Hydrogen Refuelling & Storage Infrastructure

Information Resource for Highlands & Islands Enterprise

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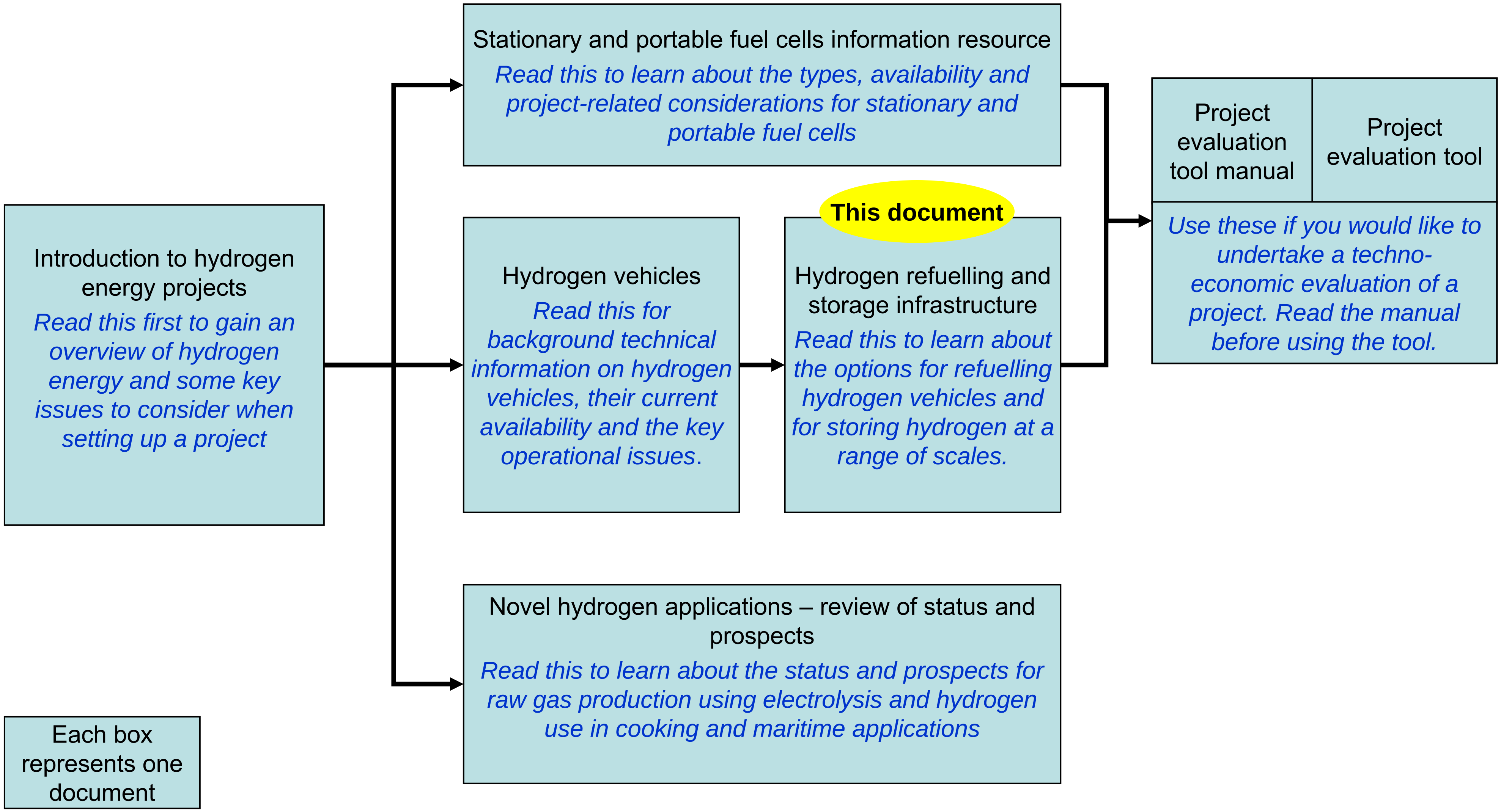
About this document

- In 2006 the HIE Renewable Energy team commissioned a consulting team to assist with the identification and assessment of hydrogen energy opportunities across the region. As part of this work the project team conducted a workshop in each LEC area to introduce the hydrogen energy opportunity and identify potential project ideas. Over 80 individual ideas surfaced, at varying levels of ambition, detail and feasibility.
- The project team worked with HIE to identify several recurrent themes among the ideas:
  - What are all the issues that need to be considered when setting up a hydrogen project?
  - What different stationary and portable hydrogen applications are there?
  - How can hydrogen be used in road vehicles?
  - How can hydrogen be stored and what refuelling facilities would be required for hydrogen vehicles?
  - What are the prospects for hydrogen use in maritime applications or cooking? Could bottled hydrogen and oxygen be produced and sold?
  - How can developers undertake technical and economic evaluation of their ideas?
- HIE judged that the best way to provide value to the LECs would be through a suite of information resources and tools based on these themes, to enable ideas to be developed and assessed further. These tools fit together as shown overleaf.

Document Map



About the authors

Element Energy

- **Element Energy is an engineering consultancy specialising in the low carbon energy sector. It formed in 2003 as a spin off from larger engineering practice Whitbybird.**
- **Services:**
  - Engineering services for low carbon energy projects
  - Innovation in new energy technologies and storage solutions
  - Strategic advice and consultancy
  - Project management and funding assistance
  - Specialist knowledge in hydrogen and fuel cell projects

E4tech

- **E4tech is a sustainable energy business consultancy, based in the UK and in Switzerland (established 1997)**
- **Services:**
  - Business strategy
  - Organisational support and interim management
  - Technology and market review to assist financing
  - Policy input for local and national government
  - Support to technology startups
  - Focus on hydrogen energy, bioenergy and sustainable buildings

PURE Energy Centre

- **The Pure Energy Centre has one aim: to give you access to the most effective energy storage techniques in the world to grow your business/community and increase your energy independence**
- **Services/products:**
  - Renewable hydrogen training courses
  - Consultancy for energy and storage technologies
  - Sales of hydrogen production units
  - R&D contract work for third parties

Commonly used acronyms

AFC Alkaline Fuel Cell

C H2 Compressed Hydrogen

CHP Combined Heat and Power

CNG Compressed Natural Gas

CRES Centre for Renewable Energy Studies (Greece)

DoE United States Department of Energy

EC CUTE European Commission Clean Urban Transport for Europe

EC HyCom EC Hydrogen Communities

FC Fuel Cell

FP6&7 Framework Programmes 6&7 (EU instrument for funding research)

H&I Highlands and Islands

H2ICE Hydrogen Internal Combustion Engine

HAZOP Hazard and Safety Operational Studies

HHV High Heating Value

HIE Highlands and Islands Enterprise

HSE Health and Safety Executive

ICE Internal Combustion Engine

LCIP Low Carbon Innovation Programme (Carbon Trust)

LEC Local Enterprise Company

LHV Low Heating Value

LNG Liquid Natural Gas

LPG Liquid Petroleum Gas

MCFC Molten Carbonate Fuel Cell

MCPs Manifold Cylinder Packs

MEA Membrane Electrode Assembly

NOx Nitrous oxides (pollutants)

O&M Operation and Maintenance

OEM Original Equipment Manufacturer

PAFC Phosphoric Acid Fuel Cell

PE Primary Energy

PEM Primary Exchange Membrane/Polymer ion Exchange Membrane

PSA Pressure Swing Absorption

R&D Research and Development

ROCs Renewable Obligation Certificates (see Defra website)

SME Small to Medium Enterprises

SOFC Solid Oxide Fuel Cell

UPS Uninterruptible Power Supply

VSA Vacuum Swing Absorption

ZEMSHIPS Zero Emission Ships

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Introduction

This document provides an introduction to hydrogen supply and storage infrastructures. The purpose of the document is to give a broad overview of the infrastructure options, the technologies that might be involved in projects and to highlight key issues. The document is not intended to provide detailed technical information or economic analysis, but directs the reader to further resources where appropriate.

The main focus of the document is on hydrogen supply and refuelling infrastructure for automotive applications, discussed in Sections 2 and 3.

The document also includes a discussion of small-scale and novel hydrogen storage technologies, which have potential relevance to both automotive and non-automotive applications (see Section 4).

There is significant recent and ongoing work on hydrogen safety, resulting in a growing body of published documents. This document highlights the main features of hydrogen that merit special attention with regards to its safe use and suggests further reading on this important subject (Section 5).

The document concludes with a list of key industrial service providers with capability in manufacture and supply of hydrogen generation, storage and refuelling systems.

Introduction – basics of vehicle refuelling

Hydrogen vehicle refuelling

The time when privately owned fuel cell cars capture any significant share of the market, and therefore a network of commercial filling stations is required to support them, is estimated to be 10 to 15 years away. However, as discussed in the companion document on hydrogen vehicles, there is a growing range of hydrogen vehicles, including buses, converted passenger cars and niche commercial and industrial vehicles, that will be available to demonstration projects in the near term.

If these vehicles are to be trialled in the Highlands & Islands they will need to be supported by local hydrogen supply and filling infrastructures.

There are a variety of options for refuelling infrastructure that are suitable for differing levels of hydrogen demand, from refuelling a single car to large refilling stations able to refuel multiple cars and buses on a daily basis.

All hydrogen refuelling infrastructure, irrespective of scale, comprises the following basic components:

Source: Reva Electric Car Company

These components are briefly introduced on the following slide.

Introduction – basics of vehicle refuelling

Hydrogen supply

Broadly there are two options for hydrogen supply – it can be delivered to the site or it can be generated on-site.

Delivered hydrogen – Hydrogen can be delivered either in a liquefied form, by tanker truck, or as a compressed gas in cylinders. As will be discussed, liquefied hydrogen tends only to be delivered in large volumes whereas compressed gas is far more scalable and can be supplied in small quantities.

On-site generation – The two main options for generating hydrogen on-site are reformation of natural gas (a process of splitting methane into molecules of hydrogen and carbon dioxide) and electrolysis of water (using electrical current to split water into hydrogen and oxygen). These two options are discussed in more detail in this document.

Hydrogen storage

If hydrogen is delivered as a liquid, a cryogenic storage vessel will be required on the site to maintain the temperature in the liquid range. Hydrogen will be decanted from a tanker truck into the storage vessel.

When hydrogen is delivered as a compressed gas, the storage vessel is usually dropped off at the site by a truck and then replaced when empty. For large volumes of hydrogen, a tube trailer will be delivered, which is a 40 foot trailer on which is mounted a bundle of pressurised tubes. For smaller volumes, the hydrogen can be delivered in cylinders, which can be bundled together into packs of varying numbers of cylinders, depending on the demand.

If hydrogen is generated on-site, it will be transferred from the reformer or electrolyser via a compressor to a compressed storage vessel. Liquefaction of hydrogen is an energy intensive process requiring large plant and would only be considered at a location where very large quantities of hydrogen were being produced.

Introduction – basics of vehicle refuelling

Hydrogen Refueller

The refueller delivers hydrogen to the vehicle's tank in a controlled manner and to the correct pressure.

Hydrogen is dispensed to the vehicle through a flexible hose and nozzle connected to the vehicle's tank, in a similar fashion to refilling with petrol or diesel. However, in addition to the dispenser, the refuelling system will comprise other components such as a compressor and potentially additional storage tanks.

For small-scale hydrogen demands the dispenser and other components may be packaged into a single compact unit, sometimes referred to as a mobile refueller. These are units that can be rapidly deployed at a site, requiring only a connection to a suitable hydrogen source. In some cases, hydrogen storage can even be included in the unit to give a truly stand-alone and mobile refuelling solution for low hydrogen demands.

The types of hydrogen refuelling solutions available at various scales are described in section 3.

There are a number of hydrogen refuelling stations around the world, trialling a variety of technologies and built at a range of scales

In total there are over 100 hydrogen filling stations in operation around the world, mostly concentrated in North America, Germany and Japan.

These filling stations are trialling a range of hydrogen supply options, including delivery in liquid or gaseous form or on-site generation.

Filling stations have been built in 10 cities in Europe to support fuel cell buses in the EC CUTE[1] project. These stations are relatively large, able to refill at least 3 buses per day.

As well as large scale initiatives such as the CUTE project, there is activity on a smaller scale.

For example the Centre for Renewable Energy Studies (CRES) in Greece has installed a small hydrogen filling station using hydrogen generated by an electrolyser linked to a 500 kW wind turbine.

The system has capacity to store around 4kg of compressed hydrogen, which is used to power a vehicle to transport visitors to the site and a fuel cell powered golf cart.

25kW electrolyser at the CRES facility

[1] *Clean Urban Transport in Europe (CUTE) was a 3 year project funded by the EC to install 30 fuel cell buses in 10 cities in Europe*

All images from www.h2stations.org

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Delivered hydrogen - hydrogen can be delivered by tanker truck in liquid form. This is usually only appropriate where large volumes are required.

Liquefied hydrogen:

Liquefaction of hydrogen requires cooling to a temperature of -253 °C and subsequent storage in cryogenic containers. Liquefaction is an energy intensive process and can consume up to 35% of the energy in the stored hydrogen.

The advantage of liquefied hydrogen is its high density compared to compressed gas, which means that more energy can be contained in a given volume. This is particularly beneficial for transportation of hydrogen.

Generally, liquefaction of hydrogen is only appropriate where it is produced in large quantities and will be transported in bulk (or over long distances). For a refuelling site this would suggest a station with a high throughput of hydrogen vehicles.

Source: Air Products

Most hydrogen vehicles are being developed with compressed gas onboard storage (although there are notable exceptions to this, for example the BMW H_2 vehicles). The infrastructure required at the site to convert the liquid hydrogen supply to a compressed gas for delivery to the vehicle is complex, involving controlled vaporisation of liquid hydrogen and compression into a compressed gas storage facility. This infrastructure is expensive and significant scale is required for it to be economic.

There are solutions for refuelling vehicles with liquid hydrogen. This type of station is relatively simple in design, as liquid hydrogen is pressure-transferred from the storage vessel to the vehicle without need for compressors or pumps. A different design of dispenser and refuelling nozzle is required for transfer of liquid hydrogen.

Delivered hydrogen - Compressed H_2 can be supplied in a range of volumes, including very small amounts, due to the modularity of compressed storage.

Compressed hydrogen

Compressed hydrogen is delivered in a variety of containers, depending on the quantity of hydrogen required.

Large quantities of compressed hydrogen are delivered in a **tube trailer**. A tube trailer consists of a pack of large pressurised cylinders, manifolded together and housed on a trailer (typically a 40 foot trailer). The trailer is delivered to the site by a truck.

The tube trailer contains around 300 kg of hydrogen at a pressure of 200 to 250 bar. As hydrogen is consumed the pressure in the trailer will drop and so the tube trailer will be connected via a compressor to additional compressed storage vessels installed on the site. Hydrogen to refuel the vehicles will be taken from these fixed vessels.

Smaller volumes of hydrogen are supplied in cylinders at 200 bar pressure. Typically the cylinders will be bundled together into packs of between 6 to 15 and their outlets manifolded together. These packs are known as **manifolded cylinder packs (MCPs)**. A 15 cylinder MCP contains around 10kg of hydrogen. MCPs are delivered to site on the back of a truck with appropriate lifting gear.

(Above) Hydrogen tube trailer containing approximately 300kgH_2. *Source: Air Products*

Manifolded cylinder pack (MCP) containing approx. 10kgH_2
Source: BOC

Hydrogen manifolded cylinder pallet (MCP)

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On-site generation – Reformation of hydrocarbon is widely used to generate hydrogen. The technology is now being developed at small-scale.

The vast majority of hydrogen produced worldwide is generated by a process of breaking up hydrocarbon molecules into H_2 and CO – this process is called reformation. Reformation is performed on an industrial scale, typically using natural gas (methane, CH_4) as a feedstock.

There are a number of technologies for reforming hydrocarbons, but the most common is a process known as steam methane reforming (SMR). SMR involves two chemical reactions, as follows

$CH_4 + H_2O_{(steam)} \rightarrow CO + 3H_2$ Steam reforming reaction

$CO + H_2O \rightarrow CO_2 + H_2$ Water-gas shift reaction

Reformation involves reacting methane (or other hydrocarbon) with steam to produce CO and H_2. The water-gas shift reaction produces further H_2 by reacting the CO with more water. The process requires heat to generate the steam, which is produced by burning a fraction of the natural gas feedstock and by burning some of the waste gas produced. The overall efficiency of the process is in the range of 65 – 70%

As interest in using hydrogen as an energy carrier has increased, attention has been focussed on the generation of hydrogen via reformation at a smaller-scale.

Systems are being developed with output as low as 20 kg/day, sufficient for refuelling 5 passenger cars per day, and there is interest in developing even smaller systems for home-based reformers or even reforming on-board the vehicle

On-site scale reformers are a developmental technology, but there are a number operating at H_2 refuelling stations around the world.

Air Products on-site reformation facility at a hydrogen filling station in Sun City, Nevada

Source: Ludwig-Bolkow-Systemtechnik

On-site generation – Electrolysis of water is another technology for on-site generation and is key for the use of renewable electricity to produce H_2

The other key contender for on-site hydrogen generation is water electrolysis. This is the splitting of water molecules into their constituent parts (H_2 and O_2) by passage of an electrical current. Electrolysers have also been developed at industrial scale, but account for only a small fraction of world-wide hydrogen production.

There are two main electrolyser technologies – alkaline, which contain liquid electrolytes (potassium or sodium hydroxide), and solid polymer electrolyte electrolysers, this is a newer technology which is essentially very similar to a PEM fuel cell operating in reverse.

The costs of industrial electrolysers (e.g. 250-500kW in capacity) are around £1000/kW. Electrolysers are available with outputs of < 1 kg/hr (i.e. < 50 kW), but costs increase sharply at small scales.

In addition to the electrolyser unit, an on-site station generating hydrogen by electrolysis will require water purification systems and a hydrogen purification and drier unit to treat the hydrogen produced.

Many electrolysers will generate hydrogen at relatively low pressure, e.g. 10 to 25 bar, so further downstream compression will be required to elevate the pressure to storage pressures.

Some small-scale electrolysers are now being developed that generate hydrogen at far higher pressure, which can reduce the requirement for further compression

- **Electrolysis is a key technology for the conversion of renewable electricity to hydrogen.** As interest in renewable hydrogen grows, so too will demand for electrolysers at economic costs and appropriate scales.

Hydrogenics Hy-STAT A alkaline electrolysis unit. This packaged unit has an integrated compressor to deliver hydrogen at storage pressures.

Source: Hydrogenics

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Vehicle refuellers – Refuelling solutions exist at a variety of scales appropriate for varying daily hydrogen throughputs

Solutions exist for refilling vehicles over the complete range of filling requirements, from single vehicle refueling to many vehicles at a single refilling point.

Source: Air Products

Bundled filling solution – unit is delivered to site with integrated high pressure cylinders appropriately configured to directly refuel a vehicle. Solutions exist with footprints under 5 m^2. An example is the Air Products mobile refueller pictured above. Filling solutions could be **available on a scale as low as one vehicle refuel per week.**

Source: Air Products

Small "mobile" refueller – a number of companies have developed flexible refuellers which can be deployed on a customer's own facility and moved if required. These fuellers include built in compressors, ready to be connected up to a source of hydrogen (delivered cylinders or generated on-site). These relatively low cost solutions are **relevant for small fleet trials and demonstration projects.**

Source: www.h2stations.org

Large scale filling station – on a large scale, a range of filling station solutions have been devised. Many of these are under investigation as a part of the CUTE project. Solutions range from on-site generation to delivery by liquid hydrogen tanker. **These stations are aimed at refueling over 50 vehicles per day**.

Vehicle refuellers – The refuelling solution includes a dispenser to transfer H_2 to the vehicle

The hydrogen dispenser is similar in appearance to a typical petrol or diesel dispenser, providing a nozzle at the end of a flexible hose for connection to the vehicle's hydrogen tank.

The filling procedure involves transfer of gases at high pressure, which will be novel to most drivers and require some training. In the past, filling facilities have required operators to wear protective clothing, but this is no longer necessary with newer designs. Refuelling times are typically longer than a petrol refuel, but this is also improving.

The pressure of the vehicle's onboard storage (typically 350 bar) is likely to be higher than bulk storage at the filling facility.

There are two methods for forcing gas into the vehicles tank to the correct pressure:

Cascade storage – The majority of the station storage will be at a pressure of 200 to 250 bar, but a small quantity of storage will be kept at higher pressure (e.g. 450 bar). During filling, once the pressure between the main storage tanks and the vehicle's tank have equalised, gas will be released from the high pressure store to complete the fill.

Booster compressor – a further compressor is included between the station's storage tanks and the vehicle tank to ramp up the pressure to the required level.

Stuart Energy hydrogen dispenser and operator.

Connection of a hydrogen dispenser nozzle for filling with compressed hydrogen

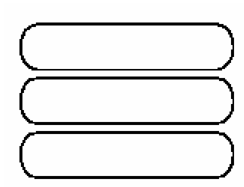
Images: Ludwig-Bolkow-Systemtechnik

Delivered hydrogen supply – Summary of options

Decreasing supply volume

Liquid H_2 – tanker truck → On-site liquid storage → Vaporisation and Compression

Compressed H_2 – tube trailer



Compressed gas storage

Refueller

Source: Hydrogenics

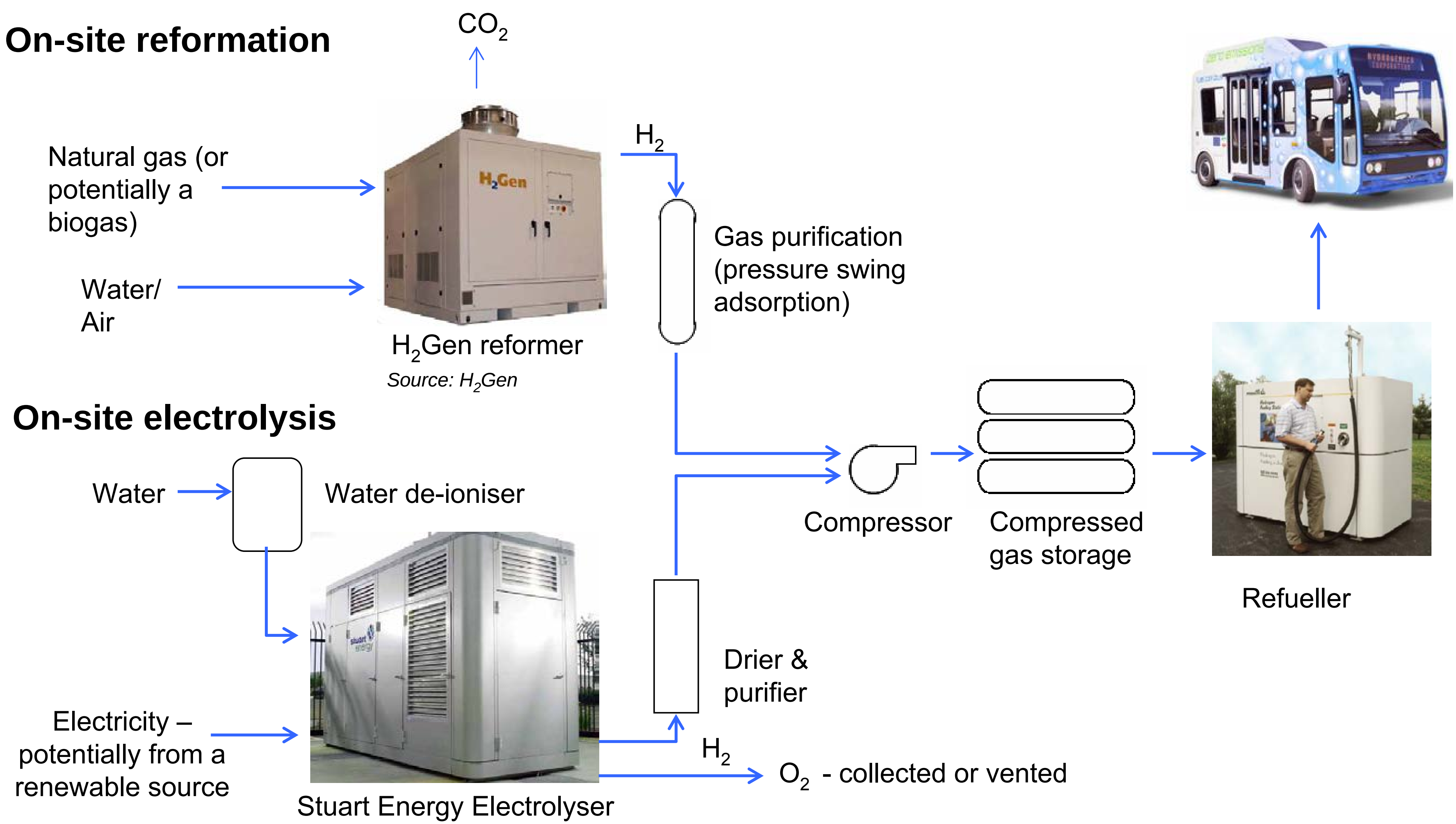
Vehicle

Hydrogen manifolded cylinder pallet (MCP)

Bundled cylinder pack

Mobile refueller (includes H_2 cylinders)

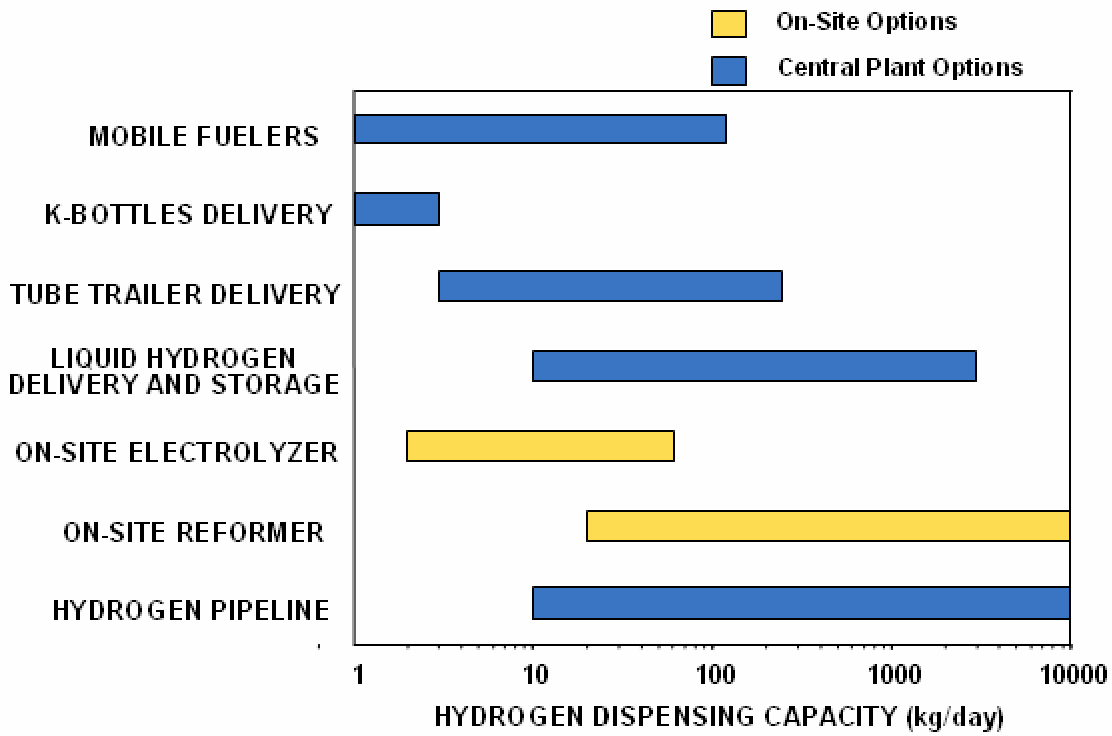
On-site hydrogen generation – summary of options



The most appropriate hydrogen supply option depends on the size of the demand, but also depends on local factors

The chart below[1] indicates the ranges of daily hydrogen use over which the various hydrogen supply and on-site generation options are appropriate.

These ranges are only approximate guidelines as suitability of both delivered and on-site generation routes is highly site specific, depending on such factors as site conditions, proximity to central hydrogen production, capital versus running cost trade-off and the demonstration priorities among others.



To give an appreciation of scale:

- A hydrogen internal combustion engine passenger car would have a tank capacity of 1.5 to 2 kg.
- A small (20 passenger) fuel cell bus may require 10 kg for a single fill.
- A full-size (40 foot) fuel cell bus might have a tank capacity of 30-35kg H_2

[1] California Hydrogen Fueling Station Guidelines – Executive Summary, California Energy Commission (2004)

Summary of hydrogen supply options

Hydrogen supply option	Relevant range of demand	Main components of system	Comments
Bundled filling solution	< 1kg/day to 10 kg/day	Mobile solution with compressed gas storage, compressor and dispenser in packaged cabinet	Suitable for small demands, e.g. a single car. Easy to deploy and relatively low cost.
Manifolded cylinder pack (MCP)	1 to 10 kg/day	MCP is delivered to site. Compressor and dispenser (could be packaged in a mobile refueller).	Suitable for small number of cars. Easy to deploy, particularly if used with a packaged refueller.
Tube trailer	10 to 300 kg/day	Tube trailer is delivered to site and connected to on-site compressor and high-pressure storage. Dispenser.	Suitable for larger demands, e.g. small number of buses.
Liquid hydrogen delivery	10 to 3000 kg/day	Liquid hydrogen storage, pumps, vaporisation equipment, compressor, compressed gas storage, dispenser.	Suitable for large demand, e.g. large-scale filling station fuelling fleet of buses and cars.
On-site reforming	> 20 kg/day	Natural gas connection to the site. On-site reformer, H_2 purification equipment, compressor, compressed storage and dispenser.	Being developed at small-scale, relevant to small number of cars or single bus. Scalable to meet much larger demands.
On-site electrolysis	<10 – 50 kg/day	Electrical connection, water de-ioniser, electrolyser, drier & purifier, compressor, compressed storage & dispenser	Available at small scales. Allows use of renewable electricity for hydrogen generation.

Refuelling solutions dispensing delivered hydrogen are a low capital option, but on-site generation may deliver lower cost hydrogen to the vehicle tank.

The lowest capital cost and easiest refuelling solution to implement is a delivered compressed hydrogen solution. A small mobile refueller and compressor system serving 10 cars/day would cost approximately £200k.

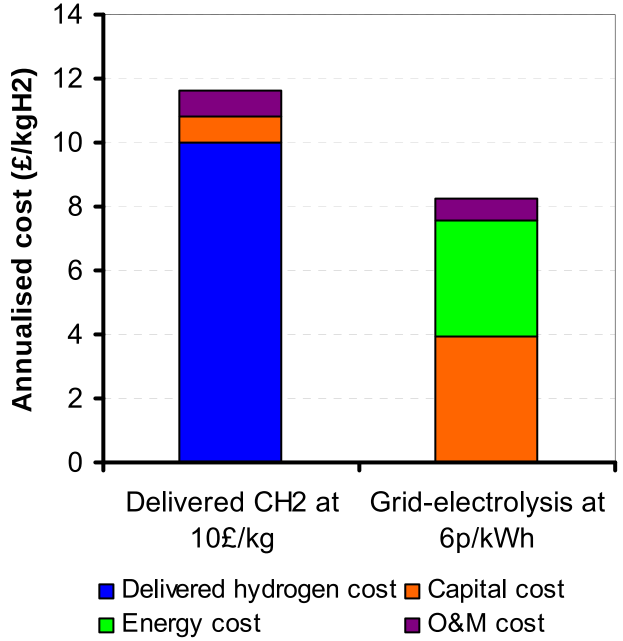
On-site generation is more capitally intensive due to the additional hydrogen production and storage equipment required (a filling station with an electrolyser sized to serve 20 cars/day would cost between £600k to £1M). However, **on-site generation may deliver lower cost hydrogen.**

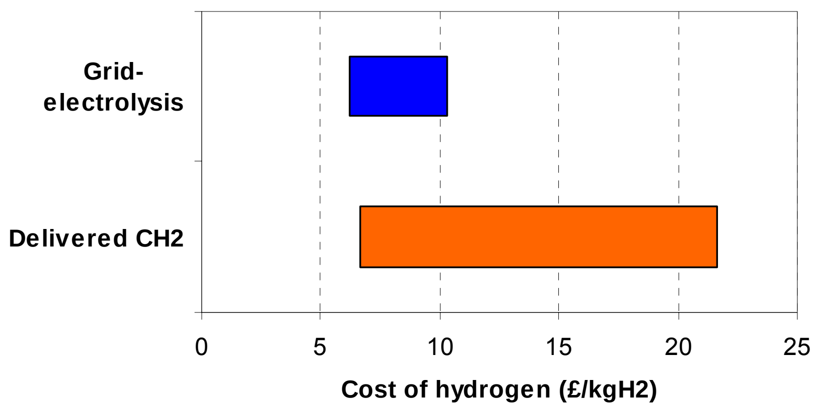
An indicative breakdown of the cost of hydrogen at the refuelling station is shown in the chart (top) for delivered compressed hydrogen and for on-site electrolysis.

For a station dispensing delivered hydrogen, the final cost of hydrogen is strongly dependent on the price of delivered hydrogen. For grid-electrolysis, the cost of hydrogen is dictated by the capital cost of the plant and the cost of electricity.

The sensitivity of the cost of hydrogen to electricity cost and delivered hydrogen price for on-site electrolysis and a delivered H_2 dispensing station is shown in the second chart (bottom).

This demonstrates that the most economical refuelling solution will depend on the available price for delivered hydrogen and the local energy costs.





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Storage technologies – Significant R&D is dedicated to developing higher capacity, lighter weight storage technologies

Hydrogen is highly energy dense in terms of its energy content per kg of mass compared to other fuels. However because it is a gas at ambient temperature and pressure it has either to be contained in a compressed form or as a liquid in cryogenic containers. These storage systems tend to be heavy.

Typical compressed hydrogen storage cylinders (i.e. steel cylinders containing hydrogen at 200 bar pressure) comprise < 1.5wt% H_2 (i.e. >98.5% of the total weight is the cylinder). The weight of energy storage is very important for vehicle and portable applications, so there is a great deal of interest in increasing the wt% of hydrogen storage.

One means of doing this is by storing in lighter-weight cylinders at higher pressures. Cylinders fabricated from wrapped carbon fibre composites are becoming available that can store compressed hydrogen at pressures of 700 bar and above. This can increase the weight percent of hydrogen to ~ 6wt%.

Higher pressure compressed gas storage has clear benefits for vehicle onboard storage, giving increased range between refills. However, higher pressure systems could also be beneficial for remote fuel cell applications, e.g. telecoms stations and navigational aids, giving longer operational duration between cylinder changes and therefore reduced frequency of visits to the application.

Lighter-weight storage could also be beneficial for marine and leisure fuel cell applications.

Wrapped carbon fibre cylinders for hydrogen storage at 700 bar

Source: Dynetek

Storage technologies - Solid-state storage methods promise high storage densities, but more development is required to realise this potential

There is considerable interest in the development of 'solid' hydrogen storage techniques. There are two main techniques for 'solid' storage – metal hydride and chemical hydrogen storage.

Metal hydride storage involves absorption of hydrogen into the structure of materials that have a strong affinity for hydrogen.

When hydrogen is absorbed, some heat is released. In order to release the hydrogen again, i.e. reverse the process, some heat has to be supplied . Useful hydrides are those that are based on light metals, absorb hydrogen at low temperature and have a fairly narrow range between temperature at which they absorb and release hydrogen (e.g. such that the waste heat from a fuel cell would be sufficient to sustain the release of hydrogen from the storage material). Systems are being developed based on metals such as sodium, magnesium, aluminium and lithium.

Source: www.herahydrogen.com

These storage systems have some safety advantages, as there is no potential for high pressure release of hydrogen. They also promise high volumetric energy density and gravimetric energy density to rival high pressure compressed gas storage. However, although some products are available, the systems are still under development and there are challenges to be overcome before the potential of hydride storage is realised.

Chemical hydrogen storage involves hydrogen being chemically bonded to another material and released via a chemical reaction. Typically the reaction would involve a chemical hydride in reaction with water to generate hydrogen and a hydroxide. The 'chemical hydrogen store' has to be regenerated by a subsequent process, for example electrolysis of the hydroxide back to the hydride state. Companies such as Millenium Cell in the US are attempting to commercialise chemical storage technologies and have reported gravimetric capacity of 4wt%.

Summary of storage technologies

Storage type	Technologies	Energy density (for small-scale storage)	Availability	Issues
Compressed gas	Steel cylinders at 200 bar	0.5 kWh/kg (1 wt%)	Most common and widely available method of storing compressed hydrogen, e.g. cylinders and MCPs.	Lowest cost storage technology but relatively heavy and bulky. Despite this, energy density is still superior to most batteries.
	Composite cylinders at 350 bar	1.9 kWh/kg (6 wt%H_2)	350 bar storage is the current standard for vehicle onboard tanks.	Main issue is finding low cost composite materials that have sufficient strength to contain the high pressure gas, without resorting to thick-walled tanks. Not used for transporting hydrogen outside of vehicles.
	Composite cylinders at 700 bar	1.6 kWh/kg (5 wt%H_2)	Target for vehicle tanks. (Although lower wt%, the volumetric energy density is higher than at 350 bar)	
Liquid hydrogen		1.7 kWh/kg (5 wt%H_2)	Hydrogen is stored as liquid for transport by tanker or in large-scale stationary vessels, not for small-scale distribution. However, small-scale cryogenic tanks have been developed for vehicles	Liquid tank costs are high and difficult to scale to small sizes. Energy penalty for liquefaction – only practical at a large-scale and for volume transport

Summary of storage technologies

Storage type	Technologies	Energy density (for small-scale storage)	Availability	Issues
Metal hydride	Hydrides of light metals, e.g. sodium, boron, lithium, magnesium	0.5 – 0.8 kWh/kg (1-2 wt%H_2)	Still a developmental technology, with a great deal of research interest in finding new materials that can improve the energy density. Some companies, such as Ovonics, Solid-H & Voller, are offering products commercially	Although the storage capacities of the materials are high, once contained the energy densities are no better than conventional compressed gas (200bar) storage. Costs are currently high. Safety advantages as no high pressure or low temperatures are involved.
Chemical hydride	Hydrides that react with water or alcohol to produce hydrogen	1.4 kWh/kg (4 wt%H_2)	Still a developmental technology and the subject of significant research. Millenium Cell are attempting to commercialise a system.	Another reactant (water or alcohol) is needed to release the hydrogen. Once spent, a further process (e.g. electrolysis) is required to regenerate the store.

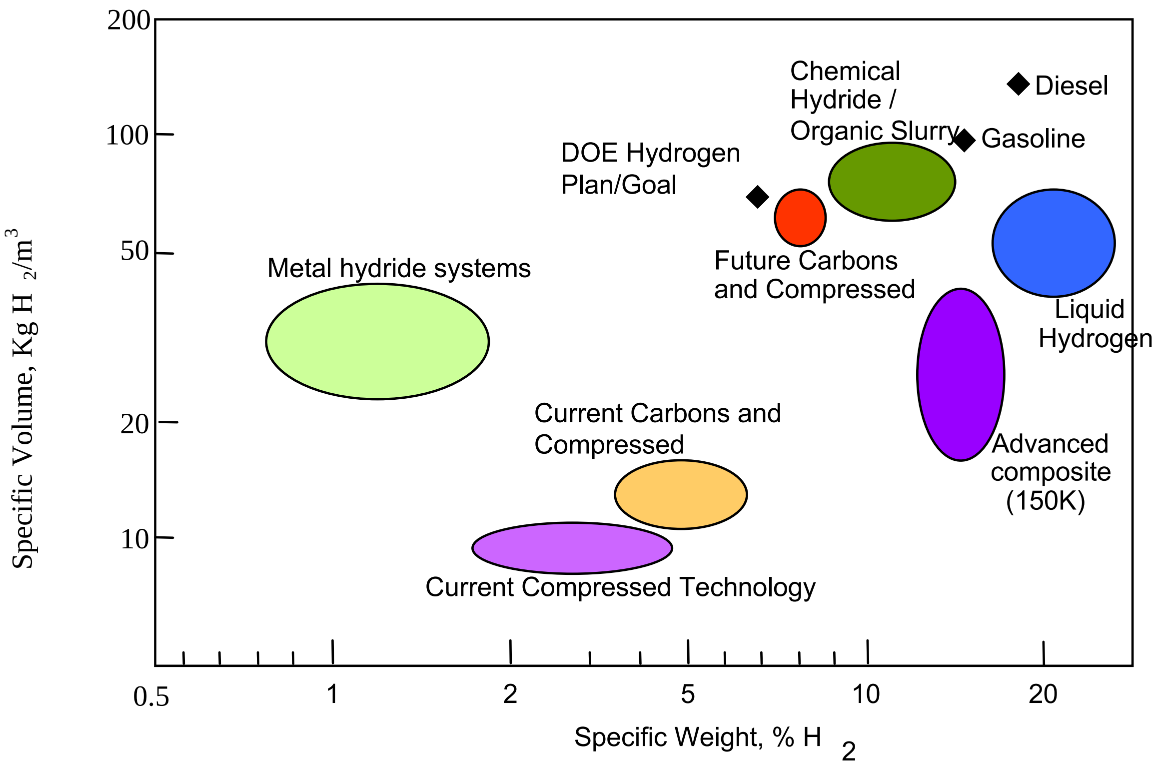
Summary of storage options – In the near term, compressed H_2 storage will be most relevant to H&I

The chart compares a range of hydrogen storage technologies on the basis of their gravimetric and volumetric hydrogen capacities.

The most relevant storage technology to the Highlands & Islands in the near term is likely to be compressed storage, as it is scalable, readily deployable and available at reasonable cost.

Liquefied hydrogen is unlikely to have a role in the near-term due to the equipment requirements and energy consumption of liquefaction. If hydrogen generation at a large-scale for export to markets outside of the H&I region develops, then liquefaction could become relevant.

Metal Hydride storage could be applicable as a convenient form of storage for niche applications, such as remote fuel cell applications or leisure and marine use.



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Hydrogen safety - Hydrogen can be dangerous if misused and has a number of properties which require special attention

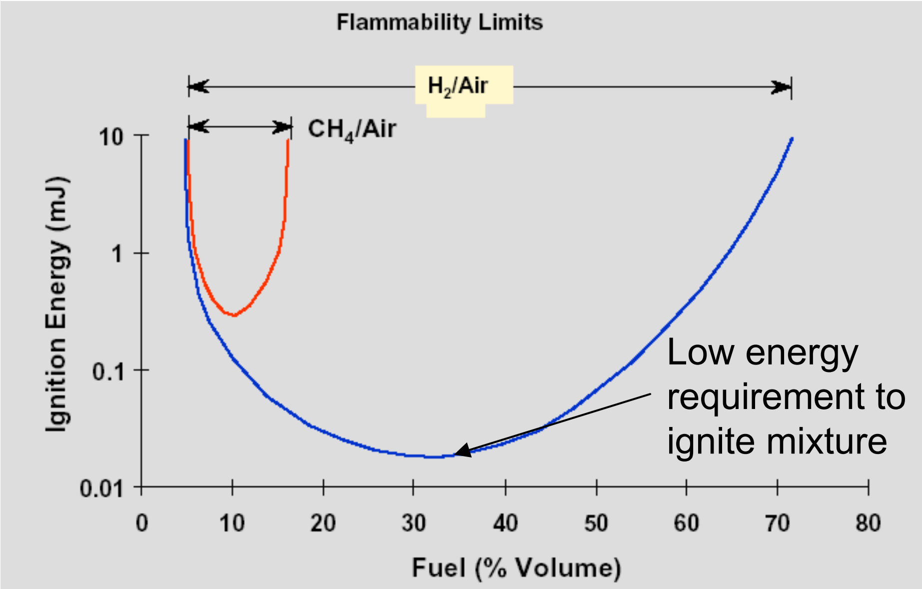
Hydrogen can be a dangerous substance if mishandled or if an accidental release of hydrogen were to become ignited. In this respect it is no different to all other fuels that are in common use today.

There are a number of properties of hydrogen that are distinct from those of hydrocarbon fuels that require special consideration:

- Mixtures of hydrogen in air are flammable over a wide range of compositions
- The energy required to ignite a hydrogen/air mixture can be very low
- Hydrogen burns with a flame that is invisible in daylight
- Hydrogen is a small molecule that can leak easily
- Hydrogen is often stored at high pressure and if released and ignited burns with a rapidly moving flame – a jet flame

Mitigating factors

- Hydrogen is very buoyant – leaks disperse quickly into the air rather than accumulating near the ground
- Escaped hydrogen has a low energy density
- Hydrogen is non-toxic



The range of flammability of H_2/air mixtures is wide. However the lower limit, which is normally most important (i.e. the point at which the mixture first becomes flammable) is similar to that of a methane/air mixture.

Hydrogen safety – H_2 has long been used safely in industry. The codes and standards governing its use are now being adapted for public applications.

A variety of codes and standards exist regarding the use of hydrogen in an industrial setting However, as the use of hydrogen as an energy carrier becomes more prevalent and hydrogen is used by the public, new standards will be required.

A considerable amount of work has been done on development of new standards, both in Europe and the US. These standards consider safety aspects of all components in the hydrogen infrastructure, including issues such as:

• Safety distances – the separation required between hydrogen equipment and sources of hazard such as power lines, electrical equipment (potential source of sparks that could ignite a hydrogen leak), other combustible materials etc.

• Design of buildings and containers for housing hydrogen equipment – requirements for good ventilation to avoid explosive mixtures forming if hydrogen is released, design of buildings to stop hydrogen accumulating etc.

• Earthing and lightning protection of hydrogen installations

• Materials and components used in hydrogen systems, including pipework, hoses, connectors, valves etc.

• Standardisation of nozzles for hydrogen dispensers to prevent accidental misuse

Codes, standards and useful resources

Below are lists of codes and standards relating to hydrogen energy and some useful resources where further information on the safe use of hydrogen can be found.

Existing codes, standards and guidance (not exhaustive)

- EIGA document 15196: Gaseous hydrogen installations
- British Compressed Gas Association (CP4 and GN2)
- NFPA 50A: Standards for gaseous hydrogen systems at consumer sites
- German TRG 406: CGH2
- ISO 15916: Basic considerations for the safety of hydrogen systems
- ATEX (supply) Regs; SI192, 1996
- Dangerous Substances and Explosive Atmospheres Regulations 2002
- BS EN 60079 Electrical app. for explosive gas atmospheres
- 'Fuel cells: Understand the hazards, control the risks', HSG243, G. Newsholme,

Useful resources:

- European Integrated Hydrogen Project (www.eihp.org)
- National Hydrogen Association (www.hydrogenassociation.org)
- Hydrogen and Fuel Cell Safety (www.hydrogensafety.info)
- ICC Ad hoc Hydrogen Committee (www.iccsafe.org)
- Compressed Gas Association (www.cganet.com)
- Health and Safety Executive (www.hse.gov.uk)

Contents

Key hydrogen infrastructure suppliers and service providers

Integrated system providers	Comment
Air Products	Major industrial gas company with expertise in many areas of the hydrogen energy chain, including separation, purification and storage. Has provided infrastructure for several hydrogen refuelling stations in US and Europe.
BOC	Major industrial gas provider with strong interest in hydrogen energy sector. Together with BP has provided infrastructure for a number of filling stations, including the U.K's first hydrogen station in Hornchurch, London.
Ballast Nedam	Ballast Nedam is a leading supplier of fuelling stations for automotive applications. Has interest in developing hydrogen fuelling infrastructure with partner Hexion (see Reformer section)
Ebara Ballard	Developing hydrogen refuelling solutions combining photovoltaics with electrolysers provided by partner organisation Hydro.
General Hydrogen	Provides hydrogen dispensers and complete refuelling solutions for industrial vehicles.
Hydro	Large Norwegian energy and metals company. Produces electrolysers, hydrogen purification equipment and complete refuelling solutions.
Hydrogenics	Hydrogenics develops PEM fuel cells and through its acquisition of Vandenborre (alkaline electrolysers) and Stuart Energy (integrator of electrolyser based infrastructure) can now offer complete refuelling solutions.
Linde	Large industrial gas company with expertise in many areas of hydrogen energy systems. Key provider of infrastructure solutions for several German filling stations, including Munich Airport.
Mobile Energy Solutions	Formed to develop advanced technology vehicles, including electric and fuel cell vehicles, MES is able to offer infrastructure solutions together with a range of strategic partners, such as Hydrogenics.
Plug Power	Primarily a developer of PEM fuel cell products, Plug Power has been awarded a contract to provide refuelling infrastructure in New York - partnering with Air Products
BP, Shell, Chevron Texaco, Total	Major energy multinationals all have an interest in developing hydrogen energy sector and have been involved in supplying hydrogen and infrastructure solutions to numerous filling station projects world-wide.

Key hydrogen infrastructure suppliers and service providers

Small-scale electrolysers	
AccaGen	Developer of alkaline electrolysers across a range of sizes (1-100 Nm3/hr). Provide pressurised electrolysers (200 bar output), obviating need for further compression for bottle filling.
Avalence	US developer of pressurised alkaline electrolysers (from <1 to 300 kg/day). The Hydrofiller unit, which can deliver hydrogen at very high pressure, is available for demonstration projects and early-adopter partners.
Hydro	Norsk Hydro Electrolysers is a major manufacturer of water electrolysis, hydrogen purification and handling equipment.
Hydrogenics (Vandenborre)	Hydrogenics offer the IMET range of alkaline electrolysers, at rated capacity from 1 to 60 Nm3/hr. Its HySTAT range of packaged hydrogen generation equipment, with integrated compression. Hydrogenics also offer a range of purification equipment.
Mitsubishi	Has developed high pressure hydrogen generation equipment (High-pressure hydrogen energy generators, HHEG) based on PEM electrolyser technology.
South West Electrolysers	U.K based manufacturer of modular water electrolysis equipment.
Small-scale reformers	
Babcock Hitatchi	A subsidiary of Hitatchi, Babcock Hitatchi has developed on-site reformation technology demonstrated at filling stations in Japan.
H2Gen	Founded to manufacture low-cost, small-scale hydrogen generation equipment for industrial, vehicle and distributed power applications. H2Gen's reformer technology produces compressed hydrogen from natural gas and propane feedstocks (at scales down to 20kg/day).
Heatric	Developed small-scale stand-alone steam methane reformer technologies, including water-gas shift reaction, to produce hydrogen at sufficient purity for use in PEM fuel cells.
HYGEAR	HyGear (formerly Hexion) develops hydrogen generation units incorporating steam methane reformers and pressure swing adsorptions purifiers. Involved in the Duogen project, to develop a unit which incorporates a reformer and a fuel cell, to generate hydrogen for vehicles or electricity for the grid from a single unit.
HyRadix	Hyradix hydrogen generation equipments produces a hydrogen rich gas stream from natural gas or LPG and can be applied to industrial, filling station or domestic applications. The company's hydrogen generator has completed 1,000 hours of operation in the field at the Thousand Palms filling station (California), where it produced hydrogen for hythane powered vehicles.

Key hydrogen infrastructure suppliers and service providers

Other component suppliers	
Dynetek	Produces lightweight compressed storage vessels for both onboard tanks and ground-based storage systems.
Fueling Technologies International	Produces dispenser systems for a range of alternative fuels, including hydrogen, LPG and CNG
HERA	Develops hydrogen storage solutions based around metal hydride technology
Ovonics	Developing metal hydride storage solutions aswell as integrated solar-electrolyser-storage solutions.
Pdc machines	Manufacturer of compressor units for hydrogen.
Quantum	Manufacturer of high pressure storage systems, control systems, metering and fuel system integration.
QuestAir	Develops and commercialises pressure swing adsorption units for purification of hydrogen (e.g. produced from reformer). The HyQuestor product operates in the 10 to 1,000 Nm3/hr range, suitable for hydrogen refuelling and industrial applications.