods than alternative options [144]. Technical components concerning each physical storage method mentioned are shown in Table 9.

Storage Type	Energy Demand - *for Conversion from Ambient Conditions* (kW/kg H_2)	Overall Efficiency (%)	Vessel Material/ Design	Volumetric Density[4] (MJ/L)
Compressed Gaseous Hydrogen	2.23 (300 bar) [145]	52 (approx. 20% of energy from initial hydrogen supplied) [145]	Steel Cylinders [146]	2.9-4.9 [146] [134]
	3.00 (700 bar) [145]	49 (approx. 20% of energy from initial hydrogen supplied) [145]	Composite Tanks (Generally Carbon Fibre with Polymer Liner) [147]	2.9- 4.9 [146] [134]
Liquid Hydrogen	10.00 [148]	30-40 (approx. 40% of energy from initial hydrogen supplied) [149]	Steel vessel with double hull with vacuum between inner and outer vessel to avoid increased evaporation [146]	6.4 [134]
Cryo-Compressed Hydrogen	8.20 [150]	33 (based on 52% compression efficiency and 64.3% vessel efficiency) [150]	Gen-3 cryo-compressed H2 storage tank system [150]	4.0 [150]

Table 9 - Outline of Technical Components of Various Physical Hydrogen Storage Options.

3.2.3 Material-Based Hydrogen Storage

Most material-based hydrogen storage systems are in the early stages of development and face challenges such as high process costs and long charging/ discharging times [133]. For this reason, several technologies will be referenced to highlight potential future storage technologies but will not be discussed in as much detail as the physical storage systems.

Despite these drawbacks, material storage systems do have clear advantages in terms of safety. For example, hydrogen does not readily discharge from storage materials thus eliminating some of the safety implications previously highlighted. Furthermore, they have high storage densities which range from 70-150kgH_2/m^3 [133]. This is considerably higher than physical based systems; see Table 8.

[4] 1L = 0.001m^3.

3.2.3.1 Liquid Organic Hydrogen Carrier (LOHC)

In LOHC storage, hydrogen is loaded onto unsaturated organic compounds through an exothermic hydrogenation reaction. Typically, this occurs at elevated temperatures and pressures [135]. For the release of hydrogen (dehydrogenation), elevated temperatures within the range of 200-450°C are required [151].

3.2.3.2 Metal Hydride

In this storage medium, molecular hydrogen gas is split into its atomic form on the surface of a metal and then diffuses into its atomic structure. Metal hydride formations can be achieved through the following reversible reaction [152]:

$$M + \frac{x}{2}H_2 \leftrightarrow MH_x + Q \tag{3}$$

Where M refers to a metal, Q is the heat of reaction and x is a stoichiometric co-efficient.

Despite the forward reaction being exothermic, the absorption rate of hydrogen is considerably low. To achieve storage capacities of approximately 5-7%, the reaction requires temperatures around 2500°C [153]. For hydrogen release, a temperature of approximately 120-200°C is required.

For metal hydride systems, the mass of hydrogen uptake is, on average, 5wt% [133]. This means that 5kg of hydrogen can be stored for every 100kg of metal. Therefore, with increased storage demands, the amount of host material required will significantly increase. This will have associated cost penalties.

3.2.3.3 Chemical

Examples of chemical storage of hydrogen include ammonia (NH_3), and formic acid (HCOOH). Ammonia can be stored and transported safely at low pressures. In comparison to formic acid, ammonia releases zero CO_2 emissions upon dehydrogenation and exhibits a greater gravimetric energy density than observed in LOHCs [133]. Formic acid contains 53 kg/m^3 of hydrogen with a density of 4.3wt% at ambient conditions [153].

3.2.3.4 Metal Organic Framework (MOF)

In physisorption systems, like MOFs, hydrogen physically adsorbs to host materials, which possess a large surface area. The temperatures required for desorption reactions are generally significantly lower than hydrogen discharge and dehydrogenation reactions in other material-based storage systems [133]. In addition to this, they exhibit uniform size, large void space and acceptable thermal stability [153]. These systems remain furthest away from practical implementation.

3.3 Hydrogen Delivery Systems

The most economic hydrogen transportation network will be dictated by specific national, regional and local resources and conditions [154]. In initial phases of hydrogen networks, where demonstration/pilot projects are present, small-scale transportation methods could be more economically viable. Once hydrogen markets are developed and there is increased demand, large-scale transportation methods will be more economically viable. This section provides an overview of the technologies available across a range of delivery capabilities.

3.3.1 Pipeline

Across the globe, approximately 4,500km of hydrogen pipelines are installed. Some of which, have been in operation for over 60 years [155, 156]. Typically, hydrogen pipelines have diameters of 25-30cm and operate between 10-20 bar [136]. In comparison to conventional gas pipelines, hydrogen pipelines are more capital intensive due to the requirement of greater diameters [157]. Other additional costs are incurred through welding procedures, leak testing and compression due to the low molecular weight of hydrogen and its associated diffusivity [66].

3.3.1.1 Blend Vs. 100%

The blending of hydrogen into existing natural gas pipelines is being explored, and tested, in the UK and other countries [158]. This warrants cost reduction by utilising existing transmission and distribution pipeline infrastructure. In the short term, it envisioned that hydrogen could be blended into most networks at 6% volume. By 2030, operators recommend a target capacity of 10% and 20% thereafter with limited changes to infrastructure [159]. Some key considerations associated with hydrogen blending are as follows:

. Appropriate hydrogen blend concentration could vary considerably between pipeline networks
. Additional monitoring and maintenance services are likely to be necessary
. Infrastructure upgrade may be required due to the degradation of metal pipes
. Permeation times of hydrogen are 4-5 times faster than methane in polymer pipes and may result in leakage
. Separation technologies could be required to extract hydrogen from mixtures in natural gas pipelines dependent on end-use application [160, 161].

3.3.2 Road Transportation

At present, hydrogen is transported via road using high pressure gaseous tube trailers and cryogenic liquid cargo trailers. The transportation of hydrogen in LOHC trailers is also gaining traction in recent literature and its potential is well received [135, 162, 163]. LOHC trailers provide an intermediate storage capacity between gaseous and liquid trailers. Unlike pipelines, road transportation systems cannot accommodate increased hydrogen demand. Therefore, as hydrogen demand increases, capital investments of infrastructure, labour costs and logistics costs also increase. However, for initial developments of hydrogen networks, road transport is generally considered the most economic [164]. A comparative overview of these three systems is given in Table 10 and an overview of all delivery systems discussed is given in Table 11.

	GH_2 Trailer	**LH_2 Trailer**	**LOHC Trailer**
Capacity (kg)	670 [135]	4000 [165]	1800 [135]
Loading Time (h)	1.5 [135]	3.0 [135]	1.5 [135]
Operating Pressure (bar)	15-250 [135]	Near Atmospheric [135]	Near Atmospheric [135]
Construction Material	$34CrMo_4$ Steel Alloy [136]	Outer Shell: Carbon Steel SA516 Inner Shell: Stainless Steel Type 304 [165]	Steel [135]

Please note that these values vary throughout literature and should only be taken as a rough indication.

Table 10 - Comparative Overview of Various Parameters for Different Options of Road Transportation.

Delivery Option	Capacity	Fixed Costs	Variable Costs	Transport Distance	Technology Status	Advantages (+) and Disadvantages (-)
Pipeline	H	H	L	H	Available	(+) Have shown safe operation globally for over 60 years [156] (-) Increased cost associated with welding, leak prevention and compression [66] (+) Offers further storage opportunity through line-packing [166] (-) Potential pipeline failure due to embrittlement which could result in jet fires, flash fires and explosions [167]
GH_2 Trailer	L	L	H	L	Mature	(+) Currently the most economic form of hydrogen road transportation [164] (-) Trailers have fixed capacities and cannot accommodate an increased hydrogen demand without increased capital investments in infrastructure, labour and logistic costs [164] (+) Composite construction materials allow for a greater capacity of hydrogen [135] (-) Composite materials are accompanied with greater capital investments [135]
LH_2 Trailer	M	M	M	H	Available	(+) Economically suitable for long transportation distances, IE) ships and trains [135] (-) Net-loss in payload due to hydrogen boil-off [136] (-) Longer average loading times compared to alternative technologies [135]
LOHC Trailer	L-M	L [151]	H	M [151]	Emerging	(+) Provide the opportunity for longer storage times then alternative technologies [151] (+) Can utilise hydrogen carriers which are not classified as dangerous goods for easier transportation [163] (+) Stepwise adaptation of conventional crude oil infrastructure is basically possible [151] (-) Dehydrogenation reactions can occur at low pressure meaning hydrogen needs to be re-compressed for end-use [135]

Table 11 - Overview of Hydrogen Delivery Options where L = Low, M = Medium and H = High - Adapted and Extended from [168].

4. Hydrogen Policy in the UK

Given that hydrogen could play a significant role in UK decarbonisation [169], it is important that stronger policy measures are adopted to ensure net-zero emission targets are met. Across the literature, there are a lack of academic papers which review hydrogen policy in a UK setting. For those which do, many focus mainly on its implications and focus less on existing policy mechanisms [170-172]. This section highlights existing UK policy measures which are supportive of hydrogen as well as resultant policy recommendations.

4.1 Emission Targets

Emission targets specify reduction levels to be achieved within a specified timeframe [173]. This sub-section highlights various emission targets which the UK have committed to. Whilst not specific to hydrogen technologies, this policy mechanism encourages the deployment of low-carbon technologies.

4.1.1 Kyoto Protocol

The Kyoto Protocol sets international emission reduction targets based on 1990 levels which are legally binding [174]. For the first commitment period (2008-2012) the UK surpassed the target of 12.5% and successfully reduced emissions by 22% [175]. However, not all industrialised countries committed to these targets and there was an overall net increase in global CO_2 emissions [176]. Twenty-nine countries are committed to the second commitment period (2013-2020), which has an emission reduction target of 20%. All are on track to reach or surpass this target [177].

4.1.2 The Climate Change Act (2050 Target Amendment)

The Climate Change Act seeks to reduce UK greenhouse gas emissions by at least 100% relative to 1990 levels [178]. Previously, this target was 80% until later amended in June 2019.

4.1.3 Carbon Budgets

Carbon budgets have been implemented to restrict the level of UK emissions across five-year periods; see Table 12. The first and second budget were successfully met. Whilst the UK is on target to outperform the third budget, it is not set to meet the fourth without greater decarbonisation efforts [179]. In December 2020, the CCC are expected to publish a recommendation on the level of the sixth carbon budget [180].

Budget Number	Time Period	Carbon Budget Allowance ($MtCO_2e$)	Reduction Compared to 1990 Levels (%)
1	2008-2012	3,018	25
2	2013-2017	2,782	31
3	2018-2022	2,544	37 by 2020
4	2023-2027	1,950	51 by 2025
5	2028-2032	1,725	57 by 2030

Table 12 - UK Carbon Budgets. Data Retrieved from [179].

4.2 Carbon Pricing

Carbon pricing is an important policy consideration for conventional hydrogen production processes because of their high carbon intensity [181]. There are two ways in which this may be implemented. One approach is carbon taxing where a fee is paid per unit of emissions. Another is a cap-and-trade system where industries purchase credits in order to emit [182]. Some advantages of carbon pricing include:

1. It is technology neutral which allows emitters to find the lowest-cost way to reduce emissions
2. It allows regulators to cost-effectively limit GHG emissions without the need to develop expertise in manufacturing processes
3. It generates government revenue which can be utilised to support investment in R&D initiatives [183].

4.2.1 EU-Emission Trading System (ETS)

The EU-ETS operates on the cap-and-trade principle. In this system, emission levels are capped, and companies can buy or receive emission allowances, which can be traded as required. If allowances are not sufficient to cover emissions at the end of the year, heavy fines are imposed [184]. A well-functioning trading system will increase the cost of carbon-intensive hydrogen production processes which could make CCS more cost competitive [181]. Until 31st December 2020, the UK will remain a full participant of the EU-ETS. Following this, a future carbon pricing system will be developed [185].

4.3 Government Strategy Papers and Other Publications

UK government has outlined its commitment to decarbonisation through various strategy papers, grand challenges and publications. This sub-section highlights those which recognise hydrogen technologies and their potential.

4.3.1 Industrial Strategy

In 2017, HM Government released the 'Industrial Strategy' white paper, which provided a structured approach to promote the transformation of the economy. The following four 'Grand Challenges' were identified as key research focus areas to enable this transformation: artificial intelligence and data revolution, the shift to clean growth, the future of mobility and an ageing society [186].

4.3.2 Clean Growth Strategy

The Clean Growth Strategy paper was published shortly after the Industrial Strategy. Clean growth is conceptualised as "growing national income while cutting greenhouse gas emissions" [187]. Challenges identified in this report included decarbonisation of the transport sector, reducing emissions from the domestic and business sector and making CCUS a viable future option. In the hydrogen pathway proposed, hydrogen production reached 750TWh by 2050 to achieve emission targets. All cars and vans were powered by hydrogen and most buildings utilised a hydrogen grid. Complementary low-carbon technologies such as renewable electricity, district heating and CCUS also had a role in this scenario [187].

4.3.3 Delivering Clean Growth

The CCUS Cost Challenge Taskforce was established by UK government to provide recommendations on how the cost of CCUS could be lowered [188]. In their report, Delivering Clean Growth, the taskforce urged that value could be unlocked through enabling a hydrogen economy by implementing CCUS technologies [189].

4.3.3.1 UK Government Response: CCUS Deployment Pathway

In response, UK government published an action plan designed to enable the deployment of the first CCUS facility in the UK, commissioning from the mid-2020s in order to allow the deployment of CCUS at scale by 2030 [190]. It was highlighted that this could contribute to the development of evidence to support decisions on the potential large-scale use of hydrogen.

4.3.4 Industrial Clusters Mission

In 2018, UK government announced the Industrial Clusters mission as part of the wider Clean Growth challenge and Industrial Strategy. The aim of this is to establish one net-zero carbon industrial cluster by 2040 and at-least one low-carbon cluster by 2030 [191]. Hydrogen is recognised as having a role in this challenge.

4.3.5 Other Strategy Documents

By quarter one of 2020, government were expected to release an Energy White Paper to outline the UK's strategy for achieving net-zero emissions as well as the role of nuclear energy [192]. Because of COVID-19 it is unknown when this document will now be published.

In July 2020, the European Commission published an EU hydrogen strategy outlining how demand for hydrogen can be driven across a range of sectors [193]. As well as the much anticipated Energy White Paper, key stakeholders are also calling for a UK-wide hydrogen strategy to unlock significant investment in hydrogen technologies across the country [194].

4.4 Investment in Research & Development (R&D)

Because hydrogen technologies are more costly than fossil-fuel alternatives, support in R&D is required, which can lead to cost decreases due to the accumulation of experience [195]. Investment in R&D can also help speed technological development [182]. This is crucial given the time limits imposed by emission targets.

4.4.1 Funding Streams to Support Hydrogen

In early 2020, UK government announced a £90m package, as part of the BEIS £500m innovation fund, dedicated to rolling out low-carbon technology. Hydrogen production projects were allocated £28m through the Hydrogen Supply competition. A list of these projects and the amount of funding allocated is shown in Table 13. Please note that hydrogen projects other than those focused on production have also been funded through alternative funding streams such as the Industrial Fuel Switching Programme.

Project	Funding Allocated (£m)
Dolpyhn Project	3.12
HyNet	7.48
Gigastack	7.50
Acorn	2.70
HyPER	7.44

Table 13 - Funding Received for Successful Hydrogen Projects in Phase 2 Hydrogen Supply Competition [196].

4.4.2 Industrial Decarbonisation Challenge (IDC)

The Industrial Decarbonisation Challenge is a £170m pot funded through the Industrial Strategy Challenge Fund. This challenge aims to enable the deployment of low-carbon technology, at scale, by the mid-2020s and will support the delivery of the Clean Growth Challenge and Industrial Clusters mission [197]. In April 2020, the winners of the phase 1 deployment and roadmap competitions were announced [198]. Further information can be found in Section 7.

4.4.3 Hydrogen Projects Funded through OFGEM

OFGEM is an official government body and Independent National Regulatory Authority, which protects the interests of existing and future electricity and gas consumers. OFGEM provides funding for low-carbon initiatives across the gas and electricity networks. Two examples of funding streams are the Gas Network Innovation Competition (NIC) and Gas Network Innovation Allowance (NIA) [199].

In 2019, the gas NIC was awarded to Northern Gas Networks for their H21 Phase 2 project. This project seeks to provide quantified safety-based evidence to confirm whether GB gas networks are suitable for 100% hydrogen. This will be achieved through an appraisal of procedures, modelling and testing [200]. For the 2020 NIC award, two projects have been chosen to proceed to the 'Full Submission' stage. One of these projects is H100 Fife (SGN) which aims to construct an end-to-end distribution network to test hydrogen. The other is HyNTS (National Grid Gas) which aims to test transmission network assets with hydrogen blends between 20-100%, at transmission pressure [201]. Project HyDeploy has also received £6.7m under the gas NIC [158]. This is a ten month demonstration project, at a private gas network at Keele University, to determine the level of hydrogen which can be used by customers safely [202].

4.4.4 UK Budget: 2020

In the 2020 Budget, HM Treasury recognised the importance of hydrogen in securely supplying low-carbon power as well as its potential in decarbonising industry [203]. Whilst there was no specific mention of a hydrogen fund in the budget, a new CCS Infrastructure Fund, of £800m, was announced. This funding will be utilised to establish CCS in at least two UK sites; one by mid-2020s and a second by 2030. This could complement the deployment of hydrogen technologies [189].

4.5 Green Subsidies

Subsidies can be delivered through various mechanisms to provide financial support for low-carbon hydrogen. Examples include grants, low-interest loans and tax exemptions [204]. As hydrogen is more expensive than conventional fuels, this will inevitably bear a greater cost to the consumer. Meaning, subsidies will initially be required to allow hydrogen to compete with the cost of alternative fuels.

Tax exemptions for hydrogen fuel are present in the transport sector. Hydrogen utilised in HFC vehicles are exempt from fuel duty. Furthermore, because they are classed as zero-emission vehicles, they are exempt from paying vehicle excise duty [205]. Other than this, there are a lack of subsidies which support hydrogen production and its end-use consumption. This differs considerably to the likes of renewable electricity which has received many subsidies over recent years. Examples include the Renewable Obligation (RO), Feed-in-Tariffs (FIT), Contracts for Difference (CfD), and the Renewable Heat Incentive (RHI). Further information on these programmes can be located at the following source: [206].

4.6 Policy Recommendations

Despite the current policy measures in place to support hydrogen in the UK, there are still many shortcomings which must be addressed before a hydrogen economy can be established [24, 207]. Some general policy recommendations, for government, found in the literature are as follows:

1. Develop a cross-departmental hydrogen strategy in government [202]

2. Provide more resources and greater powers for local authorities in decarbonisation strategy plans [192]

3. Significantly ramp up policy measures to make net-zero targets credible, particularly for heat and aviation [15]

4. Seek views on possible market and commercial structures, financing options and funding sources for hydrogen [207]

5. Address investment risks of first-movers in hydrogen technologies [11]

For specific policy recommendations concerning individual elements of a hydrogen system see Table 14.

Hydrogen Production	Hydrogen Transport and Distribution	Domestic Sector	Transport Sector	Industrial Sector
. Provide Financial support for hydrogen generation . Decrease distortive incentives by increasing VAT on carbon intensive fuels . Drive down costs and increase competiveness by prioritising demonstration projects	. Provide financial support for blending hydrogen into gas grid . Encourage green gas by changing the GSMR to accommodate hydrogen injection	. Improve supply chains so that warranties and appliances allow for hydrogen . Provide appropriate governance in the socialisation of costs	. Collaborate to establish 100 HRS by 2025 . Financial support for hydrogen in the transport sector . Develop a HRS network for haulage vehicles Allow hydrogen transport pilots	. Provide financial support for industry . Develop industrial hydrogen hubs . Promote fuel switching options and identify how costs can be lowered . Complement industrial clusters funding with market creation policies

Table 14 - Policy Recommendations for Specific Applications of Hydrogen. Retrieved from [24, 192, 202].

5. Regulatory Considerations

To best develop regulations, codes and standards for any particular technology, lengthy consultations between regulators, industry and academics are required. Sufficient regulatory frameworks for hydrogen technologies are still lacking across many countries and are still far from being harmonised [208]. Hydrogen displays various unique characteristics which inhibit the extrapolation of existing standards from conventional fuels. These include its requirements for storage at high pressure and extremely low temperatures, distinctive thermodynamic properties, high purity requirement for fuel-cell applications and difficulty in detection [209]. Such characteristics have various regulatory implications.

5.1 Hydrogen Production

At a centralised scale, there are no legal and administrative concerns or recommendations for regulatory amendments for hydrogen production processes. At a local level, where production is most likely to be electrolyser based, the regulatory procedures are aligned with centralised production with no simplified process for low volume production [210]. Typical examples of legislation required for hydrogen production infrastructure include Environmental Impact Assessments (EIA), the Town and Country Planning Act, the Hazardous Substances Act and COMAH (2015) Regulations [211].

5.1.1 Hydrogen Business Models: Could they be Regulated?

One of the most difficult non-legislative challenges faced for hydrogen production is the uncertainty around business models. There are numerous options for the operation and ownership of hydrogen infrastructure assets. They could be built, owned and financed by the private sector without commercial regulation. Or, they could operate in regulated markets through the likes of the Regulated Asset Base (RAB) model [207]. This would involve treating hydrogen as a national utility with an appropriate allocation of risk in order to reduce the cost of capital. Ultimately, this could lower the level of support required to deliver commercial projects [212].

In a recent report commissioned by the Department for Business, Energy & Industrial Strategy (BEIS), Frontier Economics identified four business model categories that could potentially provide an incentive for investment in low-carbon hydrogen production: Contractual payments to producers, regulated returns, obligations and end user subsidies [213]. Whilst this report is a step in the right direction, it focuses mainly on the supply of hydrogen to industry as well as near term investments. Due to the large decarbonisation potential of hydrogen across various sectors, further research will be required concerning the suitability of business models for alternative applications of hydrogen. In a recent publication, UK government highlighted that they would continue to work closely with industry to assess viable hydrogen business models [214].

In other sectors innovative decisions have been made to increase competition for projects and jump-start investment into capital assets. For example, the offshore transmission regime (OFTO) opened a market for transmission assets in the UK offshore wind market. Subsequently, this attracted new investors and created a secondary market. For further information, please refer to the following source: [215].

5.2 Transport and Distribution

Hydrogen transportation and distribution appears to have the most regulatory restrictions at present. Without legislation that supports hydrogen within gas networks, demonstration projects could be bottle-necked [216].

5.2.1 Gas Control of Thermal Energy Regulations (CoTER)

Under the CoTER, customers are charged based on the average calorific value of gas across thirteen zones in the UK. In order to match the calorific value of gas across an entire zone, enriching or deriching processes are required [217]. Because the thermodynamic properties of hydrogen differ to natural gas, this could potentially prohibit small-scale demonstration projects in individual locations. Any changes made to accommodate unconventional gases within this legislation must ensure customers are not disadvantaged through unfair billing [218]. To address this issue, Cadent have developed the future billing methodology project. This project seeks to create a way to measure the blend of gases and explore fair options for billing which are fit-for-purpose in a lower-carbon future. One potential option is to assign specified calorific values at a more local level to avoid the need for additional gas processing [219, 220].

5.2.2 Gas Safety (Management) Regulations (GS(M)R)

The GS(M)R (1996) stipulates that hydrogen content in natural gas supplied to domestic homes should be no greater than 0.1% molar volume [221], despite the fact that 'town gas' was distributed with approximately 50% hydrogen content until the 1970s [222] . This is consistent with other countries like Italy. However, countries like France and Denmark, have more supportive legislations where permittable concentrations range from up to 6-10% [223]. Existing Wobbe Index limits under the GS(M)R also influence permittable hydrogen content as hydrogen blends will lower this value;

see Section 2.2.1. The current restraints of the GS(M)R mean that pilot demonstration projects can only be undertaken on smaller isolated networks. It is recommended that amendments to the GS(M)R should be brought forward as a matter of urgency, to enable the large-scale demonstration of hydrogen injection into the gas grid [224]. UK government have confirmed that this is under review by the Health and Safety Executive (HSE) who have the authority to grant exemptions [218]. An exemption has already been granted to the HyDeploy project [158].

5.2.3 RIIO-2

Ofgem are responsible for overseeing the second period of price controls for network companies across the gas and electricity transmission and distribution networks. This is referred to as RIIO-2 (Revenue = Incentives + Innovation + Outputs). The new price control period for UK gas networks will run between 2021 and 2026 [225]. It is therefore important that the allowable spend on hydrogen throughout this period is clearly defined [24].

In 2019, gas network operators submitted their business plan for this period which included considerations and visions for hydrogen in the gas network. In response, the RIIO-2 Challenge Group highlighted the following conclusions concerning hydrogen:

- The workforce is not necessarily prepared for a hydrogen future and more Chartered engineers will be required
- The ability of the steel Local Transmission System to accommodate hydrogen transmission is not clear[5]
- It appears that hydrogen leaks may not be any more significant than gas in terms of safety of the public
- There is little discussion on the extent that assets are compatible with 100% hydrogen[6] [226].

At the end of 2020, Ofgem are expected to publish their final view on the price control allowances [225].

5.2.4 Appliances

It is important to note that all appliances sold after 1993, must comply with the 1990 Gas Appliance Directive (GAD) 90/396/CCE, which demonstrates that they can operate on a wider range of gas quality than specified in the GS(M)R and specifies a gas composition of 23% hydrogen [227]. Although not all appliances in the UK are post 1993 and the GAD does not consider long-term operation, this legislation could be supportive for hydrogen use in the home.

5.3 Hydrogen Refuelling Stations (HRS)

In recent years, support for HRSs has increased in the UK with best practice guides for installation now available [228]. Despite this, there are still regulatory challenges to be addressed concerning quality assurance, flow metering, quality control and sampling. Further information concerning existing codes, standards and regulations and further recommendations for improvement can be found at the following sources: [208, 229, 230].

5.4 Overview of Severity of Legal Barriers for Various Hydrogen Applications

[5] Comment made in response to Cadent's business plan.
[6] Comment made in response to National Grid Gas Transmission's business plan.

The HyLaw project aimed to provide a clear view of applicable regulations and draw attention to legal barriers concerning numerous hydrogen technologies and applications. Using conclusions from this project,

Table ***15*** highlights the severity of legal barriers faced across various hydrogen applications in the UK in comparison to the European average. In the UK and across Europe, gas grid issues have the highest severity [223]. Further information concerning this project, and the data retrieved, can be found at the following source: [231].

Application of Hydrogen	Average Severity of Barriers for Hydrogen Application for UK	Average Severity of Barriers for Hydrogen Application for Europe
Hydrogen Production	1.7	1.2
Hydrogen Storage	2.0	1.2
Transport and Distribution of Hydrogen	0.7	0.5
Hydrogen as a Fuel	1.0	1.2
Vehicles	1.8	1.2
Electricity Grid Issues	1.0	1.3
Gas Grid Issues	3.0	2.2
Stationary Power	1.3	1.9
Values shown in column 3 were calculated using Web Plot Digitizer as these were not quantified in the bar chart from the original source: [223] (Fig2, p.7).		

Table 15 - Average Severity of Legal and Administrative Processes for Various Applications of Hydrogen. Where: 0 is the lowest severity and 3 is greatest. Data Retrieved from the HyLaw project [211, 223].

6. Social Considerations

Public perception remains a critical consideration in the deployment of new technologies and has been shown to either encourage or slow down innovation [232]. In previous low-carbon projects, it has been a positive factor behind successful operation [233]. This is therefore pivotal to the establishment of both local and national hydrogen networks. This section highlights research which has focused on the acceptance of hydrogen. Please note that some studies were not conducted in the UK and where this is the case, it is indicated. Whilst conclusions drawn from these studies may not be directly translatable to a UK context, they provide insight and learning opportunities.

6.1 Acceptance of Hydrogen

Previous studies indicate that people have positive beliefs and attitudes towards hydrogen and accept its development as a fuel [234]. For example, in a recent UK study, 50% of participants supported the conversion of home heating to hydrogen [235]. At this stage of diffusion to a hydrogen economy, attitudes can change rather easily by providing short and neutral information. However, this also means that the strength and stability of positive attitudes is rather low [236]. This section covers various factors which have an influence on the acceptance of hydrogen technologies.

6.1.1 Awareness of Hydrogen

An increased knowledge and understanding can lead to greater support for hydrogen but can also lead to greater opposition and indifference [237]. This makes it an important factor for consideration.

In Spain, one study observed high-levels of awareness concerning the existence of hydrogen as a transportation fuel [238]. This differs from findings of other studies. For example, one study in America indicated that only 35% of a total sample were able to correctly answer eight questions about hydrogen technologies. Furthermore, almost 9 out of 10 individuals considered themselves 'not familiar' or 'slightly familiar' with hydrogen and fuel cell technologies [239]. Another study in Japan, in 2008, explored participants awareness of hydrogen. Only 32% claimed that they knew about hydrogen, which was lower than results observed for alternative forms of energy such as solar, nuclear and wind [240]. However, when asked again in 2015, this value increased by 12%. Generally, the literature shows low levels of hydrogen awareness as well as low numbers of participants who are able to answer technical questions concerning hydrogen [234].

6.1.2 Information Sharing

To aid in stabilising the acceptance of hydrogen, further information campaigns or projects to familiarise people with hydrogen technologies will be necessary. As long as individuals are indifferent, they can be informed and convinced about hydrogen technologies more easily [241].

As part of the HyDeploy initiative, one study found that considerably more people would be willing to use hydrogen in their homes after being giving two further pieces of information. The first was confirmation that their home appliances had been tested and deemed suitable for usage. Secondly, they were informed that town gas, supplied to homes in the past, had a high hydrogen content [242]. Another study in Japan showed higher acceptance for HRSs being built near the home once risk and safety information had been shared. This was likely because issues concerning uncertainty were addressed [243]. On the other hand, this study observed a lower acceptance for HRSs being built near a local gas station as this left participants feeling anxious after risk and safety information was shared.

6.1.3 Willingness to Pay

Several studies have assessed whether individuals are willing to pay for hydrogen. Mixed conclusions have been drawn depending on the context in which surveys were executed as well as the methodology utilised [234].

In one study in the UK, when asked about their willingness to pay for hydrogen fuel for domestic applications, over 60% of participants highlighted that they could not pay, even if they wished to, due to low wages and ever increasing energy bills [242]. Furthermore, several participants displayed sensitivity toward the possible distributional injustice of hydrogen costs. As mentioned, this is an issue addressed in the future billing methodology project [219]. Another UK study, as part of the H21 initiative, supports these findings. This study identified that participants were concerned about the higher cost of hydrogen and the need to purchase new appliances [244].

Regarding the purchase of hydrogen vehicles in the transport sector, a Spanish study identified operation and maintenance costs of HFC vehicles as key barriers [238].

A study conducted in Greater Stavanger identified that younger individuals were more likely to indicate a willingness to pay than older individuals. This is likely because younger individuals have greater access to information about the negative consequences of using conventional, carbon intensive fuels [237].

6.1.4 Overview of Other Influential Factors of Hydrogen Acceptance

This sub-section provides an overview of additional factors which can positively or negatively influence the acceptance of hydrogen. Key findings from the literature are shown in Table 16. As well as those identified in Table 16, the underground storage of hydrogen and hydrogen pipelines are factors which could also influence public acceptance. In a German study, the following statements were given to participants: "I would have no concern if hydrogen were stored underground like natural gas" and "Additional gas pipelines for the hydrogen transport would be a good solution" [245]. Respectively, 37.4% and 40.4% of participants disagreed with these statements. In comparison to other statements concerning the recognition of hydrogen for energy supply and climate protection, this level of disagreement was considerable.

Positive Factors		Negative Factors	
Environmental Impact	. Hydrogen has a favourable public perception in terms of environmental performance and sustainability [238].	**Economic Issues**	. Costs of hydrogen vehicles is a key barrier in hindering the success of hydrogen vehicles [238].
Ability to Meet Modern Heating Demands & Existing Practices	. Hydrogen is perceived as progress to a more modern version of natural gas, where the progression views for heat pumps were less clear [246]. . Hydrogen is seen to be more of a like-for-like replacement of the current natural gas system and easier to grasp than alternative technologies such as heat-pumps [246].	**Technical Issues**	. Technical issues such as availability of refuelling stations and vehicle features is a key barrier in hindering the success of hydrogen vehicles [238].
Economic Opportunities	. Hydrogen technologies are perceived as providing the opportunity to create jobs and provide services as well as allowing companies to grow their businesses [247].	**Installation Burden for Hydrogen in Homes**	. The main barrier to acceptability for hydrogen for heating is the one to two weeks disconnection from gas supply during installation periods [246]. . The need to replace all gas appliances is also perceived as a barrier to hydrogen for heating applications [246].
Ability to Address Current Energy System Flaws	. Raising awareness of problems with the current energy system influences the general acceptance of hydrogen technologies [248].	**Familiarity of Experience**	. Invisibility of hydrogen flame imagined by participants as being particularly disruptive to their practices of cooking [249]. Therefore, suitable colourants are imperative to acceptance.
		Large Scale Development and Infrastructure	. Support for hydrogen applications and infrastructure is less enthusiastic in comparison to general acceptance of hydrogen [245]. . Hydrogen technologies may be perceived as being sustainable but still a disruption to the local environment [248].

Table 16 - Overview of positive and negative factors which could influence the public acceptance of hydrogen found throughout the literature.

7. Status of On-Going Hydrogen Projects and Initiatives

7.1 Large Scale Integrated Projects (LSIPs)

LSIPs are defined as projects which involve the capture, transportation and storage of CO_2 at rates of 400,000-800,000t per annum dependent on the industrial facility [250]. As mentioned, fossil-fuel based hydrogen production requires additional carbon mitigation technologies, like CCS, to avoid an overall net-increase of CO_2 emissions [24]. To align with the scope of this article, only LSIPs which incorporate hydrogen production and CCS will be discussed. Reference will be given to those already operational as well as those proposed in various industrial cluster initiatives.

7.1.1 Global Overview of Large-Scale Hydrogen Production with CCS

Across the globe, there are few operational hydrogen plants which incorporate CCS technologies; see Table 17. Traditionally, these plants have utilised CO_2 for enhanced oil recovery (EOR). However, in more recent projects, like Quest, CO_2 has been captured and permanently sequestered for decarbonisation purposes.

Project	Location	Industry	Year of Operation	Hydrogen Production Technology	Hydrogen Production Rate (t/d)	CO_2 Capture Rate (Mt/y)
Great Plains	Beulah, North Dakota	Synfuels	2000	Coal Gasification	1300	3
Air Products	Port Arthur, Texas	Hydrogen Production	2013	SMR	500	1
Quest	Alberta, Canada	Hydrogen Production	2015	SMR	900	1
CoffeyVille	CoffeyVille, Kansas	Fertiliser	2013	Gasification	200	1
ACTL Sturgeon	Alberta, Canada	Refinery and Fertiliser	2020	Gasification and Reforming	>240 and >800	1.2-1.4
Porthos	Rotterdam, Netherlands	Refinery and Hydrogen Production	2023	SMR ATR	-	2-5
CarbonNet	Victoria, Australia	-	2025+	-	-	2-5

Please note that the CarbonNet project recognises hydrogen production as a 'possible future source' project which is referred to as 'Coal to Products'.

Table 17 - Overview of Global Projects - Large-Scale Hydrogen Production with CCS. Sources: [251-260].

7.1.2 Industrial Clusters

Industrial clusters present great opportunity for hydrogen networks as they're commonly situated near existing oil and gas facilities and potential CO_2 storage sites. Because of the close proximity of multiple industrial sites, transmission and distribution infrastructure costs are also lower [11]. One example is the Port of Rotterdam which is recognised as the most advanced cluster proposal in mainland Europe [261]. The cluster is evolving to a carbon neutral economy in a three-step transition which integrates hydrogen production, CCS and many other low-carbon technologies [262]. Proposals for low-carbon hydrogen production in the cluster include: PORTHOS [255], H-VISION [259], H2.50 as well as a 200MW green hydrogen plant [263].

In the UK, the six largest industrial clusters emit approximately 40 million tonnes of CO_2 per year, which equates to approximately one third of all business and industrial emissions [197]. For each cluster, a brief summary of large-scale decarbonisation initiatives is given, where the significance of hydrogen varies throughout. Please note this is not an exhaustive review of each cluster and further information can be found at the sources referenced.

7.1.2.1 Teesside

In 2018, the Clean Gas Project was launched by the Oil and Gas Climate Initiative (OGCI). This project entailed power generation from natural gas, with CO_2 captured and transported, via pipeline, for storage in the Southern North Sea [264]. The project sought to store 6Mt CO_2 per year in storage sites with an excess of 1000Mt storage capacity [265]. Since then, the project has expanded to include a transportation and storage system to collect CO_2 from other industries in the region including fertiliser and hydrogen plants [266]. The project is now titled Net Zero Teesside [267]. In 2019, an application for a scoping opinion was submitted to the Planning Inspectorate with a development consent application expected in the fourth quarter of 2020 [268]. No sources could be found which indicate plans for additional hydrogen production facilities in the region.

7.1.2.1.1 Humberside

The Humber is the most carbon intensive cluster in the UK and emits 14MtCO_2 each year [269]. In 2019, Drax Group, Equinor and National Grid signed a Memorandum of Understanding (MoU), committing them to work together to explore the opportunities for a zero-carbon cluster in the Humber [270]. This is split into two phases. In the first, critical infrastructure will be installed including carbon capture on one of the four Drax biomass units to enable BECCS by 2027, an ATR for hydrogen production by 2025 and the development of CO_2 transport and storage infrastructure for storage in the Southern North Sea [271]. Key proposals for phase 2 are as follows:

- BECCS capacity of 16MtCO_2 per year
- Hydrogen production capacity of 13.7 GW by 2050
- 13MtCO_2 per year captured from industry and power stations within the region

This project will align with the H21 project. More details about this can be found at the following source: [102].

7.1.2.1.2 North West

The HyNet project envisions hydrogen production with integrated CCS infrastructure. Produced hydrogen will be supplied to end users via a newly constructed pipeline that permits up to 1.5GWh of hydrogen storage through line packing. The initial end uses of hydrogen are injection into the local gas transmission system for blending and fuel switching for industrial users. The captured CO_2 from the hydrogen production plant, as well as that from industrial emitters, will be transported, via pipeline, to the Liverpool Bay gas fields for long term storage. This will have an initial capacity of 10Mt CO_2 per year [272]. In the short term, an LCH plant with a production rate of 100kNm^3/hr will be built on Essar's Stanlow Refinery, which will supply approximately 3000GWh per year of hydrogen. The Front-End Engineering Design (FEED) will be completed by March 2021 and the plant could be operational in mid-2024 [273]. CCS infrastructure is expected to follow a similar timeframe.

7.1.2.1.3 Grangemouth

Project Acorn obtained the first UK CO_2 appraisal and storage license from the Oil and Gas Authority and has the potential to be operating in 2023. This project consists of two elements: CCS and hydrogen production [274]. A repurposed pipeline will be utilised to transport industrial CO_2 emissions from the Grangemouth cluster to an injection site, at St. Fergus, for offshore storage.

Storage rates of 2Mt per year are expected [275]. A 200MW LCH production plant is planned at St. Fergus for direct blending, at 2% volume, into the National Transmission System [275]. At present, Acorn CCS is in the detailed engineering phase. The final investment decision (FID) is expected in late 2021 [274].

7.1.2.1.4 Southampton

In comparison to other clusters, the literature concerning decarbonisation initiatives in Southampton is minimal. Whilst no large-scale decarbonisation plans could be found, the following sources highlighted the lack of direct storage sites for CO_2 in the region: [276, 277]. This means that additional compression and liquefaction infrastructure would be required for CO_2 transportation to alternative storage sites, which could cause CCS operations to commence later than other clusters. No sources concerning hydrogen activity in the region were found.

7.1.2.1.5 South Wales

South Wales faces problems similar to that of Southampton with regard to offshore storage facilities for CO_2 [276]. The cluster is still in the early phases of developing a large-scale plan for decarbonisation. Despite this, there are several initiatives in the region which are exploring low-carbon technologies. ZERO2050 is an initiative led by National Grid which aims to speed up the rate of progress in meeting government targets [278]. The FLEXIS operation focuses on developing flexible energy systems and all research will focus on and be applied at a demonstrator in Tata Steel, Port Talbot. Hydrogen focused work packages within this research programme are as follows [279]:

- WP5: Hydrogen Energy Storage
- WP6: Sustainable Production and Purification of Hydrogen, Syngas, Bio-hydrogen and Bio-methane
- WP7: Hydrogen and Syngas: Efficient Use
- WP15: Energy Vectoring through Hydrogen

7.1.2.2 The Industrial Decarbonisation Challenge

The decarbonisation of UK industrial clusters is recognised as a key challenge. The IDC aims to accelerate cost-effective decarbonisation of industry as well as enabling the deployment of infrastructure at scale by the mid-2020s [197]. It is envisioned that CCUS, hydrogen, bioenergy and clean electricity will be vital technologies in these decarbonisation efforts [191].

7.1.2.2.1 Phase 1 Winners

In April 2020, the winners for the first phase of the deployment and roadmaps competitions, as part of the wider IDC, were announced. These are summarised in Table 18. For further information please see the following source: [198].

Phase 1: Deployment Competition Winners		**Phase 1: Roadmap Competition Winners**	
Name of Project	**Region**	**Name of Project**	**Region**
Scotland's Net Zero Infrastructure	Scotland	Net Zero Tees Valley - Decarbonising the Full Cluster: Roadmap Pathfinder	Tees valley
Net Zero Teesside Project	Teesside	Scotland's Net Zero Roadmap (SNZR)	Scotland

Humber Industrial Decarbonisation Deployment Project (Humber-DP)	The Humber	Humber Industrial Decarbonisation Roadmap	The Humber
HyNet Carbon Capture Utilisation and Storage (CCUS)	North West	North West Hydrogen and Energy Cluster: Route to Net Zero	North West
South Wales Industrial Cluster (SWIC)	Wales	South Wales Industrial Cluster (SWIC)	Wales
Green Hydrogen for Humber	The Humber	Repowering the Black Country	Midlands
For the deployment competition, UK businesses could apply for a share of up to £1m to develop plans for decarbonising an industrial cluster [280].		**For the roadmaps competition, UK businesses could apply for a share of up to £1m to prepare plans for their journey to achieving low carbon and net zero industrial clusters [280].**	

Table 18 - Overview of Winners from Phase One of UK Industrial Decarbonisation Challenge [198].

8. The International Importance of Hydrogen

So far, this article has focused on hydrogen technologies in a UK setting. However, at a global level, hydrogen has the potential to meet 18% of the world's energy demands and abate 6Gt of CO_2 annually [8]. Therefore, hydrogen technologies must also be considered from an international perspective. This section briefly highlights recommendations for the development of a global hydrogen market as well as international collaboration platforms concerned with this agenda.

8.1 Unlocking a Global Hydrogen Market

The Future of Hydrogen report published by the International Energy Agency (IEA) urged that international hydrogen trade needs to start soon to make an impact on the global energy system [11]. Table 19 provides an overview of some key recommendations for developing a global hydrogen market.

Recommendation	Further Information
Develop International Standards for Hydrogen	Trade will benefit from common international standards for the safety of the transportation and storage of large volumes of hydrogen. Accounting standards for different sources of hydrogen along the supply chain need to be developed on an international basis. Harmonising hydrogen blend limits across borders is a crucial step to support deployment as well as accounting for possible variations in blending levels over time.
Launch International Shipping Routes	One third of global physical trade by sea are energy products. This is an important contributor to climate change. Lessons from the global liquified natural gas (LNG) market can be leveraged for hydrogen shipment.
Establish Co-Ordinated Approaches	If governments work to scale up hydrogen in a co-ordinated way, it will help investment in infrastructure, bring down costs and enable the sharing of best practices. Some hydrogen investments may need to be managed across borders requiring international collaboration.

Table 19 - Recommendations for Developing a Global Hydrogen Market. Developed from [11].

8.1.1. Co-Ordinated Cross Border Approaches

In early 2020, German and French gas transmission system operators (TSO) signed a MoU to enhance knowledge and research sharing concerning the transportation and blending of hydrogen in their natural gas networks [281]. This agreement reinforces cross-border cooperation and is the most important to date at European Scale [282].

8.1.2 International Shipping Routes

Hydrogen can be produced, at low cost, in locations with the best resources available and then traded with consuming countries that lack the potential for affordable hydrogen production [283]. International shipping provides one option of transporting large volumes of hydrogen to consumers.

In 2019, as part of the Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD) demonstration project, hydrogen was transported from Brunei to Japan. Hydrogen was produced at a hydrogenation plant and stored in the form of methylcyclohexane (MCH). It was then transported via shipment to Japan. In future, hydrogen will be extracted at a dehydrogenation plant and the resultant toluene will be returned to Brunei for reuse as a transport medium [284, 285].

As well as this, the Hydrogen Energy Supply Chain (HESC) project seeks to transport hydrogen from Australia to Japan through international shipping. Hydrogen will be produced from the gasification of brown coal in Latrobe Valley, Australia. It will then be transported to Port of Hastings, Australia where it will be liquefied and shipped to Japan. The pilot demonstration for this project is expected to run until 2021 [286].

In 2017, Kawasaki formed a partnership with Norway's Hel Hydrogen; with the backing of Mitsubishi Corporation and Statoil (now Equinor). The companies will carry out a feasibility study for a demonstration project which comprises the production of hydrogen from hydroelectric power, and eventually wind, in Norway. This will be transported via liquid hydrogen tanks to Japan [287].

8.2 International Collaboration

To build a safe and economical worldwide infrastructure for hydrogen networks, international collaboration will be required [288]. Table 20 provides an overview of some existing international hydrogen collaboration platforms.

International Hydrogen Collaboration Platform	Aim and/or Purpose
Mission Innovation – IC8: Renewable and Clean Hydrogen	To accelerate the development of a global hydrogen market by identifying and overcoming key technology barriers to the production, distribution, storage, and use of hydrogen at gigawatt scale [289].
International Energy Agency (IEA) Hydrogen Technology Collaboration Programme (TCP)	To enable governments and industries from around the world to lead programmes and projects on a wide range of energy technologies and related issues [290].
International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)	To facilitate and accelerate the transition to clean and efficient energy and mobility systems using hydrogen and fuel cell technologies across applications and sectors [291].

Hydrogen Europe (European Hydrogen and Fuel Cell Association)	To play a crucial role in promoting best practice, helping companies become more competitive and formulating effective public policy. To provide the necessary intelligence and a solid network in order to support their members [292].
U.S. Deparment of Energy's (DOE) Fuel Cell Technologies Office	To advance hydrogen and fuel cells for transportation and diverse applications enabling energy security, resiliency, and a strong domestic economy in emerging technologies [293].
Fuel Cell and Hydrogen Joint Undertaking (FCH JU)	To demonstrate fuel cell and hydrogen technologies as one of the pillars of future European energy and transport systems, making a valued contribution to the transformation to a low carbon economy by 2050 [294].
Hydrogen Council	To accelerate the development and commercialization of the hydrogen and fuel cell sectors. To encourage key stakeholders to increase their backing of hydrogen as part of the future energy mix [295].
Hydrogen Global Charter	To deliver impact by forming a community of hydrogen actors around a shared commitment: consume, enable, and invest in blue and green hydrogen [296].

Table 20 - Overview of International Hydrogen Collaboration Platforms.

9. Conclusion

Despite considerable reductions in territorial greenhouse gas emissions in recent years, the UK must urgently decarbonise heavy emitting sectors to meet ambitious net-zero targets. Hydrogen can complement other low-carbon technologies in this effort. Though, it may not be a 'silver bullet' solution, it can address some of the challenges exhibited by alternate technologies, particularly in the transport and domestic sector. At present, BEVs cannot compete with the long driving ranges and short refuelling times exhibited by HFC vehicles. This creates a potential market for HFC vehicles where minimum refuelling times are required to avoid loss of earnings. In the short term, this could encompass buses, trains and heavy-goods vehicles. Furthermore, hydrogen has the potential to be produced at a large enough scale to accommodate future heat demand. This could address challenges faced by heat pumps such as the requirements for increased electricity generation and storage capacity as well as the intermittent availability of renewable energy. Several hydrogen technologies are now commercially available; most of which have applications within the transport sector. However, there is significant room for improvement in terms of the availability of required infrastructure as well as hydrogen compatible appliances for both domestic and industrial heat. Both of which will be essential in delivering the hydrogen economy.

There are multiple options for hydrogen production, delivery and storage pathways. Each of which have trade-offs in terms of scale, efficiency, cost and technological maturity. The most optimal technology will be dependent on the specific requirements of individual projects. In the UK, reforming technologies are expected to dominate immediate future hydrogen production. Research indicates that the LCH system is best suited for blue hydrogen production due to higher carbon capture potential at lower costs in comparison to other reforming technologies with CCS. However, other than the sources identified throughout, there is a lack of academic literature concerning this technology which stresses the importance of future research. Whilst there are no operational LSIP hydrogen projects in the UK, several initiatives have been proposed and are due to reach the FEED and FID stage in the next couple of years: subject to government funding.

The potential role of hydrogen has been recognised by UK government through various strategy documents and has also been supported through numerous funding streams. Despite this, policy incentives received for hydrogen are minimal in contrast to other low-carbon technologies. As hydrogen is anticipated to heavily decarbonise various sectors, additional policy support is necessary. Furthermore, there is no definitive outline of the role hydrogen, will have in the UK's decarbonisation strategy to 2050 and beyond thus emphasising the need for a UK-wide hydrogen strategy. This calls for significant improvements in hydrogen policy which will require a coordinated, cross-departmental approach from government alongside consultations with numerous stakeholders including academia, business and industry. Likewise, this level of collaboration will be required for the establishment of new hydrogen codes, standards and regulations. To facilitate hydrogen in the existing energy system, exemptions and amendments to existing legislations will be required. This will in turn address risk uncertainties, help secure investment and, eventually, drive down costs. From the literature reviewed, the following policy and regulatory recommendations are outlined to enhance investor confidence in hydrogen technologies and subsequently accelerate the development of a hydrogen economy in the UK:

1) Create a UK-wide hydrogen strategy which provides clarity on the future role(s) of hydrogen
2) Identify a suitable hydrogen business model
3) Adopt a cross-departmental approach to develop policy mechanisms and regulation which are supportive of, and promote, hydrogen technologies and hydrogen as a low-carbon fuel.

The general public will heavily influence the success of hydrogen technologies in the UK and must not be neglected in this transition. Generally, research suggests that the public recognise the potential of hydrogen in addressing environmental issues and current energy system flaws. However, installation burdens, unfamiliar experiences and high costs associated with hydrogen could negatively affect public acceptance. The social acceptance of hydrogen utilised within the home has been explored in the UK as part of the wider HyDeploy and H21 initiatives. Whilst there is an abundance of literature concerning the public perception of hydrogen in the transport sector at a global level, there is limited literature available for a UK context. Further research into the public acceptance of hydrogen technologies in the UK is required and could be extended to include its other applications such as industrial fuel switching and power generation.

Industrial clusters are recognised as immediate areas of focus to kick-start the global hydrogen economy due to their proximity to existing oil and gas facilities. The international trade of hydrogen must happen soon to have an impact on the global energy system. Co-ordinated approaches are encouraged to promote harmonised international standards for hydrogen and develop international shipping routes. This could progress export opportunities. International collaboration is already exhibited through numerous platforms which collectively encompass individual nations, governments, academic institutes and businesses from around the globe.

This review article set out to address an existing literature gap concerning the lack of research on hydrogen that adopts a multi-disciplinary approach. In doing so, this review has facilitated a wider conversation around hydrogen technologies in the UK by encompassing technical, policy, regulatory and social discussions. To appreciate the wider context of hydrogen, future research could benefit from adopting this approach.

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Appendix A: Data Used to Plot UK CO2 Emissions per Sector (Figure 1 in Manuscript)

Sector	Emissions in 1990 ($MtCO_{2e}$)	Contribution Percentage	Emissions in 2019 ($MtCO_{2e}$)	Contribution Percentage
Energy Supply (Including Power Generation)	242.1	40.64%	90.1	25.62%
Business and Industrial Process	111.9	18.78%	74.4	21.16%
Transport	125.3	21.03%	119.6	34.02%
Public	13.4	2.25%	8.0	2.28%
Residential	78.4	13.16%	65.2	18.55%
Agriculture	6.5	1.09%	5.7	1.63%
Waste Management	1.4	0.24%	0.2	0.07%
Total	595.7	100%	351.5	100%

This is provisional 2019 emission data retrieved from the Department of Business Energy and Industrial Strategy
[Data Source] BEIS, 2019 UK Greenhouse Gas Emissions, Provisional Figures in Statistical Release: National Statistics 2020. Available from:
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/875485/2019_UK_greenhouse_gas_emissions_provisional_figures_statistical_release.pdf

Table A. 1 - Data Used to Plot UK CO_2 Emissions per Sector in Figure 1 (Section 2) in Manuscript.

Appendix B: Data for Simple Economic Analysis (Section 3.5 in Manuscript)

Lower Heating Value (LHV) of H_2 [a]	
3	kWh/Nm^3
33.33	kWh/kg
10.80	MJ/Nm^3
120	MJ/kg
Density of H_2 [a]	
0.0899	kg/Nm^3
Yearly Average Currency Conversion (EUR to GBP) [b]	
2015	0.726
2016	0.819
2017	0.877
2018	0.855
2019	0.878
Yearly Average Currency Conversion (USD to GBP) [b]	
2015	0.654
2016	0.741
2017	0.777
2018	0.750
2019	0.784
Chemical Engineering Plant Cost Index [c]	
2015	556.8
2016	541.7
2017	567.5
2018	603.1
2019	607.5

The data shown was used to convert production rates, CAPEX and hydrogen production costs obtained from the literature into the units provided in Table B.2.

[a] [Data Source] HyWeb. Hydrogen Data The Hydrogen and Fuel Cell Information System [cited 2020 16th June]; Available from: http://www.h2data.de/.

[b] [Data Source] OFX. Historical Exchange Rates 2020 [cited 2020 16th June]; Available from: https://www.ofx.com/en-au/forex-news/historical-exchange-rates/.

[c] [Data Source] Chemical Engineering. Plant Cost Index Archives 2020 [cited 2020 16th June]; Available from: https://www.chemengonline.com/site/plant-cost-index/.

Table B. 1 - Hydrogen and Currency Conversion Data.

Source	Year of Publication	Hydrogen Production Technology	Production Rate (as in source)	Production Rate (kg/day)	CAPEX (as is in source)	CAPEX (£2019/ kW)	Hydrogen Production Cost (as in source)	Hydrogen Production Cost (£2019/kg) – Year given
[88]	2017	SMR[7]	379387 kg/day	397387	NA	NA	$2.08/kg	1.73
[297]	2017	SMR[1]	100000 Nm^3/h	215760	€170.95m	536	11.4c/Nm^3	1.19
[93]	2017	SMR[8]	NA	NA	£315/Kw	337	3.5p/kWh	1.25
[298]	2020	SMR[1]	NA	NA	€$_{2017}$8.7/GJ/y	258	NA	NA
[101]	2019	SMR[9]	107.4 kNm^3	231726	£261m	811	NA	NA
[297]	2017	SMR (with CCS) Upper Limit[10]	100000 Nm^3/h	215760	€201.8m	633	13.5c/Nm^3	1.41
		SMR (with CCS) Lower Limit[11]	100000 Nm^3/h	215760	€305.3m	958	16.5c/Nm^3	1.72
[88]	2017	SMR (with CCS)[12]	379387 kg/day	379387	NA	NA	$2.27/kg	1.89
[93]	2017	SMR (with CCS)[13]	NA	NA	£409.5/Kw	438	3.5p/kWh	1.25
[298]	2020	SMR (with CCS)[14]	NA	NA	€$_{2017}$14.5/GJ/y	430	NA	NA
[88]	2017	ATR[15]	NA	NA	$499.23/kW	415	$1.48/kg	1.23
[101]	2019	ATR[2]	107.4 kNm^3	231726	£195m	606	NA	NA
[273]	2019	LCH[16]	100kNm^3	215760	£253.9m	847	NA	NA
[101]	2019	LCH (with CCS)[7]	107.4kNm^3	231726	£159m	494	NA	NA
[88]	2017	Gasification (without CCS)[2]	139.7tn/day	139700	$149.3m	640	$1.77/kg	1.47
		Gasification (without CCS)[2]	2tn/day	2000	$6.4m	1916	$2.05/kg	1.71
[298]	2020	Gasification (without CCS)[2]	NA	NA	€$_{2017}$48.27/GJ/y	1431	NA	NA

[7] Based on conventional SMR process. Where, syngas from WGS is fed to PSA. CO_2 in PSA tail gas is fed back to SMR and leaves as flue gas to the atmosphere.
[8] No detailed process description could be identified.
[9] Majority of CO_2 located in flue gas stream.
[10] Carbon is captured from flue gas using MEA. Processes included within CCS cost assessment include cooling, absorbing, stripping, compression, dehydration, transportation and storage.
[11] Carbon is captured from shifted syngas using MDEA. Processes included within CCS cost assessment include absorbing, stripping, compression, dehydration, transportation and storage.
[12] Carbon is captured from shifted syngas using an amine solvent. Processes included within CCS cost assessment include absorbing, stripping, compression, transportation, injection and storage.
[13] No detailed process description could be identified so carbon capture technology is unknown. CO_2 transportation and storage costs are included in cost assessment.
[14] Carbon is captured from shifted syngas using chemical absorption. CO_2 compression, transportation and storage costs are included in cost assessment.
[15] 90% carbon capture is observed using ceramic ion transfer membranes. CO_2 transportation and storage costs are not included in this cost assessment.
[16] All CO_2 contained within product stream.

[125]	2015	Gasification (without CCS)[2]	NA	NA	£3708/kW	4046	NA	NA
[93]	2017	Gasification (without CCS)[2]	NA	NA	£1700/kW	1820	3.4p/kWh	1.21
[125]	2015	Gasification (with CCS)[7]	NA	NA	£4902/kW	5348	NA	NA
[93]	2017	Gasification (with CCS)[7]	NA	NA	£2100/kW	2248	3.6p/kWh	1.28
[88]	2017	Nuclear Thermolysis (Cu-Cl Cycle)	7tn/day	7000	$39.6m	3388	$2.17/ kg	1.80
[299]	2019	Nuclear Thermolysis (Cu-Cl Cycle)	4.25kg/s	390528	$400.23m / unit	579	$2.63/ kg	2.24
[88]	2017	Nuclear Thermolysis (S-I Cycle)	583tn/day	583000	$2107.6m	2165	$2.86/ kg	2.19
[299]	2019	Nuclear Thermolysis (S-I Cycle)	0.68kg/s	58752	$100.00m / unit	961	$2.83 /kg	2.22
[299]	2019	Nuclear Thermolysis (S-I Cycle)	0.77kg/s	66528	$143.00 m/ unit	1213	$2.37/ kg	1.86
[93]	2017	Electrolysis	NA	NA	£900/kW (electrical input)	963	7p/kWh	2.50
[300]	2016	PEM Electrolysis	NA	NA	NA	NA	$5.11 /kg	4.25
[107]	2018	PEM Electrolysis	NA	NA	£600/kW(electrical input)	604	NA	NA
[107]	2018	Alkaline Electrolysis	NA	NA	£750/kW (electrical input)	755	NA	NA
[301]	2019	Alkaline Electrolysis	NA	NA	€750/kW (electrical input)	659	NA	NA
[300]	2016	SOEC Electrolysis	NA	NA	NA	NA	$4.96/ kg	4.12
[107]	2018	SOEC Electrolysis	NA	NA	£1640/kW (electrical input)	1652	NA	NA

Where applicable, the available data retrieved from the sources highlighted was converted into consistent units for hydrogen production rate, CAPEX and hydrogen production costs using the data shown in Table B.1.
For CAPEX and Hydrogen Production Costs, all values shown are representative of £$_{2019}$ value. This was calculated using the Chemical Engineering Cost Index. Please see the equation used below (Equation B.1).

Table B. 2 - Data as Retrieved from Literature Review and Calculated Values After Conversion to CAPEX (£$_{2019}$/kW) and Hydrogen Production Cost (£$_{2019}$/kg).

$$\mathrm{Cost}_{\mathrm{Year2}} = Cost_{Year1} / \left(\frac{Index_{Year1}}{Index_{Year2}}\right) \qquad B.1$$

Equation B. 1 - Equation Used to Convert CAPEX and Hydrogen Production Costs to £$_{2019}$ Equivalent.

	SMR	SMR With CCS	ATR	LCH	LCH With CCS	Biomass Gasification	Biomass Gasification With CCS	Nuclear Thermolysis	Electrolysis
	CAPEX (£$_{2019}$/kW)								
Upper	536	958	606	494	847	4046	5348	3388	604
Median	486	615	511	494	847	1971	3798	1661	927
Lower	258	430	415	494	847	640	2248	579	1652
	Hydrogen Production Cost (£/kg)								
Upper	1.73	1.89	1.23	-	-	1.71	1.28	2.24	4.25
Median	1.39	1.57	1.23	-	-	1.46	1.28	2.06	3.63
Lower	1.19	1.25	1.23	-	-	1.21	1.28	1.80	2.50

The data in this table was calculated using column 6 (CAPEX (£$_{2019/\,kW}$)) and column 8 (Hydrogen Production Cost (£/kg) of Appendix Table B. This was used to plot the CAPEX and Hydrogen Production Cost graphs illustrated in Figure 4.

Table B. 3 - Data Used to Plot Economic Graphs Shown in Figure 3 (Section 5.3) in Manuscript.

1. Nikolaidis, P. and A. Poullikkas, *A comparative overview of hydrogen production processes.* Renewable and Sustainable Energy Reviews, 2017. **67**: p. 597-611.
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3. Speirs, J., et al., *A greener gas grid: What are the options* 2017: London, United Kingdom
4. Navas-Anguita, Z., et al., *Prospective techno-economic and environmental assessment of a national hydrogen production mix for road transport.* Applied Energy, 2020. **259**: p. 114121.
5. Cotton, B. *Hydrogen from Natural Gas Through Cost Effective CO2 Capture* Clean Hydrogen 2019.
6. Progressive Energy, *HyNet Low Carbon Hydrogen Plant* in *Phase 1 Report for BEIS* 2019.
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