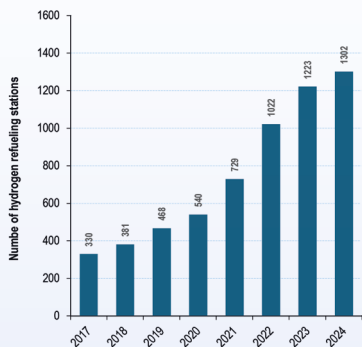
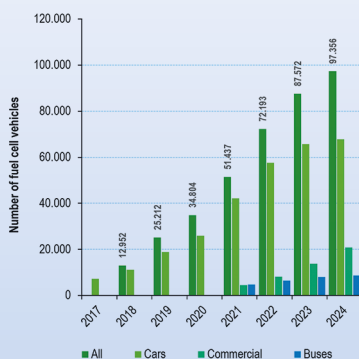




IEA Technology Collaboration Programme
Advanced Fuel Cells



Deployment of Fuel Cell Vehicles in Road Transport and the Expansion of the Hydrogen Refueling Station Network

Thomas Grube, Marietta Sander

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Deployment of Fuel Cell Vehicles in Road Transport and the Expansion of the Hydrogen Refueling Station Network

– 2025 Update –

Thomas Grube, Marietta Sander (Editors)

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1 Deployment of Road Vehicles with Fuel Cells and the Expansion of the Hydrogen Refueling Station Network

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1.1 Abstract

This report is the 2025 update in our series on the global status of fuel cell vehicle deployment in road transport. It also covers the status of hydrogen refueling stations. This information is based on the comprehensive data collected by the International Energy Agency's (IEA) Technology Collaboration Programme on Advanced Fuel Cells in early 2025. The data presented in this report indicate that the global fuel cell vehicle fleet is approaching 100,000 units. The hydrogen refueling network now includes more than 1300 stations. South Korea remains in the leading position, accounting for 36% of the total 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 global fuel cell bus fleet and between 88% and 98% of the light, medium and heavy-duty vehicle fleets. It is also noteworthy that 92% of fuel cell vehicles are operated in just four countries, namely South Korea, China, the USA and Japan. By segment, fuel cell passenger cars clearly dominate with 69% of all fuel cell vehicles. The most recent deployment of fuel cell vehicles has clearly prioritized heavy-duty trucks, with numbers increasing by 72% compared to 2023. When it comes to the network of hydrogen refueling stations, China is once again in the lead, accounting for 522 of the 1302 stations worldwide. With significantly lower numbers of stations, South Korea and Japan are in second and third place. However, the growth of fuel cell vehicles and hydrogen refueling station numbers has slowed significantly. The main reason for this is the market success of battery-electric vehicles in most road vehicle segments.

1.2 Introduction

Powering fuel cell electric vehicles with green hydrogen produced from renewable sources is a true zero-emission transport solution. It complements battery electric propulsion in situations where continuous high power is required, and only short interruptions are permitted. Examples include heavy long-distance transport and the operation of heavy non-road mobile machinery. It could also be used for high-speed, long-distance passenger transport by car. Compared to battery-electric powertrains, fuel cell systems are less affected by the weight and volume constraints of heavy-duty transport. Therefore, fuel cell powertrain technology is well-suited to transitioning the transport sector towards greenhouse gas neutrality and zero-emission

performance. Therefore, it is important to monitor the deployment of fuel cell vehicles around the world, including the status of the hydrogen refueling station network, as this is an indicator of the practical usability of hydrogen cars.

This report is based on data from 2024 collected in early 2025 [1–32], and provides an update on our 2024 analysis with the latest findings. The report provides an update on the worldwide status of fuel cell vehicles and hydrogen refueling stations, which has been reported on annually since 2018 by members of the Advanced Fuel Cell Technology Collaboration Programme (AFC TCP) [33–39]. The focus is on regional and country-specific developments, considering different categories of road vehicle. Furthermore, development trends based on the previous year's data are analyzed.

The following section 1.2 presents the most recent data on global fuel cell vehicle deployment. It includes a comprehensive and detailed data analysis, also presenting a breakdown of the numbers across vehicle categories, world regions, and countries. Subsequently, section 1.3 examines the hydrogen refueling station infrastructure by region. Consequently, section 1.4 provides a more detailed analysis of the data, presenting the historic development of fuel cell vehicles and hydrogen refueling stations over the past seven years.

1.3 Total Fuel Cell Vehicle Fleet

According to this year's update of the AFC TCP Data Survey, the number of fuel cell electric vehicles (FCEVs) in operation reached 97,356 by the end of 2024, an 11% increase from the vehicle 2023 fleet, according to the 2024 update [39]. The distribution among countries with at least 100 FCEVs is shown in Figure 1-1. The largest shares were found for South Korea with 36% and China with 28%, followed by the US and Japan with 19% and 9% respectively. These four countries account for 92% of the total FCEV fleet worldwide. In Europe, Germany has the largest fleet with nearly 2,600 vehicles. France has the second largest fleet with 1804 vehicles, followed by the Netherlands and the United Kingdom with 672 and 500 vehicles, respectively. These four countries account for 81% of the total European fleet. Other European countries with FCEV fleets of more than 100 vehicles include Switzerland, Norway, Poland, Spain and Belgium. On a global scale, countries with fleets of more than 100 FCEVs are Canada (418 FCEVs) and Australia (198 FCEVs). India, which was among these countries in our 2024 update, was reported with only 58 FCEVs this time. Reasons for this decrease could not be deduced. Operational FCEV fleets of 51 to 100 vehicles are in Italy, Austria, India, and Sweden. 11-50 vehicles are operational in Iceland, Czech Republic, Denmark, Costa Rica. Luxembourg, Portugal, Brazil, Slovakia, Estonia, Lithuania and Bulgaria report up to 10 FCEVs.

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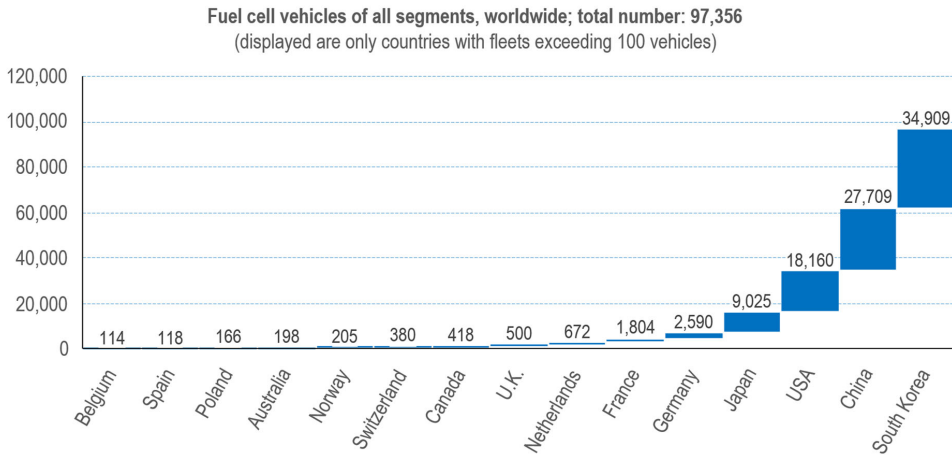


Figure 1-1. Country-based distribution of fuel cell vehicles on the road at the end of 2024.

The distribution of fuel cell vehicles by world region is shown in Figure 1-2. The respective results of our previous updates are still valid, with slightly shifted percentages: the majority of FCEVs are located in Asia, which accounts for almost three quarters of the global fleet. North America accounts for almost a fifth, while Europe has a much smaller share of 6%. Australia and Latin America have negligible shares of the global FCEV fleet.

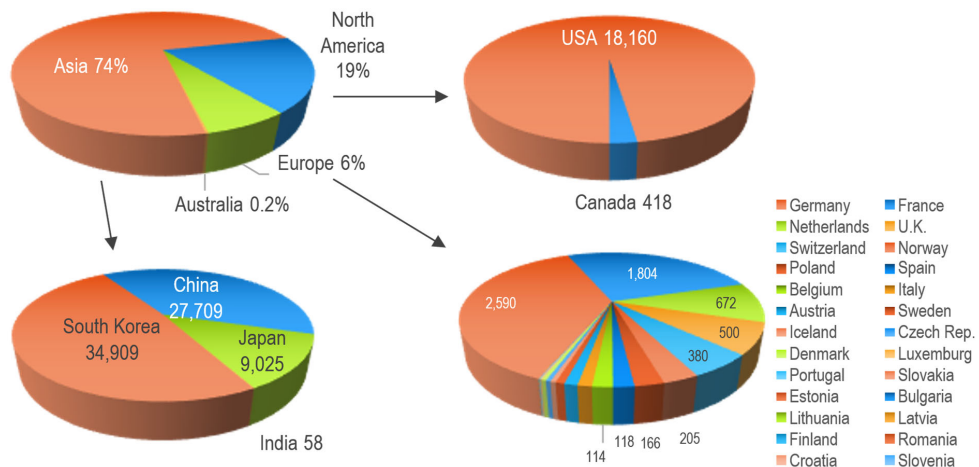


Figure 1-2. Distribution of fuel cell vehicles of all categories by world region as of the end of 2024.
Latin America is not displayed in the figure because of a fleet of only 19 vehicles.
Total fuel cell vehicle number worldwide: 97,356.

Before providing details on the distribution of vehicles between market segments, we first provide the respective definitions of the relevant vehicle categories. Table 1-1 illustrates the

vehicle segments relevant to this analysis. Apart from fuel cell passenger cars, we look at fuel cell buses (FCBs) with more than eight seats for transporting passengers, light commercial fuel cell vehicles (FC-LCVs) with a mass not exceeding 3.5 tons, medium duty fuel cell trucks (FC-MDTs) with a vehicle mass between 3.5 tons and 12 tons, and heavy duty fuel cell trucks (FC-HDTs) with a vehicle mass exceeding 12 tons. All vehicle mass definitions refer to the gross vehicle weight, i.e. the maximum weight when the vehicle is fully loaded.

Table 1-1: Vehicle categories defined for the AFC TCP data collection.

Vehicle class	Explanation
Passenger cars (FC cars)	Fuel cell electric vehicles in the category light-duty vehicles (passenger cars and vans) with a maximum mass not exceeding 3.5 tons and no more than eight seats in addition to the driver seat. Examples: Toyota Mirai, Hyundai Nexo, Honda Clarity fuel cell, etc.
Fuel cell buses (FCBs)	Fuel cell buses for the carriage of passengers with more than eight seats in addition to the driver seat
Light commercial vehicles with fuel cells (FC-LCVs)	Vehicles for the carriage of goods and having a maximum mass not exceeding 3.5 tons. Examples:
Medium-duty trucks with fuel cells (FC-MDTs)	Fuel cell trucks with a maximum mass exceeding 3.5 tons but not exceeding 12 tons; trailers and semitrailers with a maximum mass exceeding 3.5 tons, but not exceeding 10 tons
Heavy-duty trucks with fuel cells (FC-HDTs)	Fuel cell trucks with a maximum mass exceeding 12 tons; trailers and semitrailers with a maximum mass exceeding 10 tons

Figure 1-3 provides an overview of the vehicle segment shares. The graph shows that the dominant vehicle category in the global fleet is the passenger car segment with a share of 69%. This is lower than in the previous update (75%), mainly due to the significant increase in the FC-HDT share, which is now 12% compared to 8% in the 2024 update. FCBs again account for 9% and are the third strongest segment. FC-LCVs and FC-MDTs contribute 6% and 4%, respectively, to the global fuel cell vehicle fleet. It should be noted that for some countries, the numbers of light commercial vehicles are included within the passenger car segment. However, this detail would not change the general distribution shown in Figure 1-3.

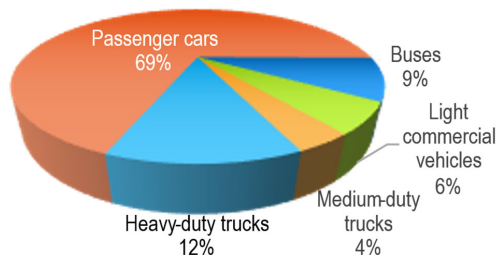


Figure 1-3. Shares of fuel cell vehicles in different vehicle categories at the end of 2024.
Total fuel cell vehicle number worldwide: 97,356.

In the following, we focus the data presentation on the different vehicle categories as introduced in Table 1-1, thereby highlighting segment-specific fleet stocks in the different world regions and countries. Figure 1-4 illustrates the distribution of fuel cell passenger cars across world regions and individual countries. The total fuel cell passenger car fleet is 67,766, only 2.6% higher than the 66,065 in the 2024 update. For comparison, the increase in the total fuel cell vehicle fleet was 11% as was mentioned above. In the upper left quadrant of Figure 1-4, the distribution across world regions is presented. According to this data, Asia has about two-thirds of all fuel cell cars, which is about the same as in our 2024 update, which was 64%. The North American share is also almost unchanged at 27% compared to 28% in our previous update. The same applies to the European and Australian figures. Compared to the global regional share of fuel cell vehicles (Figure 1-2), the share of fuel cell passenger cars is significantly lower in Asia (69% vs. 74%) and higher in North America (27% vs. 19%).

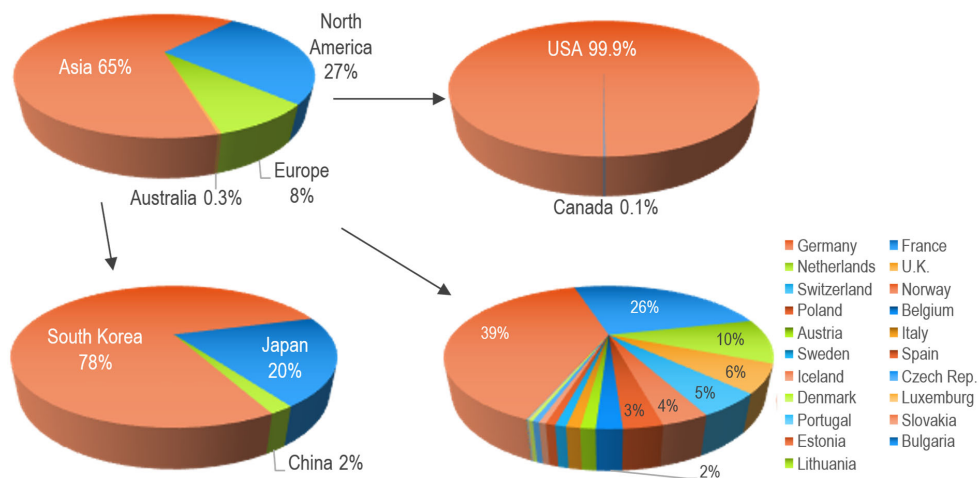


Figure 1-4. Distribution of fuel cell passenger cars across different continents and their detailed analysis.
Total number of fuel cell passenger cars worldwide: 67,766.

As shown in Figure 1-4 (lower left quadrant), the passenger car fleet in Asia is clearly dominated by South Korea with almost 80%, followed by Japan with 20% and China with only 2%. There were only minor changes compared to the previous year. Compared to the fleet of all categories (Figure 1-2), the shares of South Korea and Japan are significantly higher due to the role of the commercial vehicle fleet, where China is particularly strong. In the North American passenger car fleet, the U.S. has almost all fuel cell passenger cars. Canada's share of the fleet has decreased from 1.7% to 0.1%. Again, the role of commercial vehicles with fuel cells leads to a higher importance of Canada considering all vehicle categories (Figure 1-2). Traditionally, the situation in Europe has been very different, with only 8% of the world's fuel

cell passenger cars. According to Figure 1-4, lower right quadrant, the vehicles are spread over 21 countries, with only three countries exceeding 10%, namely Germany with 39% and France and the Netherlands with 26% and 10% respectively. The UK and Switzerland account for at least 5% and Norway, Poland, Belgium, Austria and Italy for at least 1% of the European fleet. Looking at all categories of fuel cell vehicles, the situation with regard to vehicle shares is very similar. Compared to the previous year, there is a significant change in France, whose share increases from 18% (955 FC cars) to 26% (1484 FC cars). Most of the other values, with the exception of Denmark, remain in similar ranges as in the 2024 update. Here the FC car fleet decreased from 232 to only 17 cars, resulting in a share of 0.3% coming from 1.3%.

In addition to the world regional distribution of fuel cell passenger cars, the waterfall diagram in Figure 1-5 shows the passenger car fleet by country for all countries with at least 100 passenger cars in operation. The top five countries with more than 1000 fuel cell cars are South Korea with more than 34,258 cars, the USA with 18,000, Japan with 8,734, Germany with 2,251 and France with 1,484 cars. All of these four countries showed small to moderate increases in the number of cars. An exception is France which comes from 955 FC cars in 2023 to 1484 cars. This corresponds to an increase of more than 50%. Of the remaining countries, only the Netherlands has more than 500 FC cars on the road, with 579 cars.

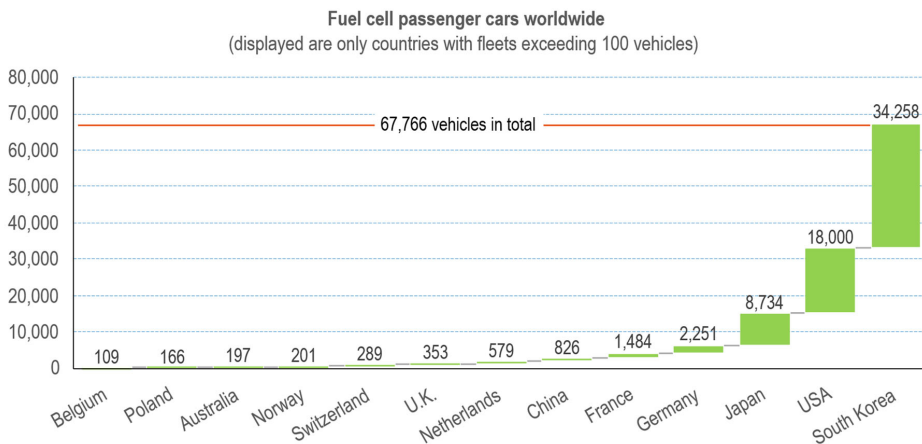


Figure 1-5. Country-based distribution of fuel cell passenger cars on the road by the end of 2024.

Proceeding with light commercial fuel cell vehicles, Figure 1-6 shows the distribution of fleets by country. According to these data, China has almost doubled the number of FC LCVs compared to the previous year, reaching a fleet of more than 5,000 vehicles. Canada and France are in second and third place with 400 and 250 vehicles, respectively. Significantly lower numbers were found in Switzerland (10), the United Kingdom (5), Denmark (2), and Australia, Austria, and Belgium (one vehicle each). It has already been observed that for some

countries the total number of vehicles in the LCV category is included in the passenger car fleet. France is a good example of this phenomenon.

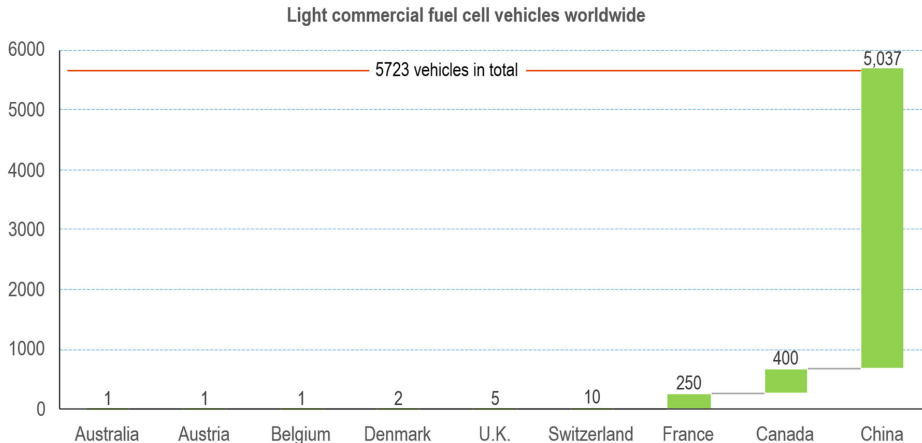


Figure 1-6. Country-based distribution of light commercial fuel cell vehicles on the road by the end of 2024.

For fuel cell buses, Figure 1-7 displays the worldwide fleet for countries with documented deployment. Once again, China leads the way with more than seven thousand vehicles, an increase of 8% over the previous update. Other countries with fleets of more than 100 vehicles include South Korea (651), Germany (201), the United States (150), Japan (127) and the United Kingdom (106). Countries with at least 50 fuel cell buses are Spain (77), India and France (58), and the Netherlands (54). Italy and Switzerland have 22 and 20 buses in operation, respectively. Typically, there has been an increase in all of the fleets mentioned.

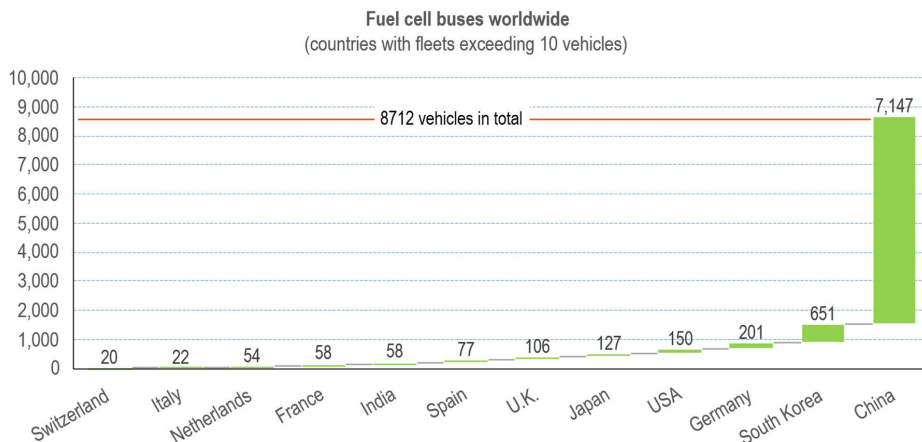


Figure 1-7. Country-based distribution of fuel cell buses on the road by the end of 2024.

For medium-duty fuel cell trucks (FC-MDTs), China is also in first place with 3399 vehicles out of a total of 3601 among all member countries, or 94%, Figure 1-8. However, according to the reported figures, China's FC-MDT fleet has decreased from 3900 to 3399 vehicles in the recent period. In contrast to the previous update, data could only be retrieved for four countries compared to six countries before. Far behind China, Japan has the second largest fleet with 159 vehicles. France and the Netherlands currently have 39 and 4 vehicles, respectively. For this update, data are not available for South Korea, Norway, the United Kingdom and Switzerland, but are available for France and Japan. The remaining three countries with reported FC-MDT fleets are Japan with 159 vehicles and the Netherlands and France with 39 and 4 vehicles respectively.

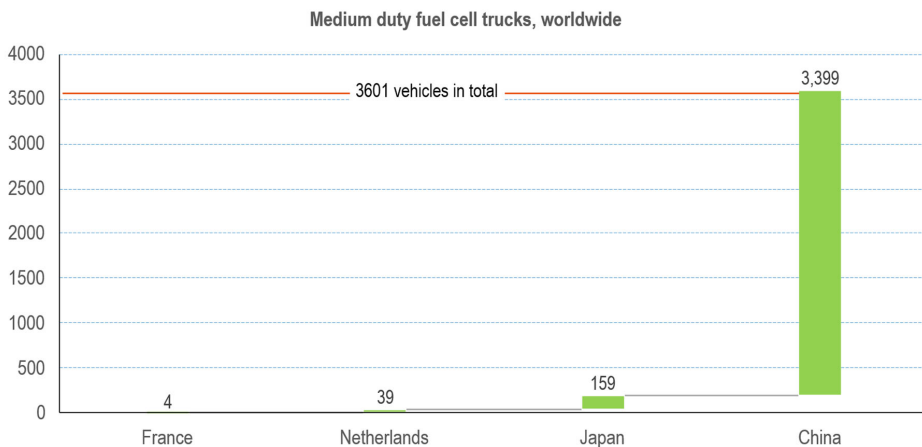


Figure 1-8. Country-based distribution of medium-duty fuel cell trucks on the road as of the end of 2024.

Consequently, and considering heavy-duty trucks with fuel cells, Figure 1-9 shows the country-specific figures. Once again, China has the largest fleet with 11,300 vehicles, a significant increase from our last update, which showed a fleet of 6500 trucks. The respective share is now 98% of the global total of 11,554 fuel cell trucks, even higher than the previous 97%. All other countries have less than 200 vehicles. Of these, Germany has the largest fleet with 122 vehicles, followed by Switzerland, the United Kingdom, and the United States with 61, 36, and 10 fuel cell trucks, respectively. The remaining six countries have fewer than 10 vehicles on the road.

A complete breakdown of the vehicle numbers can be found in Table A1-1 in the Appendix.

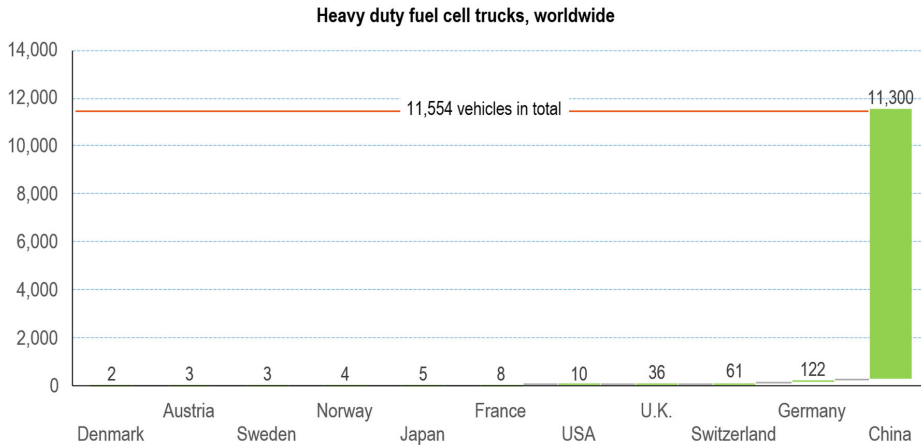


Figure 1-9. Country-based distribution of heavy-duty fuel cell trucks on the road as of the end of 2024.

1.4 Hydrogen Refueling Stations

In addition to fuel cell vehicles worldwide, the AFC TCP update includes a survey of hydrogen refueling station (HRS) infrastructure, the results and findings of which are presented below. A total of 1302 HRS are reported to be in operation in 27 countries by the end of 2024. The figures presented here focus on public refueling stations. Due to incomplete reporting, the figures for some countries may also include private refueling stations, e.g. in bus depots that are not accessible to the public.

Figure 1-10 presents the distribution of hydrogen refueling stations worldwide and shows that China has the largest stock of 522 HRS, which represents 40% of the total. With numbers over 100, second and third places go to South Korea and Japan, which have 286 (22%) and 156 (12%) hydrogen refueling stations, respectively. 15 other European countries, including 12 European countries, have HRS numbers ranging from 5 to 78.

The country-specific number of HRS may be more dynamic. In Germany, for example, HRS dedicated to car refueling are being temporarily or permanently shut down because the fuel cell car fleet is not expanding as expected. Some of these stations are being converted for truck refueling. In addition, new truck refueling stations are being built in a moderately dynamic process. In addition, some countries may have reported figures that include HRS that are fully built but not yet in operation. For some reporting periods, this was the case for China, for example. However, the trend of a growing global HRS fleet is considered stable.

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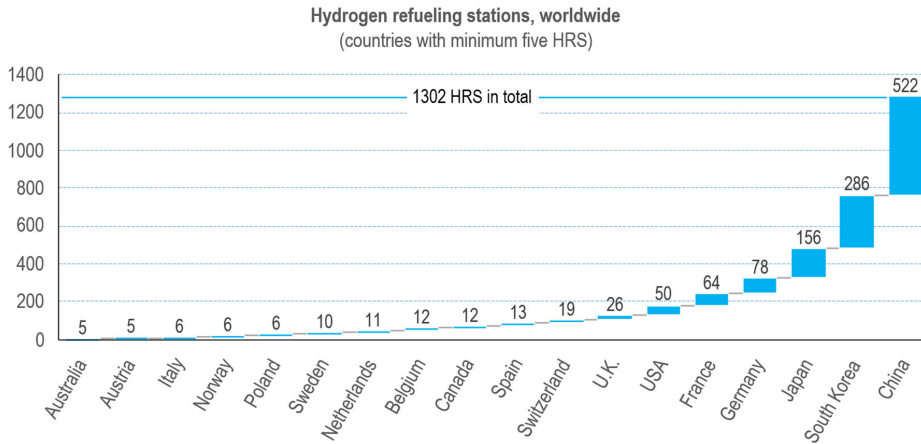


Figure 1-10. Country-based distribution of HRSs worldwide as of the end of 2024.

The geographical distribution of HRS by world region is displayed in Figure 1-11. The focus is on Asia, Europe, and North America. Latin America, Australia, and Africa have very few or no HRS in operation. The numbers for the latter group are 2 for Latin America, with stations in Colombia and Costa Rica, and 5 for Australia.

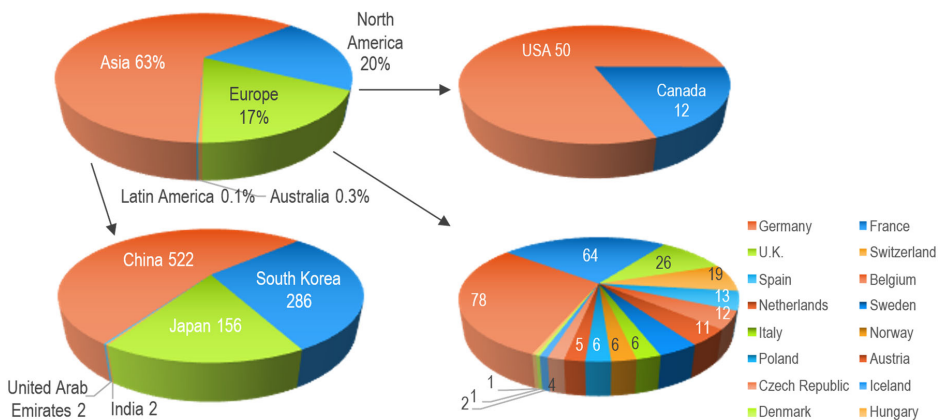


Figure 1-11. Distribution of hydrogen refueling stations to different continents and their detailed analysis.

Globally, Asia leads the way with 969 stations, up 11% from the previous reporting period. North America is second only to Europe but represents only 20% of the global HRS infrastructure. 81% of these stations are located in the United States. Europe consequently accounts for 17% of the global HRS network and ranks third with 264 stations, down 4% from last year. European stations are primarily located in Germany, France and the United Kingdom, accounting for nearly two-thirds of the European total. The remaining 13 European countries

which operate HRSs, have station numbers ranging from 1 to 19 with an average of 7. As for fuel cell vehicles, many countries in Europe have HRSs in operation, which could be advantageous given an increased use of hydrogen-based transportation on the continent.

A complete breakdown of the number of HRSs in each country can be found in Table A1-2 in the Appendix, together with further information on the stations.

1.5 Analysis

Our analysis provides more details on the deployment of fuel cell vehicles and hydrogen refueling stations from 2017 to 2024, based on the recent annual AFC TCP data collections. There may be minor differences from the data presented in our 2024 report, as some country-specific figures were updated after the publication of that report.

First, we present the global deployment of fuel cell vehicles by segment (Figure 1-12). The three commercial vehicle segments of light-duty, medium-duty, and heavy-duty vehicles are grouped together under commercial vehicles. The respective trends from 2017 to 2024 show that fuel cell deployment is clearly driven by passenger cars until 2022. After that, the growth of the passenger car fleet declines, and the commercial vehicle segment makes a stronger contribution. As a result, the last three periods from 2022 to 2024 show a declining trend for the total fleet of 40%, 21%, and 11%.

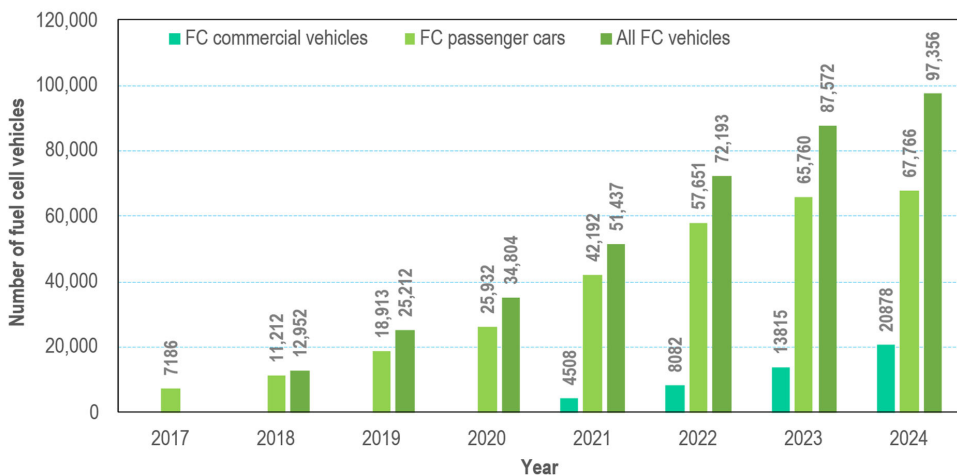


Figure 1-12. Global development of the deployment numbers of FCVs for 2017–2024.

In absolute numbers, the increase in rounded values is 21,000, 15,000 and 10,000 vehicles in this period. For the different vehicle segments, the nominal increase from 2023 to 2024 is 8% for buses, 51% for commercial vehicles and 3% for cars. Compared to previous years, there is a strong to moderate decrease in fleet expansion. The previous rates for buses were 36%

and 25% in 2021/22 and 2022/23 respectively, while for commercial vehicles they were 79% and 71% in the same periods. The increase rate for passenger cars is again particularly low with 3% compared to 15% in the period 2022/23. For this segment, the highest increase was observed for the period 2018/19 with 69%, followed by the period 2020/21 with 63%. The average for all periods is 40%.

The absolute increase in the global passenger car fleet decreases significantly from a maximum of 16,633 and 15,459 in the 2020/21 and 2021/22 periods to 8,109 and 2006 in the 2022/23 and 2023/24 periods. This trend of declining growth in the global passenger car fleet is now clearly driven by the preference for battery electric cars as the preferred solution for zero-emission personal transportation.

Comparing the two previous periods 2023 and 2024, Figure 1-13 shows the global fleet shares of fuel cell vehicles across all segments for the top five countries. The most significant change is in China, where the fleet share increased by 5% from 23% to 28%. In contrast, the shares of South Korea and the United States decreased by 3% and 2%, respectively. While Japan remains stable at 9%, Germany's share drops from 3% to 2%, bringing it in line with France, which increased its share from 1% to 2%. According to these figures, China continues to increase its share of fuel cell vehicles, with South Korea still being a strong leader.

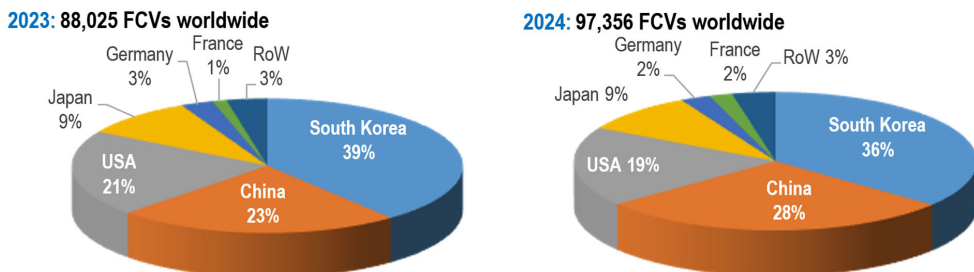


Figure 1-13. Change of fuel cell vehicle shares across all segments between 2023–2024 for the top six countries as of the end of 2024.

With respect to hydrogen refueling stations (HRS), Figure 1-14 shows the historical development of the global network. After two particularly strong periods in 2020/21 and 2021/22 with an increase in the number of HRS of 35% and 40% respectively, the period 2023/24 shows an increase of only 6%. The largest absolute increase was in 2021/22, when 293 stations were added to the network; however, the most recent increase is only 79 stations. The upward trend continues, but at a significant slower pace.

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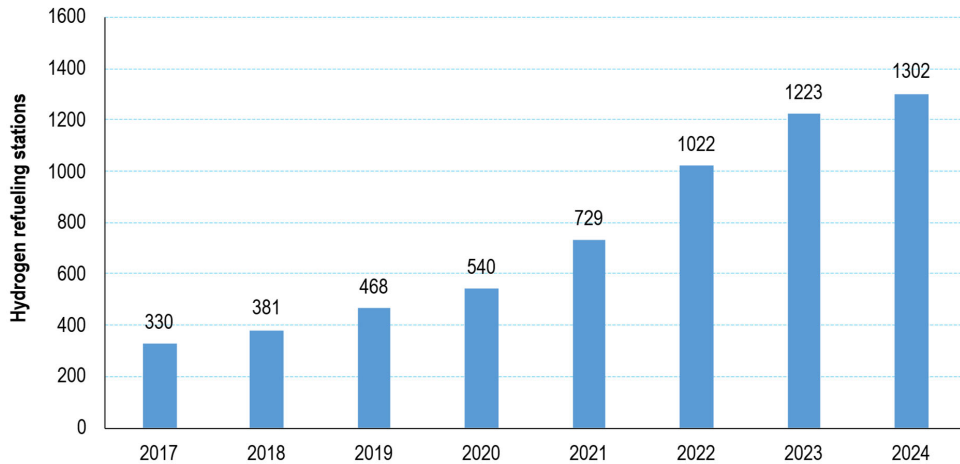
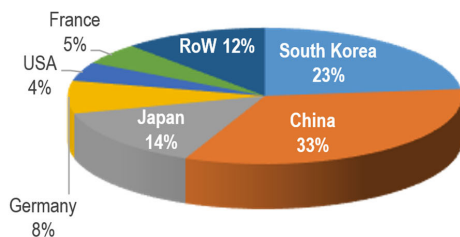


Figure 1-14. Global development of HRSs for 2017–2024.

For a detailed comparison of the top six countries in terms of HRS numbers, Figure 1-15 shows their share of the global network for the years 2023 and 2024. According to these data, China increases its share by 7%, from 33% to 40%. The situation for the remaining five countries in the top six remains stable, with a maximum deviation of 2% in network shares: up 2% for Japan, down 2% for Germany, down 1% for South Korea, and no change for the United States and France. In absolute numbers, China leads with 522 HRS in 2024, up from 406 in 2023. South Korea comes in second with 286 HRS and no change from 2023. Japan is third with 156 HRS and is one of three examples with a decrease in the number of HRS. For Japan this decrease is 18. The other two examples are Germany, which reduced its network by 17 and now has 78 HRS, and the United States with a reduction of five stations and a current number of 50.

2023: 1218 HRS worldwide



2024: 1540 HRS worldwide

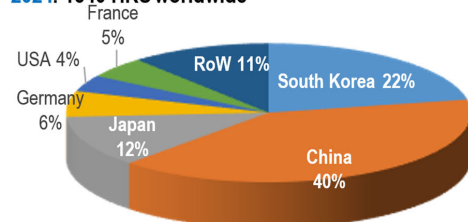


Figure 1-15. HRSs: Change of Shares 2023–2024 in the top six countries with more than 50 stations as of the end of 2024.

To give an idea of how many fuel cell vehicles are served per hydrogen refueling station, Figure 1-16 shows the corresponding data for the six countries with the largest fuel cell vehicle fleet. Other considerations, such as the geographic location of fueling stations or individual vehicle fleets, were not taken into account. The order of countries on the x-axis follows the size of each country's fleet, i.e. South Korea, with the largest fleet, is farthest to the left and France, with the smallest fleet of the six countries shown, is farthest to the right. The ratio stands out for the USA with 363 vehicles per hydrogen refueling station. In second place is South Korea with only 122, followed by Japan and China with 58 and 53, respectively. Germany and France have the lowest values with 30 and 28 respectively. As a higher number of vehicles served per station would generally be beneficial for station economics, the United States would perform best in this regard. This could be due to a concentration of vehicles and stations in densely populated areas, which would be typical of the state of California, where the majority of vehicles in the US are located. However, such a finding should be subject to more detailed analysis. Compared to the previous update, South Korea, China, and the United States show only small to moderate relative increases, as the relative change in vehicle fleets is consistently greater than the relative change in the fueling network. The latter has actually decreased in the United States, Japan and Germany.

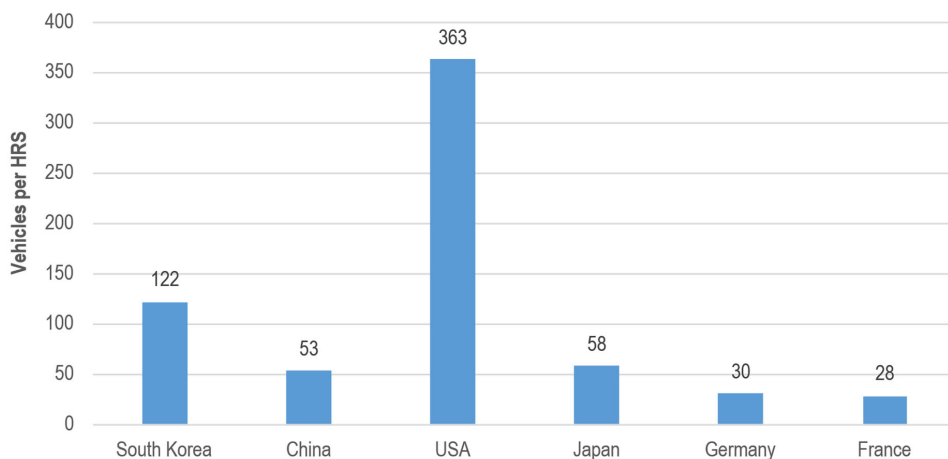


Figure 1-16. Analysis of FCVs per station in the top six countries with more than 50 HRSs in operation as of the end of 2024. (China: Highest number of HRSs; France: Lowest number amongst the top six countries).

To conclude the analysis portion of this report, Figure 1-17 shows the evolution of fuel cell vehicle (FCV) fleet sizes and the number of hydrogen refueling stations (HRS) since 2017 for the four countries with the largest vehicle fleets. Axis scaling has been chosen to be consistent for ease of comparison. In the case of South Korea, a rapid increase in the FCV fleet of at least 50% in each period between 2017 and 2022 could be seen. From 2022 to 2024, a much

smaller increase was observed, 16% for 2022/23 and 2% for 2023/24. Also for HRS, the strong development until 2023 was observed to come to a halt in 2023/24. The situation is different for China. Only between 2020 and 2021 there was no fleet expansion, but the number of HRS increased sharply by 73%. From 2022 onwards, there is a declining trend in the expansion of the fuel cell vehicle fleet with 59%, 52% and 35% in the three respective periods. The number of HRSs added shows a similar trend, however, with a sharp increase in 2021/22, followed by a more moderate upward trend in the two subsequent periods. For the United States, a linear increase in the FCV fleet was observed between 2017 and 2023. No additional vehicles were added in 2023/24, according to available data. Interestingly, the HRS network was basically stable between 2017 and 2022 at values between 61 and 68, even though a rapid fleet expansion was visible. For the recent two periods, however, there was a decrease in the number of HRS stations, from 71 stations in 2022 to 55 in 2023 and 50 in 2024. For Japan, fleet expansion was more moderate at 15% to 24% per period, with a one-time peak of 61% in 2020/21. Only in the last two periods, 2022/23 and 2023/24, did it slow even further to 6% and 10%, respectively. On the HRS side, a moderate network expansion is visible from 2017 through 2021 with rates between 13% and 23%. Since then, the number of HRS stations has decreased from 169 to 156.

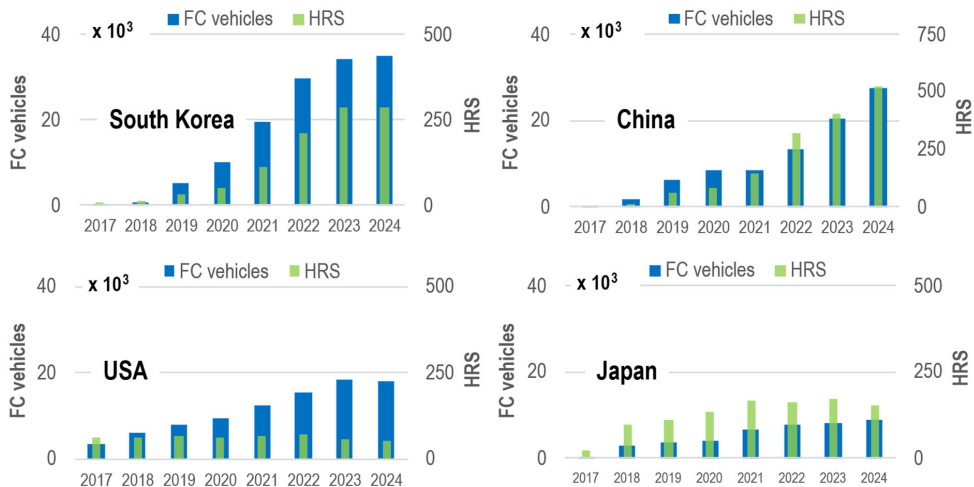


Figure 1-17. Development trends for FCV deployment and HRS infrastructure in the four countries with the highest number of FCVs on the road as of the end of 2024.

Based on available data, the number of fuel cell vehicles and hydrogen refueling stations is growing worldwide: for vehicles by 11% to a current level of 97,356 vehicles and for refueling stations by 6% to 1302 stations. However, the rate has slowed significantly in recent periods and there are large differences between countries or regions. South Korea remains the world

leader in fuel cell vehicles with a total of 34,909 fuel cell vehicles, including 651 commercial vehicles, and has 286 hydrogen refueling stations in operation. The country's FCV fleet and HRS network have not grown significantly recently. This trend is similar in most of the countries that had strong developments in the past. The exception is China, which currently has 27,709 FCVs and 522 HRS in operation, showing a strong expansion of the FCV fleet and HRS network by 35% and 29%, respectively. In fact, the number of HRS is the highest in the world. Characteristic of China is its leading position in all commercial vehicle categories, including buses, with shares of over 80% for buses and light commercial vehicles, and over 90% for medium and heavy-duty trucks. The number of fuel cell passenger cars is only 826, representing a 3% share. In contrast, South Korea has a 98% share of fuel cell passenger cars. HRS numbers typically follow the development of vehicle fleet expansion, with the exception of the United States, where the HRS network was expanded in advance and has been stable for many years. The United States also has the highest ratio of fuel cell vehicles per hydrogen refueling station of any country analyzed in this report. Recently, HRS numbers have been declining in the United States, as well as in Germany and Japan.

There may be several reasons for the current decline in fuel cell vehicle increases and the preference for battery electric vehicle (BEV) technology as the second viable zero emission powertrain alternative. Policy support for BEVs, technical advances in battery technology, and vehicle model diversity may all play a role. Typical legislative policies and incentives include purchase price subsidies and tax exemptions, or supportive regulations such as free parking in cities. Such efforts typically apply to fuel cell vehicles as well. However, a wider range of vehicle models and improved driving ranges for BEVs, bringing them closer to typical FCV ranges, may have influenced consumer choices for BEVs. In addition, the decreased availability of hydrogen infrastructure and dramatically increased hydrogen fuel prices in some regions may also be responsible for the decline in FCV sales. On the commercial vehicle side, OEMs continue to be interested in fuel cell technology, with a current focus on heavy-duty transportation. Battery technology, however, is also being strongly promoted in these market segments. OEMs worldwide are introducing new vehicle models with techno-economic vehicle performance characteristics that may prove suitable for many transportation services in the short to medium term. If fuel cell vehicles are expected to play a significant role in the decarbonization of transportation, efforts on the OEM and fuel supply side would need to be significantly increased.

1.6 Summary and conclusion

This report presents the 2025 update of the global deployment status of fuel cell electric road vehicles and the associated hydrogen refueling infrastructure. Values presented are based on data from the 2025 AFC TCP Data Survey. Data analysis was performed using data from

previous reports. Globally, the number of fuel cell vehicles across all road vehicle segments is now close to 100,000, while the number of hydrogen refueling stations exceeds 1300. The largest share of fuel cell vehicles is in South Korea, with 36% of the total. Together with the fuel cell vehicle fleets of China (28%), the United States (19%) and Japan (9%), more than 90% of the world's fleet is operated in just four countries. Interestingly, the two largest fuel cell vehicle fleets have a fundamentally different structure. While South Korea's fleet is dominated by fuel cell passenger cars (98%), China's fleet is dominated by fuel cell commercial vehicles including buses (97%). Passenger cars account for 70% of the global fuel cell vehicle fleet across all segments and are located in only three countries, South Korea, the United States and Japan. Heavy trucks and buses are in second and third place with 12% and 9%, respectively. The shares of all vehicle segments except passenger cars are clearly dominated by China with at least 82%, which also continues to have the highest increase in light commercial vehicles and heavy duty trucks with fuel cells. With 40%, China also holds the largest stock of hydrogen refueling stations, followed by South Korea (22%) and Japan (12%). The previously observed declining expansion of the global fuel cell vehicle fleet continues through 2024/25 period, based on the data collection presented in this report. The further manifestation of the trend towards battery electric road transport is now clearly contributing to the declining growth rate of fuel cell vehicle fleets worldwide. Consumer preference for battery electric vehicles is likely to be driven by the wide variety of vehicle models available, lower variable costs, purchase incentives and legislative or regulatory measures. Heavy-duty transportation is currently an exception to this trend.

In terms of hydrogen infrastructure deployment, the most recent development shows a less pronounced network expansion. The total number of hydrogen refueling stations increased by 6% in 2023/24, compared to 20% in the previous period.

1.7 Acknowledgements and Disclaimer

The authors are deeply grateful to all Executive Committee Members of the Technology Collaboration Programme *Advanced Fuel Cells* (AFC TCP) who delivered data for the annual data collection. The results from this data collection on fuel cell vehicles and hydrogen refueling stations were originally provided for the publication of the International Energy Agency (IEA), Global EV Outlook 2025 [40].

The data presented in this work is intended to provide an overview of the current status and perspectives and was prepared using available sources. The AFC TCP does not claim that the data provided is complete.

The AFC TCP functions within a framework created by the IEA. The views, findings and publications of the AFC TCP do not necessarily represent the views or policies of the IEA Secretariat or of its individual member countries.

1.8 Declaration of the Use of Generative AI and AI-assisted Technologies

During the preparation of this work the authors used DeepL in order to improve the readability and language of their own texts. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published work.

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1.10 Appendix

Table A1-1. Breakdown of the numbers of FCVs on the roads on a country and vehicle category basis.

Region	Country	Passenger cars	Buses	Light commercial	Medium-duty trucks	Heavy-duty trucks	Total
Asia	China	826	7147	5037	3399	11300	27709
Asia	India	0	58	0	0	0	58
Asia	Japan	8734	127	0	159	5	9025
Asia	South Korea	34258	651	0	0	0	34909
Australia	Australia	197	0	1	0	0	198
Europe	Austria	62	8	1	0	3	74
Europe	Belgium	109	4	1	0	0	114
Europe	Bulgaria	1	0	0	0	0	1
Europe	Croatia	0	0	0	0	0	0
Europe	Czech Rep.	28	0	0	0	0	28
Europe	Denmark	17	4	2	0	2	25
Europe	Estonia	2	0	0	0	0	2
Europe	Finland	0	0	0	0	0	0
Europe	France	1484	58	250	4	8	1804
Europe	Germany	2251	201	16	0	122	2590
Europe	Iceland	30	0	0	0	0	30
Europe	Italy	58	22	0	0	0	80
Europe	Latvia	0	0	0	0	0	0
Europe	Lithuania	1	0	0	0	0	1
Europe	Luxemburg	5	5	0	0	0	10
Europe	Netherlands	579	54	0	39	0	672
Europe	Norway	201	0	0	0	4	205
Europe	Poland	166	0	0	0	0	166
Europe	Portugal	4	2	0	0	0	6
Europe	Romania	0	0	0	0	0	0
Europe	Slovakia	3	0	0	0	0	3
Europe	Slovenia	0	0	0	0	0	0
Europe	Spain	41	77	0	0	0	118
Europe	Sweden	46	2	0	0	3	51
Europe	Switzerland	289	20	10	0	61	380
Europe	U.K.	353	106	5	0	36	500
Latin America	Brazil	0	5	0		0	5
Latin America	Costa Rica	4	10	0	0	0	14
North America	Canada	17	1	400			418
North America	USA	18000	150	0	0	10	18160
	Worldwide	67766	8712	5723	3601	11554	97356

**Deployment of Fuel Cell Vehicles in Road Transport
and the Expansion of the Hydrogen Refueling Station Network: 2025 Update**

Table A1-2. Breakdown of the numbers of HRSs in operation on a country basis. Sources: See chapter 1.4.

Region	Country	HRS number
Asia	China	522
Asia	India	2
Asia	Japan	156
Asia	Saudi Arabia	1
Asia	South Korea	286
Asia	United Arab Emirates	2
Australia	Australia	5
Europe	Austria	5
Europe	Belgium	12
Europe	Czech Republic	4
Europe	Denmark	1
Europe	France	64
Europe	Germany	78
Europe	Hungary	1
Europe	Iceland	2
Europe	Italy	6
Europe	Netherlands	11
Europe	Norway	6
Europe	Poland	6
Europe	Spain	13
Europe	Sweden	10
Europe	Switzerland	19
Europe	U.K.	26
Latin America	Colombia	1
Latin America	Costa Rica	1
North America	Canada	12
North America	USA	50
	Worldwide	1302

2 Deep Dive Hydrogen Infrastructure

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2.1 Abstract

Hydrogen refueling stations (HRS) are the operational handshake between the hydrogen value chain and road transport: they basically accept hydrogen from pipelines, trailers, liquid deliveries or on-site production and deliver fast, safe, metered fills that meet ISO 14687 fuel-quality limits. In Europe, AFIR elevates HRS from pilots to backbone infrastructure, setting coverage, capacity (≥ 1 t/day by 2030 on TEN-T) and performance targets; Japan, Korea and the U.S. are building comparable networks with growing heavy-duty focus. Two mature station families dominate—compressed gaseous hydrogen (CGH₂, 35/70 MPa) with cascades, multi-stage compressors and -40 °C pre-cooling, and liquid hydrogen (LH₂, ~ 20 K) with cryopumps and vaporizers that enable high flows at low station power—alongside emerging sub-cooled/cryo-compressed hybrids for higher onboard density. Specification hinges on four choices: pressure class, on-site hydrogen state, production location, and supply mode. Interoperability relies on ISO 17268 nozzles/receptacles, SAE J2601/J2601-2/J2601-5 fueling behavior, evolving ISO 19885-3, and (for liquid) ISO 13984. Performance is shaped by mass-flow, thermal management and redundancy; safety by layered engineered controls and accurate custody metering. Economics trade CGH₂'s higher CAPEX/OPEX (compression/cooling) against LH₂'s lower station energy and cryogenic logistics; combined configurations add flexibility. Best practice is to match station family to duty cycle, size cooling/storage/flow class to promised refill times, and design in upgrade paths (high-flow hardware, twin nozzles, heavy-duty bays, modularity) to scale without stranding assets.

2.2 Introduction

Hydrogen refueling stations (HRS) serve as the operational interface between the hydrogen value chain and the transport sector. They connect upstream hydrogen production, liquefaction, and distribution with downstream vehicle utilization, providing the critical point where hydrogen transitions from an energy carrier to an on-road fuel. In this sense, HRS represent the practical handshake linking hydrogen infrastructure to end-user mobility

application [41]. These can technically be designed to process hydrogen from pipelines, tube trailers, liquid tankers or onsite production; on the other, they deliver a fast, safe and metered fill to vehicles while preserving fuel quality to ISO limits. Done well, an HRS gives diesel-like turnaround for passenger cars, buses and heavy trucks, and does so reliably enough to underpin fleet operations rather than demonstrations. In Europe this role is being formalized by the Alternative Fuels Infrastructure Regulation (AFIR), which moves HRS from pilot assets to backbone infrastructure by setting minimum network coverage, capacity and performance targets along TEN-T corridors and in urban nodes [42,43]. Outside Europe, Japan, Korea and the United States are building comparable networks and, increasingly, orienting them toward heavy-duty freight where refueling speed, station throughput and availability are decisive [44].

There are two mature station families and a third that is emerging. Compressed gaseous hydrogen (CGH₂) stations take gas from a trailer or pipeline, dry and compress it to the vehicle's nominal working pressure, 35 MPa for buses and many municipal fleets, and 70 MPa for light-duty cars and an expanding set of heavy vehicles. High-pressure banks, typically charged to around 875–950 bar for H70, allow rapid cascade fills while multi-stage compressors top up as pressure equalizes. Pre-cooling to about –40 °C controls the in-tank temperature rise and protects component life. Liquid hydrogen (LH₂) stations receive fuel at roughly 20 K into vacuum-insulated storage; a cryogenic pump then raises pressure and either feeds liquid directly to vehicles with cryogenic tanks or passes through a vaporizer to supply a 70 MPa gaseous dispenser. Cryopumps commonly deliver on the order of 50–120 g/s, enabling short refueling times with relatively modest station electricity demand. A hybrid approach, sub-cooled liquid or cryo-compressed hydrogen, uses cold, pressurized fills to raise onboard density and is being piloted for long-range heavy-duty use.

How a station is specified depends on four practical choices that together determine user experience and cost. The first is pressure level: H35 suits large tanks and depot operations with modest cooling requirements, while H70 enables higher range per volume and now has medium- and high-flow hardware classes that support heavy trucks; some vehicles even accept twin nozzles to double effective flow. The second is the physical state of hydrogen on site: CGH₂ is broadly compatible and modular but draws the most electricity for compression and cooling; LH₂ shifts energy to centralized liquefaction and, when combined with a vaporizer, can supply both liquid and high-pressure gas from a compact footprint. The third is production location: in the case of gaseous refueling, onsite electrolyser simplify logistics and can leverage low-carbon electricity, whereas offsite production paired with pipeline or truck delivery benefits from scale but requires well-engineered offloading, metering and buffer storage. The fourth is the supply chain into the station—pipeline, tube-trailer gas or liquid tanker—which sets the design of bays, safety distances, and the need for medium-pressure buffers or cryogenic handling.

Interoperability is central to de-risking public investment and private operation. The nozzle and receptacle geometries for 35 and 70 MPa are defined in the ISO 17268 family, with heavy-duty high-flow hardware moving through publication processes. Fueling behavior is governed today by SAE J2601 for light duty and by SAE J2601-2 and SAE J2601-5 for heavy duty; ISO 19885-3 under development aims to harmonize dynamic, communication-based fast fills across larger tank sizes and higher flow classes. For liquid, ISO 13984 (currently at DIS stage) frames components and refueling procedures. Stations must also ensure fuel quality at the nozzle to ISO 14687 limits, which implies the application of rigorous cleanliness standards, moisture and contaminant controlling, and validated sampling procedures.

From an engineering standpoint the performance envelope is shaped by three levers: achievable mass flow, thermal control and redundancy. Light-duty H₇₀ fills of around 5 kg typically complete in three to five minutes; heavy-duty fills in the tens of kilograms target roughly ten to twenty minutes depending on ambient conditions, pre-cooling capacity, the flow class of the dispenser and the vehicle's acceptance profile. CGH₂ stations depend on careful coordination of compressors and cascades to avoid throttling; LH₂ stations lean on cryopump capacity and vaporizer duty, which allows high throughput with lower electrical loads. Availability in practice is governed less by nameplate flow than by mean time between failures and maintenance logistics, so layouts that provide physical access, spare plinths and N+1 on critical units consistently outperform nominally similar sites.

Safety is embedded through layered protection: hazardous-area zoning and intrinsically safe instrumentation; gas detection interlocked with ventilation and emergency shutdown; controlled vent stacks and dispersion analysis; and repeatable procedures for offloading, purging and depressurization. Early engagement with local authorities and alignment with recognized codes shorten permitting time and build public confidence. Because HRS are also metering systems, custody-transfer accuracy, traceability and calibration routines should be specified from the outset alongside electrical and process design. In the case of cryo-compressed and liquid hydrogen truck refueling, regulations must be implemented.

Economically, total cost of ownership hinges on throughput and technology choice. CGH₂-only sites tend to carry higher CAPEX for compressors and chillers and higher OPEX from electricity, though they scale well in modular steps. LH₂ or combined LH₂+H₇₀ configurations reduce station-side power and can handle peak demand with fewer moving parts, but they rely on robust liquid logistics and cryogenic expertise. A future-proof specification leaves space and utilities for additional compressor strings or pump skids, provides civil allowances for twin-nozzle upgrades and heavy-duty bays, and standardized interfaces so that vehicle mix can evolve without a wholesale rebuild.

For policymakers and engineers, the practical takeaway is straightforward: choose the station family to match the duty cycle you are serving; size cooling, storage and flow class for the refueling time you promise users; and write interoperability and reliability into the requirements just as firmly as capacity. The goal is not only to meet early deployment targets but to create a network that can absorb heavier vehicles, higher flows and new standards without stranding assets.

2.3 Liquid Hydrogen-based Refueling

A liquid hydrogen (LH₂) refueling station typically consists of a cryogenic liquid storage tank, a hydrogen transfer system, and one or more dispensers for vehicle fueling [45]. Two main refueling pathways exist, depending on whether the vehicle stores gaseous or cryogenic liquid hydrogen:

- LH₂-supplied gaseous refueling stations, where LH₂ is delivered, pressurized, and vaporized to provide high-pressure gaseous hydrogen (35 or 70 MPa), and in this case two main layouts can be present, namely pump-fed systems and pressure-fed systems
- Direct LH₂ vehicle refueling, where the vehicle itself is filled with cryogenic liquid hydrogen (e.g., subcooled LH₂ or sLH₂).

The following sections describe these concepts.

Pump-Fed System (LH₂-Supplied Gaseous Refueling)

In most existing commercial installations, liquid hydrogen is delivered and stored in a cryogenic tank at ~20 K and 1–2 bar. The LH₂ is drawn into a cryogenic pump that mechanically increases its pressure, typically to 35 MPa (350 bar) for medium-duty or 70 MPa (700 bar) for light-duty vehicles. The pressurized liquid then passes through a vaporizer, where it is warmed to ambient temperature and converted to high-pressure gaseous hydrogen, which is subsequently buffered and dispensed to vehicles equipped with compressed-gas tanks, as shown in Figure 2-1. This high-performance design enables fast flow rates and rapid fills [46]. It closely mimics diesel refueling speeds, depending on pump size and flow class. This configuration provides the highest throughput and energy efficiency for stations dispensing compressed gaseous hydrogen.

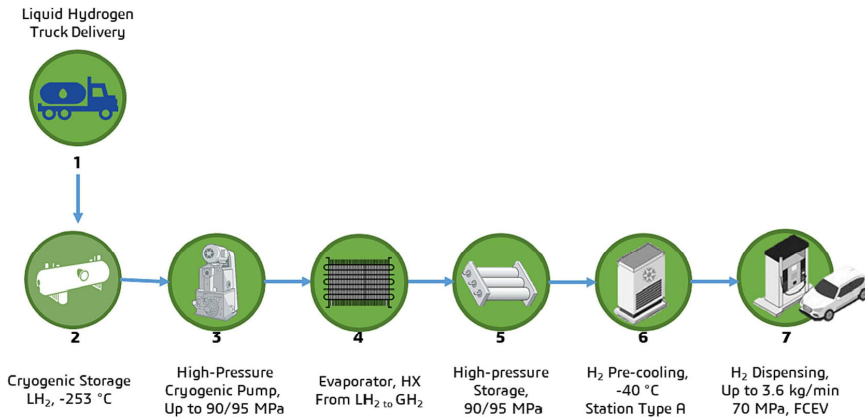


Figure 2-1. Liquid hydrogen-based hydrogen refueling station for light-duty vehicles, example of a pump-fed system [48].

Pressure-fed (Pumpless) System (LH_2 -Supplied Gaseous Refueling)

The cryogenic storage tank is kept at elevated pressure, and LH_2 is allowed to boil and self-pressurize. The hydrogen is then vaporized and fed as gas by pressure differentials to the dispenser (possibly with additional gas compression). This simpler configuration has lower performance, since the flow rate is throttled by tank pressure and control valves, resulting in longer fill times and limited fill completeness. It is generally considered a lower-cost, interim solution and not suitable for high-throughput needs (e.g. large trucks). Without a pump, the achievable outlet pressure from the tank itself is limited to roughly 5–10 MPa, but 35–70 MPa can be reached when combined with a downstream compressor, as shown in Figure 2-2.

This approach simplifies the hardware but restricts flow rate and fill completeness, making it suitable mainly for demonstration-scale or light-duty hydrogen stations.

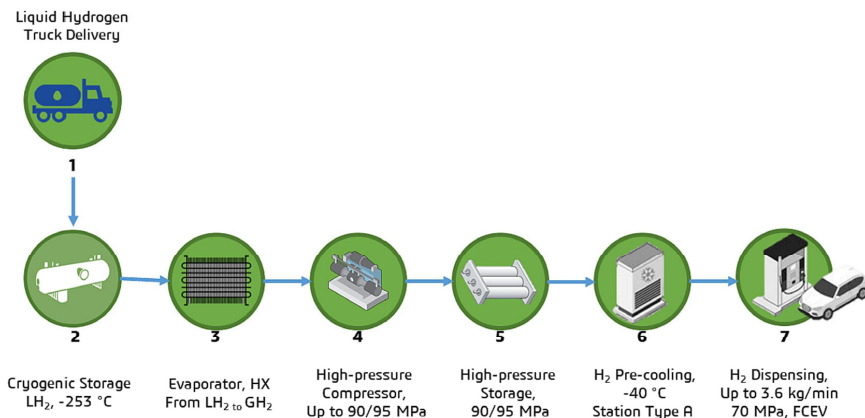


Figure 2-2. Liquid hydrogen-based hydrogen refueling station for light-duty vehicles, example of a system without pump [48].

Modern cryogenic pumps support flow rates on the order of 50–130 grams/second of hydrogen, enabling fill speeds comparable to liquid fuels [49,50]. Such rates translate to refueling speeds very similar to diesel in terms of mass per minute, although total time depends on vehicle tank size and start/end procedures. Refueling times for LH₂ vehicles can range from about 5 minutes up to 30 minutes, influenced by the pump flow capacity and the required pre-cooling and post-fill venting steps.

Direct Liquid Hydrogen Refueling

Conventional liquid hydrogen refueling transfers saturated LH₂ near its boiling point (≈ 20.3 K) at low pressure (1–5 bar). During transfer, any heat ingress causes vapor generation, so boil-off gas must be recovered or vented. Such systems have been used in early LH₂ vehicle prototypes, aerospace applications, and laboratory demonstrations where controlled venting is acceptable. The key drawback is the continuous boil-off and loss of hydrogen, which reduces fueling efficiency and increases handling complexity.

The subcooled liquid hydrogen (sLH₂) concept represents an advancement over conventional LH₂ handling. Here, hydrogen is cooled below its saturation temperature, typically to ≈ 17 K, and refueled at moderate pressures of about 3–16 bar (0.3–1.6 MPa).

Under these conditions, hydrogen remains fully liquid during transfer, without vapor formation or boil-off. The process uses a vacuum-insulated, sealed nozzle and receptacle, ensuring a closed, vent-free transfer without exposure to cryogenic gas.

Subcooling hydrogen increases its density (≈ 80 kg m⁻³ vs. 71 kg m⁻³ for saturated LH₂) and extends the time before vapor formation, providing several operational advantages:

- No venting during normal fueling, improving safety and station efficiency.
- Higher volumetric energy density, allowing longer driving range for the same tank volume.
- Simplified station operation since there is no need for boil-off recovery systems.
- Stable liquid transfer enabling rapid, consistent flow at high rates.

Heavy-duty truck prototypes (e.g. Daimler GenH2) demonstrate ~ 80 kg fills in 10–15 minutes, whereas smaller or pump-less stations may take 20–30 minutes for equivalent fills [47].

2.3.1 Station Components

A typical liquid hydrogen (LH₂) refueling station comprises several core components: an insulated cryogenic storage tank (typically containing several tonnes of LH₂ at approximately 20 K), vacuum-jacketed transfer lines and valves, a cryogenic pump (for pump-fed configurations) with its associated motor, drive, and control system, a vaporizer or heat exchanger to warm the hydrogen to ambient temperature prior to dispensing, and a dispenser unit equipped with the fueling hose, metering system, nozzle, and integrated safety controls..

In pump-fed stations, the cryogenic pump forms the heart of the system, providing both pressure boost and volumetric flow. Modern reciprocating cryogenic pumps can achieve high flow rates with relatively low energy consumption, allowing rapid refueling while maintaining system efficiency [51]. In pressure-fed designs, the storage tank itself may be equipped with pressure-build coils to maintain delivery pressure.

The dispenser design for liquid-based systems is functionally similar to gaseous stations in user interface and safety interlocks but is adapted for cryogenic operation, requiring robust thermal insulation and a hermetically sealed connection to prevent hydrogen gas venting during coupling. Current demonstration systems for liquid hydrogen fuel trucks employ vacuum-insulated, sealed nozzles that minimize cryogenic exposure and allow operators to refuel safely with minimal protective gear.

An example is the Linde–Daimler so-called subcooled liquid hydrogen (sLH₂) refueling concept, which transfers subcooled liquid or supercritical hydrogen (~17 K, 3–16 bar) directly into the vehicle’s insulated tank. This approach avoids cryogenic spillage and boil-off, enabling vent-free, closed-loop refueling and diesel-like fill times. As a result, sLH₂ hydrogen refueling station (HRS) concepts are attracting growing attention in industrial deployment, reflecting their potential for safe, high-performance heavy-duty vehicle fueling [52–54].

2.3.2 Standardization Status

International standards for LH₂ vehicle fueling are being finalized. ISO/DIS 13984 (Liquid Hydrogen – Land Vehicle Fueling Protocol) is due for publication by early 2026, establishing standardized refueling procedures (pressure ramp profiles, venting protocols, etc.) for safe fast-filling of cryogenic tanks. In parallel, the standardization of the vehicle interface (nozzle and receptacle) has begun under ISO/TC 197, aiming to harmonize connector geometry across manufacturers. The goal is to converge to a single common nozzle design for liquid hydrogen (similar to how gasoline/diesel nozzles are standard), thereby ensuring interoperability. By 2026–2027 a formalized standard connector for LH₂ refueling is expected, which will enable full compatibility of nozzles across all stations and vehicles in the market.

2.4 Gaseous Hydrogen Refueling (350 bar and 700 bar)

Gaseous compressed hydrogen (GH₂) refueling technology is well-established in two standard pressure classes: 35 MPa (H35) often used for heavy-duty or industrial vehicles, and 70 MPa (H70) used for most light-duty FCEVs and newer heavy-duty applications [55,56]. The most common configuration is the cascade-based layout, in which hydrogen gas is compressed by a multi-stage high-pressure compressor and stored in intermediate buffer cylinders (or cascade banks) at different pressure levels. A modern compressed GH₂ station includes high-

pressure compressors, storage cylinders (cascade banks), pre-cooling systems, and dispensers with standardized nozzles [57–59], as shown in Figure 2-3.

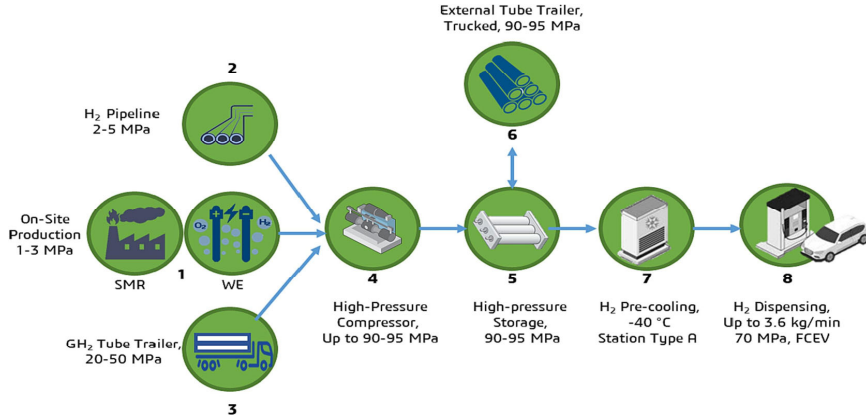


Figure 2-3. Gaseous hydrogen-based hydrogen refueling station for light-duty vehicles, example of cascade-based system [48].

These cascades, commonly arranged as low-, medium-, and high-pressure storage banks, allow controlled sequential discharge during refueling. By switching between banks, the dispenser maintains an optimal pressure gradient, minimizing compressor cycling and enabling faster fills. This layout provides good efficiency and flexibility for stations serving multiple vehicles or varying tank pressures, such as light-duty passenger cars and buses.

An alternative architecture is the direct-compression layout, which eliminates or minimizes buffer storage. A representative layout is illustrated in Figure 2-4 [60].

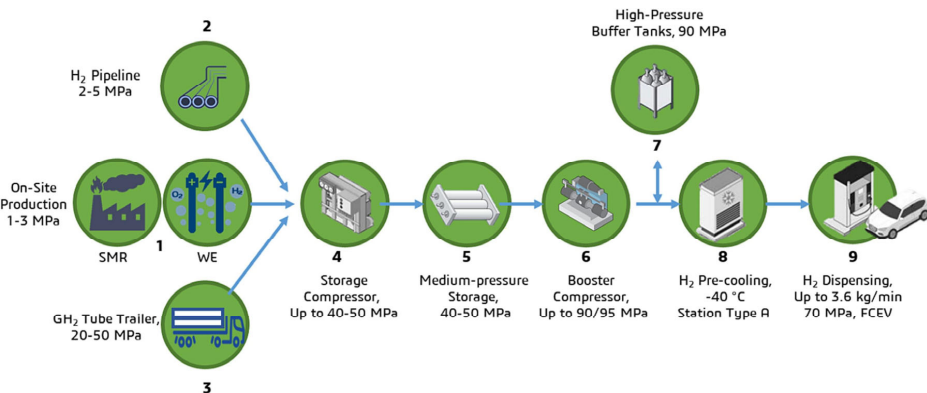


Figure 2-4. Gaseous hydrogen-based hydrogen refueling station for light-duty vehicles, example of direct compressor refueling system [48].

In this setup, hydrogen is fed directly from the compressor to the dispenser during refueling, using booster or displacement compressors capable of delivering high, transient flow rates. Because hydrogen is compressed and dispensed in real time, this design reduces storage volume and simplifies control but places higher demand on the compressor's responsiveness and thermal management. Direct-compression systems are increasingly applied in compact or high-throughput heavy-duty stations, where large vehicle tanks require sustained mass flow and energy-efficient compression.

2.4.1 Pressure Levels and Connectors

Hydrogen dispensers are classified by pressure and flow "rating." H35 refers to 35 MPa (≈ 350 bar) nominal service pressure and H70 to 70 MPa (≈ 700 bar). Within these, *different flow-rate classes* are being standardized to accommodate varying vehicle tank sizes:

- H70-T40/F60 (Normal Flow, 60 g/s): Standard nozzle for passenger FCEVs; delivers up to ~ 60 g/s peak. Suitable for cars and light-duty vehicles.
- H70-T40/F90 (Mid Flow, 90 g/s): A larger nozzle that can fuel at ~ 90 g/s peak. One H70-F90 dispenser can fill passenger cars (at lower flow) and can also fill heavy-duty vehicles. Two H70-F90 nozzles used simultaneously (one on each tank receptacle of a truck/bus) enable "twin fueling" with ~ 180 g/s combined. This dual-nozzle approach allows heavy trucks or buses to refuel faster while retaining backward compatibility – a single H70-F90 nozzle is mechanically compatible with standard H70 car receptacles (and can default to the lower flow as needed). This interchangeability is by design: mid-flow stations can serve current cars, and current (NF) stations can serve mid-flow vehicles, though communication between vehicle and dispenser is required at higher flows for safety.
- H70-HF or F300 (High Flow, 300 g/s): A high-flow 70 MPa connector under development for future large vehicles. It targets ~ 300 g/s peak flow (roughly $5\times$ the car nozzle rate). This "H70 Heavy Flow" (HF) nozzle will likely be dedicated to heavy-duty trucks/buses. It has a larger diameter and is *not* physically compatible with smaller receptacles. As of 2025, prototypes are in progress, and the interface geometry has been agreed upon; formal standardization (ISO 17268-2) is expected by ~ 2027 .
- H35-F60 (60 g/s) and H35-F120 (120 g/s): 35 MPa connectors for heavy vehicles (e.g. forklifts, older buses, or certain trucks). H35-F60 is similar to car nozzles but at 35 MPa, while H35-F120 ("Medium Flow" at 120 g/s) is a larger connector for faster fill of 35 MPa buses/trucks. These 35 MPa nozzles are not cross-compatible with 70 MPa receptacles due to different geometry and pressure class.

The nozzle and receptacle compatibility across these classes is being standardized in ISO 17268-1:2024 (for 70 MPa and 35 MPa systems). In general, smaller nozzles can connect to

larger receptacles of the same pressure (often requiring a data communication link to adjust the fill protocol), but high-flow nozzles will not mate with small vehicle receptacles for safety.

2.4.2 Fueling Protocols

Because of hydrogen's compressibility and heat of compression, fueling protocols are crucial to prevent tank over-pressure or overheating [61]. Several standards define the pressure ramp and temperature compensation algorithms:

- **SAE J2601 (2016 & 2020):** Widely used protocols for light-duty vehicles at H70-T40 and H35. Defines fill tables ("lookup" approach) for different initial conditions and targeted 100% state of charge, with pre-cooling (typically -40 °C gas) to keep the tank below 85 °C
- **SAE J2601-2 and J2601-5 TIR:** Technical Information Reports extending J2601 for large tanks. J2601-5 (published as TIR) covers heavy-duty applications: H35 fills above 6 kg and H70 fills above 10 kg capacity, allowing modified ramp rates for buses, trucks, etc. It introduces the concept of prolonged fills or multi-nozzle fills to manage heat in big vessels.
- **ISO 19885-3** (under development): An international standard fueling protocol for gaseous H₂, intended to unify approaches for light- and heavy-duty fueling. It is slated for publication around 2026, incorporating learnings from SAE protocols and Japanese protocols.
- **CEP/HRS protocols:** Europe's Clean Energy Partnership (CEP) issued an H35 protocol for large bus tanks (e.g. 20–42.5 kg at 350 bar) to ensure complete fills within pressure and temperature limits. This was implemented in early bus demonstrations.
- **JPEC S0003:** Protocol standard from Japan (JPEC) for hydrogen fueling, including parameters for H70 fills. Japan has also developed a profile for larger tanks (since some transit buses in Japan use 70 MPa systems).

Many heavy-duty stations use custom fueling algorithms today (often based on J2601-5 or pre-standards) to accommodate tanks holding 20–100 kg GH₂. The key is managing temperature rise: as ambient temperature and tank size increase, the station must adjust hydrogen pre-cooling and reduce flow rate near end-of-fill to stay within safe limits. Advanced protocols use real-time feedback (tank pressure, temp via IR communication) to optimize fills.

For 70 MPa fills, hydrogen gas is typically pre-chilled to -33 °C or -40 °C at the dispenser to offset heat of compression. Stations have refrigeration units (chillers) to achieve this cooling, especially for fast fills. Heavy-duty fueling of large tanks can generate substantial heat; higher flow classes and ambient heat may require even more cooling capacity or sequential fills. Adequate pre-cooling is a determining factor in fill speed: without it, fill rates must be throttled to avoid high temperatures. Heavy-duty stations are being designed with multi-stage cooling or heat exchangers to handle continuous high throughput.

The time to refuel with compressed gas varies widely based on station capacity (compressor size, cooling) and vehicle tank size:

- For passenger FCEVs (5–6 kg tanks), a full fill at H70 usually takes 3–5 minutes under standard conditions.
- Heavy-duty vehicles (e.g. 30–50 kg for a bus, or up to 100 kg for a Class-8 truck) can be refueled in about 10–30 minutes today, depending on station specs. Current “normal flow” heavy-duty trials often see ~20–30 minutes for ~40+ kg (using twin-nozzle or sequential filling at ~60 g/s each). For example, fueling 100 kg in 30 minutes equates to ~55 g/s average, achievable with two standard nozzles.
- The ambient temperature and initial tank conditions also influence time: in hot weather, protocols may slow the fill to manage temperature rise, extending duration towards the higher end of the range.
- With forthcoming high-flow technology, the aim is to cut heavy-duty fill times. The RHeadHy project in Germany [62] is demonstrating a high-flow dispenser targeting 100 kg in 10 minutes (≈ 167 g/s) for a 700 bar truck. Similarly, in Japan a prototype H70 dispenser achieved ~150 g/s peak in summer testing on a 1000+ liter truck tank [63].

Expected refueling times span roughly 5 to 60 minutes depending on scenario: ~5 min for a car at a capable station, ~15 min for a heavy truck at an advanced twin-nozzle or high-flow station, and up to 30–60 min in worst-case scenarios (very large tanks at a station with limited cooling or if ambient is high). AFIR targets for heavy-duty aim for the lower end (e.g. 15 min for ~40–80 kg) to ensure customer acceptance.

2.4.3 Standardization Status

Compressed GH₂ dispenser hardware is standardized by ISO 17268 [64]. Part 1 (ISO 17268-1) covering the 35 MPa and 70 MPa nozzles (F60, F90, etc.) is nearing publication in 2024, which codifies the compatibility matrix above and ensures any certified nozzle mates safely with its corresponding receptacle. Part 2 (ISO 17268-2, planned ~2027) will introduce the 70 MPa high-flow connector (H70-F300) and any additional heavy-duty features. Meanwhile, SAE J2600 and ISO 14469 also provide specifications for nozzle/receptacle design (seals, latching, dimensions) used in interim.

On fueling protocols, SAE J2601 (light-duty) and J2601-5 (heavy-duty interim) are in use now, and an ISO fueling protocol standard (19885-3) is expected by 2026 to unify these. Until then, station providers follow SAE guidelines or local standards (e.g. European CEP or Japan JPEC standards) to ensure safe fills. Overall, as of 2025:

- SAE J2601 (2016) for cars and J2601-5 (2021 TIR) for heavy vehicles are published and widely adopted.

- ISO 19885-3 is *under development* (target 2025–26).
- ISO 17268-1 is published (for existing nozzles), and the new H70 high-flow interface is *frozen in design* pending ISO 17268-2 by 2027

These standards efforts aim to support interoperability and scale-up: any compliant HRS can fuel any vehicle of the corresponding category, which is critical as Europe's Alternative Fuels Infrastructure Regulation (AFIR) pushes deployment of hydrogen stations network-wide.

2.5 Cryo-Compressed Hydrogen Refueling

Cryo-compressed hydrogen (CCH₂) refueling refers to filling vehicles with hydrogen that is stored at cryogenic temperatures and high pressure in the vehicle tank [65,66]. This technology, originally pioneered by BMW and now being advanced by companies like Cryomotive [67], combines aspects of liquid and gaseous hydrogen storage: the hydrogen is kept cold (typically 20–80 K) to achieve high density, but also under pressure (e.g. 30–40 MPa) so that it remains mostly in a dense fluid state without boiling off. The benefit is a much higher onboard storage density (up to ~80 kg/m³, even exceeding liquid hydrogen's density of 71 kg/m³) with lower boil-off losses, because the pressure buffer can hold the hydrogen longer even as it warms.

A cryo-compressed HRS is essentially a variant of a liquid hydrogen station with additional capability to pressurize the hydrogen to very high levels before dispensing [68]:

- Stations supplying CCH₂ use liquid hydrogen as the feedstock (delivered via tanker). On-site storage is a cryogenic tank (like LH₂ stations). Although, in theory, CCH₂ could be produced by cryogenic cooling of pre-compressed gaseous hydrogen, this would require on-site liquefaction and is therefore impractical for refueling applications.
- A cryogenic pump is the core component. It takes LH₂ and pressurizes it in one or multiple stages to the target pressure (e.g. 350 bar). Unlike a standard LH₂ pump, a CCH₂ pump is a high-pressure design – essentially a reciprocating cryo-pump capable of 30–40 MPa output. Companies like Fives and Cryomotive are developing such pumps (e.g. the “Cryomec Hy-Filling™” pump) specifically to generate what Cryomotive calls CRYOGAS at 300–400 bar [67].
- The pump delivers cold, high-pressure, supercritical hydrogen fluid to the dispenser. Depending on design, the hydrogen may be dispensed as a “sub-cooled” liquid that *flashes* in the vehicle tank or as a supercritical cold gas – in either case, the vehicle receives hydrogen at cryogenic temperature. The dispenser for CCH₂ needs a special nozzle: one that can handle high pressure and low temperature. In BMW's demo in 2015, a new “quick-connect cryogenic nozzle” was used, which notably required no data

communication between car and dispenser and could fill to 300 bar in one flow [69].

Modern iterations are likely similar to LH₂ nozzles but rated for high pressure.

- The protocol for CcH₂ is simpler in some sense, because the fuel is cold, there is minimal heating in the vehicle tank during fill (indeed, the tank actually absorbs heat from ambient during fill). Thus, no pre-cooling by the station is needed (the fuel is inherently cold), and fill speed is limited mainly by pump capacity and tank constraints. A single-stage, fast fill is possible: for example, BMW reported 100–120 kg/h fill rate (≈ 30 g/s) using a cryo-pump in 2011, achieving ~ 6 kg fill in 3–4 minutes [69]. Newer targets are far higher: Cryomotive aims to fuel 80 kg in 10–15 minutes at 30–40 MPa (that's ~ 320 – 480 kg/h ≈ 90 – 133 g/s) to enable 1000 km truck range [67]. These fast rates are achievable since pumping liquid is efficient and doesn't overheat the fuel. The main protocol considerations are ensuring the vehicle's final pressure does not exceed limits once the fuel warms up (so vehicles may not be filled to 100% of tank pressure if they plan to warm) and managing any gas return/venting. Ideally, a closed-loop fill (no vent loss) is used – the station may recover a small amount of boil-off gas via a return line or pressure equilibrator, but designs strive for zero routine venting.
- In addition to the cryo-pump and nozzle, the station will have an insulated dispenser hose, likely a vacuum-jacketed line to keep hydrogen cold up to the nozzle. There may also be a small ambient heater or economizer at the end of fill to slightly warm the hose hydrogen and prevent any dripping of liquid. Some designs include a buffer vessel that stores cryo-compressed hydrogen on the station side (so the pump can batch-produce high-pressure cold gas which is then quickly discharged to vehicles). Because the pump can pressurize on demand, "buffer" storage may not need to be large, since the pump effectively replaces large high-pressure storage banks, giving potentially "unlimited back-to-back fills" as long as liquid supply is available

2.5.1 Current Status (R&D and Pre-Commercial)

Cryo-compressed H₂ is still in pre-commercial stages. BMW built and tested a fleet of prototype cars with 350-bar cryo tanks in the 2006–2015 timeframe, and even opened a public dual-fuel station in Munich in 2015 (Total station Detmoldstrasse) that dispensed both CGH₂ and CcH₂ [70]. That station demonstrated the feasibility: it had a cryopump and a nozzle to fill BMW's dual-insulated 350 bar tanks. The BMW CcH₂ tanks achieved $\sim 50\%$ more capacity than 700 bar at the time, and vehicles could run over 500 km per fill. However, since then BMW shifted away from fuel cells, and cryo-compressed momentum slowed.

Now, startups like Cryomotive (Germany), in partnership with others (e.g. LLNL in the U.S., Fives in France), are reviving the concept for heavy-duty [67]. Cryomotive's vision is "CRYOGAS" fuel: hydrogen at ~ 300 bar and ~ 77 K. They claim this offers the *highest storage*

density, lowest refueling cost, and long holding time. A consortium is developing a full demo: by 2025, Cryomotive aims to have a pilot station that can fuel trucks in <10–15 min with ~80 kg hydrogen at 35 MPa. The pump under development can provide high flow with low energy consumption, contributing to a compact and efficient station. Indeed, pumping LH₂ to 35 MPa and vaporizing uses much less energy than compressing ambient gas to 70 MPa; an analysis by Daimler/Linde [47] for sLH₂ shows a factor of ~30 reduction in energy per kg dispensed and Cryomotive similarly expects large station energy savings (on the order of 70–80% less energy).

2.5.2 Standardization and Interface

There is not yet an ISO standard specific to cryo-compressed fueling. Likely, the vehicle receptacle for CcH₂ will resemble the upcoming H70-HF or a modified liquid nozzle. BMW's approach in 2015 simply used a different nozzle entirely (not the same as 700 bar gaseous or the LH₂). As interest grows, we may see new work items for a combined cryogenic high-pressure connector. In the interim, projects will use custom connectors – but industry trend (as hinted by Toyota) is that post-2030 heavy-duty may diversify to include sLH₂ and CcH₂ options [63], so standards will follow to support them.

From a regulatory perspective, a cryo-compressed station would likely be governed by both industrial gas pressure regulations and cryogenic safety standards. The dispensing of cold high-pressure gas must ensure no embrittlement of materials and safe handling of potential cold gas jets. These are engineering challenges being addressed with known technologies (vacuum insulated systems, special seals, etc.).

Cryo-compressed refueling stations marry the fast-fill, high-throughput advantages of liquid hydrogen with the non-venting, high-pressure storage advantages of compressed gas. State-of-the-art prototypes show that:

- A single dispenser could fuel a heavy truck with 80 kg H₂ in ~10 minutes
- The process is efficient; for example, energy consumption can be under 0.1 kWh/kg for the dispensing process (liquefaction energy is expended off-site)
- No active cooling by the station is needed (the cold hydrogen itself provides cooling).
- Long holding times without venting are achieved on the vehicle, eliminating boil-off loss

This is a promising pre-commercial solution to eliminate limitations of current 700 bar gas (limited range) and LH₂ (boil-off issues), and it is being watched closely as a post-2025 technology track for heavy-duty hydrogen vehicles.

2.6 Hydrogen Quality Requirements

Fuel cell vehicles require extremely high hydrogen purity to avoid poisoning the fuel cell catalysts and membranes. International standard ISO 14687 (latest 2019/2022) defines the specifications for hydrogen fuel quality, particularly Grade D for road vehicle PEM fuel cells. Key requirements include:

- Hydrogen must be >99.97% (often effectively >99.999% by volume for PEM fuel use). The allowable total of all impurities is only a few tens of parts per million. In practice, most suppliers provide “five nines” (99.999%) purity hydrogen, however, not in the case of pipeline supply where typically a dedicated purification unit is required.
- Certain contaminants have strict limits (in ISO 14687:2019):
 - Water (H₂O): ≤5 ppm (to prevent electrode flooding or freezing issues).
 - Oxygen (O₂): ≤5 ppm (to avoid affecting fuel cell cathode and efficiency).
 - Nitrogen/Helium/Argon (inert gases): collectively some tens of ppm allowed (they just reduce H₂ percentage, but too much can affect fuel cell partial pressures).
 - Carbon Monoxide (CO): ≤0.2 ppm. CO is a poison to the platinum catalyst; even 1 ppm can significantly degrade fuel cell performance.
 - Carbon Dioxide (CO₂): ≤2 ppm. CO₂ isn't poisonous per se but can convert to CO in some conditions in the fuel cell and also dilute the fuel.
 - Total Hydrocarbons: ≤2 ppm (as methane equivalent). This includes any residual methane, etc., since hydrocarbons can poison catalysts or oil-type residues can condense.
 - Ammonia (NH₃): ≤0.1 ppm (ammonia can damage membranes).
 - Sulfur compounds: ≤0.004 ppm (4 ppb) total sulfur. Sulfur (like odorants or H₂S) will poison catalysts even at ppb levels.
 - Formic acid, formaldehyde: very low ppb limits as well.
 - Particles: There's a cleanliness requirement to have no particulates above a certain size/mass, ensuring filters and injectors in the vehicle don't clog.

Hydrogen produced from natural gas via SMR is typically purified to these levels via pressure swing adsorption (PSA). Electrolytic hydrogen is very pure except it can carry over moisture or oxygen if not dried well. Liquefaction often further purifies hydrogen (because impurities either freeze out or stay gaseous in vapor phase), so LH₂ is usually high purity. However, one risk is lubricants from compressors or air contamination during handling can introduce impurities.

2.6.1 Station's Role in Quality

A station must ensure the hydrogen dispensed meets ISO specs. This means:

- Stations have filters on dispenser lines to catch any particles (from compressor wear, etc.) and often an inline dryer or cold trap to ensure no water goes through. Many stations also have a palladium or getter filter for sulfur if they fear any contamination.
- All materials in contact need to be compatible and non-leaching. E.g., avoid certain rubbers or greases that could outgas into H₂. This also keeps oxygen out (by not having permeable materials).
- Station operators often take samples periodically (e.g. every 6 months) from their dispensers, which are analyzed in labs for the full ISO 14687 spectrum. This is to ensure nothing in the station (like a new compressor lubricant leak or an air ingress) is introducing contaminants. There are also emerging on-line analyzers for some impurities (CO, sulfur, moisture).
- Delivered hydrogen usually comes with a certificate of analysis from the producer for key impurities. For liquid hydrogen, the liquefaction plant will specify the purity. The station should only source from suppliers who meet the standard. If on-site generation, the station must implement purification steps (PSA unit, etc., if needed).
- One practice is to vent the very first gas out of a dispenser hose when connecting (essentially what the IR communication triggers sometimes); this practice can remove any air that may have diffused into the nozzle between fills. Also, initial gas from storage that has sat long might have slightly higher static impurity; cascading helps here as well (using the best hydrogen from high bank to top off ensures the last gas into vehicle is from the cleanest source).

In Europe, fueling stations are subject to the Hydrogen Quality Monitoring requirements, and some countries mandate that records of quality be kept. The consequences of off-spec hydrogen can be severe: even a few ppm of sulfur or CO can degrade a car's fuel cell and potentially void warranties. Therefore, station operators take it seriously to meet the SAE J2719 / ISO 14687 specs (SAE J2719 is an equivalent standard often referenced in the US, aligning with ISO limits).

2.6.2 Differences by Supply

Delivered hydrogen remains the primary means to supply stations in early network build-out. Compressed gas trailers can serve lower-volume stations but become impractical for >500 kg/day demand due to the constant truck traffic required (each trailer may only carry a few hundred kg). High-pressure composite trailers can carry more hydrogen and are being introduced to support 700 bar stations, though they require compatible high-pressure receiving systems. Liquid hydrogen delivery offers the highest payload: modern LH₂ tankers can transport 3–4 tonnes in a single load, which significantly reduces delivery frequency for a busy

station (one truck can supply ~3 days of a 1 t/day station). LH₂ unloading is relatively fast, but stations must manage the cryogenic process safely. Pipeline-supplied stations (like those in some industrial areas or near H₂ hubs) may beneficially use “on-tap” hydrogen and typically simpler equipment (no trailer interface), but this is only feasible with an existing H₂ pipeline network and typically require a purification unit to comply with ISO 14687. On-site generation (via electrolysis) is being deployed in some locations, especially where electricity is cheap or hydrogen transport is very costly. It offers independence from delivery schedules and can improve sustainability (if powered by renewables) but requires substantial capital and space. In all cases, hydrogen quality must be maintained from source to station (trailers and tanks are sampled to ensure ISO 14687 compliance). Also, trailer filling logistics (e.g. filling a tube trailer itself takes ~4–8 hours at the plant) and return of empties factor into overall supply chain efficiency, though these occur upstream of the station.

Table 2-1. Hydrogen supply logistics for stations.

Supply Mode	Delivery capacity per truck	Resupply frequency (for ~1 t/day)	Offloading time & method
GH ₂ Tube trailer (200–300 bar)	~250–500 kg H ₂ (typical steel or Type IV cylinder trailer)	2–4 trailers per day	~1–2 hours per trailer via pressure decanting. The trailer is connected and cascades H ₂ into station storage; booster compressors may be used to empty to residual pressure ~20–30 bar. Trailer swap systems can speed up the process (drop-and-go).
GH ₂ High-pressure trailer (500–600 bar)	~800–1100 kg H ₂ (new composite MEGC modules)	~1 trailer per day	~2 hours offload. Higher pressure allows faster transfer and leaves less residual H ₂ . However, requires station storage that can accept >500 bar or use of a compressor to top up station vessels.
LH ₂ tanker (cryogenic tanker)	~3500 kg H ₂ (e.g. 40 kl LOX/LH ₂ tanker)	~1 delivery every 3 days	~1 hour transfer via cryogenic pump on tanker or at station. Liquid is pumped into the station's insulated tank. Connections must be purged and cooled before transfer. Boil-off gas from the tanker can be recovered by station or vented during unloading.
Pipeline supply	virtually unlimited (as per pipeline capacity)	N/A (continuous supply)	No offloading – H ₂ flows continuously. Pipeline delivery (common near large industrial H ₂ sources) eliminates trucking; station just regulates pipeline H ₂ to needed pressure. Rare for vehicle stations (exists in some hubs).
On-site production (electrolyser or SMR)	tailored to station (e.g. a 1 t/day electrolyser)	N/A (on-demand production)	No offloading; hydrogen is generated on-site and fed directly to storage/compressor. Requires significant electrical/utility input. Typically paired with buffer storage to handle peak dispense rates.

Pipeline hydrogen could have impurities if the pipeline carries mixes (some older H₂ pipelines allow up to 1–2% N₂ or have odorants). In such cases, the station might need a purifier unit on-site (like a mini-PSA or getter bed) to clean to fuel cell grade. In case of ammonia-based hydrogen, with cracked ammonia on-site to get H₂, it is important to be extremely careful to remove NH₃ traces (because 0.1 ppm NH₃ limit is very low).

Electrolyser hydrogen typically only has moisture and maybe oxygen. Dryers and catalytic recombiners (to remove O₂ by reacting it with H₂ to water) handle that. Liquid hydrogen, by virtue of how it's made, is often very pure (impurities get concentrated in boil-off gas or in residuals; liquid delivered is usually 99.999%). However, liquid tanks can get air ingress if pressure drops too low, forming liquid air on valves (which can introduce oxygen/nitrogen). Good station practice avoids that by keeping positive pressure and purging lines properly.

2.6.3 Hydrogen Quality Standards Evolution

ISO 19880-8 is a document providing guidelines for hydrogen quality control at stations (under development), indicating how to set up a quality plan, sampling methods, etc. This underscores that as the network grows, ensuring consistent fuel quality is vital to avoid a few bad fills tarnishing the technology's reputation.

A suitable HRS ensures Grade D hydrogen at the nozzle by sourcing high-purity hydrogen and maintaining that purity through proper storage, handling, and filtration. Meeting these stringent quality requirements is an indispensable part of station operation, since the vehicles' performance and warranty depend on it.

2.7 Technical and Economic Analysis of Stations

In this section, a high-level **technical and economic aspects** of different hydrogen refueling station configurations are presented, for a standard 700 bar station for medium-flow (MF) fueling, a high-flow (HF) 700 bar station, a liquid hydrogen (LH₂) station, and a combined LH₂ + 700 bar station. Key factors include capital and operating costs, throughput capacity, component performance, reliability, and efficiency.

2.7.1 Capacity and Throughput

A typical H70 station for light-duty (and mid-flow heavy-duty with twin nozzles) might have a capacity of ~200–500 kg/day for light-duty usage, or up to 1000 kg/day if designed for some bus/truck usage. It can fuel cars (~5 kg in 3 min) and, with multiple nozzles, trucks (~40 kg in ~20 min). Peak flow per nozzle is about ~60–90 g/s [63], and stations serving heavy fleets often are scaled to ~1000 kg/day or more.

A future high-flow station (with H70-F300 nozzles) is intended for heavy-duty fleets. Capacity could be 1–3 tonnes H₂ per day to serve dozens of trucks [71]. Such a station might fuel 200+

kg in <20 min for one vehicle. Designs include multiple dispensers and possibly parallel fills. For example, Korea's new high-capacity station can fuel 15 buses/trucks per hour (300 kg/h throughput), equating to >1.5 ton/day capacity

LH₂ stations can be built at large capacities relatively easily by increasing storage size and pump flow. Daimler/Linde's pilot sLH₂ station has a capacity of 400 kg/hour and can exceed 8 tons/day with adequate hydrogen supply [47]. Even smaller LH₂ stations (with one pump) typically can dispense several hundred kg per day due to fast turnaround and no need for large buffer storage. They are well-suited to heavy throughput (multiple trucks back-to-back) as long as the storage tank is kept filled.

A combined station theoretically merges capacities but is usually limited by the liquid supply. If built on a large LH₂ tank, it could similarly handle tons per day. However, adding a 700-bar system introduces compressors or additional pumps that may cap the gaseous side throughput (e.g. a compressor set sized for 500–1000 kg/day). In practice, a hybrid station's total throughput can be very high (since liquid dispensers and gas dispensers can operate simultaneously), but the utilization would depend on demand split. These stations are likely targeted for multi-use hubs (serving both cryogenic trucks and 700 bar FCEVs).

LH₂ pumps can achieve very high flow, but vehicle tank acceptance rate and vent management limit actual fill rates. 700 bar car stations today use ~30–60 g/s flows (3–5 min fills), whereas heavy-duty 700 bar aims for ~200–300 g/s to fill ~80 kg in 10 minutes. 35 MPa fueling (older bus/truck standard) allows higher flows per nozzle due to lower pressure, but total fill amounts are smaller (limited range at 35 MPa). Cryo-compressed fueling, pursued by e.g. Cryomotive (Germany), would pump LH₂ to ~300 bar and –150 to –240 °C, combining high density with high pressure. This could enable ~10-minute fills for >80 kg tanks without precooling or vent losses but is still in R&D stage.

Table 2-2. Flow rates, refueling times, and nozzle types for various H₂ fueling systems.

Fueling System	Typical peak flow rate	Approx. filling time (target)	Nozzle type/standard
LH ₂ (liquid) – Heavy duty	~100–120 g/s (cryopump)	~10–15 min for ~80 kg (truck)	Cryogenic LH ₂ nozzle (ISO 17268-LH) (<i>in development</i>)
CGH ₂ – 35 MPa (H35)	~60–120 g/s (std/HF)	~10–20 min for 20–40 kg (bus)	H35 or H35HF nozzle (35 MPa, NGV type)
CGH ₂ – 70 MPa (H70, LDV)	up to 60 g/s (NF)	~3–5 min for ~5 kg (car)	H70-NF nozzle (70 MPa, SAE J2600/ISO 17268)
CGH ₂ – 70 MPa (H70, HDV)	~60–300 g/s (NF–HF)	~10–15 min for 40–80 kg (truck)	H70-MF or H70-HF nozzle (high-flow)
Cryo-compressed (CcH ₂)	~60–150 g/s (<i>est.</i>)	~10–15 min for ~80 kg (<i>expected</i>)	Cryogenic high-pressure coupling (<i>ISO draft</i>)

Light-duty 700 bar stations (as deployed in 2020s for cars) typically have capacities of a few hundred kg H₂ per day (e.g. 200–400 kg/day) and one or two dispensers. This supports dozens of cars daily. Heavy-duty capable stations are being built to at least 1 tonne H₂/day minimum, in line with AFIR regulations (≥ 1 t/day by 2030), with multiple high-flow dispensers to serve trucks. Future highway stations may scale to several tonnes/day. LH₂-based stations can more easily scale storage; a single 3.5 t LH₂ delivery can fuel ~70–100 trucks (at ~50 kg each) before resupply. The 2004 Berlin combined station (CEP project) had an LH₂ tank of tens of tons capacity, enabling ~100 refuels per day (mix of LH₂ and GH₂) in a trial. In general, combined stations provide flexibility – e.g. one station could fuel a fleet of cars in the morning and several trucks in the afternoon without running out, as long as total mass stays within daily capacity. By leveraging liquid storage, combined designs can handle surges in demand more readily than all-gas systems (which are limited by compressor throughput and cascade storage size). 35 MPa systems (older bus stations) were often smaller (hundreds of kg/day) and are being phased out in favor of 70 MPa for new heavy vehicles due to range needs.

Table 2-3. Station capacity and throughput by configuration.

Station configuration	Typical daily capacity	Throughput (vehicles per day)
700 bar HRS (LDVs)	~200–400 kg/day	~40–80 fills/day (5 kg per car)
700 bar HRS (HDVs)	1000–2000 kg/day	~20–40 fills/day (25–50 kg per truck)
Liquid H ₂ (sLH ₂) station	~1000 kg/day (1 ton/day)	~15–20 truck fills/day (50–80 kg each)
Combined (Dual-mode) HRS	1000+ kg/day (scalable)	Flexible: e.g. 50 cars + 10 trucks/day (example mix)
Demo/legacy 35 MPa station	~100–300 kg/day	~5–15 bus fills/day (20 kg each)

2.7.2 Efficiency and Energy Consumption

700 bar (gas) stations are energy intensive. Gas compression to 900 bar and precooling to -40 °C consumes on the order of 10–15 kWh per kg of H₂ dispensed (for heavy-duty flow rates) in current designs. For instance, chilling alone can be ~3–5 kWh/kg and compression ~6–10 kWh/kg depending on technology. Some data indicate conventional 700 bar stations use ~1.5 kWh/kg just for dispensing (not counting production). Efforts are underway to reduce this: using better compressors, heat recovery, etc. The *specific energy* might drop to ~6–8 kWh/kg with optimized systems. Still, gaseous systems have many moving parts and heat generation points.

Liquid H₂ stations are much more energy-efficient on-site. The energy for liquefaction (~10 kWh/kg) is expended at central production, not at the station. On-site, a cryopump uses only about 0.05–0.1 kWh per kg to pressurize the liquid. The Daimler/Linde sLH₂ station claims

0.05 kWh/kg consumption, which would be by a factor of 30 less than a typical 700 bar station [47]. This dramatic saving is because pumping a liquid is far more efficient than compressing gas, and no heavy precooling chiller is required (the hydrogen is already cold). Overall well-to-tank energy may favor neither strongly (since liquefaction vs compression energy can be similar magnitudes), but from the station owner's perspective, the electrical demand and operating cost of an LH₂ pump station is significantly lower.

Combined stations will have a mixed efficiency profile. If using the integrated pump strategy, the gas fueling part also benefits from cryo-pump efficiency (so compressing via liquid). In that case, the gas fueling energy per kg could drop to ~0.1–0.2 kWh/kg (mostly pump plus a small gas booster if needed) – much better than conventional. If the combined station instead has a separate gas compressor, then its gas side efficiency will be like a normal 700 bar station. For truly optimized hybrid designs, the expectation is an efficient liquid pump provides both services, so overall energy per kg is minimal (aside from the centralized liquefaction energy).

2.7.3 CAPEX (Capital Costs)

Capital cost depends on capacity and technology. The Clean Hydrogen Joint Undertaking (EU) [71] gives indicative ranges for current HRS costs per capacity:

- For 700 bar stations, approximately €1,500–4,000 per kg/day capacity. This means a 1,000 kg/day 700 bar station might cost on the order of €1.5–4 million. The wide range reflects economies of scale and technology maturity: larger stations (or newer designs) trend to the lower end per capacity. A medium-flow station (using mostly off-the-shelf compressors, standard dispensers) might be around €2k/(kg/day). High-flow heavy-duty stations (more cooling, bigger compressors) initially are at the high end of that range due to additional hardware.
- Since 350 bar stations are simpler and require lower pressure, in EU it is estimated an amount of €650–2,500 per kg/d, cheaper because of lower pressure equipment.
- Liquid H₂ stations have roughly similar to 700 bar in CAPEX today, €1,500–4,000 per kg/day. Daimler claims their sLH₂ design can cut station investment by a factor of 2–3. If achieved, future LH₂ stations could be significantly cheaper than gaseous ones for equivalent throughput. Current large LH₂ pumps and cryogenic components are costly (low-volume specialty items), but as they scale, an 8 ton/day LH₂ station might become much more cost-effective than eight 1-ton/day 700 bar stations.
- For combined stations, the CAPEX here is higher than a single-mode station because it must include equipment for both. However, it can be lower than building two separate stations. Some components can be shared (storage tank, site infrastructure, control systems). If an integrated design is used (common pump), CAPEX might only

incrementally rise for the additional dispenser type. Precise figures are case-specific; a rough estimate might be that a dual LH₂+CGH₂ station costs perhaps +50% of a single type station of similar capacity. For instance, if one had €3M for a large LH₂ station and €3M for a large 700 bar station, a combined might be on the order of €4–5M instead of €6M if done cleverly. This area hasn't been fully benchmarked in public literature yet due to few examples.

Table 2-4. CAPEX, OPEX and expected hydrogen cost for different station types.¹

Station type	CAPEX (est., ≈1 tonne/day scale)	OPEX/energy use	Hydrogen cost impact
700 bar CGH ₂ (High-flow)	€3–5 million (for 500–1000 kg/day)	High: compressors + chillers (1.5–2 kWh/kg)	Lower production cost, H ₂ ~€8–10/kg (no liquefaction)
LH ₂ (Liquid) station	€1.5–2.5 million (for ~1000 kg/day)	Low: cryopump (≈0.5 kWh/kg)	Liquefaction adds cost, H ₂ ~€11–14/kg (incl. B/O losses)
Combined LH ₂ +CGH ₂	~€2–3 million (est.)	Low: cryopump-based (no compressor)	Single LH ₂ supply for gas & liquid – avoids duplicate equipment, slightly higher CAPEX vs. LH ₂ -only (extra vaporizer, etc.)
700 bar CGH ₂ (LDV only)	~€1–2 million (200–400 kg/day)	Moderate (small compressors)	Typically, ~€10–15/kg at pump (small scale, higher unit costs)

2.8 Global Deployment Overview

To provide an international comparison of hydrogen refueling infrastructure, Appendix A2 summarizes the current deployment status, technology trends, and representative projects for major global regions (Tables A2-1 to A2-20). These tables compile consistent metrics, including the number of operational stations, pressure classes (35 MPa and 70 MPa), presence of liquid hydrogen (LH₂) or cryogenic systems, supply logistics, and projected network expansion toward 2030.

China (Tables A2-1 and A2-8) leads worldwide with more than 500 operational HRS, most serving heavy-duty fleets at 35 MPa, while early LH₂ pilots are emerging in coastal hubs such as Daxing. Japan (Tables A2-9 and A2-10) operates 150–170 stations, largely 70 MPa public sites, and is expanding HD-capable depots for buses and coaches. Republic of Korea (Tables A2-11 and A2-12) reports 250–300 stations with a growing share of 70 MPa and initial LH₂ truck hubs such as Ulsan Myeongchon. Germany (Tables A2-13 and A2-14) maintains ~80 stations integrated into the H₂Mobility network, with increasing emphasis on AFIR-aligned heavy-duty corridors and LH₂ pilots for trains and trucks. The United States (California) (Tables

¹ The “Hydrogen Cost Impact” column in Table 6 represents the dispensed hydrogen cost at the station, combining on-site compression, cooling or pumping energy use with delivered hydrogen supply costs.

A2-15 and A2-16) counts ~70 retail 70 MPa stations and early high-capacity HD hubs co-located with renewable H₂ production, e.g. the Toyota Tri-Gen Port of Long Beach facility. France, the Netherlands, the UK, Italy, and Austria (Tables A2-17 to A2-20) represent the developing European network, emphasizing regional bus depots, corridor-based HD sites, and AFIR-compliant expansion toward 2030.

Collectively, these datasets highlight distinct national strategies: Asia emphasizes high-volume fleet depots and early LH₂ integration, while Europe focuses on harmonized multi-pressure (35/70 MPa) networks linked to AFIR and TEN-T corridors.

2.9 General Design Best Practices

Drawing together best practices and the evolving technologies, it is possible to outline what a “suitable” hydrogen refueling **station** (HRS) looks like for the coming decade. This includes both generalized design principles and considerations for specific locations or use-cases, aligned with AFIR targets and beyond:

- **Multi-Standard Capability**

- A state-of-the-art HRS should provide at minimum the support of 700 bar dispensing (H70) for both light-duty and heavy-duty vehicles. However, different vehicle classes have distinct nominal pressure requirements: **Heavy-duty trucks** and long-distance coaches are increasingly designed for 350 bar (H35) and 700 bar storage (H70) to maximize driving range and reduce refueling frequency. **City buses** and local delivery vehicles, on the other hand, generally use 350 bar (H35) systems, which offer sufficient onboard capacity for planable routes and shorter daily ranges, while simplifying tank and system design.

Accordingly, an advanced HRS should ideally provide both H35 and H70 dispensers, or at least dual-pressure capability, to serve mixed fleets. A typical configuration includes one H70 dispenser compatible with both cars and heavy vehicles, and one or more H35 dispensers for buses or 350-bar trucks. This dual-pressure setup enhances station versatility and ensures compliance with current refueling standards (ISO 17268-1). As the industry transitions toward high-flow hydrogen fueling for heavy vehicles, such as the emerging H70-F300 interface or cryogenic liquid (LH₂/sLH₂) solutions, future-proof stations should include space and provisions for upgrading to these higher-capacity systems.

- **High Throughput & Capacity**

- To meet AFIR requirements (minimum 1 tonne/day by 2030 with ability to serve trucks) [72], a suitable HRS likely features multiple dispensers and robust equipment. For example, a layout might include 2 or more fueling positions for simultaneous service,

with a daily capacity of ~1,000–2,000 kg. A design could include a cluster of compressors (for CGH₂) or one cryogenic pump per dispenser (for LH₂/sLH₂ stations), as is standard in high-performance configurations such that even during peak hours (e.g. several trucks in a row), refueling times remain within ~15 minutes each. Ensuring redundancy (e.g. two compressors where one can back up the other, or a buffer storage that covers if pump stops briefly) contributes to reliability.

- **Pre-Cooling and Thermal Management**

- A modern HRS will have adequate hydrogen pre-cooling for fast fills. This might mean refrigerant chillers for gas systems sized to handle heavy-duty filling without slow-down. In an LH₂-based station, this means proper vacuum insulation and subcooling to prevent boil-off during transfer. The station should be designed so that ambient heat (on equipment or stored hydrogen) does not compromise fill speed – for instance, using canopy shade, reflective surfaces on storage, and cooled dispensers if necessary, in hot climates.

- **Digital Controls and Communication**

- A suitable HRS uses intelligent control systems that interface with vehicle communication (SAE J2799/ISO 23273 data exchange for pressure/temperature during fill), ensuring optimal fueling profiles for each fill. It should also be integrated with network operations – e.g., remote monitoring and diagnostics, and potentially smart queue management for high-demand stations (scheduling fills or guiding drivers to the right dispenser). This reduces waiting times and prevents equipment strain by smoothing demand peaks

- **Safety and Compliance**

- Safety cannot be compromised; a “suitable” station meets or exceeds all codes (ATEX-rated electricals, proper vent stack height, leak detection, emergency shutoffs, deflagration vents for equipment enclosures, etc.). It would implement the 11 pillars of safety identified by experts [73]: robust mechanical integrity (quality components, regular checks), well-planned layout with required setback distances, ventilation to avoid H₂ accumulation, continuous hydrogen leak detection, and accessible emergency response equipment. A culture of safety training for any operators is in place. Additionally, hydrogen quality control is part of the design (filters, dryers if needed, and periodic sampling to ensure ISO 14687 purity compliance so fuel cells are not damaged by impurities).

In a city or town, a suitable HRS may prioritize compact footprint and possibly co-locate with existing fuel stations. It might focus on H70 car fueling but still should have at least H35 or H70 mid-flow for medium vehicles like delivery trucks or buses. Noise reduction (enclosures for compressors) and aesthetics (since urban sites have public visibility) could be emphasized.

For example, Shell's and Total's urban HRS designs often hide equipment behind walls or in containers. If space permits, adding LH₂ storage in urban areas is possible but might face stricter zoning due to liquid hazards, so many urban HRS will remain gaseous supply (pipeline or trailer) until usage grows.

Along highways, stations should be designed like truck stops: easy ingress/egress for large trucks, multiple high-flow dispensers, and minimal wait. A highway-focused HRS might definitely incorporate LH₂ supply to handle the volume economically. For instance, by 2030 one can envision stations on major corridors each with a 4-ton LH₂ tank (like the Daimler/Linde design) feeding both a cryopump for trucks and a small compressor for cars. The station could fuel a truck and a car simultaneously without one slowing the other. For heavy throughput, modular expansion is a good practice: the site is built with space for adding extra storage or an extra compressor/pump as demand grows.

Though AFIR is about public infrastructure, in practice many truck fleet operators will have depot HRS. A suitable design for a depot (like a bus garage or trucking depot) might combine on-site production (if renewable power is available) or large tube trailers with fast-fill capability. Depots might lean towards 350 bar or LH₂ if all vehicles are the same type, but as a best practice, incorporating the ability to serve others (public or different pressure) could provide backup and extra revenue. For instance, a city bus hydrogen depot might also open at night for local fuel cell cars, thus a "suitable" design would consider dual pressure dispensers (350 for buses, 700 for cars) or at least compatible nozzles.

The ideal HRS in 2025–2035 must be adaptable. A prudent design would:

- Reserve physical space and utility connections for adding a liquid hydrogen tank in the future, if starting as gaseous-only. Or vice versa: if starting as LH₂-only for trucks, consider provisions to add a 700-bar compressor and car dispenser should demand arise.
- Use a modular compression/pump setup. This mitigates risk, since modules can be serviced one at a time (improving uptime) and scaled up by adding more modules rather than replacing whole system.
- Ensure the dispenser connectors can be upgraded. Since ISO 17268-2 will define the 70 MPa HF nozzle by 2027, a station built in 2025 with only F90 nozzles might plan to retrofit an F300 nozzle later. Using dispenser designs with interchangeable hoses or an extra hose port can allow adding the new connector without rebuilding the whole dispenser. In fact, some heavy-duty dispensers are being built dual-hose: e.g. one hose H70-F90, one hose H70-F300 (future) or LH₂, etc., capped off until the standard is ready.
- Incorporate hydrogen supply flexibility. A truly resilient station might have multiple supply options: e.g. it can take liquid deliveries but also has a provision to hook up a tube trailer of gas as backup, or even on-site electrolyser for redundancy. This kind of hybrid supply

ensures that even if one supply chain is disrupted, the station remains operational – a factor that could be important for “mission critical” stations (like one serving an isolated region).

In the broader vision of sustainable infrastructure, a top-tier HRS might integrate with on-site solar or energy storage to reduce its grid impact (especially for compressors which draw high power). Some stations use fuel cell backup power (running on stored H₂) to keep running during grid outages, leveraging the hydrogen on site. Also, co-location with EV charging (“multi-fuel” stations) could become common; a well-designed site plan would separate hydrogen equipment per safety distances but share customer facilities.

Finally, a suitable HRS should offer smooth, safe and quick user experience: intuitive instructions, automated sequence (driver just connects nozzle, the station handles the fill), clear indication of fill progress and transaction. The fueling process should be as similar to diesel as possible in terms of steps and time, to encourage adoption. That means no exotic procedures for drivers, reliable equipment that doesn’t jam or leak, and standardized connectors so drivers don’t have to guess.

The ideal hydrogen station circa 2030 is:

- Large-capacity and fast, meeting heavy-duty needs (80 kg fills in ~10–15 min) and servicing multiple vehicles per hour.
- Flexible in fuel form, possibly offering both 700 bar gas and LH₂ (or at least upgradeable to either), ensuring it can fuel any hydrogen vehicle type that arrives.
- High reliability (near 99% uptime) via redundancy, quality components, and smart maintenance, matching the expectations set by conventional fueling.
- Compliant and safe, but also user-friendly (self-service, no extensive training needed to fuel).
- Cost-effective, leveraging technologies like liquid pumping or advanced compression to keep operational costs low, which in turn supports affordable hydrogen pricing for customers – a crucial factor for commercialization.

Such stations will form the backbone of the hydrogen corridor network envisaged by AFIR and similar initiatives, eliminating the limitations (slow fueling, high costs, low reliability) that early infrastructure faced, and thereby instilling confidence in hydrogen as a viable fuel for both policymakers and end-users.

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2.11 Appendix

Table A2-1. China HRS Status.

Category	Field	Summary
General	Scope	Public + depot HRS
Deployment	Total HRS	~500–600
	Passenger (H70)	~120–160
	Heavy-duty / depot	~350–420 (35 MPa prevalent)
Technology & Supply	Pressure/state	35 MPa (HD), 70 MPa (LD & new HD); early LH ₂ pilots
	Supply chain	Tube trailers; pipeline in hubs; LH ₂ tankers coastal
Performance & Ops	Typical refuel times	Cars 3–5 min (H70); HD 10–20+ min (H35/H70 MF or twin)
	Uptime target	>95% at fleet depots
Standards	Interop & fuel quality	ISO 17268; SAE J2601/-5; ISO 14687
2030 outlook	Network direction	2–3k stations; HD corridors with higher-flow and more LH ₂

Table A2-2. China HRS Relevant Project.

Name	Status	Capacity	Supply chain	Key takeaways
Beijing Daxing HRS	In service	≈3.6–4.8 t/day design	Off-site supply (LH ₂ /GH ₂), high-throughput multi-bay	One of the world's largest HRS; built for large fleets and events; showcases high-capacity urban hub

Table A2-3. Japan HRS Status.

Category	Field	Summary
General	Scope	Public + depot
Deployment	Total HRS	~150–170
	Passenger (H70)	Majority
	Heavy-duty / depot	~15–30 (bus/truck)
Technology & Supply	Pressure/state	70 MPa LD; 35/70 MPa for HD; some LH ₂ -fed via vaporizer
	Supply chain	Tube trailers; LH ₂ deliveries; some on-site
Performance & Ops	Refuel times	LD 3–5 min; HD 10–25 min
	Uptime target	≥97% urban retail
Standards	Interop	ISO 17268; SAE J2601; JPEC
2030 outlook	Network direction	Expansion toward HD-capable, higher-throughput sites

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Table A2-4. Japan HRS Relevant Project.

Name	Status	Capacity	Supply chain	Key takeaways
Tokyo Gas FC bus HRS (Ariake/Senju class)	In service	Up to ~20 FC buses/day (≈300 kg/day equivalent)	Off-site GH ₂ /LH ₂ to gas	Large city bus-capable HRS; 82 MPa dispensing; built for event-scale loads

Table A2-5. Republic of Korea HRS Status.

Category	Field	Summary
General	Scope	Public + depot
Deployment	Total HRS	~250 - 300
	Mix	H70 LD + 35 MPa bus; first LH ₂ truck hubs
Technology & Supply	Pressure/state	GH ₂ + emerging LH ₂ ; 70 MPa MF/HF for HD
	Supply chain	Pipeline in clusters (e.g., Ulsan), tube trailers, LH ₂
Performance & Ops	Refuel times	LD 3–5 min; HD 10–20 min; high-flow pilots
	Uptime target	>95%
Standards	Interop	ISO/SAE; HF interfaces in development
2030 outlook	Network direction	600+ stations incl. dozens of LH ₂ HD hubs
General	Scope	Public + depot

Table A2-6. Republic of Korea HRS Relevant Project.

Name	Status	Capacity	Supply chain	Key takeaways
Ulsan Myeongchon CV HRS	In service (2025)	Up to ~300 kg/h, 3 buses simultaneous	High-capacity GH ₂ (95 MPa class), multi-lane	Korea's largest CV HRS; 24/7 operation; designed for hundreds of trucks/day

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Table A2-7. Germany HRS Status.

Category	Field	Summary
General	Scope	Public + depot
Deployment	Total HRS	~80
	Passenger (H70)	Majority
	Heavy-duty/Depot	~20–30 (bus/train/HD)
Technology & Supply	Pressure/state	70 MPa retail; 35 MPa bus; LH ₂ HD pilots
	Supply chain	LH ₂ deliveries + vaporizers; GH ₂ in some
Performance & Ops	Uptime	96–98% at refurbished sites
Standards	Interop	ISO 17268; SAE J2601/-5; HF pilots
2030 outlook	Network direction	AFIR-aligned backbone, HD high-flow sites
General	Scope	Public + depot

Table A2-8. Germany HRS Relevant Project

Name	Status	Capacity	Supply chain	Key takeaways
Bremervörde HRS (regional trains)	In service	~1.6 t/day	Industrial by-product H ₂ ; fixed rail HRS	First commercial train HRS; fuels 14 multiple units; one of the largest daily throughputs

Table A2-9. USA (California) HRS Status.

Category	Field	Summary
General	Scope	Retail LDV + initial HD hubs
Deployment	Total HRS	~50 retail LDV; a few HD pilots
Technology & Supply	Pressure/state	70 MPa LD; 35/70 MPa HD pilots; LH ₂ for HD
	Supply chain	Predominantly LH ₂ delivery; some on-site (tri-gen/electrolysis)
Performance & Ops	Refuel times	LD 3–5 min; HD 10–20 min
Standards	Interop	SAE J2601/-5; ISO 17268; NIST metrology
2030 outlook	Network direction	>200 LDV sites + multi-ton HD hubs along freight corridors
General	Scope	Retail LDV + initial HD hubs
Deployment	Total HRS	~70–80 retail LDV; a few HD pilots
Technology & Supply	Pressure/state	70 MPa LD; 35/70 MPa HD pilots; LH ₂ for HD

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Table A2-10. USA (California) HRS Relevant Project.

Name	Status	Capacity	Supply chain	Key takeaways
Toyota TLS Tri-gen (Port of Long Beach)	In service (2024)	Up to ~1.2 t/day H ₂	On-site tri-gen (RNG → power + H ₂ + water)	Co-located H ₂ production & dispensing; supports port drayage HD HRS and LDV

Table A2-11. France HRS Status.

Category	Field	Summary
General	Scope	Public + depot
Deployment	Total HRS	~60–70
	Mix	Many 35 MPa fleets (bus/utility) + growing 70 MPa
Technology & Supply	Pressure/state	GH ₂ prevalent; LH ₂ in studies/hubs
	Supply chain	On-site electrolysis + GH ₂ /LH ₂ delivery
Performance & Ops	Refuel times	LD 3–5 min; HD 10–25 min
Standards	Interop	ISO/SAE; national metrology
2030 outlook	Network direction	AFIR-aligned highway coverage; regional green hubs
General	Scope	Public + depot
Deployment	Total HRS	~60–70

Table A2-12. France HRS Relevant Project.

Name	Status	Capacity	Supply chain	Key takeaways
Paris-Orly high-capacity HRS (HysetCo)	In service (2025)	~1 t/day	Delivered green H ₂ ; multi-lane urban hub	Upgraded airport site; serves large taxi/LCV fleets; backbone node for Île-de-France

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Table A2-13. Netherlands HRS Status.

Category	Field	Summary
General	Scope	Public + depot
Deployment	Total HRS	~10 (strategic locations)
Technology & Supply	Pressure/state	70 MPa LD/MD; 35/70 MPa HD; LH ₂ planned in ports
	Supply chain	Integration with industrial clusters; GH ₂ delivery + local electrolysis
Performance & Ops	Notes	High reliability on few sites; corridor focus (A15/A1)
2030 outlook	Network direction	Dozens of corridor sites; cross-border interop (DE/BE)
General	Scope	Public + depot
Deployment	Total HRS	~15–20 (strategic locations)
Technology & Supply	Pressure/state	70 MPa LD/MD; 35/70 MPa HD; LH ₂ planned in ports
	Supply chain	Integration with industrial clusters; GH ₂ delivery + local electrolysis

Table A2-14. Netherlands HRS Relevant Project.

Name	Status	Capacity	Supply chain	Key takeaways
Hysolar/Greenpoint Nieuwegein (Utrecht)	In service	350 bar + 700 bar; local production up to ~300 t/yr	On-site electrolysis + delivered GH ₂	Public multi-pressure HRS tied to new 2.5 MW electrolyzer; cars, buses, trucks

Table A2-15. United Kingdom HRS Status.

Category	Field	Summary
General	Scope	Public limited; strong depot focus
Deployment	Total HRS	<30 operational; mostly depots
Technology & Supply	Pressure/state	35 MPa bus depots; planning 70 MPa/LH ₂ for HD
	Supply chain	GH ₂ /LH ₂ deliveries; some on-site
Performance & Ops	Notes	High utilization at depots; retail very limited
2030 outlook	Network direction	Dozens of sites tied to bus/truck programs
General	Scope	Public limited; strong depot focus
Deployment	Total HRS	<10 operational; mostly depots
Technology & Supply	Pressure/state	35 MPa bus depots; planning 70 MPa/LH ₂ for HD
	Supply chain	GH ₂ /LH ₂ deliveries; some on-site

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Table A2-16. United Kingdom HRS Relevant Project.

Name	Status	Capacity	Supply chain	Key takeaways
Aberdeen Kittybrewster Bus HRS	In service	~360 kg/day (350 bar)	On-site electrolysis + storage	Long-running depot; dual-pressure upgrades across city; benchmark UK depot HRS

Table A2-17. Italy HRS Status.

Category	Field	Summary
General	Scope	Public + depot
Deployment	Total HRS	<10 operational
Technology & Supply	Pressure/state	35 MPa bus + 70 MPa LD/MD; early LH ₂ studies
	Supply chain	GH ₂ /LH ₂ deliveries; PNRR-backed on-site electrolysis in projects
Performance & Ops	Notes	Early network; upgrades underway (corridors, urban nodes)
2030 outlook	Network direction	AFIR: ≥1 t/day every 200 km on TEN-T; first HD high-flow & LH ₂ hubs
General	Scope	Public + depot
Deployment	Total HRS	<10 operational
Technology & Supply	Pressure/state	35 MPa bus + 70 MPa LD/MD; early LH ₂ studies
	Supply chain	GH ₂ /LH ₂ deliveries; PNRR-backed on-site electrolysis in projects

Table A2-18. Italy HRS Relevant Project.

Name	Status	Capacity	Supply chain	Key takeaways
Bolzano South HRS (A22/SASA)	In service; upgrade in progress	~<400 kg/day today; upgrade to multi-hundreds kg/day incl. 700 bar	On-site production (expanded) + delivered GH ₂	Pioneer Italian HRS; moving from 350-bar bus depot to multi-pressure public hub

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Table A2-19. Austria HRS Status.

Category	Field	Summary
General	Scope	Public + depot HRS
	Data date	2024-02-14 (IEA/AFC TCP submission)
Deployment	Total HRS	5
	Passenger (H70)	4
	Heavy-duty / depot	1
Technology & Supply	Pressure/state	4 sites at 700 bar; 1 unknown; gaseous hydrogen
	Onsite vs offsite	Offsite production
	Supply chain	Truck delivery (gaseous)
	Geographic distribution	Mainly suburban
Standards	Interop & fuel quality	EN 17127 compliance (4 units); ISO 17268 / ISO 14687 practice
2030 outlook	Planned installations	+5 by 2030 (AFIR TEN-T core grid)

Table A2-20. Austria HRS Relevant Project.

Name	Status	Capacity	Supply chain	Key takeaways
Austria (Vienna) — public 700 bar HRS	In service	—	truck delivery	Representative public site; gaseous, truck-delivered; aligns with national snapshot

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