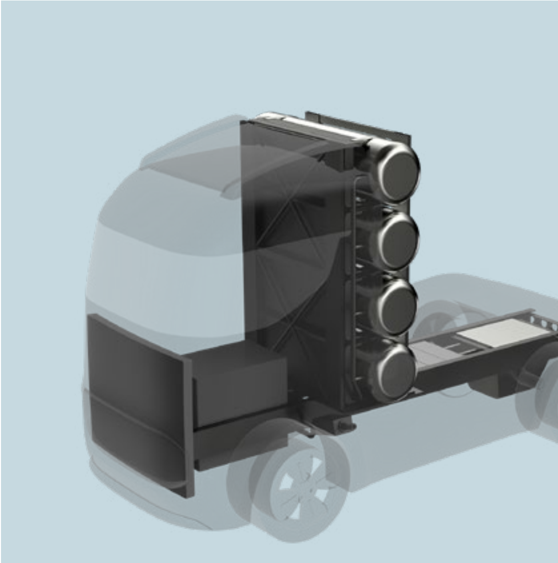
08/2021

H2MOBILITY

Overview
Hydrogen Refuelling For Heavy Duty Vehicles

#FuellingProgress



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»WITH OUR REFUELLING INFRASTRUCTURE WE ASPIRE TO BE A KEY ENABLER FOR THE WIDESPREAD USE OF CLEAN HYDROGEN IN TRANSPORT.«

Nikolas Iwan, CEO H2 MOBILITY

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INTRODUCTION – HYDROGEN WILL BE THE GAME CHANGER

We have all agreed to create a cleaner future, we all believe in energy from renewable sources and we all want to preserve or even improve economic progress, wealth, jobs and health. Hydrogen can play a significant role in achieving that: it enables us to store power from sources like wind, water and sun and can be used regardless of when or where it was produced. This is especially relevant in certain sectors like transportation and logistics.

H2 MOBILITY has established the first country-wide hydrogen refuelling infrastructure in Germany. We are building the basis for a mobile future of rapid refuelling, long range travel and clean, quiet electric mobility in line with expected market growth. While the main growth drivers so far have been passenger vehicles (PV) and busses, we expect the momentum to shift to medium- (MDV) and heavy-duty vehicles (HDV) within the next years. H2 MOBILITY will be building up public hydrogen refuelling infrastructure for the MDV and HDV segments with the most suitable refuelling technology in terms of costs and availability. Refuelling options for PV, LDV and busses are already established and in operation, but technology options for hydrogen refuelling stations (HRS) for MDV and HDV are still under development (besides the established 350 bar option for MDV), since they require higher quantities of hydrogen to be refuelled in a short timeframe.

For logistic companies looking to shift towards zero emission alternatives, the most important consideration factors are convenient refuelling times, payload, range and costs related to their specific use cases. For example, long haul use cases usually require 500 km or more per tank fill, in comparison today's long haul HDV can travel 1,000+ km without refuelling. With an average consumption between 7 and 8 kg H_2 / 100 km for HDV, a minimum of 40 kg of onboard H_2 storage is required if no refuelling stops shall be allowed. Currently, various technology options for MDV/HDV hydrogen refuelling that offer different advantages and trade-offs are under development. This paper focuses on possible hydrogen refuelling options that are under development by at least one original equipment manufacturer (OEM) and one HRS engineering company. These are refuelling of compressed gaseous hydrogen (CGH_2) with 350 bar or 700 bar, cryo-compressed hydrogen (CcH_2) and subcooled liquid hydrogen (sLH_2). Since these different refuelling technologies are in varying stages of development, the goal of this paper is to give a comprehensive overview of the different options. We will analyse each one's technical specifications for hydrogen refuelling, their advantages and disadvantages, the consequences for the design and footprint of HRS, as well as a first assessment of their technology readiness and cost drivers. This analysis is done from the perspective of H2 MOBILITY as a refuelling infrastructure provider with the goal of customer satisfaction in mind.

Disclaimer: This paper is based on the know-how of our internal experts as well as interviews we conducted with industry experts. It represents the subjective view of H2 MOBILITY only and is intended to start and structure a necessary discussion. Hydrogen technologies are evolving rapidly – this paper reflects the status of August 2021. Any feedback is welcome and can be sent to **feedbackoverview@h2-mobility.de**

02 SAFETY

Hydrogen is a non-toxic, odourless gas that is not self-igniting and has been used prevalently in the gas industry for over 100 years. However, like in other applications involving high flows of energy, there are certain risks which need to be managed and mitigated. Additionally, the use of hydrogen at public refuelling stations is relatively modern and is not something the general public is accustomed to. Therefore, safety in everything we do, be it at the office or at the stations, is a priority at H2 MOBILITY.

To ensure safe handling, transport and storage of hydrogen as well as secure operation at stations, there are well-established technical standards and safety procedures in place. All technical equipment found at HRS as well as hydrogen vehicles are tested comprehensively to comply with regulations and to ensure the highest levels of safety. Examples of such regulations that are relevant to the safe construction and operation of HRS in Germany are, among others, the technical rules for operational safety (TRBS).

With regard to the construction and operation of HRS, H2 MOBILITY always adheres to the established certification and safety regulations which are state of the art in the industry. These include supplementary tests and additional regulations to ensure safe operation at public refuelling stations. As part of this safety enhancement effort, H2 MOBILITY records all performance and safety related incidents during the construction and operation of each HRS. In cooperation with the shareholders of H2 MOBILITY, all incidents are systematically analysed with regard to HRS operation and design. Furthermore, the impact on FCEV is also analysed in order to identify potential failures early on for appropriate countermeasures to be taken. In case of a serious incident, a coordinated emergency response procedure is in place to implement necessary measures immediately.

On a national level, H2 MOBILITY is a member of the CEP (Clean Energy Partnership), an association of companies throughout the hydrogen mobility value chain. Within the CEP, technological and safety aspects are analysed based on the combined experience of all members to develop the framework conditions for the future of hydrogen mobility. The CEP tests (DIN EN 17127), a combination of complementary performance and safety tests developed in cooperation with HRS manufacturers and OEMs, are the bases for the release of each HRS from H2 MOBILITY for public operation.

We have built basic infrastructure for cars and light to medium duty vehicles in Germany. Now, we will enable emission-free hydrogen in heavy duty transport too.

HYDROGEN REFUELLING INFRASTRUCTURE

3.1. Status Quo HRS

The hydrogen refuelling station network is growing all over the world. Currently Asia is leading with 275 HRS. In Europe there are around 200 HRS, of which nearly 100 are located in Germany, along national highways and trans-European corridors. In North America there are 75 HRS, of which 49 are located in California.

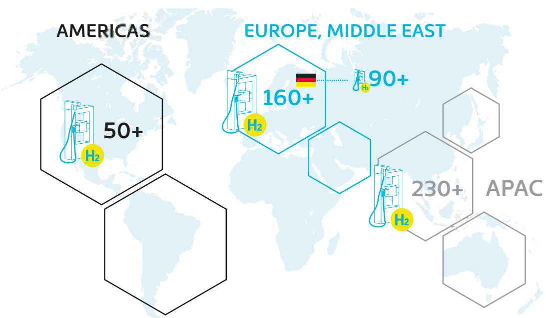

Figure 1 –Hydrogen refuelling network worldwide (2021)

The German Network

In recent years, the strategy in the German market has been to build the first nationwide reliable hydrogen refuelling infrastructure network. The advancement of HRS technology from the research and development stage to high performance commercial application and availability is proving successful. Small stations (max. throughput of 200 kg H2/day) and medium stations (max. throughput of 500 kg H2/day) are built for the first initial ramp up of public HRS. H2 MOBILITY currently operates more than 90 filling stations in Germany and Austria and is the biggest single HRS operator in the world. Refuelling at 700 bar CGH_2 for PV and LDV and 350 bar CGH_2 for busses is the set standard. LDV and MDV fuelling is already possible at some of H2 MOBILITY's HRS. The hydrogen is usually transported and stored at the HRS in gaseous form. Nevertheless, there are already multiple HRS that store and are being supplied with liquid hydrogen.

3.2. Future HRS Development

Europe's future hydrogen refuelling infrastructure will be built according to expected demand. It should allow for international coverage along all important transport corridors for trans-European logistics. Additionally, HRS should be built close to key logistic and distribution centres for consumer convenience.

Multiple stakeholders on the international, European and German level have committed themselves to building comprehensive hydrogen refuelling infrastructure. Due to Germany's central location, trans-European routes are an integral part of the transportation infrastructure. A nationwide strengthening of the HRS network – be it through upgrades of existing or the building of new stations – is necessary. In particular, in order to provide the amount of hydrogen needed to refuel several HDV at the same time, upgrades of the HRS are inevitable. With increasing demand for MDV and HDV, the upgrade of large or even extra-large HRS will be in the focus. Utilizing the synergies between the already existing infrastructure and the upcoming roll out is economically favourable.

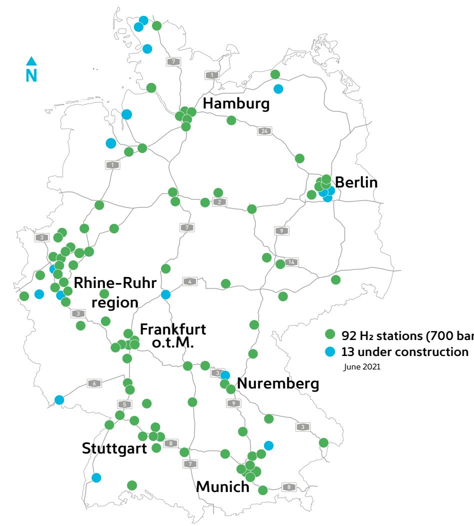

Figure 2 – Hydrogen refuelling network in Germany (2021)

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HYDROGEN REFUELLING INFRASTRUCTURE

Size	S	M	L	2XL
Max. hydrogen throughput per day	200 kg	500 kg	1,000 kg	4,000 kg
Vehicle	PV, LCV	(PV, LCV, busses), MDV	(PV, LCV, busses), MDV, HDV	(PV, LCV, busses), MDV, HDV
Average hydrogen throughput per day	150 kg	350 kg	700 kg	2,500 kg
Annual demand	1 - 10 t	100 t+	500 t+	900 t+
Refuelling nozzle	1	2	2 - 3	2 - 4
Size components area	80 - 250 m²	200 - 350 m²	250 - 800 m²	depending on HRS technology

Figure 3 – Size definitions of different HRS

From a technical standpoint, the possibility to upgrade the stations from size S to size M or even to L and 2XL exists. To serve specific customer needs each HRS configuration can be adjusted in terms of hydrogen demand, peak performance and efficiency. When looking at future large-scale truck refuelling, a 2XL configuration with 2.5 t/day average hydrogen throughput will most likely be needed. Assuming an average hydrogen demand of 60 kg per fill, more than 40 HDV can then be refuelled per day per station.

If no special peak utilization is required, two refuelling nozzles will most likely be sufficient. With this set-up, up to eight HDV can be refuelled every hour at the targeted refuelling time of 10 to 15 minutes. To decide whether an upgrade on a specific site is possible or if a new HRS should be built, the space required by the stations must be carefully examined. Moreover, in the case of a potential HRS expansion, technological feasibility and economic impact will be considered. The HRS technologies and supply chain possibilities that will be used at H2 MOBILITY HRS in the future depend on future vehicle configurations, the maturity of technology, total costs and synergies with existing HRS infrastructure.

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HEAVY DUTY FUEL CELL ELECTRIC VEHICLES

4.1. Status Quo and Future Development

Fuel Cell Electric Vehicles (FCEV) are already in use in various parts of the world. Besides the use of hydrogen in PV in the longterm, the focus of fuel cell drivetrains is moving towards the HDV sector. Since battery electric trucks and charging will, most likely, continue to have limitations regarding range, payload and recharging times, the attributes of fuel cell drivetrains bring specific advantages for heavier and commercially used vehicles. Multiple established and new vehicle manufacturers are intensively developing, testing and deploying commercial FCEV around the world. Within the next years, the market and availability of commercial FCEV will grow rapidly with the ongoing push to reduce emissions in the transport sector, especially where daily mileages are high. To keep up with these developments, HRS infrastructure needs to be established for these vehicle types. Essential interdependencies between hydrogen refuelling technology and the vehicle exist, especially with regard to packaging and local weight limitations of hydrogen vehicles. Well-coordinated collaboration between infrastructure providers, vehicle manufacturers and the end customer is necessary to fulfil all consumer and regulatory objectives.

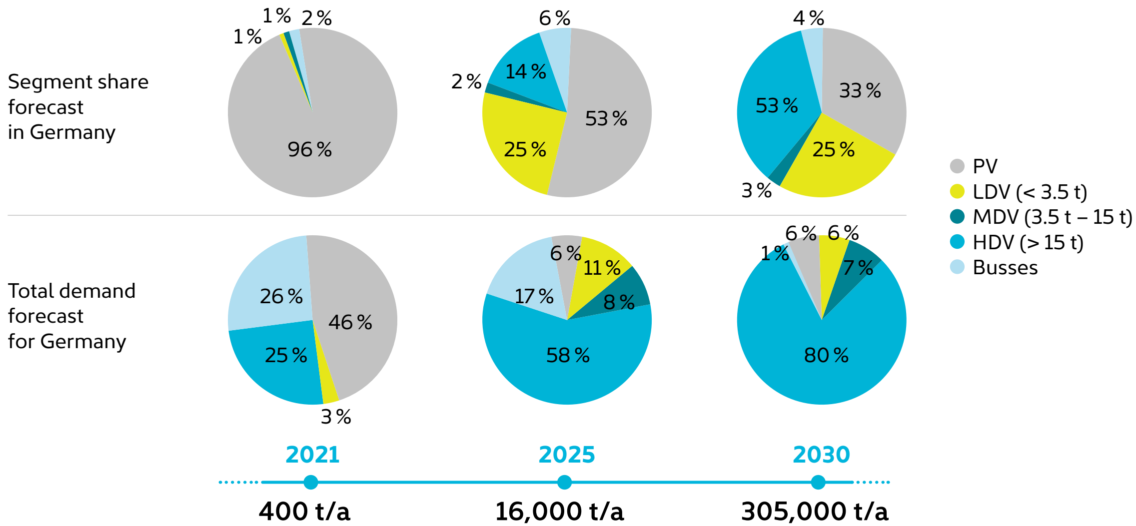

Figure 4 – FCEV and hydrogen demand development through 2030
(Source: McKinsey (2021) & H2 MOBILITY)

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HEAVY DUTY FUEL CELL ELECTRIC VEHICLES

With successful, widespread market entry of hydrogen powered vehicles, we expect that almost 80 % of the German national hydrogen demand for street-bound mobility in 2030 will come from the HDV segment due to their high mileage, weight and therefore consumption. The PV, LDV and bus segments will play a smaller role in terms of demand but a bigger role in terms of the number of vehicles on the market and business cases for OEMs.

Total hydrogen demand based on the projected number of vehicles is expected to reach around 300,000 tons per year in Germany by 2030. Stronger emission standards within the EU for all types of vehicles, as well as a market pull for emission-free vehicles will be the main growth drivers for the demand of hydrogen in mobility.

Figure 5 – Existing and announced fuel cell HDV manufacturers for the European market

05

HYDROGEN SUPPLY CHAIN

The hydrogen supply chain consists of multiple stages. The chapters to come will focus on how hydrogen can be dispensed to customers rather than production, transportation, and storage methods. These parts of the supply chain are briefly introduced in this chapter.

5.1. Hydrogen Transport

Depending on the refuelling technology, the hydrogen can be delivered to the HRS in either gaseous or liquid form. For commercial use, supply by trailer (CGH_2 or LH_2 trailer) or pipeline (CGH_2) are being considered. Furthermore, it is also possible to generate the hydrogen on-site with electrolysis. Other supply options, such as liquid organic hydrogen carriers (LOHC), are not considered in this paper. Currently, tube trailers carrying vessels at a pressure level between 200 and 500 bar are used to transport CGH_2. Depending on the material used, the weight-to-volume ratio of the storage vessels varies significantly. Newer type IV composite cylinders are significantly lighter and more durable than comparable type III cylinders. Recent changes in safety regulations make it possible for storage vessels to become lighter and more cost-effective in the future and make it possible for the same tank configurations to handle higher pressure levels. Hydrogen compressed to 200 bar has an storage density of 14.9 kg/m³ at 15 °C, while at 500 bar it doubles to 31.6 kg/m³. More than 1,000 kg of usable hydrogen can be carried on one 40 ft 500 bar trailer. A higher trailer supply pressure allows for more efficient gaseous refuelling concepts. However, in order to reach higher trailer pressures longer filling times and more compressor power at the filling plants are required.

Another alternative are liquid hydrogen (LH_2) supply trailers with vacuum-insulated cryo-tanks. Due to the particularly high storage density of 71.4 kg/m³ (at -253 °C and 3 bar), such a trailer can transport significantly more hydrogen than a CGH_2 tube trailer. Therefore, when supplying a 2XL HRS, fewer trailers would be used and fewer delivery cycles would be needed. This could reduce logistics costs.

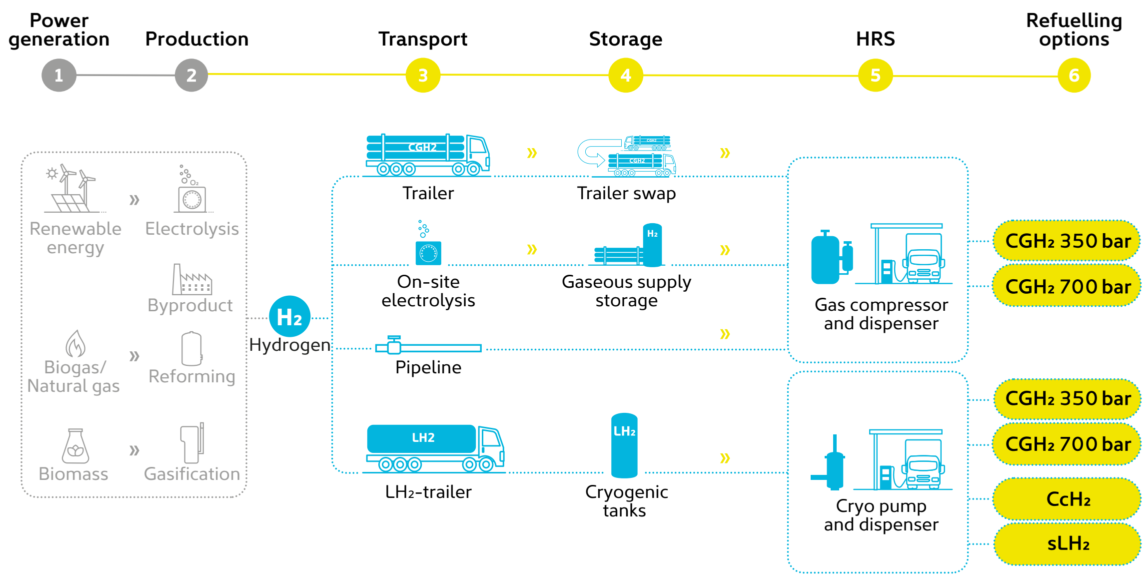

Figure 6 – The hydrogen supply chain

Guaranteeing the availability of LH_2 is a major challenge in meeting the increasing demand. Currently there are only three hydrogen liquefaction plants in Europe.

Another option is to supply gaseous hydrogen via pipeline. Currently, the process of using existing natural gas pipeline infrastructure to transport future hydrogen throughout Europe (European Hydrogen Backbone) is being explored. Specifically, the process of integrating and connecting the pipeline and HRS network is being studied and investigated. To ensure that the quality of hydrogen is sufficient for mobility, a hydrogen purifier will likely be required at offtake locations (e.g. the HRS).

5.2. Hydrogen Storage

Generally, hydrogen can be stored in a physical or material state. Recent materials-based options for hydrogen storage like metal hydrides or LOHC are still in an early market launch phase. 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. The steady growth in the number of FCEV will lead to an increase in the demand of hydrogen available per station per day, which is why greater on-site storage capacity will be required. Another HRS supply option which is already in application is the so-called trailer swap. In this case, the trailers act as mobile storage systems, replacing stationary tanks.

06 HYDROGEN REFUELLING

6.1 Introduction

Depending on the state of the hydrogen in the vehicle storage system (VSS) CGH_2 or LH_2, different refuelling technologies apply. Generally, the aim is to have a HDV refuelling time of 10 to 15 minutes.

Today, CGH_2 can be refuelled at 350 or 700 bar either by compressing and pre-cooling the refuelled CGH_2 or by "cryo pumping" liquid hydrogen, which then needs to be heated before entering the VSS. While gaseous refuelling standards for PV, LDV and busses have been established, there are no high-performance refuelling protocols for heavy duty tank sizes (up to 100 kg) yet.

In order to refuel long haul trucks in under 15 minutes the European "PRHYDE" (protocol for heavy-duty hydrogen refuelling) project is developing high-flow protocols.

Further refuelling options like sLH_2 and CcH_2 in general require a supply of liquid hydrogen. The sLH_2 technology will pressurize liquid hydrogen to about 16 bar, whereas CcH_2 technology will compress hydrogen to 300 bar in a cryogenic but gaseous state. Both sLH_2 and CcH_2 refuelling protocols are being developed by companies, progress is shared and discussed within the CEP.

In figure 7, the maximum VSS hydrogen storage density for each technology is shown. This graph illustrates that 350 bar CGH_2 has the lowest storage density and CcH_2 potentially the highest.

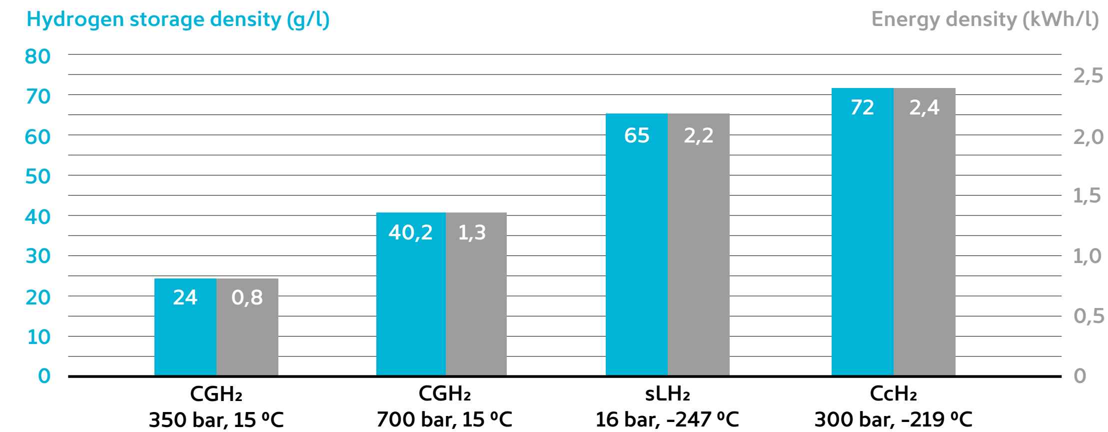

Figure 7 – Hydrogen storage and energy density (VSS)

Hyundai Xcient Fuel Cell – the first 350 bar hydrogen truck produced in series

06
HYDROGEN REFUELLING

6.2 350 bar Compressed Gaseous Hydrogen (CGH_2)

Status Quo

Today, different types of vehicles like fuel cell electric busses, LDV, MDV and HDV use 350 bar CGH_2 technology. These vehicles are used when a maximum range of 400 km is sufficient. Out of the four technologies described in this paper, 350 bar CGH_2 has the lowest volumetric energy density (0.8 kWh/l). Onboard storage capacity limits the ability to travel greater distances without refuelling. Refuelling protocols for up to 42.5 kg H_2 will be published shortly. The maximum amount of hydrogen that can be stored in each vehicle type is still dependent upon consumer needs and technological development and innovation.

Vehicle

Today there are multiple busses and trucks driving with 350 bar VSS, which consist of type III or type IV vessels with aluminium or polymer liners. One of the first HDV found in Europe, the Hyundai Xcient Fuel Cell, stores about 35 kg of hydrogen, which allows for a range of approximately 400 km. This vehicle class is currently utilized for regional distribution use cases. To apply the 350 bar technology to 40 t long haul trucks, new vehicle packaging designs will be necessary.

HRS

The 350 bar CGH_2 HRS can be supplied in gaseous or liquid state which means that all supply chain options are possible. Depending on the option selected, a compressor or cryo pump is necessary to refuel the vehicles. According to the Society of Automotive Engineers (SAE), standard flow rates of up to 120 g/s are already feasible today. Compared to 700 bar HRS, the 350 bar HRS requires less overall energy for compression and pre-cooling. Nevertheless, significantly higher flow rates and suitable, yet-to-be-developed components will be necessary for commercial use and for the back-to-back refuelling of 80+ kg VSS. The pre-cooling demand in the future will depend strongly on refuelling strategies, protocols and technological development.

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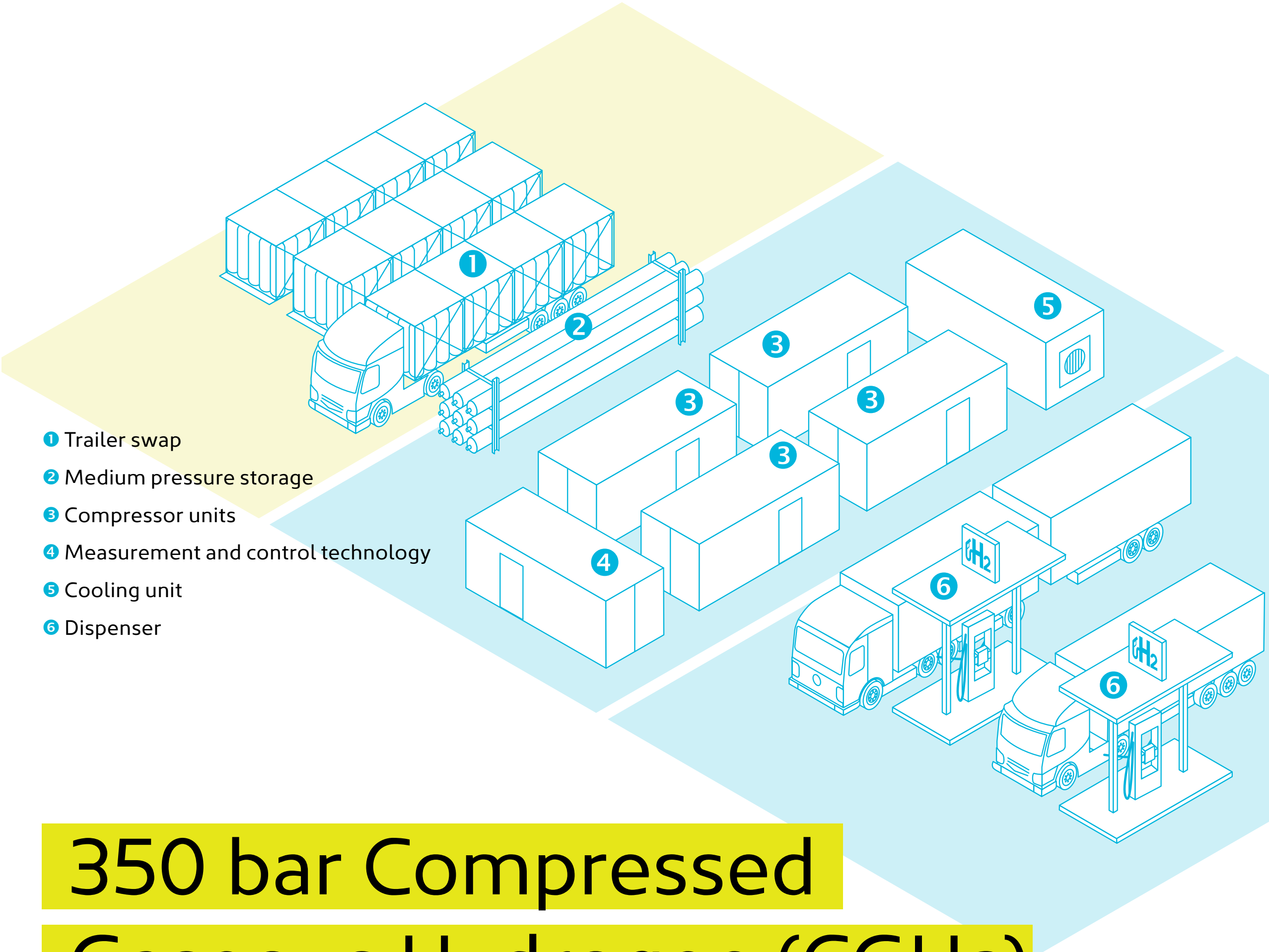
HYDROGEN REFUELLING



1 Trailer swap
2 Medium pressure storage
3 Compressor units
4 Measurement and control technology
5 Cooling unit
6 Dispenser

350 bar Compressed Gaseous Hydrogen (CGH2)

A Potential 350 bar CGH2 HRS Layout

In this figure an example of a potential 2XL HRS, refuelling HDV at 350 bar CGH2, is shown. In the depicted HRS case, hydrogen is supplied by trailers. A trailer swap model is replacing stationary supply storage. In order to deliver enough hydrogen per station, approximately three trailers per day are necessary. The trailer swap could be handled by a trailer drive-through concept to avoid time-consuming manoeuvring. The refuelling of one or multiple vehicles begins with over pressure flow out of the trailer vessels until direct compression takes over and fills up the VSS. Medium pressure storage at the HRS can be used as a buffer to empty the trailers. According to current standards, the refuelled hydrogen must be precooled in order to achieve fast refuelling times but not exceed temperature limits.

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HYDROGEN REFUELLING

350 bar Compressed Gaseous Hydrogen (CGH_2)

Status

- Increasing availability of CGH_2 HRS infrastructure
- Mature HRS technology
- Growing bus & MDV/HDV market (all for up to 42.5 kg onboard storage so far)

Exemplary OEM Projects in Europe

- Xcient Fuel Cell (Hyundai Motors)
- HyMax 450 (Hyzon Motors)

Advantages	Disadvantages
› Proven and established technology › Various H_2 supply chain options	› Low energy density › Limited driving range › Data communication needed

HRS Specifications	
Supply options	CGH_2, LH_2
Main components	H_2 storage, compressor or cryo pump, cooling unit (if gaseous supply), dispenser (nozzle, hose)
HRS H_2 storage type	Depending on specification either › Trailer swap › Supply storage › Pipeline
Refuelling pressure	350 bar
Ease of expanding to 700 bar PV refuelling	Complex and costly integration due to higher compressor ratio and cooling demand
Data communication between HRS and vehicle	Necessary for better performance
Targeted max. flow rate	300 g/s

Vehicle Specifications	
Vehicle H_2 tank pressure (max. allowable working pressure - MAWP)	350 bar (437.5 bar)
Vehicle H_2 tank temperature	-40 °C to +85 °C
Vehicle storage capacity	› Today < 42.5 kg › Intended > 42.5 kg

Multiple OEMs are developing 700 bar hydrogen powered trucks.

06
HYDROGEN REFUELLING

6.3 700 bar Compressed Gaseous Hydrogen (CGH_2)

Status Quo

In comparison to 350 bar, 700 bar reaches a higher volumetric energy density (1.3 kWh/l), which is its main advantage when it comes to issues of storage space. Nowadays, all PV are equipped with 700 bar VSS with storage capacities of 4 - 6.5 kg H_2. Since 2021, garbage collection trucks operating in Germany use 700 bar and have a capacity of 16 kg H_2 divided into two storage sections. Further HDV are announced using 700 bar storage technology due to the request for higher driving ranges and the limited available storage space in vehicles.

Vehicles

When it comes to heavy duty transportation, several OEMs that focus on 700 bar VSS are profiting from existing technology synergies and the need for long distance driving without refuelling. Typically, type IV vessels are used in order to keep the weight as low as possible. Namely, the Toyota Hino Class 8 truck, with a 700 bar VSS, can achieve a range of up to 600 km. Together, Nikola Motors and Iveco are developing a Class 8 truck with a range of up to 1,200 km for the US.

HRS

Similar to 350 bar, a 700 bar CGH_2 HRS can be supplied with gaseous and liquid hydrogen through all the transport options described in the drawing on the following page.

Still-to-come is the ability to refuel 700 bar CGH_2 up to 100 kg since suitable refuelling protocol and HRS technologies are still under development. Currently, there is no official, standardized refuelling protocol that allows for the flow rates needed to achieve refuelling times of 10 - 15 min. Technical challenges such as durable and safe refuelling equipment to ensure high operational availability have to be tackled for future high pressure and high flow refuelling requirements.

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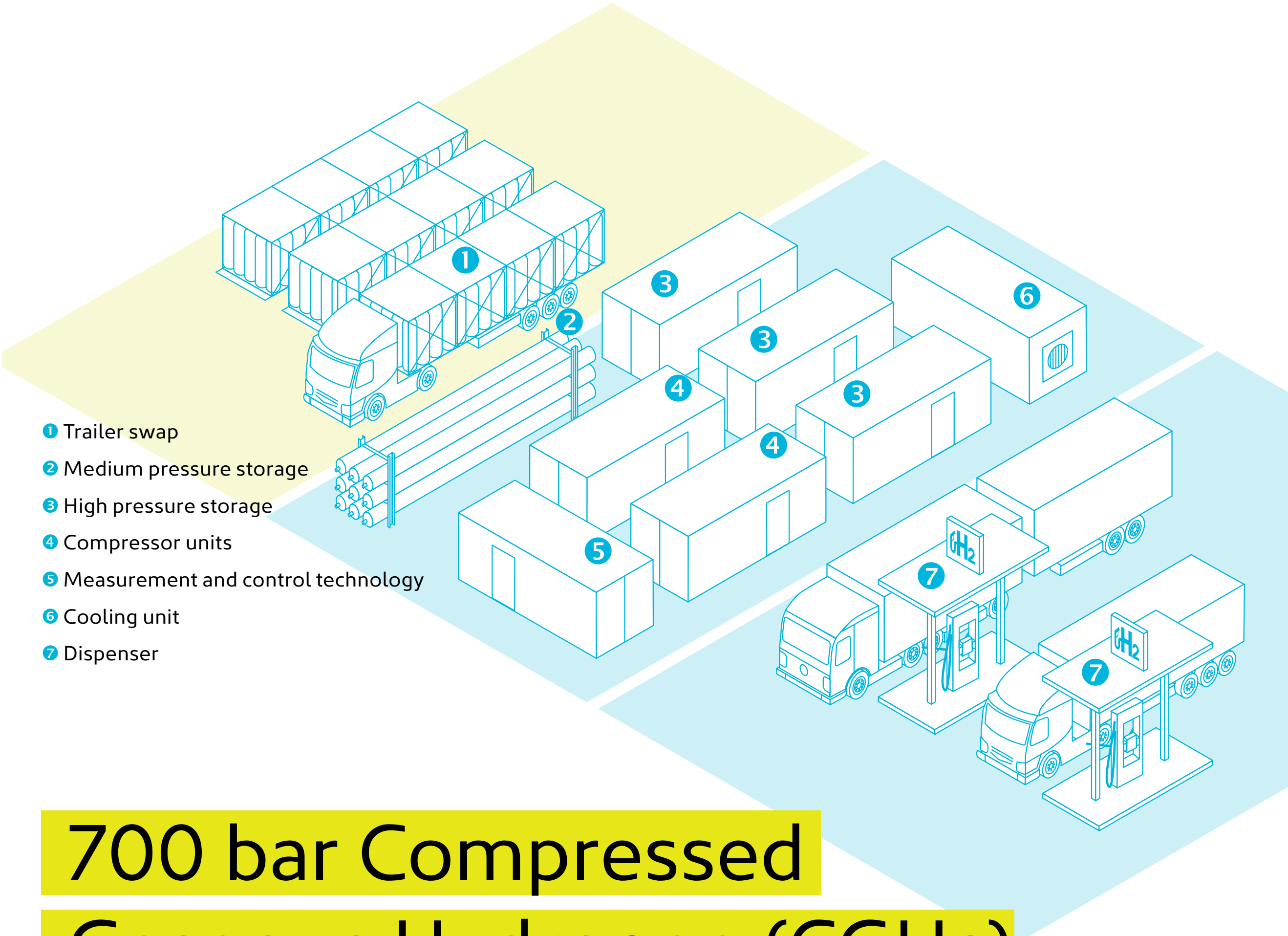
HYDROGEN REFUELLING



1 Trailer swap
2 Medium pressure storage
3 High pressure storage
4 Compressor units
5 Measurement and control technology
6 Cooling unit
7 Dispenser

700 bar Compressed Gaseous Hydrogen (CGH_2)

A Potential 700 bar CGH_2 HRS Layout

The concept depicted in this figure illustrates the HRS being supplied by a trailer swap. The principles of 700 bar HRS are similar to 350 bar refuelling. Overflowing and direct compression will be the likeliest refuelling strategies. Due to the higher target pressure compared to 350 bar, an additional container for high-pressure storage would be useful for supporting direct compression. Both the compressor capacity and the hydrogen pre-cooling process are more energy- intensive compared to 350 bar. Therefore, both may result in a larger footprint and power supply for the 700 bar technology.

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HYDROGEN REFUELLING

700 bar Compressed Gaseous Hydrogen (CGH_2)

Status

- Existing refuelling technology and protocols for PV, LDV, MDV (garbage collectors etc.)
- HRS and VSS for HDV in pilot stage

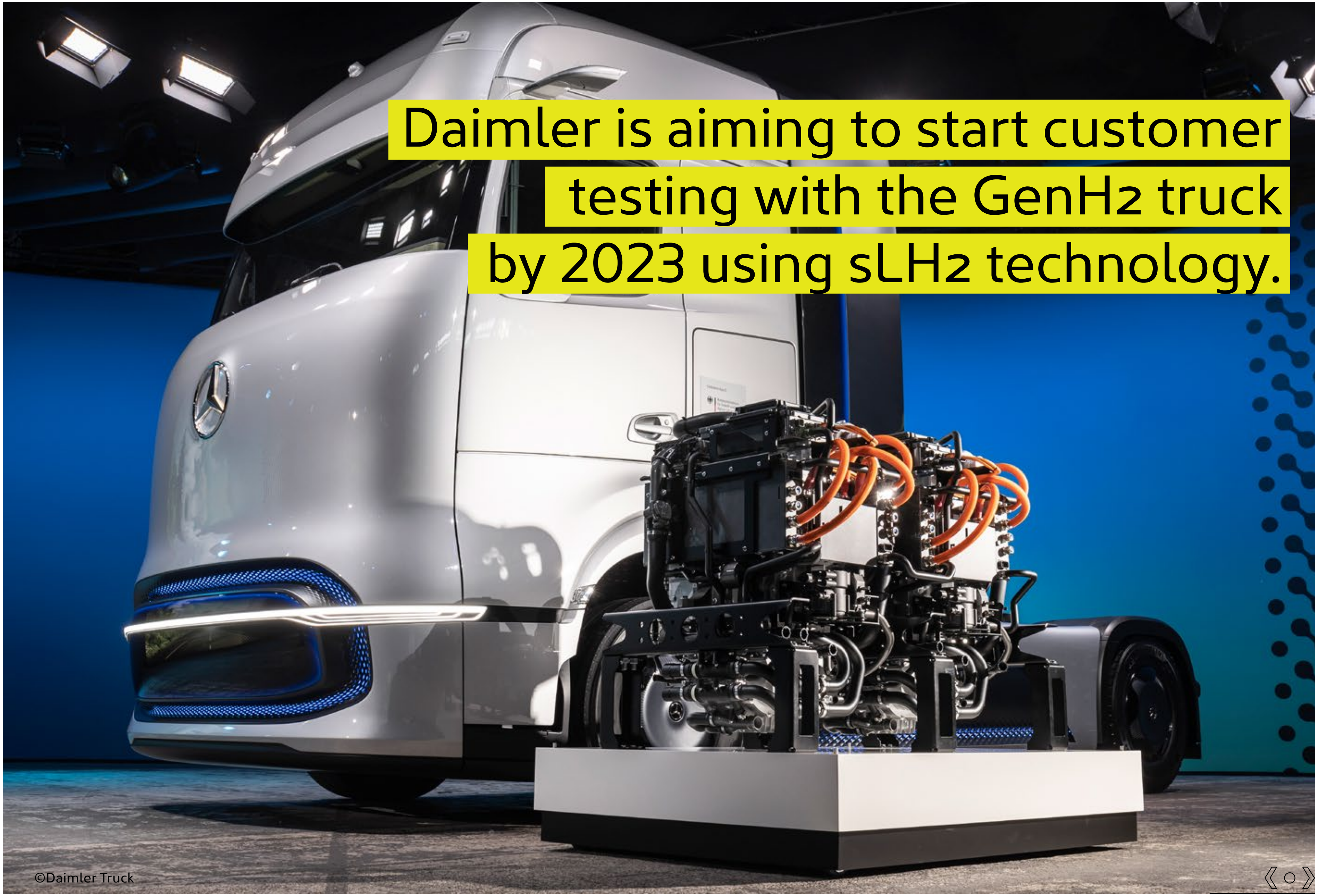
Exemplary OEM Project in Europe

- Nikola TRE (Nikola Motors & Iveco)

Advantages	Disadvantages
› Highest range for gaseous storage › Existing refuelling protocols for vehicle tanks > 10 kg, but not for high flow applications › Various H_2 supply chain options	› High material requisition means costly components › Highest compressor and cooling power demand › Data communication needed

HRS Specifications	
Supply options	CGH_2, LH_2
Main components	H_2 storage, compressor or cryo pump, high pressure storage, cooling unit (if gaseous supply), dispenser (nozzle, hose)
HRS H_2 storage type	Depending on specification either: › Trailer swap › Supply storage › Pipeline
Refuelling pressure	700 bar
Ease of expanding to 700 bar PV refuelling	Relatively simple expandability due to existing technology and lower performance requirements
Data communication between HRS and vehicle	Necessary for better performance
Targeted max. flow rate into vehicle	300 g/s

Vehicle Specifications	
Vehicle H_2 tank pressure (MAWP)	700 bar (875 bar)
Vehicle H_2 tank temperature	-40 °C to +85 °C
Vehicle storage capacity	Intended: Up to 100 kg


Daimler is aiming to start customer
testing with the GenH2 truck
by 2023 using sLH2 technology.
©Daimler Truck

6.4 Subcooled Liquid Hydrogen (sLH_2)

LH_2 has a significantly higher volumetric energy density compared to gaseous hydrogen. However, with hydrogen in this physical state, it is challenging to keep heat input and boil-off to a minimum. Former attempts at developing liquid hydrogen refuelling (for passenger cars) have faced several difficulties (boil-off losses, gaseous return lines parallel to refuelling, etc.). The sLH_2 (recent development) and CcH_2 (continuation of former BMW development; see next chapter) aspire to solve these drawbacks.

Status Quo

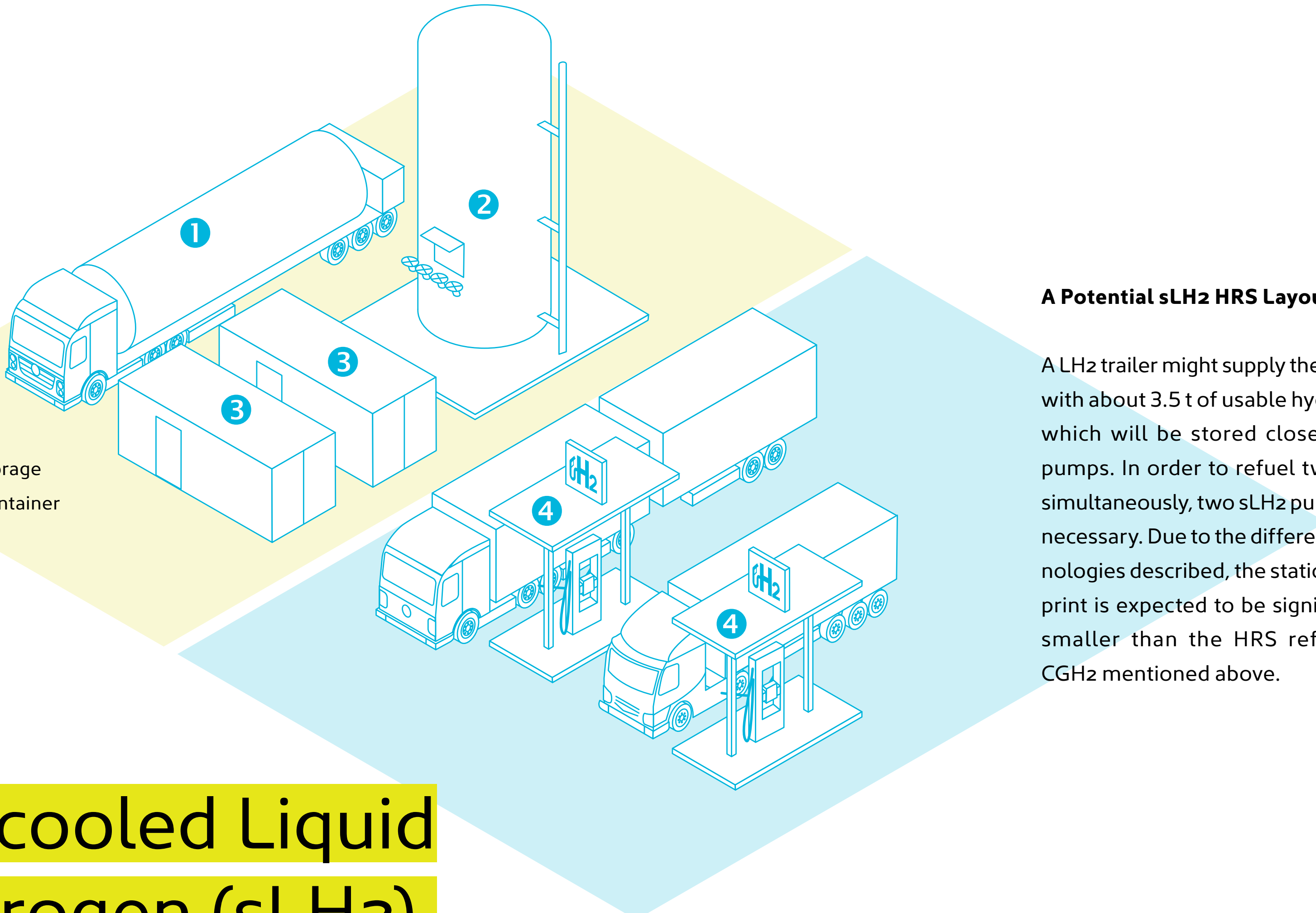
The sLH_2 technology is currently pushed by Daimler Truck from the vehicle side and Linde from the HRS side. The subcooled liquid hydrogen technology is projected to allow for high onboard storage capacities, high flow refuelling and high driving ranges with high energy efficiency. Currently the technology is still in the R&D stage, with first prototypes close to validation.

Vehicles

Daimler Truck has announced a series production starting in 2027 and is working on the first prototypes of the GenH2 Truck using sLH_2 technology. The refuelling of sLH_2 into the insulated vehicle tank will be realised at about -247°C with pressures of up to 16 bar, resulting in an energy density of 2.2 kWh/l. The idea is to increase the boiling point to higher temperatures so that greater heat input can be endured until phase transformation starts, thereby reducing boil-off. In comparison to CGH_2 storage the sLH_2 tanks will not need any carbon fibre cladding. Instead, vacuum insulation is necessary to minimize heat input and prevent fast boil-off. Refuellings without GH_2 return gas can be achieved during regular, continuous truck operation. However, long idle times or partial refuellings under sub-optimal conditions will lead to hydrogen losses.

HRS

HDV will be directly refuelled with liquid hydrogen. Thus, the only suitable supply case is LH_2. On-site storage will be the most likely option, however, a trailer swap concept could also be possible. Each refuelling point will need a dedicated sLH_2 pump that requires only a fraction of the power demand of a comparable CGH_2 compressor. The refuelling process itself won't need continuous data communication between the HRS and vehicle, which reduces complexity. Some of the major challenges are the lifetime of components exposed to cryogenic temperatures, flow metering and ensuring that vacuum-insulated piping is kept short to lower the risk of boil-off.



1 LH_2 trailer
2 LH_2 supply storage
3 sLH_2 pump container
4 Dispenser

Subcooled Liquid Hydrogen (sLH_2)

A Potential sLH_2 HRS Layout

A LH_2 trailer might supply the station with about 3.5 t of usable hydrogen, which will be stored close to the pumps. In order to refuel two HDV pumps simultaneously, two sLH_2 pumps are necessary. Due to the different technologies described, the station footprint is expected to be significantly smaller than the HRS refuelling CGH_2 mentioned above.

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HYDROGEN REFUELLING

Subcooled Liquid Hydrogen (sLH_2)

Status

- Expected advancement of LH_2 technology
- HRS and VSS in R&D stage

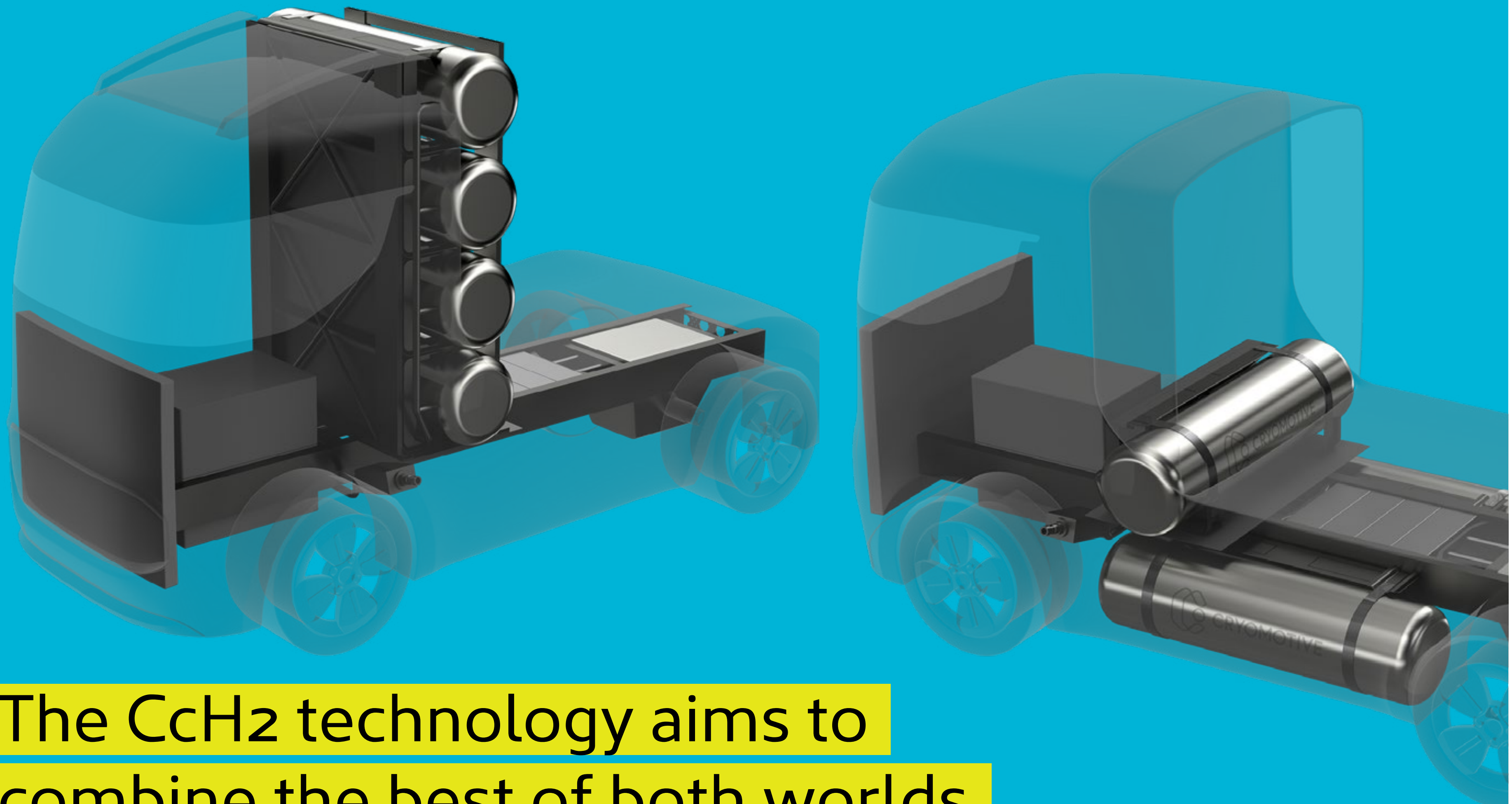
Exemplary OEM Project in Europe

- GenH2 Truck (Daimler Truck AG)

Advantages	Disadvantages
› Highest range for MDV / HDV and limited onboard storage space › (Potentially) lowest cost of onboard storage › Probably no data communication needed	› Lowest holding time before boil-off › LH_2 supply chain constraints › No synergies with existing CGH_2 infrastructure › Early stage of development (VSS and HRS)

HRS Specifications	
Supply options	LH_2
Main components	LH_2 storage, sLH_2 pump, dispenser (nozzle, hose)
HRS H_2 storage type	Depending on specification either: › Supply storage or › Trailer swap
Refuelling gas pressure	Approx. 16 bar
Ease of expanding to 700 bar PV refuelling	Complex and costly integration of additional high pressure cryo pump system, nozzle, hose etc.
Data communication between HRS and vehicle	Not required
Targeted max. flow rate per pump	400 - 500 kg/h

Vehicle Specifications	
Intended vehicle H_2 tank pressure (MAWP)	Approx. 5 - 16 bar
Vehicle H_2 tank temperature	-248 °C to -245 °C
Intended vehicle storage capacity	> 80 kg



The CcH_2 technology aims to combine the best of both worlds.

6.5 Cryo-compressed Hydrogen (CcH_2)

Cryo-compression offers the possibility to combine the two storage methods mentioned before and therefore increase storage density even more. The technology foundations were developed by BMW in the early 2000s to avoid problems that arose with LH_2.

Status Quo

The technology behind the refuelling and on-board storage of cryo-compressed hydrogen is well-known and has been tested for passenger cars for years. As the hydrogen is kept at cryogenic temperatures close to the critical point (-240 °C) and is compressed up to 300 bar, the volumetric energy density (2.4 kWh/l) is the highest of the four technologies described. Today, the company Cryomotive is developing this technology for future use in HDV e. g. by developing a vacuum-insulated high pressure tank system. However, the low temperatures and high pressures require VSS technology and HRS components that are yet-to-be-developed.

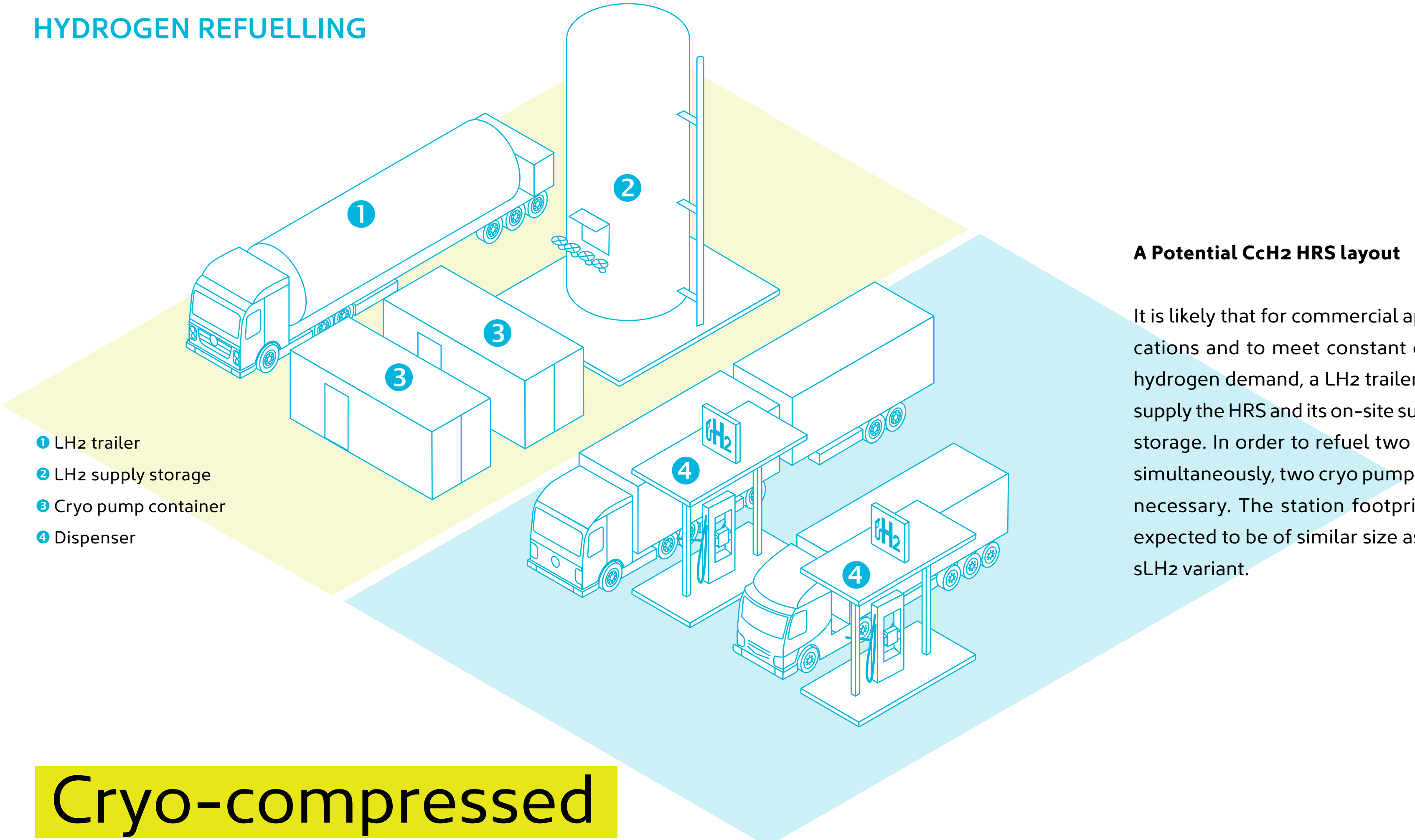
Vehicles

There are no CcH_2 trucks so far. First truck prototypes are expected to be announced in 2022 - 2023.

HRS

The CcH_2 HRS will most likely use cryo pumps to compress hydrogen from the liquid state to 300 bar. Thus, a LH_2 supply storage or LH_2 trailer swap but no extra cooling will be necessary. The biggest challenges concern the durability of station components and materials in contact with the pressurized cryogenic hydrogen, such as the refuelling hose and nozzle. Another challenge is the H_2 metering, that also need to be reliable in order to make the technology market ready. Once this is the case, a CGH_2 interface could be integrated relatively easily to refuel vehicles to 350 bar. The CcH_2 refuelling process is more robust in terms of fulfilling boundary conditions compared to the sLH_2 refuelling process. Refuellings without return gas can be achieved even under suboptimal conditions, however, maximum storage density might not be reached in these cases.

06
HYDROGEN REFUELLING



1. LH2 trailer
2. LH2 supply storage
3. Cryo pump container
4. Dispenser

A Potential CcH2 HRS layout

It is likely that for commercial applications and to meet constant daily hydrogen demand, a LH2 trailer will supply the HRS and its on-site supply storage. In order to refuel two HDV simultaneously, two cryo pumps are necessary. The station footprint is expected to be of similar size as the sLH2 variant.

Cryo-compressed Hydrogen (CcH2)

06

HYDROGEN REFUELLING

Cryo-compressed Hydrogen (CcH2)

Status

- Expected advancement of LH2 technologies
- VSS and HRS for HDV in R&D stage (existing pilots and data for PV scale)

Exemplary OEM Project in Europe

Will be announced in 2022/23

Advantages	Disadvantages
› Highest volumetric density in VSS › No data communication needed › Lighter VSS than for 350/700 bar	› High material requisition due to high pressure and low temperatures › LH2 supply chain constraints › Early stage of development (VSS and HRS)

HRS Specifications	
Supply options	LH2 (CGH2 feasible)
Main components	LH2 storage, cryo pump,dispenser (nozzle, hose)
HRS H2 storage type	Depending on specification either: › Supply storage or › Trailer swap
Refuelling gas pressure	300 bar
Ease of expanding to 700 bar PV refuelling	Complex and costly integration of additional high pressure cryo pump system, nozzle, hose etc.
Data communication between HRS and vehicle	Not required
Targeted max. flow rate per pump	200 - 800 kg/h

Vehicle Specifications	
Intended VSS operating pressure (MAWP)	≤ 300 bar (350 bar)
Intended VSS operating CcH2 temperature	Approx. -240 °C to -150 °C
Intended vehicle storage capacity	> 80 kg

7.1. Technology Readiness Level

To provide an indicative insight about the readiness of each technology, the different HRS are clustered by their stage of development. The readiness levels of the different HRS concepts are evaluated in the following four criteria: the supply chain, the vehicle storage system, HRS readiness and the maturity of standards for HRS.

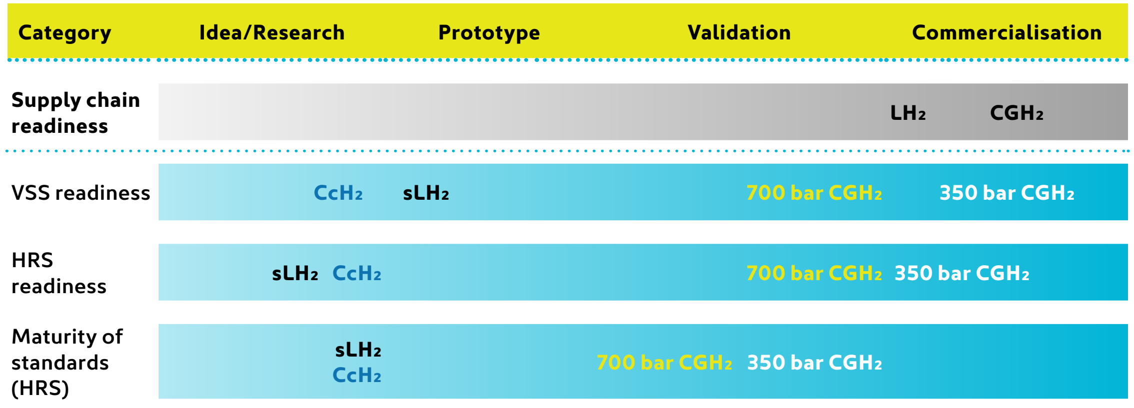


Figure 8 – Technology readiness level of HRS options for heavy duty applications

Supply Chain Readiness

The supply chain of gaseous and liquid hydrogen is an established and proven technology and process. The challenge lies in making hundreds of tons of hydrogen available and delivering high daily quantities to the HRS to meet expected demand. Today's capacity of gaseous hydrogen trailers is approximately 500 kg to 1,000 kg H_2. Although advancements in technology and standardization will increase capacities of CGH_2 trailers, they will not be able to compete with the transport capacity of LH_2 trailers because of their lower storage density. Supply via hydrogen pipeline is currently only available in limited regions in Europe and is used only for demonstration projects. The initial investments for a new pipeline network would be high and a big opportunity seems the upgrading of existing pipelines. Pipeline transport of hydrogen is probably the cheapest alternative over long distances. For liquid hydrogen transport, there are capacity limits of approximately 3.5 t of usable hydrogen per CGH_2 trailer.

However, the production capacity of LH_2 is still rather low in Europe. To date there are three production facilities in Europe with an overall capacity of 25 t of LH_2 per day . However, LH_2 can become an important vector during the next 5 - 10 years to import renewable energy from where it can be produced at low cost using carrier ships.

Vehicle Storage System Readiness

VSS already exists for 350 bar CGH_2 technology and the technology for 700 bar CGH_2 is being established, since higher amounts of hydrogen have to be stored onboard. The challenge for 350 bar CGH_2 in long haul applications lies in range limitations respective to vehicle packaging. New length regulations and tank configurations for trucks could help to increase driving ranges, especially for trucks with 700 bar VSS to reach over 1,000 km of range.

sLH2 technology is in later research stages and needs to be validated as the first prototypes will be developed in the next years. The major challenges for sLH_2 include the refuelling process and thermal tank management as boil-off losses need to be kept to a minimum. If used in the logistics industry where vehicles are running on a regular daily basis, the boil-off on the vehicle side may become negligible (however the challenge during refuelling stays). For CcH_2 the industry has been working with PV VSS for some time and a proof of concept was developed for PV VSS. The CcH_2 VSS now needs to be scaled and validated to fit HDV requirements. Even though boil-off losses are a lower challenge compared to sLH_2, additional high-pressure requirements increase the complexity of ensuring high durability.

HRS Readiness

The 350 bar CGH_2 technology is already in use for busses and MDV. The latest refuelling protocol will be published in Q3 2021 and is showing refuelling rates for storage capacities of up to 42.5 kg. An adjustment for bigger VSS of HDV is considered viable. However, higher flow rates will be required to achieve reasonable refuelling times.

The same applies to 700 bar CGH_2 technology which has already been in use in the PV, bus and MDV sector. However, the higher flow rates for 700 bar CGH_2 bring greater challenges for pre-cooling and reliable, durable compression technology, which has yet to be validated.

Former LH_2 HRS prototypes performed PV refuellings, however no sLH2 refuellings have been demonstrated so far. Although the sLH_2 pump technology seems promising and less complex, the validation of the concept is still ongoing. The CcH_2 HRS, however, has already been tested for PV, facing challenges in the choice of material and metering. All components in contact with hydrogen have to withstand high temperature changes and pressure levels of up to 300 bar. Today both, sLH_2 and CcH_2 can be seen as being in the R&D stage when it comes to refuelling HDV since some fundamental questions have to be addressed and validated.

Maturity of Standards (HRS)

Technology standards are essential to a successful rollout of heavy duty HRS and long haul trucks. It is extremely important to standardize refuelling protocols so that refuelling can be done as quickly as possible, without safety risks like exceeding tank temperature or pressure limits. To date, there are no high flow standards for the 350/700 bar CGH_2. The sLH_2 and CcH_2 technologies are in an even earlier stage of development, although refuelling protocols will be a lot simpler. Similarly, standardization of hardware interfaces, like nozzles, receptacles, and other filling equipment still has to be done. Furthermore, measuring devices and quality standards like accurate hydrogen metering and permissible deviations must be established. This might be easy to adjust for 350/700 bar CGH_2 and high flow application, but will be more challenging when dealing with cryogenic and liquid hydrogen.

7.2. Costs of Infrastructure

When assessing different technologies, the cost of the refuelling infrastructure must also be considered. For this assessment, the capital expenditures (CAPEX) (i.e. compressor, cryo pump, piping, storage, cooling unit, civil works, power connection), the operational expenditures (OPEX) (maintenance, repair, stock loss, energy consumption) and cost of goods sold (COGS) are evaluated across all refuelling options. In this case, HRS with the same capacities are compared and the vehicle side is not considered.

CAPEX

Comparing the costs of building and commissioning HRS with the same capacities, there are specific cost drivers for each technology. For example, cost drivers for CGH_2 stations are the compressor / pump, storage units and pre-cooling. In contrast, for both CcH_2 and sLH_2 stations, a large part of the preconditioning takes place in the LH_2 production plant. This reduces CAPEX on the HRS side as a result. HRS with liquid storage tend to have lower space requirements. This leads to less investment in the purchase or leasing of commercial properties.

OPEX

For the 350 bar and 700 bar CGH_2 HRS, the cooling unit and the compressor are the most vulnerable and energy-consuming components. Liquefaction in the production plant can save costs in the operation of the HRS. In addition, energy consumption for the cryo pump is lower. However, this cost advantage is partially offset by increased stock-loss (boil-off). In this context, the procurement of spare parts must also be taken into account. When it comes to CGH_2, there is a large number of suppliers who have already gained experience with hydrogen and other gases. This not only offers the advantage of lower spare parts prices, but also greater security of supply. For LH_2, the cost of spare parts is still very high due to low economies of scale and very few suppliers.

COGS

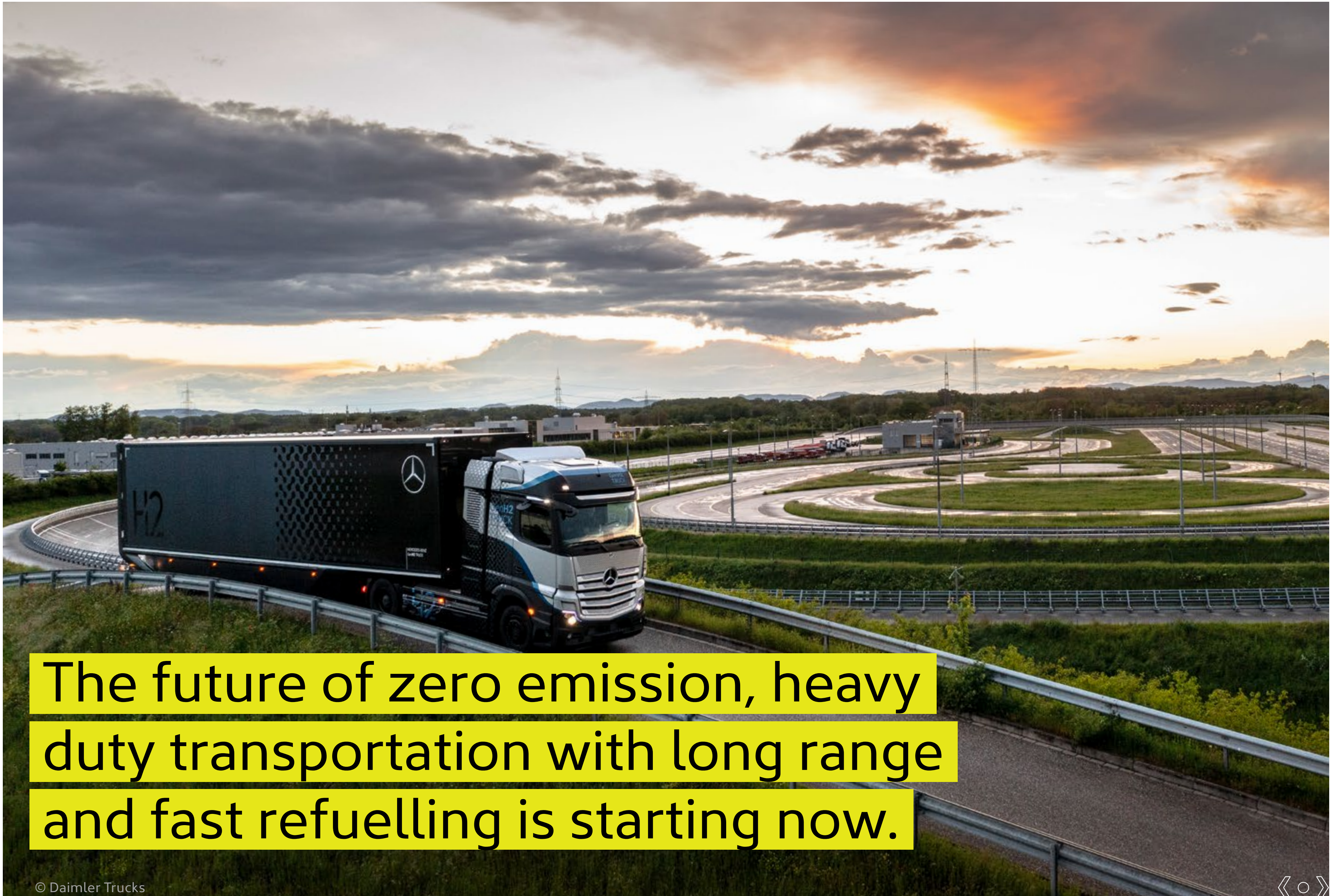
If hydrogen supply is performed via trailer, the specific logistics costs of LH_2 become lower, as up to three times the amount of hydrogen can be delivered with one trailer. On the other hand, the production structure of LH_2 is more centralised, which means that in the mid-term, longer delivery routes have to be assumed. In the long term, the delivery of gaseous hydrogen via dedicated hydrogen pipeline can drastically reduce transport costs. When connecting to a pipeline, special attention must be paid to the hydrogen's quality. Additional investments into purification will likely be required.

Outlook

It can already be forecasted that due to the high specific turnover volumes of trucks, all of the HRS technologies described will enable profitable HRS operation in the long term. The prerequisite for long term, economic viability is the introduction of high numbers of FCEV into the market, with the help of government subsidies for vehicles and infrastructure.

Technology	**350 bar CGH_2**		**700 bar GH_2**		**sLH_2**	**CcH_2**
Supply	**CGH_2**	**LH_2**	**CGH_2**	**LH_2**	**LH_2**	**LH_2**
Main cost drivers (from today´s perspective)	› CAPEX (Pre-cooling, storage costs)	› COGS (longer delivery distance, boil-off) › OPEX (repair costs)	› CAPEX (Compressor, storage, pre-cooling) › OPEX (energy costs, maintenance and repair costs)	› COGS (longer delivery distance, boil-off) › OPEX (repair costs)	› COGS (longer delivery distance, process gases, cost of molecules) *no data on equipment available yet*	
Possible pathways	› Economies of scale › Direct compression › Higher supply pressure	*See sLH_2 / CcH_2*	› Direct compression › Economies of scale	*See sLH_2 / CcH_2*	› Higher utilization of HRS & economies of scale › More LH_2 sources and suppliers › Pilot stations to generate data on equipment	

Figure 8 – Cost drivers for each technology


The future of zero emission, heavy duty transportation with long range and fast refuelling is starting now.
© Daimler Trucks

08
SUMMARY

This overview summarises the state of four technology options for the refuelling of HDV: two technologies with gaseous hydrogen (350 bar and 700 bar), one option with hydrogen in liquid stage (sLH_2), and the cryo-compressed (CcH_2) technology. We have chosen these four technologies because they are currently in focus for hydrogen in mobility purposes. Therefore, one or a combination of these four are likely candidates for becoming the standard technology for refuelling HDV with hydrogen.

All four technologies have specific strengths and challenges: the 350 bar CGH_2 technology for up to 42.5 kg is close to a standardisation. It is a proven and established technology but requires the most on board vehicle space and therefore comes with (storable) quantity and range limitations*. To a degree, 700 bar CGH_2 is established as well (at least for smaller quantities of up to 8 kg) and it reduces the packaging problem in vehicles for long ranges. However, it comes with higher costs on the refuelling infrastructure side. For example, higher pressure levels result in greater complexity and maintenance costs. The liquid technologies solve the quantity and range issue most credibly, but are still in a relatively early stage of development when it comes to VSS and HRS.

The momentum is high for hydrogen in transport – therefore, we expect expeditious progress in terms of technology development and innovation. The faster (zero emission) hydrogen becomes the norm over diesel in commercial transport, the better. To increase the use of hydrogen as a fuel fast, we need to narrow down the options and select the most sustainable one or two (the 350 bar CGH_2 option could well co-exist). To explore and test all four options is important, but to pursue them simultaneously would be economically inefficient. Furthermore, synergies with the current infrastructure and synergies between the technologies should be considered. In the coming 24 months, the most promising option(s) for commercial truck refuelling should become clear based on technical feasibility, costs and commitment of a group of companies. We at H2 MOBILITY have built a basic infrastructure for light to medium duty vehicles in Germany. Now we are looking forward to playing a role in enabling the widespread use of emission-free hydrogen in heavy duty transport too. This overview has given us the opportunity to analyse the different options and share this knowledge. Moreover, we believe it will inform stakeholders and help structure discussions happening within the industry. Therefore, we are publishing this overview as an accessible, informational resource to transparently show the state of hydrogen refuelling in mobility.

If you have any feedback, please connect with us using feedbackoverview@h2-mobility.de

** Some analysis do not include the 350 bar solution in a discussion about HDV transport because quantities of 80 - 100 kg are likely to be needed. We specifically did not not want to exclude this option, as customer behaviour may change as well and a higher frequency of refuelling may be acceptable for some customer use cases.*

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ABOUT H2 MOBILITY

H2 MOBILITY aspires to be a pathfinder and enabler for hydrogen in mobility. We have grown to become the largest hydrogen refuelling station operator worldwide. The goal of the first phase was to establish a country-wide network of HRS in seven German metropolitan areas (Hamburg, Berlin, Rhine-Ruhr, Frankfurt, Nuremberg, Stuttgart and Munich) and along connecting motorways and highways.

At all stations, PV and LDV can refuel up to 8 kg H_2 at 700 bar CGH_2. Additionally, multiple stations can refuel small fleets of busses, MDV and HDV with 350 bar CGH_2 as well. In the next phase starting in 2022, we will be expanding the network for all vehicle classes. Furthermore, we will focus on stations which meet the demand of commercial vehicles while strengthening the existing network.

Besides empowering the truck, bus and car market with our stations, we aspire to enable others to build further HRS. Therefore, we provide our knowledge and experience to potential infrastructure investors with H2 MOBILITY SERVICES. Our SERVICES include consulting, planning, construction and the complete operation of HRS. We stand for the highest safety and security standards in operation, reliability, transparency through system monitoring, digital maintenance management, clear processes and the availability of our on-site team.

Shareholders

Associated Partners

Funding

For more information see www.h2-mobility.de

ABBREVIATIONS

BetrSichV	Betriebssicherheitsverordnung (Industrial safety regulation)
CAPEX	Capital expenditures
CcH_2	Cryo-compressed hydrogen
CGH_2	Compressed gaseous hydrogen
COGS	Costs of goods sold
FCEV	Fuel cell electric vehicle
HDV	Heavy duty vehicle
HRS	Hydrogen refuelling station
LDV	Light duty vehicle
LH_2	Liquid hydrogen
LOHC	Liquid organic hydrogen carriers
MAWP	Maximum allowable working pressure
MDV	Medium duty vehicle
OEM	Original equipment manufacturer
OPEX	Operational expenditures
PV	Passenger vehicle
R&D	Research and development
sLH_2	Subcooled liquid hydrogen
TCO	Total cost of ownership
TRBS	Technische Regeln für Betriebssicherheit (Technical rules for operational safety)
TRL	Technology readiness level
VSS	Vehicle storage system

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