22nd December 2024

A catalog of technical standards and norms for hydrogen refueling stations dedicated forheavy duty transportation in the BSR

Keywords:

Hydrogen Refueling Stations, Heavy Duty Transportation, Hydrogen Storage, Hydrogen Supply, Standards, Norms, Recommendations, Automotive

The project HyTruck is supported by the Interreg Baltic Sea Region Programme 2021-2027

1.1.1.1 Table of Content

1.1.1.2 List of Abbreviations

AFIR	Alternative Fuel Infrastructure Regulation
BSR	Baltic Sea Region
CGH_2	Compressed Gaseous Hydrogen
CHSS	Compressed Hydrogen Storage System
cCH_2	Cryogenic Compressed Hydrogen
HRS	Hydrogen Refueling Station
HDV	Heavy Duty Vehicle
HSV	Hydrogen Surface Vehicle
LDV	Light Duty Vehicle
LOHC	Liquid Organic Hydrogen Carriers
PV	Personal Vehicle
sLH_2	Subcooled Liquid Hydrogen
WIP	Work In Progress

1. Introduction

1.1. Overview of the Project

PSPA participates in the project called “HyTruck”, which is included in the program “Interreg Baltic Sea Region”. PSPA’s goal is to support public authorities in developing a network of refueling stations dedicated for heavy duty vehicles.
PSPA has subcontracted AVL for analysis of technical norms, standards and usage specificationsto sum-up currently used and planned technologies in area of HDV hydrogen refueling. Topics covered by AVL in this report are described in point 1.2.

1.2. Objectives and Scope

PSPA and AVL agreed jointly that AVL perform development of a catalog of technical specifications for hydrogen refueling stations dedicated to heavy-duty vehicles, taking into account following points:

1. Currently applied technological standards in the construction of hydrogen refueling stationsin the BSR (Baltic Sea Region):
    - Identification of hydrogen storage technologies, pressure levels, and typesof refueling nozzles currently used in individual countries;
2. Development of the assortment and technology for hydrogen refueling of heavy-duty vehicles:
    - Analysis of future technical specifications encompassing hydrogen refueling and storage technology by vehicles;
3. Identification of carrier expectations regarding the use of hydrogen technologies in heavy-duty vehicles:
    - Identification of key expectations regarding refueling time and technical parametersof stations;
4. Legal aspects regulating the technical standards of fuel stations in Europe:
    - Analysis of legislative assumptions along with guidelines regarding technologies and specifications used at hydrogen refueling stations in the EU (including standards specified in the AFIR Regulation);
5. Recommendations concerning the technological aspects of hydrogen refueling stations in heavy road transportation in Europe.

2. Current Technological Standards in Hydrogen Refueling Stations

2.1. Hydrogen refueling stations network in Europe

The hydrogen refueling station network is growing all over the world. A record number of 45 newpublic hydrogen filling stations were opened in Europe in 2022, as major refueling networks beginto take shape. The number represents an 22% increase from 2021 and takes the total numberof public hydrogen filling stations in Europe to 254. Globally, 130 new hydrogen filling stations went into operation in 2022, bringing the worldwide total to 814.

As of May 2023, Germany has the most public hydrogen refueling infrastructure in Europe, with 96 filling stations, followed by France with 21 and the Netherlands with 14. A number of major hydrogen refueling networks are in the process of being built across Europe [1] [2]. In the Baltic Sea Region (excluding Germany) there are currently only a handful of HRS scattered across thecountries with Denmark and Sweden in the lead (7 operating stations each), followed by Norway
(5) Poland (3) and Latvia (1). There are, however, several stations in development phase in this region [3].

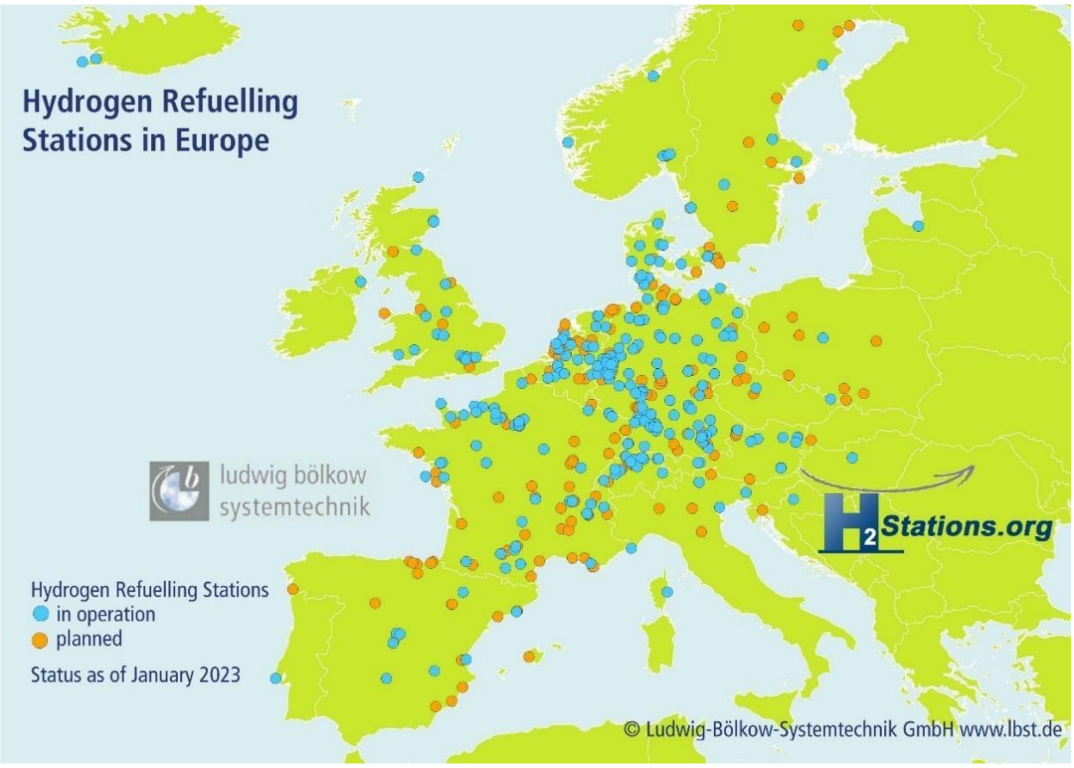

Figure 1 Hydrogen Refueling Stations in Europe, as of January 2023 [4]

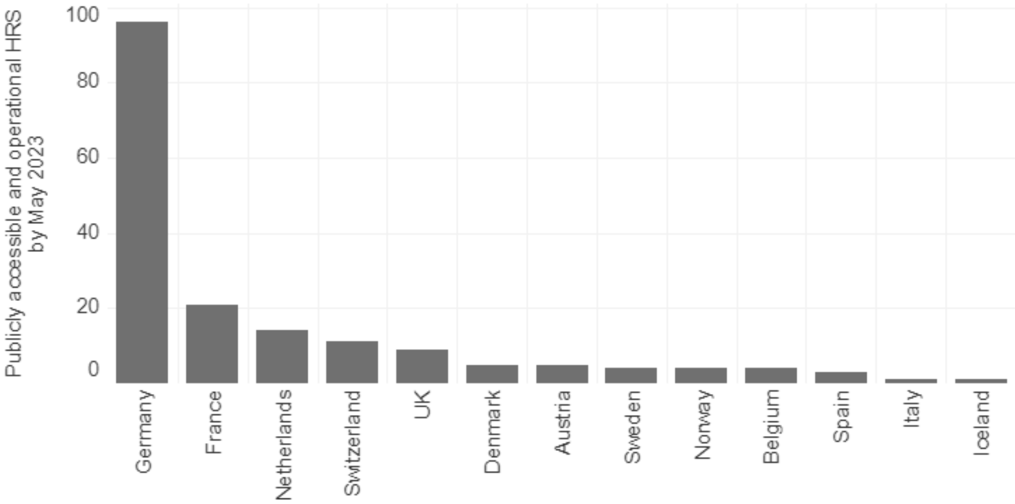

Figure 2 Number of public HRS per country in Europe, as of May 2023 [5]

2.2. Hydrogen refueling station infrastructure

The hydrogen supply chain consists of multiple stages, illustrated in Figure 3. It begins with hydrogen production, achievable through off-site plants or on-site electrolysis. Depending on thechosen refueling technology, hydrogen is transported to the HRS (Hydrogen Refueling Station) either as a gas or liquid via trailers or pipelines. Ultimately, two primary types of refueling stationsexist: gaseous and liquid, each employing distinct equipment to facilitate efficient refueling operations. In this chapter, different elements of the hydrogen supply chain required for hydrogenmobility are described – from production to dispensing.

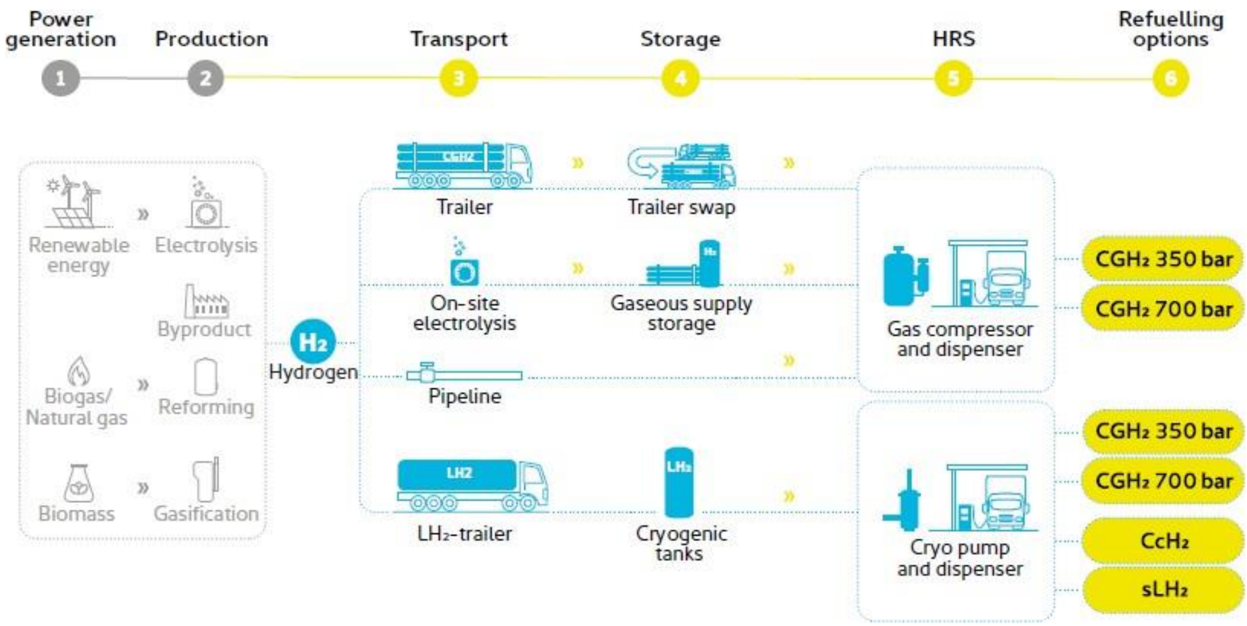

Figure 3 The hydrogen supply chain [6]

2.2.1. Hydrogen transport and storage

Currently, hydrogen is mainly produced by large steam methane reforming plants. While electrolysis is a technologically mature application, it captures only a small market share at the moment (although it is expected to increase in the future) [7]. Hydrogen can be produced either on-site (by electrolysers or “small” reformers) or off-site and delivered from a production facility. The most relevant methods for hydrogen distribution are pipelines or tube trailers.

The supply of hydrogen by pipelines is a convenient end efficient solution, in particular when theHRS is located close to a hydrogen ecosystem that includes a centralized H_2 production plant, and one or more off-takers can be connected to an H_2 distribution grid [7].

Another possible hydrogen supplying method is via trailers which are commonly made up of200 bar tube trailers with long horizontal metallic tubes with average capacity of around 300-500 kg H_2. With new trailers using composite cylinders (withstanding up to 600 bar pressure)the capacity of hydrogen transportation can reach 1000 kg. Another possibility are cryogenic liquid hydrogen trailers which can carry up to 5000 kg of hydrogen. Such trailers are, however, susceptible to the hydrogen boil-off effect which causes hydrogen loss up to 0.6% per day [7].

Figure 4 - Air Liquide LH_2 trailer (left) and GH_2 tube trailer (right) [8]

At the HRS hydrogen can be stored in a physical or material state, however materials based options for storage like metal hydrides or LOHC are still in an early market launch phase [6].

Today the most relevant commercial application is physical hydrogen storage by compression and/or liquefaction. Existing PV and LDV HRS store hydrogen almost exclusively with on-site supply storage tanks. In gaseous form, common pressure levels are 45 to 200 bar, whereas $LH_2$is stored in cryogenic storage tanks (-249 °C) by up to 3-4 bar. Another HRS supply option whichis already in application is the so-called trailer swap. In this case, the trailers act as mobile storagesystems, replacing stationary tanks [6].

Figure 5 Cryogenic storage tank (left), gaseous storage supply (right) [9]

2.2.2. Hydrogen refueling station

A hydrogen refueling station is a refueling station that supplies hydrogen to hydrogen surface vehicles (HSVs). Its operation is similar to conventional refueling stations. The design and configuration of the HRS depends on many factors, such as the level of demand or the type of vehicle to be refueled.

Today, CGH_2 can be refueled typically at 350 or 700 bar either by compressing and pre-cooling the refueled CGH_2 or by “cryo-pumping” liquid hydrogen, which then needs to be heated before entering the vehicle [6]. Figure 6 and Table 1 present a simplified comparison between these twotypes of refueling stations.

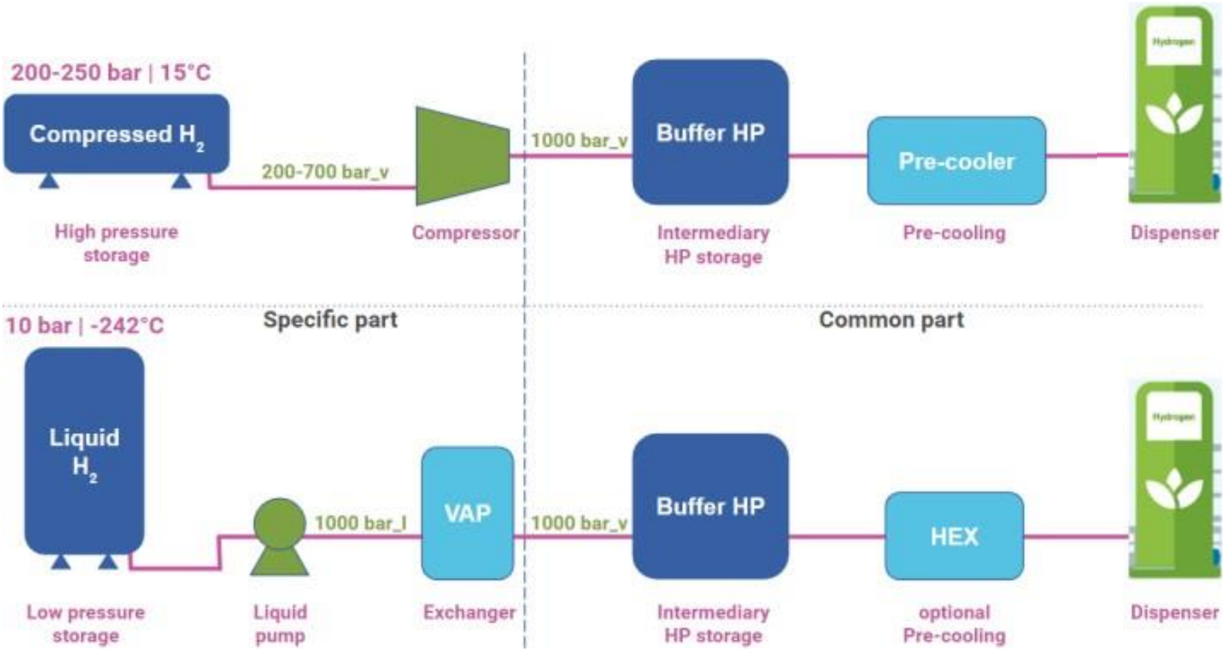

Figure 6 Simplified comparison between gaseous and liquid hydrogen refueling stations [7]Top: gaseous HRS, Bottom: liquid HRS.

Table 1 Comparison between LHRS and HRS [7].

	LHRS	HRS
Storage	Liquid hydrogen, cryogenic temperature (-240°C), low pressure (up to 10 bar)	Gaseous hydrogen, ambient temperature, high pressure (from 200 to 500 bar)
Refiling of the station	Transfer of liquid hydrogen from trailer to storage	Mainly swap (= full for empty)
Pressurization of hydrogen	Liquid pump and vaporizer required to deliver gaseous H_2	Compressor

As hydrogen is usually delivered at low or medium pressures (around 10 bar for liquid H_2 and 200 bar for compressed gaseous H_2), there is the need for compression to elevated pressure levels up to 850-1000 bar for storage – in intermediary tanks – before being dispensed to the vehicle’s tank (standard required pressure: 350 or 700 bar) [8].

Compression is not required if the hydrogen supplied is at a higher pressure level than that required by the vehicle. In this case, the vehicle is refueled by the difference in pressure.

Depending on the chosen way of compression, it is possible to reach the final maximum pressure required for the filling [7]:

- in two steps with a medium (~400 bar) and a high pressure (~1000 bar) compressor;
- or with a single compressor which is able to deliver the maximum pressure.

There are different types of compressors for gaseous hydrogen depending on the required flow rate and pressure, these include mechanical compressors (mechanical piston, liquid piston, diaphragm, linear, ionic liquid) and non-mechanical compressors (cryogenic, metal hydride). The most common are boosters and diaphragm compressors. The booster is driven by compressed air and is used for low mass flow rates, whereas the diaphragm compressor is electrically driven and is recommended for high mass flow rates [8].

Figure 7 Diaphragm compressor (Neumar & Esser) (left) and booster (Haskel) (right)

On the other hand liquid hydrogen station requires pumping liquid hydrogen and vaporizing in order to refill the vehicle. In the first step cryogenic pumps allow to transfer liquid from the storage tank to the heat exchanger. The pressure of liquid hydrogen is then slightly increased. The aim of the vaporizer is to increase pressure of the gaseous hydrogen which will be stored in intermediary buffers at a pressure up to 900 bar. Temperature of hydrogen is increased as wellfrom -220 to -30°C. Several technologies are available for this heat exchanger. The main are atmospheric and tube-in-tube vaporizer [7].

Figure 8 Cryo-pump (Cryostar) and vaporizer (HQHP)

Dispensing is the part of the refueling station which allows the consumer to fill their hydrogen vehicles. The dispenser is at the interface between the station and the vehicle. In the standard configuration, external hydrogen dispenser is offering a comparable experience to existing

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conventional fuel (petrol/diesel) stations. The dispenser enables a fast, easy and safe connection between the station and the vehicle to process the fueling. Several designs of dispensers are available according to the manufacturer and refueling station evolutions (Figure 9) [7].

Figure 9 Hydrogen dispensers [7]

2.3. Hydrogen vehicles and physical connection

Typical hydrogen capacity for hydrogen vehicles falls within such ranges [10]:

- 4 – 7 kg for passenger vehicles;
- 20 – 40 kg for mid-sized buses or mid-sized trucks;
- 40 – 80 kg for heavy duty trucks.

Examples of hydrogen passenger vehicles include:

- Toyota Mirai II (5,6 kg H_2 on-board);
- Hyundai Nexo (6,33 kg H_2);
- Hyundai ix35 (5,64 kg H_2).

Heavy-duty trucks powered with hydrogen are still under development, and among the most relevant projects, the following can be named [6]:

- Xcient Fuel Cell (Hyundai Motors) – supplied with 350 bar CGH_2;
- HyMax 450 (Hyzon Motors) – 350 bar CGH_2;
- Nikola TRE (Nikola Motors & Iveco) – 700 bar CGH_2;
- GenH2 Truck (Daimler Truck AG) – sLH_2.

Figure 10 Toyota Mirai and fuel-cell semi-truck [11]

The connection between the vehicle and the refueling point is made using a nozzle-receptacle pairing to ensure compatibility and where necessary, act as a mechanical lockout device to prevent unsafe situations. The requirements for nozzle and receptacle pairings are standardizedthrough two documents: ISO 17268 (*Gaseous hydrogen land vehicle refueling* *connectiondevices*) and SAE J2600 (*Compressed hydrogen surface vehicle fuelling connection devices*), which are aligned with each other. The scope of standards is design, safety and operation characteristics of gaseous hydrogen land vehicle (GHLV) refueling connectors. Those documentsapply to devices which have pressure classes of H11, H25, H35, H50 or H70 (Table 2), which means that they cover connectors operating on typical pressure levels of hydrogen vehicles(350 and 700 bar).

Table 2 Pressure classes according to SAE J2600 and ISO 17268

Pressure Class	Nominal Working Pressure @ 15°C	Design Pressure (1.5 x NWP)
H11	11 MPa	16.5 MPa
H25	25 MPa	37.5 MPa
H35	35 MPa	52.5 MPa
H50	50 MPa	75.0 MPa
H70	70 MPa	105.0 MPa

Acc. to aforementioned standards the main intention of standardized physical connectors is to:

- Prevent vehicles from being fueled with a pressure class greater than vehicle's pressure;
- Allow vehicles to be fueled with pressure class equal to or less than vehicle's pressure,
- Prevent vehicles from being fueled by other compressed gases dispensing stations;
- Prevent other gaseous fueled vehicles from being fueled by hydrogen dispensing stations.

Typically, refueling connectors consist of the following components, as applicable: receptacle and protective cap (mounted on vehicle), nozzle, and communication hardware. The interoperability of nozzles and receptacles for different classes and exemplary nozzles are depicted below.

Figure 11 Nozzle-receptacle matrix (left), nozzle for LDV refueling (middle), nozzle for HDV refueling (right) (WEH)

Refueling interface is illustrated in Figure 12.

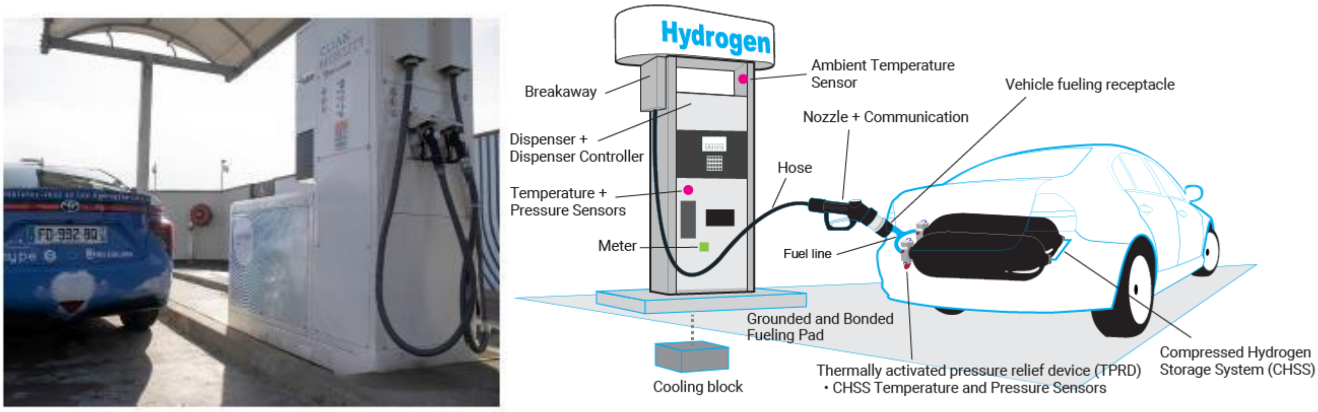

Figure 12 Dual dispenser for LDV refueling (left), scheme of refueling interface (right) [7]

3. Advancements in Hydrogen Refueling Technologies for Heavy-Duty Vehicles

To fulfil future heavy-duty vehicles refueling needs such as fuelling a 100 kg heavy duty truck storage system in 10 minutes, an heavy duty vehicle refueling point should reach a mean fuelling rate of approximatively 170 g/s with a peak fuelling rate up to 300 g/s. To guarantee optimal refueling performances, reliabilities and costs for a wide range of possible HDV storage capacities and configurations, new fuelling protocols based on advanced and safe communication betweenvehicle and station must be implemented [12].

Currently, requirements for a refueling process for hydrogen vehicles and relevant connectors are described in a range of standards:

- SAE J2600 - Compressed Hydrogen Surface Vehicle Fueling Connection Devices;
- SAE J2601 - Fueling Protocols For LD Gaseous Hydrogen Surface Vehicles;
- SAE J2601-2 - Fueling Protocols For HD Gaseous Hydrogen Surface Vehicles;
- SAE J2799 - HSV to Station Communications Hardware and Software;
- ISO 17268-1 - Gaseous hydrogen land vehicle refueling connection devices: Part 1;
- ISO 19885-1 - Gaseous hydrogen - Fuelling protocols for hydrogen-fueled vehicles.

In the near future the following standards are going to be published, partially replacing the former:

- SAE J2601-5 - High-Flow Prescriptive Fueling Protocols for Gaseous Hydrogen PoweredMedium and Heavy-Duty Vehicles;
- ISO 19885-2 - Fuelling protocols for hydrogen-fueled vehicles;
- ISO 19885-3 - High flow hydrogen fuelling protocols for heavy duty road vehicles;
- ISO 17268-2 - Gaseous hydrogen land vehicle refueling connection devices: Part 2.

The diagram below depicts the relations between ISO and SAE standards as well as the future revisions and relations between them.

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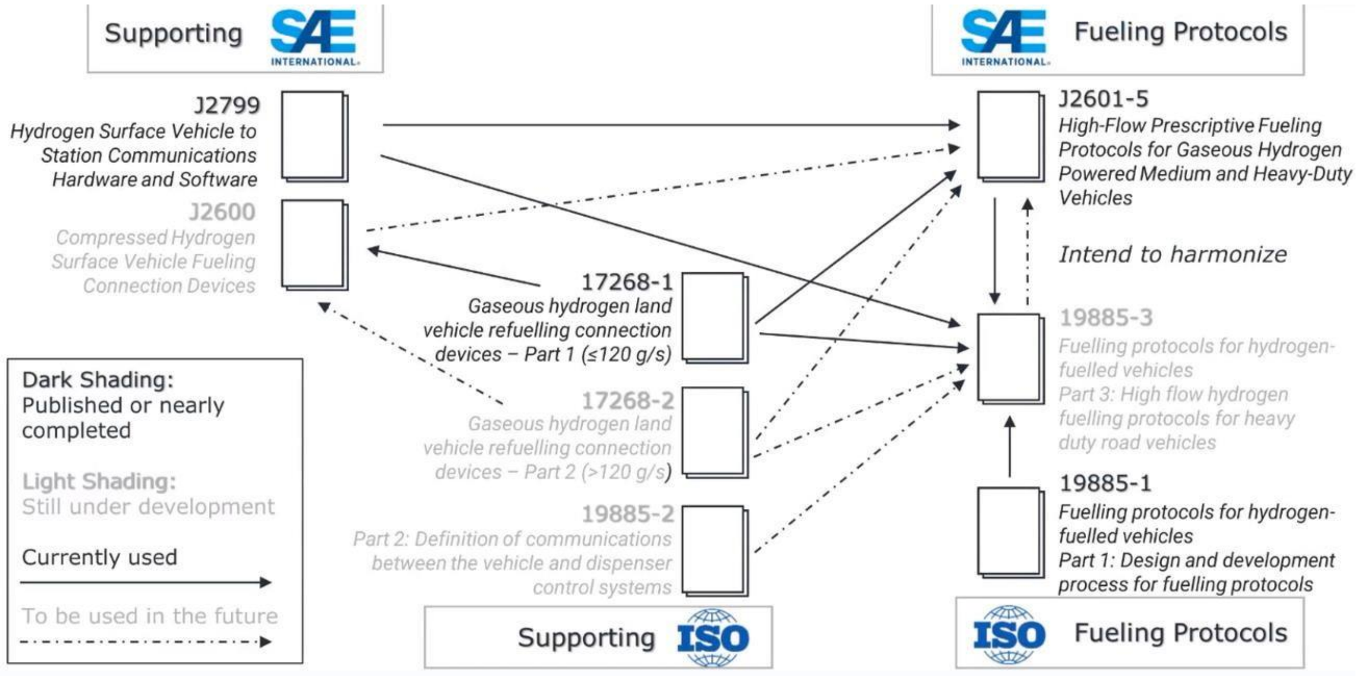

Figure 13 Relation between refueling standards, as of December 2023 [13]

3.1. SAE J2601 Fueling Protocols For LD Gaseous HydrogenSurface Vehicles

SAE J2601 (*Fueling Protocols For Light Duty Gaseous Hydrogen Surface Vehicles*) is currently being used as a basis for hydrogen vehicle fueling worldwide. The goal of SAE J2601 is to fuel all hydrogen storage systems quickly to a high state of charge (SOC) without violating the storage system operating limits of internal tank temperature or pressure. For a H70 (operating pressure 70 MPa) CHSS these temperature and pressure limits are -40 to 85°C and 0.5 to 87.5 MPa, respectively. Figure 14 shows the boundaries for a H70 fueling, crossing of which would cause overpressure and/or overheat of the system. The maximum density (100% SOC) provides an additional boundary.

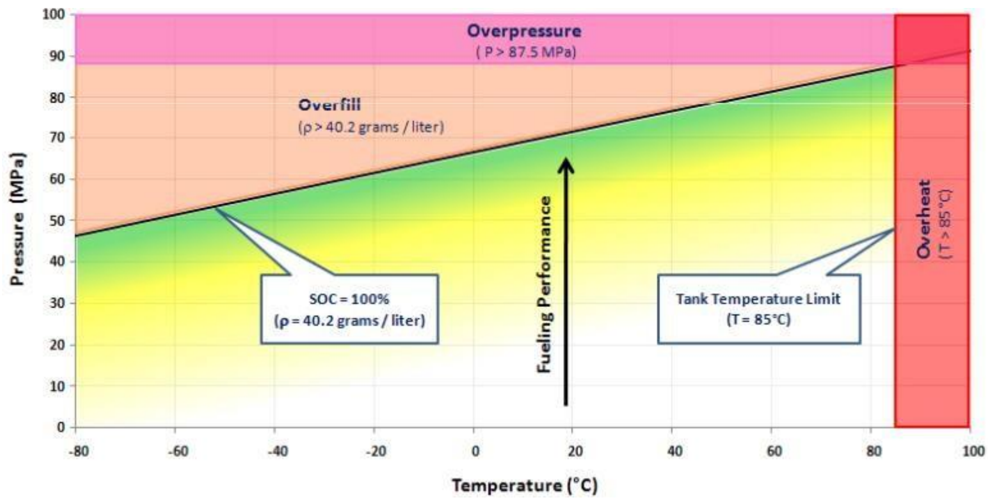

Figure 14 Hydrogen Storage System Fueling Window – 70 MPa case (from SAE J2601)

In order to keep the CHSS within its operating boundaries, the station must adjust the flow of thegas depending on the full set of initial conditions. Parameters that affect the refueling process arethe initial pressure in the vehicle's CHSS, the ambient conditions and the fuel temperature and pressure at the dispenser. Dispenser measures initial tank pressure, tank volume, ambient temperature and fuel delivery temperature to calculate fill rate and final pressure. In SAE J2601's philosophy station assumes full responsibility, no exchange of safety critical fueling data, thereforelarge safety margins are implemented.

SAE J2601 has been recently (2020) revised in order to incorporate an extension of the compressed hydrogen storage system sizes above 248.6 L (>10 kg) for H70 only. Still, considering this protocol for heavy-duty vehicles would make the fueling times >30 min for a tank system size of 80 kg H_2 [14].

Table 3 SAE J2601 content

<table>
<tr><td colspan="2">Pressure Class Designation</td><td colspan="3">H35</td><td colspan="3">H70</td></tr>
<tr><td colspan="2">CHSS Capacity Range (Liters)</td><td>< 49.7</td><td>49.7 to 248.6</td><td>> 248.6</td><td>< 49.7</td><td>49.7 to 248.6</td><td>> 248.6</td></tr>
<tr><td colspan="2">CHSS Capacity Range (kg)</td><td>< 1.19</td><td>1.19 to 5.97</td><td>> 5.97</td><td>< 2.0</td><td>2.0 to 10.0</td><td>> 10.0</td></tr>
<tr><td colspan="2">CHSS Capacity Categories (nomenclature)</td><td>TBD</td><td>A, B, C</td><td>D</td><td>TBD</td><td>A, B, C</td><td>D</td></tr>
<tr><td colspan="2">Maximum Flow Rate (g/s)</td><td>≤ 60</td><td>≤ 60</td><td>≤ 60</td><td>≤ 60</td><td>≤ 60</td><td>≤ 60</td></tr>
<tr><td rowspan="5">Fuel Delivery Temperature Category</td><td>T40</td><td rowspan="5">Not Included</td><td rowspan="3">Included</td><td rowspan="5" colspan="2">Not Included</td><td rowspan="3" colspan="2">Included</td></tr>
<tr><td>T30</td></tr>
<tr><td>T20</td></tr>
<tr><td>T10</td><td rowspan="2"></td><td rowspan="2" colspan="2"></td></tr>
<tr><td>Ambient</td></tr>
</table>

3.2. SAE J2601-2 Fueling Protocol For Gaseous HydrogenPowered HDV

SAE J2601-2 (*Surface Vehicle Information Report - Fueling Protocol For Gaseous Hydrogen Powered Heavy Duty Vehicles*) is a performance based protocol document that also provides guidance to fueling system builders, manufacturers of gaseous hydrogen powered heavy duty transit buses, and operators of the hydrogen powered vehicle fleet [15].

The original intent of this document was to establish the safety limits and performance requirements for 35 MPa hydrogen dispensing systems for refueling transit buses and heavy duty vehicles. However, as the market developed, additional fueling protocols have been published inthe SAE J2601 context (for example: CHSS Capacity Category D). Now, the purpose of this document is to provide performance requirements for hydrogen dispensing systems used for fueling 35 MPa heavy duty hydrogen transit buses and vehicles (other pressures are optional).

SAE J2601-2 should only be utilized at non-public access hydrogen stations where the vehicles being fueled are known and appropriate administrative controls are enforced. Users of SAE J2601-2 are also advised that SAE J2601 may contain requirements and considerations that should be applied to fueling protocols developed under SAE J2601-2. It is the responsibility of thefueling protocol developer to ensure that the resulting protocol can be used under all operating conditions for all vehicles and CHSS configurations.

The summary below depicts current (as of December 2023) use of hydrogen refueling protocols and connection types for pressure level, amount of hydrogen and flow rate.

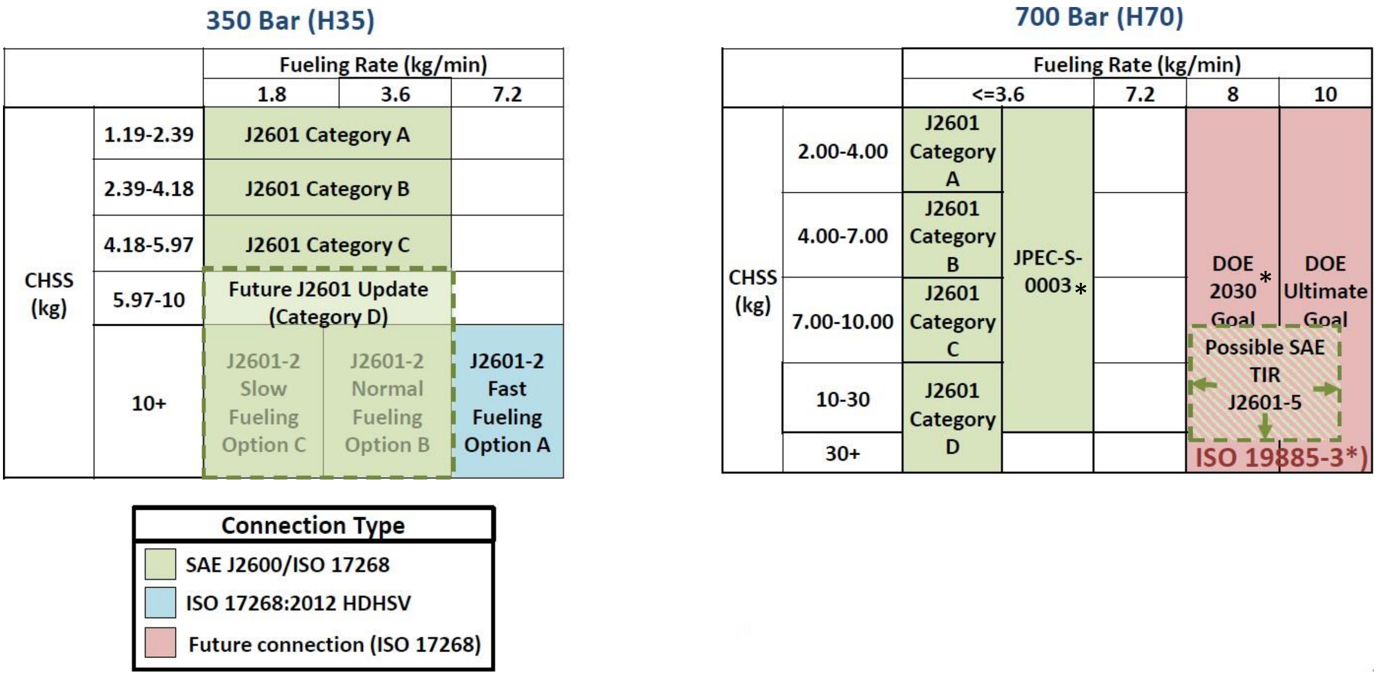

Figure 15 Summary: Current H2 Fueling Protocols/Guidance and Hardware [16]

*JPEC-S-0003 is a Japanese standard, **DOE – US Department of Energy

3.3. SAE J2601-4 (WIP) Ambient Temperature Fueling

SAE J2601-4 (Work In Progress) establishes the protocol and process limits for hydrogen fueling of light duty vehicles when the fuel delivery temperature is not pre-cooled, so called "ambient fueling" [15]

These process limits (including the fuel delivery temperature, the maximum fuel flow rate, the rateof pressure increase and the ending pressure) are affected by factors such as ambient temperature, fuel delivery temperature and initial pressure in the vehicle's compressed hydrogenstorage system. SAE J2601-4 establishes standard fueling protocols based on a series of design cases representing fueling system engineering categories. These categories are intended to provide performance targets which allow decreasing fueling times relative to the most simple design case. Similar to the table and formula based approaches of SAE J2601, this approach establishes a minimum performance criteria leaving open options for innovation to decrease fueling times.

3.4. SAE J2601-5 (WIP) High Flow Protocols for MD and HDvehicles

TIR SAE J2601-5 will establish prescriptive general-purpose high-flow fueling protocols and process limits for hydrogen fueling of vehicles with compressed hydrogen storage system (CHSS)volume capacities between 750 and 2500 liters. These process limits (including the fuel deliverytemperature, the maximum fuel flow rate, the rate of pressure increase, and the ending pressure)are affected by factors such as ambient temperature, fuel delivery temperature, and initial pressure in the vehicle's compressed hydrogen storage system [15].

SAE J2601-5 will initially be published as a Technical Information Report (TIR). Publication date is expected to be late January of 2024 [13]. TIR SAE J2601-5 will include two sets of fueling protocols:

- high-flow versions of the Category D protocol described in SAE J2601;
- an MC Formula-based fueling protocol which utilizes a dynamic pressure ramp rate continuously calculated throughout the fill.

TIR SAE J2601-5 will cover higher flow than SAE J2601 for vehicles with higher hydrogen capacity, detailed protocols characteristics shown below.

Protocol Name	Pressure Class	Flow Rate Maximum Class (Non-Comm)	Flow Rate Maximum Class (Comm)	Range of CHSS Capacity (liters / kg)	Range of Tank Sizes within the CHSS (liters)	Coupling Type*	Fuel Delivery Temperature Range
Category D HF	H70	FM60	FM60 (w/o OD) FM90 (with OD)	248.6 to 5000 (10kg to 201kg)	50 to 800	H70 (4mm bore)	-40°C to -17.5°C
MCF-HF-G	H35	FM120	FM120	248.6 to 7500 (6kg to 180kg)	50 to 1000	H35HF	-40°C to +20°C
	H70	FM60	FM60 (w/o OD) FM90 (with OD)	248.6 to 5000 (10kg to 201kg)	50 to 800	H70 (4mm bore)	-40°C to 0°C
		FM300	FM300			H70HF**	

Figure 16 Coupling types, range of CHSS sizes, tank sizes and fuel delivery temperatures for SAE J2601-5 [13]

3.5. ISO 19885-3 (WIP) High flow hydrogen fuelling protocols forheavy duty road vehicles

Previous protocols such as SAE J2601 are based on the assumption that an HRS has no,or extremely limited, information on the vehicle that can be used to define the fueling protocol: forinstance, the CHSS properties (total volume, unitary volume, tank types, thermodynamic properties of the tank material, tank shapes etc.), or the gas thermodynamic gas conditions (temperature and pressure). Due to this lack of information, such fuelling protocols are required to take conservative approaches, which leads to unoptimized fuelling. The absence of communicated information about the CHSS also leads to the overdesign of the station for the required precooling, which affects both OPEX and CAPEX.

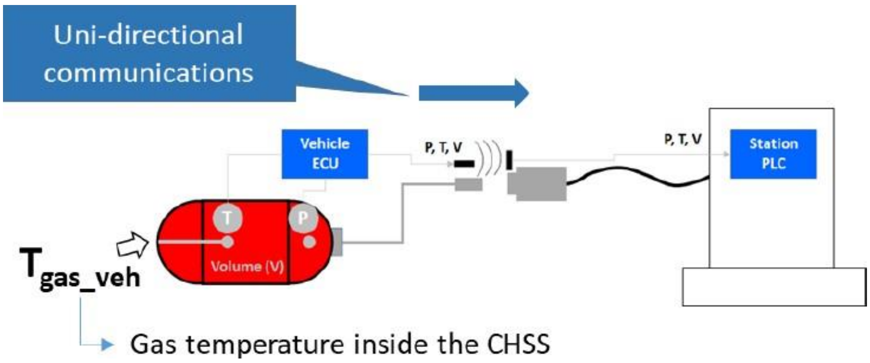

Figure 17 State-of-the-art refueling process and communication acc. to SAE J2601 [17]

To make refueling more efficient different solutions are possible: reducing safety margins, communicating extended tank parameter set and fueling with feedback control (pressure and temperature transmitted continuously). The latter two assume availability of communication channel for safety-critical information (Figure 18).

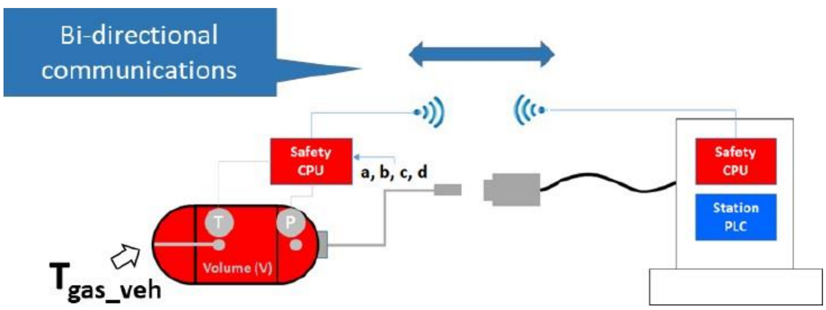

Figure 18 Possible future refueling process and communication [17]

New ISO 19885-3 is planned to standardize protocols developed by so called PRHYDE project. The PRHYDE project aimed to develop recommendations for a non-proprietary heavy duty refueling protocol used for future standardization activities for trucks and other heavy duty transport systems applying hydrogen technologies.

Based on existing fueling protocols and current state of the art for compressed (gaseous)

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hydrogen fuelling, different hydrogen fueling protocols concepts were developed for large tank systems with 35, 50, and 70 MPa nominal working pressures using simulations as well as experimental verification. Furthermore a broad industry perspective was captured via an intense stakeholder participation process throughout the project.

Figure 19 PRHYDE project logo [7]

3.6. ISO 17268-1 (WIP) Gaseous hydrogen land vehicle refuelingconnection devices

ISO 17268:2020 is the current ISO standard defining the design, safety and operation characteristics of gaseous hydrogen land vehicle (GHLV) refuelling connectors.

ISO 17268-1 will describe gaseous hydrogen land vehicle refuelling connection devices with flowcapacities up to and including 120 g/s, which is needed to fulfil intended refueling speed from planned SAE J2601-5. The next planned standard ISO 17268-2 (2026) is planned to allow 300g/sfueling flow rate [13].

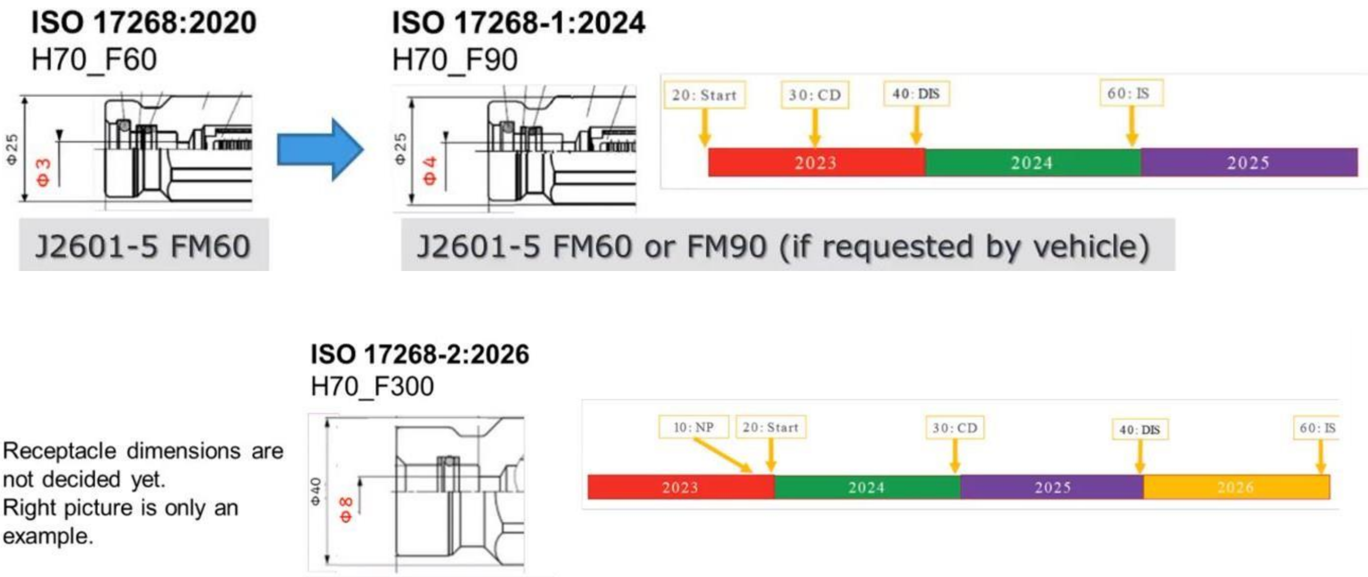

Figure 20 Improvement of coupling type in time with increased allowed flow rate [13]

3.7. ISO 19880 Gaseous hydrogen - Fuelling stations

ISO 19880 defines the minimum design, installation, commissioning, operation, inspection and maintenance requirements, for the safety, and performance of fuelling stations that dispense gaseous hydrogen to light duty road vehicles. While this document is targeted for the fueling of light duty hydrogen road vehicles, requirements and guidance for fueling medium and heavy duty road vehicles (e.g. buses, trucks) are also covered.

Many of the generic requirements within this document are applicable to fueling stations for other hydrogen applications, including but not limited to the following:

- fueling stations for motorcycles, fork-lift trucks, trams, trains and other;
- fueling stations with indoor dispensing;
- residential applications to fuel land vehicles;
- mobile fueling stations; and
- non-public demonstration fueling stations.

Current status of ISO 19880 parts are listed in Table 4 below.

Table 4 ISO 19880 status [18]

ISO 19880-1:2020	GH_2 — Fuelling stations — Part 1: General requirements	available
ISO/DIS 19880-2	GH_2 — Fuelling stations — Part 2: Dispensers and dispensing systems	available
ISO19880-3:2018	GH_2 — Fuelling stations — Part 3: Valves	available
ISO 19880-4	GH_2 — Fuelling stations — Part 4: Compressors	proposed
ISO 19880-5:2019	GH_2 — Fuelling stations — Part 5: Dispenser hoses and hose assemblies	available
ISO/CD 19880-6	GH_2 — Fueling stations — Part 6: Fittings	deleted
ISO/DIS 19880-7	GH_2 — Fuelling stations — Part 7: Rubber O-rings	under development
ISO 19880-8:2019	GH_2 — Fuelling stations — Part 8: Fuel quality control	available
ISO/DIS 19880-9	GH_2 — Fuelling stations — Part 9: Sampling for fuel quality analysis	available

3.8. ISO 13984 Liquid hydrogen - Land vehicle fuelling systeminterface

ISO 13984:1999 specifies the characteristics of liquid hydrogen refueling and dispensing systemson land vehicles of all types in order to reduce the risk of fire and explosion during the refueling procedure and thus to provide a reasonable level of protection from loss of life and property. ISO 13984:1999 is applicable to the design and installation of liquid hydrogen (LH_2) fuelling and dispensing systems. It describes the system intended for the dispensing of liquid hydrogen toa vehicle, including that portion of the system that handles cold gaseous hydrogen coming from the vehicle tank, that is, the system located between the land vehicle and the storage tank. However, upcoming revision of ISO 13984 standard is intended to provide Liquid Hydrogen LandVehicle Fueling Protocol.

4. Identification of Carrier Expectations Regarding Hydrogen Technologies in HDV

At present, the set standard involves refueling PV and LDV vehicles at 700 bar CGH_2 and buses at 350 bar CGH_2. Nevertheless, various OEMs are working on or are funded by European projects to develop heavy-duty trucks that operate at distinct pressure levels and utilize varying hydrogen states. Some instances of this development include [6]:

- 350 bar CGH_2 - Xcient Fuel Cell (Hyundai Motors), HyMax 450 (Hyzon Motors);
- 700 bar CGH_2 - Nikola TRE (Nikola Motors & Iveco);
- sLH_2 - GenH_2 Truck (Daimler Truck AG);
- cCH_2 – CryoTRUCK (Cryomotive).

Every hydrogen storage technology follows a distinct development path and faces its own problems. Therefore it is important to acknowledge that each carrier may expect certain technology advancements regarding their fleet technology.

Figure 21 Existing and announced fuel cell HDV manufacturers for the European market [6]

However, universal carrier expectations to be fulfilled by HRS network include:

- Robust hydrogen infrastructure: Carriers anticipate the development of refueling stations along key transportation routes. They expect the infrastructure to support efficient and widespread adoption of hydrogen-powered heavy-duty vehicles;
- Cost-Effectiveness: Carriers seek cost-effective solutions, to make hydrogen technologies competitive in terms of fuel price with diesel;
- Minimal modification of hydrogen refueling stations compared to conventional stations: Carriers expect minimal changes to be made to hydrogen refueling stations compared to conventional refueling stations. This approach aims to make it easy for drivers to transitionto hydrogen vehicles without the need for significant adjustments or additional training;
- Short refueling time: Carriers emphasize the importance of short refueling times tomaximize vehicle uptime. Hydrogen refueling stations should provide fast and efficient refueling processes, similar to refueling with conventional fuels like diesel or gasoline;
- Pressure level compatibility: Carriers require hydrogen refueling stations to provide hydrogen at a pressure level that is adequate for their fleet's needs. It is essential to matchthe pressure levels of the hydrogen storage tanks in the vehicles to avoid inefficiencies and ensure safety. Lower pressure levels, while possible, are generally undesired due to reduced efficiency.

Some of the listed expectations go hand in hand with latest EU regulations, including those aimed at regulating truck drivers' time to ensure the safe operation of heavy-duty fleets. For instance, Regulation (EC) No 561/2006 enforces mandatory breaks for drivers (of at least 45 minutes, separable into 15 minutes followed by 30 minutes), so it can be concluded that a total refueling time of 10-15 minutes would be suitable for truck drivers to comply with worktime regulations.

It is also a common target for standardization committees to achieve a hydrogen fill rate of 60-80 kg within a 10-15 minute timeframe. This target is essential to facilitate a smooth transition to hydrogen-powered vehicles in the trucking industry [20].

Currently, the specific pressure level standards for hydrogen refueling stations remain uncertain,as the industry's direction is hard to predict. There are trucks being developed to accommodate both 350 bar and 700 bar compressed gaseous hydrogen, as well as liquid hydrogen. However, it is worth noting that providing a station with 350 bar dispensers means that it is not only capableof refilling 350 bar vehicles but also 700 bar vehicles, just to a lower state of charge, making it more versatile.

The project HyTruck is supported by the Interreg Baltic Sea Region Programme 2021-2027

5. Legal Aspects Governing Technical Standards of Fuel Stations in Europe

The hydrogen refueling station is a building structure that constitutes a functional whole. Consequently, its design, construction, commissioning for operation, and operational principles are regulated by numerous normative acts concerning constructional, technical, safety, and environmental aspects. Some of the relevant EU documents demonstrating the EU's comprehensive approach to tackling climate change and promoting sustainability with the use ofhydrogen technologies are listed in the table below.

Table 5 Legal documents issued by the European Parliament and the Council (if not stated otherwise)

Document Name	Date of Issue	Main Purpose
Regulation 2021/1119	30 Jun. 2021	Achieving climate neutrality
Directive 2018/2001	11 Dec. 2018	Promotion of the use of energy from renewable sources
Commission Delegated Regulation 2023/1184	10 Feb. 2023	Detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin
Directive 2014/94/EU	22 Oct. 2014	Development of alternative fuels infrastructure
Regulation 2019/631	17 Apr. 2019	Setting CO_2 emission standards for cars and light commercial vehicles
Regulation 2019/1242	20 Jun. 2019	Setting CO_2 emission performance standards for new heavy-duty vehicles
Regulation 347/2013	17 Apr. 2013	Guidelines for trans-European energy infrastructure
Directive 2003/87/EC	13 Oct. 2003	Greenhouse gas emission trading scheme within the community
Directive 2010/75/EU	24 Nov. 2010	Industrial emissions (integrated prevention and pollution control)
Regulation 2020/852	18 Jun. 2020	Establishment of a framework to facilitate sustainable investments
Commission Implementing Regulation 2022/996	14 Jun. 2022	Rules for verify sustainability and greenhouse gas emissions saving criteria
Commission Implementing Decision	9 Oct. 2014	Conclusions on Best Available Techniques for industrial emissions, for mineral oil and gas refining
Council Regulation 2021/2085	19 Nov. 2021	Establishing joint undertakings under Horizon Europe
Regulation 1316/2013	11 Dec. 2013	Creation of the "Connecting Europe" Facility
Regulation 2023/957	10 May 2023	Amendment of the EU Emissions Trading System
Regulation 2023/851	19 Apr. 2023	Amending CO_2 emission standards for vehicles

5.1. Alternative fuels infrastructure regulation (AFIR)

The AFIR, standing for the Regulation (EU) 2023/1804 on the deployment of alternative fuel infrastructure, is an important regulation in the realm of hydrogen infrastructure. Published in theOfficial Journal of the European Union at the end of September 2023, it repeals Directive 2014/94/EU. This regulation is set to enter into force on April 13, 2024, marking a significant milestone in the development of alternative fuel infrastructures across Europe.

The AFIR sets binding national targets for the development of adequate EU alternative fuel infrastructure (incl. hydrogen infrastructure). The new regulation also establishes common technical specifications and requirements regarding the information to vehicle users for the provision of data and payment requirements.

According to AFIR hydrogen refueling infrastructure that can serve both cars and trucks must bedeployed from 2030 onwards in all urban nodes and every 200 km along the TEN-T core network,ensuring a sufficiently dense network to allow hydrogen vehicles to travel across the EU.

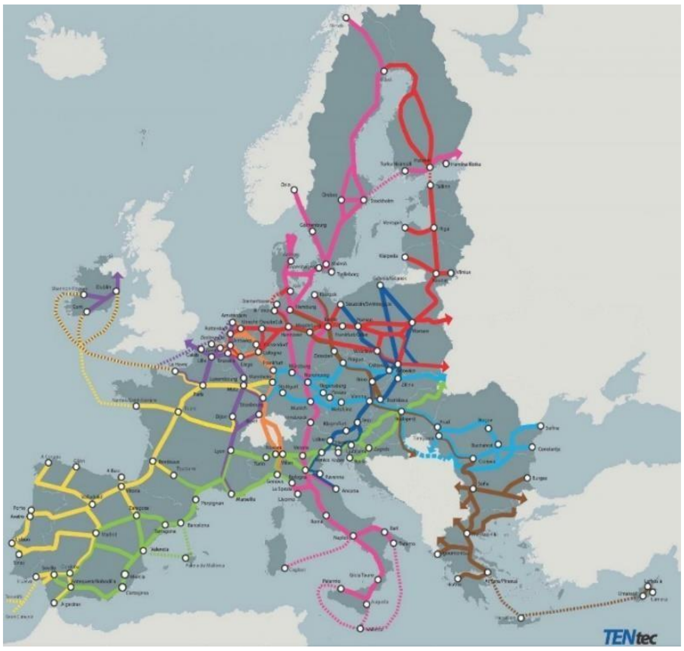

Figure 22 TEN-T core network [20]

These stations should have:

- a cumulative capacity of at least 1 ton hydrogen per day,
- be equipped with a 700 bar dispenser,
- with a maximum distance of 200 km between them.

Additionally, by the same deadline, at least one publicly accessible hydrogen refueling station must be deployed in each urban node. The deployment should consider multimodal hubs to accommodate various transport modes.

Regulations for operators of hydrogen refueling points include:

- Ad hoc refueling accessibility: Operators of publicly accessible hydrogen refueling points must allow end users to refuel on an ad hoc basis. They should accept widely used Unionpayment instruments for electronic payments, such as payment card readers or contactless payment devices;
- Fair and transparent pricing: Operators must set reasonable, easily comparable, transparent, and non-discriminatory prices for hydrogen refueling. Discrimination between end users or mobility service providers is prohibited, though differentiation in prices is allowed if objectively justified;
- Price information transparency: Operators should clearly display the price per kg for ad hoc refueling at their stations, enabling end users to compare prices before startinga refueling

session;

- Contractual refueling services: Operators can provide hydrogen refueling services to customers through contracts with mobility service providers. These providers must charge end users reasonable, transparent, and non-discriminatory prices. Mobility service providers must offer all specific price information before the refueling session starts througheasily accessible electronic means, outlining all charges and fees, including e-roaming costs, applied by the hydrogen refueling point operator.

Furthermore, hydrogen refueling station characteristics shall comply with the requirements described as in the table below.

Table 6 Subjects and standards listed in AFIR

Quality of hydrogen	EN 17124:2022
Outdoor hydrogen refueling points dispensing gaseous hydrogen	EN 17127:2020 (at least the interoperability requirements)
The fueling algorithm	EN 17127:2020
Connectors for motor vehicles	EN ISO 17268:2020 (once the process of certification of standard is concluded)

5.2. Codes and standards for a hydrogen refueling station

Apart from aforementioned regulations, there are other technical standards that continuously systematize the available technical knowledge and set standards for hydrogen refueling stations.The table below attempts to summarize already described standards as well as some other regulations, which may be helpful in the design of hydrogen refueling station.

Table 7 HRS standards - summary

Standard	Description
HRS: Construction and Design	
ISO 19880-1 Gaseous hydrogen - Fueling stations - Part 1: General requirements	This document defines the minimum design, installation, commissioning, operation, inspection and maintenance requirements, for the safety, and, where appropriate, for the performance of public and non-public fuelling stations that dispense gaseous hydrogen to light duty road vehicles (e.g. fuel cell electric vehicles). While this document is targeted for the fuelling of light duty hydrogen road vehicles, requirements and guidance for fuelling medium and heavy duty road vehicles (e.g. buses, trucks) are also covered.
EN 17127 Outdoor hydrogen refueling points dispensing gaseous hydrogen and incorporating filling protocols	This document defines the minimum requirements to ensure the interoperability of hydrogen refueling points, including refueling protocols that dispense gaseous hydrogen to road vehicles (e.g. Fuel Cell Electric Vehicles) that comply with legislation applicable to such vehicles. The safety and performance requirements for the entire hydrogen fuellingstation, addressed in accordance with existing relevant European and national legislation, are not included in this document.
ISO 17268 Gaseous hydrogen land vehicle refueling connection devices	This document defines the design, safety and operation characteristics of gaseous hydrogen land vehicle (GHLV) refueling connectors.
ISO 22734:2019 Hydrogen generators using water electrolysis - Industrial, commercial, and residential applications;	This document defines the construction, safety, and performance requirements of modular or factory-matched hydrogen gas generation appliances, herein referred to as hydrogen generators, using electrochemical reactions to electrolyse water to produce hydrogen.

SAE J2600 Compressed Hydrogen Surface Vehicle Fueling Connection Devices	This document applies to the design and testing of Compressed Hydrogen Surface Vehicle (CHSV) fueling connectors, nozzles, and receptacles. Connectors, nozzles, and receptacles must meet all SAE J2600 requirements and pass all SAE J2600 testing to be considered as SAE J2600 compliant.
ISO 17268:2020 Gaseous hydrogen land vehicle refuelling connection devices	This document defines the design, safety and operation characteristics of gaseous hydrogen land vehicle (GHLV) refuelling connectors.

ISO 13984:1999 Liquid hydrogen - land vehicle fuelling system interface	This standard specifies the characteristics of liquid hydrogen refuelling and dispensing systems on land vehicles of all types in order to reduce the risk of fire and explosion during the refuelling procedure and thus to provide a reasonable level of protection from loss of life and property. This International Standard is applicable to the design and installation of liquid hydrogen fuelling and dispensing systems. It describes the system intended for the dispensing of liquid hydrogen to a vehicle, including that portion of the system that handles cold gaseous hydrogen coming from the vehicle tank, that is, the system located between the land vehicle and the storage tank.
ISO/TR 15916:2015 Basic considerations for the safety of hydrogen systems	ISO/TR 15916:2015 provides guidelines for the use of hydrogen in its gaseous and liquid forms as well as its storage in either of these or other forms (hydrides). It identifies the basic safety concerns, hazards and risks, and describes the properties of hydrogen that are relevant to safety. Detailed safety requirements associated with specific hydrogen applications are treated in separate International Standards.
NFPA 2 Hydrogen Technologies Code	This is a The National Fire Protection Association (NFPA) standard. This code provides fundamental safeguards for the generation, installation, storage, piping, use, and handling of hydrogen in compressed gas (GH2) form or cryogenic liquid (LH2) form.
HRS: Fire protection	
ISO 14687:2002 Hydrogen fuel — Product specification	This document specifies the minimum quality characteristics of hydrogen fuel as distributed for utilization in vehicular and stationary applications.
IEC 60079-10-1:2020 Explosive atmospheres — Part 10-1: Classification of areas — Gas atmospheres;	IEC 60079-10-1:2020 is concerned with the classification of areas where flammable gas or vapour hazards may arise and may then be used as a basis to support the proper design, construction, operation and maintenance of equipment for use in hazardous areas.
ISO/TR 15916:2015 Basic considerations for the safety of hydrogen systems;	ISO/TR 15916:2015 provides guidelines for the use of hydrogen in its gaseous and liquid forms as well as its storage in either of these or other forms (hydrides). It identifies the basic safety concerns, hazards and risks, and describes the properties of hydrogen that are relevant to safety. Detailed safety requirements associated with specific hydrogen applications are treated in separate International Standards.
HRS: Fueling Protocols	
SAE J2601 (2020) Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles	SAE J2601 establishes the protocol and process limits for hydrogen fueling of vehicles with total volume capacities greater than or equal to 49.7 L. These process limits (including the fuel delivery temperature, the maximum fuel flow rate, the rate of pressure increase, and the ending pressure) are affected by factors such as ambient temperature, fuel delivery temperature, and initial pressure in the vehicle's compressed hydrogen storage system.
SAE J2601-2 (2023) Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles	SAE J2601-2 is a performance based protocol document that also provides guidance to fueling system builders, manufacturers of gaseous hydrogen powered heavy duty transit buses, and operators of the hydrogen powered vehicle fleet(s).
SAE J2601-5 (WIP – 2024) High-Flow Prescriptive Fueling Protocols for Gaseous Hydrogen Powered Medium and Heavy-Duty Vehicles	TIR SAE J2601-5 establishes prescriptive general-purpose high-flow fueling protocols and process limits for hydrogen fueling of vehicles with compressed hydrogen storage system (CHSS) volume capacities between 750 and 2500 liters which have been qualified to UN GTR #13. These process limits (including the fuel delivery temperature, the maximum fuel flow rate, the rate of pressure increase, and the ending pressure) are affected by factors such as ambient temperature, fuel delivery temperature, and initial pressure in the vehicle's compressed hydrogen storage system.

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Hydrogen Quality	
SAE J2719 (2020) Hydrogen Fuel Quality for Hydrogen Vehicles	This standard provides background information and a hydrogen fuel quality standard for commercial proton exchange membrane (PEM) fuel cell vehicles.
ISO 14687 Hydrogen fuel quality — Product specification	This document specifies the minimum quality characteristics of hydrogen fuel as distributed for utilization in vehicular and stationary applications.

ISO 19880-8 Gaseous hydrogen — Fueling stations — Part 8: Fuel quality control	This document specifies the protocol for ensuring the quality of the gaseous hydrogen at hydrogen distribution facilities and hydrogen fuelling stations for proton exchange membrane (PEM) fuel cells for road vehicles.
Other standards	
SAE J2579 Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles	The purpose of this document is to define design, construction, operational, and maintenance requirements for hydrogen fuel storage and handling systems in on-road vehicles.

6. Recommendations for Technological Aspects of Hydrogen Refueling Stations in Heavy Road Transport in Europe

In the hydrogen strategy for a climate-neutral Europe, the heavy-duty segment was identified asthe most likely segment for the early mass deployment of hydrogen-powered vehicles. In this regard actions must be taken to ensure that a reliable hydrogen infrastructure will be built in the upcoming years. Therefore recommendations to HRS designers and constructors include:

1. Refueling infrastructure
   - Accommodation of different vehicle segments: While it is suspected that future hydrogen refueling infrastructure should focus on heavy-duty segment, it should be alsoallowing light-duty vehicles to fuel at publicly accessible hydrogen refueling stations.It is recommended to construct hydrogen refueling stations with dispensers for both light-duty and heavy-duty vehicles;
   - Future fuel technologies: Currently the leading hydrogen storage technology in vehiclesis CGH_2, but the roll out of the infrastructure should also take into account the emergence of new technologies, such as liquid hydrogen or cryo-compressed gaseous hydrogen, that allow for a larger range for heavy-duty vehicles and are expected to bethe preferred technology choice of some vehicle manufacturers;
   - Scalable design: As hydrogen demand grows, the refueling stations should be designedto be easily scalable. Modular components can be added as needed to increase capacity without significant disruptions;
   - Integration with existing infrastructure: Possibilities for integrating hydrogen refueling infrastructure with existing fuel stations or industrial sites can be also explored to leverage current logistics and supply chains;
2. Technical parameters
   - Pressure level: Hydrogen truck manufacturers are researching different storage technologies (350 and 700 bar CGH_2, sLH_2, $cCGH_2$) and it is difficult to predict which one will be the future standard. However, in compliance with AFIR requirements for interoperability, publicly accessible hydrogen stations shall at least provide gaseous hydrogen at 700 bar. Provision of both 350 bar and 700 bar options is advised, noting the incompatibility of 700 bar dispensers with vehicles equipped with 350 bar tank systems;
   - Hydrogen capacity: It is recommended to follow AFIR requirements, according to which publicly accessible hydrogen refuelling stations should be designed for a minimum cumulative capacity of 1 tonne per day;
   - Hydrogen storage: New storage methods, such as Liquid Organic Hydrogen Carriers (LOHC) and liquid hydrogen, are recommended to be researched for their potential in enhancing storage efficiency at refueling stations.
3. Miscellaneous
   - Operator training: The introduction of comprehensive training programs for operators of hydrogen refueling stations is strongly recommended, ensuring safe and efficient operation.

- Continual monitoring of regulations: Regular updates on evolving EU regulations and standards related to hydrogen fueling infrastructure are recommended to be monitoredfor compliance and adaptability.

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