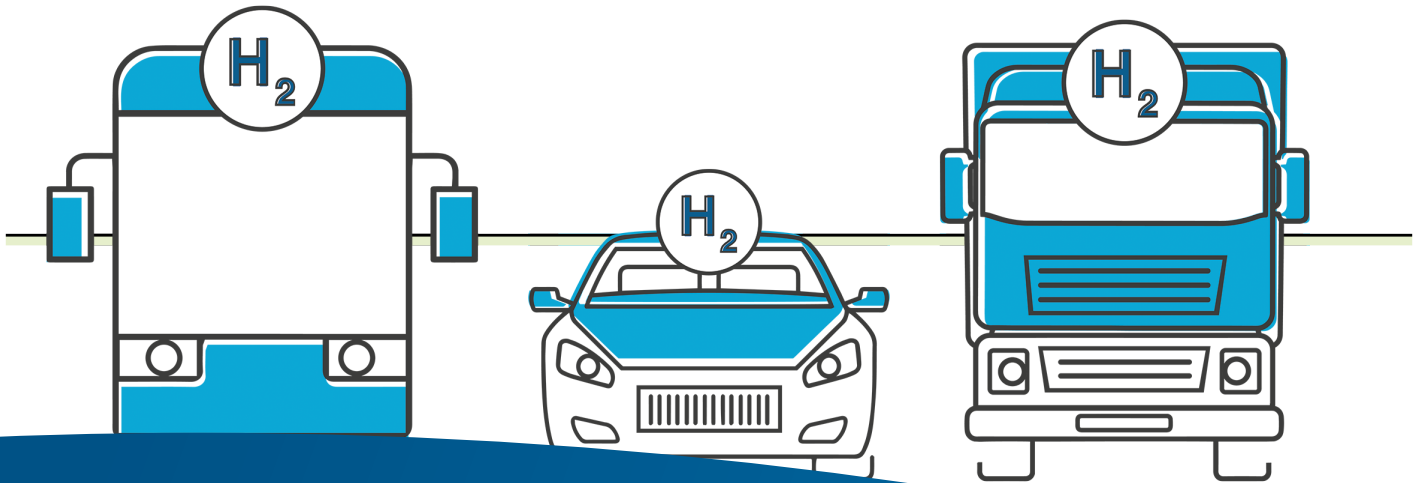




Lowering your emissions  
through innovation in transport  
and energy infrastructure



# An Introduction to Hydrogen Fuel Cell Electric Vehicles and Refuelling Stations

Cenex Insight - May 2021



## Hydrogen

Hydrogen ( $H_2$ ) is the first element in the periodic table and is a fundamental building block for many of the chemicals, materials and processes we use every day. It is the simplest, lightest, and most abundant element in the universe. However, it is also very reactive so is rarely found on Earth in its purest, unbound form.

Therefore, unlike coal for example, it is not a primary energy source, as it needs the input of energy to break bonds to release it for use. Instead, hydrogen is an energy vector as its production means that it can be used to store and transport energy.

Hydrogen has a much higher energy density by weight compared to other low emission fuel sources such as batteries for electric vehicles. A single kilogram of hydrogen has 33.6 kWh of energy in it, compared to about 12 kWh per kg for diesel and around 250 Wh of energy per kg for a typical EV battery.

However, unlike a battery, uncompressed hydrogen takes up a lot of space. It takes around 11 m<sup>3</sup> of space to store 1 kg of hydrogen at atmospheric pressure (1 bar; a bike tyre is pumped to 3-5 bar), roughly two thirds of the cargo space of a Ford Transit. The storage space required can be reduced by compressing or liquifying it. This means 1 kg of hydrogen can be stored at 700 bar in about 0.04 m<sup>3</sup> or 40 litres – similar to a medium sports bag.

Fuel cell electric vehicles (FCEVs) use hydrogen to produce electricity. FCEVs offer efficient and quiet transport with no exhaust emissions other than water. If fuelled by hydrogen produced from renewable sources, they are a true zero emission solution. However, they are a relatively new technology, and as such, there are very few models available and are relatively expensive to buy and operate. There are also very few hydrogen stations to fuel them.



A hydrogen car can refuel in as little as 3 minutes

## Hydrogen Production



Traditionally, hydrogen has been extracted from fossil fuels and this still accounts for 95% of hydrogen global output. Industrial hydrogen production techniques include:

### > Steam methane reforming (SMR)

SMR is the most common fossil fuel based H<sub>2</sub> production technique. SMR is the reaction of methane with water at high temperatures, in the presence of a catalyst, to produce H<sub>2</sub> and carbon dioxide. SMR is the single most common method of H<sub>2</sub> production in at the moment. Most sources agree that worldwide, around 95% of the commercial hydrogen production is from SMR.

### > Electrolysis

Electrolysis uses a direct electric current to drive a chemical reaction. When water is electrolysed, it breaks down into hydrogen and oxygen. Electrolysis of water and aqueous solutions of water with other chemicals accounts for the remaining 5% of H<sub>2</sub> production. The most common form of electrolyser at the moment is the alkaline electrolyser. Instead of separating pure water, a solution of potassium

hydroxide is used to increase the conductivity of the water, and therefore much improve the efficiency of the process.

### > Proton Exchange Membrane (PEM)

An alternative, but less mature, method is the PEM electrolyser which uses distilled or highly filtered water instead of aqueous potassium hydroxide. PEM electrolysers are based on the same technology as the PEM fuel cells (PEMFCs) used in automotive FCEVs. Both types of electrolyser produce H<sub>2</sub> and O<sub>2</sub>.

## Electrolysis



While most of the world's hydrogen is made via SMR, this is not always the case for hydrogen used in transport applications. Hydrogen transport is still a relatively novel technology and its success is dependent on its zero-emission credentials.

Electrolysed hydrogen, often referred to as green hydrogen when using renewable energy, is often preferred for several reasons in transport:

### > True net zero

A key factor that makes electrolysed hydrogen attractive is that it can be, when powered from renewable resources, a true green, zero emission solution.

### > Guarantee of supply

Hydrogen generated onsite, gives more control of the supply chain, and means less hydrogen has to be stored at any one time.

### > Integration of renewable energy

Renewable energy supplies such as wind and solar are intermittent – i.e. if there is no wind, there is no wind generation. Pairing intermittent renewables

with hydrogen generation (through electrolysis) is one way of helping smooth the peaks and troughs of renewable energy generation.

### > Purity

PEM fuel cells used in automotive applications are sensitive to carbon monoxide and carbon dioxide (called poisoning) and therefore require very pure hydrogen. SMR hydrogen requires additional processing to ensure these pollutants are removed from the main hydrogen feed. Using electrolysed hydrogen eliminates this concern.

## Fuel Cell Electric Vehicles



Hydrogen's ability to store and release energy make it an ideal vehicle fuel. It can be used to fuel vehicles in two main ways:

- > Burned with oxygen in an internal combustion engine (ICE) like conventional fossil fuels. This is being considered mainly for larger forms of transport like aviation and marine
- > Combined with oxygen in an electrochemical device called a fuel cell to provide electrical power to a vehicle.

Fortunately, hydrogen is very well suited to a form of device called a fuel cell that converts its energy to electrical energy. A vehicle that uses a fuel cell to generate power is known as a Fuel Cell Electric Vehicle (FCEV).

A typical passenger car FCEV consumes between 1 and 1.4 kg of H<sub>2</sub> per 100 km driven and stores less than 10 kg of H<sub>2</sub> onboard, whereas a heavy goods vehicle can consume around 10 kg of H<sub>2</sub> per 100 km but stores 30-35 kg of hydrogen.

Fuel cells are inherently more efficient than an ICE because they do not burn the fuel. Instead, O<sub>2</sub> and H<sub>2</sub> are separated, in a sequence of electrochemical reactions using catalysts, and combined into water (H<sub>2</sub>O) whilst generating electricity and heat. The overall process is much more efficient than combustion.

A fuel cell vehicle is made up of fuel cell stack (multiple fuel cells combined to generate sufficient power to propel the vehicle), hydrogen tanks, battery, power electronics, and electric motor. If the battery provides more power and is plugged into a socket to recharge, we call that vehicle a range extended fuel cell electric vehicle (RE-FCEVs)

The workings of a fuel cell electric vehicle are summarised below:

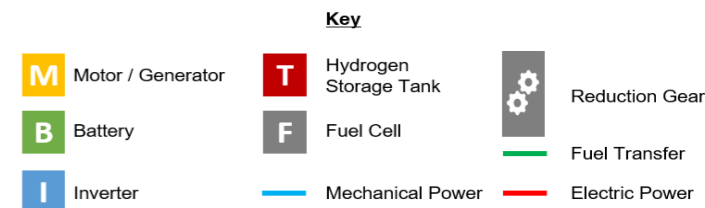
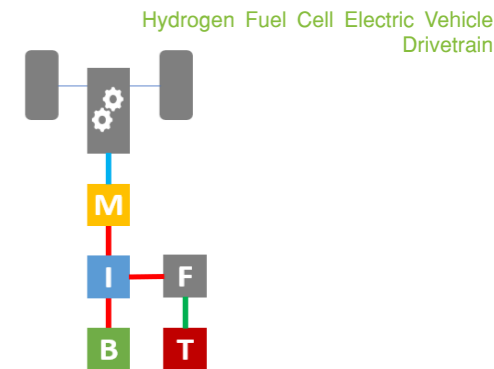
- > Hydrogen gas from the tank is supplied to the fuel cell stack.
- > Air is also supplied to the fuel cell stack.
- > The oxygen and hydrogen combine in the fuel

## Fuel Cell Electric Vehicles



cell stack to generate electricity and water. The most common type of fuel cell used in FCEVs is a proton exchange membrane fuel cell (PEMFC), also known as polymer electrolyte membrane (PEM) fuel cell.

- > Electricity generated through the reaction is supplied to the electric motor and/or battery. The battery acts as an energy store, providing additional energy to the vehicle for acceleration events, and can also capture regenerative energy from braking to improve vehicle efficiency.
- > The motor provides power to the wheels and the waste material is emitted from the vehicle via the exhaust – in this case, water.



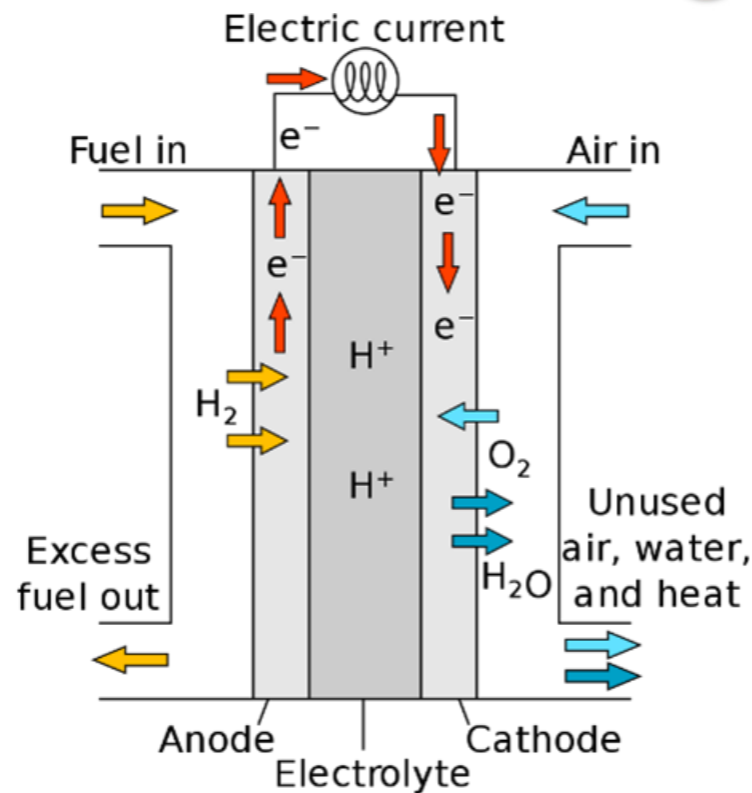
## Fuel Cell Electric Vehicles

### Inside a Fuel Cell

A fuel cell is quite a simple device. In essence, there are two electrodes (termed the Anode and Cathode), in between them is an electrically conducting substance called an Electrolyte. Different electrolytes result in a more or less efficient reaction.

In a PEMFC, a solid electrolyte is used. The electrodes in a PEMFC contain platinum to catalyse the fuel cell reactions. On the anode, hydrogen is converted to a proton and an electron. The electron is drawn out of the cell as electrical current, while the proton can travel through the membrane toward the cathode. The oxygen (from air) reacts at the cathode with the protons and electrons to form heat and water.

Individual cells are separated, allowing multiple fuel cells to be located together in what is called a 'stack'. Stacking cells allows useful quantities of electrical power to be generated.



Inside a Fuel Cell



## Fuel Cell Electric Vehicles

A fuel cell's efficiency (the amount of energy extracted from the fuel) is about 90%. However, in a vehicle it is tough to make use of all of the fuel cell's efficiency. Approximately half of the energy the fuel cell is released as low-temperature heat. In a passenger car, it is challenging to make use of this low-grade heat reliably. Therefore, in a passenger car, a fuel cell's working efficiency is closer to 45% when powering an electric motor. By the time we start thinking about overall efficiency of transferring the energy to the wheels, a PEMFC powered passenger car's total efficiency is closer to 30%.

As a 'rule of thumb,' you can assume that a PEMFC vehicle will always be around twice as efficient as an equivalent ICE vehicle.

As well as improved efficiency, the electrochemical operation of a fuel cell means that that FCEVs are much quieter than ICE vehicles. Crucially, their only emission is water, which offers a potentially compelling advantage over ICE vehicles. Hydrogen

therefore offers a route to true zero emission transport, providing that green (zero emission) hydrogen is used to fuel the vehicle.



## Hydrogen Refuelling



Filling a fuel cell electric vehicle (FCEV) with hydrogen gas is a broadly similar experience to filling a conventional internal combustion engine (ICE) vehicle with diesel or petrol and takes place at a hydrogen refuelling station (HRS).

A typical passenger car FCEV operates with 5 kg of hydrogen on board at 700 bar. Larger vehicles such as buses or heavy goods vehicles have more space available to store the fuel, and therefore generally employ 350 bar storage which uses cheaper cylinders. A bus stores around 25kg in roof-mounted cylinders at 350 bar.

There are 12 HRS in the UK, with around 150 across Europe, the majority of those in Germany.

A typical HRS set up shown schematically:



### Hydrogen production

A HRS can be supplied by onsite or offsite production:

- > Onsite uses a local production unit (generally an electrolyser) to generate the hydrogen. This has the advantage of eliminating the operating costs and emissions associated with transporting hydrogen to the HRS from an offsite generation site.

The primary disadvantages of onsite generation are the initial capital cost of purchasing the electrolyser and associated gas processing facilities, and the complexity of maintaining and operating individual relatively small-scale generation units at each HRS. However, onsite electrolytic hydrogen generation offers an

## Hydrogen Refuelling



attractive solution for HRS where there is a plentiful localised supply of renewable electricity and water to generate green hydrogen.

- > Offsite production involves a centralised, generally large-scale production unit and the transport of hydrogen to the HRS. The hydrogen is generally transported by road in a tube trailer as a compressed gas at 200 bar. This compression requires energy, and the tube trailers are currently fuelled by diesel which means that the process is relatively energy intensive.

Offsite production benefits from economies of scale of large-scale operation and is generally simpler and cheaper for the hydrogen producer. The main disadvantages are the operating costs and emissions from transporting hydrogen to the station. Future options for a large-scale network of HRS could involve transporting hydrogen by pipeline from a centralised production facility to individual HRS. This would mean a higher initial expense of installing the pipelines, but has the

potential to be cheaper in the long term due to savings in operating costs, as well as eliminating emissions from transporting the hydrogen to the HRS.

### Storage

The HRS needs to have sufficient storage to meet customer demand over a period of hours or days, and to fit around the frequency of hydrogen delivery or the rate of generation. Most HRS utilise a two-step storage approach:

- > Low pressure storage tanks provide the main reservoir of hydrogen for dispensing. Low pressure HRS storage operates at 200 bar (effectively 200-times atmospheric pressure).
- > Hydrogen from the low pressure storage tanks is then compressed to ~900 bar (to enable 700 bar refuelling) and stored in high-pressure tanks. This high pressure hydrogen is then used to refuel the vehicle.

## Hydrogen Refuelling



### Compression

FCEVs store hydrogen in onboard tanks at 350 or 700 bar. However, atmospheric pressure is only 1 bar, meaning that hydrogen needs to be compressed to get it to the right pressure. Compression presents one of the main challenges in HRS operation at present and remains a topic of active research. There are three main reasons for this:

- > Compression of hydrogen gas is energy intensive, and the provision of onsite storage is expensive
- > The practical operation of a HRS – in terms of its ability to supply and satisfy customers demand – is a balance between the capabilities of the compressor (the faster the compression rate, the more expensive the compressor) and the amount of low pressure and high pressure storage available at the HRS (again, more storage means more initial cost for the station)
- > Compressors are the primary source of failure at a HRS

### Precooling

Hydrogen is a relatively unusual gas because it has a 'reverse Joule-Thomson effect' – unlike most gases, it heats up when it expands through a nozzle. This increase in temperature makes the rapid refuelling of vehicles problematic, not least because the relatively lightweight hydrogen tanks used on FCEVs (so-called Type IV tanks) contain materials which are not rated for temperatures above 85 C.

To ensure refuelling is safe, it is important to cool the hydrogen gas to a pre-defined temperature (called the T rating of the refuelling). In the case of 700 bar passenger FCEVs, refuelling according to the current industry standard is carried out at -40 C, and is therefore called T40 fuelling.

Along with compression and dispenser issues, precooling is one of the main sources of HRS failures.

## Hydrogen Refuelling



### Dispensing and refuelling

Hydrogen dispensers are superficially similar to those used for conventional fuels in that they have a nozzle and a trigger to release the hydrogen, but they are by necessity much more complex (and expensive) devices.

To ensure the safety of hydrogen refuelling with all vehicles, FCEV and HRS manufacturers work to create refuelling protocols, including a maximum fuel temperature at the dispenser nozzle, the fuel flow rate, the rate of pressure increase, and other factors related to the station's cooling capability.

These refuelling standards are critically dependent on monitoring and maintaining the temperature and pressure of refuelling during the whole process. As such, most modern dispensers are equipped with sophisticated infrared devices that maintain a constant two-way communication process with the vehicle during fuelling (known as comm fuelling).

T40-rated dispensers target a fuelling time of 3 minutes to fill a standard passenger FCEV.



## Cenex Hydrogen Activity



Cenex has over 15 years' experience in fuel cell technology and is involved in hydrogen research projects, large scale demonstrations, and private consultancy.

### Hydrogen Transport Economy (HyTrEc-2)

HyTrEc-2 puts the people, skills and experience required in the North Sea Region to kickstart the hydrogen transport economy by developing experience with hydrogen vehicles and refuelling stations so that others can benefit.

There are over 25 vehicles on the road as a result of the project, driven by members of the public and local council staff, and Cenex monitor how effectively those vehicles and several HRS work together.

### Hydrogen Mobility Europe (H2ME)

H2ME was the first phase of the largest European deployment for hydrogen mobility to date and demonstrates that FCEVs in urban applications can be viable for fleets compared to diesel alternatives.

Cenex conducted data capture and analysis of the FCEV and HRS performance to establish the technical readiness of vehicles and stations for wider deployment.

The project compiled an unrivalled dataset since 2015: 630 FCEVs were deployed in 10 countries and 37 new HRS installed in 8 countries, achieving 14.5 million km driven and 147 tonnes of hydrogen dispensed across 68,000 refuelling events.

### Hydrogen Fleets for Utility Providers

Utility providers operate a wide range of vehicles with specific usage profiles and weight limitations with very high onboard energy demands. Hydrogen could meet the demands where battery electric vehicles may not be able to perform these duties.

Through this project, Northern Gas Networks, Wales and West Utilities, and Cenex will better understand the vehicle duty cycle and power requirements of the fleets to assess the suitability of hydrogen.

## Further Reading



### An Introduction to Battery Electric Vehicles

<https://www.cenex.co.uk/resources/an-introduction-to-battery-electric-vehicles/>



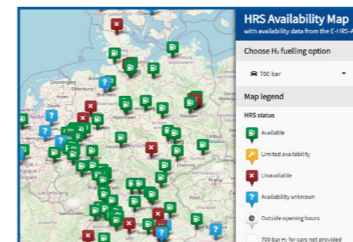
### Zero Emission Fleet vehicles for European Rollout

[www.zefer.eu](http://www.zefer.eu)



### H2ME Project Presentation

[https://h2me.eu/wp-content/uploads/2021/01/H2ME\\_project\\_presentation2020.pdf](https://h2me.eu/wp-content/uploads/2021/01/H2ME_project_presentation2020.pdf)



### HRS Availability Map

[www.h2-map.eu](http://www.h2-map.eu)



### Introduction to Low Emission Road Transport - Future Learn Course

<https://www.futurelearn.com/courses/introduction-to-low-emission-road-transport>



### Hydrogen Fleets for Utility Providers

<https://www.cenex.co.uk/projects-case-studies/hydrogen-fleets-for-utility-providers/>





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