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Need to Know Guide RE4
Hydrogen Fuel

RISK INSIGHT, STRATEGY AND CONTROL AUTHORITY
REDUCING INSURABLE RISK THROUGH RESEARCH, ADVICE AND BEST PRACTICE

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Cover image: Getty/Olemedia

Contents

1 Introduction

The purpose of this guide is to raise awareness and understanding of potential developments and expansion of hydrogen usage as an emerging fuel, focusing on applications in transportation and domestic/commercial heating. Whilst general hydrogen safety guidance is provided, this is not intended as a detailed engineering guide.

Industry has been using hydrogen, both in gaseous and liquid form, for decades, so there is already a body of knowledge on how to store and handle hydrogen safely. But as the potential for more widespread use of hydrogen progresses, the technology relating to hydrogen use and safety must develop to keep pace.

Hydrogen is produced by a number of processes, including:

- Electrolysis of water, producing hydrogen and oxygen. When electrolysis is powered by renewable energy sources, this is known as 'green hydrogen'.
- Natural gas reforming (natural gas reforming using steam currently accounts for the majority of hydrogen produced). Carbon dioxide (CO2) is captured through a process called carbon capture usage and storage (CCUS). This is known as 'blue hydrogen'.
- Biomass-derived liquid reforming (e.g. from ethanol reacted with high-temperature steam).
- Microbial biomass conversion (the conversion of biomass into sugar-rich feedstocks that can be fermented to produce hydrogen).

Other technologies are in development.

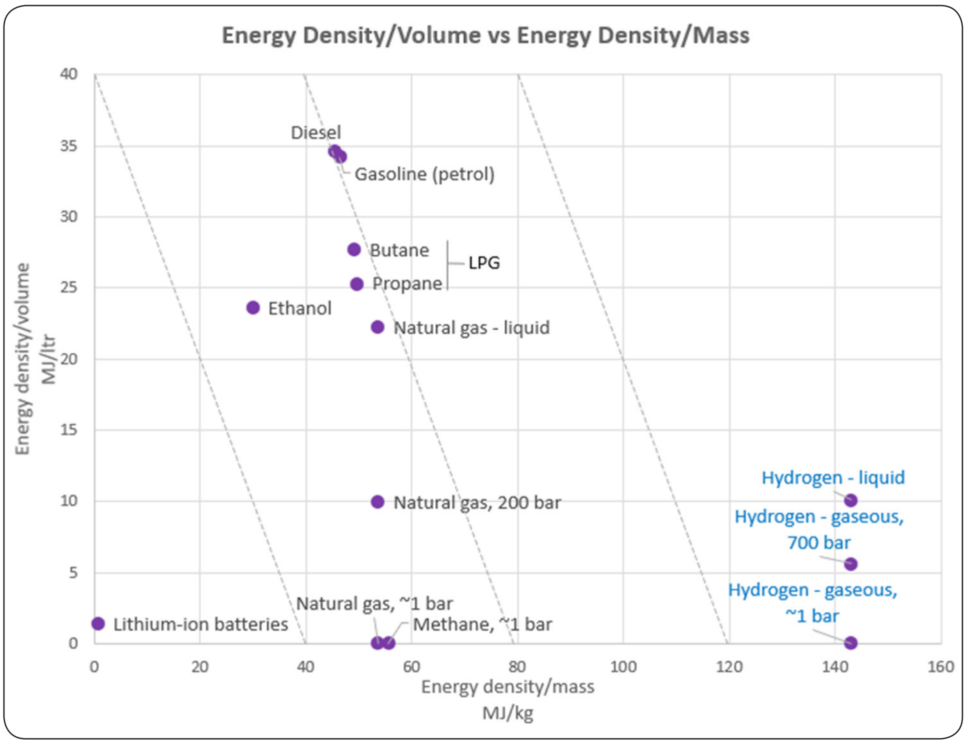
The UK government's energy strategy considers hydrogen to be critical for meeting the UK's legally binding commitment to achieve net zero by 2050, with an ambition to achieve a thriving hydrogen economy by 2030. The use of hydrogen as a fuel will support the delivery of flexible energy across power, heat, and transport applications (ref. *HM Government UK Hydrogen Strategy*, 2021).

1.1 Why is hydrogen fuel attractive compared to other fuels?

Hydrogen is becoming an important sustainable fuel for future development, as it has energy-density* and transportation properties that make it suitable for use in transport and building heating applications.

* The amount of energy stored in a given system per unit volume or unit mass. In road vehicles, this can be equated to how far a vehicle can travel on a single tank of fuel or battery charge.

1.2 Fuel energy comparison



Whilst hydrogen fuel storage can be bulky compared to hydrocarbon-based fuels (although this is improved with compression and liquefication), on an energy-density by mass (weight) basis, it is superior to traditional fuels. In comparison, lithium-ion batteries have a very poor energy-density, compared to both hydrogen and hydrocarbon-based fuels.

2 Applications

Hydrogen is expected to expand in industrial and power production, but in this guide, we focus on transportation and building heating applications.

2.1 Building heating

The use of hydrogen as an alternative to natural gas (either as a natural gas/hydrogen mix, or pure hydrogen) for building heating is being studied as part of a multi-vector approach to sustainable heating, as hydrogen has the potential to be a straightforward replacement to natural gas, where air-source or ground-source heat pumps or electrical heating are either not viable or are a less economic alternative.

The UK's first live pilot to inject zero carbon hydrogen into a gas network to heat homes and buildings was successfully completed at Keele University in 2021. In this pilot project, 20% (by volume) of hydrogen was injected into Keele University's existing natural gas network, feeding 100 homes and 30 faculty buildings.

Following the Keele University pilot, the H100 Fife project, on the east coast of Scotland, will directly supply clean power to produce hydrogen gas for domestic heating, offering renewable hydrogen to homes and replacing natural gas. During the first phase, in 2024, the network will heat around 300 local homes using clean gas produced by a dedicated electrolysis plant, powered by a nearby offshore wind turbine. The design and build will provide similar safety and reliability standards to the current natural gas system, and an on-site storage unit will hold enough hydrogen to ensure supply will not be disrupted during the coldest weather conditions.

In addition, the UK government is now working with industry, Ofgem, and the Health and Safety Executive (HSE) on a programme of research and development and test projects to build the evidence base for the widespread use of hydrogen as an alternative to natural gas for building heating. A 'hydrogen village trial' in northern England will convert a large village of around 1,000–2,000 properties to hydrogen, instead of natural gas (or alternative heating solutions for those households that opt out). The trial, which should be operational by 2025, provided that safety factors meet HSE approval, is expected to last a minimum of two years. This will trial the conversion of existing gas network infrastructure in the local area, repurposing it for 100% hydrogen, and will involve replacing consumers' natural gas appliances with hydrogen-compatible equivalents and making any other adjustments required to properties. The existing natural gas network will be appropriately modified to ensure hydrogen can be transported safely.

Additionally, the UK government is committed to developing plans by 2025 for a possible follow-up to the village trial with a hydrogen heated town, which should have at least 10,000 metering points to trial hydrogen for heating. The aim of the outline plan for the town project is to provide further information to inform policy decisions and future roll-out plans. Proposals for the initial pilot hydrogen heated towns are being considered by the government across all UK gas network areas.

The above proposals are currently the subject of discussion and may change.

2.2 Transportation

As the transport sector faces increasing pressure to lower emissions, applications for hydrogen fueled vehicles are becoming increasingly attractive.

Most road vehicle development uses hydrogen fuel cell electric vehicle (FCEV) technology.

FCEVs use a propulsion system similar to that of electric vehicles, where energy stored as hydrogen is converted into electricity by a fuel cell. Most FCEVs today use batteries to recapture braking energy, provide extra power during short acceleration events, and smooth out power delivery from the fuel cells, with the option to make idle or turn off the fuel cell during low power needs. FCEVs are more efficient than conventional internal combustion engine vehicles and produce no harmful exhaust emissions, i.e. they only emit water vapour and warm air.

But whilst there has been little take-up for hydrogen fuel cell cars, with lithium-ion battery power systems dominating the market for internal combustion engine (ICE) replacement, FCEVs are being deployed in some commercial mass-transportation applications, notably in bus fleets.

FCEVs are fueled with pressurised hydrogen at hydrogen refuelling stations (HRS) that typically sit alongside conventional hydrocarbon fuel dispensers (petrol, diesel). The number of operating hydrogen fuel stations across the UK is subject to variation, with some original hydrogen filling stations closing, in part due to prototype technology reaching the end of its service life. A Cranfield University press release indicates that (as of March 2023) there are 11 public hydrogen refuelling stations open in the UK. However, a UK-wide network of refuelling stations, primarily for HGVs, is in planning by two hydrogen developers.

A simple HRS consists of hydrogen storage tanks, gas compressors, a pre-cooling system, and a hydrogen dispenser, which dispenses hydrogen to pressures of 350 or 700 bars depending on the type of vehicle.

Safety features include specialised high-integrity containers/vessels/piping/tubing/fittings, safety pressure-release devices, and breakaway couplings installed on dispensing systems (in case of a vehicle driving away whilst still connected). Similar to other types of fuel dispensing stations, hydrogen self-service stations also feature electrostatic grounding and fire sensors. Additionally, sensors measuring the pressure, temperature, and leakage of hydrogen gas are installed. Hydrogen fueling stations are designed to safely vent hydrogen in case of exposure to extreme heat, such as a nearby petrol fire.

Hydrogen is stored on board vehicles in very robust containers that have been tested to withstand extreme impacts and that are equipped with thermally-activated pressure relief devices.

Restrictions on the use and storage of hydrogen FCEVs are similar to that for LPG fueled vehicles and UK restrictions currently only apply to transportation on LeShuttle (Eurotunnel), where gas powered vehicles are prohibited.

Other hydrogen fuel applications in aviation and shipping are in the early stages of development and deployment, with liquid hydrogen being a potential fuel in these applications.

3 Hazards

Hydrogen is non-toxic, but some of hydrogen's properties require more stringent engineering controls to enable its safe use, compared to natural gas and LPG.

A specific concern is hydrogen's wide range of flammable concentrations in air, compared to hydrocarbon gases and petrol vapour.

Material	LEL %	UEL %
Hydrogen	4	75
Methane/natural gas	4	17
Propane	2	10
Butane	1	8
Gasoline (petrol) vapour	1	8

Note: The minimum concentration of a particular combustible gas or vapour necessary to support its combustion in air is defined as the Lower Explosive Limit (LEL). The maximum concentration of a gas or vapour that will burn in air is defined as the Upper Explosive Limit (UEL).

Whilst this wide flammable range must be carefully considered in hydrogen system design, it should be borne in mind that design-for-safety with flammable gas systems is normally based on maintaining concentrations at less than 10–25% LEL, rather than maintaining concentrations above the UEL (i.e. too rich to be ignited).

Other hazardous properties of hydrogen gas compared with methane and other hydrocarbon gases are listed as follows:

- Hydrogen burns with a nearly invisible flame
- It leaks more easily:
  - Hydrogen leaks about three times faster than methane
- It burns more quickly:
  - The burning velocity of hydrogen-air mixtures is greater than for similar methane-air mixtures, with potential to increase explosion pressures beyond those expected for comparable methane explosions*
    *Noting that explosions are complex phenomena and explosion intensity is dependent on numerous parameters
- Hydrogen flames can pass through smaller gaps than methane
- It has lower ignition energy (i.e. easier to ignite, even by weak static discharges)
- High-pressure hydrogen released into air will often spontaneously ignite without any apparent ignition source (shock-wave ignition)
- It detonates more readily
- Hydrogen can diffuse into and permeate through both metals and polymers
- Some metals can become brittle when exposed to hydrogen – see the '*Hydrogen embrittlement*' section below.

Hydrogen is very low density (much lighter than air), which can result in the accumulation of hydrogen gas within enclosures at high level, but can also improve dispersion and dilution to a nonflammable concentration where good ventilation is provided*.

*Hydrogen diffuses rapidly, nearly 4 times faster than natural gas

Whilst hydrogen leaks often ignite spontaneously, presenting a fire hazard, this phenomenon does have the benefit of avoiding accumulation of flammable vapour.

Similarly to natural gas, hydrogen has no odour in its normal state. Natural gas supplied via gas mains has a special odorant added to it to give it its characteristic smell so that leaks can be readily detected. Adding hydrogen to natural gas may dilute the smell, but will not change its effectiveness, and if needed, additional odorant can be added to compensate for this. Work is ongoing to establish the most suitable odorisers for use with 100% hydrogen networks.

The primary reasons for the accidental releases of gaseous hydrogen for equipment include:

- Delivery of gas when a dispensing nozzle is not connected, or inadequate sealing of a dispensing nozzle to a hydrogen storage vessel.
- Leak in flexible-hose/pipe connecting a hydrogen storage vessel.
- Incompatible materials of construction of pipes or vessels.
  'Hydrogen embrittlement' is a known cause of material failure for hydrogen systems – *discussed below*. Other causes of degradation of storage containers and pipes include corrosion and erosion.
- Equipment connections, including seals and mechanical fittings being unsuited for hydrogen service.

Hydrogen system design needs to carefully consider all of these factors, with appropriate controls implemented, including leak detection, special flame detection, and adequate ventilation. When hydrogen accumulates it will inevitably find an ignition source, so high-level natural ventilation is key in most circumstances.

Hydrogen is a named dangerous substance under UK COMAH regulations*. The threshold (used/stored) quantities are 5 Tonnes (lower tier) and 50 Tonnes (upper tier).

*Control of Major Accident Hazards Regulations (COMAH) 2015

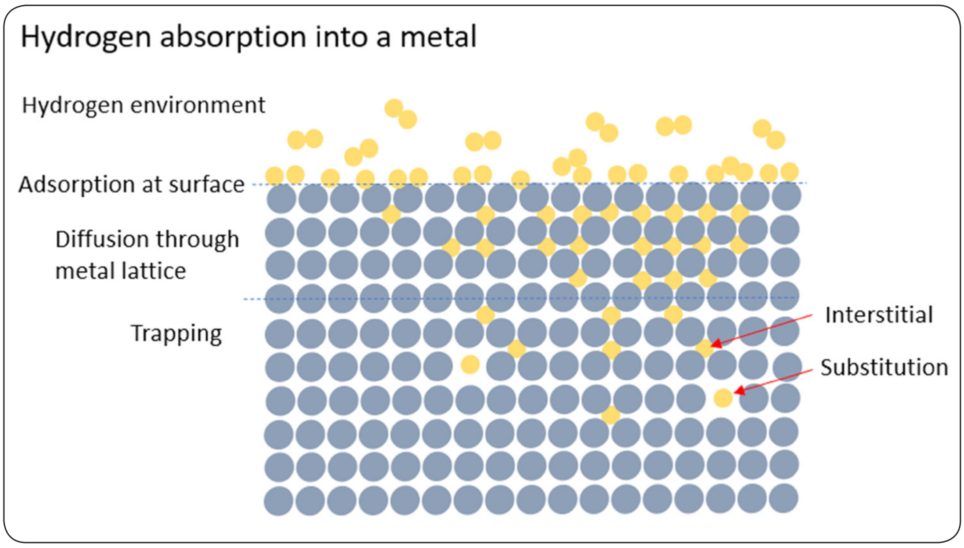
3.1 Hydrogen embrittlement

Selecting appropriate materials of construction is essential to the design of safe hydrogen systems.

Some metals can become brittle when exposed to hydrogen, especially steel, iron, nickel, titanium, cobalt, and their alloys. Whilst transporting gaseous hydrogen via existing pipe networks is a low-cost option, the potential for hydrogen embrittlement of pipes, vessel walls, and welds (that have increased susceptibility to hydrogen embrittlement) must be carefully assessed and may require substantial modifications, depending on conditions.

Because hydrogen atoms are so small, they can permeate solid metals. Hydrogen embrittlement, aka hydrogen-assisted cracking or hydrogen-induced cracking, is a reduction in the ductility of a metal due to adsorbed and diffused hydrogen and can lead to a reduction in key mechanical properties or localised cracking.

A number of factors impact the severity of hydrogen embrittlement, especially pressure, temperature, and applied stress. If hydrogen at the surface is removed, hydrogen can re-diffuse out and ductility is restored, provided that lattice damage has not occurred. Permeation rates vary from material to material and can be slowed by barrier materials.



Hydrogen embrittlement of materials is being investigated by the HSE to determine safe arrangements.

4 Losses

Fire and explosion losses involving hydrogen have been relatively rare.

The Hindenburg disaster was an airship accident that occurred in 1937, in New Jersey, United States. This air accident remains a sentinel moment in airship history that brought to the fore the flammability of hydrogen. Hydrogen was the only very light gas available at the time to provide buoyancy for airships and proved to be vulnerable in this accident, which was thought to have been caused by an electrostatic discharge that ignited leaking hydrogen. Thirty-six people died, although sixty-two survived.

4.1 Modern-day hydrogen incidents

The following are well-documented, relatively recent fire/explosion losses involving hydrogen plants that provide an indication of the type and scale of these types of events. There is currently little documented fire/explosion loss data related to consumer hydrogen installations.

Source: FleetEurope

Sandvik, Norway (2019)

A hydrogen refuelling station experienced an explosion and subsequent fire. The explosion triggered some of the airbags in nearby cars to activate and two people required medical attention due to injuries sustained from these inflations.

The root cause of the incident was identified as an assembly error of a specific plug in a hydrogen tank in the high-pressure storage unit. This led to a hydrogen leak, which created a flammable hydrogen mixture in air that ignited. Following the incident, the operator (subsequently fined 25 million Norwegian kroner or approximately £2 million) changed the assembly procedures of its hydrogen refuelling stations.

Source: Korea Herald

Gangneung, South Korea (2019)

A hydrogen tank explosion occurred in a pilot water electrolysis plant (producing hydrogen), resulting in two fatalities, with six injured. Several buildings, some over 100 meters away, were seriously damaged.

The cause of the explosion was oxygen that had permeated into a 40 m3 hydrogen storage tank (with an operating pressure of 1 Mpa). There was no secondary fire.

Santa Clara, California (2019)

Due to a miscommunication between a senior driver who had disassembled hydrogen supply piping to trailer mounted cylinders and a trainee, an uncontrolled release of high-pressure hydrogen occurred at a facility that transfers gaseous hydrogen (from pressurised liquid hydrogen storage) into high-pressure road trailer assemblies.

A flammable hydrogen-air mixture formed in and around the trailer module, ignited, and generated deflagration (explosion) overpressures, and whilst the closing of air-actuated valves stopped the uncontrolled release of hydrogen after about three seconds, the explosion resulted in localised jet fires that led to irreparable damage to the trailer module.

There were only two minor injuries and Santa Clara Fire Department successfully used aerial water spray application to cool the liquid hydrogen tank and the surrounding equipment exposed to residual fires. Damage to nearby trailers and equipment was repairable.

Following this incident, the equipment was modified to prevent a similar uncontrolled release and the training of drivers and operational procedures were improved.

Note: *There are on average around 30 natural gas explosions in the UK each year.*

5 General fire safety measures for fixed gaseous hydrogen installations

Hydrogen piping and equipment must be carefully designed, installed, and maintained to minimise potential leaks and allow for early detection and provide adequate ventilation.

The following general fire safety measures apply to plant and equipment handling, processing, and storing gaseous hydrogen:

1. Carry out suitable fire and process risk assessments.

2. It is essential that the engineers specifying, designing, and managing new or retrofit hydrogen gas installations clearly understand the properties of hydrogen gas, its associated hazards, and suitable controls. This is important to ensure that the methodologies applied and the assumptions made are applicable and relevant to hydrogen gas systems, rather than hydrocarbon gas systems.

   Relevant competence can be demonstrated by Chartered or Incorporated Engineer membership of the Institution of Gas Engineers and Managers (IGEM), or another relevant professional engineering institute, combined with specific expertise in hydrogen gas installations.

3. Plant and equipment should be designed to appropriate codes and standards – *see examples in the 'Codes and standards' section below.*

4. Equipment should be constructed using materials compatible with hydrogen service, considering potential for diffusion, hydrogen embrittlement, corrosion, and abrasion, designed to tolerances suitable for safely containing hydrogen gas.

5. Locate gaseous hydrogen storage installations at a suitable distance from other equipment, buildings, and parked vehicles. Minimum separation distances should be based on the fire risk assessment, with reference to bulk storage system volume and pressure – *refer to the relevant codes.*

6. Ensure that electrical equipment is selected and located in accordance with a suitable hazardous zones assessment (DSEAR/ATEX)* with specific reference to hydrogen equipment – see the 'Codes and standards – Hazardous zones' section below.

   Note that hazardous zone distances for hydrogen are typically 3–4 times greater than for methane, based on similar equipment tolerances (i.e. potential leakage path dimensions)

   * Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR)

7. Locate the hydrogen plant in the open air. Where some enclosure cannot be avoided, ensure that suitable and adequate natural and/or mechanical ventilation is provided.

8. Design hydrogen systems to limit release flow rates in case of outlet or dispensing hose failure.

9. Ensure that hydrogen equipment is fitted with adequate alarms, interlocks, safety-shutoff valves, and pressure relief devices, based on a suitable process risk assessment.

10. Provide hydrogen piping and equipment with electrical earthing and bonding to prevent the build-up of static electricity.

11. As appropriate, install hydrogen flame detection systems.

    Note that hydrogen burns a very pale blue to nearly invisible flame. Hydrogen flame detectors use the non-visible spectrum of electromagnetic radiation.

12. Ensure that suitable safe systems of work and preventive maintenance programmes are implemented, and that work is carried out by suitably trained and qualified technicians in accordance with OEM recommendations.

13. Establish an emergency response plan for accidental hydrogen releases and that adequate fire protection resources (based on the fire risk assessment) are available.

    Note that additional considerations are required for liquid hydrogen.

Similar principles apply to consumer hydrogen installations, accepting that design and material selection of equipment packages will be completed by suppliers.

For general guidance on the safe handling and storage of industrial gas cylinders, refer to RC08: *Recommendations for the storage use and handling of industrial gases and cylinders*.

6 Codes and standards

The following aims to provide a list of codes and standards relevant to hydrogen installations, but it is not exhaustive. *Refer to the latest editions*.

6.1 Hazardous zones

- IGEM/SR/25 Edition 2 with amendments, Hydrogen Supplement 1
  The hydrogen supplement is to be read in parallel with Standard IGEM/SR/25 Edition 2 – with Amendments August 2013. It is based on work detailed in HSE report FD/21/01 "Development of a Hydrogen Supplement for use with IGEM/SR/25" and provides a procedure for hazardous area classification around installations handling hydrogen, including a 20% NG/H blend providing a basis for the correct selection and location of fixed electrical equipment in those areas.
- Energy Institute, Model code of safe practice Part 15: Area classification for installations handling flammable fluids
- BS EN IEC 60079-10-1: Explosive atmospheres – Classification of areas. Explosive gas atmospheres

6.2 Other

- HSE Installation permitting guidance for hydrogen and fuel cell stationary applications
- NFPA 2 – Hydrogen technologies code
- FM Datasheet 7-91 Hydrogen
- ASME B31.12 Hydrogen piping and pipelines
- PD ISO TR 15916 Basic considerations for the safety of hydrogen systems

- ISO 22734 – Hydrogen generators using water electrolysis – industrial, commercial, and residential applications
- BS7910 – Guide to methods for assessing the acceptability of flaws in metallic structures
- Pressure Systems Safety Regulations (PSSR)
- European Clean Hydrogen Alliance – Roadmap on hydrogen standardisation, 2023 British Compressed Gases Association (BCGA) and European Industrial Gases Association (EIGA) – *various*
- APEA, Guidance on hydrogen delivery systems for refuelling of motor vehicles, co-located with petrol fuelling stations

7 Key references

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