Agenda M2N: *Moving2Neutrality*

Project 3.3 – Task 1 Report - Literature review – Hydrogen transport options for vehicle supply

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1. Introduction

Among the different applications in which hydrogen technology has become the protagonist, the transport sector should be particularly mentioned. It is expected that, by 2030, 1 in 12 cars sold in Germany, Japan, California, and South Korea will be powered by hydrogen, and that more than 350,000 hydrogen trucks will be able to transport large quantities of goods, while thousands of trains and ships can carry passengers without emitting carbon dioxide into the atmosphere. The decarbonisation of road transport can be achieved by implementing fuel cells in electric vehicles. Fuel Cell Electric Vehicles (FCEV) are a necessary complement to Battery Electric Vehicles (BEVs). FCEVs are more convenient for long distances with better performance for heavy vehicles that can benefit from the higher autonomy provided by hydrogen for long-distance transport, but it has lower energy efficiency than BEVs (Genovese & Fragiacomo, 2023). However, the possibility of rapid refuelling is an important advantage (Sinigaglia et al., 2017). However, the success of the implementation of this new technology is facing several obstacles. Among them, the lack of suitable and connected infrastructure and the high initial investment cost. So, hydrogen refuelling stations (HRSs) must be fully implemented as they are one of the most important parts of the hydrogen economy in the transport sector.

Figure 1 presents a scheme of the total value chain of the hydrogen economy, from the primary energy for hydrogen production to its use in the transport sector. Note that other sectors and uses are not considered in the figure.

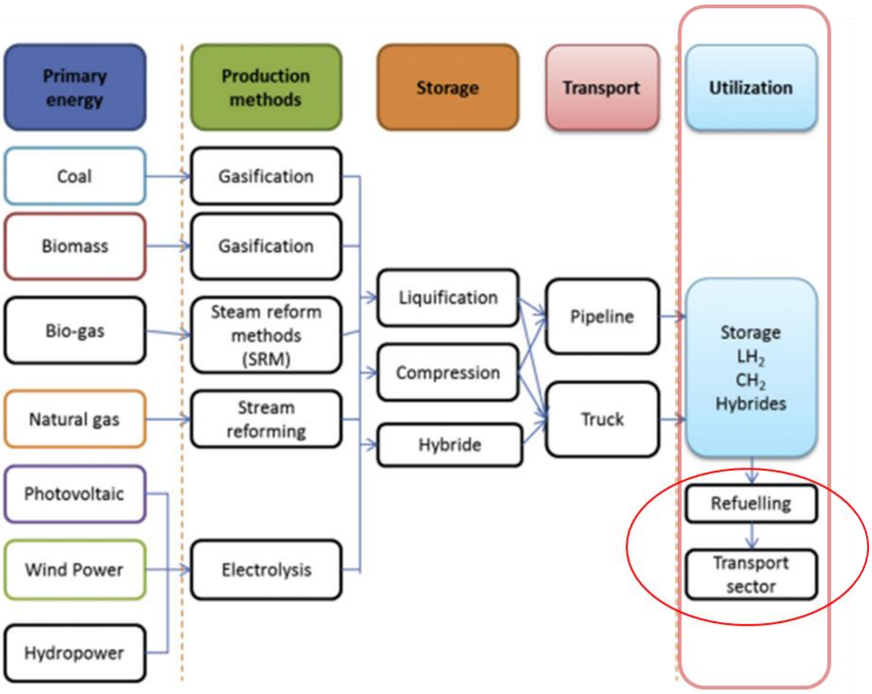
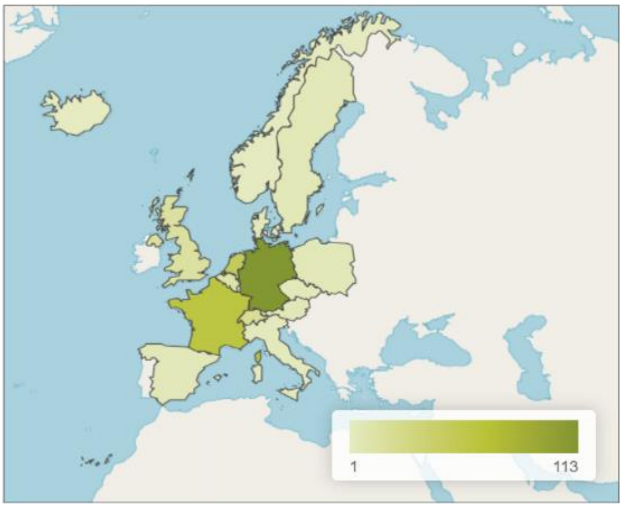


Figure 1. Scheme of the total chain of the hydrogen economy for transport utilization (Sinigaglia et al., 2017).

In several places worldwide, targeted build-out programs with clustering stations are already being implemented in areas chosen by the main players. Compared to past strategies, this system allows more effective refuelling networks and cost reduction. Refuelling stations represent a key point for the diffusion of FCEV technology (Grüger et al., 2018). One of the main constraints hindering their diffusion is the low number of installed and operational stations compared to classic refuelling stations.

At the end of 2020, 540 hydrogen refuelling stations (HRS) were in operation, including both public and private installations (Can Samsun et al., 2021). A continent-based analysis reveals that most HRSs were concentrated in Asia, with a total of 278, followed by Europe, with 190, and 62 in North America. The country with the highest number of stations was Japan (137). Germany (90) and China (85) have the second and third place, respectively, in this ranking. At the end of 2023, the country distribution was similar. Nowadays, the supply stations in operation are distributed mainly in Europe, the United States and

Japan. In the United States, 56 public stations are in operation, and 22 stations are in the planning stage. In the United States, the region with the highest concentration in quantity is California due to the involvement and support of the government and companies and the creation of the California Fuel Cell Partnership in 1999 to promote the development of fuel cell vehicles. There are 55 supply stations in California (https://h2fcp.org/by_the_numbers). In the European Union, there are 175 stations able to supply at high pressure and 134 able to supply hydrogen at low pressure. Figure 2 shows the segregation by country of stations able to supply at high-pressure (and low-pressure), for example, Germany has 85 (28) stations, France 21 (41), the Netherlands 23 (26), Switzerland 11 (10), the United Kingdom 6 (10), and other countries with less than 10 stations of any kind (https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/eu27-uk-norway-iceland-switzerland-turkey-liechtenstein). In Portugal, no station was reported, and only 4 in Spain (Figure 2). Nevertheless, at least one mobile station in the municipality of Cascais is currently active in supplying hydrogen to public transport buses.



Country	H2 High Pressure HRS	H2 Low Pressure HRS
Austria	5	
Belgium	8	4
Czech Republic	2	2
Denmark	3	1
France	21	41
Germany	85	28
Iceland	1	
Italy	1	2
Netherlands	23	26
Norway	2	
Poland	2	4
Spain	1	4
Sweden	4	2
Switzerland	11	10
United Kingdom	6	10
Total	**175**	**134**

Figure 2. The total number of hydrogen (H2) refuelling points by European country (2023) .

Research and development projects have also supported the increased number of HRS installations worldwide. Different authors have analysed the economic viability and conducted experimental activities on operating hydrogen stations. Some of these will be discussed in the following sections. Section 2 presents the literature search and review methods, and afterwards the main findings (Section 3), followed by the conclusions and references.

2. Literature search and review methods

The main aim of this work was a systematic literature review to identify and analyse published materials. A semi-structured literature review approach was adopted, aiming to analyse the state-of-the-art Hydrogen transport options for vehicle supply. This means that formal and systematic criteria for the literature search were partially applied.

The bibliographical search process was based on the analysis of two categories of published literature: (1) scientific literature, mainly articles in peer-reviewed scientific journals, and (2) some grey literature (to a lesser extent), such as government publications, reports, or thesis and dissertations. The search privileged mainly the former types of publications.

The methodology implemented involved two main phases (see Figure 3). The first phase refers to a two-tier iterative stage process, adopted starting by manually searching for the latest literature (2017–2024) in well-known sources and referenced journals. This was followed by the identification of more potentially relevant papers via a modified snowballing approach, i.e., by selecting potentially relevant publications amongst the ones included in the reference list in each published paper.

Figure 3. Overview of the methodological review process.

The following databases and online search tools were used for identifying relevant publications: Science Direct, Scopus, Web of Science, ResearchGate and Google Scholar. Regarding keywords, the following were introduced in the several search engines: hydrogen, refuel stations, Fuel Cell Electric Vehicles, hydrogen fuelling systems. This first phase led to a total sample size of 34 papers that were reviewed and analysed and 5 were used as reference.

The second phase involved a systematic search using Web of Science database. Table 1 presents a sequential overview of the process adopted in the second phase of the search and review process.

Table 1. Overview of the second phase of literature search and evaluation methodology of results adopted in the review.

Literature search criteria	Description	Comment
Criteria for inclusion	English-language publications searched in Web of Science.	Search was not restricted by time.
Literature identification	Search results obtained from using the following two strings: i) *Topic*: “hydrogen” and the following terms for *All fields*: AND “refuel stations” AND “hydrogen fuelling systems”; and ii) *Topic*: “hydrogen” and the following terms for *All fields*: AND “transportation hydrogen infrastructure” AND “Hydrogen refuelling station”.	The search results include repeated entries. Most of them due to publications being indexed in more than one journal/proceeding.
Screening for inclusion	This process involved the screening of title, abstract, keywords, and fitness of the topic related to HRS. Preference was given to review articles due to their compilation and summary of knowledge published.	Non-review articles were partially excluded, but according to the need to get deeper or to clarify certain sub-topics, original articles were also reviewed (i.e., further review was performed on as needed basis).
Quality and eligibility assessment	Scanning of pre-screened results were classified in high-quality outputs from reputable sources and low-quality sources.	Documents from low-quality and non-peer reviewed publications, and low-reputable publishers were excluded at this step. Preference was given to recent publications especially from 2017-2024.
Further screening	Grey literature and reports were also examined on as needed basis.	Attention was given to high-reputation and reliable organisations, like government publications, International Energy Agency (IEA), International Renewable Energy Agency (IRENA), United Nations (UN), among others. Information was included based on its relevance.

The search on the Web of Science produced 513 scientific papers published for the first string of terms (see Table 1), and their distribution over time is presented in the histogram below. It is evident that there has been a significant increase in publications on the target topic since 2019. The first publications related to hydrogen fuelling infrastructures were mostly on liquid hydrogen systems. Generally, researchers are increasingly interested in these energy systems, working on a wide range of diverse study areas, including equipment and technology innovation, station layout design, and data collection for performance testing.

The total number of review articles is 28 out of the 513 obtained. When further exclusions are applied for the topics of “aerial vehicles” and “nanomaterials”, 25 review articles are left and considered for review. Additional selected publications are also analysed on an as-needed basis in this document.

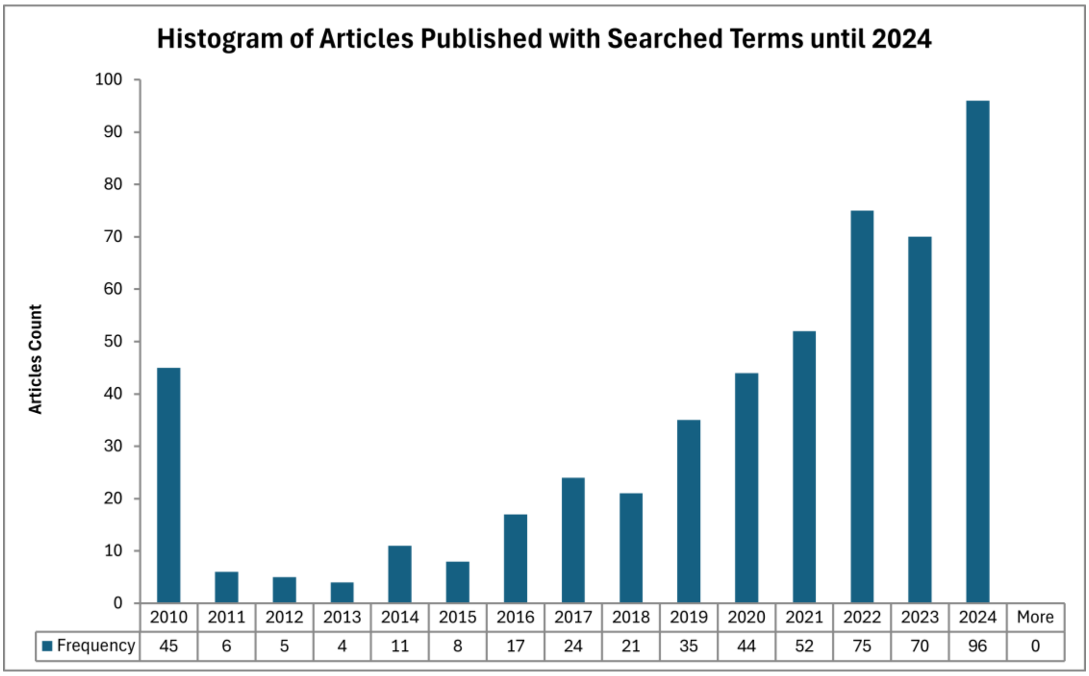


Figure 4. Histogram of articles count per year, published between 1998 and 2024, based on research terms in Web of Science database. Counts represented in 2010 are the sum of articles from 1998 to 2010.

The search on the Web of Science produced 141 publications for the second string of terms (see Table 1), from which 12 are review papers and are therefore considered for analysis. Eight over 12 papers were published between 2019 and 2024. In summary, the intersection of the two-phase search produced 28 papers for review after excluding duplicate papers. The following sections present the main information considered of interest and extracted from this final set of publications.

3. HRS systems

Fuelling stations are one of the most important parts of the hydrogen economy associated with the transport sector. Realising a clean hydrogen economy warrants the proper infrastructure to support it, and one of the critical components of a hydrogen infrastructure is HRSs.

3.1 HRS Classification

Hydrogen refuelling stations can be classified according to i) the location of the hydrogen production, ii) the hydrogen storage, iii) the construction form, and iv) the construction content (Tian et al., 2022).

i) According to the location of the hydrogen production

HRSs may comprise, on one hand, a local production of hydrogen, designed to supply, compress and store an amount of hydrogen adequate to meet the hydrogen demand. Hydrogen can be produced at the local refuelling station via reformers (i.e. SR, POX, etc.) or small-scale electrolysers, for example. On the other hand, hydrogen production can be off-site, produced in other locations, and transported to the HRS (Kurtz et al., 2019). In the latter case, hydrogen transport may be done through either one or a combination of the following methods: pipelines, tube trailers for gaseous hydrogen, and/or liquid hydrogen vessel trucks. For small quantities and short distances, delivery of gaseous hydrogen via tube trailers is usually the best option.

Furthermore, a complete characterisation requires information on the method or technology for producing hydrogen, such as water electrolysis or steam methane reforming.

ii) *According to the hydrogen storage*

HRSs may also be classified according to the type of storage and hydrogen storage state (Lahnaoui et al., 2018), i.e. the storage may be in gaseous or liquid forms, and it can be done in gas tanks or cryogenic tanks, for example. Furthermore, the storage can be permanent (i.e., stationary) or mobile, the latter, for instance, through trailers or trucks that are substituted every certain period of time, for example, daily. Currently, refuelling fuel cell vehicles from liquid hydrogen storage requires a pre-gasification process.

iii) According to the construction form

HRSs can be stationary or mobile according to their construction form (Sun et al., 2014). Stationary HRSs cannot be moved and are more commonly used (Tian et al., 2022). Mobile HRSs may help achieve some flexibility according to demand and location. They are usually skid-mounted and can be modular, allowing connection to other HRS networks (stationary or mobile).

iv) According to the construction content

HRSs can form part of a wider refuelling and charging system, in this case, the service refuelling station is said to be a hybrid or combined one, which might provide the refuelling of oil-based fuels, charging of electric vehicles, and hydrogen refuelling systems (Tian et al., 2022). Furthermore, there might be dispensers for internal combustion engines (ICE) that could handle a mixture of natural gas-hydrogen or oil-hydrogen, for example. This would also fit in the hybrid or combined (re)fuelling station. In contrast, HRSs might comprise only hydrogen dispensers. In this case, the refuelling station is considered an HRS independent station.

3.2 HRS Components and configuration

HRSs usually comprise hydrogen production, compression, storage, refuelling and control systems (Tian et al., 2022). Each system must also comply with strict safety protocols and components. The components or equipment comprising such systems depend on the configuration, mainly associated with the HRS handling gaseous and/or liquid hydrogen. Figure 5 shows some schematic configurations of HRSs (Abdin et al., 2020). When hydrogen is produced and consumed on-site, it is produced in a gaseous state, so the liquid form is usually not considered. Furthermore, Table 2 summarises the main components of a gaseous HRS. It does not consider the water electrolysis system.

The basic components of an HRS using gaseous hydrogen are the hydrogen production unit, the purification unit to achieve at least 99.97% purity hydrogen (some regulations require even higher purity of 99.999%), high-pressure hydrogen compressors, storage tanks (for both gaseous and liquid hydrogen), pressure regulators, a cooling unit to decrease the hydrogen temperature for safety reasons while refilling vehicle's tank, safety features (such as pressure relief valves, sensors, and fire suppressants), and dispensers to supply high-pressure hydrogen. The pre-cooling of hydrogen is needed only for passenger cars, which run on higher-pressure ranges, not for HRS for buses that have significantly bigger storage tanks (typically between 30 and 50 kg of H2) and operate at lower pressures.

Most stations for passenger cars operate at 700 bar, and bus stations normally use 350 bar. The HRS Availability Map (https://h2-map.eu/) of The Clean Hydrogen Partnership (former Fuel Cells and Hydrogen 2 Joint Undertaking - FCH 2 JU) of the European Commission indicated 188 public HRS stations in Europe, of which 175 stations provide 700 bars for passenger cars, 55 provide 350 bar, also for passenger cars, and 73 provide 350 bar for buses (retrieved on 30/07/2024). Several stations offer more than one pressure level possibility. In 2021, some of the stations in Europe funded by the FCH 2 JU were analysed regarding the hydrogen delivery system. Nine of the 350-bar, three of the 700-bar stations and six of the dual stations (350 and 700 bar) operated with hydrogen produced off-site; six of the 350-bar and ten 700-bar stations with on-site-produced hydrogen (Can Samsun et al., 2021).

Genovese & Fragiacomo (2023) present two possible HRS configurations for H2 gas dispensing HRS: HRS layout with cascade refuelling process and HRS layout with a booster dispensing compressor (Figure 6 and Figure 7). The main difference between the two configurations is associated with the compression units and pressure levels, which would require at least two compression stages and a high-pressure buffer tank in the configuration with the booster compressor. Being the cascade refuelling configuration simpler, with the only compression stage working at high-pressure connected to a high-pressure storage tank.

Considering HRSs with liquid hydrogen and the dispensing to the FCEVs being in gaseous form, the main components are similar to a gaseous HRS. Major differences are associated with the need for cryogenic storage tanks and evaporator systems to gasify the liquid hydrogen before buffer storage in gaseous form and the potential need for a cryogenic pump. Genovese & Fragiacomo (2023) present at least two HRS configurations: HRS layout with evaporator/heat exchanger and HRS layout with cryogenic pump, as shown in Figure 8 and Figure 9. In the configurations shown, the liquid hydrogen is supplied to the refuelling station through liquid hydrogen trucks, transferring the liquid hydrogen to cryogenic tanks, where it is stored. In these two HRS layouts, gaseous hydrogen is obtained through a heat exchanger by the evaporation of liquid hydrogen, which is stored afterwards in high-pressure tanks (Ravi & Aziz, 2022).

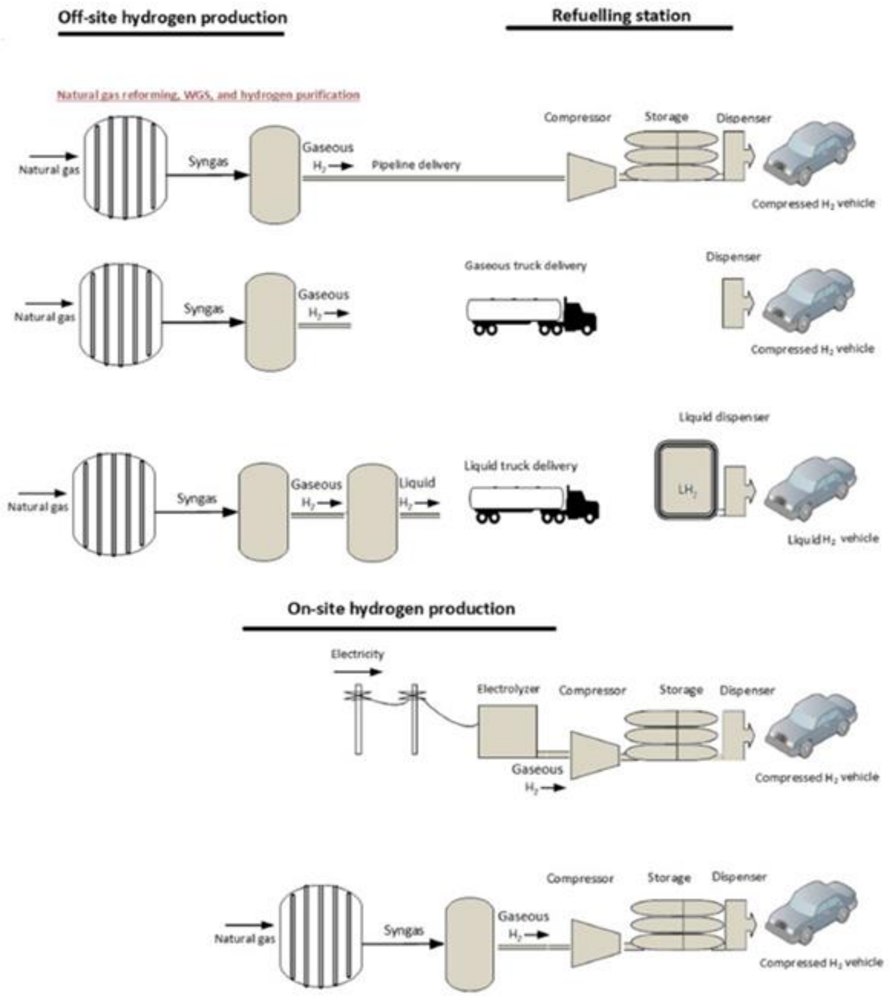


Figure 5. Hydrogen Refuelling Stations (HRSs) classification options considering hydrogen production and storage (Abdin et al., 2020).

Table 2. Main components of a gaseous HRS.

Component	Type / Characteristics	Main Typical Operational Conditions	Observations
Compressor	Some examples of types: **Mechanical compression**: i) piston, ii) diaphragm, iii) linear, iv) ionic liquid compressors (Sdanghi et al., 2019). **Non-mechanical compression**: i) cryogenic, ii) metal hydride, iii) electrochemical, iv) adsorption compression.	Compressors should reach compression levels according to the storage pressure. Typically, about 900-950 bar for dispensers operating at 700 bar, or about 500 bar for dispensers operating at 350 bar.	It dominates the HRS costs(Bhogilla & Niyas, 2019).
Storage vessel	Transport vessels are typically classified as Type I, II, III, and IV. They are usually made of metallic material, but they can also have non-material components or be completely made of non-metallic materials. Vessels Type III and IV are usually used in mobility applications, while Type I and II are more intended for stationary systems (Hunt et al., 2023).	The HRS buffers operate typically between 500 and 950 bar. In general, low-pressure vessels are considered those with pressure between 100 to 300 bar, medium-pressure vessels between 300 and 400 bar, and high-pressure vessels between 400-1000 bar (Tian et al., 2022).	The hydrogen storage vessel is a core component that determines the hydrogen supply capacity (Tian et al., 2022).
Pre-cooling unit (PCU)	APCU is based on typical thermodynamic refrigeration cycles, which include a (two-stage) compressor, condenser, thermostatic expansion valve, and evaporator heat exchanger (Elgowainy et al., 2017).	Protocol SAE J2601 requires pre-cooling hydrogen to be between -33 and -40 ºC before distribution to limit vehicle vessel temperature below its maximum value (85 ºC) during rapid filling (Tian et al., 2022).	The cost of the pre-cooling unit accounts about 10% of the total equipment costs in HRSs (Reddi et al., 2017). Two major factors affecting the refrigeration performance are the Joule-Thomson expansion process (or throttling effect) at the variable area control device (VACD) in the pre-cooling system and the filling capacity requirements, especially at expected peak hours (Elgowainy et al., 2017).
Dispenser **(Hydrogen filling system)**	A dispenser has several components integrated, such as high-pressure pipelines, pneumatic shut-off valves, explosion-proof solenoid valves, electronic pressure regulations, gas guns, temperature and pressure sensors, mass flow meters, monitor, sequential gas monitor control panel and controller (Tian et al., 2022). The design of the dispenser must allow a safe and quick filling of hydrogen at the right conditions and be able to detect faults and leakages and act accordingly. Dispensers may have only one or multiple filling units. They can operate at only one filling pressure or be designed to operate at 350 and 700 bar.	Dispensers typically operate at 350 or 700 bar.	It is a core component and interface equipment between the HRS and the hydrogen-fuelled vehicles.

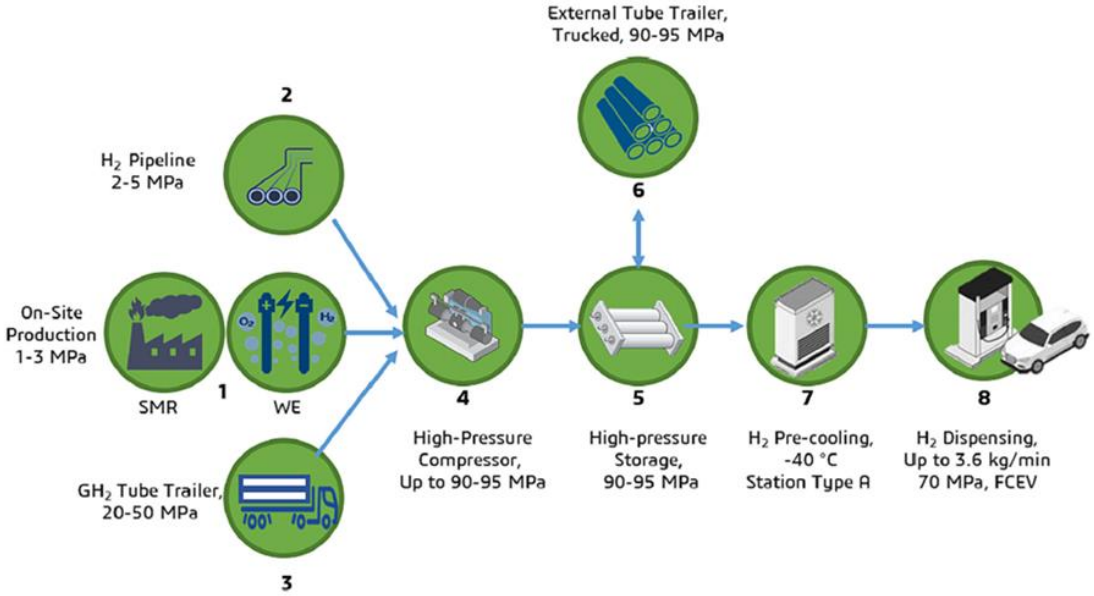


Figure 6. HRS layout with cascade refuelling process for gaseous hydrogen (Genovese & Fragiacomo, 2023).

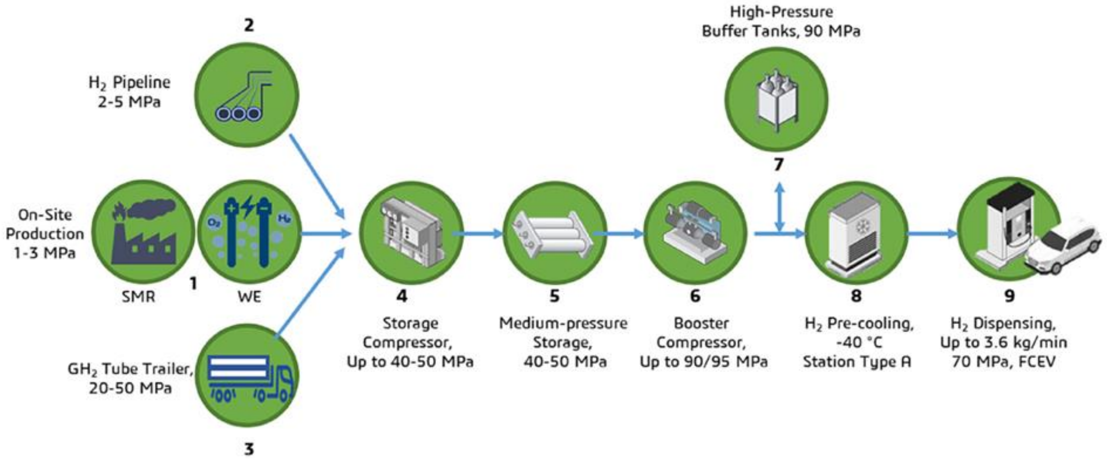


Figure 7. HRS layout with a booster dispensing compressor for gaseous hydrogen (Genovese & Fragiacomo, 2023).

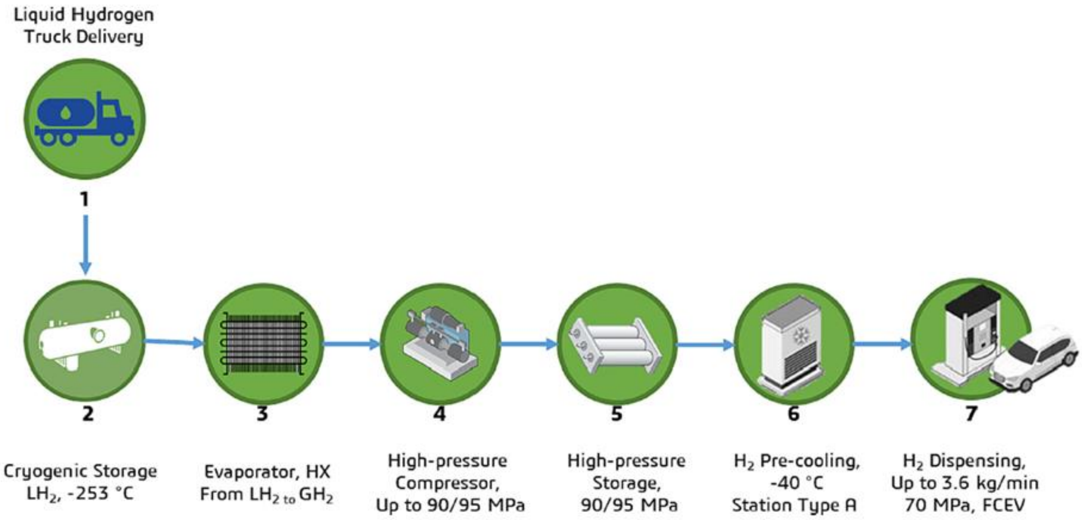


Figure 8. HRS layout with evaporator/heat exchanger for liquid hydrogen (Genovese & Fragiacomo, 2023).

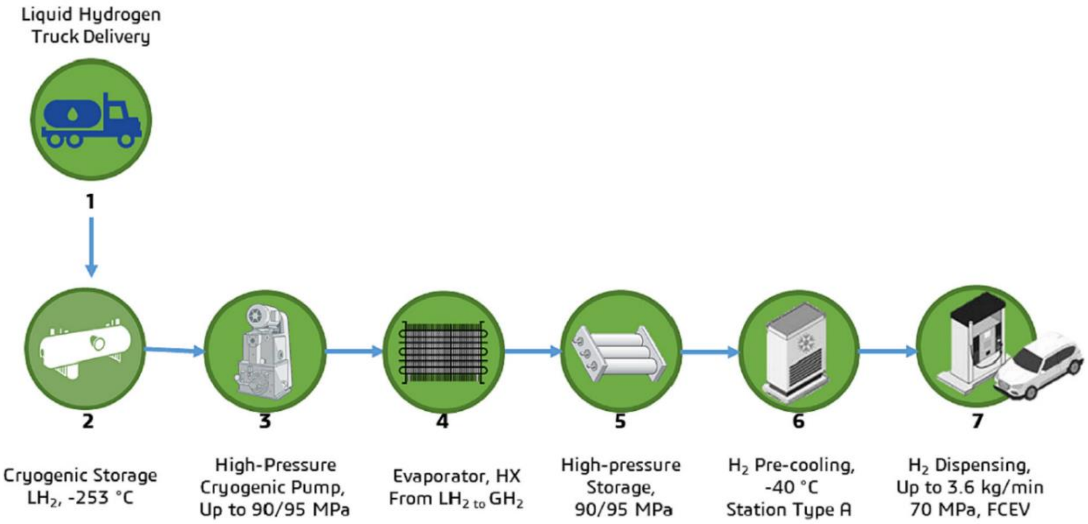


Figure 9. Liquid hydrogen storage: HRS layout with cryogenic pump for liquid hydrogen (Genovese & Fragiacomo, 2023).

In the analysis made by Genovese & Fragiacomo (2023) of the different configurations of refuelling stations. They highlighted some strengths and weaknesses of each of them and concluded that whatever the volume of data and information acquired, there is not an ideal system for hydrogen stations as it depends highly on the surrounding circumstances and geopolitical situations and, also, on the local market scenarios, the number of cars to be supplied daily, distances from centralised hydrogen production centres, supply choices, regulations, and local standards (Genovese et al., 2022).

For example, depending on the hydrogen amount and distance, it can be transported from production facilities to retailers differently. The hydrogen to refuelling stations could be supplied by each of these means:

1) hydrogen can be transported from a centralised hydrogen production facility via gaseous trailers (hydrogen pressure levels for gaseous truck transport range over 35 MPa–50 MPa), liquefied trucks, or pipelines. On the other hand, liquid hydrogen

trucks are preferred for long distances and average hydrogen amounts. The typical tanker capacity is 400–4000 kg of liquid hydrogen; however, boil-off can occur during liquid hydrogen transport.

Regarding the hydrogen transport network, pipelines were about 5000 km long in 2022 (Ravi & Aziz, 2022). However, the efficient transportation of hydrogen would require a much more extensive and widespread network, with the increase in infrastructure costs. Comparatively, the global natural gas network has a transport and storage capacity of over 100 GWh, which has been attracting a lot of attention to the possibility of using the same network for hydrogen transportation (Ravi & Aziz, 2022). One fundamental advantage highlighted in hydrogen injection through the existing natural gas pipelines is that mixing hydrogen with natural gas will contribute to GHG emissions reduction, especially when the hydrogen is produced from renewable energy sources. This strategy will significantly decrease the infrastructure investment cost needed so it can play a decisive role in the transition toward a hydrogen economy, especially in its early stages (Ravi & Aziz, 2022).

3.3 HRS Simulation and optimisation

Results from a simulation tool of a gaseous HRS coded in Matlab/Simulink have been presented and validated through real HRS, including water electrolysis production, compression, storage, dispensing unit and vehicle fuelling (Riedl, 2020). That work provides a mathematical description of components.

Other tools besides Matlab/Simulink presented in the literature are those developed in the open-source object-oriented acasual and equation-based language Modelica. Some works related to the optimisation of hydrogen vehicle refuelling and energy consumption in cascade fuelling stations using Modelica language and the commercial platform Dymola were presented by Rothuizen et al. (2013) and Rothuizen & Rokni (2014). In the former, it was reported that one of the main factors affecting the mass flow and peak cooling requirements in the refuelling process was the pressure loss in the vehicle's storage system. Furthermore, the design of the HRS does not influence the refuelling process when the SAE J2601 requirements are met. Regarding the energy needs of the HRS, it was observed that by having multiple pressure stages instead of a single high-pressure tank, both the energy for cooling and compressors could be reduced by 12% and 17%, respectively. In the latter reference, it was concluded that the optimal number of tanks regarding the energy consumption in an HRS was three to four. It was shown savings of approximately 30% in the energy consumption for three tanks, and the marginal saving afterwards was only 4%.

Other dynamic models implemented in Modelica language have been reported in the literature to assess the trade-off of benefits and risks of HRS (Kawatsu et al., 2022, 2024; Suzuki et al., 2021). These types of studies were driven by the numerous HRS accidents reported worldwide and the need to quantify risks so risk-informed decisions can be made, for example, to determine safety distances or risk mitigation measures and to study HRS systems under faults or leakages.

Xie et al. (2024) present a summary of different tools for the risk assessment of HRSs. These tools use a combination of risk assessment methodologies, such as Event Tree Analysis (ETA) or Fault Tree Analysis (FTA), and fluid and thermo-fluid simulation tools and methods, such as PHAST, FLACS, GASFLOW-MPI, and Modelica-based dynamic models. Hydrogen risk assessment models, such as HyRAM, HyRAM+, and HyKoRAM, PHAST + Safeti, are widely used in HRS projects. Xie et al. (2024) present a probabilistic assessment method that considers the uncertainties of people's locations and the probability of occurrences of various events (failure of components, shutdown failure, leakages isolation, ignition, occupation of the location). They conclude that there are potentially significant differences in the quantification of risks in the comparison of their methodology and other methods. Furthermore, they recommend including the quantification of the uncertainty of the number of fatalities due to the randomness of the occupation of the HRS location. Complementarily, Zhang et al. (2024) present an evaluation of the safety resilience of HRS based on an improved TOPSIS approach. They propose a series of resilience indicators that grasp, based on the authors, the ability of the HRS to adapt to various uncertainties, not only in post-disaster response but also those related to daily operation aspects based on a safety and resilience thinking perspective.

3.4 Planning of HRSs and coupling power-hydrogen-transportation networks

The objectives to become carbon neutral have increased significantly the interdependency of electric power, hydrogen fuel, and transportation networks (Y. Zhou et al., 2024). The integration and holistic assessment of these interdependencies present some gaps that will need to be addressed soon. Y. Zhou et al (2024) highlight that the transportation network is represented by flexible users of electric vehicles (EVs) and hydrogen fuel cell ones (HFCEV), which require electric charging stations for the EVs and HRS for the HFCEVs. Furthermore, they highlight the negative effect that may pose the random charging behaviour on the power network that could be mitigated through pricing strategies (e.g., time-of-use pricing) and intelligent dynamic systems, while the excess renewable energy output could be directed to the production of hydrogen fuel. Nevertheless, the latter strategy might not result in significant gains regarding the LCOH, if the water electrolysis project relies merely on the curtailed energy from renewable sources, only under very stringent conditions would such projects become economically viable (Troncoso & Newborough, 2011). The integration of power-hydrogen-transportation networks can increase efficiencies in all three systems, but there are some challenges (Y. Zhou et al., 2024) that are more notorious for the EV charging network due to their greater usage compared to HFCEVs.

3.5 HRS Location

Infrastructure planning regarding the location and size of HRSs is an unavoidable aspect within the hydrogen economy and its use in the transport sector. Coomonte et al (2024) presented a literature review focused on the location of HRSs. Neumann et al. (2020) presented an infrastructure location model linking HRS and energy systems, which is deemed important for efficient and effective hydrogen production and distribution to satisfy the hydrogen demand in FCEV (Coomonte et al., 2024). Crönert and Minner (2021) presented a model to solve the location problem of HRSs to maximise capture of final users (Coomonte et al., 2024). Shukla et al. (2011) proposed a model to determine the best locations for HRSs that considered factors such as demand, cost, and accessibility (Coomonte et al., 2024). Furthermore, Kavadias et al. () studied the sizing, optimization and economic feasibility of green hydrogen HRS in remote locations (Coomonte et al., 2024).

The California Air Resources Board (CARB) has developed the California Hydrogen Infrastructure Tool (CHIT), which is a web-based GIS tool (California Hydrogen Infrastructure Tool (CHIT) | California Air Resources Board) to aid in HRS location decision-making and encompasses data of existing and planned HRS, and the potential demand of hydrogen for transport in different regions (Coomonte et al., 2024).

Zhen et al. (2024) applied a novel approach for the HRS location optimisation problem considering the integration of network planning and hydrogen scheduling. It addresses the size and location of HRS alongside the management of supply relations and hydrogen transportation scheduling (Zhen et al., 2024). The model incorporates uncertainty factors regarding hydrogen demand by using a two-stage multi-period stochastic programming (MILP) model with the objective of minimizing both the construction and operational costs under variable demand scenarios. The authors' contribution is focused on a proposed metaheuristic algorithm compared to results using CPLEX for sample cases. Results showed small differences in the use of the two approaches but with a significant decrease in computation time for the proposed algorithm. The problem is a complex one due to the link between long-term decisions associated with the construction of the HRS network and the short-term decision of transportation scheduling.

J. Zhou et al. (2024) presented an interesting study that reviewed about 20 models for optimizing HRS location in urban areas, freeway intersections, general roads, and highways. The research study focused on China and considered two models. Both considered the integration of hydrogen sources and transportation. Furthermore, one of the models involved the co-location of other fuels' refuelling and HRS (J. Zhou et al., 2024).

Figure 10 depicts a scheme of the operation of HRS in expressways. The following table presents the known parameters considered for the reference cases. The objective function was defined as the minimization of the unit hydrogen cost. The two models were designed and compared. One is continuous, named HTCM, and the other is discrete, named HTDM, both treated as mixed integer nonlinear programming models (MINPL). The programming was done in the General Algebraic Modelling

System (GAMS) software, and the Simple Branch and Bound (SBB) solver was used for the optimisation (J. Zhou et al., 2024). Results showed that HTCM has lower unit hydrogen costs than HTDM. For the same reference case considering the maximum allowable spacing between HRSs, the optimal unit of hydrogen cost was 50.44 CNY/kgH2 at the maximum allowable spacing of 300 km for the HTCM; and for the HTDM was 51.13 CNY/kgH2 with a 340 km spacing.

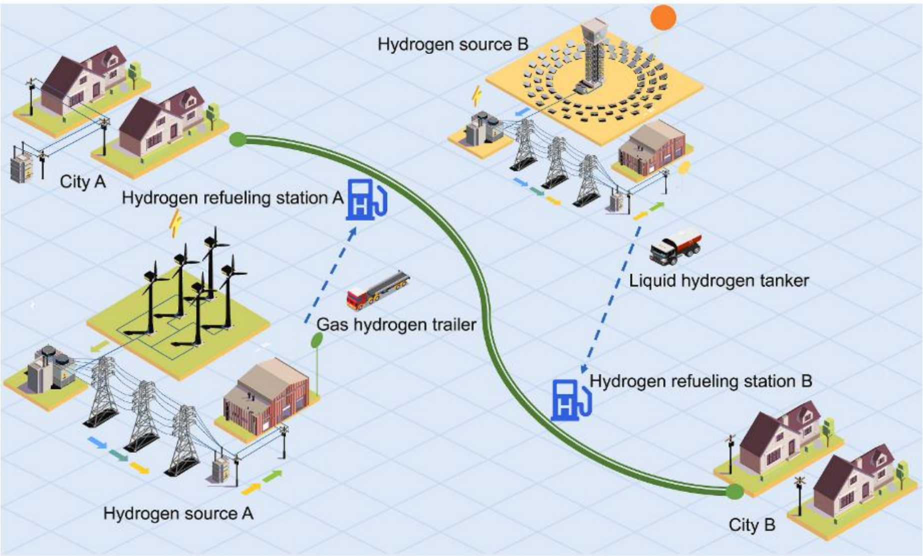


Figure 10. Schematic representation of the operation of HRSs along an expressway (J. Zhou et al., 2024).

Table 3. Parameters considered for the optimisation problem (J. Zhou et al., 2024).

Parameter Group	List of Parameters
Hydrogen Refuelling Stations (HRSs)	Hydrogen demand for HRSs; construction investment cost of HRSs; annual operational costs of HRSs; discount rate and depreciation lifespan of HRSs; annual operating days for HRSs; the minimum and maximum allowable spacing between HRSs.
Hydrogen Sources (HSs)	Coordinates of HSs; daily production capacity of HSs; price of hydrogen.
Transportation	Transportation price; drivers' daily wages; driver's daily working hours; transportation capacity of the vehicle; average speed of the vehicle; Loading/unloading duration.
Non-buildable sites (restricted areas, such as bridges, lakes, etc.)	Coordinates of non-buildable sites; the radius of the non-buildable region.

The models' brief description presented in this section was a selection to show the models' complexity involved in the optimisation of HRS location considering multi-variate analysis. The reader is referred to the recent works introduced above for more details and links to other related publications.

3.6 Costs of HRSs and price of hydrogen

The cost of tube trailers has been reported in the literature. In 2018, it reported different tube trailer configurations, according to their capacities and costs (Reddi et al., 2018). For example, the cost reported for one 1000 kgH2 tube trailer is about 1150 US$ (~978 EUR). These costs were reported in 2018.

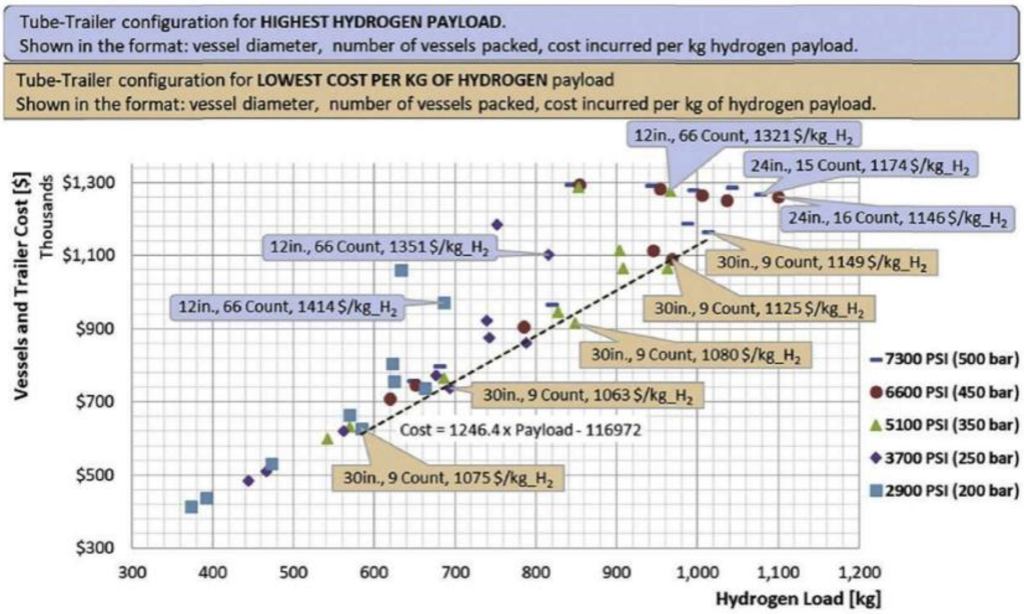


Figure 11. Tube trailer payload and final cost for different configurations (Reddi et al., 2018).

HRS costs have been also reported in the literature. For example, in Japan the CAPEX of an HRS with dispensing pressure of 700 bar was about 330 million JPY (2.7 million EUR) with OPEX of about 10% of CAPEX in year 2020 (Eichman et al., 2016). In China, the CAPEX cost of one HRS is about 15 million CNY (1.9 million EUR), including land costs, being highlighted that the compressor, the storage tank and refuelling system represent the three main cost components, with the highest being the compression system with about 32% (Eichman et al., 2016).

Caponi et al. (2022) reported that the levelized cost of hydrogen (LCOH) of HRSs with on-site hydrogen production was found to have LCOH due to savings in the retail of hydrogen and transport with a reduction in LCOH of 35%. The study focused on large-scale applications. Results also showed that hydrogen delivery costs can be reduced by 30% with the use of high-capacity trailers in off-site hydrogen production scenarios (Caponi et al., 2022).

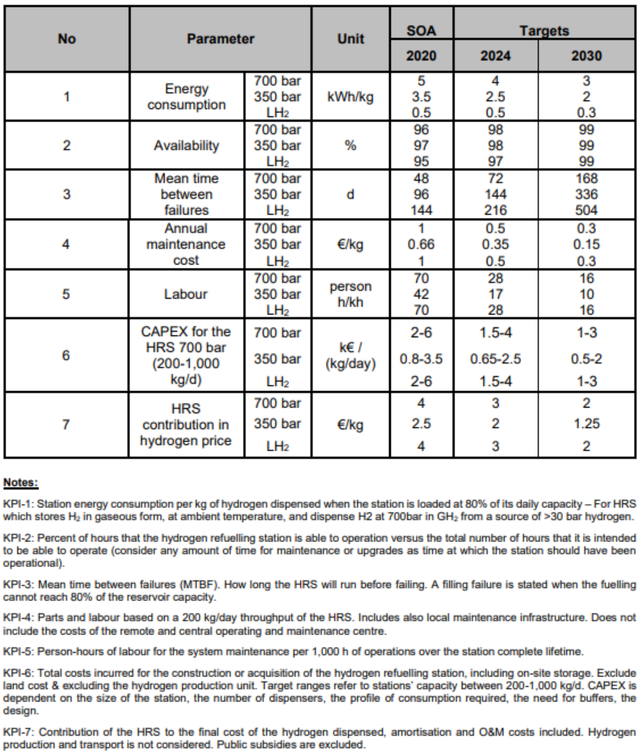
The Clean Hydrogen Partnership reported different sets of data regarding costs and performance about HRSs with target values for 2024 and 2030.

Figure 12 presents the reproduction of Table 15 of the report accounting for the key performance indicators (KPIs) considered for HRSs. The CAPEX of HRSs expected by 2024 are 0.65 to 2.5 kEUR/kgH2-day for stations operating at 350 bar, for those operating at 700 bar using compressed gas or liquid storage are 1.5 to 4 kEUR/kgH2-day (Clean Hydrogen Partnership, 2022).

Genovese et al. (2023) worked further on the information presented in

Figure 12, and elaborated a graph for the HRS contribution to hydrogen price linked to HRS design capacity. Figure 13 presents this KPI) for HRS operation at 300 and 700 bar, and those handling liquified hydrogen.

The costs of compression systems for HRS and purification units have been also reported by The Clean Hydrogen Partnership. CAPEX for HRS compressors have been estimated at 7700 EUR/kW in 2020 and is expected to become 5600 EUR/kW in 2024 (Clean Hydrogen Partnership, 2022). Regarding OPEX, values of 0.1 and 0.07 EUR/kgH2 were reported for 2020 and 2024, respectively. Furthermore, purification units were reported as 1.5 and 1 EUR/kgH2 for 2020 and 2024, respectively. The energy consumption for these units was in the order of 4 and 3.5 kWh/kgH2 in 2020 for separation and purification, respectively. For 2024, these costs are expected to become 3.5 and 3 kWh/kgH2 accordingly.



No	Parameter		Unit	SOA	Targets	
				2020	2024	2030
1	Energy consumption	700 bar	kWh/kg	5	4	3
		350 bar		3.5	2.5	2
		LH_2		0.5	0.5	0.3
2	Availability	700 bar	%	96	98	99
		350 bar		97	98	99
		LH_2		95	97	99
3	Mean time between failures	700 bar	d	48	72	168
		350 bar		96	144	336
		LH_2		144	216	504
4	Annual maintenance cost	700 bar	€/kg	1	0.5	0.3
		350 bar		0.66	0.35	0.15
		LH_2		1	0.5	0.3
5	Labour	700 bar	person h/kh	70	28	16
		350 bar		42	17	10
		LH_2		70	28	16
6	CAPEX for the HRS 700 bar (200-1,000 kg/d)	700 bar	k€ / (kg/day)	2-6	1.5-4	1-3
		350 bar		0.8-3.5	0.65-2.5	0.5-2
		LH_2		2-6	1.5-4	1-3
7	HRS contribution in hydrogen price	700 bar	€/kg	4	3	2
		350 bar		2.5	2	1.25
		LH_2		4	3	2

Notes:

KPI-1: Station energy consumption per kg of hydrogen dispensed when the station is loaded at 80% of its daily capacity – For HRS which stores H_2 in gaseous form, at ambient temperature, and dispense H2 at 700bar in GH_2 from a source of >30 bar hydrogen.

KPI-2: Percent of hours that the hydrogen refuelling station is able to operation versus the total number of hours that it is intended to be able to operate (consider any amount of time for maintenance or upgrades as time at which the station should have been operational).

KPI-3: Mean time between failures (MTBF). How long the HRS will run before failing. A filling failure is stated when the fuelling cannot reach 80% of the reservoir capacity.

KPI-4: Parts and labour based on a 200 kg/day throughput of the HRS. Includes also local maintenance infrastructure. Does not include the costs of the remote and central operating and maintenance centre.

KPI-5: Person-hours of labour for the system maintenance per 1,000 h of operations over the station complete lifetime.

KPI-6: Total costs incurred for the construction or acquisition of the hydrogen refuelling station, including on-site storage. Exclude land cost & excluding the hydrogen production unit. Target ranges refer to stations' capacity between 200-1,000 kg/d. CAPEX is dependent on the size of the station, the number of dispensers, the profile of consumption required, the need for buffers, the design.

KPI-7: Contribution of the HRS to the final cost of the hydrogen dispensed, amortisation and O&M costs included. Hydrogen production and transport is not considered. Public subsidies are excluded.

Figure 12. KPIs for HRSs (Clean Hydrogen Partnership, 2022).

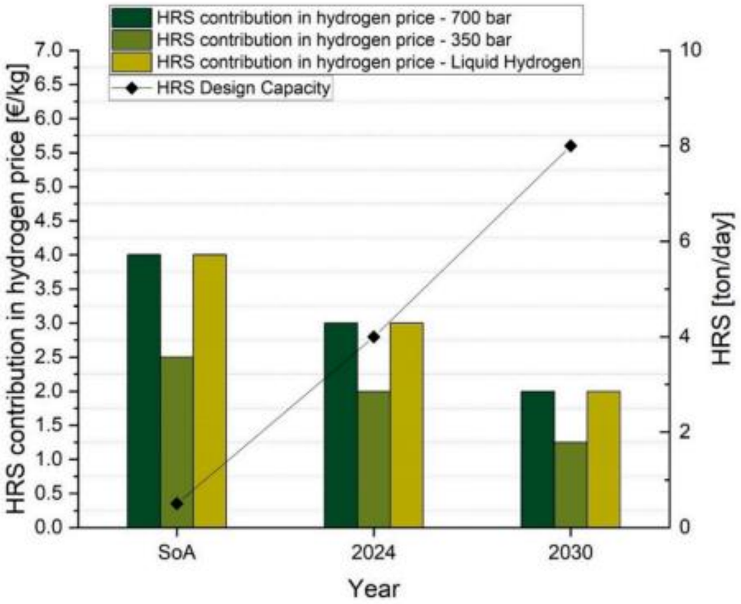


Figure 13. Hydrogen station, CAPEX, KPI in Europe (a), energy consumption, KPI in Europe (b), and contribution to H2 Price & HRS Size (c) (Genovese & Fragiacomo, 2023).

The price of hydrogen in public German and Austrian stations managed by H2Mobility are 12.85 EUR/kgH2 for both 350 and 700 bar fuelling (Our H2-stations - H2Mobility (h2-mobility.de)). H2Mobility has the goal of achieving 100% green hydrogen by 2028. In contrast, prices were already lower than nowadays, the price in Germany per kgH2 was 9.50 EUR in 2021 (Platts launches hydrogen pump prices in Germany, Japan and California | S&P Global Commodity Insights (spglobal.com)). This price increase is suspected to be partially by the "ramp-up of green hydrogen" strategy (i.e., gradual increase of green hydrogen) in H2Mobility's HRSs.

4. Conclusions

The success of the implementation of a hydrogen economy is facing several obstacles. One of them is the lack of suitable and connected infrastructure and the high initial investment cost. So, hydrogen refuelling stations (HRSs) must be fully implemented as they are one of the most important parts of the hydrogen economy. The ongoing research in hydrogen fuelling stations focuses on improving the efficiency and safety of the hydrogen storage and distributing systems and developing new and sustainable methods for producing hydrogen on-site. Complex logistic and infrastructure planning models are designed for HRS location planning, while other thermodynamic and Multiphysics models are more concerned with increasing efficiency and safety and decreasing costs. All these efforts are directed to achieve the techno-economic feasibility of hydrogen use in the transport sector. Overall, this brief overview of HRSs current research, concepts, and layouts provides information and insights to understand the current state of hydrogen fuelling infrastructure and its influence on transportation, energy systems and the environment.

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