Observatorio
Tecnológico
del **Hidrógeno**

Hydrogen as a vector for land mobility:

Technologies, market and challenges for its deployment

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GLOSSARY

AEM	Anionic Exchange Membrane
AFC	Alkaline Fuel Cell
AFIR	Alternative Fuel Infrastructure Regulation
BEV	Battery Electric Vehicle
BOP	Balance of Plant
CAPEX	Capital Expenditure
CEF	Connecting Europe Framework
cH_2	Compressed hydrogen
CcH_2	Cryo-compressed hydrogen
CO_2	Carbon dioxide
DC	Direct Current
DI	Direct Injection
DMFC	Direct Methanol Fuel Cell
ESG	Environmental, Social, and Governance
ETS	Emissions Trading System
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
H_2	Hydrogen
HDV	Heavy Duty Vehicle
HPDI	High Pressure Direct Injection
ICE	Internal Combustion Engine
IDAE	Institute for Energy Diversification and Saving
IEA	International Energy Agency
IPCEI	Important Projects of Common European Interest
ISO	International Organization for Standardization
LH2	Liquefied Hydrogen
LOHC	Liquid Organic Hydrogen Carrier
MEA	Membrane Electrode Assembly
SIE	Spark-ignition Engine
MOF	Metal Organic Framework
N_2	Nitrogen
NH_3	Ammonia

NO_X	Nitrogen oxides
OPEX	Operating Expenditure
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
PFA	Perfluoroalkyl substances
PFI	Port Fuel Injection
PHEV	Plug-in Hybrid Electric Vehicle
PNIEC	National Integrated Energy and Climate Plan
PRTR	Recovery, Transformation and Resilience Plan
RED III	Renewable Energy Directive III
RFNBO	Renewable Fuels of Non-Biological Origin
SAE	Society of Automotive Engineers
sLH2	Subcooled Liquid Hydrogen
SOFC	Solid Oxide Fuel Cell
TCO	Total Cost of Ownership
TEN-T	Trans-European Transport Network
TRL	Technology Readiness Level
EU	European Union
UNE	A Spanish Standard
UNECE	United Nations Economic Commission for Europe

EXECUTIVE SUMMARY

Hydrogen is poised to play a pivotal role in decarbonizing road transport, particularly in applications where direct electrification via batteries faces technical, operational, or economic limitations. These limitations are most pronounced in terms of range, refueling time, payload capacity, usage intensity, and operational availability. In this context, hydrogen's contribution is particularly valuable for long-haul, heavy-duty transport; buses; captive fleets; machinery; and off-road applications, where the energy and operational demands of zero-emission alternatives are more severely constrained by other technologies.

This technical report, developed by the Hydrogen Technology Observatory in collaboration with Bosch, CIDAUT, CMT - Clean Mobility and Thermofluids of the Universitat Politècnica de València, Enagás, CIRCE Foundation, Inetum, Linde and the University of Barcelona, provides a comprehensive analysis of the role of hydrogen as an energy carrier in road mobility. The document addresses the main use technologies for vehicles, storage systems, refuelling infrastructure, market trends, and the European and Spanish regulatory frameworks.

From a technological point of view, the report identifies two primary routes for the use of hydrogen in the automotive sector. The first route is fuel cells, which convert hydrogen into electricity through a highly efficient, locally emission-free electrochemical process. Fuel cells are currently the most mature option for zero-emission, hydrogen-based mobility. In vehicle applications, PEMFC (Proton Exchange Membrane Fuel Cell) technology is dominant due to its fast start-up, power density and compatibility with electric propulsion systems. The second route involves hydrogen-fuelled internal combustion engines (H_2-ICEs). While these are less energy efficient, they offer a significant industrial advantage in the form of the partial reuse of platforms, supply chains and knowledge accumulated in internal combustion engines. This reduces development times, initial CAPEX and adoption barriers in certain applications.

However, when comparing the two technological routes, efficiency and maturity should not be the only factors considered. Stack durability is a critical factor in fuel cells, particularly in intensive or applications involving long operating cycles. Unlike internal combustion engines, the degradation of which is better understood and generally has a less significant impact on efficiency, fuel cells may require refurbishment or partial stack replacement over the vehicle's lifetime.

Technology	Current status	TRL	Strengths	Weaknesses	Development trends
Fuel Cells (FC, mainly PEMFC)	Commercial / fully tested in an operational environment	9	- High efficiency. - Zero local emissions. - High power density. - Good integration in electric propulsion systems.	- High initial cost. - Use of platinum-based catalysts. - High purity of H_2 required. - Competitiveness conditioned by the availability of infrastructure and the cost of H_2.	- Consolidation in heavy transport and fleet applications. - Evolution of materials and membranes. - Development of alternatives such as AEM. - Progressive reduction in the use of critical catalysts.
Internal combustion engines (H2-ICE)	Early deployment / Advanced commercial validation	Up to 8 (maximum observed in trucks)	- Reuse of existing platforms. - Lower initial CAPEX. - Mechanical robustness. - Lower purity of H_2 required. - Rapid implementation.	- Lower efficiency than FC. - NO_X emissions controllable but present. - Need for specific components.	- Move towards dedicated H_2designs. - Improved combustion and emission control. - Focus on heavy trucks, machinery and off-road applications.

Hydrogen storage is one of the most important technical and economic factors determining a vehicle's competitiveness. Due to hydrogen's low volumetric energy density under ambient conditions, the design of the storage system directly affects range (i.e. the amount of hydrogen stored), vehicle integration, safety and cost. At the system level (vehicle + hydrogen tank), hydrogen offers a favourable ratio of occupied on-board volume to available useful energy, especially in applications requiring long ranges without unduly penalising usable space, cargo capacity or operational continuity.

Currently, high-pressure gaseous storage is the dominant and most commercially viable solution, while liquid hydrogen is emerging as an alternative with high potential for long-haul heavy transport thanks to its superior volumetric energy density. However, it is still hindered by the need for storage at cryogenic temperatures, operational complexity, and associated investment requirements. Solutions based on solid materials or cryo-compressed storage are in the early stages of development and have relevant constraints that prevent their widespread deployment on the road.

Technology	Current status	TRL	Strengths	Weaknesses	Development trends
High-pressure gaseous hydrogen storage (cH2)	Commercial / dominant solution for road mobility	9	-Most widely deployed technology in hydrogen-powered vehicles. -Compatible with fast refuelling. -Widely used at pressures of 350 bar and 700 bar. -Established tank, regulation and safety architecture.	-Low volumetric energy density compared to liquid fuels. -Integration constrained by safety, ventilation, structural strength and crash management requirements.	-Optimisation of multi-cell designs. -Structural integration of tanks. -Evolution towards solutions offering greater range, especially at 700 bar.
Liquid Hydrogen Storage (LH2)	Emerging alternative for long-haul heavy mobility	9	-High volumetric energy density. -Enables a reduction in system volume for the same amount of stored energy. -Potential for greater ranges.	-High technical complexity. -Boil-off losses. -Limited refuelling infrastructure.	-Improvement of cryogenic tanks and boil-off management. -Development of sub-cooled storage to increase density and reduce evaporation.
Cryo-compressed hydrogen storage (CcH2)	Technology under development / not yet widely deployed on the road	5	-Can achieve higher energy densities than liquid or compressed hydrogen separately. -Potential to increase the amount of hydrogen stored in a given volume.	-Increased complexity due to the combination of cryogenic and high-pressure requirements. -Lack of clear commercial maturity in land mobility.	-Improved safety, insulation and vehicle integration. -Technical validation of pressurised cryogenic systems.
Solid-state hydrogen storage	Development phase / limited adoption in mobility	5	-Potential to store hydrogen more compactly and at lower pressure than gaseous systems.	-Relevant restrictions for widespread road deployment. -Potential penalties in terms of mass, integration and charge/discharge dynamics.	-Development of metal hydrides, LOHC and adsorbent materials. -Reduction of system mass and improvement of adsorption/desorption kinetics.

Refuelling infrastructure constitutes the other major enabler. The report outlines various hydrogen refuelling station architectures and emphasises that market viability depends on the coordinated deployment of refuelling stations, vehicle availability and competitively priced hydrogen supply. The European Alternative Fuels Infrastructure Regulation (AFIR) and the rest of the European framework provide a decisive market signal in this regard by introducing binding targets for infrastructure deployment in the Trans-European Transport Network, thereby reducing some of the regulatory risk. The RED III Directive also strengthens the role of hydrogen in transport by introducing specific binding targets for renewable fuels of non-biological origin (RFNBO) for the first time, setting a target for these fuels to account for more than 1% of transport energy consumption by 2030. In Spain, this framework is reinforced by instruments such as the National Integrated Energy and Climate Plan (PNIEC), the Recovery, Transformation and Resilience Plan (PRTR), and funding calls from calls of the Institute for Energy Diversification and Saving (IDAE), which support innovation and the deployment of vehicles and refuelling stations.

In terms of the market, the document portrays an early stage of development, with clear signs of segmentation. Currently, light-duty fuel cell vehicles account for a significant share of the hydrogen vehicle fleet, with a limited number of manufacturers and regions dominating the market. However, their commercial maturity is still limited and heavily influenced by competition from battery electric vehicles. More than 90% of these light-duty vehicles are found in South Korea, the United States, Japan and China. Conversely, the greatest recent momentum has shifted towards heavy transport, captive fleets and off-road applications. The most recent deployments have clearly prioritised heavy-duty trucks, of which there are now 72% more than in 2023. Meanwhile, the global refuelling network has grown to exceed 1,302 stations, with China leading the way.

In terms of the market's evolution, the report outlines a three-stage trajectory. In the short term, development will continue to rely on pilot schemes, early commercial fleets and niche applications with dedicated infrastructure, particularly in heavy transport and off-road applications. There will be a strong dependence on public support and incentives. In the medium term, technological maturation, the consolidation of hydrogen corridors and cost reductions should enable industrial scale-up in trucks and buses, reducing the total cost of ownership to match diesel benchmarks for certain intensive uses. In the long term, hydrogen is expected to be integrated into a multimodal ecosystem alongside electric vehicles and synthetic fuels, specialising in energy-intensive applications where its structural advantages are most evident.

While the report primarily focuses on road mobility, it also includes a specific annex on hydrogen rail applications. This is not so much due to the potential volume of energy demand from rail, which is expected to be lower than that of other mobility segments, but rather due to the technological, industrial and systemic synergies that can be generated through the development of heavy road transport.

In conclusion, hydrogen can play a significant role in the energy transition of road transport, provided its deployment is segmented rather than based on indiscriminate adoption. Its success will depend on the availability of renewable hydrogen at competitive prices, reliable infrastructure deployment, coordination between regulation, investment and technological supply, and the development of integrated business models connecting production, distribution and consumption. Under these conditions, fuel cells and H_2-ICEs engines will be able to coexist in a complementary manner, contributing in a realistic, scalable, and economically rational way to the decarbonisation of transport segments that are difficult to electrify.

1. PURPOSE OF THE REPORT

This report aims to present the most relevant aspects of hydrogen technologies as applied to road transport, in both passenger and heavy-duty vehicles. The content is structured schematically to facilitate understanding of the key concepts in each aspect considered:

- Hydrogen use technologies in vehicles
- Hydrogen storage systems in vehicles
- Hydrogen refuelling technologies
- Global vehicle market
- European and Spanish regulatory framework

It also includes annexes on railway applications due to the technological and systemic synergies they present in relation to the consolidation of hydrogen as a reference energy vector in the effective decarbonisation of transport. There are also annexes on hydrogen quality and basic safety aspects.

The report is the result of collaborative work between several partners of the Hydrogen Technology Observatory: **Bosch, CIDAUT, Clean Mobility and Thermofluids/Universitat Politècnica de València, Enagás, CIRCE Foundation, Inetum, Linde and the University of Barcelona**. Furthermore, this report is **endorsed by Gasnam-Neutral Transport**.

2. USE OF HYDROGEN TECHNOLOGIES

Hydrogen can be used as an energy vector in road transport through two main technological approaches:

1. **Electrochemical conversion of hydrogen into electricity** via fuel cells (FC).
2. **Thermo-mechanical conversion via combustion** using hydrogen-adapted internal combustion engines (H_2-ICE).

These technologies have **different architectures, performance levels, technology readiness level and application areas**, justifying their coexistence within the hydrogen-based mobility ecosystem. Throughout the chapter, the **fundamentals**, **types** and **applications** of fuel cells and engines are explained in detail.

The chapter also mentions an **emerging technology** system based on the **combination of reformers and on-board fuel cells**, and concludes with a **structured comparison** of the two technology routes, alongside an analysis of the **technology readiness level (TRL)** associated with each. This comprehensive approach provides a clear picture of the current status of hydrogen mobility technologies and their foreseeable evolution in the transition to decarbonised transport systems.

It is important to note that successful deployment of hydrogen in mobility requires not only integration of the hydrogen use technology, but also of the type of on-board storage - the ‘energy pack’ - into the vehicle. The same applies to the technology deployed in hydrogen refuelling stations.

2.1. Fuel Cells (FC)

Fuel cells are one of the most well-established technologies for using hydrogen as an **energy vector** in mobility. They operate based on the direct electrochemical conversion of hydrogen into electricity, enabling high-efficiency operation and **zero local emissions**, as the only by-product of the reaction is water.

2.1.1. Fundamentals of fuel cells

A fuel cell is an **electrochemical device** that converts the chemical energy of hydrogen directly into **electrical energy** through a controlled redox reaction between **hydrogen** (the fuel) and **oxygen in the air** (the oxidant).

Unlike combustion-based systems, this conversion does not require heat generation as an intermediate stage. This avoids the thermodynamic limitations imposed by the Carnot cycle, allowing **higher efficiencies** to be achieved. Only **water** is generated as a product of the reaction, with no local emissions of pollutants such as nitrogen oxides (NO_x), since the process takes place at relatively low temperatures.

Any chemical reaction involves an exchange of electrons between atoms, with some atoms being more likely to give up electrons than others. The synthesis of water from hydrogen and oxygen in fuel cells takes place in two half-reactions. In each of these, the electron involved will have a certain voltage at which reduction or oxidation will occur; this is called the **reduction potential**.

There are different types of hydrogen fuel cell, which will be discussed later. For a basic explanation, we will use the PEM (Proton Exchange Membrane) fuel cell as a reference; this is currently the most widely used type of fuel cell for mobility.

Oxidation at the anode

Starting with two molecules of diatomic hydrogen (H_2) in a gaseous form, these come into contact with the negative electrode (the anode), where they release four electrons in the presence of a catalyst and under a certain potential, becoming oxidised in the process:

$$2\,H_2\,(g) \rightarrow 4\,H^+\,(aq) + 4\,e^-$$

The protons (H^+) formed then dissolve in the water that humidifies the electrode and diffuse through a semi-permeable, electrically insulating proton exchange membrane (PEM), which prevents the passage of gases. The electrons circulate in the external electric circuit, and their energy is used by the vehicle’s electric motor.

Cathode reduction

At the cathode, diatomic oxygen (O_2) captures electrons at the electrodes in the presence of a catalyst and is reduced to two O^{2-} ions.

$$O_2\,(g) + 4\,e^- \rightarrow 2\,O^{2-}$$

Immediately, the protons (H^+) combine with O^{2-} ions to form two water molecules.

A schematic of the operation of a PEM fuel cell is shown in Figure 1.

Ideally, these two half-reactions would produce a combined **voltage** of **1.23 V** (the sum of their respective **reduction potentials**), but the actual voltage is around **0.7 V**. This is because of irreversibility in the process due to minimum activation voltages, resistive losses, and fluid transport phenomena.

The **current** generated is proportional to the number of molecules reacting per unit time. Given the slow reaction kinetics at room temperature, specific catalysts are used on both electrodes.

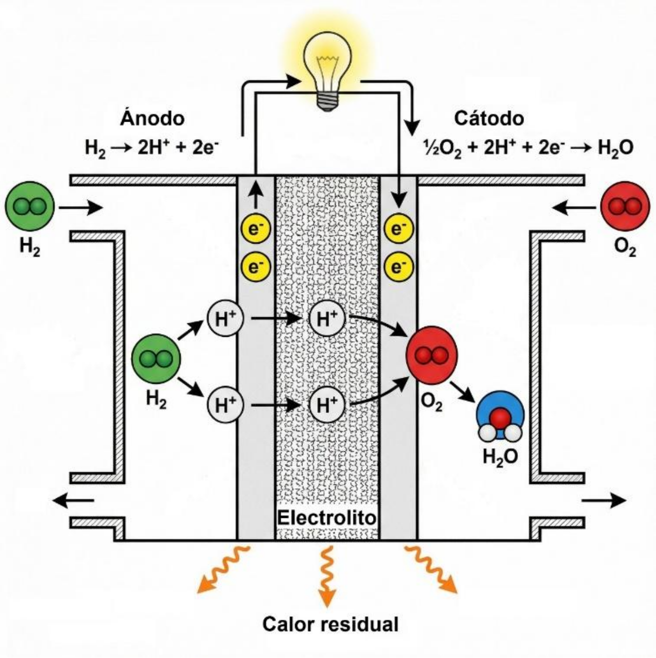


Figure 1. Working principle of a fuel cell (Source: own elaboration).

The relationship between generated voltage and current is not constant, but follows a **polarisation curve** (Figure 2), specific to each fuel cell type and design, although the general behaviour is similar in all cases. This curve shows that the voltage is at its maximum in open-circuit conditions (zero current) and drops sharply in the low current region due to the activation voltages of the reactions. Subsequently, it enters a practical operating zone with resistive behaviour, where the voltage decreases proportionally with the current level. Finally, as the current increases towards high values, there is a sharp drop in voltage caused by **transport losses** due to difficulties in supplying the electrodes with reactive gases and removing the water generated. This final region defines the operational limits of the stack, influencing its design and control. Due to the variability of voltage with current, it is essential to incorporate a **power conditioning** system, typically a DC/DC converter. This adapts the battery’s electrical output to provide a stable voltage compatible with the vehicle's propulsion system and auxiliary battery.

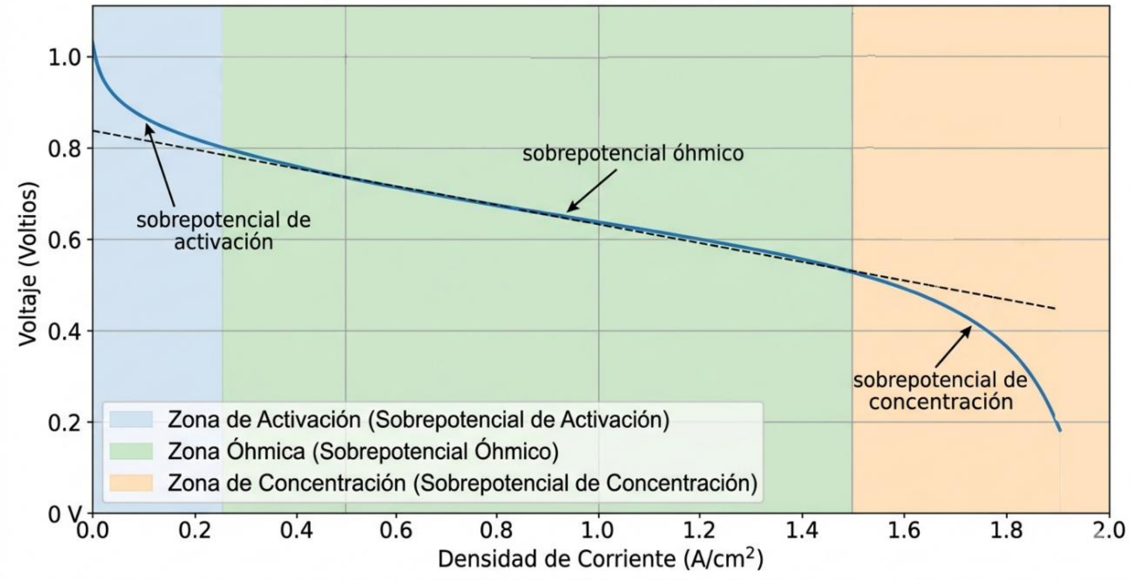


Figure 2. Polarisation curve of a fuel cell (Source: own elaboration).

Unlike traditional heat engines, fuel cells are **more efficient at low loads**, which is a relevant feature for their integration into fuel cell electric vehicles (FCEVs).

2.1.2. Cell Stack and Balance of Plant

To achieve usable electrical voltages for mobility applications, fuel cells do not operate as single, isolated electrochemical cells. Instead, **stacks of numerous individual cells** - typically in the order of tens or a few hundred - are constructed, with the cells connected electrically in series. This set is called a **stack**. Each cell in the stack consists of a **membrane and two electrodes**, collectively known as an **MEA (Membrane Electrode Assembly)**, and is sealed at the sides by **bipolar plates**. These plates are metal sheets that provide a seal between the hydrogen and air sides while maintaining electrical conductivity between cells. In this design, the **ionic circuit** runs internally through the membrane of each cell in series, advancing from one end of the stack to the other and summing the voltages of each cell. The **external electrical circuit** extends from the collector plate at one end and connects to the corresponding collector plate at the other end (Figure 3).

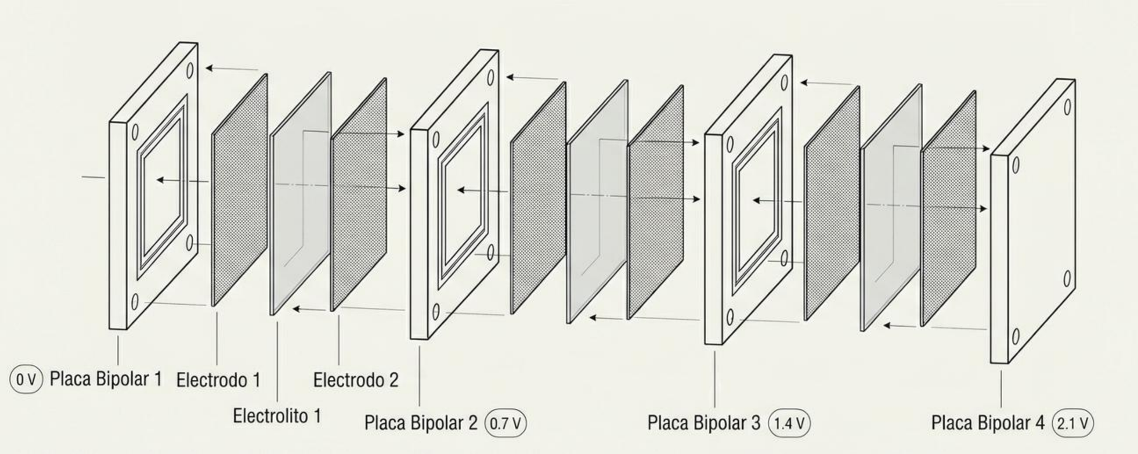


Figure 3. Fuel cell stacking (Source: own elaboration).

Just as an internal combustion engine needs auxiliary systems such as a radiator, oil filter or exhaust catalyst, the fuel cell **stack** requires a number of **external components** in order to function properly. These auxiliary systems form the so-called **balance of plant (BOP)**, which brings together all the elements necessary for the fuel cell to operate under optimum conditions, ensuring stable and safe performance during vehicle operation.

The balance of plant consists of the following subsystems:

- **Hydrogen supply system**. This subsystem includes a **pressure regulator** to adjust the hydrogen from the tanks to the conditions required by the anode, as well as a **purge valve** to evacuate any water that may accumulate on this side of the cell. Excessive water can cause **flooding of the anode** and compromise proper operation. Depending on the design, the system can also incorporate a **hydrogen recirculator** to improve efficiency by utilising hydrogen that did not react during the previous pass through the anode.
- **Air supply system**. The oxygen supply for the electrochemical reaction is provided by an **air blower**, which introduces the necessary flow through a **filtration system** to ensure that impurities and environmental particles do not reach the inside of the cathode. This supply must be continuous and stable to ensure the correct feeding of the oxidising side of the fuel cell.
- **Humidification system**. Both the hydrogen and the air must be kept at an appropriate **moisture level**, as the proton-conducting membrane requires moisture to maintain its electrochemical functionality. Humidification is essential for preserving proton conductivity and avoiding damage or loss of membrane performance during operation.
- **Cooling system.** The stack must operate within a narrow temperature range and therefore uses a **cooling circuit** comparable to that of an internal combustion engine.

However, specific technical requirements arise from the stack's electrochemical operation. Cooling enables the heat generated during the reactions to be extracted, maintaining the necessary thermal stability to prevent the premature degradation of the MEA's constituent materials.

- **DC/DC converter**. The system incorporates a **DC/DC converter** that provides a stable and suitable voltage for the vehicle's battery and electric motor. This is due to the fuel cell's own electrical behaviour, whereby the voltage varies according to the current intensity and operating state.
- **Control unit**. The system requires a **control unit** to manage hydrogen and air flows, humidification, temperature, generated electrical power, and overall stack safety. It coordinates all balance-of-plant subsystems to ensure the stack operates stably and efficiently within the set operating limits.

2.1.3. Fuel cell types

The **proton-conducting membrane** is a decisive element in the fuel cell's functioning, as it determines the operating conditions. As a thin polymeric film, this membrane must operate at low, precisely-controlled temperatures. Membranes used in **PEM technology** are mainly based on **perfluoroalkylated (PFA)** materials, such as Nafion®, and require high-activity **platinum-family** catalysts capable of withstanding a highly acidic electrode environment. However, these PFAs are among the so-called 'forever chemicals', meaning that they will ultimately need to be replaced by more environmentally friendly alternatives.

In the search for alternative electrolyte and membrane solutions, new concepts have emerged, such as **AEM** (Anion Exchange Membrane) fuel cells. In this variant, it is the hydroxide ion (OH^-) rather than the proton (H^+) that is transported. This basic environment allows the use of **less expensive catalysts and materials**, representing a significant development in terms of sustainability and cost.

There are numerous ion-conducting materials available, resulting in different families of fuel cells:

- **Liquid potassium hydroxide electrolyte (KOH).** The oldest technology used this type of electrolyte. Although it is widely used in **electrolysers** (the reverse technology of the fuel cell), its use in fuel cells is very limited because potassium hydroxide reacts with atmospheric CO_2 resulting in precipitation, which makes stable operation in open environments difficult.

- There are also **ceramic materials** capable of conducting O^{2-}ions, but they require very high temperatures, in excess of 600°C. While these systems are highly efficient, they are not suitable for mobility applications due to the frequent starts and stops required.
- Another prominent technology is **phosphoric acid fuel cells (PAFC),** which were the first to be commercialised and used in urban mobility applications in the United States during the 1990s. However, they have been displaced by lighter PEM technology with better starting characteristics due to their heavy weight and the long warm-up time required.

The following Table 1 compares the different types of fuel cells, showing the advantages and limitations of each topology.

Table 1. Summary of the different fuel cell technologies.

Fuel cell	Description	Advantages	Limitations
PEMFC - Proton Exchange Membrane Fuel Cell	Proton exchange membrane	- Solid polymer electrolyte, greater simplicity as no liquids need to be managed - Low operating temperature (60ºC-80ºC) - Quick start-up. - Excellent dynamic response - High current density - Compact design and high specific efficiency	- Highly acidic environment. - High-performance materials, higher cost - Use of platinum-based catalysts: higher cost and high-purity of hydrogen required (CO sensitivity). - The water generated is in liquid form
DMFC - Direct Methanol Fuel Cell	PEMFC variant that can process methanol	Better storage and logistics of methanol compared with hydrogen	Lower current density, higher platinum catalyst load, lower efficiency
'High temperature' PEM	PEMFC variant using membranes operating above 100°C.	- The water generated is in gaseous form, making it easier to manage. - Easier to cool - Increased tolerance to CO	- Lower durability - Slow start-up - Increased chemical degradation
AFC - Alkaline Fuel Cell	Alkaline electrolyte (KOH solution)	- Reduced costs due to low-cost materials. - Durability	- Very sensitive to CO_2 (electrolyte precipitation), needs pure O_2 instead of air (use limited to space applications). - Corrosive electrolyte in the event of leakage
SOFC - Solid Oxide Fuel Cell	Ceramic electrolyte, conductive at high temperature (600-1,000°C)	- High overall efficiency. - Capable of direct processing of conventional fuels	-Slow start-up -Thermal shock risk

2.1.4. Application of fuel cells in vehicles

Fuel cells are integrated into **fuel cell electric vehicles (FCEVs),** which use hydrogen as an energy carrier to generate electricity on board through an electrochemical reaction between hydrogen and oxygen in the air. This electricity powers the vehicle's electric propulsion system, typically with the support of an auxiliary electrical storage system such as batteries or supercapacitors.

In fuel cell propulsion, the fuel cell supplies the driving power and the battery is used exclusively for energy recovery during braking through regenerative braking and for electric assistance during acceleration.

In **passenger cars**, the fuel cell typically has power ratings in the range of **100 to 150 kW**, while the battery has high power density but low energy capacity, typically of around **1 to 2 kWh**. The hydrogen tank is stored under high pressure and typically contains **between 5 and 6 kg of hydrogen**, allowing a range of up to **600 km**. Energy is supplied exclusively by hydrogen refuelling.

Another architecture is the **range extender configuration**, where the **battery** mainly provides the power for propulsion and the fuel cell **charges the battery while driving**, thus increasing the vehicle's range. Extended-range cars typically feature a lower fuel cell power density, a high-capacity battery, a low-power fuel cell (20-30 kW) and a small, pressurised hydrogen tank. This configuration enables the vehicle to be designed as a **plug-in model**, combining conventional electric charging with hydrogen refuelling to provide greater operational flexibility.

The main **benefits associated** with the use of fuel cells in mobility are as follows:

- Wide power range, adaptable to multiple applications.
- Leading power density, with reduced space requirements.
- High customisation capacity, depending on the required operating conditions.
- Availability at different levels of integration, depending on the customer's needs.
- Cross-applicability from passenger cars through specialised fleets to heavy commercial vehicles.

A comparison of fuel cell vehicles is presented in Table 2 . The following are included: vehicle types, applications, configuration, advantages and observations.

Table 2. Categories of fuel cell vehicles for land transport.

Category	Applications / Examples	Features / Architecture	Advantages / Key reasons	Observations
Light vehicles (passenger cars and vans)	Passenger cars, taxis, urban fleets	Hybrid FCEV (fuel cell + battery)	- High ranges (500-700 km) - Quick refuelling (3-5 min) - Zero local emissions	Especially attractive for intensive use and fleets where downtime is critical.
Heavy road transport	Long-haul trucks, intercity and city buses, heavy-duty logistical vehicles		- BEV limitations on battery weight - Improved energy scalability of hydrogen - High operational availability	Priority segment for fuel cell deployment in the medium term
Special applications and captive fleets	Municipal vehicles, internal logistics (forklift trucks, etc.), airports, ports, industrial environments and special vehicles (public works, mining, etc.).		-Dedicated infrastructure available - Increased technical and economic feasibility	Particularly viable in controlled environments

2.1.5. Propulsion systems based on the combination of a reformer and a fuel cell

Fuel cell-based mobility poses a significant challenge: **increasing** the amount of hydrogen on board in order to extend the **vehicle's range** and thus its applications**. While it is possible to increase range by** storing hydrogen under pressure or in **liquid form**, a third alternative is emerging: producing hydrogen directly on board the vehicle from other **liquid molecules** containing it, such as methanol or ammonia. This strategy involves the integration of a reforming system and a fuel cell on board the vehicle itself. It is an emerging technology still under development.

The concept involves **catalytic reforming** of the liquid fuel to produce a hydrogen-rich stream. This stream then feeds a **hydrogen fuel cell**, which converts the chemical energy of the generated hydrogen into electrical energy for propulsion. Using liquid molecules with high **volumetric energy density** reduces the total volume needed for onboard energy storage, particularly in vehicles with **high energy demands** due to power requirements or range needs.

Where **high autonomy** is required, the complete system (reformer, fuel cell and liquid fuel tank) can be more compact than a solution involving the direct storage of compressed or liquefied hydrogen alongside the fuel cell. This **increased compactness** is advantageous in segments where onboard space is limited or where the volume of the storage system significantly affects vehicle design.

The **use** of these **streams**, obtained from **reforming** liquid molecules into hydrogen, generally requires **adaptation** of the fuel **cell**, as the anode stream will be composed of hydrogen and another inert substance (e.g. CO_2 if methanol or ethanol is reformed, or N_2 if ammonia is cracked). Open-anode fuel cells are normally used.

2.2. Hydrogen-fuelled internal combustion engines (H_2-ICE)

The **hydrogen-fuelled internal combustion engines** are among the most widely studied alternatives for incorporating this **energy vector** into current land mobility systems.

2.2.1. Fundamentals and characteristics of H_2-ICE engines

Unlike fuel cells, which convert the chemical energy of hydrogen into electricity through an electrochemical process, H_2-ICE engines employ a more traditional operating principle: the **controlled combustion of hydrogen in a thermal engine**. In this process, the chemical energy of the fuel is first converted into thermal energy, which is then converted into mechanical work through the engine’s thermodynamic cycle.

While the overall efficiency of these engines is theoretically lower than that of fuel cells, they have a decisive advantage: the great **technological similarity with conventional internal combustion engines**. Consequently, much of the existing industrial infrastructure, accumulated knowledge and current supply chains can be reused or adapted relatively easily, thereby reducing development times and initial costs.

Hydrogen has specific **physicochemical properties** that profoundly **influence its behaviour** as a fuel in internal combustion engines:

- **Wide flammability range**. Hydrogen can ignite in air mixtures ranging from approximately **4% to 75% by volume** - a significantly higher range than that of hydrocarbon fuels. This feature enables the engine to operate with **lean mixtures**, i.e. with a relatively low hydrogen-to-air ratio, which can improve efficiency and reduce the average combustion temperature.

- **High flame propagation speed**. The hydrogen flame spreads faster than that of conventional fossil fuels, promoting rapid and potentially more complete combustion. However, this same property increases the risk of undesirable phenomena such as **pre-ignition** or **flashback** towards the inlet.
- **Low volumetric energy content**. Although hydrogen has a high specific energy per unit mass, its **density is very low**. This means that equivalent energy storage requires high-pressure or liquid storage systems, which has direct implications for vehicle and fuel system design.
- **Environmental aspects**. Since hydrogen contains no carbon, its combustion **does not produce CO_2**. However, the high temperatures that can be reached during the process favour the formation of **nitrogen oxides (NO_x)**. Nevertheless, recent studies suggest that these emissions can be significantly reduced through effective combustion strategies and after-treatment systems. In particular, it has been reported that the gross NOx emissions of an H_2-ICE engine can be approximately **an order of magnitude lower** than those of a conventional diesel engine and that levels **close to zero** can be achieved with the incorporation of specific control systems. [1]

2.2.2. H_2-ICE engine types

Within the scope of H_2-ICE engines, different types can be distinguished depending on the ignition system and the original engine design.

2.2.2.1 H_2-ICE engine types by ignition system

This first classification is based on the **mechanism** by which the **combustion** of the air-hydrogen mixture inside the cylinder is **initiated** .

a) Spark Ignition Engines (SIE)

The **spark ignition engines** are the most widespread and technologically mature configuration. In these engines, which are based on the **Otto** thermodynamic cycle, the air-hydrogen mixture is introduced into the cylinder during the intake phase, compressed, and then ignited by a spark generated by a spark plug.

The introduction of hydrogen into the cylinder can be accomplished by different **injection strategies,** (Figure 4):

- **Port Fuel Injection (PFI).** It is one of the simplest systems. In this system, the injectors are located in the intake manifold close to the inlet valve, so that the hydrogen mixes with the air before entering the cylinder. This configuration is suitable for **dual-fuel** engines, where hydrogen is supplied through the intake and combined with an additional fuel injected directly into the cylinder (petrol, diesel, natural gas).
- **Direct injection** (**DI**). Hydrogen is injected directly into the combustion chamber. This architecture reduces the risk of flashback, enables more precise mixture formation and improves specific power, while also providing better control of pre-ignition phenomena. It enables more precise control of the mixture and can contribute to improved engine specific power. This system achieves high efficiency and a significant reduction in emissions.

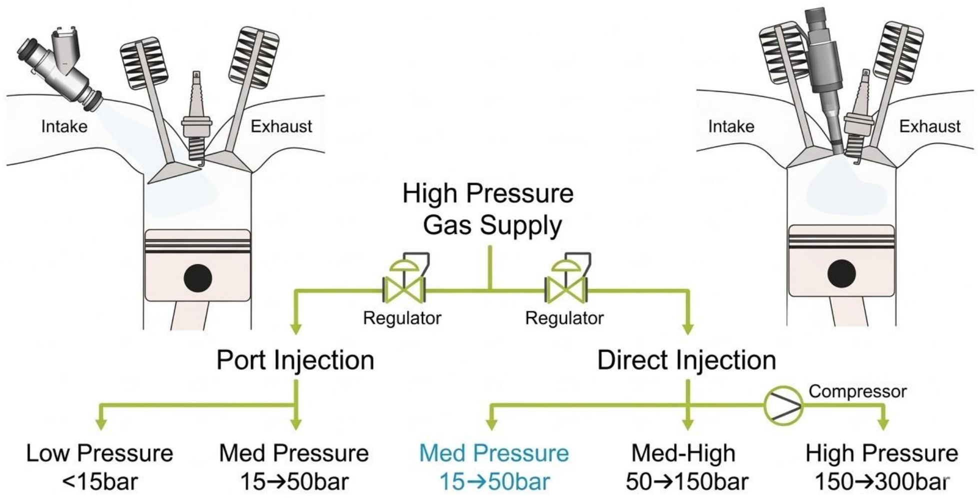


Figure 4. *Indirect (PFI) and direct (DI) injection technology.* [2]

The **spark-ignition engines** are **highly compatible** with existing petrol engine platforms, facilitating their development and reducing the associated costs of technological transition.

One of the main **advantages** of hydrogen-fuelled spark ignition engines is the ability to operate with **very lean mixtures**. **Excess air reduces the combustion temperature** and therefore **limits** the formation of NO_x, whilst improving the engine's thermal efficiency.

However, using **hydrogen** also introduces a number of technical **challenges**:

- A lean mixture means a **lower fuel input** to the engine combustion chamber, resulting in reduced power output. This can be alleviated by using a **greater degree of supercharging**, although the necessary energy is not always present in the exhaust gases to achieve the required turbocharging. Combining these systems with electric supercharging systems increases power output, though this reduces effective efficiency.

- **Pre-ignition must be controlled** to avoid the formation of hot spots within the cylinder, which can occur due to the low ignition energy of hydrogen. Backfire towards the intake system must also be prevented (this is more easily controlled in the case of direct injection). Furthermore, while the efficiency of these engines may be high in the context of thermal engines, it is still lower than that achieved by fuel-cell-based systems.

b) Compression-ignition engines (dual-fuel or H_2-CI)

Another possible configuration is **compression ignition engines** operating in **dual-fuel mode**. In these systems, hydrogen acts as the main fuel, but combustion is initiated by injecting a small amount of **pilot fuel** (diesel or synthetic fuel) representing up to 5% of the total energy input. The pilot fuel self-ignites due to the high compression ratio characteristic of diesel engines and generates the flame front necessary to initiate the combustion of hydrogen in the chamber. Although this solution is less common than spark ignition, it has attracted considerable interest in **heavy-duty transport** applications.

The main **advantage** of the **dual-fuel engines** lies in their ability to **utilise existing** robust, high-efficiency **diesel engine** platforms with a high capacity to generate torque at low engine speeds, *Figure* 5 and *Figure 6*. These characteristics are particularly valuable in applications such as freight transport or industrial machinery.

However, this architecture also has some **important limitations**:

- The use of a pilot fuel implies carbon emissions from the vehicle. Nevertheless, high-pressure direct injection technology is capable of replacing 95% of diesel with hydrogen and is therefore classified as zero-emission under current European regulations.
- **Combustion control** is also more **complex** as the injection of both fuels needs to be properly coordinated to ensure stable and efficient combustion.

Figure 5. Truck with HPDI technology.

Figure 6. Truck developed by EVARM with a dual-fuel system used in the Dakar Rally. Source: EVARM.

2.2.2.2 H_2-ICE engine types according to original engine design

Another way of classifying H_2-ICE engines is to analyse whether the engine **design** is **specifically** intended for **hydrogen** operation, or if it is an **adaptation** of an existing design.

- **Dedicated hydrogen engines**. Their geometric design and materials are optimised from the outset to take advantage of the particular properties of this fuel. This may involve specific compression ratios, adapted valve configurations, or materials that can better withstand the thermal and chemical conditions associated with hydrogen combustion.
- **Adapted engines or retrofitting**. The aim is to modify existing engines so that they can use hydrogen as a fuel, either partially or fully. This approach is particularly attractive from

an economic and logistical point of view, as it enables the use of existing equipment and platforms. There are several possible conversion strategies. For example, an engine originally designed for natural gas can be adapted to run on a mixture of natural gas and hydrogen. Similarly, a diesel engine can be converted into a dual-fuel system that uses a mixture of hydrogen and a small amount of diesel as a pilot fuel. In some cases, it is even possible to convert an engine to run on hydrogen alone.

2.2.3. Typical H_2-ICE applications in land mobility

H_2-ICE engines are emerging as a **transitional** or complementary **solution** in the **decarbonisation** of land transport. Although fuel cells and battery electric systems are often considered the most promising technologies in the long term, hydrogen combustion engines offer significant advantages in certain niche applications.

2.2.3.1 Heavy transport and machinery

One area where this technology is particularly attractive is **heavy-duty transport and industrial machinery**. Vehicles such as construction trucks and machinery, as well as heavy-duty industrial equipment, require robust propulsion systems capable of operating for extended periods under challenging conditions.

In these contexts, the **mechanical robustness** of internal combustion engines constitutes a significant advantage. Furthermore, **integrating** H_2-ICE engines into **existing platforms** is relatively straightforward, **reducing** both **development time** and **upfront costs**.

Compared to fuel cell-based systems, which require more complex and costly components, **hydrogen combustion engines** can **offer** a **more economical solution** at certain stages of the energy transition.

2.2.3.2 Off-road applications and controlled environments

Another important application area relates to **off-road environments** and **sectors** where **vehicles operate** in relatively **controlled areas**. Activities such as agriculture, mining and construction often take place in specific locations where refuelling infrastructure is designed specifically for that purpose.

In these cases, the **availability of hydrogen refuelling stations** does **not** depend on an **extensive public network**, thereby **facilitating** the **early adoption** of this technology. Moreover, the dominant criterion in these sectors is often the total cost of ownership (TCO), which includes both the initial investment and the operating costs over the equipment's lifetime.

If H_2-ICE engines can reduce carbon emissions without significantly increasing these costs, they may be particularly attractive.

2.2.3.3 *Existing fleets and technology transition*

Hydrogen combustion engines could play a significant role in the technological transition of **existing fleets**. Many transport companies and operators have large fleets of vehicles equipped with conventional internal combustion engines. **Converting or adapting** these engines to use hydrogen offers a relatively rapid means of reducing carbon dioxide emissions, without requiring complete vehicle replacement or redesign of the propulsion architecture.

Additionally, this strategy enables the **utilisation of existing supply chains**, **manufacturing** processes, and decades of accumulated experience in thermal engine development.

The following are some of the **advantages** of alternative internal combustion engines that use hydrogen as fuel in the mobility applications.

- An ICE is used, with consolidated experience in Europe in the use of other fuels.
- Various fuel options: Pure H_2 or in combination with natural gas and diesel, etc.
- Lower hydrogen purity requirements than those of fuel cells.
- CO_2 reduction proportional to the equivalent energy fraction provided by H_2.
- Adaptability of existing internal combustion engines (petrol, natural gas, diesel)
- Lower cost of vehicles (new or retrofitted) compared to fuel cell vehicles.
- Generation of short-term demand for hydrogen, thereby enabling the deployment of hydrogen production, distribution and supply systems.

At the same time, however, hydrogen internal combustion engines have certain **limitations:**

- Lower on-board energy efficiency (higher H_2 consumption) compared to fuel cells.
- Limited commercial availability for trucks: rigids, tractor units, off-road.
- There is a need to extend the availability of specific components for H_2 operation, such as spark plugs, injectors, tanks, advanced boosting systems and exhaust after-treatment systems.

Overall, **H_2-ICE** engines represent a technological alternative that **combines continuity** and **innovation**. While their theoretical efficiency does not rival that of other hydrogen-based solutions, their compatibility with existing technologies and their adaptability to multiple applications make them a relevant option in the current sustainable mobility landscape. In particular, their ability to integrate into sectors where direct electrification is more challenging suggests that these engines could play a significant role in the intermediate stages of the decarbonisation of transport.

2.3. FC vs H_2-ICE technology comparison (conceptual synthesis)

The technological comparison between **fuel cell** (FC) systems and **hydrogen-fuelled internal combustion engines** (H_2-ICE) is central to assessing the different trajectories of hydrogen deployment in land mobility.

While both options reduce dependence on fossil fuels, they differ significantly in some respects, as reflected in Table 3.

Table 3. Comparison of fuel cell technology vs H2-ICE

Aspect	Fuel cells	H2-ICE
Energy conversion	Electrochemistry	Thermochemistry
Efficiency	High	Medium / High
Local emissions	Zero	NO_x (controllable)
Initial cost	High	Moderate
Optimal applications	Heavy transport, fleets	Off road applications, transition technologies

When comparing fuel cells and hydrogen-fuelled internal combustion engines, it is important to consider not only average efficiency, but also the load profile of the application. While fuel cells are most advantageous in variable or partial-load applications, H_2-ICE engines perform relatively better under sustained high-load conditions, approaching and even surpassing fuel cells in certain intensive applications such as construction machinery, mining and industrial processes. This reinforces the idea that the two technologies do not follow the same operational pattern, and that their suitability depends largely on the mission type, operating regime, and continuous power requirement.

A comparison of the two technologies must also consider other systemic and operational factors. Firstly, H_2-ICE engines tolerate lower purity hydrogen better than fuel cells do. This could have economic implications for the supply chain. However, this difference is not neutral: a system designed to supply engines with lower purity standards may not be suitable for fuel cell vehicles, thereby affecting the interoperability of the ecosystem.

Secondly, the lower efficiency of H_2-ICE penalises not only specific hydrogen consumption but also requires a higher on-board storage capacity to achieve an equivalent range. This has the potential to impact tank sizing, occupied volume and available payload.

Finally, combustion engines have a better-known and more predictable degradation trajectory in terms of efficiency over their lifetime. In contrast, fuel cells may require stack refurbishment, which is a particularly relevant aspect for fleets with intensive use or long operating cycles. Taken together, these factors reinforce the complementary nature of both technologies and justify evaluating them based on specific use cases rather than making a simplified comparison based solely on nominal efficiency[1].

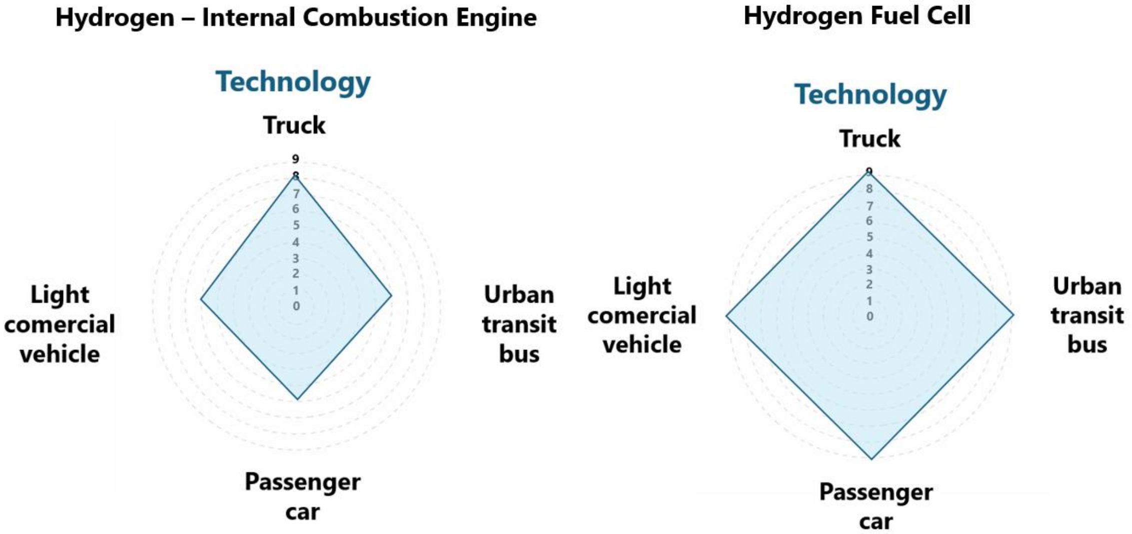
2.4. Technology Readiness Level of the different technologies

The maturity of the different technologies associated with hydrogen-based mobility can be assessed using the **TRL (Technology Readiness Level)** indicator, which is widely used to determine the level of development and proximity to commercial deployment of a technology. This scale, ranging from **TRL 1** (basic principles observed) to **TRL 9** (system tested under real operating conditions), enables a homogeneous comparison of the development stage of different technological solutions.

This section analyses the Technology Readiness Level of the main hydrogen-based propulsion technologies for land transport, namely **fuel cells** and the **hydrogen-fuelled internal combustion engine**. The analysis is performed for different vehicle types, including passenger cars, light commercial vehicles, urban transit buses and trucks.

The TRL values have been obtained from the technology database developed by the International Energy Agency (IEA) [3], (Figure 7). For **internal combustion engines**, the highest level of maturity is observed in **trucks**, where the technology reaches **TRL 8**. For the other categories, the technology has slightly lower levels of maturity.

Fuel cell technology shows a homogeneous level of maturity across the different vehicle types, with all segments at **TRL 9**. This indicates that the **technology** is **fully proven** in a real operating environment and is already present in commercial applications.



Hydrogen – Internal Combustion Engine

Hydrogen Fuel Cell

Figure 7. Maturity level of the various technologies. Source: IEA [3]

These results suggest that fuel cell technology has now reached full technological maturity in land mobility. Meanwhile, hydrogen-fuelled internal combustion engines are moving towards full commercial validation, particularly in heavy-duty transport applications. Both solutions have considerable development potential and can play complementary roles in decarbonising transport depending on operational needs, associated costs, and the development of hydrogen supply infrastructure.

Recent evidence from projects and deployments supports this interpretation of technological maturity. In the case of **fuel cells**, developments are no longer limited to isolated prototypes but are supported by commercial demonstrations and the first operational fleets, as well as projects aimed at the industrialisation of components. In Europe, projects such as **H2Haul**[4] constitute a particularly significant reference, as they involve the development and demonstration of **16 heavy-duty trucks weighing between 26 and 44 tonnes** in real-world commercial operations. These vehicles are adapted to the needs of the European market and are supported by high-capacity refuelling stations. Furthermore, by 2025, the consortium had completed the construction of its **12 Iveco vehicles**, and **more than 15,000 km** had already been accumulated during validation and compatibility tests with the project’s refuelling stations. Another significant initiative is the **H2Accelerate TRUCKS**[5], a large-scale European initiative funded with approximately **€30 million** by the Clean Hydrogen Partnership, which aims to deploy **125 hydrogen-powered trucks** weighing between **41 and 44 tonnes** across **six European countries** by 2030, thereby contributing to the transition from demonstration to pre-commercial deployment. Another notable initiative is the Swiss ecosystem developed by **Hydrospider** [6], which focuses on the production and distribution of **green hydrogen** for heavy-duty transport and is structured around a real value chain connecting renewable energy generation, supply, and fleet operations. This model has helped consolidate particularly valuable experience in hydrogen-powered heavy mobility in Switzerland, supported by an operational national refuelling network. In parallel, maturity of the technological ecosystem is reinforced through projects such as **StasHH**[7], which focuses on the development of an **open European standard for heavy-duty fuel cell modules** in terms of size, interfaces, control and testing protocols, and **IMMORTAL**[8], which is focused on the development of **high-power-density, durable membrane electrode assemblies (MEAs)** for heavy-duty applications.

Outside Europe, the maturity of fuel cell technology is also supported by recent advances in scale and real-world operation. In **China**, at the end of **2025** there were **almost 40,000 fuel cell vehicles**, confirming the existence of a significant installed base for their deployment [9]. In **South Korea**, Hyundai has reinforced this trend with its **XCIENT Fuel Cell** heavy-duty truck programme, which had surpassed **20 million cumulative kilometres in Europe** by January **2026**, evidencing a significant degree of operational validation [10]. In **Japan**, consolidation is reflected in industrial policy and technological developments: Toyota introduced its **third-generation** fuel cell system for commercial applications, and together with Isuzu announced in **2026** the development of the **first mass-produced fuel cell light truck in Japan** [11].

In the field of **hydrogen-powered internal combustion engines (H_2-ICE)**, companies such as **Volvo** began road testing hydrogen-powered heavy trucks in 2026 and are aiming for a commercial launch in Europe by 2030 [12]. **MAN** has taken this a step further with the **MAN hTGX**: a limited series of hydrogen-fuelled heavy-duty trucks that were delivered to customers in several European markets in **2025**. The vehicle has a range of **up to 600 km**, takes **less than 15 minutes to refuel** and has a specific **H45** engine with **520 hp** and **2,500 Nm** [13]**.** In parallel, **Cummins** is developing the value chain of this solution through projects to improve performance and durability, such as **Project Brunel.** In 2025, Cummins introduced **turbochargers specifically designed for on-road H_2-ICE engines**, demonstrating a shift from conceptual adaptation to industrialising dedicated components. [14]. In off-road machinery and applications, **JCB** has developed more than **130 evaluation engines** and obtained **full EU approval** in 2025 for its hydrogen combustion engine, intended for backhoe loaders, telehandlers and generator sets [15]. In the same vein, **DEUTZ** has consolidated its own industrial approach with its **TCG 7.8 H2**, which in **2025** became the **first hydrogen combustion engine certified according to EU Stage V** and went into **mass production** at its Cologne-Porz plant [16].

3. HYDROGEN STORAGE SYSTEMS IN VEHICLES

The **hydrogen storage system** is a critical component of the architecture of fuel cell electric vehicles (FCEVs) and hydrogen-powered internal combustion engines (H_2-ICE).

Unlike conventional liquid fuels, hydrogen has a **low volumetric energy density** under ambient conditions. This requires the use of storage technology solutions that strike a balance between **autonomy, safety, mass, cost, and vehicle integration**.

The Figure 8 shows the energy density of various ways of storing hydrogen for later use. Table 4 shows the difference in energy density (calorific value) of the main fuels used in mobility and that of hydrogen. As a mass-based reference, all hydrogen storage systems have the same energy content, regardless of their physical state.

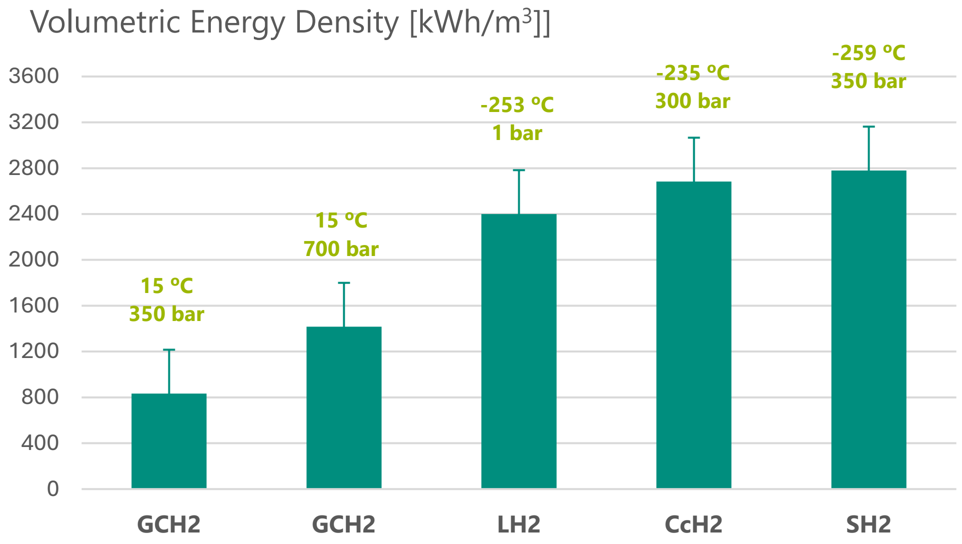


Figure 8. Volumetric energy density of different forms of hydrogen storage.

Table 4. Calorific value of conventional fuels vs Hydrogen *[17]*.

Fuel	Lower calorific value (MJ/kg)
Petrol	43.2
Diesel	43.1
Synthetic diesel (FT/HVO)	44
H_2	120

In vehicular applications, hydrogen is primarily stored as a **compressed gas** or **liquefied hydrogen.** There are also emerging storage technologies, such as cryo-compressed storage, metal hydrides, liquid organic hydrogen carriers (LOHCs) and adsorbents, which are in the early stages of development or have a more limited degree of maturity

3.1. General requirements for hydrogen vehicle storage

Automotive hydrogen storage systems must meet the following requirements simultaneously:

- High gravimetric and volumetric energy density to maximise autonomy.
- Intrinsic and functional safety, guaranteeing resistance to impact, overpressure and leakage, with controlled failure modes.
- Compatibility with rapid refuelling cycles, withstanding repeated pressurisation cycles and thermal variations without accelerated degradation.
- Structural durability, with resistance to fatigue, vibration and environmental conditions (temperature, humidity, corrosion and embrittlement).
- Integration with the vehicle, including space management, mass distribution and compliance with crash management requirements.
- Compliance with international regulations and type-approval standards applicable to design, materials and safety.

These requirements influence the geometry and composition of the tanks, as well as the auxiliary elements of the system, such as valves, sensors, regulators and thermal protection systems.

3.2. High-pressure gaseous hydrogen storage (cH2)

Compressed gaseous **hydrogen gas** storage is currently the dominant technology for mobility applications. The hydrogen is stored in pressurised tanks and supplied to the propulsion system via a regulation and safety chain.

3.2.1. Storage principle

Hydrogen is stored in a gaseous state in **pressurised tanks**. The hydrogen supply to the vehicle during refuelling is based on the **pressure difference** between the station’s storage system and the vehicle’s tank. Typical pressures in land transport are:

- **350 bar**. Typical in **heavy transport**, bus and industrial applications.
- **700 bar**. Standard in **light vehicles**, with a growing trend towards use in heavy transport to provide longer ranges.

3.2.2. Types of pressurised tanks

Four types of tanks are currently used, classified according to the materials used and the storage pressure, as shown in Table 5. A fifth type is under development, which aims to combine the advantages of Types III and IV.

Table 5. Types of compressed hydrogen tanks (Lean Hydrogen, 2025). *[18]*.

Type	**Main material**	**Maximum pressure (bar)**	**Energy density (kWh/kg)**	**Typical application**	**ISO standard**
I	Steel or aluminium (100% metal)	200-250	~0.5	Refuelling stations	ISO 9809 [19]
II.	Metallic tank with partial fibreglass/carbon-fibre wrap	1,000	~0.9	Refuelling stations	ISO 11119-1 [20]
III	Metallic liner (aluminium) + full carbon-fibre wrap	700	~1.5	Heavy-duty mobility, trains, refuelling stations	ISO 11119-2 [21]
IV	Polymeric liner + full carbon-fibre wrap	700	~2	Passenger cars, buses and trucks, refuelling stations	ISO 11119-3 [22]
V	(Under development)	>700	>2	Future: aviation, drones…	Under development

Type IV tanks are currently the most widely used in the automotive sector due to their **low mass**, high mechanical resistance and favourable integration characteristics. However, their cost is directly linked to the carbon fibre material costs, the filament-winding processes and quality-control requirements.

3.2.3. In-vehicle storage system components

A complete high-pressure storage system includes, in addition to the **tank** itself, a range of safety and control components, as shown in Figure 9. These components ensure safe operation under a wide range of operating conditions. They include:

- Automatic shut-off valves
- Thermally activated Pressure Relief Devices (TPRD)
- Pressure and temperature sensors

- Regulators and high-pressure lines
- Leak detection systems
- Communication systems for interaction with the refuelling station
- Hydrogen storage control unit (HSCU)

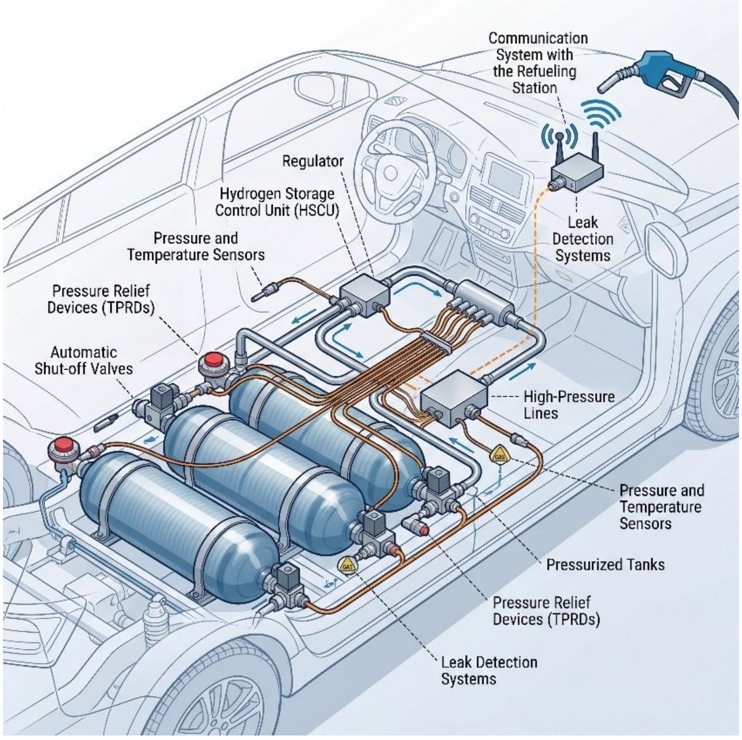


Figure 9. Storage system components. Source: Own elaboration

3.2.4. Safety of high-pressure storage in vehicles

Safety is a central aspect addressed both through intrinsic **design** measures and through **functional** safety systems. For type-approval purposes, these systems must pass stringent tests to verify their structural integrity and performance under adverse conditions:

- Impact and puncture resistance (individual tests and vehicle crash tests). Controlled shocks are applied to the tank to check for leaks, after which a penetrating impact is simulated to verify that it does not fail explosively.
- Fire tests. These tests are intended to assess the tank’s integrity over a specified period of time, ensuring that the relief devices operate correctly and that hydrogen is being released safely.
- Pressure cycle fatigue testing. Several filling and emptying cycles are reproduced to check that the material and joints do not develop cracks or structural degradation.

- Ventilation management and pressure relief routing to avoid dangerous build-up. Analysis of how hydrogen disperses in the event of an unplanned release.

The systems are designed to **fail in a controlled manner** by releasing hydrogen vertically, thus avoiding build-up that could lead to explosive mixtures.

3.2.5. Advantages and limitations

The main **advantages** of high-pressure hydrogen gas storage include:

- Mature, certified and commercially established technology
- Fast refuelling, comparable to conventional liquid fuels
- Flexibility of integration into different vehicle platforms

At the same time, high-pressure gaseous hydrogen storage also presents several **limitations**:

- Low volumetric energy density even at 700 bar, resulting in larger storage volumes than liquid fuels
- High cost of composite materials and tank manufacturing
- Impact on vehicle chassis design and vehicle packaging (with the added need to protect tanks and lines from shocks).

3.3. Liquid hydrogen storage (LH_2)

Liquefied hydrogen storage is an alternative to storage in the form of compressed gas.

3.3.1. Principle of cryogenic storage

Hydrogen is cooled to cryogenic temperatures, close to its boiling point (**-253°C** at 1 bar pressure), which **significantly increases** its **volumetric density** compared to compressed gas. This reduces the required storage volume for the same amount of stored energy. However, it requires the use of tanks with a high degree of thermal insulation, as well as energy consumption in the liquefaction process close to 30% of the energy content of the hydrogen itself with current technology [23].

Liquefied hydrogen storage involves considerable technical **complexity**. Cryogenic **tanks** require advanced **thermal-insulation** systems to minimise boil-off losses and ensure system safety. These tanks are expensive, increase the weight of the vehicle, and require specific infrastructure for refuelling and onboard fuel handling.

Although the **design pressure** of the tank can be as high as 4 or even 8.5 bar to handle the pressure increase resulting from the boil-off of the liquid hydrogen due to external heat input, the hydrogen must be maintained at near atmospheric pressure.

3.3.2. Technical specifications

- The **cryogenic vessels** consist of an **inner tank** and an **outer tank**, with a vacuum and insulating material between them to minimise external heat input that could cause hydrogen boil-off.
- **Boil-off management**: the external heat causes the progressive vaporisation of the LH_2, raising the internal pressure.
- Specific **venting, relief and safety systems** are required, along with defined strategies to limit losses and maintain safe operating conditions within the tank.

3.3.3. Advantages and limitations

Some **advantages** of liquid hydrogen storage are listed below:

- High volumetric energy density
- Longer ranges, particularly for heavy-duty transport

At the same time, liquid hydrogen storage has some **limitations**:

- High technical complexity
- Boil-off losses
- Limited refuelling infrastructure
- High energy costs associated with liquefaction

As an **emerging technology**, its commercial deployment is limited to long-haul pilot projects.

3.3.4. Subcooled storage

One variant of liquid hydrogen is subcooled storage, which consists of keeping hydrogen in a liquid state at a temperature **lower than its normal boiling point** (≈20.3 K at 1 bar), but **without solidifying it**. When subcooled, liquid hydrogen **increases its density** and **reduces its vapour pressure**, making it possible to store slightly more mass in the same volume and reduce boil-off compared to conventional liquid hydrogen. Some tests indicate density increases of 7–10% when operating below the normal boiling point. However, this solution requires additional cooling, highly demanding thermal insulation and increased system complexity.

3.4. Cryo-compressed storage

Another alternative for hydrogen storage is to combine **low temperatures** (cryogenic conditions) and **high pressure** to achieve a higher energy density than either liquid hydrogen or compressed gaseous hydrogen separately.

Cryo-compressed storage combines moderate cryogenic temperatures and high pressures (≈300 bar, ≈38 K (-215 ºC), achieving densities of approximately 80 g/L, compared with around 70 g/L for liquid hydrogen.

This technology is still under **development**.

3.5. Solid-state hydrogen storage

The most developed method of storing hydrogen in **solid materials** is currently based on **metal hydrides**. This is a well-established technological solution from a scientific point of view. However, its adoption in both light and heavy mobility applications remains limited.

They are mainly used in specific niches, such as certain micromobility solutions (e.g. hydrogen-powered bicycles), where the requirements for range, weight, and operating dynamics are less demanding.

From a technical perspective, metal hydrides offer several **advantages**:

- High volumetric storage density, which can reach values comparable to those of compressed hydrogen at pressures of around 1,000 bar.
- They also offer a high level of intrinsic safety, as hydrogen is stored in solid form within the crystal lattice of the material and operates at relatively low pressures (typically below 35 bar under operating conditions and significantly lower when at rest) [24]. This feature significantly reduces the risks associated with leakage or structural failure compared to high-pressure storage systems.

However, there are **structural limitations** that affect their competitiveness in mobile applications:

- The low gravimetric density of the hydrogen in the alloys (typically around 1.5% by weight) means that there is a significant mass penalty for the system. In practical terms, storing 1 kg of hydrogen may require systems weighing around 100 kg, which is incompatible with the efficiency and payload requirements of most vehicles.

- Thermal management of the system is also a significant challenge. The hydrogen absorption process in metal hydride is exothermic, while desorption is endothermic. This means that heat must be supplied to the system during unloading to ensure adequate hydrogen flow rates, particularly in applications demanding high delivery rates or high outlet line pressures. This requirement introduces additional complexity to system design, both in terms of both thermal integration and operational control.

Consequently, **metal hydrides are not** currently considered to be a **competitive solution** for **on-board storage** in **road vehicles**. Instead, technologies such as high-pressure compressed hydrogen (350 or 700 bar) dominate industrial development in mobility applications.

3.6. In-vehicle storage integration

Integrating hydrogen storage into land vehicles is critical for the design, as it affects **mass distribution, centre of gravity, usable space and chassis architecture**.

In the case of **compressed hydrogen**, high-pressure vessels occupy significant volume, so their location must be determined in conjunction with safety, ventilation and system robustness requirements:

- In **passenger cars**, the tanks are usually integrated into low areas of the bodywork, especially **under the floor**, to reduce the centre of gravity and limit the loss of habitability and load volume. A representative example is the **Toyota Mirai**, whose official technical documentation [25] indicates that the tanks are arranged in a 'T' configuration, with a main tank under the floor and others located under the rear seats and luggage area; Toyota further notes that this arrangement contributes to a lower centre of gravity and avoids compromising usable space. 700 bar tanks, volume focus and passive safety are employed.
- In **urban buses**, the most common configuration is to install **roof-mounted tanks**, as this solution preserves the low floor and does not reduce passenger space. This can be seen on buses such as the **Solaris Urbino 12 hydrogen** [26]. As with goods vehicles, 350 bar tanks are often used. In trucks, tank integration varies, with tanks located at the rear of the cab and/or on the chassis itself.

3.7. Regulations and approvals

Hydrogen storage in vehicles is regulated by **international standards**. The main ones are listed below:

- **UNECE R134**: specific requirements for hydrogen storage systems [27]. It sets requirements for the vehicle fuel system, including the compressed storage system, piping, joints and components in the presence of hydrogen.
- **ISO 19881**: focused on gaseous hydrogen tanks [28]
- **ISO 11114**: related to hydrogen compatible materials [20] [21]
- **European vehicle type-approval regulations** [29]

Compliance with these standards is mandatory for the **registration and placing on the market** of hydrogen vehicles.

3.8. Trends and development paths

In-vehicle hydrogen storage is still in its early stages. Some of the technological trends and developments in this area are listed below:

- Increase the use of carbon fibre
- Multi-cell design optimisation
- Structural integration of tanks
- Implementation of above-standard storage at 700 bar for heavy-duty transport.
- Development of LH_2 for heavy-duty transport.
- Hybrid solid storage research

4. HYDROGEN REFUELLING TECHNOLOGIES

The **hydrogen refuelling** process connects **production** and **storage** to **end use** in the vehicle. It directly affects the user experience, the operational availability of fleets, and the economic viability of hydrogen mobility. From a value chain perspective, the refuelling station acts as an interface between hydrogen production, conditioning, transport and storage infrastructure, and different demand vectors (e.g. cars, buses, trucks and trains).

The **design of the refuelling station** critically influences parameters such as vehicle refuelling time, dispensing capacity (kg/h), system energy efficiency and operational availability. These parameters are particularly relevant in heavy-duty applications.

Depending on the form of hydrogen supply to the station and the type of hydrogen to be supplied to vehicles, three main configurations of **hydrogen refuelling technologies** can be distinguished:

- **Compressed hydrogen** refuelling stations fuelled with **hydrogen gas**.

  ($cH_2 \rightarrow cH_2$)
- Refuelling stations for **compressed hydrogen** fuelled with **liquid hydrogen** ($LH_2 \rightarrow cH_2$)
- Refuelling stations for **liquid** `on-board’ ($LH_2 \rightarrow LH_2$)

Regarding the last of these, historical hydrogen refuelling solutions exist, but current technological development and standardisation work is mostly oriented towards **subcooled liquid hydrogen** (sLH_2) architectures stored on-board the vehicle especially for long-haul heavy-duty transport applications. sLH_2 systems reduce boil-off, improve the stability of the filling process and enable high flow rates compatible with heavy-duty transport applications.

The Figure 10 schematically shows the **primary technological architectures** of hydrogen refuelling stations as a function of the hydrogen status along the station-vehicle chain. The following are distinguished: gaseous hydrogen-based solutions; liquid hydrogen-based solutions used for gaseous refuelling logistics; and liquid refuelling solutions for vehicles with on-board cryogenic storage.

Figure 10. Hydrogen refuelling station architectures according to fuel state: Source: Linde, 2026

4.1. Gaseous hydrogen-fuelled cH2 stations ($cH_2 \rightarrow cH_2$)

Compressed **hydrogen** (cH2) is the **most widespread option** in refuelling stations for road mobility, both in light-duty vehicles and heavy-duty transport applications. The hydrogen is **delivered to the vehicle at high pressure** (350 bar or 700 bar), following standardised protocols that guarantee safe operation and filling times comparable to conventional fuels.

This configuration is the most mature and commercially widespread solution, particularly in the **early stages of infrastructure deployment**, due to its direct compatibility with most vehicles currently in operation.

In a cH_2 station fuelled with gaseous hydrogen, the hydrogen arrives in a gaseous state. This can be from an on-site electrolyser, via a connection to a transport or distribution network, or via elements that enable hydrogen to be transported by road at high pressure, such as cylinder blocks, *semi-trailers* or *tube trailers*.

The heart of the station is the **high-pressure compression system**, which raises the hydrogen receiving pressure to the levels required for storage and subsequent dispensing. The most common compression technologies are piston compressors, membrane compressors, and more recently, ionic liquid and electrochemical compressors. Each technology has different trade-offs in terms of efficiency, maintenance, and cost. Commercial, state-of-the-art ionic liquid compressor systems (such as those from Linde) can compress hydrogen at output pressures of up to 900 bar, with specific consumption rates of around 0.5–3.3 kWh/kg, depending on the inlet pressure.

After compression, the **hydrogen is stored** in high-pressure cylinder blocks organised by pressure range or stage. Vehicles are supplied by transferring the already compressed and stored hydrogen in the station's cylinder blocks to the vehicle's tank via a simple pressure differential. Storing the compressed hydrogen enables fast refuelling without overloading the compressor in real time. This storage scheme is essential for decoupling compression from the refuelling process, which allows for a reduction in installed compression power and an improved response to peak demand. Additionally, using different pressure ranges or stages for storage and sequentially managing them during supply increases the efficiency of the entire compression and refuelling process. Vehicles are supplied with **compressed hydrogen gas** through dispensers equipped with standardised hoses and nozzles, certified metering systems, and temperature control to ensure compliance with filling protocols (H35/H70[1]).

As will be discussed in more detail later, to maintain safe operations and increase refuelling speed, **hydrogen refuelling stations** tend to install **cooling** units that allow the gas to be pre-cooled to temperatures of around -40°C before the dispenser. This is to meet the in-tank temperature limits defined by international protocols[2].

The systems that make up an installation of this type are:

4.1.1. Hydrogen supply to the station

The choice of **supply mode** influences station design, particularly with regard to inlet pressure, supply continuity and operational costs:

- **In-situ electrolysis**: it generates hydrogen at low pressure, requiring higher compression
- **Transport or distribution pipeline**: it is a continuous and stable supply.
- **Tube-trailers**: a flexible supply, pressures typically higher than electrolyser and pipeline pressures, but dependent on external logistics

In all cases, a **regulation** and **conditioning** system is required to adapt the inlet pressure to the compression system.

4.1.2. Hydrogen compression system

The **compression system** consists of one or more compressors which raise the pressure of the hydrogen from the supply to the defined storage pressure in the hydrogen storage system.

The most commonly used compressors for this type of application are:

- **Piston:** mature, robust, widely available technology

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[1] H35 refers to a hydrogen supply pressure of 35 MPa/350 bar. H70 refers to a hydrogen supply pressure of 70 MPa/700 bar[32].

[2] Unlike most gases, hydrogen heats up as its pressure decreases.

- **Membrane**: high purity and gas tightness, suitable for mobility
- **Ionic liquid**: an emerging technology with reduced mechanical wear, as well as improvements in efficiency and operation, especially in on-site production configurations.
- **Electrochemical compressor:** another emerging technology that also offers lower mechanical wear and improvements in efficiency and operation.

The characteristics of the different compression technologies are summarised in Table 6 from technical industry sources, including NREL studies [30] and industry literature.

Table 6. Characteristics of compression technologies in cH2 refuelling stations.

Technology	Advantages	Limitations	Typical use in HRS
Piston compressor	• Mature and widely available technology • Capable of reaching high pressures • Relatively low capital investment cost • Robust for a wide range of applications	• Increased mechanical wear (numerous moving parts) • Frequent maintenance requirements (valves, seals) • Risk of gas contamination from lubricants • High levels of vibration and noise	• Conventional stations • General purpose applications • Cases with limited CAPEX
Membrane compressor	• High hydrogen purity (no contact with lubricants) • Excellent gas tightness • Suitable for sensitive applications (mobility, high purity H_2) • Good performance at high pressures	• Higher CAPEX cost • Limited flow rate (less suitable for large stations) • Membrane fatigue → requiring periodic maintenance • Mechanical complexity	• High purity HRS • Applications where gas quality is critical • Medium-sized stations

Ionic liquid compressor	• High energy efficiency • Reduced mechanical wear (less friction) • Good high pressure capability • Quieter and more stable operation • Potentially lower OPEX cost	• Less mature technology (more limited operational track record) • Higher CAPEX requirements • Dependence on specific suppliers or proprietary technologies	• Advanced stations • Integration with electrolysis systems (low inlet pressure) • Next generation / high efficiency projects
Electrochemical compressor	• High energy efficiency. • Absence of moving parts. • Integrates hydrogen purification into the process.	• Technology still under development. • Dependence on specific suppliers or proprietary technologies	• High-capacity stations

Due to the flow and power limitations of the compressors, hydrogen cannot be supplied directly from the compressor to the vehicle. Instead, it is supplied via the **buffer storage** system described below. The size of this system depends on the type of hydrogen supplied (350 or 700 bar) and the demand to be met.

4.1.3. Hydrogen storage system.

The **buffer storage system** stores hydrogen at a pressure that enables it to be supplied directly to vehicles by **pressure differential**. There are two maximum working pressure levels for these systems, depending on the pressure of compressed hydrogen to be supplied:

- **Hydrogen supply at 350 bar**: the storage system typically operates at maximum pressures in the range of 450-500 bar.
- **Hydrogen supply at 700 bar**: the storage system typically operates at maximum pressures in the range of 900-1,000 bar.

The hydrogen storage system comprises a set of pressure vessels grouped into banks organised into different pressure levels or stages thereby forming a **cascade storage** system. Typically, two or three pressure levels are used. This strategy of storing hydrogen at different pressure stages increases the efficiency of the station in terms of both CAPEX and OPEX.

On the one hand, cascade storage allows part of the storage system to be designed for pressures below the maximum required thereby improving CAPEX efficiency. On the other hand, the compression system does not need to fill the entire storage capacity at maximum operating pressure thereby improving OPEX efficiency.

Storage sizing is a critical factor as it determines the station’s capacity to accommodate consecutive (back-to-back) refuelling operations and cover peak demand. Furthermore, the storage system has a direct impact on the station's CAPEX of the station and overall operational capacity.

4.1.4. Hydrogen dispenser system

The **hydrogen refuelling system** involves connecting the station’s storage system to the vehicle’s tank to supply hydrogen to vehicles. Since the hydrogen in the storage system is at a higher pressure than that in the vehicle tank, the hydrogen flows by **pressure differential**.

The hydrogen dispenser interfaces between the vehicle and the installation **controlling** the **transfer** of **hydrogen** from the station's storage system to the vehicle tank.

From an operational perspective, the main **parameters to be controlled** are as follows:

- Prevent overfilling of vehicle tanks by ensuring that the vehicle tank filling pressure does not exceed the target pressure (350 bar or 700 bar).
- Prevent the temperature of the hydrogen from exceeding the vehicle tank from rising above tank’s permissible levels limits due to the heating effects of hydrogen generated during refuelling.
- Complete the process in the shortest possible time.

This process is governed by **standardised filling protocols** (such as SAE J2601) [31], which dynamically adjust the supply conditions according to the vehicle tank’s condition. In particular, the dispenser continuously regulates the hydrogen flow rate, pressure and temperature during refuelling to ensure the safety and efficiency of the process.

The ISO 17268[32] family of standards defines the connection geometries (nozzle and receptacle) for 350 and 700 bar pressures, while protocols such as SAE J2601 govern the dynamic filling behaviour for light vehicles and their heavy-duty extensions. In parallel, **new standards** are being developed for high-throughput and dynamic fast refuelling applications, including solutions based on station-to-vehicle communication.

The most common tank filling rate currently achievable is 60 g/s (216 kg/h), but devices capable of supplying hydrogen at higher flow rates of 90–120 g/s already exist, and technologies are under development that will allow flow rates of up to 300 g/s [33] [34]. These flow rates require hydrogen pre-cooling in any case.

Stations must also guarantee the **quality of the hydrogen** supplied in accordance with ISO 14687 [35] or UNE-EN 17124 [36], which implies strict requirements in terms of purity, contaminant control and sampling procedures. Additionally, dispensers incorporate certified metering systems, flow control systems and safety interlocks to ensure interoperability between stations and vehicles from different manufacturers.

4.1.5. Cooling system

Gaseous **hydrogen** behaves differently from other common gases, such as natural gas. The **Joule-Thomson** coefficient of hydrogen is negative at room temperature, meaning that hydrogen heats up during expansion.

During refuelling, hydrogen experiences a temperature increase due to the combined effects of Joule-Thomson expansion and gas compression inside the vehicle tank. The greater the pressure difference between the station's storage system and the vehicle tank, as well as the hydrogen flow rate supplied, the greater the heating effect.

This effect is critical in hydrogen refuelling, as the **hydrogen gas tanks** in vehicles have a temperature limitation (typically 85°C) to ensure their integrity, and the supply process may exceed this temperature if thermal control measures are not applied. Therefore, when refuelling at high pressure (especially 700 bar), it is necessary to **pre-cool the hydrogen** to compensate for the heating that occurs during the process.

This cooling is achieved by means of a **chiller**, comprising an industrial cooling system (down to approximately -40°C) and a heat exchanger to cool the hydrogen before it enters the vehicle. Pre-cooling of hydrogen to around -40°C is standard practice to enable quick and safe refuelling in accordance with operational requirements (e.g. SAE J2601).

This system is particularly critical in **high-capacity stations**, where high refuelling flow rates and high repeatability of operation (back-to-back refuelling) are required. Likewise, the chiller represents one of the main **energy consumption auxiliaries** of the station and affects both the filling time and the capacity for back-to-back refuelling.

Cooling systems based on industrial refrigerants or CO_2 may be used. In certain industrial configurations a cryogenic source already available in the installation (e.g. liquid nitrogen streams) can be used, provided that compliance with the required pre-cooling conditions is ensured.

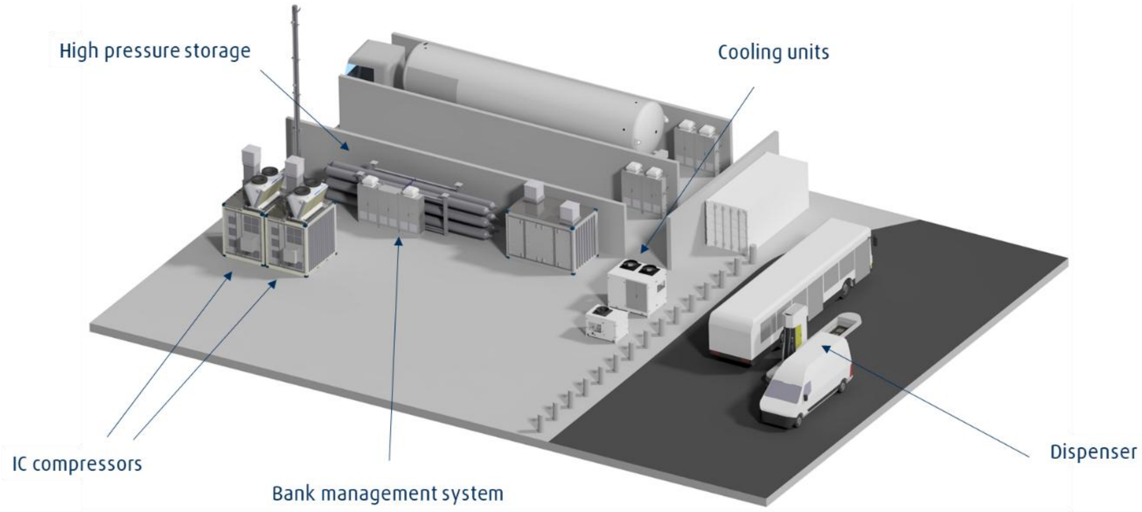


Figure 11. Example of a compression system based on IC90 ionic liquid technology (Source: Linde, 2026). The system integrates an industrial chiller and a heat exchanger for hydrogen pre-cooling the hydrogen prior to refuelling.

4.1.6. Auxiliary systems

The other systems that make up a refuelling station include the electrical and control systems, the air or nitrogen instrumentation systems, and the fire protection and safety systems. Although these elements are not directly part of the refuelling process, they are essential to ensure the safety, reliability, and operational continuity of the station.

The **electrical and control system** integrates:

- Power supply to all main equipment (compression, storage, cooling and dispensing).
- Station automation, monitoring and control systems, enabling safe and efficient operation. This system includes the necessary instrumentation for measuring key variables (pressure, temperature, flow).
- Hydrogen leak detection systems, ventilation and safety interlocks allowing automatic shutdown in case of abnormal conditions.
- Advanced stations are complemented by remote monitoring and diagnostic solutions to facilitate continuous operation and predictive maintenance, maximising the availability of the installation.

The **instrumentation air or nitrogen system** is used for the pneumatic operation of valves and actuators, as well as for inerting equipment and lines. This reduces the risk of flammable mixtures forming during start-up, shut-down or maintenance operations.

Fire protection and safety systems are designed to manage hydrogen-related risk scenarios, including early detection, adequate ventilation, and mitigation measures in accordance with applicable regulations.

4.2. cH2 stations supplied with liquid hydrogen ($LH_2 \rightarrow cH_2$)

In **cH_2 stations supplied with liquid hydrogen**, hydrogen is received as LH_2 in cryogenic tanks at low pressure and cryogenic temperature (approximately -253°C at 1 bar). In this configuration, **liquid hydrogen** primarily acts as a **logistics vector**, enabling large quantities of hydrogen to be supplied to the station with high volumetric energy density.

The supply of cH_2 could involve regasifying and compressing the hydrogen, but one advantage of this form of supply is compressing the hydrogen to the supply pressures in a liquid state.

Unlike stations fuelled with gaseous hydrogen, the pressure rise in cH_2 stations fuelled with liquid hydrogen is achieved by means of a **cryogenic pump** that pressurises the hydrogen in its liquid phase. This is significantly more energy efficient than compressing gaseous hydrogen. Once **pressurised**, the **hydrogen evaporates** and is conditioned for **dispensing** as compressed hydrogen gas to **vehicles**.

This solution combines the **logistical advantages of transporting** and storing **liquid hydrogen** (it has a higher volumetric energy density and can be shipped in large quantities), as well as compressing it, while being **fully compatible with vehicles** that store **hydrogen** in **gaseous** form on board at 350 or 700 bar. Using liquid hydrogen significantly reduces the logistical complexity of station supply, as fewer deliveries are required and high-capacity stations are easier to supply. Additionally, using cryogenic pumping instead of gaseous compression reduces the energy consumption associated with pressure boosting, which is important for high-flow stations.

This architecture is particularly interesting for **high-flow stations** in heavy transport corridors, where cryogenic supply enables large daily consumption to be managed while maintaining the flexibility to refuel fleets of trucks, buses or trains using gaseous storage.

From a design perspective, these stations incorporate cryogenic LH_2 storage tanks, cryogenic pumping systems, vaporisers, and thermal conditioning systems, as well as the cascade storage and dispensing subsystems typical of cH_2 stations. As an example of the technological solutions used in this type of station, Figure 12 shows a cryogenic pumping system used for the pressurisation of liquid hydrogen.

Thus, the $LH_2 \rightarrow cH_2$ architecture can be considered an **evolution of conventional refuelling stations**, aimed at improving the scalability and efficiency of the refuelling infrastructure.

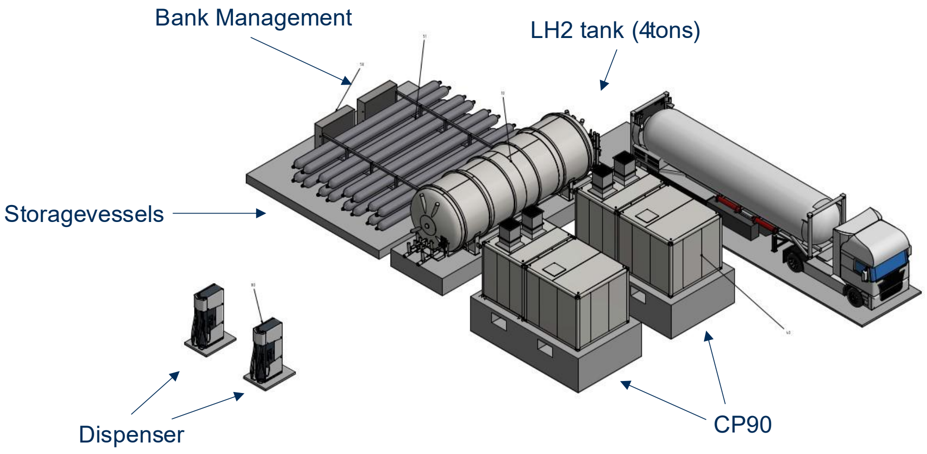


Figure 12. Example of cryogenic pumping system for LH_2 refuelling stations using → cH_2.. Illustrative configuration with two cryogenic pumps, H70 dispensers, a vertical LH_2 tank and high pressure storage. Source: Linde, 2026.

4.3. ‘On-board liquid refuelling stations ($sLH_2 \rightarrow sLH_2$)

On-board liquid refuelling stations are intended for vehicles equipped with **on-board liquid hydrogen storage**, such as certain long-haul trucks and rail applications. In this type of station, hydrogen is stored as liquid hydrogen in cryogenic tanks and supplied to the vehicle whilst remaining in this liquid phase throughout the entire refuelling process.

Although, in principle, liquid refuelling could be performed with hydrogen at near-saturation conditions, industrial practice uses **subcooled liquid hydrogen** (sLH_2), which **improves process stability** and reduces boil-off, enabling more precise filling control. sLH_2 refuelling is typically performed at temperatures in the range of -247 to -253 °C and moderate pressures (≈ 10-20 bar). These conditions are selected to keep the hydrogen in the liquid phase without the presence of a gas phase and to ensure the stability of the filling process.

In these stations the hydrogen is also **stored** as **LH_2** in cryogenic tanks. However, the cryogenic pump raises the pressure and delivers subcooled liquid hydrogen directly to the vehicle's cryogenic tank. The sLH_2 refuelling eliminates the intermediate gas phase stage, which differentiates this architecture from $LH_2 \rightarrow cH_2$ stations, reducing energy losses associated with vaporisation and **simplifying the hydrogen conditioning chain** .

This approach allows **very high refuelling flow rates** (hundreds of kilograms per hour) with refuelling times of 10-15 minutes, comparable to conventional fuels. This facilitates long ranges and high utilisation factors for heavy transport. However, it requires an **advanced cryogenic system design** to minimise boil-off, and to optimise energy efficiency.

The high volumetric energy density of liquid hydrogen maximises vehicle range, thereby reducing the frequency of refuelling and improving the operational efficiency of fleets.

From a station perspective, the absence of gaseous compression and deep cooling stages reduces the process's specific energy consumption (by around 0.05 kWh/kg of hydrogen dispensed), which is a **potential advantage** over cH_2-based architectures.

However, this configuration requires an advanced cryogenic system management approach, encompassing the control of extremely low temperatures, minimisation of boil-off and design of secure vehicle-to-station interfaces. Furthermore, sLH_2 refuelling introduces new requirements in terms of interface standardisation, filling protocols, and operational validation, all of which are currently under development at an international level.

In terms of deployment, this technology is **still emerging**, with pilot projects and the first commercial deployments underway, but it has significant potential to become a key solution for high-demand heavy mobility applications.

The development of sLH_2 refuelling reflects a trend towards solutions with higher energy density and operational performance for applications where logistical efficiency and autonomy are critical factors.

For the refuelling of **liquid hydrogen**, specific **standards** are **under development**, notably ISO 13984 [37], which defines cryogenic supply components and procedures.

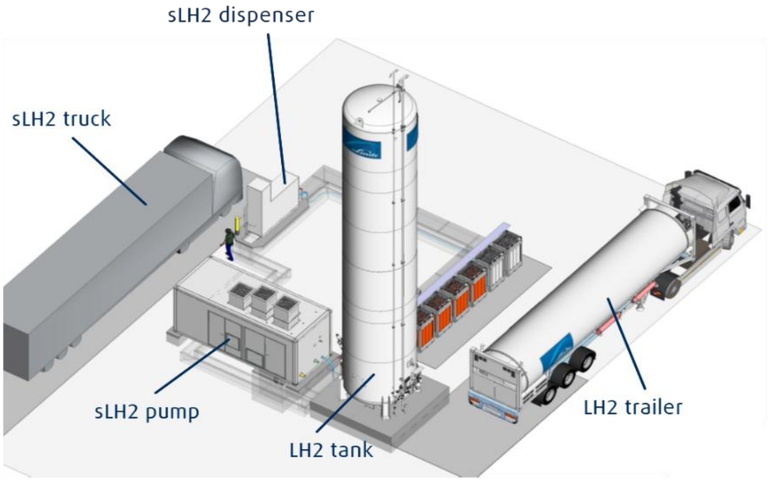


Figure 13. Illustrative schematic of a subcooled liquid hydrogen (sLH_2) refuelling station, including cryogenic tank, pumping system, dispenser and supply logistics.

4.4. Technology comparison hydrogen refuelling architecture

Table 7 summarises the architecture of the different hydrogen refuelling station options.

Table 7. Summary of hydrogen refuelling station architectures.

Architecture	In-vehicle status	Typical flow rate	Maturity	Dispensing temperature	Dispensing pressure	State of H_2 in supply	Main objective
cH_2	Gas	Medium	High	~ –40°C	350 – 700 bar	Compressed gas	Simplicity and compatibility with existing vehicles
$LH_2 \rightarrow cH_2$	Gas	High	Average	~ –40°C	350 – 700 bar	liquid	Improving logistics and efficiency vs cH_2
sLH_2	Net:	Very high	Emerging	~ -247 to -253°C	~ 10–20 bar	Subcooled liquid	Maximising energy density and operational efficiency

4.5. Common hydrogen refuelling infrastructures

In addition to these variants, hydrogen refuelling stations for road transport usually comprise the following main **subsystems**:

- **Hydrogen reception module**. Reception of compressed or liquid hydrogen trailers, pipeline connections, or integration with a local electrolyser.
- **Compression or pumping unit**. High-pressure compressors for cH2 or cryogenic pumps in the case of LH2.
- **Buffer storage**. High-pressure gas storage banks to handle peak demand and cryogenic tanks for LH2.
- **Conditioning systems**. Temperature management, cooling systems and flow control to ensure fast and safe refuelling.
- **Dispensers**. Refuelling points equipped with standardised hoses and nozzles, certified metering systems and user interface displays.
- **Security and control systems**. Leak detection, ventilation, safety interlocks, remote monitoring and automation of operation.

These solutions have a wide range of applications, from materials handling and internal logistics to light vehicles, buses and trucks. The most suitable gas/liquid combination is selected according to the use case and the requirements for range, space and cost.

For **heavy transport applications**, the station design of the station must consider high refuelling flow rates, back-to-back operation (multiple consecutive truck refuellings) and high system availability. This requires advanced storage, compression and maintenance strategies.

Figure 14. Hydrogen refuelling station in the Barcelona Free Zone. Source: J.R. Morante

4.5.1. Types of hydrogen refuelling station according to refuelling method

The following categorisation is presented according to the characteristics of hydrogen supply to a refuelling station:

- **Refuelling stations supplied by semi-trailer.** These receive compressed hydrogen gas at various working pressures. Historically, hydrogen was usually transported at pressures of around 200 bar, but higher pressures of 350 and 380 bar are now starting to be used.
- **Refuelling stations supplied by pipeline**. These stations receive hydrogen from a network, either because the location has on-site or off-site hydrogen production facilities.
- **Refuelling stations supplied by liquid hydrogen**. These supply hydrogen to vehicles in both liquid and compressed gaseous form.

4.5.2. Types of refuelling stations depending on whether or not there is onsite production

Depending on whether on-site production is available, the following differentiation is made:

- **Refuelling station with onsite hydrogen production.** Colloquially known in Spain as *hidrogeneras*.
- **Refuelling stations without onsite hydrogen production.** Colloquially known in Spain as *hidrolineras*.

4.6. State of development and emerging business models

Public and private stations now coexist, with progressive deployment across Europe. At a national level, the lack of refuelling stations is seen as one of the main issues **holding back the market**. Although the development of refuelling stations is slower than expected, there is significant growth potential if deployment is coordinated with vehicle supply and renewable hydrogen production.

Internationally, the network of hydrogen refuelling stations is **unevenly distributed geographically**, with a higher concentration in certain European countries, North America, and Asia, and a clear prioritisation of heavy transport corridors.

Current trends show how **new business models** will prioritise **higher-capacity stations**, with an emphasis on **digitalisation**, remote monitoring, and advanced operation and maintenance services to ensure high levels of availability. There is also growing **vertical integration** in production, distribution, replenishment and use **chains** ('***hydrogen as a service***'), with long-term supply contracts and synergies with local renewable generation, particularly in captive fleet and heavy transport projects.

5. GLOBAL HYDROGEN VEHICLE MARKET AND INFRASTRUCTURE

The hydrogen-based land mobility market is in a **transition phase between advanced demonstration and early deployment**, with a clearly **asymmetric evolution by segment**. While progress in the light-duty vehicle sector is moderate, the most dynamic growth is expected in **heavy-duty transport, captive fleets and off-road applications**.

Hydrogen is in a phase of **transformation** driven by the convergence of three main factors: regulatory pressure, institutional support, and technological innovation. On a global scale, these dynamics manifest differently in different regions:

- **Asia** (particularly China, Japan and South Korea) has prioritised specific vehicle and station demonstration and early deployment programmes.
- The **European Union** has set binding emission reduction targets and established infrastructure support frameworks.
- **North America** combines state and federal initiatives that focus on heavy transport and logistics corridors.

The **EU** has set **binding targets for reducing emissions** that will require a significant transformation of the vehicle fleet in the coming decades. For example, emissions from heavy-duty vehicles are expected to fall by 90% by 2040. This regulatory framework provides clear signals to the market and informs investment decisions. In parallel, the **deployment of infrastructure** is being consolidated as a critical **enabler**. The European Alternative Fuels Infrastructure Regulation [38] establishes **concrete targets** for developing hydrogen refuelling stations along the trans-European transport network, thereby creating predictability and reducing regulatory risk.

Meanwhile, countries such as **China** have set **quantitative roadmaps** for **fleets of hydrogen vehicles** and a **number of hydrogen refuelling stations**, with national plans targeting several hundred thousand fuel cell vehicles and in the order of 1,400 refuelling stations by 2035. This reinforces China's role as a leading market at this early stage.

Financial instruments such as the Innovation Fund, the European Hydrogen Bank and the future Sustainable Transport Investment Plan complement this framework by supporting investment and, foreseeably, upstream operational costs. In other markets, this role is played by national demonstration funds, regional fleet programmes, and public-private partnership mechanisms targeted at specific heavy transport corridors.

The development of the hydrogen-powered vehicle market depends on the coordinated evolution of several key factors:

- sufficient deployment of **refuelling infrastructure** in the priority corridors
- **synchronisation between vehicle and station availability**.
- **access to renewable hydrogen at competitive prices**.
- a **stable and predictable regulatory framework**.
- **progressive acceptance** by operators and end-users.

In addition, **economies of scale and standardisation** must continue to advance, as these will be decisive in reducing costs, limiting adoption risks, and improving the competitiveness of these solutions compared to other technological alternatives.

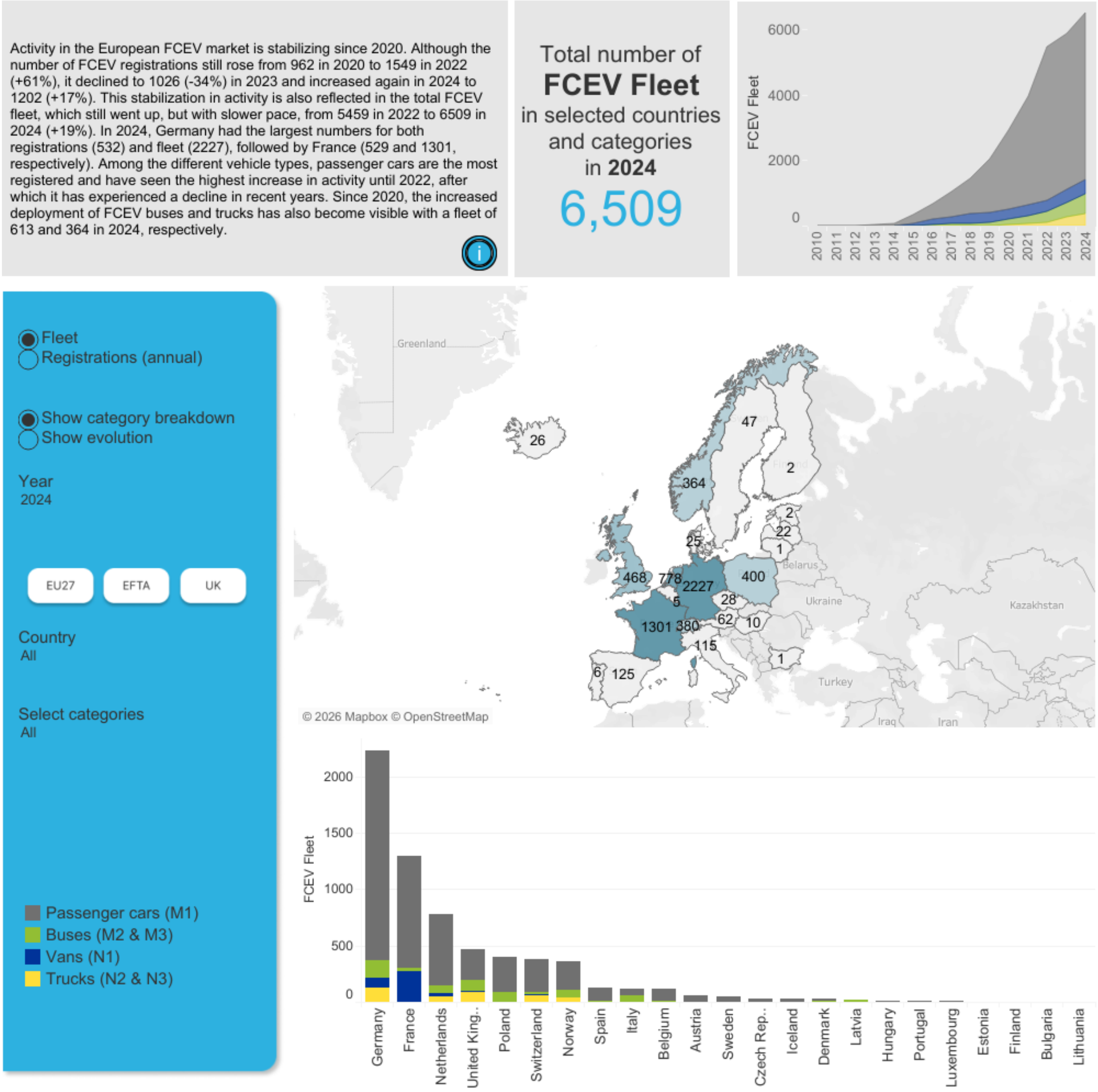
5.1. Global Context

In **Spain**, since 2020, the proliferation of **demonstration projects** linked to the use of hydrogen in land mobility has generated fleets of fuel cell vehicles associated with these projects. By the end of 2025, there were **74 fuel cell buses** operated by urban transport companies in Barcelona (more than 30), Madrid (more than 10) and other cities. Additionally, there were **45 fuel cell light-duty vehicles** in operation (Toyota Mirai and Hyundai Nexo), **two fuel cell electric range extender vans** (Renault Master) and **seven fuel cell powered handling trucks** .

In terms of hydrogen refuelling stations, Spain has **11** private stations with reduced capacity (350 bar supply pressure), as well as three stations for forklift trucks and material handling equipment. An estimated six new refuelling stations under construction are expected to open soon, as indicated in Figure 15.

Figure 15. Refuelling stations in Spain *[39]*.

In the **European** framework, the European Hydrogen Observatory reports that by the end of 2024 there were **6,509 fuel cell vehicles**, mainly light-duty vehicles, as indicated in Figure 16.



Activity in the European FCEV market is stabilizing since 2020. Although the number of FCEV registrations still rose from 962 in 2020 to 1549 in 2022 (+61%), it declined to 1026 (-34%) in 2023 and increased again in 2024 to 1202 (+17%). This stabilization in activity is also reflected in the total FCEV fleet, which still went up, but with slower pace, from 5459 in 2022 to 6509 in 2024 (+19%). In 2024, Germany had the largest numbers for both registrations (532) and fleet (2227), followed by France (529 and 1301, respectively). Among the different vehicle types, passenger cars are the most registered and have seen the highest increase in activity until 2022, after which it has experienced a decline in recent years. Since 2020, the increased deployment of FCEV buses and trucks has also become visible with a fleet of 613 and 364 in 2024, respectively.

Total number of
FCEV Fleet
in selected countries
and categories
in **2024**
6,509

● Fleet
○ Registrations (annual)

● Show category breakdown
○ Show evolution

Year
2024

Country
All

Select categories
All

Figure 16. Fuel cell vehicle (FCEV) fleet in Europe [29].

Globally, the International Energy Agency (IEA) estimates that there are around **100,000 fuel cell vehicles** and expects rapid growth from 2030 onwards. South Korea has the largest fleet of light fuel cell vehicles (more than 30,000 FCEVs), while China is focusing on fuel cell buses and trucks [40].

South Korea remains in the lead with 36% of the total fuel cell vehicle fleet and 51% of the passenger car fleet. In the commercial vehicle segment, China is by far the leading country, accounting for 82% of the world's fuel cell bus fleet and between 88% and 98% of the light, medium, and heavy-duty vehicle fleets. It is worth noting that 92% of fuel cell vehicles are operated in just four countries: South Korea, China, the United States and Japan. Fuel cell passenger cars clearly dominate by segment, accounting for 69% of all fuel cell vehicles. The most recent deployment of this technology has prioritised heavy trucks, with a 72% increase compared to 2023.

According to the IEA, the **worldwide network** of hydrogen refuelling stations totals **1,302**. China again tops the list, with 522 refuelling stations. With significantly fewer stations, South Korea and Japan are in second and third place.

However, the **growth** of fuel cell vehicles and hydrogen refuelling stations has **slowed** in recent years. The main reason is the market success of **battery electric vehicles** in most road vehicle segments [41].

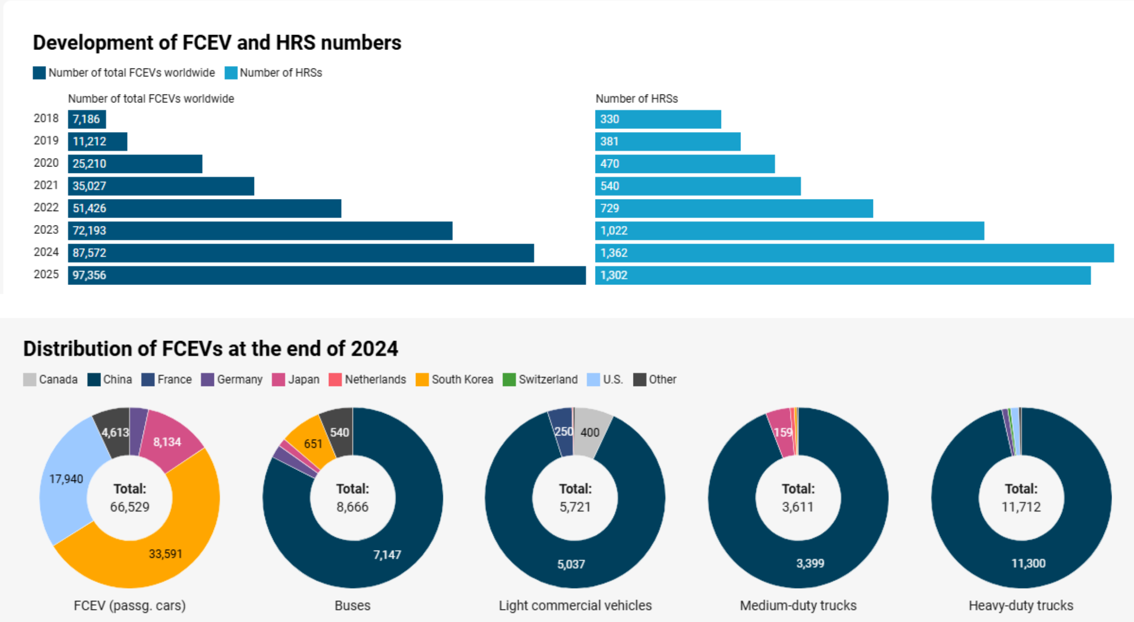


Figure 17. Development of fuel cell vehicles and refuelling stations. *[40]*

In China specifically, its leading position in commercial vehicles and refuelling stations coexists with a very small share of fuel cell vehicles in its overall annual vehicle production, in a context where battery electric vehicles are absorbing most of the market growth. However, China's national roadmaps envisage a significant increase in hydrogen vehicle fleets and the hydrogen refuelling network by 2030–35, which will reinforce its role as a key driver of the early deployment of hydrogen mobility.

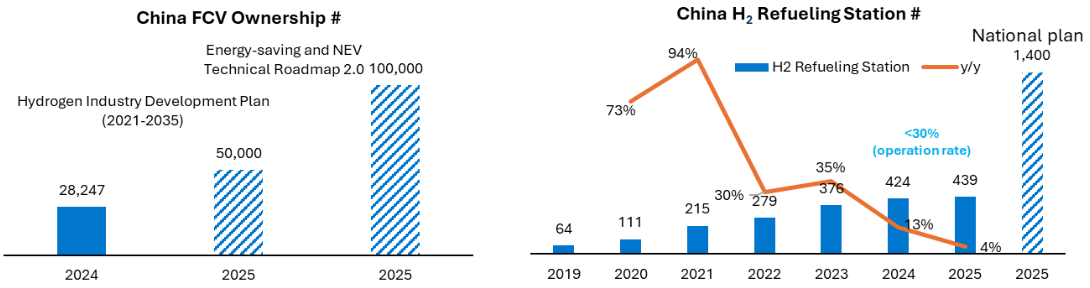


Figure 18. Projected evolution of the hydrogen fuel cell vehicle (FCV) fleet in China according to national hydrogen industry development plans. (Figure adapted from CAAM - China Association of Automobile Manufacturers)

5.2. Light vehicles (passenger cars and light commercial vehicles)

The global market for **hydrogen-powered light vehicles**, **primarily fuel cell electric vehicles (FCEVs)**, currently has a **low deployment volume** and a **limited degree of commercial maturity**. Their market presence is concentrated among **a limited number of manufacturers** (mainly Toyota and Hyundai for light-duty vehicles) in certain geographical regions (more than 90% of these vehicles are in South Korea, the United States, Japan, and China) where there is a greater deployment of hydrogen refuelling infrastructure.

This segment is characterised by:

- **A highly concentrated product offering**, with a limited number of models available on the market.
- **Short or medium mass production**, reflecting the emerging nature of this technology.
- **Focused marketing in specific markets**, mainly in countries or regions where **refuelling station infrastructure** and active policies to support hydrogen-based mobility are available.
- **High dependence on public incentives** for both vehicle acquisition and associated infrastructure development.

In the current context of the transition to low-emission mobility, **light hydrogen vehicles** are in direct competition with other electrified transport technologies, particularly **battery electric vehicles (BEVs)** and **plug-in hybrid electric vehicles (PHEVs).** These alternatives currently have a **stronger market presence,** mainly due to **more widespread charging infrastructure** and **greater economies of scale in their production**.

The deployment of hydrogen in the light-duty vehicle segment currently faces a number of **structural barriers** that affect its competitiveness compared to other propulsion technologies, particularly battery electric vehicles (BEVs):

- **Total cost of ownership** (TCO)[3] is generally higher in most markets, driven by both the price of vehicles and the cost of hydrogen as an energy carrier.
- Insufficient and geographically dispersed **refuelling infrastructure** restricts vehicle usability and creates uncertainty for the end user.
- **Relative disadvantage** in terms of the *well-to-wheel*[4] **full cycle efficiency**, due to losses associated with its production, compression, transport and conversion to on-board electricity via fuel cell.
- The **high technological maturity** and growing social acceptance of **battery-electric vehicles** (BEVs) consolidates their position as the dominant solution in the short and medium term, reinforced by economies of scale, expanding charging networks, and an established industrial ecosystem.

However, hydrogen has **niche applications** where its unique properties provide clear operational advantages:

- These include **taxi fleets** and **vehicles with high daily usage,** where the ability to refuel quickly versus the time taken to recharge an electric vehicle maximises asset availability.
- There are also opportunities in **regions** with explicit **public policies** to promote hydrogen, where regulatory incentives and infrastructure development significantly reduce barriers to entry.
- It is also suited to users who prioritise a **long range** and **refuelling times** comparable to those of conventional fuels - characteristics that are difficult for BEVs to match without compromising weight, cost or refuelling times.

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[3] The Total Cost of Ownership is a financial analysis that assesses the total direct and indirect cost of acquiring, operating and maintaining the vehicle throughout its entire service life, not just the initial purchase price.

[4] The Well-to-Wheel (WtW) cycle is a comprehensive analysis of a vehicle's environmental impact. It assesses all stages, from the extraction, production and transport of the fuel or energy (Well-to-Tank), to its final consumption during driving (Tank-to-Wheel), providing an overview of the total emissions.

In these specific contexts, light-duty hydrogen vehicles can be positioned as a complementary alternative to battery electrification, providing value in scenarios where **operational flexibility** and **continuity of service** are critical factors.

5.3. Heavy goods vehicles and goods transport

The **heavy-duty vehicle** segment is currently one of the **main areas** of development for hydrogen-based technologies within the mobility sector. Unlike light vehicles, its evolution is marked by market dynamics that are more oriented towards **progressive industrialisation** and adoption in real **operational environments**.

China is the world leader in the use of hydrogen fuel cell buses and trucks. South Korea and Japan also have significant fuel cell bus and truck programmes, while in Europe and North America pilot fleets linked to logistics corridors and heavy transport decarbonisation projects are being progressively deployed.

Figure 19. Hydrogen refuelling station for fuel cell buses in South Korea. Source: Linde.

In recent years, traditional **manufacturers** have **gradually begun** to integrate hydrogen solutions into their technology roadmaps. This process is accompanied by the implementation of pilot projects on a commercial scale, which validate the technical and economic performance of the technology under real operating conditions. Framework contracts with major **logistics companies** are also being finalised, reflecting a shift from experimentation to more structured business models. All of this aligns with corporate decarbonisation strategies, in which hydrogen is positioned as a vital means of reducing emissions in **sectors that are difficult to electrify**.

In this context, **heavy road transport**, including long-haul trucks, intercity buses and coaches, is considered the **main growth vector** for hydrogen in land transport. This priority is driven by a number of **structural reasons**:

- **The physical limitations of battery electric vehicles** (BEVs), such as range and payload, become more critical as distances and charging requirements increase.
- Heavy transport requires high **operational availability**, with minimal downtime, favouring solutions with **rapid refuelling,** such as hydrogen.
- Many of these operations take place on **predictable routes** and **defined logistics corridors**, facilitating the planning and **deployment of dedicated refuelling infrastructure**. This significantly reduces one of the main barriers to hydrogen: the lack of infrastructure.

From a technological point of view, **fuel cells** (FC) are emerging as the dominant solution in the medium to long term, thanks to their higher efficiency and their ability to offer **long ranges** without significantly reducing payload capacity. In parallel, **hydrogen internal combustion engines** (H_2-ICE) are emerging as a **complementary alternative**, particularly in cost-sensitive or less technologically mature markets, where they can leverage existing platforms and supply chains.

Typical configurations include fuel cell trucks for long-distance transport, city and intercity buses adapted to zero-emission environments, waste collection vehicles with intensive operation and fixed routes, as well as solutions for regional freight transport. Taken together, this ecosystem forms a **high-potential industrial scale-up** segment set to play a central role in the transition to decarbonised heavy mobility.

The technical and economic feasibility of the mass deployment of battery-electric buses depends on factors such as network capacity, the availability of charging infrastructure in depots, topography, and the length and demands of routes. In regions where networks are close to saturation and in challenging operational scenarios, **hydrogen fuel cell buses** could be a **more reliable option**, despite the lower initial cost of battery electric vehicles. Market developments confirm this trend towards **complementarity**.

The role of hydrogen takes on an even more strategic dimension in **heavy transport**. **Trucks** are the backbone of the European logistics system and, despite improvements in energy efficiency, growing demand for road transport is cancelling out some of the progress made. **Total electrification** based exclusively on batteries would **require** enormous amounts of **energy** and infrastructure. Each HGV charging station would require power equivalent to the consumption of a small town, and the complete electrification of all European trucks would necessitate volumes of renewable energy comparable to the annual electricity demand of **major European economies.**

In this scenario, **hydrogen** offers **advantages** for long-distance transport and high-demand operations, including greater range, shorter **refuelling times**, and **reduced** payload **losses** compared to battery-only solutions.

Industrial deployment is proceeding gradually but steadily. In addition to Hyundai's mass-produced hydrogen truck launched in 2019, other manufacturers are developing solutions at advanced testing and pre-production stages.

The most effective strategy for each sector is not the exclusive substitution of **one technology for another**, but rather their **coexistence and complementarity** in order to maximise the rate of vehicle substitution.

5.4. Off-road vehicles and special applications

The **off-road vehicles** and special applications segment comprehend a heterogeneous set of mobile equipment characterised by **operation outside conventional traffic environments** and often outside the standard registration requirements.

This category includes agricultural machinery, construction vehicles and mining equipment, as well as machinery used in port and airport environments. It also includes a number of commercial vehicles designed for specific uses in private or restricted-access areas.

From a technological and regulatory perspective, this segment presents certain **favourable conditions** for introducing hydrogen-based propulsion solutions:

- Reduced regulatory pressure for type approval allows for faster adoption cycles compared to conventional road transport.
- Many of these operations take place in closed or highly controlled environments, favouring the implementation of private and dedicated refuelling infrastructure.
- The high daily energy consumption of this equipment increases the economic viability of alternatives such as hydrogen compared to other technologies. In this context, both hydrogen-fitted internal combustion engines (H_2-ICE) and fuel cells (FC) are positioned

as technically feasible solutions, each offering specific advantages depending on the use case.

There is growing interest in **adoption**, driven by ESG (environmental, social and governance) objectives, especially in **emission-intensive sectors**. In the early stages, H_2-ICE technologies are favoured due to their lower cost and greater operational robustness, while fuel cells are gaining ground in applications requiring low acoustic emissions and zero local emissions. Overall, this segment is emerging as a **key catalyst** in the early stages of hydrogen market development, acting as a test bed for scaling up in other transport and industrial areas.

5.5. Market trends

The **development of hydrogen fuel cell vehicles** is **transitioning** from technology demonstration to progressive commercial adoption, driven by technical advances, market dynamics, and structural factors within the energy ecosystem. On a global scale, the roadmaps of countries such as China predict substantial growth in the number of hydrogen vehicles and hydrogen refuelling stations by 2030–2035. This will reinforce the role of these Asian economies as the main drivers of the early deployment of hydrogen technology.

5.5.1. Technological trends

Technologically, a **progressive reduction in fuel cell costs** is expected, driven by improvements in manufacturing processes and the optimisation of materials, especially catalysts, as well as increased production volumes. This cost reduction is essential for improving competitiveness against conventional technologies.

At the same time, significant advances are being made in the **durability and power density** of systems, which will enable an **increase in vehicles' service life** and improve their operational **performance**, particularly in intensive applications such as heavy goods transport.

In terms of complementary technologies, the development of **hydrogen-fuelled internal combustion engines** (H_2-ICE) is noteworthy, as they are evolving from adaptations of conventional engines to **designs specifically optimised for hydrogen**, offering improvements in efficiency and emissions reduction.

Similarly, the development of **liquid hydrogen** (LH_2) storage solutions is emerging as a key element for long-haul applications, due to their higher volumetric energy density compared to compressed hydrogen. This makes it possible to extend vehicle range without significantly reducing cargo capacity.

5.5.2. Market trends

The market trends identified by time horizon are presented below:

- **Short term (0-5 years):**

  During this initial phase, the market will be characterised by a proliferation of **pilot projects** and the first commercial fleets, often driven by **public-private partnerships**. The use of hydrogen will mainly be concentrated in heavy transport (trucks and buses) and off-road applications (mining, construction and port logistics), where electric batteries are most limiting. During this period, market development will depend heavily on subsidies, **tax incentives**, and favourable regulatory frameworks, since total ownership costs will still exceed those of traditional alternatives.

- **Medium term (5-15 years):**

  As technology matures and infrastructure expands, **industry scaling** is expected in segments such as trucks and buses, accompanied by further technology standardisation. The consolidation of hydrogen corridors (refuelling infrastructure on strategic routes) will facilitate continuous fleet operation. Over this time frame, **cost reductions** will bring the total cost of ownership of hydrogen vehicles close to, and in some cases below, that of diesel, particularly for intensive use applications where uptime and range are critical.

- **Long term (>15 years):**

  In a more mature phase, hydrogen will be fully integrated into **multi-modal transport systems**, **coexisting** with other technologies such as battery electric vehicles (BEVs) and synthetic fuels. Hydrogen use will tend to be specialised for applications with **high energy demands**, such as long-distance transport, non-electrified railways, trucks and heavy machinery, where its structural advantages are clearer than those of other alternatives.

5.6. Hydrogen vehicles

Market developments in hydrogen vehicles are already evident in the existence of specific models in various mobility segments. To illustrate this, two tables are presented below. The first shows representative examples of fuel cell-based vehicles and the second includes applications with hydrogen-fuelled internal combustion engines, particularly in trucks and civil engineering machinery. The selection of manufacturers and models presented here is intended to be illustrative and technologically representative, and is not exhaustive of all the solutions available on the market.

Table 8. Fuel cell vehicle models on the market.

Brand	Type of vehicle	Model name	Reference
Hyundai	Car	NEXO	Hyundai Nexo
BMW	Car	iX5 Hydrogen	BMW iX5 Hydrogen.
Honda	Car	CR-Ve: FCEV	Honda CR-V e: FCEV
Toyota	Car	Mirai	Toyota Mirai
SAIC	Van	Maxus MIFA Hydrogen	SAIC MAXUS MIFA Hydrogen
Mercedes-Benz	Bus	eCitaro Fuel Cell	eCitaro fuel cell
Solaris	Bus	Urbino 12 hydrogen	Solaris Urbino 12.
Toyota	Bus	SORA	Toyota SORA.
Mercedes-Benz	Truck	GenH2 Truck	GenH2 Truck.
Hyundai	Truck	XCIENT Fuel Cell	XCIENT Fuel Cell Truck .
Nikola[5]	Truck	Tre FCEV	Nikola Tre FCEV
Kenworth	Truck	T680 FCEV	Kenworth T680 FCEV.

Table 9. Internal combustion engine vehicle models on the market.

Brand	Type of vehicle	Model name	Reference
MAN	Truck	hTGX	MAN hTGX.
Ashok Leyland	Truck	H2 Truck	Ashok Leyland H2 Truck.
JCB	Backhoe	3CX	JCB 3CX.
KEYOU	Truck	18t Truck	KEYOU 18t Truck.

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[5] Withdrawn from the market due to financial problems.

6. EUROPEAN AND SPANISH REGULATORY FRAMEWORK

The **regulatory framework** is essential for the deployment of hydrogen-based mobility. The European Union has developed a set of strategies, directives and regulations aimed at ensuring an orderly transition towards decarbonising transport. Spain has adapted and complemented this EU framework through national plans, sectoral legislation and financing instruments.

6.1. European regulatory framework

The development of hydrogen mobility in the European Union forms part of a complex regulatory framework integrating the following:

- Overall decarbonisation strategy and targets for 2030 and 2050
- Development of the European hydrogen market
- Deployment of Refuelling Infrastructure across the Trans-European Transport Network (TEN-T)
- Harmonisation of technical standards, safety requirements and hydrogen quality specifications

6.1.1. Overall EU strategies and objectives

The European Union has identified hydrogen, particularly renewable and low-emission hydrogen, as a key energy vector for achieving EU climate targets, including **climate neutrality by 2050** and an intermediate reduction in greenhouse gas emissions of at least 55% compared with 1990 levels by 2030 'Fit for 55'. In this context, hydrogen has been incorporated as an **alternative fuel and as part of the decarbonisation strategy for land transport sectors that are difficult to electrify exclusively through battery-electric solutions.**

In parallel, the EU has launched specific hydrogen strategies, such as the **EU Hydrogen Strategy**, together with its integration into programmes such as **REPowerEU**. These initiatives aim to reduce dependence on imported fossil fuels and promote more resilient energy systems.

6.1.2. European hydrogen market

A central component of the new European regulatory framework is **Directive (EU) 2024/1788**[42] and **Regulation (EU) 2024/1789**[43], adopted on 13 June 2024, establishing **common rules for the internal markets in renewable gas, natural gas and hydrogen**. These measures are intended to:

- Ensure a competitive and transparent hydrogen market.

- Facilitate certification of origin and traceability of renewable and low-emission hydrogen.
- Establish conditions for access to transport and storage networks.

A key issue is establishing a legal definition within the EU of which hydrogen sources can qualify as **renewable or low-emission** and developing a methodology for assessing their greenhouse gas emissions footprint.

The aim is to create a coherent, interoperable and safe European hydrogen marketing ecosystem within the EU.

Furthermore, although not specifically focused on the transport sector, the **RED III**[44] directive will support the use of hydrogen in transport because it introduces **specific binding targets for renewable hydrogen** in transport for the first time, under the category of **RFNBO** (Renewable Fuels of Non-Biological Origin), as part of the mechanisms to reduce greenhouse gas emissions and increase the consumption of renewable energy in EU Member States. It sets a target whereby more than 1% of transport energy consumption must come from RFNBOs by 2030. In any case, it leaves the definition of sector-specific quotas to the discretion of Member States.

Regarding hydrogen utilisation technology, RED III is neutral and does not distinguish between fuel cell and H_2-ICE vehicles.

6.1.3. Hydrogen refuelling infrastructure for transport

Specific regulation governing alternative-fuel infrastructure is essential hydrogen mobility on roads. In this area, **Regulation (EU) 2023/1804 on the deployment of alternative fuels infrastructure (AFIR)** replaces former Directive 2014/94/EU, setting out binding obligations for Member States regarding the deployment of refuelling infrastructure. Some key aspects relating to hydrogen use in land transport include:

- Member States must ensure **public hydrogen refuelling stations are available at 200 km intervals along the Trans-European Transport Network (TEN-T)** and at major urban nodes.
- Obligations include **interoperability** and transparent services for users, as well as simple, non-discriminatory payment conditions.

This regulation is pivotal in facilitating the commercial adoption of hydrogen fuel cell (FC) and hydrogen-adapted internal combustion (H_2-ICE) vehicles by ensuring minimum refuelling conditions for road mobility.

6.1.4. Regulatory harmonisation

In addition to public policy obligations, a technical body of European and international standards (EN and ISO) applies to the **safety, design, approval and operation** of hydrogen installations and equipment:

- **EN 17127** [36]: for supply points dispensing hydrogen gas.
- **EN ISO 19880-1** [45]: Safety and requirements for hydrogen refuelling stations.
- **EN ISO 14687** [35]: Hydrogen fuel quality specifications.
- **UNECE R100** [46]: applicable to fuel cell vehicles in relation to the safety of their high-voltage components and the rechargeable energy storage system.

This body of legislation establishes a **technical framework for the type approval of hydrogen refuelling infrastructure and vehicles**, reducing technical barriers and facilitating **harmonisation at a European level.**

Interoperability in hydrogen refuelling is essential to minimise the risks associated with public investment and private operation. Important concepts to ensure **interoperability** include:

- The ISO 17268 family of standards defines nozzle and receptacle geometries for 350 and 700 bar.
- Heavy-duty high-flow hardware is in the process of being published.
- The most widely accepted refuelling protocols are those specified in SAE J2601 for light-duty vehicles and in SAE J2601-2 and SAE J2601-5 (TIR) for heavy-duty vehicles.
- ISO 19885-3 [47], which is still in development, aims to harmonise communication-based dynamic fast fills for larger tanks and higher flow classes.
- For liquids, ISO 13984 [37] defines the components and refuelling procedures.
- According to ISO 14687 limits, stations must ensure fuel quality at the nozzle, which implies the application of rigorous standards for cleanliness, humidity and contaminant control, and validated sampling procedures.

6.2. Regulatory framework in Spain

Spain has incorporated European regulations into its legislation and developed its own **regulatory framework** based on additional instruments to promote hydrogen-based mobility.

6.2.1. Integration of European legislation

As an EU Member State, Spain is obliged to **transpose and implement European regulations and directives** affecting hydrogen and hydrogen mobility. These include:

- The **AFIR Regulation (EU) 2023/1804** on alternative fuels infrastructure.
- The hydrogen market rules set out in **Directive (EU) 2024/1788 and Regulation (EU) 2024/1789**.

The transposition and effective implementation of these acts in Spain are coordinated through ministries such as the **Ministry for Ecological Transition and Demographic Challenge (MITECO)** and the **Ministry of Transport and Sustainable Mobility (MITMA)**, which coordinate national hydrogen deployment plans and refuelling stations in line with European targets.

6.2.2. National legislation and plans

Spain has adopted various regulatory and planning initiatives that reinforce the use of hydrogen, including the following:

- The **Integrated National Energy and Climate Plan (PNIEC)**, which includes quantitative targets for the production and use of renewable hydrogen in various sectors, including transport.
- Instruments derived from the **Recovery, Transformation and Resilience Plan (PRTR)**, which finance hydrogen and sustainable mobility projects. Spain's participation in the **Important Project of Common European Interest (IPCEI) Hy2Move** is one example of this, receiving state support to promote innovation in hydrogen mobility in collaboration with other Member States.
- Calls for national grants, managed by bodies such as the **IDAE (Institute for Energy Diversification and Saving)**, allocate resources to **R&D+i** projects and the deployment of hydrogen technologies for mobility applications, including in heavy-duty vehicles and refuelling stations.

6.2.3. Infrastructure regulation

In Spain, the **deployment of public hydrogen refuelling stations** and their integration with energy networks are governed by Royal Decree 919/2006, as well as by national planning for the deployment of alternative fuels.

The regulatory role of MITMA (Ministry of Transport and Sustainable Mobility of Spain) and regional and local administrations is key to:

- Authorising and managing hydrogen refuelling stations in accordance with technical and safety standards.
- Integrating these plans with road transport networks and urban planning frameworks.
- Coordinating public incentives and investments with European, national and territorial cohesion funds.

6.2.4. Tax conditions and financial support

Although there is no specific hydrogen-related mobility legislation with particular tax effects (e.g. tax exemptions differentiated by fuel type), Spanish and EU policy incorporates **economic incentives and financial support mechanisms** to accelerate the adoption of low-emission technologies. These incentives mechanisms include:

- Funding from the **Connecting Europe Facility (CEF)** to supporting the deployment of hydrogen refuelling stations and other alternative refuelling infrastructure.
- Funding lines under the PRTR for innovation, industrialisation and deployment in hydrogen mobility.

The coordination between **energy, transport and industrial policy** seeks to ensure that Spain advances in the implementation of hydrogen as a vector for **decarbonising road transport**, both in the light vehicle segment and in heavy duty transport and commercial fleets.

6.3. Applicable cross-cutting regulatory issues

In addition to the general framework for hydrogen and infrastructure, the **type-approval of hydrogen-powered vehicles (FC or H2-ICE)** follows the **European and UNECE regulations** applicable to **safety, emissions** and technical requirements. European and UN (UNECE) type-approval standards include specific safety requirements for high-pressure systems and components of fuel cells and propulsion systems.

In Spain, transport authorities apply these European and international standards to **register and certify** new vehicles that use hydrogen as a fuel.

6.4. Areas of application and regulatory challenges

Despite significant progress, current regulatory developments still present some challenges that affect the uptake of hydrogen. These include:

- Although a general framework for infrastructure and the market exists, certain technical aspects of the **certification of low-emission hydrogen** are still being discussed at a European level. For example, the classification of hydrogen produced from nuclear energy as ‘low-emission’ hydrogen is still under discussion.
- **Specific tax harmonisation for alternative fuels** and the internalisation of transport’s external costs (i.e. the social cost of emissions) are still evolving, with proposals aimed at including transport in extended emissions trading schemes (ETS2).

Progressive resolution of these issues will be key to the mass deployment of hydrogen mobility.

7. CONCLUSIONS

Road mobility with hydrogen is emerging as a complementary and strategic technological pathway within the process of decarbonisation of transport. Its value does not lie in replacing all existing solutions, but in providing an effective response in segments where direct battery electrification presents significant operational, energy or economic constraints. In this context, hydrogen is particularly well suited to heavy-duty long-haul transport, buses, captive fleets, machinery and off-road applications, where range, refuelling time, payload and operational availability are critical factors.

- **Technological complementarity: fuel cells and H_2-ICE**

The two main technological routes analysed, fuel cells and hydrogen-fuelled internal combustion engines, should not be interpreted as mutually exclusive options, but rather as complementary solutions with differentiated fields of application. Fuel cells are notable for their higher energy efficiency and for operating without local emissions, making them the most robust option for heavy-duty road transport, buses and high-utilisation fleets. H_2-ICE engines offer a deployment path that is closer to the existing industrial base. They have a lower initial cost and are easier to adapt for certain uses, especially in industrial applications, machinery, controlled environments and transition phases. The ability of these engines to operate with lean mixtures adds a significant technical advantage by allowing lower combustion temperatures and limiting NO_x formation at certain operating speeds, albeit with a potential penalty in specific power and higher combustion control requirements.

- **Hydrogen storage systems in vehicles**

On-board storage is another major technical and economic challenge for the hydrogen vehicle. Currently, high-pressure gaseous storage is the dominant commercially viable solution, while liquid hydrogen has potential for long-haul heavy transport due to its higher volumetric energy density. However, this second option is hindered by the complexity of using a cryogenic liquid, as well as by boil-off, the required infrastructure and the associated costs. Solutions based on solid materials or cryo-compressed storage are of technological interest, but are not yet competitive for widespread on-road applications due to their early stage of development. In practice, storage evolution will affect range, vehicle integration options and total system cost, thus influencing the real competitiveness of hydrogen against other alternatives.

- **Hydrogen refuelling technologies**

The refuelling infrastructure is one of the most critical elements for the viability of hydrogen mobility, connecting the production and logistics of the fuel to its use in vehicles. Their relevance is not limited to the physical existence of stations but depends on their ability to supply hydrogen under the conditions of pressure, temperature, flow and availability required for each application. In light-duty vehicles, 700 bar refuelling is mainly used, whereas in buses, trucks and other heavy-duty applications, the 350 bar environment is dominant. There is an increasing focus on liquid hydrogen-based solutions and, in the longer term, on subcooled liquid hydrogen, which increases range and refuelling speed. This implies that station design (compression, buffer storage, cooling, dispensers and auxiliary systems) directly affects refuelling time, supply capacity and fleet operational availability.

- **Global hydrogen vehicle market and infrastructure**

Market developments confirm that uptake of hydrogen in land transport will be progressive, selective and clearly segmented, rather than following a uniform trajectory. Light-duty vehicles are expected to experience contained, niche-specific growth, whereas heavy-duty transport, captive fleets and off-road applications have the greatest deployment potential in the short to medium term. This is because hydrogen offers a stronger value proposition in segments where range, refuelling time, payload and operational availability are critical factors. Consequently, market consolidation will depend on its ability to be deployed in specific applications where it can compete with other decarbonisation alternatives.

- **European and Spanish regulatory framework**

The development of hydrogen mobility is already supported by an increasingly well-defined European and national regulatory framework. Policy and regulatory provisions such as AFIR, RED III and national support schemes introduce binding targets, harmonised standards and funding mechanisms, providing a more favourable environment for vehicle and infrastructure deployment. However, the sector's progress will continue to depend on one key factor: the lack of synchronisation. If regulation, infrastructure, vehicle supply and the availability of competitive hydrogen do not proceed in a coordinated way, deployment will be slow, costly and fragmented.

- **Final conclusion**

The use of hydrogen in land transport should not be viewed as a universal solution, but rather as a valuable option for segments that are more challenging to electrify. Its main strengths (short refuelling times, long range, and a favourable ratio between on-board volume and stored useful energy) are particularly relevant for heavy-duty vehicles, where factors such as availability, payload, on-board space, and operational continuity are critical. Its success will depend on its deployment with a logic of specialisation, prioritising those uses where its operational and energy benefits clearly outweigh its costs and complexities. In this scenario, fuel cells and H_2-ICE engines will coexist, accelerating the transition of road transport towards sustainable and resilient models compatible with European climate targets.

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9. ANNEXES

9.1. Annex: Railway applications.

In general, the carbon footprint of rail does not have a significant impact in comparison with other mobility sectors, especially in Europe, where electrification levels, the solution that makes rail's greater efficiency sustainable, reach values of 60%.

For this reason, rail is primarily seen as a decarbonisation tool aimed at accelerating modal shift, i.e. replacing road use with rail, taking advantage of existing synergies in logistics intermodality. These synergies could also extend to the energy sector as H_2 becomes more widely used as an alternative fuel in both modes of transport.

However, due to its mainly urban (last mile) and regional structure, as well as interoperability problems hindering continuity on the main rail freight corridors, the rail sector presents unique challenges. In particular, there are sections with different voltage electrification systems, and sections whose electrification would not be profitable in the medium term. In this context, the rail sector requires specific solutions based on alternative fuels that allow for the complete elimination of diesel traction.

There are some notable pilot experiences. Among them, the one developed by the Spanish narrow-gauge railway operator FEVE in Asturias in 2011 stands out. This initiative involved adapting an old tram to carry a fuel cell and compressed hydrogen storage on board, and made Spain the first European country with a hydrogen rail vehicle on the track. However, more than a decade later, the rail industry still lacks commercially available platforms for passenger services based on ‘power packs’ using a combination of fuel cells and compressed storage of H_2.

The use of H_2 in railways has different levels of technological maturity depending on the traction segment considered: passenger railcars, shunting and line locomotives. For passenger railcars, which belong to the light-duty sector, there are already commercial solutions available that are compatible with the main approved vehicle platforms. However, 100% battery-based solutions are now more competitive and advanced. Nevertheless, these solutions are not yet capable of achieving significant industry-wide penetration by 2035. This is expected to change once the backbone of H_2 transport and storage infrastructures in Europe has been developed, user-scale refuelling solutions have been deployed under AFIR and certain technical issues with a major impact on the industry have been resolved. Challenges include the long-term behaviour of the fuel cell and its performance under industry-specific operating and environmental conditions.

Currently, there are no significant commercial initiatives or development projects for heavy rail and/or high power and autonomy requirements. Alternatives to electrification require dual solutions (bi-mode and tri-mode) that can operate flexibly and efficiently with and without a catenary. In these circumstances, the competitive use of H_2 will depend on the availability of a three-pronged approach consisting of propulsion technology (ICE or FC), on-board storage, and batteries. The latter would be necessary to simplify engine and storage system requirements. The energy density of the assembly, in terms of both volume and mass, must be equivalent to that of the traction systems it replaces. This poses a challenge for the development of a power pack that can be integrated into the current vehicle platforms approved for this segment, especially given the level of maturity of alternative storage systems to compressed solutions and the still small number of units developed, around 1,500 at EU level and around 30,000 worldwide, a figure far removed from the millions we are used to in the heavy-duty on-road segment.

Having identified the background, current status and challenges of the sector, as well as the commonalities at the power pack and supply levels, it can be concluded that accelerating the development of technology solutions in the heavy road sector could leverage the potential of H_2 in the light rail sector.

This annex provides an overview of different hydrogen-based rail projects developed in Europe and the United States. It presents initiatives in the demonstration phase and in commercial operation that use fuel cells as an alternative to diesel traction on non-electrified lines, as well as projects that aim to standardise and define technical requirements at a European level.

The aim is to provide an overview of the current state of technology, identifying the main solutions adopted and their degree of development in the railway field.

Commercial solutions based on the adaptation of approved vehicle platforms:

Coradia iLint Project (Germany)

The Coradia iLint, developed by Alstom, was the first hydrogen fuel cell-powered passenger train to enter commercial service. It began operating on 16 September 2018 in Lower Saxony, Germany, connecting the cities of Cuxhaven, Bremerhaven, Bremervörde and Buxtehude. This marked a milestone in the decarbonisation of non-electrified regional rail transport.

The train has two hydrogen storage tanks, with a capacity of 130 kg each, located on the roof and operating at a pressure of approximately 350 bar. Propulsion is provided by two fuel cells, each with a power output of 210 kW, and a lithium-ion battery manages energy recovery during braking and supplies auxiliary systems. The alternating current electric traction system enables the train to reach a maximum speed of 140 km/h.

In real-world operation, the Coradia iLint has demonstrated high performance, achieving a world record distance of 1,175 km on a single hydrogen fill-up in September 2022. Operating consumption ranges from approximately 0.25 to 0.30 kg H_2 per kilometre depending on operating conditions.

Refuelling can be done without shutting down the fuel cells, with times ranging from 20 to 60 minutes. A dedicated station for passenger trains in Bremervörde supports the infrastructure, with a supply capacity of up to 1,814 kg of hydrogen per day. This is designed to serve a fleet of 14 trains with a daily consumption of 1,633 kg; each unit can refuel with approximately 260 kg of hydrogen at the station.

Figure 20. Coradia iLint train.

Stadler FLIRT Project H_2 (United States)

The Stadler FLIRT H_2 is a hydrogen fuel cell-powered electric multiple unit for passengers developed by Stadler with the aim of decarbonising regional services on non-electrified lines in the United States. The system obtains electricity from hydrogen to power the traction and auxiliary systems, as well as charging the lithium-ion battery, providing a direct alternative to conventional diesel traction with zero-emission operation on the track.

Hydrogen is stored in tanks integrated into the unit, usually located on top of the train. The platform can incorporate a pantograph, enabling hybrid operation under a catenary on electrified sections, as well as the use of hydrogen on sections without electrical infrastructure. This optimises the overall energy efficiency of the system.

In operational terms, the FLIRT H_2 has a range of over 460 km, a maximum speed of 127 km/h, and takes less than 30 minutes to refuel. It is available in two- to four-car configurations, with a typical capacity of around 116 passengers.

Project website: https://www.stadlerrail.com/en/solutions/rolling-stock/mainline-flirt-h2

Siemens Mireo Plus H Project (Germany)

The Siemens Mireo Plus H is a hydrogen-powered electric multiple unit developed by Siemens Mobility to replace diesel trains on the Bayerische Regiobahn (BRB) network in Germany. The project began operating in December 2024 and is presented as one of the first prototypes in commercial service to integrate an advanced hybrid fuel cell and lithium-ion battery system in a single vehicle. The propulsion system combines a fuel cell with a highly reliable battery that manages the delivery of power, the storage of energy recovered in regenerative braking, and the supply to auxiliary systems. To maximise energy efficiency and reduce noise emissions, both power converters and auxiliary systems incorporate silicon carbide (SiC) technology. Hydrogen storage is provided by Type IV tanks located on the roof of the train. These consist of pressure cylinders with a carbon fibre-reinforced non-metallic lining, which are protected by a structural cover. The system is designed to offer a range of up to 1,200 km, and the projected life of the fuel cell is approximately 30,000 operating hours. In operational terms, the train can be refuelled in approximately 15 minutes. The system supports on-station hydrogen pre-cooling to optimise refuelling times, and the refuelling ports are accessible from both sides of the train to improve logistics and avoid the need for additional manoeuvres during refuelling.

Project website: https://www.mobility.siemens.com/global/en/portfolio/rolling-stock/commuter-and-regional-trains/mireo/mireo-plus.html

Vehicle Innovation Projects:

FCH2RAIL Project (Spain-Portugal)

Demonstration project (2021-2025) that validated the technical feasibility of a bimodal passenger train (catenary + hydrogen) on the Spanish and Portuguese rail networks, with the participation of CAF, Toyota and Renfe.

The train incorporates 160 kg of H_2 at 350 bar (32 type III cylinders), Toyota Gen2 fuel cells (6 × 80 kW) and a backup battery (238 kWh), operating in hybrid mode. It achieved a range of 804 km, with an average fuel consumption of 0.22 kg H_2/km and 10,000 km of operation in hydrogen mode.

The project developed a modular and transportable hydrogen refuelling station, capable of refuelling 160 kg in about 20 minutes (4 kg/min). High-capacity fast refuelling was identified as the main challenge for commercial operation.

H_2 is stored in a compressed gaseous state (350 bar) at room temperature without cooling; PEM cells use liquid cooling to operate between 60-80°C.

Project website: https://www.fch2rail.eu/.

Figure 21. Train FCH2RAIL, licence CC BY-NC-ND 4.0. Source: CAF

Hympulso Project (IDAE Spain)

The Hympulso project (2023-2026), led by Talgo, aims to integrate a hybrid H2+battery system in a high-speed/Intercity train (Talgo 250), making it the first dual unit (EMU+ HEMU) with high interoperability on dual-voltage sections: 25 kVAC of high-speed lines and 3 kVCC of the conventional network) or without catenary and of different track gauges (as it has an automatic track gauge system adaptable to conventional or international gauge networks), as well as high-speed and long-distance lines, and the integral development of the value chain, including both the production of renewable H_2 and the development of supply and refuelling logistics for the railway unit.

The prototype will feature significant powertrain innovations, including highly efficient converters, safe passive ventilation models, a driving model optimising the use of different energy sources for specific routes using a virtual twin, and the application of additive manufacturing to enhance the weight and durability of equipment, thereby improving efficiency and ultimately contributing to the decarbonisation of mobility.

Project website: https://www.talgo.com/es/

FP4-Rail4EARTH Project (Europe's Rail JU)

The FP4-Rail4EARTH (2022-2026) project, driven by Europe's Rail Joint Undertaking, aims to improve the sustainability of the European rail system and contribute to climate neutrality by 2050. The initiative focuses on developing and pre-standardising alternative propulsion solutions for rail, including battery-electric trains (BEMU) and hydrogen trains (HMU), as well as optimising energy management at system level. In the specific field of hydrogen, the project establishes common, Europe-wide technical specifications for future trains. The minimum target range is 1,000 km, with the ultimate goal being 1,500 km. This would require approximately 250 kg of hydrogen compressed at 350 bar (CGH_2). The initiative also sets a benchmark of a 15 minute refuelling time, comparable to the operation of diesel trains. To this end, work is underway on standardising interfaces between rolling stock and refuelling infrastructure, as well as developing advanced energy management systems to optimise consumption and operational integration.

Project website: https://rail-research.europa.eu/rail-projects/fp4-rail4earth/

HydroFLEX Project (UK)

The HydroFLEX project (UK) is developing the UK's first hybrid hydrogen train in collaboration with Porterbrook and the University of Birmingham. The project's main objective was to demonstrate the technical feasibility of adapting existing electric rolling stock for hydrogen operation, enabling autonomous operation on non-electrified lines.

The demonstrator was based on a retrofitted Class 319 electrical multiple unit (EMU). Unlike conventional configurations, where the equipment is housed in a rack, the power system was installed in one of the wagons to allow for easier access and testing. The propulsion incorporates a Ballard HD100 100 kW fuel cell and two lithium-ion traction batteries with a combined capacity of 84 kWh, which cover peak energy demands.

Hydrogen storage is provided by four Type III tanks, with a total capacity of 20 kg of H_2. This hybrid configuration enables operation under a 25 kV catenary on electrified sections, as well as switching to hydrogen mode on sections without electrical infrastructure.

While the project successfully demonstrated the technical feasibility of hydrogen traction on the British rail network, it remained an experimental initiative and did not evolve into a commercial fleet, primarily due to economic and scalability constraints.

Project website: https://www.porterbrook.co.uk/innovation/hydroflex-cop

Hycerail Project (Spain)

The Hycerailproject, promoted by the Institute for Just Transition (ITJ) and CIUDEN, aims to demonstrate the viability of renewable hydrogen as an alternative to diesel on non-electrified railway lines, using the Ponfeblino tourist train infrastructure around Villablino (León) as a test bed. Unlike fuel cell-based trains, Hycerail employs an H_2-ICE approach, integrating a hydrogen-powered internal combustion engine in a refurbished railcar, with the aim of validating the solution in real operation and with infrastructure requirements closer to a conversion of existing material. The first track tests were carried out at the end of 2025, initially on the first 11 km of the route, where the Ponfeblino will run.

The project relies on a local hydrogen production and logistics scheme associated with CIUDEN, which is aimed at closing the supply cycle for rail mobility. In addition to the demonstration value, Hycerail aims to reactivate the historic Ponfeblino infrastructure as a technological platform that can be replicated for other non-electrified regional lines. The project will evaluate the operating, maintenance and safety conditions linked to the use of hydrogen as a railway fuel.

Transversal Innovation Projects:

Hydrogen Risks Project (UIC)

The HYDROGEN RISKS Project is a UIC (Union Internationale des Chemins de Fer) initiative that aims to prepare the rail system for the safe integration of hydrogen as an energy carrier. Rather than focusing on the development of trains or physical infrastructure, the project's focus is on analysing, structuring and harmonising the management of risks associated with hydrogen in rail. This approach addresses the entire value chain - production, storage, distribution and on-board use - and explicitly compares these risks with those of ammonia as an alternative fuel.

This safety and standardisation framework project is being developed to generate cross-sectoral knowledge before hydrogen is widely adopted. The aim is to inform future technical guides, RAMS analysis processes and regulatory decisions in the context of the increasing deployment of hydrogen railway demonstrators. The project builds on limited experience and previous studies, including tests carried out by Renfe, Enagás and CNH2 in 2020 at the Barredo Foundation's facilities in Asturias. These tests simulated the effects of H_2 leaks on a real scale in a railway environment subject to the main constraints for railways: a tunnel with a catenary. The results anticipate the type of mitigating measures to be adopted at vehicle and infrastructure levels.

The project's main objectives are to consolidate the results of existing risk analyses, harmonise safety criteria between operators, manufacturers and infrastructure managers, create a library of reusable best practices and reduce the regulatory uncertainty currently hindering the deployment of hydrogen in railways. HYDROGEN RISKS thus acts as a strategic enabler, ensuring that the technology transition to hydrogen can be made in a safe, comparable and defensible way.

Project website: https://uic.org/projects-99/article/hydrogen-risks

9.2. Annex: Properties of H2

Table 10. Physico-chemical properties of hydrogen. Properties under ISO reference conditions: 15°C and 1,013 bar for volume and 15°C for combustion calculations. Source: Enagás

Physical and chemical properties	
Molecular weight (kg/kmol)	2.0159
Density (kg/m^3)	0.0899
Relative density	0.0696
Superior Calorific Value (MJ/kg)	141.948
Superior calorific value (kWh/m^3)	3.5523
Higher calorific value (MJ/m^3)	12.103
Higher Wobbe index (kWh/m^3(n))	13.4684
Specific heat, C_p (kJ/kg.K)	14.268
Joule-Thompson coefficient (K/bar)	-0.028
Speed of sound (m/s)	1293.9
Viscosity (mPa.s)	0.00871
Thermal conductivity (W/m.K)	0.1815
Boiling point (K)	20.3

Melting point (K)	14
Diffusion coefficient in air (m^2/s)	0.69
Flame temperature in air (K)	2318

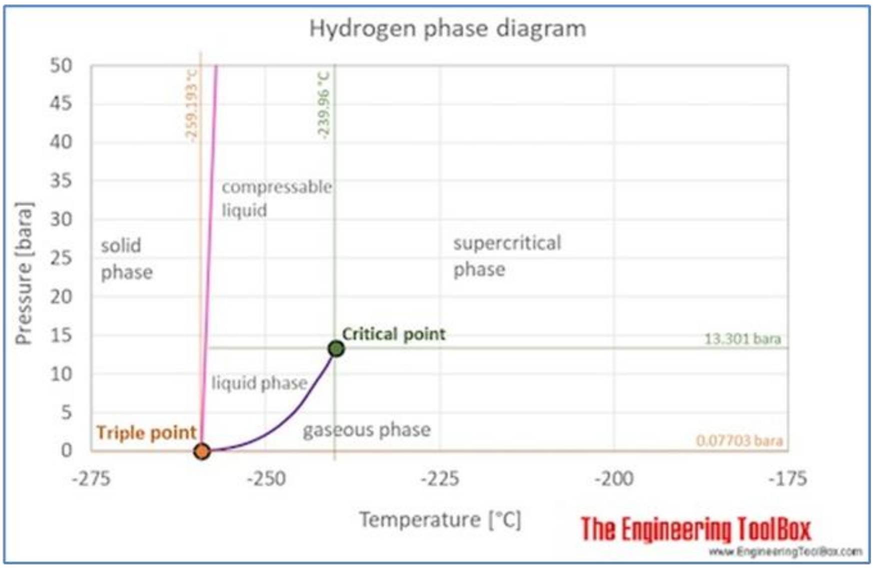

Figure 22. Phase diagram of hydrogen. *[48]*

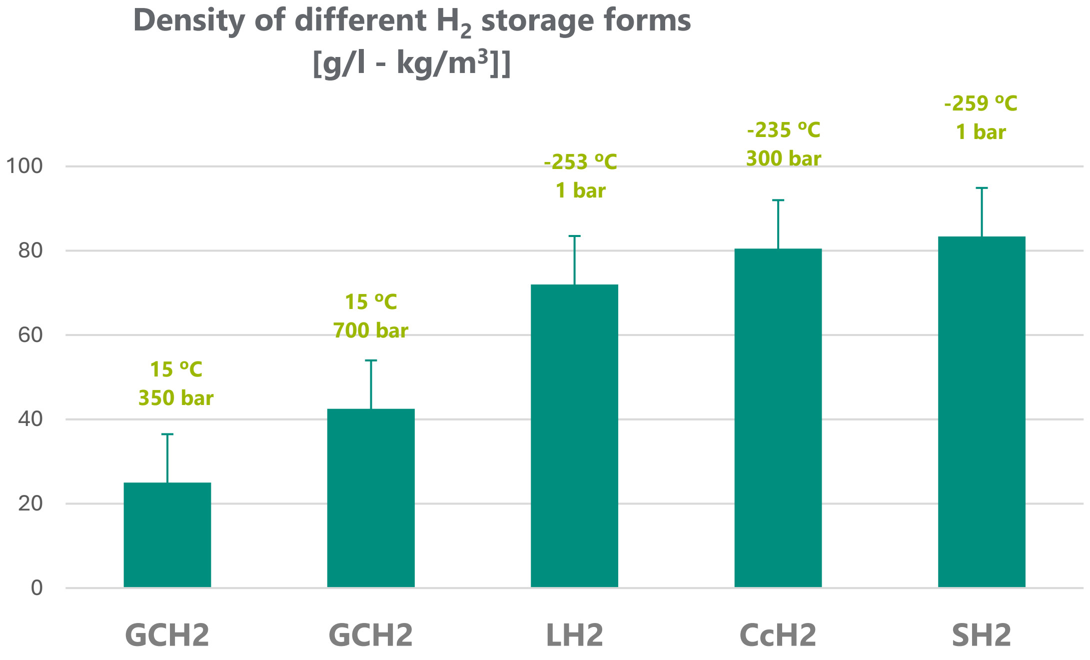

Figure 23. Energy density of hydrogen as a function of pressure and/or temperature. Source: Own elaboration

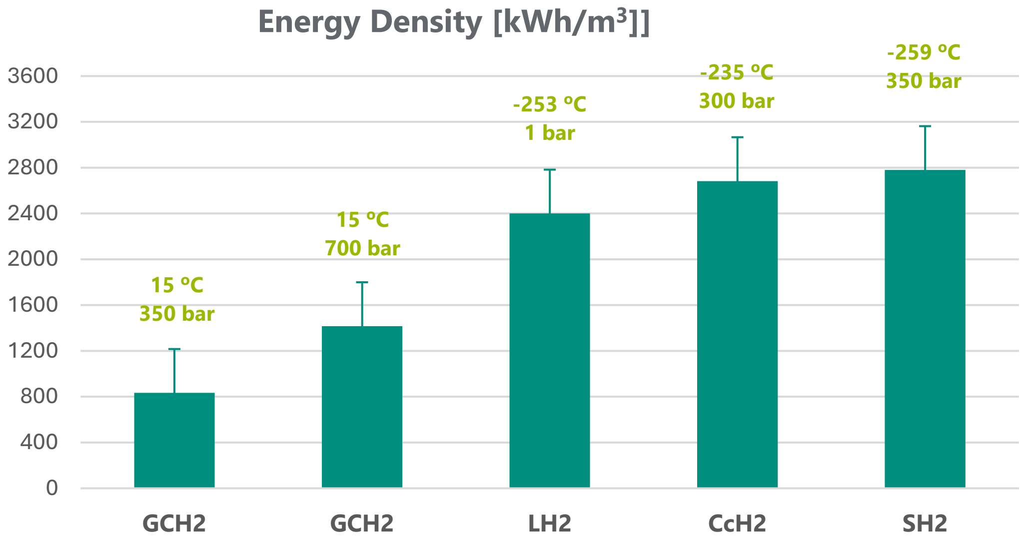

Figure 24. Energy density of hydrogen as a function of pressure and/or temperature. Source: Own elaboration

GCH_2: Compressed hydrogen
LH_2: Liquefied hydrogen
CcH_2: Cryo-compressed hydrogen
SH_2: Solid hydrogen (slush state)

Table 11. Lower calorific value and volumetric energy density of conventional fuels vs. hydrogen *[17]*. *[49]*

Fuel	Lower calorific value (MJ/kg)	Volumetric energy density (MJ/ l)
Petrol	43.2	32
Diesel	43.1	35.7
Synthetic diesel (FT/HVO)	44	-
H_2 350 bar	120	2.8
H_2 700 bar	120	4.7
Liquid H_2 (LH_2)	120	8
Cryo-compressed H_2 (CcH_2)	120	9.6
Solid H2 (slush state, SH_2)	120	~10

9.3. Annex: H2 fuel quality standard

In hydrogen-based mobility systems, ensuring the proper functioning, durability and safety of propulsion systems, especially in fuel cell applications, requires attention to fuel quality. The presence of certain impurities in hydrogen can adversely affect the performance of these systems, cause catalyst degradation, and lead to operational problems in storage, distribution, and refuelling equipment. For this reason, the industry has developed specific standards setting out purity requirements and maximum permissible limits for pollutants in hydrogen intended for use as fuel. The two main reference standards today are **ISO 14687:2025** and **EN 17124:2022.** The main international reference is **ISO 14687:2025**, which defines quality specifications for hydrogen as a fuel for various energy applications, including use in fuel cells for land transport. The standard sets out minimum and maximum allowable values for a number of contaminants that could be present in hydrogen, as well as other relevant physicochemical parameters, for different applications. For use in mobility applications, the standard categorises hydrogen as follows:

- **Type I**: hydrogen gas.
- **Type II**: liquid hydrogen.

Which in turn can be divided into:

- **Grade C**: hydrogen for fuel cell or internal combustion engine applications in off-road vehicles.
- **Grade D**: hydrogen for fuel cell or internal combustion engine applications in on-road and off-road vehicles.
- **Grade F**: hydrogen for internal combustion engines in vehicles.

Table 12 shows the minimum hydrogen concentration required for each type/grade as well as the maximum for some of the main pollutants.

At the European level, the **EN 17124:2022 standard** specifies the quality characteristics of hydrogen supplied to proton exchange membrane (PEM) fuel cell electric vehicles. These quality requirements align with Type I, Grade D hydrogen as defined in ISO 14687:2025.

It should be noted, however, that both standards set additional limits for other trace components (such as CO, CO_2, etc.) that must be considered, and the exact limitations are described in the respective standards. Similarly, the standards must be consulted for additional requirements/limitations imposed on the quality of H_2.

Table 12. Hydrogen fuel quality specifications for vehicles according to ISO 14687:2025 and EN 17124:2022.

Components	Type I and Type II Grade D	Type II Grade C	Type I Grade F
Hydrogen	≥ 99.97%	≥ 99.995%	≥ 98.0%mol
Total gases other than hydrogen	≤ 300 µmol/mol	≤ 50 µmol/mol	≤ 2%mol
Maximum concentration of individual pollutants			
Water (H_2O)	≤ 5 µmol/mol	a	≤ 5 µmol/mol
Methane (CH_4)	≤ 100 µmol/mol	b	≤ 100 µmol/mol
Other			
Helium (He)	≤ 300 µmol/mol	b	-
Nitrogen (N_2)	≤ 300 µmol/mol	a	-
Argon (Ar)	≤ 300 µmol/mol	≤ 39 µmol/mol	-

a) Nitrogen, water and hydrocarbons combined: maximum 9 µmol/mol.
b) Oxygen and argon combined: maximum 1 µmol/mol.

9.4. Annex: Safety aspects

In the context of the explosive atmosphere regulation (ATEX) [50], instruments for use in areas with the presence of hydrogen must belong to group IIC, which applies to those flammable gases having the following characteristics

- Maximum Experimental Safe Gap (MESG) in mm < 0.5
- Minimum Ignition Current (MIC) in mA < 0.45

Table 13 shows some of the main safety-related properties of hydrogen.

Table 13. Safety-related properties of hydrogen. Source: Enagás

Main safety properties	Value
Lower Flammability Limit (LFL), mol%.	4.0
Upper Flammability Limit (UFL), mol%.	77.0
Limiting Oxygen Concentration (LOC) in mol%.	4.3
Auto-ignition temperature (AIT), °C	560
Minimum Ignition Energy (MIE), mJ	0.017
Maximum safe experimental gap, (MSEG), mm	0.29
Maximum explosion pressure, p_{max}, bar	8.3

K_G value, bar x m/s	990
Laminar combustion velocity (S_L), m/s	3.12

More extensive information on different hydrogen-related safety aspects can be found on the following web pages6:

- ***HySafe***: International Association for Hydrogen Safety, https://hysafe.info/.
- ***Chemsafe***: Database for safety characteristics in explosion protection, https://www.chemsafe.ptb.de/home.
- ***HyTools***: Hydrogen tools, https://h2tools.org/.
- ***HyResponder***: European Hydrogen Train the Trainer Programme for Responders, https://hyresponder.eu/.

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[6] Accessed 26 March 2026