Hydrogen for road transport

Introduction

Hydrogen is a potential zero-emission form of energy storage, which can be used to produce electricity or a high temperature flame, for different applications. In transport, hydrogen should generally be used in a fuel cell to produce electricity, as this produces no emissions at the tailpipe and is the most efficient way of using hydrogen for propulsion. There is already a substantial hydrogen industry, as a feedstock used in the petrochemical and chemical industries. In 2022, global hydrogen use was around 95 million tonnes, with less than 0.1% of the demand coming from new applications such as transport and power generation. This is currently not low carbon hydrogen, and responsible for over 900 million tonnes of carbon dioxide (CO_2) emissions in 2022, and so this industry needs to decarbonise, as well as producing more hydrogen for potential new applications.

The UK Hydrogen Strategy (2021) set out the UK's ambition to deliver 5 GW of low carbon hydrogen production by 2030, and in the British Energy Security Strategy (2022), this was doubled to 10 GW, with at least half produced by electrolysis. In transport, the Hydrogen Strategy sets out an expectation that hydrogen will be necessary to fully decarbonise the transport sector, but mostly used in heavy transport 'where batteries cannot reach', such as heavy goods vehicles, international shipping, and aviation.

This technical advice note is intended to provide an overview of hydrogen and fuel cell electric vehicles (FCEVs), focusing on their fundamental principles and applicability in transport sectors. The focus of this note is on current availability, and how this could fit into your fleet decarbonisation programme at the time of writing. Although there is significant research and development going into the hydrogen and FCEV industries, this note aims to provide you with the information relevant to vehicle decarbonisation and procurement at present.

Basic characteristics of hydrogen

Hydrogen is the simplest element on Earth, composed of a single proton and electron. While it is Earth's most abundant element, it rarely occurs naturally and accessibly (although recent research is exploring the availability of naturally occurring hydrogen) – meaning that hydrogen needs to be produced. Because it is light, hydrogen has a very high energy density by mass (142 MJ/kg, versus 46 MJ/kg for diesel), but it has a very low energy density by volume (13 MJ/m^3, versus around 38,000 MJ/m^3 for diesel). This means that although hydrogen can offer a lightweight energy source, it needs compressing or liquefying in order to be a useful volume.

Safety considerations

Hydrogen is flammable, with a flammability range of 4% and 75% when mixed with air. Its lightweight nature causes it to rise when released, mandating comprehensive ventilation and monitoring systems for indoor applications. Conversely, in open-air environments, hydrogen will rise and dissipate swiftly.

Emission profile and environmental impact

Hydrogen has the potential to be a useful means of energy storage without emissions, however this greatly depends on the production method, and how the fuel is used. Furthermore, hydrogen has a global warming potential (GWP) estimated at 11, meaning it has an impact on climate change 11 times greater than that of CO_2, albeit significantly lower than methane's GWP of around 30. It is important to note that this GWP is only relevant when hydrogen escapes into the atmosphere unburned.

Hydrogen production methods

The emissions intensity of hydrogen is fundamentally determined by its production method, making this aspect pivotal for its role in a decarbonised energy system. In 2022, the global average emissions intensity of hydrogen ranged between 12-13.5 $kgCO_2e/kgH_2$, accounting for approximately 1,100-1,300 million tonnes of CO_2 equivalent[1] globally. Often different production methods will be referred to by colour, however there is no standardisation for this, so it is not a reliable way of defining how your hydrogen might be being produced. We will mention some of the more popular colours in the following definitions, with the caveats attached. Below are the primary production methods:

- Steam methane reforming (SMR): in this approach, fossil fuel-derived methane undergoes a reaction with high-pressure steam, yielding hydrogen, carbon monoxide, and carbon dioxide. The resultant hydrogen generally requires further purification. The emissions intensity of SMR is around 9 $kgCO_2e/kgH_2$. SMR can be combined with carbon capture and storage (CCS) to reduce the carbon intensity. Although capture rates of up to 99% have been shown to be technically feasible, the sixteen large scale facilities currently in operation capture only 40-60% of the CO_2 emitted, around 11 million tonnes of CO_2 globally in 2022 – and most of this is reused rather than stored. SMR with CCS is often called 'blue hydrogen', and SMR without CCS is usually called 'grey hydrogen'.
- Electrolysis: this method uses electricity to split water into hydrogen and oxygen, creating very pure hydrogen which can be used directly in a fuel cell. This method requires 9 L of ultrapure water per kg of hydrogen, and the emissions intensity depends on the source of electricity – at the global average of 460 gCO_2e/kWh it is 24 $kgCO_2e/kgH_2$, but with the UK average of 190 gCO_2e/kWh it is around 9.5 $kgCO_2/kgH_2$. This method can be zero-emission, if the electricity used is from direct renewable sources – although due to the efficiency losses versus using the electricity directly, best practice is for this to be curtailed/excess renewable electricity. Electrolysis with renewable electricity is generally called 'green hydrogen', however be aware this can sometimes be used to refer to electrolysis using grid electricity, which may not be so 'green'.
- Coal gasification: this method is significantly emissions-intensive, with values ranging between 22-26 $kgCO_2e/kgH_2$ and is usually termed 'black hydrogen'.

There are other methods of producing hydrogen in developmental stages, such as biomass/waste gasification, pyrolysis, and algae production. In 2022, 62% of global hydrogen production was produced through steam methane reforming, followed by 21% from coal gasification, and 16% as a by-product from the petrochemical industry, with only 0.1% from electrolysis and 0.6% from fossil fuel sources (SMR and coal) with CCS.

Transport and storage

Owing to hydrogen's low energy density by volume, compression is essential for its storage and transportation. The standard pressures for storing compressed hydrogen gas are either 350 (H35) or 700 (H70) bar, dependent on the specific use-case. Cryogenic liquid storage at approximately -250°C has

[1] CO_2 equivalent (CO_2e) includes other reportable greenhouse gas emissions, standardised to the global warming potential of carbon dioxide.

also been considered, but is not only pursued in limited amounts for transport applications.

Hydrogen is predominantly transported via road, in high-pressure cylinders. It can also be transported through pipelines, akin to the natural gas network. It is feasible to blend hydrogen and natural gas for pipeline transport, however as hydrogen can damage steel over time, this imposes constraints on its concentration in the UK's existing network.

Fuel cells

Hydrogen serves as a versatile energy carrier, amenable to both combustion and fuel-cell-based electricity generation. When combusted, hydrogen does not produce carbon dioxide, but it does still produce nitrogen oxides (NO_x) which are regulated air pollutants, as they cause harm to human health. This is also an inefficient use of the hydrogen, and would only be recommended where a high temperature flame is needed, or the working environment means a fuel cell would not function.

For road transport applications, a more efficient and cleaner option is to use hydrogen in fuel cells to generate electricity. In a fuel cell, hydrogen atoms are separated into protons and electrons. The electrons then flow through an external circuit, producing electricity. At the end of this process, the electrons, protons, and oxygen from the air combine to produce water as the only by-product.

There are several types of fuel cell, but the one most commonly used in vehicles is the Proton Exchange/Polymer Electrolyte Membrane Fuel Cell (PEMFC). These fuel cells operate at temperatures of 80-100°C and have an efficiency of around 50%. One of the main cost factors in PEMFCs is the use of a platinum catalyst.

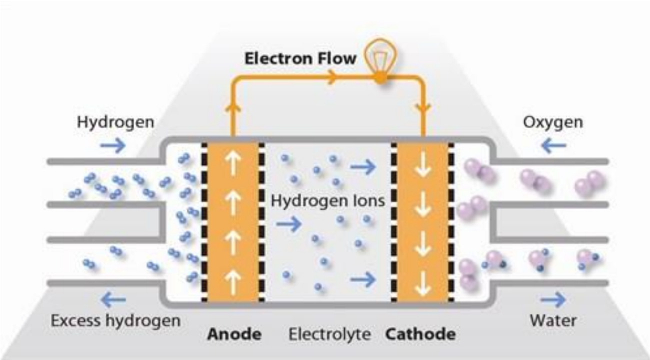

Image from Fuel Cells Works

Hydrogen vehicles

While there are vehicles that use hydrogen combustion or a combination of hydrogen and diesel dual fuel, these technologies present some significant drawbacks. Firstly, they are far less efficient in converting hydrogen's energy into useful work. Secondly, they produce nitrogen oxides, contributing to air pollution. Therefore, this technical advice note will solely focus on fuel cell electric vehicles (FCEVs), as the most relevant application of hydrogen in the transport sector.

Functionality of FCEVs

FCEVs operate on the same fundamental principle as Battery Electric Vehicles (BEVs), using electricity to power an electric motor. The key difference lies in the source of that electricity, and in FCEVs an on-board fuel cell, powered by hydrogen, generates the electricity. FCEVs also incorporate a small battery to supplement the fuel cell. This battery serves multiple purposes: smoothing out the power delivery from the fuel cell, capturing energy through regenerative braking, and providing additional power boost when needed.

It is crucial to consider the efficiency drawbacks when discussing the applicability of FCEVs in the transport sector. According to a study by Zemo in 2021, FCEVs require approximately five times the amount of energy compared to a BEV for equivalent performance. This energy requirement accounts for the full cycle: from hydrogen/electricity production and transport to the actual use in the vehicle. This inefficiency underscores the importance of using curtailed or excess renewable energy for hydrogen production. If general grid electricity is used for hydrogen production, it amplifies the inefficiency, given that the same electricity could be more effectively used directly or in a BEV.

Advantages and refuelling infrastructure

The high energy requirement does not make FCEVs universally unsuitable, but it does constrain their most effective applications. They may still be beneficial for specific uses where BEVs are unsuited, such as in heavy transport sectors, emergency vehicles, or in conditions unsuited to batteries. One of the most significant benefits is the rapid refuelling time, akin to traditional petrol or diesel. Refuelling would consist of a network of hydrogen refuelling stations, much the same as the network of fuel stations today. It is also possible for organisations (a local authority for example) to have their own on-site depot refuelling, similar to a bunkered fuel system.

However, implementing a full hydrogen refuelling network requires a significant amount of development and investment, and hydrogen stations are not yet widely available. At time of writing, there are seven stations open in the UK, and a further four planned, though this is subject to updates. The volatility in station availability further adds a layer of uncertainty, making long-term planning difficult for organisations. This limited infrastructure inherently imposes constraints on the effective range and directions one can travel with an FCEV, thus somewhat negating the advantages of rapid refuelling and longer ranges. For those dependent on public refuelling stations, the underdeveloped network presents a certain level of risk.

Moreover, hydrogen refuelling stations face logistical challenges tied to hydrogen supply. Either the hydrogen must be produced on-site – necessitating access to pure water and excess renewable electricity – or it needs to be transported in. The latter option could add strain to the road network, and add to energy requirements.

Vehicle availability

The FCEV market is still in development, with limited availability across vehicle categories. Notable manufacturers such as VW and First Hydrogen, BMW, Rivus, Mercedes, HVS are still in the pilot or testing phases. Vauxhall provides an exception, with the Vivaro-e Hydrogen available in France and Germany, and soon to be available in the UK, in limited numbers. Among passenger cars the Hyundai Nexo and Toyota Mirai are available in the UK.

Some local governments have adapted existing fleets. Aberdeen, for instance, has implemented hydrogen-diesel dual fuel systems in refuse collection vehicles, tippers and sweepers. St Helens' has gone a step further by introducing a hydrogen fuel cell refuse collection vehicle.

Fuel cell buses, for example Wrightbus, have a somewhat longer history in the UK, but still represent a small fraction of the overall public transport network. There is also potential for integrating fuel cells into emergency vehicles, where the speed of refuelling could offer distinct advantages.

Summary

The development of hydrogen and FCEVs continues apace, and there will be a place for hydrogen in our decarbonised energy system, especially in areas such as heavy industry, potentially offroad vehicles for agriculture and construction, long-haul transport, and seasonal energy storage. However, the existing hydrogen sector itself needs significant decarbonisation, which with a global 900 million tonnes of CO_2 emissions is a significant project. The choice of production methods is central to the sustainability of hydrogen as an energy carrier, with electrolysis from surplus renewable electricity standing out as the only genuine zero-emission approach.

As for its role in transportation, hydrogen does have the potential to be a zero-emission fuel, but the technology is still underdeveloped. The existing infrastructure for hydrogen refuelling is also quite limited, both in reach and reliability. With 2030 often cited as a net-zero target year for many Local Authorities, it remains unclear whether hydrogen will offer a reliable and cost-effective option by that time, though there are areas in which it may prove invaluable.

There may be niches within the transport sector where FCEVs could have an edge over BEVs. However, given the rapid and continuing advances in current battery technology (Energy density improvement between 2008 and 2020) , and new technology like semi-solid (Neo) and solid state batteries (Toyota) already in the production and pre-production phase, these niches are likely to be limited, especially with regard to cars and light commercial vehicles. Where viable battery-based solutions already exist, hydrogen technologies are currently likely to supply limited complementary benefits, but may not prove a significant disruption to existing electric capability.

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