Introducing
Hydrogen in Railways

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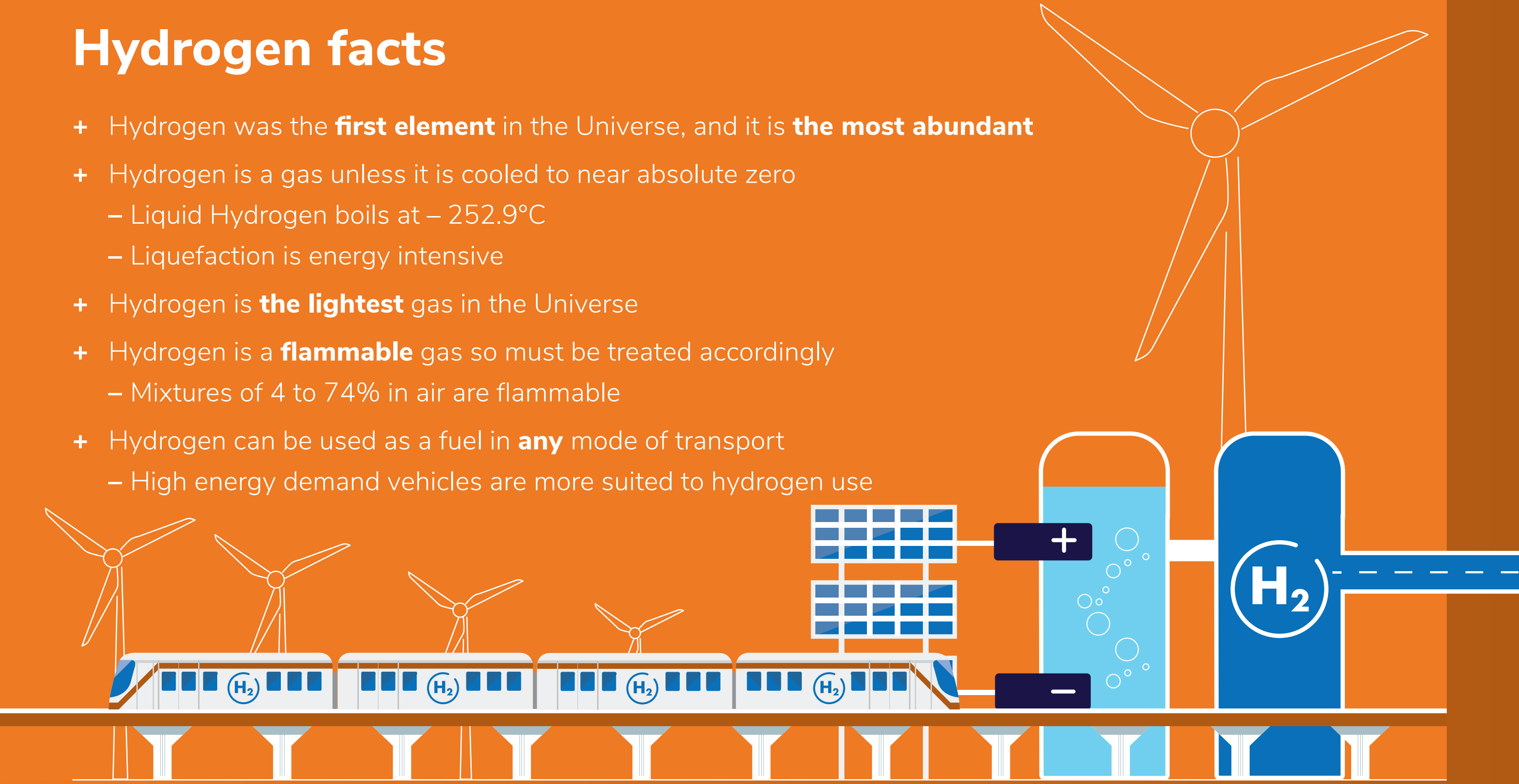
Hydrogen facts

+ Hydrogen was the **first element** in the Universe, and it is **the most abundant**
+ Hydrogen is a gas unless it is cooled to near absolute zero
  – Liquid Hydrogen boils at – 252.9°C
  – Liquefaction is energy intensive
+ Hydrogen is **the lightest** gas in the Universe
+ Hydrogen is a **flammable** gas so must be treated accordingly
  – Mixtures of 4 to 74% in air are flammable
+ Hydrogen can be used as a fuel in **any** mode of transport
  – High energy demand vehicles are more suited to hydrogen use



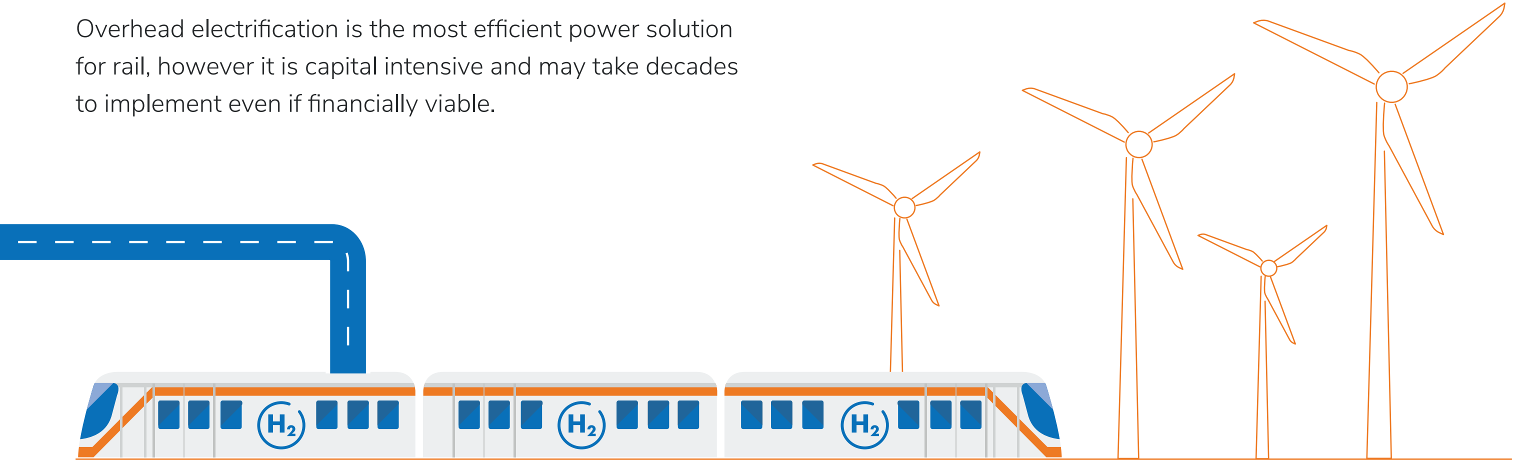
Why hydrogen?

Over 20% of global carbon emissions originate from transport and the need to rapidly reduce CO_2 emissions is widely accepted.

Whilst battery power is feasible for passenger cars, heavier vehicles including railways pose a bigger challenge as the weight and volume of battery storage can become impractical.

Overhead electrification is the most efficient power solution for rail, however it is capital intensive and may take decades to implement even if financially viable.

Hydrogen as an energy source (or more accurately energy vector), offers the potential to decarbonise these heavy-duty forms of transport, as it offers a higher energy density per unit weight and **allows refuelling to be completed within minutes rather than hours.**



Hydrogen sources

Hydrogen is a colourless gas, but a colour name is often used to show how that hydrogen is produced.

COLOUR	FUEL	PROCESS	PRODUCTS
BROWN/BLACK	Coal	Steam reforming or gasification	$H_2 + CO_2$ (released)
WHITE	N/A	Naturally occurring	H_2
GREY	Natural Gas	Steam reforming	$H_2 + CO_2$ (released)
BLUE	Natural Gas	Steam reforming	$H_2 + CO_2$ (% captured and stored)
TURQUOISE	Natural Gas	Pyrolysis	H_2 + C (solid)
RED	Nuclear Power	Catalytic splitting	$H_2 + O_2$
PURPLE/PINK	Nuclear Power	Electrolysis	$H_2 + O_2$
YELLOW	Solar Power	Electrolysis	$H_2 + O_2$
GREEN	Renewable Electricity	Electrolysis	$H_2 + O_2$

Hydrogen sources

Often several colours may be grouped together as they share many attributes. The three main types commonly discussed at present are:

Brown hydrogen

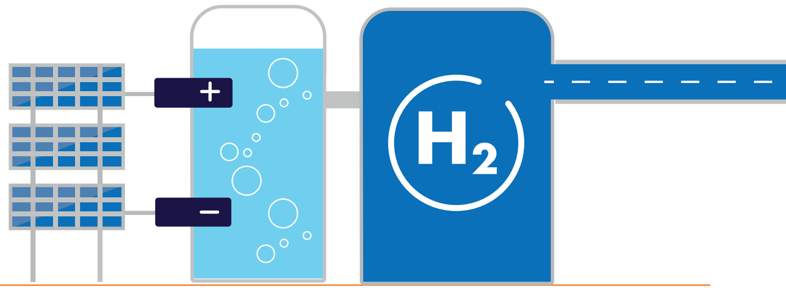
Brown is used by many in industry to cover brown, black and grey hydrogen sources. All three processes take a fossil fuel from the ground and turn it into hydrogen gas, releasing CO_2 to the atmosphere. Over 90% of commercially available hydrogen is currently in this category.

Blue hydrogen

Blue hydrogen can be expanded to encompass any fossil fuels used as the energy source (rather than just natural gas) and just like brown hydrogen, it too generates CO_2. The key difference is that developing technologies are then used to capture a proportion of the generated CO_2 and store it, often beneath the ground. The carbon intensity of this process can vary significantly. The carbon capture area is currently the subject of much research and development. Blue hydrogen has the potential to be a low carbon fuel.

Green hydrogen

Green hydrogen uses a renewable energy source (wind, solar, tidal etc) to generate electricity. This electricity is used to split water (H_2O) via electrolysis into hydrogen and oxygen gases (H_2 and O_2). This process generally results in a low carbon fuel.

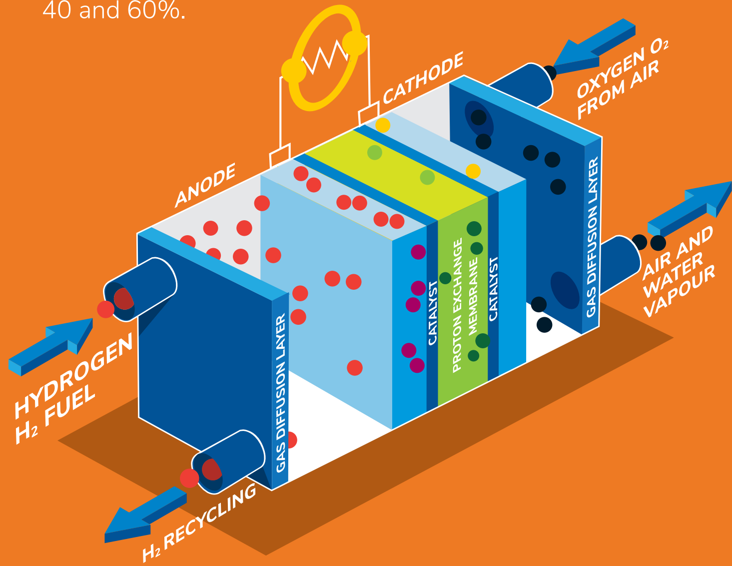


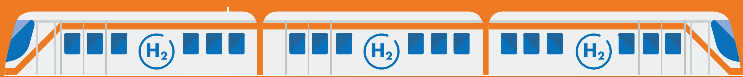
Hydrogen uses

Fuel cells are an electrochemical cell that generates electrical power by taking hydrogen (or a hydrogen carrying fuel) and combining it with oxygen (usually from the air). Combining hydrogen and oxygen to form water vapour causes an electrical current to flow, providing a source of electrical power. Fuel cells can produce electricity continuously for as long as fuel and oxygen are supplied, so in practice the **range of a fuel cell vehicle is determined by how much hydrogen it can carry.**

There are many types of fuel cells, but they all contain an anode, a cathode and an electrolyte that allows ions, usually positively charged hydrogen ions (protons), to move between the two sides of the fuel cell, causing an electrical current to flow. Fuel cells are often classified by the type of electrolyte they use. The most common fuel cell type in vehicle developments are Proton-Exchange Membrane Fuel Cells (PEMFC).

The energy efficiency of a fuel cell is generally between 40 and 60%.





Hydrogen internal combustion engine

A perhaps surprising fact is the first hydrogen powered internal combustion engine was created in 1807 by François Isaac de Rivaz, so the hydrogen internal combustion engine is not new.

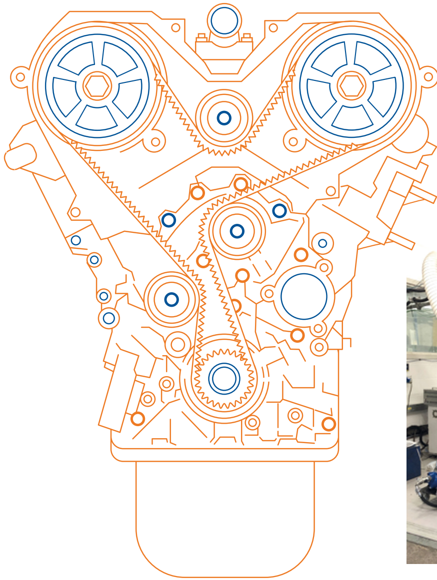
Both liquid and gaseous fuels have been used in internal combustion engines for over a century and **Ricardo has over 100 years of experience in engine design.**

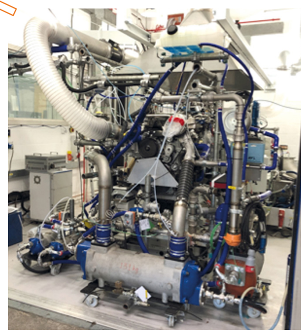
Hydrogen gas has a wide range of flammability in air, so it can be used in suitably designed or adapted internal combustion engines to provide power for vehicles.

Over 100 manufacturers are developing hydrogen internal combustion engines particularly for heavy-duty applications where long lifetimes and challenging service conditions favour their robustness, together with their smaller size and lower costs compared to fuel cells.

The energy efficiency of a hydrogen internal combustion engine can be 40-50%.

The photo shown is a Ricardo modified 12.7litre Scania engine awaiting testing in the hydrogen test cell at our Shoreham facility.





Fuel cell and internal combustion engine comparisons

PARAMETER	HYDROGEN FUELLED ENGINE (H_2ICE)	FUEL CELL (PEM TYPE)	WINNER
Efficiency	~44%+ expectation for DI H_2 fuelled ICE	~60% peak electrical efficiency (at ~25% load) ~44% at full load	**In theory – fuel cell in use – similar**
Emissions in use	Engine– out NOx [low] Trace oil derived emissions	No tailpipe emissions	**Fuel cell**
Technology maturity	ICE well understood, modification to burning H_2 in development	Existing FC system providers further optimisation to suit niche application needed.	**Similar**
Noise/vibration	Substantial NVH effort	Quiet	**Fuel cell**
Fuel purity requirement	Tolerant to fuel contaminants/ lower grade H_2 standard not yet defined	ISO H_2 purity standard (ISO 14687 Grade D)	**H_2ICE**
Air quality requirement	Robust to small particles	Sensitive to air contamination	**H_2ICE**
Durability	Diesel ICEs durable for >10,000 hours H_2 ICEs expected to be similar	Durability & reliability improved to >10.000 hours	**Similar**
Auxiliary heat output	High grade heat similar to current ICE	Thermal management of low-grade heat for PEMFC required.	**H_2ICE**

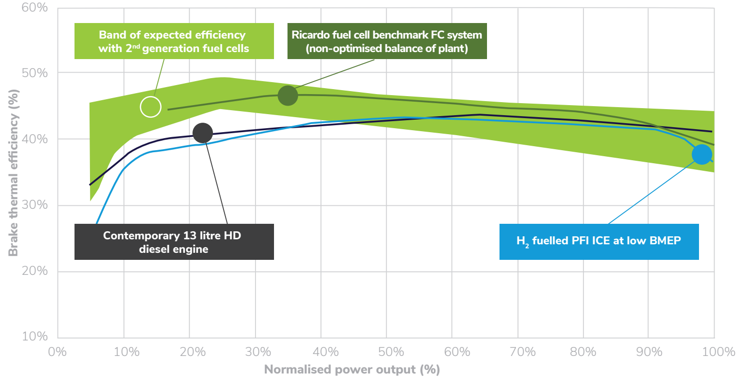
Efficiency comparison

Hydrogen fuelled internal combustion engines have a similar efficiency profile to diesel engines (but lower exhaust emissions). A typical duty cycle for rail vehicle generally experiences long periods at high loads (as the vehicle accelerates), or low loads (during cruising or slowing).

This makes the practical differences in efficiency between fuel cell and internal combustion engines smaller than perhaps expected when only comparing the peak efficiencies of the two power sources.

Fuel cell and H_2ICE system efficiencies

Brake thermal efficiency of traction

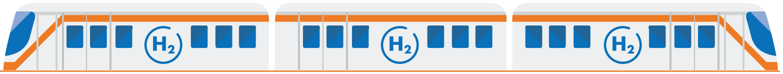


Fuel cell vehicle traction system efficiencies

- DC–DC converter – 95%
- Inverter – 96%
- E-motor – 95%
- Transmission – 97%

Internal combustion engine vehicle traction system efficiencies

- Transmission – 97% for mechanical



Storage

Hydrogen can be stored either as a gas or as a liquid.

Storage of hydrogen as a gas requires high-pressure tanks, typically either 350 or 700 bar pressure.

Whilst you can store more hydrogen in a higher pressure tank, the extra strength required for the tank also increases its weight and cost significantly. This is the reason that 350 bar tanks are still used in applications where weight is the prime concern as they can offer a higher weight and cost efficiency. Where space (volume) is the prime consideration then 700 bar tanks are often favoured.

Storage of hydrogen as a liquid requires extremely low cryogenic temperatures. The boiling point of hydrogen at one atmosphere pressure is –252.9°C.

Hydrogen can also be stored as chemical compounds, e.g, Ammonia, which can then have the hydrogen released when required.

Hydrogen-containing liquid fuels generally have a much higher energy density than pressurised gaseous hydrogen and are therefore attractive in high energy demand applications such as maritime shipping.

Sources of more info

Ricardo hydrogen hub

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Pathways to a hydrogen future in rail

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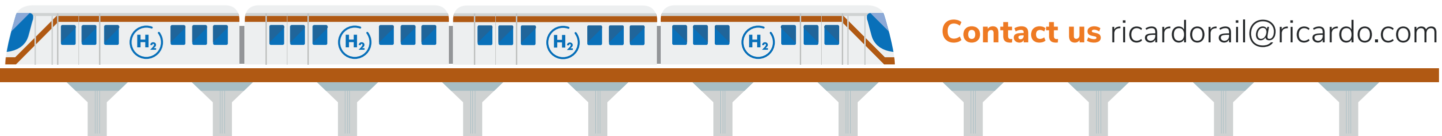

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