HYDROGEN OVERVIEW - DISTRIBUTION, STORAGE, APPLICATIONS

Doc 247/24

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1 Introduction

The purpose of this publication is to provide an overview of distribution methods, storage systems and applications of hydrogen within Europe.

Use of hydrogen in industry is undergoing a period of rapid expansion and diversification with many newcomers; this document provides a general overview and highlights safety considerations of the hydrogen supply chain.

2 Scope and purpose

2.1 Scope

The scope of this publication covers gaseous and liquid hydrogen equipment and applications within Europe.

The main areas covered in this publication are:

- Hydrogen Safety
- Distribution of hydrogen
- Storage systems
- Applications

This document does not cover:

- Hydrogen Production facilities – EIGA Doc 242 [1]
- Cylinder filling facilities - EIGA Doc 15 [2]
- Detailed facility or plant design and specification - EIGA Doc 242 [1]
- Product quality - EIGA Doc 242 [1]

Transportation of hydrogen by air is not covered in this publication.

2.2 Purpose

This publication provides general information on equipment and methods used in the hydrogen supply chain. It is written in a way to be understood by all, including newcomers to the industry.

For more detailed information, refer to the publications as referenced.

3 Definitions

For the purpose of this publication, the following definitions apply.

3.1 Publication terminology

3.1.1. Shall

Indicates that the procedure is mandatory. It is used wherever the criterion for conformance to specific recommendations allows no deviation.

3.1.2 Should

Indicates that a procedure is recommended.

3.1.3 May

Indicates that the procedure is optional.

3.1.4 Will

Used only to indicate the future, not a degree of requirement.

3.1.5 Can

Indicates a possibility or ability.

3.2 Technical definitions

Liquid hydrogen: Also known as LH_2, liquid hydrogen is a form of hydrogen that is cooled to cryogenic temperatures.

Pressure: In this publication bar shall indicate gauge pressure unless otherwise noted, i.e. (bara) for absolute pressure.

ADN	Transport of Dangerous Good by Inland Waterways
ADR	Transport of Dangerous Goods by Road Regulations
AET	Acoustic Emission Testing
ASME	American Society of Mechanical Engineers
ATEX	The name commonly given to the two European Directives for controlling explosive atmospheres.
BCGA	British Compressed Gas Association
BD	Bursting Disc
BIC	Bureau International des Containers
BPVC	Boiler and Pressure Vessel Code
DOT	Department of Transport
ERA	European Union Agency for Railways
FCEV	Fuel Cell Electric Vehicle
GH_2	Gaseous hydrogen
IMDG	International Maritime Dangerous Goods Code
IMO	International Maritime Organisation
ISO	International Standards Organisation
LEL	Lower Explosion Limit
LH_2	Liquid hydrogen
MAP	Maximum Allowable Pressure
MAWP	Maximum Allowable Working Pressure
MEGC	Multi Element Gas Container
NH_3	Ammonia
PBUC	Pressure Build Up Circuit
PED	Pressure Equipment Directive (European)
RID	International Carriage of Dangerous Goods by Rail
RORO	Roll on Roll Off
SP	Special Permit
SRV	Safety Relief Valve
TPED	Transportable Pressure Equipment Directive (European)
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UEL	Upper Explosive Limit
US	United States
UTS	Ultimate Tensile Strength

UT Ultrasonic Testing

4 Physical characteristics of hydrogen

Hydrogen is the lightest element in the periodic table. It is a highly flammable, colourless, odourless, nontoxic, chemical substance. At ambient conditions it is in gaseous phase as a diatomic pair of atoms, H_2.
H_2 has a wide range of flammability in air, ranging from 4% to 74.5%. The minimum required energy of ignition is very low at 0.02 millijoules, which is at least ten times lower than hydrocarbons like methane or propane. This ignition energy is so low that sometimes auto-ignition can occur, at high velocities, venting or depressurisations. The auto-ignition temperature of H_2 at atmospheric pressure is 535°C. H_2 burns with an invisible flame in daylight.

Liquid hydrogen (LH_2) exists only at extremely low temperatures, at atmospheric pressure its melting point is -259.3 °C and boiling point is -252.9 °C. LH_2 is a colourless, odourless liquid with a density at boiling point and atmospheric pressure of 70.8 kg/m^3.

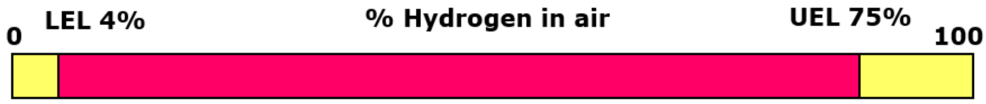

Figure 1: Flammability range of hydrogen

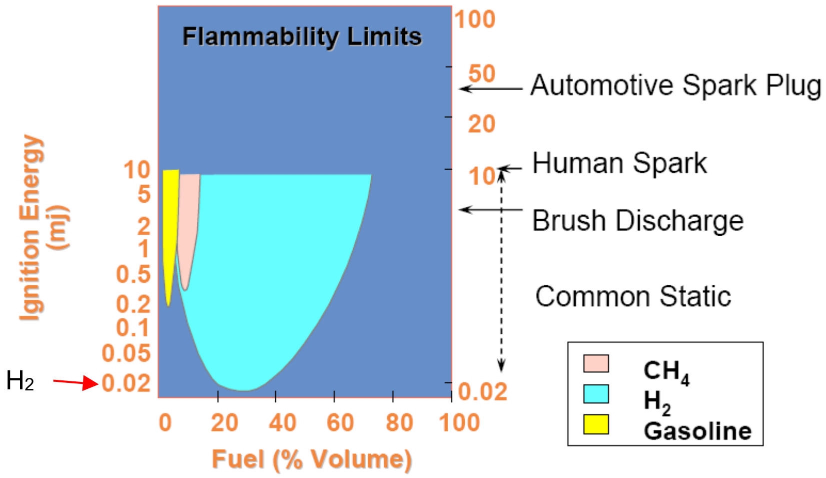

Figure 2: Comparison of ignition energy for typical flammable substances

5 General safety concerns

Due to the flammable range and very low temperature described above, additional safeguards are required as outlined in this publication and in EIGA hydrogen e-Learning information:
[Hydrogen eLearning - EIGA : European Industrial Gases Association]

Hydrogen is a very small molecule, and therefore able to find leak paths through small imperfections of materials and joints. H_2 leaks need to be avoided, due to high flammability as described above.

5.1 Material compatibility

Polymers used in seals, seats and gaskets, as well as steels, need to be compatible with H_2 to avoid the hydrogen embrittlement phenomenon. Refer to EIGA Doc 15 [2] for more detailed information.
Due to extreme cold, materials in contact with LH_2 require careful selection to avoid cold embrittlement fracture.
When working in areas where H_2 is present, manual tools and Personal Protective Equipment (PPE) are non-sparking. Refer to EIGA Doc 136 [3].

5.2 Hazardous Areas

Zoned areas are used to enforce safe working in product storage, and for handling equipment in areas with potentially explosive atmospheres. The equipment complies with the European ATEX directive 2014/34/EU [4]. This directive explains the requirement for Hazardous area classification and restricted zones, to ensure hazards such as sparks and other ignition sources are kept a safe distance away. Refer to EIGA DOC 134 for further information on Potentially Explosive Atmospheres [5].

5.3 Management of liquefied air and Oxygen enriched atmospheres

Care is needed with pipelines containing LH_2, as the low temperature causes air to condense on the outside of the pipe. This liquid air leads to a localised area of oxygen enrichment, reducing the ignition temperature of surrounding materials. Refer to EIGA Doc 6 [6].

6 Distribution

6.1 Introduction

The technical requirements and regulatory framework for the distribution of dangerous goods is complex. Generally, European Directives state ***what*** shall be done, and regulations and standards outline ***how*** the Directive requirements can be achieved.
The requirements for design, fabrication, testing, approval and operating equipment and components subjected to pressure, including compressed, liquefied and cryogenic gases are outlined in two European Union Directives:

- Pressure Equipment Directive (2014/68/EU) [7] - known as PED, covers stationary pressure equipment such as vessels, piping and associated components.
- Transportable Pressure Equipment Directive (2010/35/EU) [8] – known as TPED, covers transportable equipment that is under pressure.

For flammable products, all equipment complies with the European ATEX Directive for equipment operating in potentially explosive atmospheres.
The mechanism for implementing the Directives is via European and/ or Country level Regulations. These regulations reference European and International Standards published through the European Committee for Standardization (CEN). The European regulatory framework allows pressure equipment produced using comparable EN and ISO standards, and codes such as the American ASME Boiler and Pressure Vessel (BPV) Code Section VIII Divisions 1 & 2.

6.2 States and substances used to distribute hydrogen

This section provides a summary of:

- the physical states and substances used to distribute hydrogen,
- Distribution modes of road, rail, sea and pipelines, and their regulatory frameworks,
- The product containment, often referred to as packaging, for the different hydrogen states and distribution modes,
- Safety considerations.

Note: transportation of hydrogen by air is not covered in this publication.

The principal objective of distribution is to safely move as much product as possible within economic, environmental and time constraints. Hydrogen is distributed in several states depending on quantities, distances, speed, flexibility/resilience of supply routes and available infrastructure. All European legislation draws upon the United Nations (UN) classifications, product numbering and labelling, for example compressed gaseous hydrogen is designated number UN1049 while Liquid hydrogen is UN1966. Gaseous hydrogen is the least capital intensive to distribute but is also the least efficient (payload per distance), liquid with its higher density and very low temperature is more capital intensive but is more efficient, other methods such as using Chemical Compounds is more capital intensive than liquid but in large quantities can be more efficient:

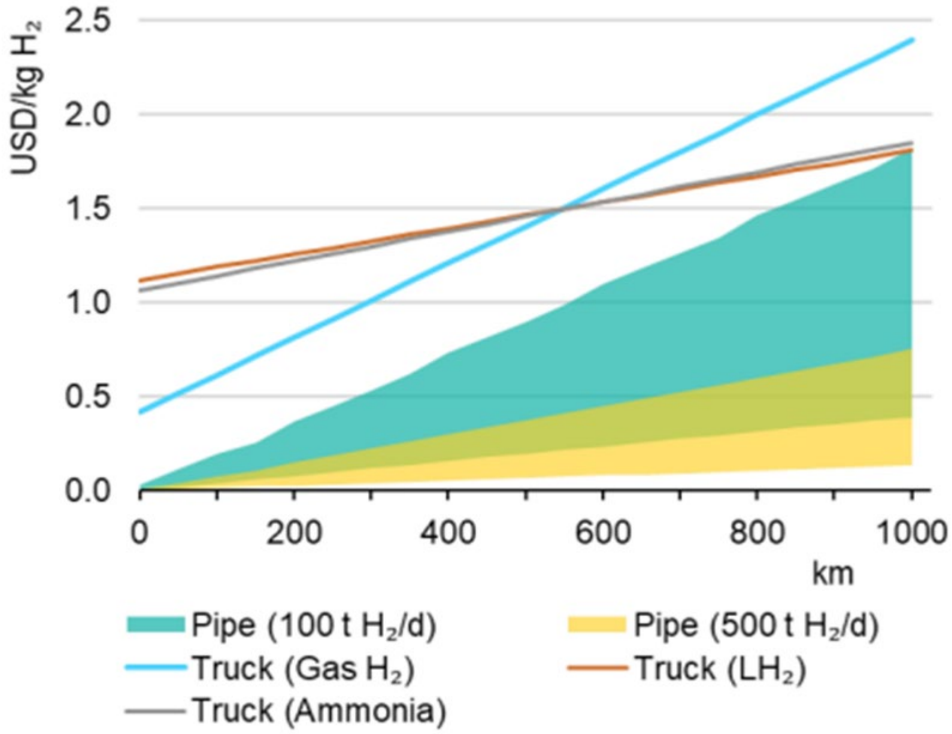

Figure 3: Estimated distribution costs per unit of hydrogen via truck and pipeline (see IEA – Global Hydrogen Review 2021 [9])

6.2.1 Gaseous hydrogen

Typically distributed through pipelines or by vehicles containing multiple pressure vessels known as cylinders and tubes.

Cylinders and tubes contain H_2 at ambient temperatures with pressures usually between 200 to 700 bar. Pipelines usually operate at pressures of 10 to 20 bar but can be up to 210 bar. (see EIGA Doc 121 – Hydrogen Pipeline Systems [10]).

6.2.2 Cryogenic liquid hydrogen

With temperatures around -253ºC and pressures up to 11 bar liquid hydrogen is distributed in cryogenic pressure vessels and pipes consisting of an inner vessel wrapped in multi-layer insulation, supported within an outer jacket with a vacuum established between the two.

6.2.3 Chemical hydrogen compounds

Also known as hydrogen carriers, these require chemical processing before and after transport. Significant infrastructure is needed to achieve economies of scale. Several compounds are being researched, the most common currently in use are:

6.2.3.1 **Liquid Ammonia (NH_3):** temperatures between -33ºC and +50ºC with corresponding pressures of 1 to 24 bar, used to distribute large quantities of hydrogen by road, rail, sea and pipelines. This distributes a greater mass of hydrogen per unit volume than liquefied hydrogen, utilising existing infrastructure. The future concept is bulk carriage of ammonia by sea, with cracking into hydrogen (and nitrogen) performed at the import terminal. The onward transport of this hydrogen is by road or pipeline, which minimises the hazard associated with transporting toxic ammonia.

6.2.3.2 **Methanol (CH_3OH):** has the advantage that liquid is distributed at ambient temperatures and pressure by road, rail, sea and pipelines. This also distributes a greater mass of hydrogen per unit volume than liquefied hydrogen, and also utilises existing infrastructure. Although not currently used for bulk transportation of hydrogen, methanol is being considered for smaller scale distribution. Methanol can also be economically 'reformed' to release hydrogen on a small scale, with the future possibility of reforming locally at automotive refuelling stations for use in hydrogen Fuel Cell Electric Vehicles (FCEV).

6.2.3.3 Liquid Organic Hydrogen Carriers (LOHC): organic compounds that can absorb and release hydrogen through chemical reactions. LOHCs can therefore be used as distribution and storage media for hydrogen. LOHCs utilise existing transportation infrastructure.

6.2.3.4 Metal Hydride (MHx): usually powder form that require cooling and heating under pressure to load and release hydrogen. Technology is being developed for scale deployment of substances such as Lithium Borohydride ($LiBH_4$), which has a higher energy density per litre than conventional hydrocarbon fuels such as gasoline, $LiBH_4$ is being used to developed on-board vehicle storage packaging for FCEV.

6.3 Overview of product distribution modes and regulatory frameworks

6.3.1 Distribution by Road

The distribution of hydrogen by road is governed by regulations known as the 'Agreement concerning the International Carriage of Dangerous Goods by Road (referred to as ADR)', published by the UN under the auspices of the United National Economic Commission for Europe (UNECE).

To operate on European roads, hydrogen distribution equipment is designed, manufactured and tested, and inspected by an approved authority in accordance with the relevant ADR chapters, notably chapters 6 and 9. Upon approval, to signify compliance with the relevant regulations the equipment is stamped with the Greek letter '**π**' (known as Pi Mark) or stamped with 'U' (to signify US ASME Pressure Vessel Code). To use equipment manufactured using the US ASME Pressure Vessel Code on European roads, it must also be approved as UN pressure equipment (receptacle). For equipment containing a single large transportable pressure vessel the π mark appears on the equipment approval plate but for equipment containing cylinders, tubes and multiple pressure vessels the π mark appears on both the individual pressure vessels and on the equipment approval plate. Cylinders and tubes approved using the ASME pressure vessel code have DOT stamped on them to signify they are suitable for transporting the product by road. Road transport equipment follows the European vehicle type approval process, these inspections first assess compliance to dangerous goods requirements for product containment and safety followed by compliance to road regulations and road worthiness.

Note: To operate on roads within the United Kingdom, a similar process is followed, however a 'rho' or '**ρ**' mark replaces the '**π**' mark. Refer to BCGA publication GN48 – Type approval and Conformity Assessment of Transportable Pressure Equipment in the UK [11].

6.3.2 Distribution by Rail

The regulatory framework for operating on European railways is implemented by the 'European Union Agency for Railways' (known as ERA), for the distribution of hydrogen by rail ERA references the 'Convention concerning International Carriage by Rail (COTIF), Appendix C – Regulations concerning the International Carriage of Dangerous Goods by Rail (known as RID)'. European Directive 2008/68/EC [12] transposes RID into EU regulations, which is transposed into individual country transport regulations.

To operate on European railways, hydrogen distribution equipment is designed, manufactured, tested and inspected by an approved authority in accordance with this regulatory framework. The equipment is stamped with the 'π' mark (or 'U' stamp) and letters 'RID' on the approvals plate attached to the equipment. Dangerous goods equipment for use on Railways follow a slightly more onerous inspection and approvals process than for road vehicles.

6.3.3 Distribution by Inland Waterways and Sea

The distribution of dangerous goods by water is governed by two regulations. The ‘European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways’ (known as ADN) and the ‘International Maritime Dangerous Goods (IMDG) Code’ published the ‘International Maritime Organisation’ (IMO) for transport on the open sea.

For the bulk carriage of liquefied gases (ambient and refrigerated), in addition to ship design, construction, approval and operational requirements, ships comply with ‘The International Code for the Construction and Equipment of Ships Carrying Liquified Gases in Bulk (IGC Code)’ and carry the IMO stamp on the name plate. The organisation governing the design of ships is the European Committee for Standardisation in Inland Navigation (CESNI).

6.3.4 Distribution by Pipeline

The European pipeline standards and regulatory framework are divided between on-shore and off-shore. For each sector there are too many regulatory requirements to cover in this document, but at present hydrogen pipeline distribution is on-shore which can be sub-divided by above and below ground. Vacuum insulated liquid pipelines are usually found above ground within a defined site or between adjoining sites and are used to distribute hydrogen from a liquefier or storage tank to a process. Whereas gaseous pipelines can be found above or below ground, also used to distribute hydrogen within a site and used to supply hydrogen to distant or multiple customer sites via dedicated networks. Useful reference documents include:

Gaseous pipelines:

- EIGA Doc 121 Hydrogen Pipeline Systems [10]
- EN 10208-2: 2009 Steel pipes for pipelines for combustible fluids – Technical delivery conditions – Part 2: Pipes of requirement class B [13]

Liquid pipelines:

- ASME B31.12-2019 Hydrogen Piping and Pipelines [14] – includes both liquid and gaseous pipelines.

6.3.5 Distribution of Packages

Dangerous goods are contained within what is called a ‘package’, usually defined by the pressure boundaries of the equipment.
For efficient distribution it is desirable to keep the weight of the package low, whilst ensuring all safety and legislative requirements are met. Note that individual countries have different limits for Gross Vehicle Weights (GVW).

6.3.5.1 Cylinders and tubes

For compressed (gaseous) hydrogen the packages range in size, quantity, and weight, ranging from a relatively small single unit to a large unit consisting of multiple elements, typical individual packaging types are Cylinders and Tubes. In Europe cylinders and tubes are known as receptacles. The acceptable European standards for the design, manufacture, testing, approval of cylinders and tubes, and the transport service equipment are defined in sub-parts 6.1 and 6.2 of the ADR, RID or IMDG regulations.

In summary:

Individual Sizes; Cylinders are up to 150 litres and Tubes range from 150 to 3000 litres.

Number of packages; To achieve distribution efficiencies it becomes necessary to ‘package’ several cylinders or tubes together to increase the transportable volume and aid handling. Packages consisting of more than 2 cylinders, each with cylinder capacities not exceeding 150 litres with a common manifold, valve and frame are called bundles of cylinders, these must fulfil a 1.2 metre drop test. Assemblies of multiple cylinders or tubes connected by a manifold and fixed into a frame that is demountable from a vehicle are known as Multiple-Element Gas Containers (MEGC), ISO Container frames are frequently used for MEGC's. Vehicles constructed with multiple cylinders or tubes connected by a manifold that are not demountable from a vehicle in normal operation are known as battery vehicles.

Compressed hydrogen MEGC's and Battery vehicles typically have up to 400 cylinders or 8 to 10 tubes.

Figure 4: Cylinder Bundle

Figure 5: Battery Vehicle

Figure 6: Battery Vehicle (commonly known as a Tube Trailer)

Figure 7: MEGC –demountable from chassis

6.3.5.2 Cryogenic Vessels

The materials and construction of these vessels (as outlined in 6.2.2 above) are designed, fabricated, tested and approved for refrigerated liquefied hydrogen in accordance with sub-parts 6.1, 6.2 and 6.8 of ADR, RID and/or IMDG regulations. Examples of transportable pressure vessel standards and codes include:

- EN13530 Cryogenic Vessels – Large transportable vacuum insulated vessels.
- ASME BPVC Section VIII Division 1 or Section XII with piping complying with ASME B31.12
- ISO 20421 Cryogenic vessels – Large transportable vacuum-insulated vessels.

6.3.5.3 Labelling and Placarding

To identify the hazards, all 'packages' (vessels, tanks, containers, receptacles etc.) containing hazardous and dangerous goods are labelled correctly on the outside in accordance with the respective regulation (ADR, RID or IMDG). The multiple placarding locations are defined in the regulations, according to the transport mode. Hazardous and dangerous goods (also known as consignments) must be transported with documentation. Bulk vehicles, ISO containers and rail wagons are fitted with placards at designated locations that identify the hazards and the UN Product number. Additional information labels are located on the outside of these packages, for example:

- MAP of pressure vessels,
- contact telephone number of the organisation responsible for the consignment.

Care is needed when defining and implementing these requirements, as the label and placard sizes may vary due to quantities carried and differences between transport modes.

Transportable units that are unaccompanied by a driver (or operator) are equipped with waterproof holder for the documents.

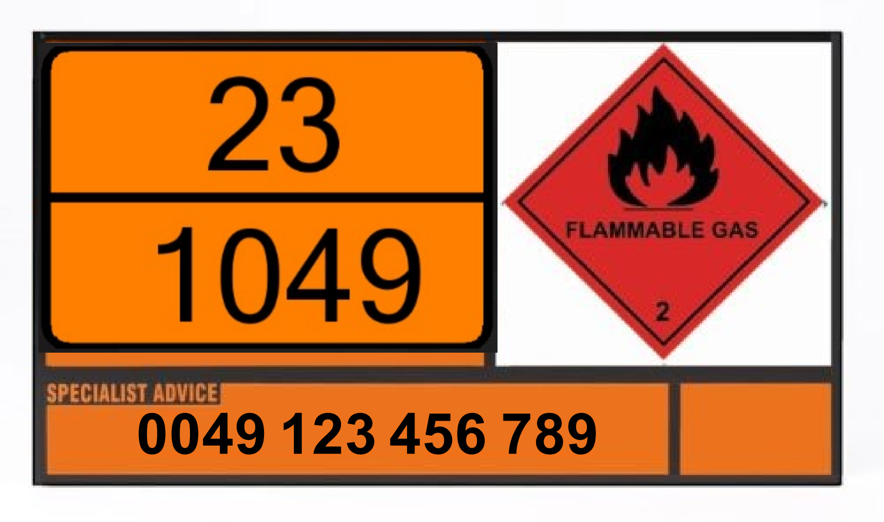

Figure 8: Example of placarding for Gaseous Compressed H_2
23: Hazard identification: Flammable Gas
1049 : Hydrogen, compressed

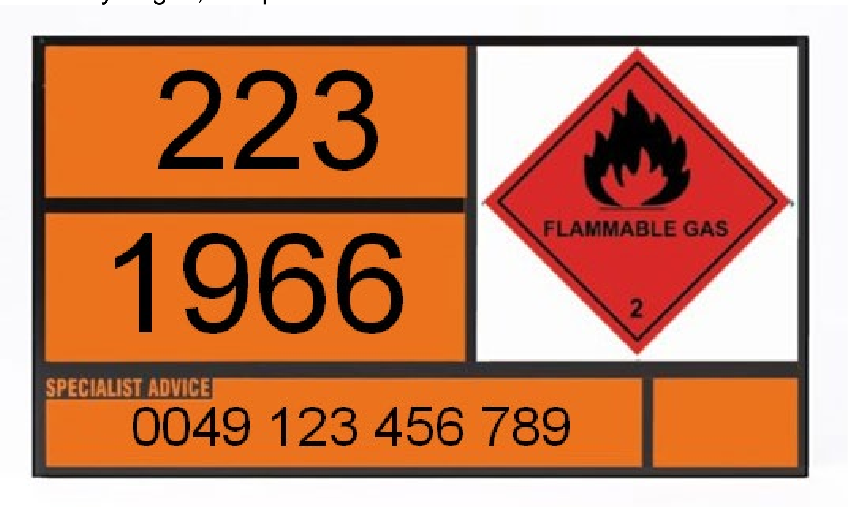

Figure 9: Example of placarding for Cryogenic Liquid H_2
223: Hazard identification: refrigerated liquified gas, flammable
1966 : Hydrogen, Refrigerated liquid

6.3.6 Transportable Distribution Equipment

Distribution equipment complies with national and European legislation. The following section summarises equipment types used for transporting hydrogen.

6.3.6.1 Trailers

Truck and trailer combinations are used to distribute gaseous or liquefied hydrogen on public highways and conform to Directive (EU) 2015/719 (authorised dimensions and weights for trucks, buses and coaches involved in international traffic). These combinations, with some additional features complying to RID and IMO, can also be transported using 'Roll-On Roll-Off' (RORO) rail wagons and ships. Two types of trailers are typically used, depending on the hydrogen state:

Compressed hydrogen Trailers: Older trailers use up to 400 Type 1 cylinders (see Appendix 2 for 'Type' descriptions) rated at 200 Bar which makes for very heavy tare weights and corresponding low payloads of about 160kg. The next generation of trailers make use of tubes rated up to 220 bar with payloads up to 370kg. The latest trailer technology utilises Type 4 cylinders or tubes, payloads close to 1 tonne can be achieved at pressures of 300 bar, and over 1.5 tonnes when filled at 700 bar.

Liquid hydrogen Trailers: Due to the cold temperature and potential for hydrogen embrittlement, only certain types of Austenitic Stainless Steels are permitted in the construction of Liquid hydrogen containment and product handling components. To prevent cold temperature cracking of Carbon Steels, the trailer section where pipes pass through the outer jacket are always made from Austenitic Stainless Steel. The rest of the outer jacket is made from either Carbon Steel or Austenitic Stainless Steel. The low liquid density results in trailer payloads being limited by country vehicle dimension regulations making it challenging to achieve payloads much above 3500 kg, because these trailers fall within the country weight limits there is no benefit from using lighter materials to lower tare weights.

ISO Containers: ISO containers, also referred to as Intermodal Containers, tank-containers, portable tanks and MEGC's. The product containment for compressed (gaseous) and liquid hydrogen are similar to trailers but are packaged within a frame that complies with international standards governing design, fabrication, size, lifting and securing attachments, weights, support loading, inspection and testing, widely used for bulk material handling and shipping. It is important to note the transport design loadings vary depending on the transport mode (road, rail or sea). These standards include but are not limited to:

- ISO 6346 Freight containers [15] – Coding, identification and marking
- ISO 668 Series 1 freight containers [16] - Classification, dimensions and ratings
- ISO 1161 Series 1 freight containers [17] – Corner and intermediate fittings – Specifications
- ISO 1496-3 Series 1 freight containers [18] – Specification and testing – Part 3: Tank containers for liquids, gases and pressurized dry bulk

Figure 10: LH_2 ISO Container

Product	Length mm (feet, inches)	Width mm (feet, inches)	Height mm (feet, inches)	Designations		Maximum Mass kg	Typical Payload kg
				Size [ref ISO 668]	Type [ref ISO1496-3]		
LH_2	12192 (40’)	2438 (8’ 6”)	2591 (8’)	1AA	T75	30480	2700
GH_2	12192 (40’)	2438 (8’ 6”)	2591 (8’)	1AA	T79	30480	See table 2

Table 1: Typical ISO container dimensions

Gaseous hydrogen ISO Container Payloads		
Cylinder/ Tube Type	Pressure (bar)	Typical Payload kg
1	200	340
4	300	850
4	700	1600

Table 2: Typical Compressed (Gaseous) H2 ISO container payloads

ISO Containers have information plates attached for three categories of information:

a. Pressure vessel design code, material of construction, manufacturer, approvals, pressure vessel serial number, date of approval
b. Products for which the container is approved to carry
c. Container Safety Convention (CSC) plate: approval country and reference, date of manufacture, serial number, gross mass, allowable stacking weight and rack test.

Most Industrial ISO Containers are registered with the Bureau International des Containers (BIC) in Paris. This organisation issues a unique BIC code that is attached to the outside in specific locations with a standard font for ease of identification. The code consists of three letters to identify the owner (called the owner code), followed by one letter to identify the equipment (U for most Industrial Gas equipment), followed by six numbers for the serial number determined by the owner, followed by one number (called the check digit) used to validate the recording and transmission accuracies of the unit.

Rail Wagons: Rail Wagons, also known as rolling stock, freight wagons and railcars, can be used to distribute hydrogen. There are many Directives, Regulations and Standards governing the European Rail Network and Rolling Stock, some of the technical requirements are described in Commission Regulation (EU) No 321/2013 "Concerning the Technical Specification for Interoperability to the Subsystem 'Rolling Stock – Freight Wagon' of the rail system in the European Union". Gaseous hydrogen is usually distributed using 40' ISO Containers (see section above), or using road trailer mounted packages driven onto RORO Rail Wagons.

Ships: Most hydrogen distributed by ships within compressed (gaseous) and liquid 'packages' are primarily ISO Containers but can also include trailers and other MEGC sizes. These must be designed, manufactured, inspected and approved in accordance with IMDG and have the letters 'IMO' added to the approvals plate attached to the equipment, in addition to the '**π**' stamp (and/or 'U', and/or 'ρ') and the letters stamped for other relevant transport modes.

Due to transport efficiencies, gaseous hydrogen is usually only transported on relatively short sea routes. Hydrogen, in either liquid or chemical form, is transported on the longer sea routes.

Globally there are very few deep-sea bulk ships for liquid hydrogen, however it is likely that the requirement for this type of transport will increase as the global hydrogen economy grows.

6.3.7 Distribution Equipment Safety Features

Distribution equipment complies with the ATEX Directive as outlined above in section 6.1

Pressure Relief Devices: All equipment for compressed or refrigerated liquefied gases has a maximum pressure at which the equipment can be operated, known as the maximum working pressure (or maximum filling pressure at 15°C) for compressed gasses and Maximum Allowable Pressure for refrigerated liquified gases. (The equipment is validated to operate at the maximum pressure by conducting pressure tests during manufacture and by conducting periodic tests during the service life.

To protect against pressure vessels exceeding the maximum pressure, refrigerated liquified gases and some gaseous equipment are fitted with safety relief devices to discharge excess pressure. Pipes that can trap cryogenic liquids between two closed valves are fitted with pressure relief devices which discharge excess pressure when the pipe warms. Transportable gaseous hydrogen assets using European-approved tubes and cylinders do not require safety relief valves or burst discs because their test pressure is higher than the pressure attained during fire engulfment. Some transport assets using the US DOT approval may require safety relief devices.

Vents and Vent Stacks: The discharges from vents and safety relief devices are piped to vent outlets known as the 'vent stack'. This discharges hydrogen to atmosphere in a safe elevated location on the equipment. Vent stack outlets are carefully designed to manage vent stack fires that are not uncommon due to the flammability of hydrogen. Due to its flammability, gaseous and liquid hydrogen distribution equipment have facilities to vent and purge the pipes and pressure vessels to either remove air during commissioning or to remove hydrogen during decommissioning. Nitrogen and/or helium are used for purging, but care is needed to avoid nitrogen freezing and blocking pipes at liquid hydrogen temperatures.

Degree of Filling: refrigerated liquefied gases transported in closed pressure vessels are never completely filled with liquid to allow for expansion. The degree of filling is the volume occupied by the product divided by the volume contained by the metal known as the water (or gross) volume, expressed as a percentage. Since the liquid volume expands as its temperature and pressure increases, the maximum permitted degree of filling for liquified hydrogen is 98% determined at the MAP.

Automated Shut-off Valves and Emergency Stop Buttons: Transportable liquid hydrogen distribution equipment is fitted with automated shut-off valves in the filling and delivery pipe(s). There are two valve types used, both are held shut with a powerful spring (termed 'normally closed'), most are opened by an actuator that requires compressed air controlled from a switch panel by an operator. One type, known as fire valves, utilises fusible links which melt in the event of a fire allowing the valve to automatically close. The other type discharges compressed air from the actuator holding the valve open and allowing the valve to close. The discharge from the actuator is initiated either by pressing an Emergency Stop button or by the nylon compressed air pipe melting.

Piping Cabinets: The pipes, valves, gauges and safety devices needed for product handling are housed in a cabinet located at one end of the vehicle or along the sides. For security the cabinets are equipped with locks. When carried on the vehicle, product transfer hoses are stowed in dedicated compartments. Hose stowage compartments are fitted with retaining devices to prevent loss of hoses during transport. Piping cabinets have ventilation louvers fitted to dissipate hydrogen in the event of a leak. It is also advisable for cabinet panels located adjacent to the tyres to be made from stainless steel to help protect the components in the event of a tyre fire.

Drip trays: Due to its low temperature, liquid hydrogen causes large amounts of air to condense onto cold surfaces. Liquefied air is enriched with oxygen which increases the ability for materials to burn, consequently all non-vacuum insulated liquid hydrogen pipes and some cold gaseous hydrogen pipes, valves and other components have drip trays fitted underneath. This collects the liquefied air and pipes it to a safe location where it can be evaporated without causing high oxygen concentrations near combustible materials such as plastics, rubber (tyres and suspension components), paint and bitumen road surfaces.

Anti-Tow away systems: Vehicles used to deliver dangerous goods are fitted with systems that prevent the vehicle being moved by apply the parking brake when connected to or interfaced with stationary equipment. For more information refer to EIGA Document 63 – Prevention of Tow-away Incidents [19].

Motor Vehicles Towing Trailers Containing hydrogen: motor vehicles conform with ADR Part 9 (‘FL’ rating). These have additional features for transporting flammable products.

Figure 11: Liquid hydrogen Trailer

7 Storage systems

The following section can be used as a guideline. For more detailed information refer to EIGA Doc 15 – Gaseous Hydrogen Installations [2].

7.1 General Information

A hydrogen storage system is an installation in which hydrogen is stored and discharged to the customer process piping and/or application. The system typically includes stationary vessels, pressure regulators, safety relief devices, manifolds, interconnecting piping and controls. It does not necessarily include storage systems consisting of bundles or individual cylinders that are taken away for refilling.
The storage system terminates at the point where hydrogen, at nominal service pressure, enters the process piping.

Hydrogen systems are designed, fabricated and tested in accordance with recognized pressure vessel and piping codes, and, where appropriate, in accordance with statutory requirements, for example the Pressure Equipment Directive (PED) 2014/68/EU [7] or Transportable Pressure Equipment Directive (TPED) 2010/35/EU [8].
Pressure relief devices are installed to prevent over pressure where this can occur.
Equipment and systems are earthed and, where necessary, bonded to give protection against the hazards of stray electrical currents, lightning and static electricity.

The selection of the site and the layout of storage equipment considers industrial facilities, residences located in the surrounding area, and the on-site usage of flammable materials. Equipment spacing takes into consideration the constraints associated with the facility fire protection system, maintenance requirements, and the electrical equipment hazardous classification.
Hydrogen storage systems are installed with suitable safety systems in the open air, or under canopies with suitable ventilation and are located so that they are readily accessible to distribution vehicles, firefighting services and provide unrestricted means for escape of personnel in the event of an emergency.
Care is taken with regard to their location relative to sources of fuel, such as pipelines or bulk storage containing other flammable gases or liquids, or other potential hazardous substances which could jeopardise the integrity of the installation.

Safety and separation distances are determined based on various factors, including the properties of the stored hydrogen, vessel design, piping configuration, weather effects, and more. These distances should not be less than applicable national regulations and codes, and they should consider access for emergency services, protection of people and equipment, and other basic needs.
To determine the distances, experience and risk assessments are taken into account, and are measured from potential leakage points. Protective structures such as firewalls can be installed, but they should not envelope or constrict the vessel, and a minimum distance should be maintained if the vessel is installed in close proximity to a building or fire-resistant wall. Refer to EIGA Doc 75 – Methodology for Determination of Safety and Separation Distances [20], and NFPA 2 Hydrogen Technologies Code [21].

7.2 Layout

The layout considers:

- user operability,
- maintenance,
- location of vents,
- vehicle and safe personnel access,
- safety and separation distances, and hazard zones,

- hazard detection including flammable gas leak and fire detection, and

- emergency response planning such as firefighting, evacuation, alerting neighbours, plus co-ordination with third parties such as emergency responders and the public.

Leaks of hydrogen from pipes, vessels and equipment can result in a jet flame if the hydrogen ignites for example by friction or static. The jet flame length depends on the hydrogen pressure and leak size. The layout of equipment considers escape routes and paths such that they are not impacted from potential jet fires. This can be achieved if needed using fire walls.
The layout of equipment also considers the possibility of jet flames from potential leaks impinging on other equipment to avoid the domino effect.

Hydrogen product safety concerns are related to its physical characteristics: flammability, low ignition energy, oxygen displacement, and high pressure. The amount of hydrogen gas required to produce an asphyxiant atmosphere is well within its flammable range, making fire and explosion the primary hazards associated with hydrogen and air mixtures.

Hydrogen is kept away from heat, hot surfaces, sparks, open flames, and other ignition sources.
In case of leaking gas fire, it is recommended not to extinguish, and preferably stop the leak safely by isolating the source of leaking gas, this is to avoid forming a flammable gas cloud.

As hydrogen is very buoyant, any vents from valves or pressure relief devices are typically elevated above ground, away from personnel. See EIGA document 211 - Hydrogen Vent Systems for Customer Applications [22] for more information.

Customer installations avoid any confined spaces as far as possible, and all precautions to monitor and prevent oxygen displacement are put in place.

Safeguards to minimise the risk from hazards include:

- Atmospheric detection equipment, used to check Lower Explosion Limit (LEL), and oxygen levels as applicable.

- Adequate ventilation to prevent any build-up of gases.

- Selection and use of suitable personal protective equipment for the hazards at the site, such as overalls manufactured to meet EN11612 [23] for heat and flame resistance, and EN1149-5 [24] for anti-static properties.

Access to all hazardous areas is restricted to authorised and trained personnel.
Hydrogen systems are installed according to the European ATEX Directive 2014/34/EU [4].

7.3 Site storage types

Storage of hydrogen at a customer site is typically in either gaseous or liquid form. The following sections detail the key safety and legislative requirements.

7.3.1 Gaseous storage

Gaseous hydrogen is typically stored at either high pressure, typically 200 bar or greater, in cylinders or bundles, or up to 50 bar in medium pressure vessels.

All materials used are suitable for hydrogen service and for the pressures and temperatures involved. Typical materials used for storage systems are carbon-based steels, aluminum and more recently composite materials.
Failure mechanisms such as hydrogen embrittlement, high temperature attack and stress corrosion cracking are considered depending on service temperatures, pressures and environments. Refer to EIGA Doc 100 – Hydrogen Cylinders and Transport Vessels [25] for information regarding selection of materials for hydrogen service.

Vessels for the storage of hydrogen are designed, fabricated and inspected in accordance with the Pressure Equipment Directive (PED). These vessels are subject to fatigue loading by cyclic pressures, and therefore are also designed and constructed in accordance with fatigue design rules.

Pipes and fittings are designed and fabricated according to the PED together with recognised standards such as EN13480, Metallic industrial piping [26] , or ASME B31.12, Hydrogen Piping and Pipelines [27].

7.3.1.1 High pressure cylinder bundles or packs (200bar or greater)

Typical high pressure storage systems are fabricated from multiple cylinders assembled to form a pack or bundle. See figure below.

Figure 12: Typical High-pressure bundles.

There are four cylinder types (see distribution section 6.3.5). Refer to Annex 2 for more detailed information.

Type	Materials	Typical Pressure (bar)
I	All-metal construction	200 - 300
II	Metal vessel reinforced with composite wrap excluding dome	200 - 300
III	Metal liner with full composite wrap	up to 500
IV	All-composite construction	300 to 1000

The bundles are assembled using vessels manufactured to the European Pressure equipment directive (PED) or ‘π’-marked cylinders complying with the Transportable Pressure Equipment Directive (TPED). These vessels are grouped together and assembled with a manifold to create one storage unit. Typically, each bundle will have its own structural frame and one or more isolation valves. Each

assembled bundle is manufactured as a pressure assembly within the PED, and is CE marked to this directive.
Multiple bundles can be installed together to form the required storage volume. These bundles are positioned with appropriate access to enable change out for periodic testing by forklift or overhead crane. Where the frame allows, the packs are stacked on top of one another in some installations.

Periodic Inspection - Pressure retest of vessels and piping systems:

Bundles are subject to periodic inspection and testing, according to country of operation and the design code of the original vessels. Typically, the bundles are removed from site, disassembled and the vessels subject to a visual inspection combined with a hydraulic pressure test.

Some European countries permit the replacing of the hydraulic test by an Acoustic Emission Test (AET) and follow-up crack detection ultrasonic test (UT). These are performed at a specified pressure. For more information see EIGA Doc 96 – *Alternatives to Hydraulic testing of Gas cylinders* [28], and ISO 16148, *Gas cylinders — Refillable seamless steel gas cylinders and tubes — Acoustic emission examination (AET) and follow-up ultrasonic examination (UT) for periodic inspection and testing* [29].

High pressure gaseous storage systems remain on site and are filled via battery vehicles or MEGCs (see section 6 above). A dedicated area is required for the trailer to perform the filling operation. Transfer of hydrogen occurs by pressure discharge, flowing from the high pressure in the trailer to the lower pressure depleted storage system.

Battery vehicles or MEGCs consist of multiple banks or sections. This enables cascade filling techniques to be used to optimise distribution efficiency.

One or more fill stanchions are installed to enable connection of the trailer to site pipework via a flexible hose. The stanchion also allows for safe venting of the hose and piping after a fill. To prevent static electricity build up and discharge, the vehicle is typically connected to earth via the installation equipment.

Figure 13: Gaseous hydrogen installation

7.3.1.2 Medium pressure vessels

Medium pressure vessels are single-walled containers constructed from carbon steel, with volumes typically ranging from 25 to 100m³, designed for either horizontal or vertical orientation. These vessels can handle a maximum pressure of up to 50 bar and are fabricated in accordance with the PED requirements (2014/68/EU).

Periodic testing
As per high pressure storage above, medium pressure vessels are subject to periodic inspection and testing, according to country of operation and the design code of the original vessels. However due to their size, the periodic inspection is usually an internal visual inspection, combined with AET and/or Ultrasonic test.

Medium pressure vessels are filled in the same way as high-pressure bundles. High-pressure battery vehicles are used to fill these vessels, however a pressure regulating manifold or system is installed to reduce the hydrogen pressure entering the vessel.

Figure 13: Medium Pressure Storage vessels (gaseous hydrogen)

7.3.1.3 Using trailers as storage

Battery vehicles as described in Section 6.3.5.1 can be used as storage for sites that require a large supply of gaseous hydrogen.
The trailer replaces the need for high pressure site storage. Once depleted, a new full trailer is placed on site, and the depleted one is removed for filling.

To facilitate movement of the trailers, two dedicated and marked trailer bays are required at the installation. Each bay has its own fill stanchion described above.

Anti-tow systems are installed to avoid the risk of moving trailers whilst still connected and rupturing hoses and piping. These systems are typically installed on the trailer themselves, ensuring the trailer brake systems cannot be released whilst hoses are attached.

7.3.2 Liquid hydrogen

7.3.2.1 Safety and mitigations for liquid storage

EIGA Document 6 – Safety in Storage, Handling and Distribution of Liquid Hydrogen [6] gives general guidelines for LH_2 tanks at customer sites.

In addition to the fire, explosion, and asphyxiation hazards for gaseous hydrogen, the main hazard associated with LH_2 is exposure to extremely low temperatures. Cold burns may occur from short contact with frosted lines and equipment. Because of its extremely cold temperature, all LH_2 equipment is designed for low temperature operation. On inadequately insulated equipment, air will condense and leads to oxygen enrichment. Oxygen enriched air will increase the combustion rate of materials.

LH_2 transfer lines are typically vacuum insulated to minimise boil off. Closed-cell non-flammable foam insulation is also used in some cases. This type of insulation is installed in such a way to ensure no air gaps allow cryo-pumping, leading to oxygen enrichment and build up of hydrocarbons.

Any LH_2 spills will rapidly vaporise and create an immediately flammable atmosphere.

Tanks are labelled with a warning for any responding fire department to not spray water on the vent stack. Spraying water on the vent stack can cause the water to freeze due to the extremely low temperatures, resulting in a blockage. This warning serves as an important precautionary measure to prevent any potential hazards caused by blocked vents during fire emergencies.

Owing to the extreme cold temperatures involved in producing LH_2, there are very few contaminants which can remain in the LH_2 product. Most impurities found in air (for example CO_2, H_2O, CH_4, N_2, O_2, Ar) would solidify in the liquid, therefore careful purging of piping and equipment used for liquid hydrogen is performed.

7.3.2.2 Cryogenic tanks

The construction of cryogenic storage tanks is similar to those described in section 6.3.6.1.

Vessels used for the storage of cryogenic liquids consist of an inner pressure vessel, insulation, an outer jacket (not required to be a pressure vessel) and the auxiliary equipment. The space between the inner vessel and the outer jacket (annular space) is under vacuum.

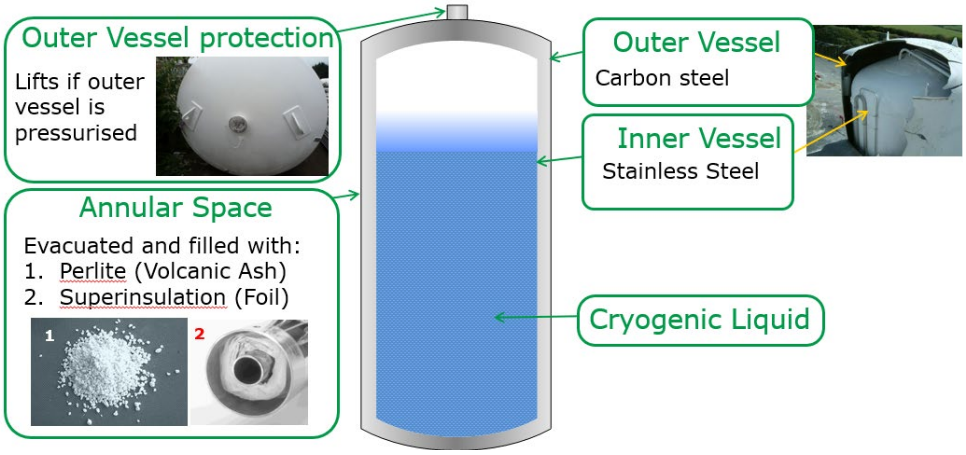

Figure 14: Typical construction of cryogenic storage tank

Figure 15: Typical LH_2 Cryogenic tank

Hydrogen cryogenic tanks have multi-layer insulation with the inner tank kept in position using materials with low conductivity such as glass or carbon reinforced plastics. Typical volumes range from 10-75m³ with pressures between 1 and 12 bar.

Manufacturing the inner vessel of pressure vessels with 300 series austenitic stainless steels is common practice.

Hydrogen is often stored as a liquid as it has a higher density compared to high-pressure H_2. Where hydrogen is required in its gaseous state, downstream equipment such as pumps, vaporizers, and manifolds are installed to change state from liquid into gas.

The safety of a storage tank is crucial, and thus it is located in a way that allows access by authorised personnel and the delivery vehicle. Suitable access for emergency equipment, such as fire department equipment, is provided. It is important to note that the installation is not situated near electric power cables or any piping containing other flammable, combustible, or oxidising materials.

In case of liquid spillage, diversion kerbs or grading are used, and the ground slope provides normal water drainage.

The tank supports are non-combustible and able to withstand any potential damage caused by cryogenic liquid spillage.
The majority of stationary storage tanks are of vertical construction; however, some are horizontal type. Typically, horizontal tanks are installed due to permitting and height restriction requirements.

The liquid transfer area is designated as a "NO PARKING" area with unimpeded access and exit for tankers. The fill coupling of the installation is within the tank plinth area, and a non-combustible surfacing is provided under the liquid delivery vehicle.

Cryogenic tanks are equipped with a number of safety features:

- Relief devices to prevent pressure increase due to heat leak and boiling of the liquid
- ‘Trycock’ indication to facilitate correct fill levels and minimize overfills.
- Emergency automatic Fire control valves fitted on the liquid outlets. These valves are typically pneumatically actuated, with instrumentation lines made from plastic. In the event of a fire, this supply line melts and the valves close, shutting off the LH_2.
- Outlets of all pressure relief or process vents, are directed into one or more main vent stacks, which typically have outlets above the top of the tank.

7.3.2.3 Cryogenic ISO Containers

In the cases where it is not practical or permissible to have permanent large LH_2 storage on a site, the liquid can be suppled via an ISO container described in section 6.3.6 above. In the same way as gaseous hydrogen tube trailer swaps, a full LH_2 ISO container is connected to the site pipework, and the depleted container returned to the plant for re-filling.
At least two clearly marked and controlled bays are required to facilitate safe swap of containers.

7.3.2.4 Filling Interfaces

For liquid filling, vacuum jacketed flexible hoses are used to connect a cryogenic tank to a tanker. The fill is typically completed via pressure difference between the tanker and the tank however a pump can also be used. Vacuum jacketed couplings are specific to the industry and used to connect the vacuum jacketed hoses.

A non-return valve is incorporated in the fill connection to prevent storage discharge in the event of a hose failure.

Additionally, a filter may be installed to protect downstream equipment such as pressure regulators from particles. A vent valve is included to allow purging of the system, from the trailer to the inlet isolation valve, to prevent air from entering the storage system.

7.4 Downstream Process equipment

7.4.1 Cryogenic Source – Pumps

Depending on the application, cryogenic pumps can be utilised after the storage tank to increase pressure of the hydrogen. These pumps can be either reciprocating or centrifugal type; reciprocating type used in applications requiring high pressure/lower flow, and centrifugal pumps used for high flow, lower pressure applications. The pumps are typically designed and installed according to the Machinery (2006/42/EC), ATEX (2014/34/EU) and Pressure Equipment (2014/68/EU) Directives.

7.4.2 Cryogenic Source - Vaporisers

When the H_2 site storage is a cryogenic tank, the liquid hydrogen needs to be changed from liquid into gaseous form for use by the user. Typically, this is done using ambient vaporisers. These consist of a number of aluminium finned tubes forming a large heat exchange area. Heat is transferred to the liquid hydrogen mainly from liquefaction of ambient air condensing on the external surface, and the large temperature difference between ambient air and liquid hydrogen. These vaporisers are designed in accordance with the PED.

To account for temperature changes, interconnecting piping must be flexible enough to expand and contract. The vaporiser and its piping must have a pressure relief valve to prevent overpressure from trapped liquid boil off. The vaporiser must also be properly sized for the user's maximum flow requirement and equipped with low-temperature protection to prevent damage to downstream equipment or the user's process due to cold temperature. For more information, refer to EIGA Document 133 [30] – Cryogenic Vaporisation Systems – Prevention of Brittle Fracture of Equipment and Piping.

7.4.3 Regulator Manifold

To regulate the pressure to the user, the gaseous hydrogen passes through a pressure reducing station, which consists of pressure gauges, isolation valves, filters, non-return valves and one or more pressure regulators. This system may be duplicated to facilitate maintenance. Downstream of the pressure reducing station, a relief valve can be installed to protect the user line and equipment.
A pressure indicator is used to measure the pressure in the line, while a non-return valve is installed to prevent backflow from the process. Once the hydrogen has passed through these components, it is transported through the pipeline to the end-user's system.

A typical arrangement showing the regulator manifold can be seen in the figure below.

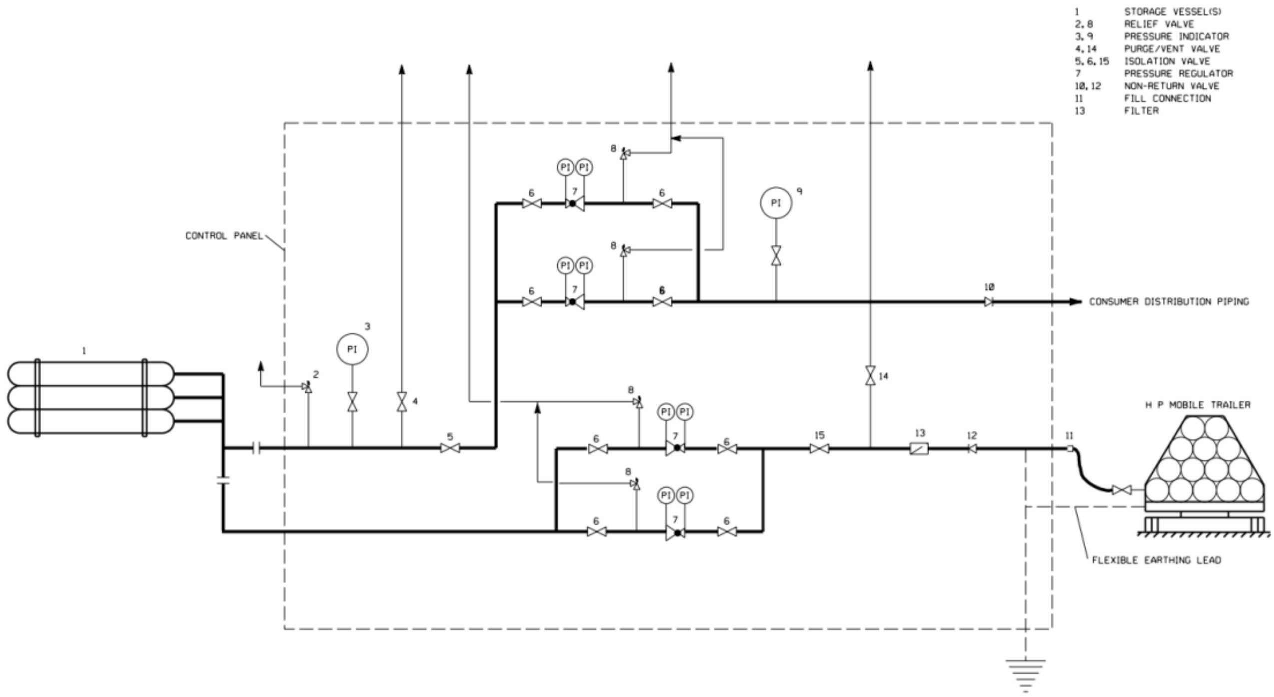

Figure 16: Typical Flow diagram of Gaseous H_2 installation [2].

8 Applications of Hydrogen

8.1 Hydrogen as a fuel

In addition to material and energy applications in various industries, the industrial use of hydrogen also includes its use as a fuel in heavy-duty and commercial municipal transport. Instead of fossil fuels, hydrogen can be burnt to generate heat.

Hydrogen is used in many industrial sectors.

8.1.1 Chemical industry / Petrochemicals / Refining

In refineries the main use of hydrogen is to remove the sulfur from crude oil to produce cleaner fuels.

In the Chemical industry hydrogen is widely used in ammonia synthesis. Nitrogen and hydrogen react at temperatures up to 500 °C and a pressure around 300 bar to form ammonia (NH_3).

hydrogen supply for methanol synthesis is largely based on steam reforming. To produce methanol, a mixture of hydrogen and carbon monoxide/dioxide reacts in an exothermic process at 200 - 300 °C and a pressure of 50-100 bar to form methanol.

8.1.2 Metals

In the metal industry, a distinction can be made between ferrous and non-ferrous metals. Ferrous materials include those containing Iron, for example steels. Non-ferrous metals include, for example, aluminium, copper and zinc.

Ferrous metals: Iron and steel

In steel and iron production, green hydrogen and electrified processes could make the classic coal blast furnaces redundant - and enable climate-neutral steel production.

In steel production, so-called direct reduction plants can be operated with green hydrogen. Here, liquid pig iron is no longer produced, but a solid iron sponge that is refined into crude steel in a furnace known as an electric arc furnace. The direct reduction of iron ore is by no means new terrain: the technology has already been used on a pure natural gas basis for some time - especially in countries where natural gas is available in sufficient quantities and at low cost. Although less CO_2 is released in this way than in the traditional blast furnace process with coal, the steel is not yet climate neutral.

In the classical blast furnace route, hydrogen can replace some of the coke and therefore reduces CO2 emissions as it burns clean and does not contain carbon.

Non-ferrous metals
In addition to the iron and steel industry, high-temperature processes are used in aluminium production. After extraction of bauxite and processing to aluminium oxide, this is reduced to aluminium by means of fused-salt electrolysis. The temperature is 950 °C. However, the necessary energy requirement is covered entirely by electrical energy.

For production using recycled aluminium, scrap is processed and melted. The process conditions for melting the scrap depend on the furnace used, but the temperature is usually around 660 °C. The scrap is then melted in a furnace with a temperature of around 1,500 °C. In this process 93 % of the energy supply comes from natural gas and 7 % from heavy fuel oil. hydrogen can be combined with natural gas to limit the use of fossil fuels.

8.1.3 Casting of metals

In the casting process, (liquid) metals are poured into various moulds. The energy requirement of the casting process is dependent on the metal and is typically provided by burning natural gas. hydrogen can be combined with natural gas to limit the use of natural gas.

8.1.4 Minerals

Clinker kilns, used in the cement production process, require high-temperature heat and are normally operated with fossil fuels. The characteristics of hydrogen are not sufficient to completely replace the need for fossil fuels. However, by using biomass and fossil fuels in combination with hydrogen the CO2 emissions of fossil fuels from cement production can be reduced.

8.1.5 Glass (float, containers, tableware, …)

Glass production is a very energy-intensive high-temperature process. Currently, furnaces use either oxygen and fossil fuels, or use preheated air in regenerative glass furnaces.

In general, there are several approaches for the use of hydrogen in the glass industry. In some cases, some of the natural gas can be replaced by hydrogen, otherwise it is possible to convert to an electrical melting furnace, that uses supplementary heating from a hydrogen/oxygen mixture. heating.

Currently, the effects of hydrogen on both combustion and glass quality are being investigated, with promising results. hydrogen is one of the solutions for switching from conventional to renewable energy sources. The investigations carried out so far have shown that the use of hydrogen maintains the glass quality, with control strategies that keep the furnace chamber temperature and heat transfer constant.

8.1.6 Food (sugar, …)

In food production processes such as sugar manufacturing, heat is required at different temperature levels. At present, fossil fuels such as natural gas, lignite and hard coal are mainly used for economic reasons. Here, in addition to the use of biomass fuels, the use of hydrogen for heat generation is also possible.

8.1.7 Pulp and Paper

The production of pulp and paper requires process heat at different temperature levels. At present, fossil fuels such as natural gas, lignite and hard coal are mainly used for economic reasons. Here, in addition to the use of biomass fuels, the use of hydrogen for heat generation is also possible.

8.1.8 Domestic Heating

Tests to enrich natural gas with hydrogen are ongoing with the aim of reducing CO2 emissions in home heating. The tests are in the early stages, to determine whether this will be an economical solution.

8.2 hydrogen as Feedstock

Chemical Industry

Ammonia
By far the largest demand is for ammonia production using the Haber-Bosch process. The synthesis of NH3 consumes almost 60 % of the hydrogen produced worldwide. Ammonia is mainly used for the production of fertilizers. Additional applications include the production of various explosives and polyamides.
Carbon emissions can be reduced from approximately 1.6-1.8 t CO_2/t NH_3 to almost zero by replacing the hydrogen traditionally produced from fossil fuels with hydrogen produced from renewable sources.

The simplified storage and transport capability also qualifies ammonia as a potentially promising energy carrier of the future, see section 6.2.3.1 above.
The amount of hydrogen required to produce one metric ton of ammonia is approximately 0.17 tons. When extracting hydrogen from Ammonia, there is an approximate 2% reduction on hydrogen yield.
The utilization takes place at pressures of 150-250 bar and at temperatures higher than 350 °C.

Production of Ammonia using 100% renewable energy; transport as Ammonia, separate back to hydrogen nearer to use points – one example of Green H2

Methanol
Methanol synthesis is the world's third largest consumer of hydrogen. In exothermic downstream processes, so-called syngas (mixture of H_2 and CO or H_2 and CO_2) is converted to methanol in low- or medium-pressure processes using catalysts.
Substituting syngas with hydrogen does not affect the methanol quality.
However, in replacing the syngas with pure hydrogen from renewable methods, CO2 is no longer produced as a by-product. Therefore, CO2 will need to be generated and recovered from other sources such as combustion processes.

Methanol demand is projected to increase 31% by 2030. Methanol, similar to ammonia, offers many advantages as a potential future energy source. If methanol becomes established as a hydrogen carrier, further increases in demand can be expected. In this case, the demand for hydrogen will increase accordingly.

Substitute or Synthetic Natural Gas (SNG)
The SNG production process takes place in two stages in power-to-gas plants: First, electrolysers use electricity from wind power or photovoltaics to split water (H_2O) into its components hydrogen (H_2) and oxygen (O_2). The hydrogen can be used directly or subsequently becomes the starting point for downstream products such as SNG or liquid e-Fuels.
In the case of SNG, the hydrogen is "methanised" in a second process step by adding carbon dioxide (CO_2) - for example from neighboring biogas plants. The end product is synthetic methane (CH_4), chemically identical to fossil natural gas and renewable biomethane.

This is seen as a use of hydrogen in the long term, relevant only after hydrogen is no longer produced from Natural Gas.

Hydrogenation
Hydrogenation is another application of hydrogen in the chemical industry. The alcohols formed in the presence of excess hydrogen are an important starting product for further processing into e.g. ionic and non-ionic surfactants. These are typically used in softeners, dishwashing liquids, emulsifiers and cosmetics.

Petrochemical Industry
After the chemical industry, the petroleum industry is the world's second largest user of hydrogen. In 2019, refineries were responsible for 38 million tons of hydrogen consumption (out of a total global demand of 115). The replacement of grey hydrogen (produced by steam reforming) by green hydrogen is comparatively easy. The integration of the more ecological alternative does not require any major investments in the production infrastructure.
The hydrocracking and hydrotreating processes are particularly important. Hydrocracking involves the targeted shortening of long-chain hydrocarbon compounds in order to obtain higher-value products such as gasoline and other derivatives from the crude oil. The breaking of the carbon-carbon compounds and the subsequent hydrogenation takes place in a hydrogen-rich atmosphere using catalysts.
Approx. 27 kg of hydrogen are required for the processing of one ton of input material.

In hydrotreating, mineral oil products are desulfurized (hydrodesulfurization) by incorporating hydrogen and again using certain catalysts. In addition, the process can be used to remove oxygen (hydrodeoxygenation) and other components. The process is therefore used to remove impurities from distillates such as kerosene and diesel. The hydrogen demand in this process is quantified in a range of 2 to 9 kg of H_2 per ton of feed material. In all these processes, hydrogen from SMR could be replaced by electrolyser-based hydrogen, produced with renewable power.

Metal Industry (Reduction)
hydrogen is widely used to reduce metal oxides to produce the corresponding metals. The oxide-hydrogen reaction makes it possible to obtain very pure metals in powder form. This process is therefore used on a large scale in the production of metals such as tungsten and molybdenum. However, hydrogen is also used for the reduction of other metal oxides and chlorides, to produce precious metals such as iridium or platinum.

Material processing (Welding, Heat treatment, …)
Industrial welding using hydrogen as shielding gas (arc atom) was first replaced by welding with helium and later with argon and is of little importance in industrial applications. Even a better availability of hydrogen will most probably not lead to an increased use of hydrogen as shielding gas for welding, because besides the safety concerns, the reactivity of hydrogen is also problematic. hydrogen will continue to play a role as a shielding gas in industrial welding but will not be considered further due to its low prevalence.

In heat treatment processes, hydrogen is used for its reducing properties and because it has high heat transfer capabilities. hydrogen/Nitrogen mixtures are used as protective atmospheres instead of dissociated Ammonia.

Semiconductor Industry
hydrogen is also increasingly used in the semiconductor industry as a reducing agent and also for etching. In addition, its good heat transfer properties are being exploited. The use of hydrogen is thus becoming established above all in wafer annealing, where it supports uniform heat distribution and directly reduces oxides. As a reducing agent, hydrogen is also used to deposit new crystalline layers or to enhance the insulating effect of silicon thin films. Another important hydrogen property for application in the semiconductor industry is to extend the shelf life of individual electrochemicals.

Glass Industry (protective atmospheres)
In float glass production in the glass industry, hydrogen is used as a protective gas. After the melting of the various raw and recycled materials, the molten glass is drawn over a tin bath in a protective overpressure atmosphere without mixing with the tin. The protective atmosphere for

inerting the molten glass consists of 90 % nitrogen and 10 % hydrogen to prevent possible oxidation of the tin surface.

Food Industry (fat hardening)
The hardening of oils and fats is also based on the chemical process of hydrogenation. In the presence of nickel catalysts and hydrogen, unsaturated fatty acids are converted into saturated fatty acids, the melting point of the fats is increased, and their shelf life is improved. A well-known example product is margarine, which is produced by catalytic hydrogenation of edible oils. From the mass balance of margarine production from palm oil, the hydrogen demand is 227 kg H_2 per ton of margarine.

8.3 Other uses of hydrogen

Cooling

Because of its high heat capacity, hydrogen is used as a coolant in power plants and industrial facilities. In particular, hydrogen is used where liquid cooling can be problematic. The heat capacity comes into use where the gas cannot circulate or can only circulate slowly. Because the thermal conductivity is also high, flowing H_2 is also used to transport thermal energy into large reservoirs (e.g. rivers). In these applications, hydrogen protects equipment from overheating and increases efficiency.
Liquid hydrogen is suited as a cryogen, i.e. as a coolant for extremely low temperatures. Even larger amounts of heat can be absorbed well by liquid hydrogen before a noticeable increase in its temperature occurs. In this way, the low temperature is maintained even in the event of external fluctuations.

Lifting gas (Buoyancy)

Due to Helium becoming increasingly scarce, combined with much improved understanding and safety measures, hydrogen is having renewed interest as a lifting gas.

Hydrogen in Transport and Mobility

Using hydrogen as a fuel in transport has several potential benefits.
When hydrogen is used as a fuel for mobility, it produces only water vapour in fuel cell applications, only NOx emissions when combusted (at point of use).

As hydrogen can be produced using renewable sources of energy such as wind, solar, and hydropower, or using fossil resources together with CO2 capture, it can significantly reduce the global warming contribution of transport.

Hydrogen has a high energy density enabling it to store significant amounts of energy onboard vehicles allowing fast refueling, which makes it more convenient than batteries when charging time is an issue.

Using hydrogen as a liquid on-board vehicle is under development, to enable greater range and higher payloads.

Hydrogen can be used in a variety of vehicles, including cars, buses, trucks, trains, and even ships and airplanes, either directly in a fuel cell or through combustion in an internal combustion engine or in a turbine.

Hydrogen fuel cell vehicles (FCVs) use hydrogen gas to generate electricity through an electrochemical reaction with oxygen in the air. This electricity is used to power an electric motor that propels the vehicle. FCVs have the potential to be very efficient (50 to 60% efficiency) and have zero emissions, making them a promising alternative to conventional gasoline and diesel vehicles.
hydrogen can be used to power heavy-duty vehicles such as trucks and buses. These vehicles have high energy demands and require a fuel source that can provide sufficient power and range. hydrogen can meet these requirements, making it a promising alternative to diesel engines and Battery Electric Vehicles.

In the Maritime, Aviation and Rail sectors, hydrogen can be used as a fuel, either directly in a fuel cell or through combustion in an internal combustion engine. This has the potential to reduce emissions of greenhouse gasses and other pollutants, making these modes of transport more sustainable.
Hydrogen is distributed to mobility applications through hydrogen Refueling Stations (HRS) which are specialized facilities designed to store and dispense hydrogen fuel for vehicles.

An HRS is mainly composed of:

- An onsite hydrogen storage. This storage may be gaseous or liquid. It may also be fixed or mobile in which case empty tanks (or trucks) are swapped with full ones when needed. Refer to storage section above.
- A system used to compress the hydrogen to the required pressure. This may be performed with compressors or using LH2 pumps when hydrogen is stored at site as a liquid. The hydrogen is typically compressed to fill vehicle tanks at 350 or 700 bar [35 or 70 MPa].
    - A dispenser, which is the interface between the HRS and the vehicle. It is equipped with a nozzle that is connected to the vehicle's fuel tank, and a dispenser control unit that regulates the flow of hydrogen and ensures that the vehicle is fueled according to the required protocol, such as SAE J2601 or MC method. The purpose of the protocol is to ensure that the conditions (pressure, temperature, state of charge) of the vehicle's tank remain within design parameters.

A variety of safety systems are incorporated into the design of an HRS to ensure safe operation. These include sensors and alarms to detect leaks, ventilation systems, and emergency shutoff systems.

Figure 17: Photo of typical Liquid H_2 Refuelling Station

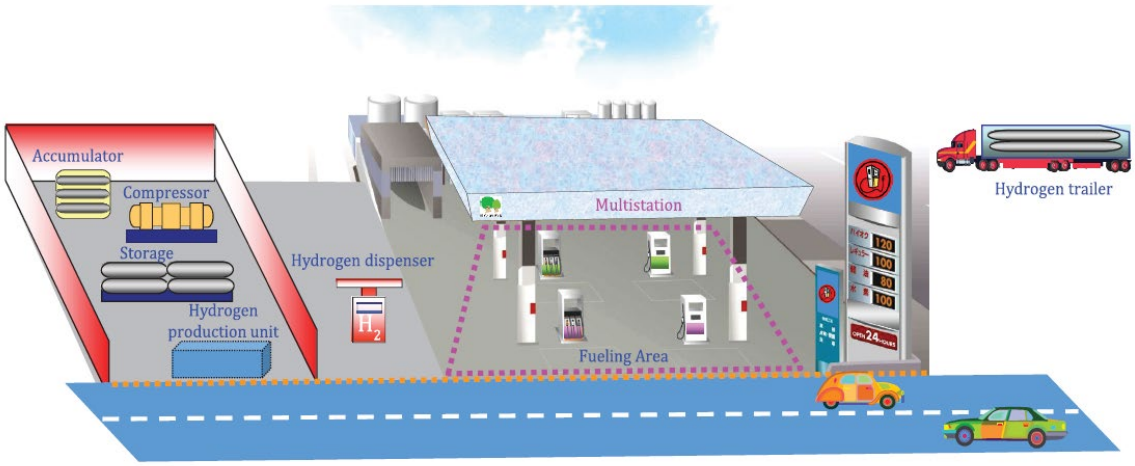

Figure 18: Typical layout of an HRS (from ISO 19880-1)

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Unless otherwise specified, the latest edition shall apply.

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Appendix 1 - Transport Modes of Hydrogen

Table: Major hydrogen transmission methods

Transmission Type	**Pipeline**	**Tube trailer**	**Liquid – road**	**Liquid – ships**
Suitability	Short, medium, and large distance transfer of large and very large quantities in a gas state	Short distance gas state transfer	Short and medium distance transfer of large volumes of fuel	Very large quantities of gas for international transportation
Investment Costs (Note : data from 2010)	€200,000-€1,000,000 per km depending on the terrain	Around €300,000+ per trailer (200 Bar technology)	€800,000-€1,100,000 per trailer	€465,000,000-€620,000,000 for each LH2 barge
Capacity	Up to 100 tons h–1 (3.9 GW)	Up to 400 kg per trailer (with 200 Bar technology)	Up to 3,500 kg per European trailer	Up to 10,000 tons per shipment
Operating and Maintenance costs	Around €0.03 per kg for pipeline compressors	Driver labour at around 18 € h– 1	Driver labour at around 18 € h– 1	Crew labour and fuel consumption costs unknown
Efficiency	Over 99.2% per 100 km	94% per 100 km	99% per 100 km (liquefaction efficiency is around 75%)	0.3% boil-off per day
Energy required	Electricity required for pipeline compressors	Vehicle fuel consumption	Vehicle fuel and liquefaction energy consumption	Transport fuel
Advantages	Large and very large quantities can be transported to any distance with high efficiency, low running costs, and very low variable expenses. This method also provides storage and buffering possibilities. Existing gas pipelines could be utilised.	Small scale deployment possibilities	Larger volumes than gas Transportation	International transportation of massive quantities for long distances

Disadvantages	Relative expensive investment costs and requirement of the very large amount of hydrogen delivery to be justified. Existing pipelines are not designed for high concentration H2, requiring modifications.	Small scale delivery per vehicle, energy inefficiency, short-distance transportation	Costs and inefficiency of liquefaction and boil-off product losses	There isn't any industrial experience of shipping LH2. It's not feasible until large supply and demand exist. Boil-off losses are more significant than road transport
Total transmission cost (€ kg− 1 100km− 1)	€0.10 to €1.00	€0.50 to €2.00	€0.30 to €0.50	€1.80 to €2.00

Appendix 2 – Cylinder Types

Types and Pressures ratings are defined by material and construction:

Type	Materials	Typical Pressure (bar)
I	All-metal construction	200 – 300
II	Metal vessel reinforced with composite wrap excluding dome	200 – 300
III	Metal liner with full composite wrap	up to 500
IV	All-composite construction	300 to 1000

Type 1 All metal: Carbon Steel construction with lowest purchase price, but for normal steel with Ultimate Tensile Strength (UTS) above 950MPa the hydrogen molecule is able to produce cracks in the cylinder/ tube wall which is known as hydrogen Embrittlement (See EIGA Doc 100[7]). Consequently, ductile low strength Carbon Steels (UTS below 950MPa) are used for hydrogen because these materials are impacted less by this phenomenon but results in thicker heavier cylinders and tubes that are inefficient for hydrogen distribution above pressures of 200 Bar(g) – for other products Type 1 Cylinders and Tubes are made from other steel with higher UTS.

Type 2 Fibre Hoopwrapped Metal Liner: Seamless Carbon Steel or Aluminium Alloy with the parallel section wound with composite material such as Carbon Fibre, more expensive than Type 1 but about 35% lighter, but not as light as Type 3. Pressures above 200 Bar(g) (e.g. 300 or 500Bar(g)) are achievable but for distribution these are not as efficient as Types 3 and 4 so are not widely used for hydrogen – for other products Type 2 cylinders are made from other metals.

Type 3 Fibre Full wrapped Metal Liner: Aluminium liner and neck which is completely wound with composite material such as Carbon Fibre, glass fibre can also be used but is heavier and less common. Up to 30% lighter than Type 2 cylinders and tubes and with pressures up to 1000 Bare(g), these offer significant distribution efficiency over Type 2. The liner can also be wound with Glass Fibre, but these cylinders are heavier and less common.

Type 4 Fibre Full wrapped Polymer Liner: Aluminium neck, Polymer liner and fully wound with composite material such as Carbon Fibre but glass fibre is also used. These offer up to 35% weight saving compared to Type 3 cylinders and tubes, and with pressures up to 900 Bar(g) this Type is the most efficient for distribution.