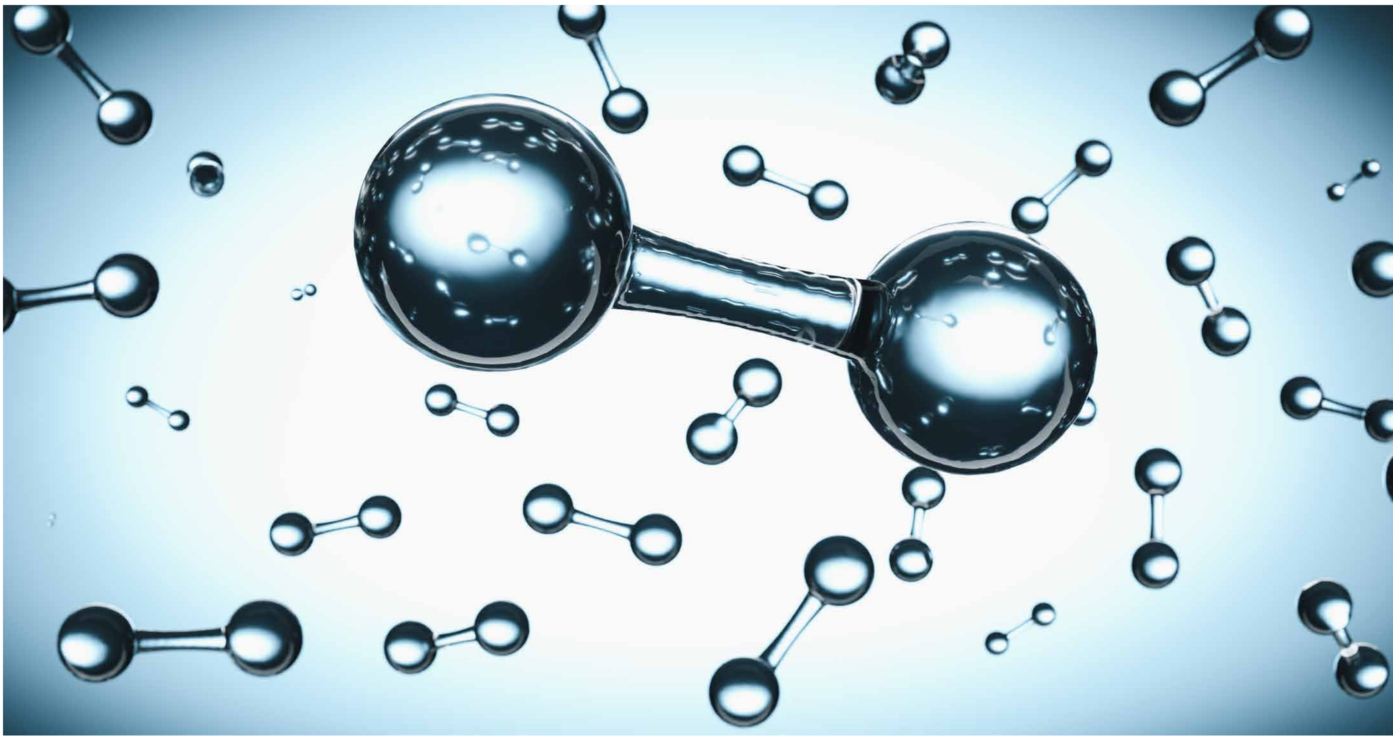
The Institution of Engineering and Technology

Hydrogen's potential as a fuel for road transport

A guide to the key factors that will determine hydrogen's future as a sustainable road transport fuel.

theiet.org/transport



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Please note that the views expressed in this publication are not necessarily those of the IET. This report only intends to identify the relevant issues and to inform a public policy debate around the topic, rather than to provide any definitive solution.

The IET Transport and Energy Sector Panels welcome comments on the contents of this report as well as ideas for future digital publications. Please get in touch by emailing **sep@theiet.org**.

The Institution of Engineering and Technology

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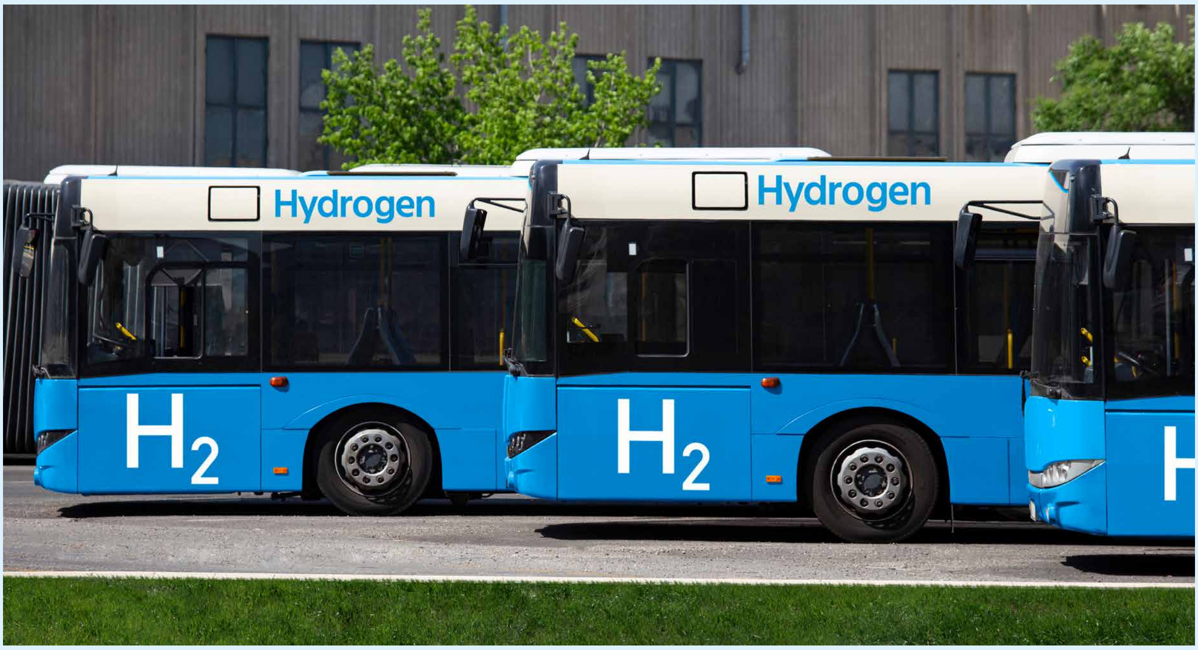

Hydrogen's potential as a fuel for road transport has been produced by the Institution of Engineering and Technology (IET) to examine the role played by fuel grade hydrogen in the UK Government's pathway to net zero carbon dioxide emissions by the mid-21st century. Hydrogen fuel is an emerging player in the road transport energy mix and part of a portfolio of green energy solutions that are at different points on their evolutionary timelines for replacing fossil fuels – petroleum-based petrol and diesel. This report is written for government, policymakers, transport industry and technology professionals.

Hydrogen could be a clean and flexible energy source that can support zero-carbon energy strategies, if production methods are selected to eliminate or minimise climate impact and infrastructure is developed effectively. Hydrogen powered road vehicles – more correctly 'fuel cell electric vehicles' (FCEVs) – come armed with some advantages over other road vehicles. The primary advantage is that there are no harmful emissions at the point of use – once produced, hydrogen generates electrical power in a fuel cell, emitting only water vapour and warm air. The use of hydrogen as a combustible fuel would also eliminate oil dependency and depending on the production methods reduce overall greenhouse gas (GHG) emissions.

The main low carbon and zero emission alternative technology to hydrogen is battery electric technologies. Battery electric vehicles (BEVs) are well established and are likely to be the most effective solution in many common road transport applications, including for cars and commercial vans. However, FCEVs could meet the requirements of some road transport applications more effectively than BEVs, especially when the speed of refuelling is a priority and/or if the vehicle has a large or heavy payload. Because of these positive attributes, FCEVs promise to play an important role in the UK's road vehicle future, as well as having the potential to form the core of corporate sustainability programmes.

But there are challenges with the introduction of FCEVs which need to be overcome if hydrogen is to realise its potential as a sustainable fuel for road transport. Importantly, not all forms of hydrogen production are inherently 'low carbon'; the environmental credentials of hydrogen depend on its production methods and there is currently no widespread hydrogen distribution and refuelling infrastructure. From a consumer perspective, FCEVs are expensive with fewer consumer options for vehicle choice, and hydrogen technology in vehicles is less mature than BEVs, so may not be as durable in the long run. There is also the need for public education to accelerate the understanding of hydrogen's potential benefits.

Hydrogen fuel has the potential to become a key player in the sustainable energy transport sector. Factors that will influence the role of hydrogen in transport include the requirements of different transport applications for rapid refuelling and heavy payloads, consumer awareness and choice, and the development and maturity of low and zero carbon hydrogen production and fuelling infrastructure.

This report was written by members of the IET Transport Panel, the IET Energy Sector Panel, and an expert volunteer group that creates thought leadership and policy advice to inform government, regulators and communication sectors. The authors of this report are:

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Gareth is a Chartered Chemical Engineer who has specialised in net zero and decarbonisation, particularly with regard to hydrogen production, distribution and use in the transport sector and for industrial heat. He is currently advising the Environment Agency on producing hydrogen from electrolysis and led a hydrogen demand assessment for vehicles for Cardiff Council, on behalf of Welsh Government. This investigated the feasibility of hydrogen demand from different types of road vehicle, when integrated with a hydrogen supply from an innovative scheme to generate biohydrogen from waste biogas.

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As a Transport Energy and Clean Mobility Adviser, Jamie brings excellent strategic and practical knowledge of the decarbonised transport infrastructure industry. He has experience in end-to-end battery electric vehicle infrastructure planning, design and delivery as well as undertaking strategic studies around the potential demand for hydrogen powered fuel cell electric vehicles, most recently for Cardiff Council, Welsh Water and Welsh Government. Previous roles in decarbonised transport space include B2B EV lead at EDF and Clean Mobility Infrastructure Funding Consultant for Horizon Energy Infrastructure. These positions have given him deep experience and expertise around the challenges and opportunities involved in the roll out of zero emissions road transport solutions for large scale private and public sector entities.

2. Introduction

The Challenge

Transport and the environment

- The largest emitting sector in the UK in 2019 was transport, responsible for 27 percent of all GHG emissions.
- The main source of transport sector emissions in 2019 was petrol and diesel fuel for road vehicles.
- In its 10-point plan for a green industrial revolution, the UK Government has committed to reaching net zero by 2050, as set out in its *Net Zero Strategy: Build Back Greener*[1] publication.

The UK Government has laid out a framework to achieve a net zero emission transport network before 2050. Sustainably produced electricity, hydrogen and other zero-carbon fuels need to become the dominant energy sources to achieve this.

There is significant focus on electricity as a viable alternative energy source for road transport, and in many cases battery electric vehicles (BEVs) are likely to be the most appropriate option. However, hydrogen has the potential to provide another alternative, particularly for certain applications where the characteristics of hydrogen are an advantage for the consumer. This report summarises:

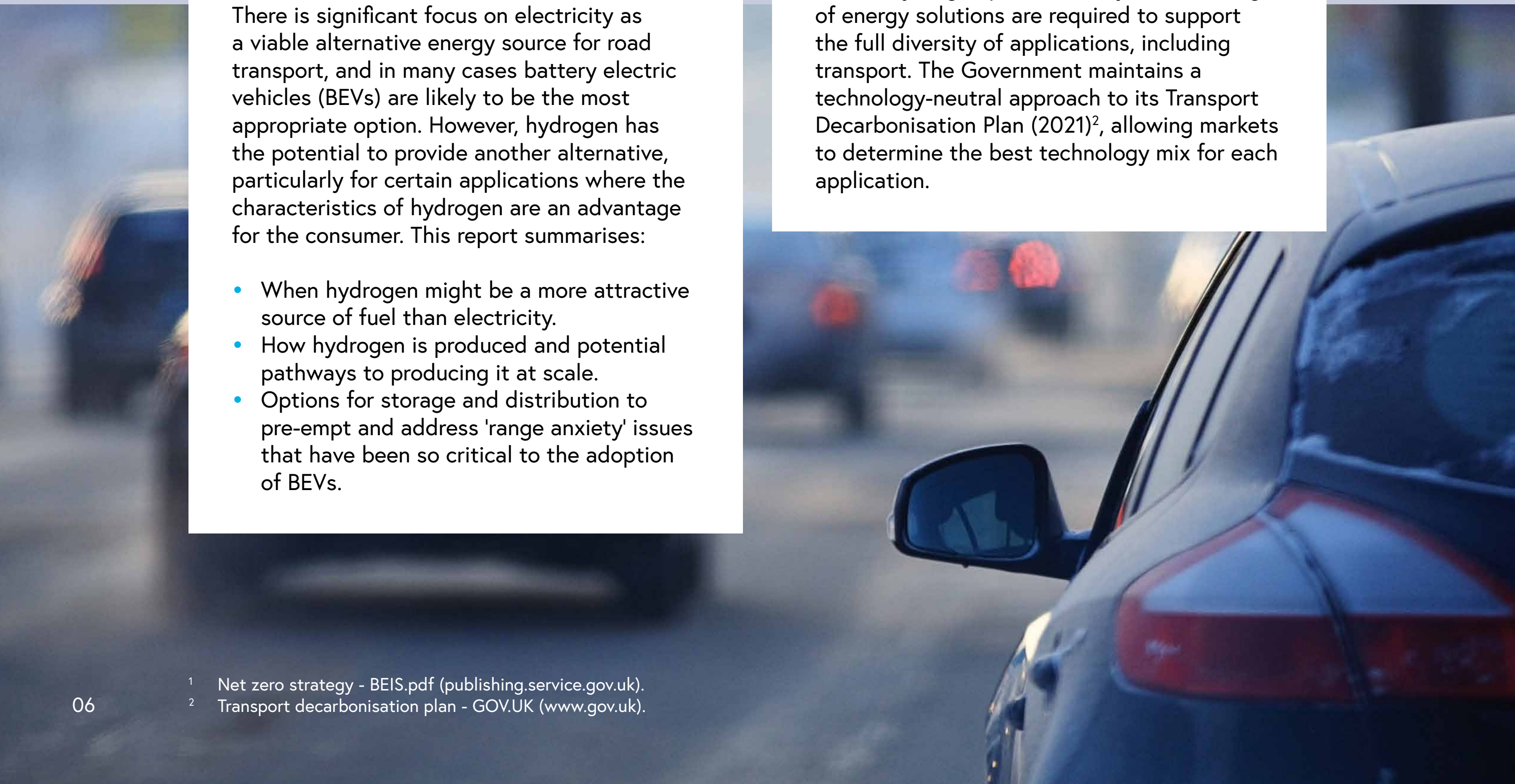
- When hydrogen might be a more attractive source of fuel than electricity.
- How hydrogen is produced and potential pathways to producing it at scale.
- Options for storage and distribution to pre-empt and address 'range anxiety' issues that have been so critical to the adoption of BEVs.

The UK's strategy

Net Zero Strategy: Build Back Greener states the UK Government's four key approaches to ending the UK's domestic contribution to climate change by 2050.

1. Working 'with the grain of consumer choice'.
2. Ensuring that the biggest polluters pay the most for the transition through fair carbon pricing.
3. Ensuring that the most vulnerable are protected through Government support.
4. Working with businesses to deliver cost reductions in low carbon technology.

The strategy states that the net zero economy will be underpinned by cheap, clean electricity generated in the UK, alongside 5GW of low carbon hydrogen production by 2030. A range of energy solutions are required to support the full diversity of applications, including transport. The Government maintains a technology-neutral approach to its Transport Decarbonisation Plan (2021)[2], allowing markets to determine the best technology mix for each application.



[1] Net zero strategy - BEIS.pdf (publishing.service.gov.uk).
[2] Transport decarbonisation plan - GOV.UK (www.gov.uk).

3. Consumer choice

The situation today

At the end of 2020 there were 38.6 million licensed road vehicles[3] in the UK ranging from scooters carrying individuals over short distances, to heavy goods vehicles (HGVs) carrying large freight loads over long distances. Most were powered by petrol or diesel.

Changes in demand and vehicles

2020 was a landmark year for alternative fuel cars, as more of this type of vehicle were registered than petrol or diesel cars for the first time. This focus on alternative fuel car registrations will increase by 2030, when the sale of new petrol and diesel cars will be banned.

Society's transport demands and preferences may also change over time, affected by factors including societal attitudes, climate emergency and technological advances. Other factors include:

- **Widespread availability** of ultra-low emission vehicles (ULEVs)
- **Growth in e-commerce** and reduced commuting (accelerated by the Covid pandemic)
- **Accessibility and increase** in car-share behaviours
- **Accessibility and growth** of 'micromobility' (use of vehicles such as bicycles, e-bikes, electric scooters, electric skateboards and electric pedal-assisted 'pedelec' bicycles)
- '**Active travel**' (cycling, walking etc), promoted in the UK's *Gear Change strategy*
- **Greater uptake** of public transport use.

Working towards the hydrogen economy

Hydrogen transport solutions are being investigated for use in road, rail, bulk shipping and long-haul aviation. Beyond transport, hydrogen use is being investigated for manufacturing, energy storage and heating, meaning that a future UK hydrogen economy could emerge. The volume and variety of hydrogen uses within a geographic area will dictate hydrogen demand: this will drive supply and infrastructure development. As the use of hydrogen increases across these diverse sectors there is almost certain be a greater application of hydrogen vehicles.

These factors, along with technology innovations (such as connected and autonomous vehicles) will present increased choices to consumers. So, it is anticipated that consumers will increasingly need more easily accessible information to enable them to make their most effective transport decisions. For that reason, the *UK Hydrogen Strategy* (2021)[4] commitment to continued support for transport decarbonisation is most welcome. This includes: deployment, trials and demonstration of hydrogen buses, HGVs, shipping, aviation and multi-modal transport hubs. One example of this support is the £3 million being invested in the UK's first multi-modal hydrogen transport hub in Tees Valley in response to the masterplan produced in 2021.

[3] Vehicle licensing statistics: annual 2020 (publishing.service.gov.uk).
[4] UK hydrogen strategy - GOV.UK (www.gov.uk).

Case study 1 Tees Valley

March 2021 saw the publication of the UK Government's Tees Valley Multi-Modal Hydrogen Transport Hub Masterplan, outlining a Department for Transport (DfT) initiative to establish the Tees Valley hydrogen transport hub (HTH).

This HTH is envisioned as a large-scale, long-term initiative that will make the region (and the UK) a pioneer in hydrogen-powered transport research and development. It provides a 'living lab' acting as a catalyst for the fulfilment of green hydrogen's role in decarbonising transport in sectors ranging from road vehicles through to domestic aviation. The DfT's aim is to establish Tees Valley as a model for "*positioning the UK as a global leader in energy transition.*"

The documents states:

> "*Ultimately the purpose of the Hub will be to deliver evidence to support the use of hydrogen for transport that will inform the DfT's long term strategy, and the role it may play in supporting the decarbonisation of the transport sector in the UK.*"

The Hub will comprise a set of facilities for the production, storage and distribution of green hydrogen linked to a network of hydrogen refuelling stations that will service operational trials across transport modes in the period 2025-2030. Prior to this, there are opportunities for demonstrators to test and learn from hydrogen-transport technologies, with the DfT procuring temporary refuelling infrastructure from HRS developer Element2.

Green hydrogen projects at the hub will contribute to future large-scale hydrogen-based operational trials, while supporting long-term groundwork for the hub. All projects use hydrogen vehicles in an operational setting to replace, complement or add to existing transport fleets or operations. Toyota is delivering several hydrogen vehicles, including a forklift truck, a passenger bus and 10 fuel cell passenger cars. These cars will be deployed in rapid response services, such as Cleveland Police and NHS patient support. A further funding call to increase the scale of the activity is expected to be announced later this year.

Commenting on the initiative, Secretary of State for Transport Grant Shapps said:

> "*By harnessing the power of hydrogen technology, we can pave the way for its use across all transport modes, creating cleaner, greener more efficient transport systems across the UK.*"

www.gov.uk/government/publications/tees-valley-multi-modal-hydrogen-transport-hub

Ultra-low emission vehicles (ULEVs) explained

ULEVs emit less than 75g/km (grammes of carbon dioxide per kilometre driven) and are classed as alternative fueled vehicles. Battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and hydrogen fuel cell electric vehicles (FCEVs) are all classed as ULEVs.

Most ULEVs use electricity or hydrogen to drive an electric motor that powers the wheels, with automotive batteries used to store energy on the vehicle. In BEVs, batteries are recharged by plugging the vehicle into a dedicated chargepoint or an ordinary electrical socket connected to the mains electricity supply. FCEVs can be replenished at hydrogen refuelling stations, with fast refuelling (typically five minutes). Their range is typically more than 480km (300 miles).

User considerations

Factors influencing vehicle design have historically gone beyond form and function, to reflect consumer considerations such as price, fuel-economy, on-board technology, ease of maintenance, brand alignment and aesthetics. As emphasis on environmental credentials increases, the most economic and environmentally conscious choice for most households (or private consumers) who require personal motorised transport will be a BEV.

Choices made by fleet operators tend to be more complex due to more operational factors and cost sensitive (see Figure 1).

Key features of hydrogen fuel cell electric vehicles (FCEVs)

FCEVs and BEVs are more energy efficient than internal combustion engine-based (ICE) vehicles. They recover energy through the conserving technique of regenerative braking, with hydrogen supplying peak power for rapid acceleration and steep gradients.

Hydrogen has a higher energy density than electric battery systems, but a lower energy density compared with petroleum fuels. Stored as a compressed gas, it yields a similar range to conventional ICE vehicles, but unlike BEVs, does not need cabin space for large batteries.

Figure 1 – Fleet operator vehicle selection criteria.

Vehicle profile
- Payload/weight
- Use cases
- Quantity of vehicles
- Vehicle lifetime

Travel profile
- Daily distance
- Route location: urban, rural, mixed
- Predictability: of routes & distances

Use profile
- Daily duration
- Days of use/week
- Rest periods between trips: duration & location

Refuelling profile
- Locations
- Power source
- Spare capacity

Business profile
- Business objectives
- Investment plans: vehicles & infrastructure
- Sustainability
- Procurement plans

Battery electric vehicles (BEV) versus hydrogen fuel cell electric vehicles (FCEV)

	BEV	FCEV
Vehicle cost	Best	
Vehicle choice	Best	
Refuelling infrastructure availability	Best	
Refuelling time		Best
Efficiency	Best	
Running costs		Best

The principal user advantages of hydrogen powered vehicles are their short refuelling time (comparable with petrol station dwell time), as well as their comparable range and that comparable payloads can be achieved without adding to vehicle weight.

The range of a hydrogen powered vehicle is broadly comparable to its petrol or diesel counterpart but, as the UK's EV roll-out has demonstrated, having readily available refuelling points in the right locations (and in sufficient quantities) is necessary to give consumers the confidence to adopt alternative fueled vehicles.

Use case #1: Emergency fleet service

Police, ambulance and fire services emergency response vehicles need to be on standby 24/7, prepared for travel over unpredictable distances and over urban and rural terrain. Due to the requirement to carry life-saving equipment, many have heavy payloads. Such equipment needs to be powered from the vehicle's energy resources. Emergency response vehicles therefore may benefit from long-range capability with short refuelling times. While zero emissions have become an important consideration, availability of hydrogen refuelling points is a critical factor influencing the specification of alternative fuel vehicles in this sector (see Figure 2).

Figure 2 – An emergency fleet use case at a glance.

Emergency vehicle fleet manager

"Our vehicles must be ready to go anywhere whenever a call comes in so we need quick turnaround times, and powering the life-saving equipment on our vehicles is also a key requirement"

Daily routine

Unpredictable journeys | Little time to recharge | Heavy payload | High energy requirement | Varied topography

Goals & motivations
- Quick response, life-saving service
- Environmental
- Cost

Considerations
- High daily energy requirement
- High reliability required – both vehicle & powered equipment
- Musn't reduce response times
- Where can we stop to replenish energy quickly?

Use case # 2: Road freight service

During the Covid-19 pandemic personnel involved in the production and distribution of food, drink and essential goods were classified as critical.[5] By extension, associated road freight is an essential logistical component. Goods are moved long distances between distribution centres and stores across the UK with time-critical delivery schedules. Payloads are heavy and can require additional services such as refrigeration for food and medicines (see Figure 3).

While cost is a primary consideration for road logistics fleet managers, reduction of environmental impact is becoming increasingly important. Improvements to ICE technology and bio-fuel alternatives have emerged, but cleaner solutions are required. A disadvantage of BEVs is that battery weight needs to be factored into payload viability, while lengthy recharging durations affect delivery schedule efficiencies. Other options such as electric road systems (where power is delivered via overhead catenary systems) and hydrogen are currently being explored.[6]

Figure 3 – A supermarket logistics use case example.

Supermarket chain fleet manager

"We really need to cut the emissions from our distribution HGVs carrying products across the country"

Daily routine

Long journeys | Little time to recharge | Heavy payload | Varied topography | Fresh produce

Goals & motivations
- Environmental impact
- Company image
- Cost

Considerations
- High daily energy requirement
- High vehicle utilisation
- Where can we stop to replenish energy quickly?
- Musn't increase our delivery times

[5] https://www.gov.uk/guidance/essential-workers-prioritised-for-covid-19-testing
[6] Zero emission transport – long-haul heavy goods vehicles (catapult.org.uk).

Case study 2 Commercial Limited

Cheltenham-based Commercial is the UK's largest independently owned business services provider, committed to achieving carbon Net Zero by 2028. To do this, the company will be providing zero-emission deliveries to its clients, with hydrogen and electric renewable energy a key focus. Commercial has retrofitted its Ford Transit delivery fleet with hydrogen tanks as part of its commitment to sustainable best practice and cutting its carbon footprint.

Having worked with several consortia researching zero-emission fleets, the company feels well-equipped to push the boundaries of exploring sustainable transport options: *"We advocate the importance of businesses trialling new advancements and approaches, including researching the viability of decarbonisation technologies."* Commercial is continuing its research into electric vehicles *"which are ideal for our car fleet."*

> *"For us, hydrogen was the most viable source of sustainable fuel, based on our requirements for medium-to-long-haul and heavy-payload-capable light vans. Renewable energy is a key focus for us, as our delivery fleet represents our largest individual source of emissions."*

In 2019, Commercial integrated 12 hydrogen-powered vans into its portfolio, making it the UK's largest privately-owned fleet of hydrogen-fuelled vans. Apart from hydrogen being a 'zero-tailpipe' emission fuel, the company sees the main benefit of hydrogen power as the potential to carry out carbon free deliveries without 'range anxiety'. Working alongside hydrogen for transport company Ulemco, Commercial also produces valuable real-time data for its deliveries.

Reflecting on the way the company now makes its deliveries, Commercial says that the two main challenges for hydrogen adoption are: *"financial (in terms of retrofit and running) and its carbon footprint (retrofit and maintenance of the vehicles). However, even with these challenges for our business model, hydrogen by far outweighs a diesel or petrol option from an environmental perspective."* Overall, the company recommends hydrogen, while advising others of the importance of being self-sufficient in terms of refuelling options.

Commercial's hydrogen-powered fleet has not only reduced emissions, but raised awareness of sustainability issues, *"both in our organisation and with customers, suppliers and partners, through marketing campaigns, client collaboration and communication."*

www.commercial.co.uk

Use case # 3: Specialist local public services

Refuse collection, gritting and street cleaning operate in residential areas, making emission reduction important to local councils responsible for these services. These vehicles have significant on-board energy demands and require high energy density solutions. Service schedules along predictable routes include downtime between shifts to refuel (see Figure 4). Hydrogen refuelling systems can be installed in central depots to supply multiple types of vehicles on their return to base or to common destinations (such as waste to energy plants).

Figure 4 – A refuse collection use case.

Refuse collection fleet manager

"Our heavy vehicles spend lots of time moving slowly through housing areas, so we want to reduce their impact on residents"

Daily routine

- Predictable journeys
- Urban areas
- Heavy payload
- Central depot & destination

Goals & motivations

- Environmental impact
- Social responsibility
- Cost

Considerations

- High daily energy requirement
- High vehicle reliability required, in all weathers
- Downtime available to replenish energy between shifts
- Energy & space needed to replenish energy at depot or waste disposal site

Use Case #4: Bus services

Buses normally operate in local areas where air quality improvements are a priority. Time for refuelling and recharging between scheduled services can be minimal, especially if delays occur due to road network congestion (see Figure 5). Hydrogen-powered buses emit only water and heat as by-products of the journey, and the heat can be reused to maintain passenger comfort while increasing energy efficiency. Bus routes are predictable, with vehicles returning to a central depot at the end of each shift or between scheduled services with minimal downtime, allowing refuelling infrastructure to be centrally located to support an entire fleet.

Figure 5 – A bus use case.

Bus fleet manager

"Our heavy vehicles spend lots of time in housing areas and in heavy traffic, so we want to reduce their impact on residents and road users"

Daily routine

- Predictable journeys
- Heavy payload
- Little in-shift time to recharge

Goals & motivations

- Environmental impact
- Social responsibility
- Cost

Considerations

- Musn't hinder punctuality
- Musn't reduce passenger capacity
- Musn't reduce passenger journeys
- Different energy requirements – rural v urban routes

Use case # 5: Construction and agriculture services

Heavy-duty vehicles used in off-road applications such construction or agriculture consume large amounts of energy in challenging terrains, so would require very high-capacity batteries to operate as BEVs, adding to vehicle weight and reducing energy efficiency. They can also be difficult to transport and can be in-use for long durations, so on-site refuelling is a requirement. Hydrogen-powered vehicles could be better suited to these environments, as supplies of hydrogen can be transported to site for remote refuelling, with the added advantage of incurring minimal downtime.

Figure 6 – A construction vehicle use case.

Construction vehicle fleet manager

"Cutting carbon from construction activities is key but some vehicles we use are difficult to transport, on-site refuelling is essential."

Daily routine

High energy requirement | On site refuelling needed | Varied topography | Little in-shift time to recharge

Goals & motivations

- Environmental impact reduction
- Quick refuelling time to maximise availability
- Cost

Considerations

- High energy use for powered equipment
- Vehicles are captive on site
- High reliability and availability required – both vehicle and powered equipment

Summary: Consumer choice

BEVs are likely to remain the most widespread choice for sustainable road vehicles. But hydrogen presents as a viable option in applications where:

- **There is an essential requirement to fully recharge in less than ten minutes, such as with emergency response vehicles.**
- **Weight and payload cannot be compromised to accommodate batteries.**
- **Availability of an electricity supply is an issue, such as in off-highway usage in construction, or remote rural areas.**

FCEVs have an advantage over BEVs in being the most similar alternative fuel to petrol or diesel in terms of the user experience related to the time taken to refuel and energy storage space requirements. However, these vehicles and their refuelling infrastructure have a 'chicken and egg' relationship; and both are currently in the early stages of development and roll-out in the UK.

This leads to the conclusion that initially hydrogen could become be a place-based transport solution, suited to areas where hydrogen is produced and has multiple uses and therefore circular economies are possible. In the longer term though, it is entirely possible that a network of refuelling infrastructure could be developed, aimed particularly at fleet operators of vehicles that need to be on the road most of the time or where there is significant payload or vehicle weight.

4. Hydrogen production

Hydrogen production requirements for road transport

Appropriate hydrogen production solutions, locations and scales will depend heavily on the take-up of hydrogen across all applications; so a future hydrogen production sector in the UK will not be serving road transport alone but would form part of an overall hydrogen economy. For the road transport applications identified as potential use cases for hydrogen (see use cases 1 to 5), uptake will likely depend on the environmental drivers for the organisations and institutions that operate these vehicles, as well as the availability of vehicle technology and the availability and reliability of hydrogen fuel supplies. Until these aspects are in place, vehicles that are not suitable for electrification are likely to continue to be fuelled using fossil fuels, or potentially converted to another alternative fuel. It is therefore difficult to accurately predict the scale and timing of hydrogen production that might be called for to support demand from this sector.

How hydrogen is produced

Different hydrogen production methods include:

Electrolysis of water: Using electricity to convert water into hydrogen and oxygen.

Reformation of fossil methane: Converting hydrocarbons from natural gas or other fossil fuels to produce hydrogen and carbon dioxide.

Hydrogen from biomass: Non-combustion gasification of biomass crops or waste streams, or biomethane reformation.

Hydrogen as a by-product of industrial processes: For example, the chlor-alkali process, which is used to make chlorine and sodium hydroxide, or as a by-product of the sewage treatment process.

Carbon intensity should be a key consideration when selecting a fuel for road transport. This must be considered on a whole system basis (i.e. from source energy extraction, through to its end use). Among the lowest carbon approaches include production of hydrogen from some biomass or industrial processes. When coupled with carbon capture and storage (CCS) technologies, production of hydrogen from sustainably sourced and transported biomass could be carbon negative. But hydrogen production from biomass processes will not be scalable to the levels needed to provide the kind of systemic change needed internationally to achieve net zero because:

- **Production of fuel crops** for biomass energy production has land use and biodiversity limitations.
- **Hydrogen from waste biomaterial** cannot be scaled beyond the production capabilities of the underlying processes.

Whilst these opportunities should be leveraged when they are present, scaling issues mean that these hydrogen production methods are unlikely to form a significant proportion of the hydrogen market. However, it is viewed as an early enabler, with BEIS promoting the development of bio-hydrogen in the UK for instance.

For production of hydrogen at scale, electrolysis of water and methane reforming are the two most viable options and are therefore the focus of the remainder of this section. The carbon intensity of electrolysis of water is dependent on the electricity source used, and electrolysis using renewable electricity (green hydrogen) is considered very low or zero carbon. Unabated methane reformation of natural gas is highly carbon intensive. This can be reduced with the use of CCS, though even with this the technology is not zero carbon. These two methods are compared in Table 1: Comparison of the most viable options of hydrogen production at scale.

Colours of the hydrogen spectrum

Different hydrogen production technologies are given colour-coded names; there is no physical difference between the different types of hydrogen, but the colours are used to signify the production methods used to create it. This can be a useful method of referring to production techniques, but it can also be imprecise, for example, 'blue hydrogen' might have very varied proportions of CCS deployed meaning they have very different carbon intensities, and hydrogen produced from nuclear energy is sometimes called yellow, or pink hydrogen, which can create confusion. The end-product remains the same and vehicles are not restricted to any given colour.

GREEN	Electrolysis of water using only renewable electricity.
GREY	Methane reformation using natural gas.
BROWN	Hydrogen production from coal.
BLUE	Fossil methane reformation using CCS to reduce carbon intensity.

Table 1 – Comparison of the most viable options of hydrogen production at scale.

Electrolysis of water	Reforming of fossil-based methane
Produced from electricity and water using electrolysers. Technologies include Proton Exchange Membrane (PEM), Alkaline and Solid Oxide. If the electricity is: – Created 100% from renewable electricity, it is called green hydrogen. – Created from nuclear energy is called yellow/pink hydrogen.	**Produced** from natural gas or other fossil fuels using steam methane reformation (SMR). – When carbon capture and storage (CCS) is used to prevent carbon emissions, it is called blue hydrogen. – Otherwise, it is often referred to as grey hydrogen (from natural gas), or brown hydrogen (from coal).
Requires electricity and water.	**Requires** fossil natural gas, water, heat energy.
Produces hydrogen and oxygen.	**Produces** hydrogen and carbon dioxide.
Zero carbon roadmap[7]: Carbon emissions are associated with the source of electricity: – Green hydrogen is inherently zero carbon. – The carbon intensity of hydrogen from nuclear electricity is up to 5 gCO_2e/MJ. – When hydrogen is produced using electricity from the National Grid, it is dependent on the generation mix used. Currently, in Great Britain, this might be about 75 to 100g CO_2e/MJ, although this is expected to rapidly decarbonise, falling under 5gCO_2e/MJ by 2040 and beyond.	**Zero carbon roadmap:** Emissions are from two main sources: – From the production itself, can be more than 75 to 100 CO_2e/MJ (although this can be reduced by CCS technologies to 10 to 45 gCO_2e/MJ). – CO_2 and methane emissions from gas processing, including leaks and venting, make a significant contribution to climate change. There are various schemes to aim to limit the impact of this. However, research suggests that the extent of methane venting (which is around 30 times worse as a greenhouse gas than CO_2[8]) may be much larger than previously thought.[9]
Cost[10]: The main cost is that of the electricity. When using curtailed renewable electricity (limiting energy costs), costs could be approx. £50/MWh by 2030 for PEM and Alkali technology. Use of grid electricity could mean costs of around £150/MWh in 2030. Use of a dedicated offshore wind generation for hydrogen could cost £80/MWh in 2030.	**Cost**[10]: Estimated at around £60 to £65/MWh in 2030 (based on production at scale in illustrative 300MW or 1000MW facilities).
Benefits: Clear zero carbon roadmap relying on established renewable generation technology. Hydrogen production can be flexible, supporting the electricity system in adopting intermittent renewable energy generation. Green hydrogen is the most sustainable source, and the technologies needed already exist today.	**Benefits**: Fossil fuel supply chain is well-established. Infrastructure already exists. Blue hydrogen (using CCS) has the potential to provide low carbon fuel (lower than electrolysis from the grid, but still higher than green hydrogen) in the next decade.
Challenges: Providing enough renewable electricity infrastructure over the next decade to hit decarbonisation targets (including grid decarbonisation as well as hydrogen production). Use of critical materials (rare earth metals) in electrolyser manufacture requires construction and deployment of enough electrolyser capacity (number of units and scale) to support hydrogen needs. There are projects underway to deploy electrolysers at scale, for example a project in South Africa's Northern Cape which could produce over 400 kilotons of hydrogen every year.[11]	**Challenges**: **No clear zero carbon roadmap**. CCS can reduce the carbon intensity of the reformation process, but extraction of natural gas results in the release of methane, a potent greenhouse gas. Blue hydrogen production is still an undeveloped industry, with only a small number of facilities in operation globally, which are achieving capture rates of only 29% to 43%. Although an instantaneous capture rate of ~95% is achievable, plant availability and reliability have affected the capture rate typically achieved to date. There are several plants planned with targets to achieve these higher rates, and the UK government business model issued in May 2021 was based on a rate of 85%, perhaps indicating the level of capture that appears likely in the future, although this target has subsequently been relaxed further.

7 Options for a UK low carbon hydrogen standard: report - GOV.UK (www.gov.uk).
8 Sixth Assessment Report — IPCC.
9 More methane in atmosphere linked to more fracking (nationalgeographic.com).
10 Levelised costs, taken from: Hydrogen production costs 2021 (publishing.service.gov.uk).
11 Sasol looking at massive Green Hydrogen project in South Africa – creating 6,000 new jobs (businesstech.co.za).

Hydrogen production pathways

How hydrogen will be produced at scale is a subject of ongoing debate. In the long term, carbon intensity characteristics of the hydrogen produced, probably as defined by the UK Government's Low Carbon standard (currently in draft)[12], will drive decision-making. This will favour renewable power (and possibly nuclear), meaning that over the next two decades green hydrogen could become the dominant technology. The pathway to reach that state remains the subject of active debate.

Viewpoint #1: A pure green hydrogen future. Hydrogen produced from renewable, and zero carbon electricity sources is the only scalable net zero production path and should be adopted as soon as possible. From this viewpoint, pursuing blue hydrogen could divert focus from development of green hydrogen and would also extend large scale fossil industries, resulting in greater environmental impact.

Viewpoint #2: Blue hydrogen as an enabler for green. Blue hydrogen is a realistic way of raising overall hydrogen production rates to provide enough hydrogen to meet growing demand short-term. From this viewpoint, blue hydrogen will support the hydrogen economy because production can be established at scale more quickly than electrolysis, until manufacture of sufficient electrolysis units becomes practical.

The UK Government has not committed to supporting one process over another and has included both pathways in its 10-point plan for a Green Industrial Revolution.[13]

As mentioned above, the UK Government is in the process of defining low carbon hydrogen standards[14], which may play a part in defining the eventual pathways taken for hydrogen production. It has also committed to funding low carbon hydrogen projects using a mix of technologies.

Summary: Hydrogen production for transport use

There are six key production requirements that will affect the adoption of hydrogen as a fuel for road transport in a net zero future.

1. **Hydrogen production and use must be developed with the whole economy in mind**. Hydrogen for road transport cannot be considered in isolation, but as part of a wider emerging low carbon hydrogen sector, which is in turn part of a wider decarbonising energy sector.

2. **Low carbon hydrogen production methods must be rolled out at scale.** There are technical and commercial barriers to at-scale production whichever pathway is chosen, but it is expected that these barriers will be overcome.

3. **Funding must be available for early, innovative projects**. Initial low carbon hydrogen production projects are unlikely to obtain funding through traditional lenders and funding mechanisms. Funding support through the government and innovative funding mechanisms will be critical to early success.

4. **Hydrogen demand must grow alongside its production.** The most viable initial projects are likely to closely connect production with the support of innovative business models and funding approaches.

5. **Standards and regulation must be established for the hydrogen sector**. Safety, quality and sustainability standards are needed to ensure that customers can be certain of the quality and safety of the fuel they are buying. Regulation needs to be in place to support a safe, fair and innovative industry.

6. **Decarbonisation of the hydrogen sector should be prioritised**. This should be supported by low carbon hydrogen standardisation and transparency to ensure net zero can be achieved. This could include carbon labelling of hydrogen to enable customer choice, which might favour lower carbon intensity production methods.

[12] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1067392/low-carbon-hydrogen-standard-guidance.pdf
[13] The ten point plan for a green industrial revolution (publishing.service.gov.uk)
[14] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1067392/low-carbon-hydrogen-standard-guidance.pdf

5. Hydrogen storage, distribution and scenarios for refuelling

Hydrogen Storage requirements

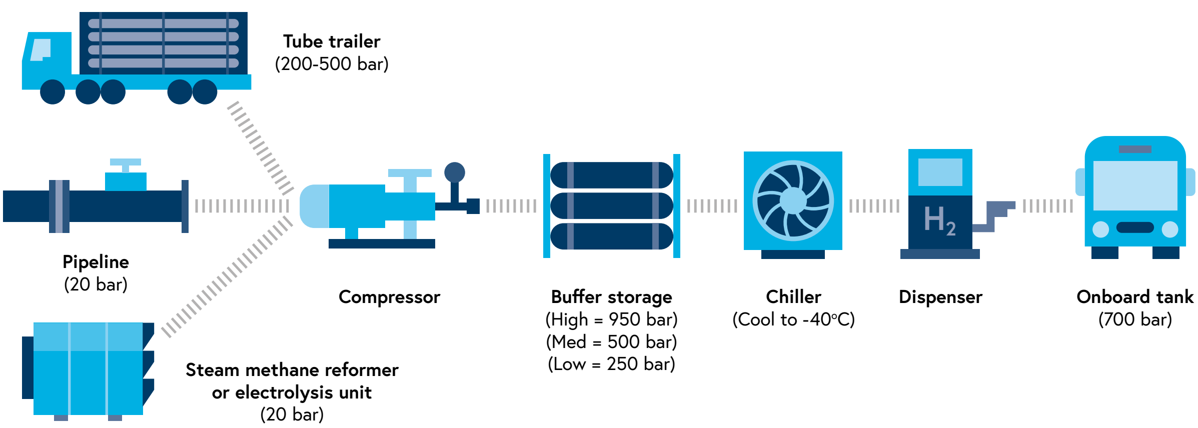
Hydrogen vehicles have an advantage over BEVs in that in performance terms, they are more comparable to petrol or diesel vehicles. This is of benefit if:

- The time needed to refuel/recharge is limited and critical.
- Access to recharge electricity supply is limited or problematic.
- Payload is heavy and bulky and cannot be compromised.

But what infrastructure will be needed to ensure this vehicle technology can refuel effectively and efficiently? As can be seen in Figure 7, from its source, hydrogen is either supplied directly or shipped by tube trailers or pipeline to the refuelling station where it is compressed, stored and chilled. It is then moved to a dispenser and is made available to the end-user.

Storage of hydrogen presents more challenges compared to fossil transport fuels: it can be stored as a compressed gas in high pressure tanks or as a liquid at around -253°C. The material properties of hydrogen also mean that it could escape storage or transport vessels easily, and as hydrogen is an indirect greenhouse gas, this needs to be prevented. This means that hydrogen refuelling stations are likely to be more complex and expensive to build than electric forecourts (assuming the maximum capacity of the local electricity grid is not exceeded), but they do provide a higher daily capacity (principally due to the shorter refuelling time) to meet increasing demand. The assumption that there is excess capacity in the local electric grid does need to be tested though; in instances where there is a potential for insufficient capacity, the provision of hydrogen refuelling stations could offer the same value for less investment compared to increasing the capacity of the local, regional or national electricity networks.

Figure 7 – Hydrogen distribution system overview.



Case study 3 NanoSUN

According to mobile hydrogen refuelling specialist NanoSUN, despite the 'promising development' of fixed hydrogen refuelling stations, "implementation of an effective hydrogen refuelling structure is slow." A typical fixed facility takes up to two years to build and can cost around £2 million. These factors hinder the adoption of hydrogen-fuelled, zero-emission vehicles, due to fleet owners struggling to fund the high capital expenditure.

NanoSUN has developed a mobile hydrogen refuelling station (HRS) that can deliver transportation-grade hydrogen directly to the point of use. Called the Pioneer, it has been designed to assist users with implementing a mobile hydrogen refuelling network until their fleets increase to the point where a fixed hydrogen refuelling station is justified.

There are several benefits to using a mobile HRS. First is that capital cost is much lower than a fixed hydrogen refuelling station, as no compressor is required at the point of delivery. Second, there is no requirement for fixed utilities such as power or water, making it ideally suited for field and mobile refuelling, while the capability for units to back each other up increases the reliability of the refuelling network.
Founded in 2017 by veterans of the industrial gases and hydrogen fuel-cell industries, NanoSUN develops hydrogen storage, distribution and dispensing technologies that enable users to operate zero-emission products. Focused on accelerating hydrogen transportation across the UK and Europe, NanoSUN's mobile HRS has been highly visible recently.

When the world's first hydrogen double-decker bus – developed by Wrightbus – drove from London to COP26 in Glasgow, it was supported on its journey by a Pioneer HRS that provided two hydrogen refuels at different locations in one day. The first hydrogen refuel was carried out at NanoSUN's green hydrogen farm in Lancaster, where the Pioneer was prepared and set up on site, ready for the arrival of the vehicle. Following the completion of the first refuel, the Pioneer HRS was packed up and followed the bus on its journey to Glasgow, where it carried out the second refuel at a Suttons Tankers site in Scotland.

www.nanosun.co.uk

Mobile storage and transporting

Currently, the most cost-effective and convenient way of storing and distributing hydrogen is in its gaseous form in high-pressure cylinders, tubes or tanks because the hydrogen economy is still very small. In the future (assuming larger demands for hydrogen) it is expected that pipelines could prove to be the most effective method of transporting large volumes of across large distances, with metal hydrides and carbon nanotubes also playing a part.

For these reasons, currently there is a reliance on trailer-based road transport to satisfy the current and near future demand for hydrogen fuel where it's needed away from the production site. There are two main types of tankers used to move compressed hydrogen by road: tube trailers and composite vessels (See Figure 8 and 9).

Refuelling Scenarios

Before exploring refuelling scenarios, it is important to compare the volumes of fuel needed by the different types of FCEV entering the market (see Figure 10).

Figure 8 – Tube trailer for transporting hydrogen.

Figure 9 – Composite trailer for transporting hydrogen.

Figure 10 – Indication of tank size, range, and distribution needs.

Use case/vehicle type	Tank size	Real world range	Number of vehicles a single 1200kg composite trailer could fuel
Emergency fleet services for smaller vehicles such as motorcycles, cars, ambulances and small vans	5kg (dispensed at higher 700bar pressure due to tank size).	Around 300 miles (60 miles per kg of fuel).	240*
Road freight logistics services such as HGVs	Variable - likely to be mix of gaseous and liquid solutions.	300 – 600 miles initially.	Variable, depending primarily on payload.
Specialist local public services such as refuse collection vehicles	30kg (dispensed at lower 350bar pressure as vehicle tank volume is larger).	Around 100 miles (3 miles per kg of fuel).	40
Bus services	50kg (dispensed at lower 350bar pressure as vehicle tank volume larger).	Around 500 miles for a single decker bus (10 miles per kg of fuel). Around 350 miles for a double decker bus (7 miles per kg of fuel).	24
Construction and farm services	Variable – likely to be mix of gaseous and liquid solutions.	300 – 600 miles initially.	Not relevant as it is unlikely that a significant volume of these type of vehicles would be refuelled per trip made by the mobile refuelling vehicle

*For comparison, a petrol or diesel tanker (with a capacity of around 37,000 litres), can refuel 740 50-litre tank vehicles).

Distribution scenario #1: Same site production and distribution facility. To reduce the cost of distribution, commercial entities will look to develop fuel grade hydrogen production facilities as close as possible to end user refuelling needs. Potential use cases could range from heavy industrial plant, rail freight terminals or ports through to combined production and refuelling facilities for buses and heavy-duty vehicles. The site of a facility needs to have enough space and access to power and water to fuel the production process. Size of the production facility can be scaled/futureproofed to match the operational fuel needs of the vehicle fleets that the facility is producing hydrogen for.

Distribution scenario #2: Industrial supply hub that can cater for different business users. In these cases, a site owner may seek to develop and operate an on-site hydrogen fuelling station for a portfolio of clients from different industry sectors. This could be achieved in collaboration with a hydrogen producer to service the requirements of customers who are looking at a fuel cell vehicle solution to decarbonise their transport fleet. Technology solutions exist to enable development of the right sized refuelling system for an organisation – incorporating storage tanks, compressors and pump nozzles with options to administer the gas at different pressures to suit a range of vehicles.

Distribution scenario #3: Specific fleet depot supply facility. This is where a fleet operator transitions all (or part) of its fleet to a hydrogen solution and wants to develop on-site refuelling. This scenario could be employed by any number of industry types – from bus operators to retail logistics, emergency services to councils. Technology solutions would need to suit a range of vehicles, using similar technology solutions to distribution scenario #2.

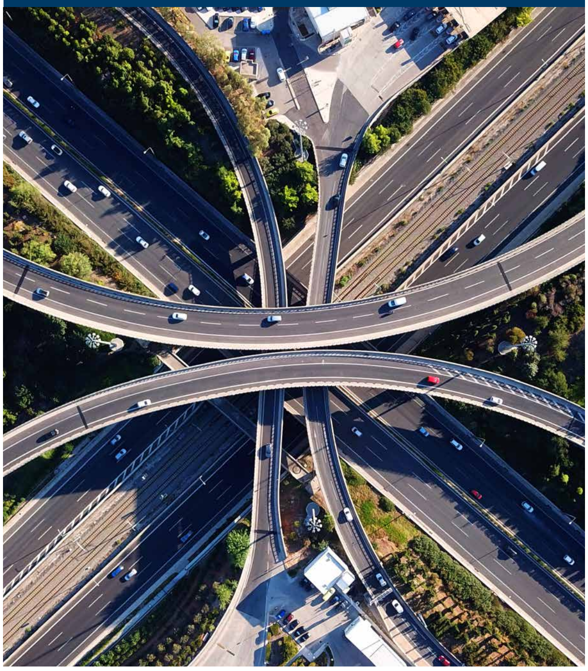
Distribution scenario #4: Mobile delivery. There may be many instances where a hydrogen solution could apply to users where the volume of owned or leased vehicles is small, or there is an aspiration to pilot hydrogen technology to ensure it suits the operating environment. In the early days of hydrogen distribution, mobile supply will be a useful way to advance the industry – with mobile hydrogen fuelling services being offered as a commercial enterprise either by hydrogen producers or vehicle manufacturers to help kick start the industry and spearhead the development of a more established supply network.

Distribution scenario #5: Publicly available hydrogen refuelling stations. There are currently only a handful of hydrogen refuelling stations in service in mainland UK, with only a further handful currently planned. Such numbers will not sustain a nationwide rollout of hydrogen vehicles. As the technology matures and more FCEV fleets appear, the business case for private sector investment in hydrogen production and supply forecourts is anticipated to grow, particularly along the UK's strategic road network to support a decarbonised road freight logistics service.

Summary: Hydrogen storage and distribution already exists in the UK, although certainly there is not enough to support transportation at a nationwide level. Research and innovation in storage technologies (such as use of metal hydrides and carbon nanotubes) is showing promise, and there is potential for pipelines if hydrogen is adopted for use more widely.

In the short-term, hydrogen could become a hub-based transport solution.

In the longer term, the provision of publicly available hydrogen refuelling stations will depend on the uptake of both hydrogen vehicles and more generally, the production and use of hydrogen for other purposes. The manner in which the road-freight logistics service decarbonise their fleets is considered to be key in influencing if and when this will occur.



[15] Stations | UK H2Mobility.

6. Conclusion

Sustainably produced transport energy sources must become the norm. As stated in the introduction, key factors that will influence the role of hydrogen in transport are:

- **Consumer choice**
- **Production of zero carbon hydrogen at scale**
- **Development of hydrogen storage and distribution.**

Whilst for many consumers BEVs are likely to be the most appropriate low carbon vehicle, fuel grade hydrogen offers an alternative where vehicles need to be in use for long shifts, and may become the leading option for heavier vehicles. Important factors include:

- **The need to fully refuel/recharge in under 10 minutes is essential**
- **Weight and payload cannot readily be compromised to accommodate batteries**
- **The availability of suitable electric charging facilities presents an issue.**

Hydrogen is well-suited to applications where fleets are operated such as emergency services, local public services and buses which require a high level of service availability and where vehicles return regularly to fixed locations such as depots, stations, garages and loading/unloading sites. When used with a mobile refuelling solution, hydrogen may be more suitable than electricity as a form of fuel for construction or agricultural services in remote locations, which also require a high level of service availability but are often constrained locally to a site.

At-scale, zero carbon hydrogen production is an important ambition that extends far beyond the transport sector into the whole economy. The Government has included hydrogen production as a key part of its 10-point plan for a Green Industrial Revolution.

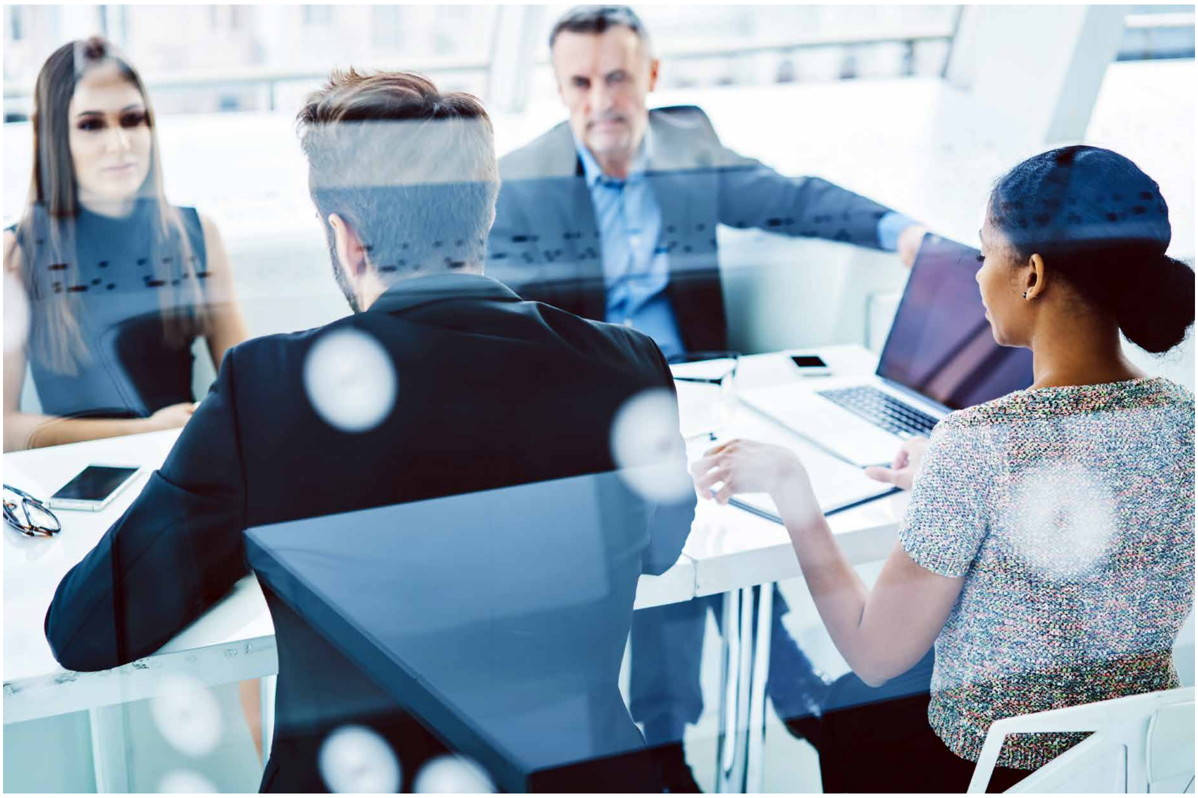
Bringing hydrogen energy into suitable industrial sectors will be critical to achieving a net zero economy. It will also have the additional benefit of reducing the UK's dependence on energy from overseas, while creating employment opportunities in the green energy sector.

As an emerging industry, initial zero-carbon and low carbon hydrogen production projects need to be made attractive to traditional lenders and they may need to choose whether blue hydrogen, green hydrogen or a blend of both is to be invested in. Governmental funding support and innovative funding mechanisms will be critical to early success. Such funding needs to take place alongside governance and assurance standards so that customers are certain of the quality and safety of the fuel they are buying and that there is resilience in its availability.

While there is ongoing debate over which hydrogen production methods will be put in place, achieving net zero can only happen with net zero production methods. Based on the status of available technologies, green hydrogen appears to be the most appropriate large scale production method for 2035 and beyond.

The three key factors under review in this report – consumer choice, hydrogen production, and storage and distribution – require significant investment and development for hydrogen to evolve into a viable and sustainable transport fuel. The largest commitment and investment should be targeted at the safe and efficient production of zero carbon and/or low carbon hydrogen at scale, with the whole economy (not just transport) in mind.

8. About the IET



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