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Subcooled Liquid Hydrogen Technology for Heavy Duty Trucks

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Executive Summary

Subcooled Liquid Hydrogen (sLH2) is an onboard storage as well as a hydrogen refueling technology that is currently being developed by Daimler Truck and Linde to boost the mileage of heavy duty trucks, while also improving performance and reducing complexity of hydrogen refueling stations. In this presentation, the key technical aspects, advantages, challenges and future developments of sLH2 at vehicle and infrastructure level will be explored and highlighted.

Abstract

On the way towards carbon neutral road transport mobility, **h**eavy **d**uty **t**rucks (HDT) are one of the most challenging applications to decarbonize [1]. In this context, truck OEMs are exploring a dual technology-open strategy, with both **b**attery **e**lectric **v**ehicles (BEV) and **f**uel **c**ell **e**lectric **v**ehicles (FCEV) being developed and adopted as complementary solutions [2, 3].

BEV are considered the best choice for short distance, with plannable routes and lighter load. On the other hand, FCEV are the preferred technology for use cases with high mileage and energy consumption, such as long haul and on-demand applications [4]. Furthermore, FCEV are projected to be an attractive option also when flexibility is required and where there are local grid constraints [3]:

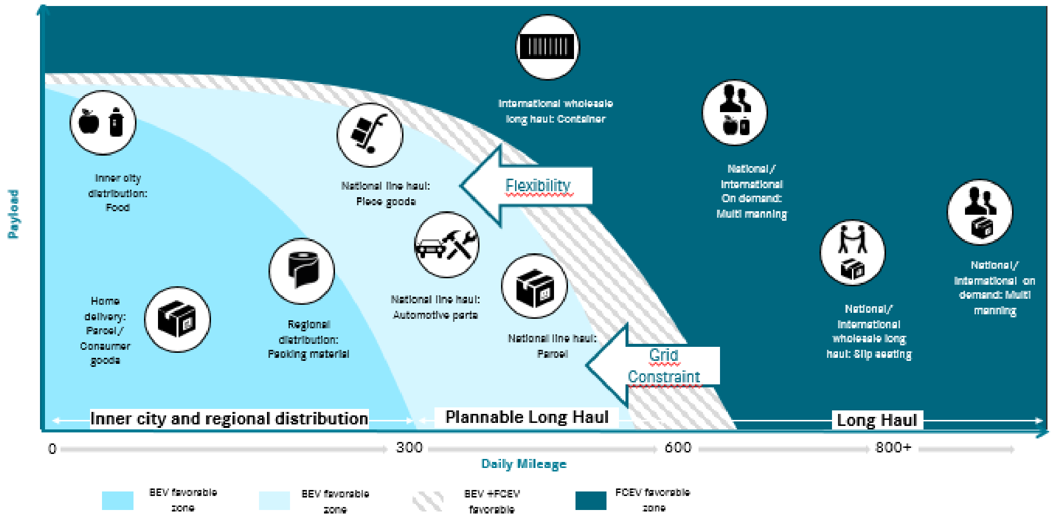


Figure 1: Technology fit for commercial vehicles based on daily mileage and payload

In a FCEV one of the main components is the onboard hydrogen storage system. Despite having a high gravimetric energy density, hydrogen has a very low volumetric density, when stored at ambient temperature and pressure. In order to reach the mileage targets (as in Figure 1), hydrogen**,** therefore**,** needs to be either stored at higher pressure or lower temperature. To this end, several potential candidates for onboard hydrogen storages can be considered [5-7], namely:

1) compressed hydrogen gas (CHG) at room temperature and high pressures
2) cryo compressed hydrogen (cCH2) at low temperatures and high pressures
3) liquid hydrogen (LH2) at very low temperatures (<20°C) and low pressures (<10 bar)

Each of these storage technologies has a different storage pressure as well as density (Figure 2).

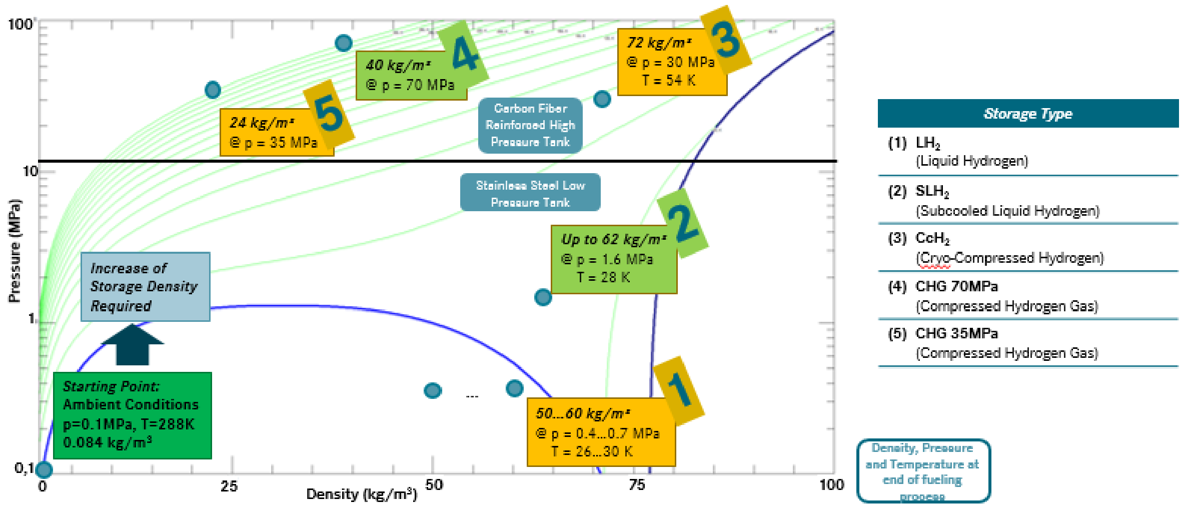


Figure 2: Density vs pressure diagram for different on-board storage technologies

While CHG hydrogen can only reach storage densities of up to ~40 kg/m3 (at 700 bar and 15°C), subcooled liguid hydrogen (sLH2) can arrive up to ~62 kg/m3 (at ~16 bar and -245°C). By combining higher pressures (e.g. 350 bar) and low to cryogenic temperature (e.g. -250/-200°C), it is possible to reach even higher energy densities (e.g. ~72 kg/m3). However, the storage technologies of cryco-compressed hydrogen (cCH2) is more complex and has nowadays a **l**ower **t**echnology **r**eadiness level (TRL) compared to the previously mentioned two technologies, as it needs to handle both very low temperatures as well as high pressure in both the tank system and the refueling line (pipes, connectors, …). In this paper, we will therefore focus on CHG and LH2.

Today, compressed hydrogen at 70 MPa (CHG70) and 35 MPa (CHG35) is used in light duty vehicles [8] and for buses respectively. With respect to the more challenging HDT use cases however, OEMs are currently pursuing different concepts [6]. Considering that such a technology choice has a large impact on the whole hydrogen value-chain, it is of outmost importance that OEMs and infrastructure players collaborate and work closely together.

In this context, Daimler Truck and Linde are jointly developing a new storage and refueling solution, namely "subcooled liquid hydrogen" (sLH2). Thanks to an improved tank and interface design encompassing an increased pressure (up to ~20-25 bar), sLH2 enhances refueling performances while reducing complexity of protocols and hardware at the hydrogen refueling stations (HRS) [9]. Some of the key parameters/advantages at vehicle and HRS level will be detailed in the following subsections.

Vehicle advantages

The transition of HDT towards zero emission vehicles implies a profound transformation of vehicle architecture. In FCEV, one substantial challenge is the integration of large tank-systems, to achieve range and payload target. Considering sLH2 and CHG70 as reference technologies for heavy duty long haul trucks, the architecture of the respective tank systems as well as their integration in the vehicles will differ substantially, resulting in different vehicle characteristics (Figure 3).

Key Assessment Criteria		
Capacity on Truck	> 80 kg (4x2)	~60 kg (4x2)
Operating pressure	4-8bar	20-700bar
Target pressure	16bar	700bar (p_target depend on p-initial and Tamb)
Range	> 1000 km	~600-700 km
Hold Time (w/o Boil off)	SOC 100% ≈ 10 h (1) SOC 50 % ≈ 200 h (1)	n.a.
Handling / Refueling	**Multiple tank filling possible, no return gas, no communication**	Multiple tank filling possible, no return gas, **communication required**
Tank Type	Stainless steel without additional reinforcement, vacuum insulated	Typ IV (liner + carbon/glass fibers)
Material Cost	+	++

Figure 3: Comparison of main vehicle characteristic of a 4x2 HDT equipped with sLH2 and CHG70 tank-systems (left and right respectively)

sLH2 has approximately 50% higher density (up to 62 kg/m3 at p = 16 bar and T = 28K) compared to CHG70 (40 kg/m3 at p = 700 bar and $T = T_{amb}$). At the same time, an insulated stainless steel low pressure tank is sufficient to store sLH2, compared to Type IV high pressure tanks reinforced with carbon fibers typically used in a CHG70 configuration [10].

This results in lighter (approximately 20-30% less weight per stored kg of hydrogen) and cheaper (approximately 40-50% lower costs per stored kg of hydrogen) tanks with lower volumes, higher stored mass of hydrogen and mileage (sLH2 showcases approximately 50% range increase, from ~700 km of CHG70 to more than 1000 km of sLH2, depending on the consumption profile) [10].

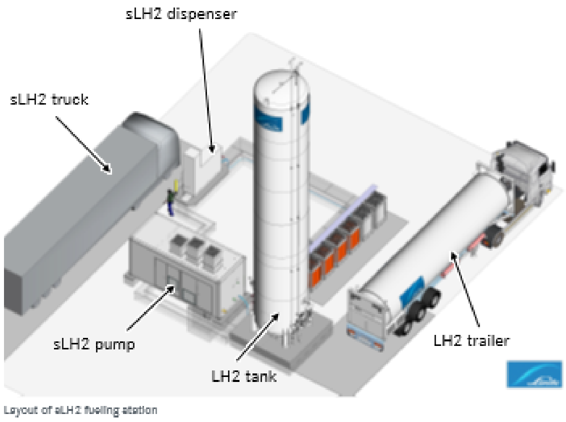
Overall we therefore summarize that the sLH2 technology has clear advantages in terms of ranges, vehicle investment costs and payloads, compared to the more common CHG technology. Furthermore, despite being a novel technology, the necessary know-how to develop sLH2 tanks is quite similar to the wide-spread liquid natural gas (LNG) tank, resulting in multiple potential suppliers and/or manufacturers that can scale-up and industrially produce such tank system.

Despite such clear advantages, one challenge with sLH2 on the vehicle side, is the boil-off onboard. However, internal simulations and tests indicate that boil-off kicks in after approximately 8h if the **s**tate **o**f **c**harge (SOC) is 100% and only after more than 160h when the tank is half empty (~ 50% SOC). However, in consideration that HDT are normally driven on a daily basis, these values suggest that boil-off would be a rather rare event during normal operation.

Refueling protocol and HRS advantages

The sLH2 refueling process is based on an improved LH2 refueling, without back-gas or limitation towards multiple tank or back-to-back refueling. To achieve this, Linde developed a novel sLH2 refueling station including an sLH2-pump with a flow rate exceeding 400 kg/h with a target pressure of 16 bar during refueling [10]. Fueling times of less than 10 min for typical HDT can be realized with this configuration.

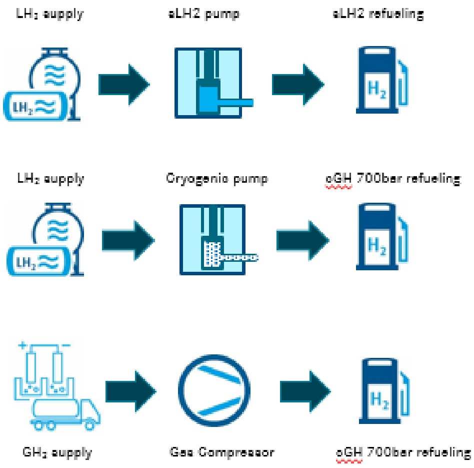
Thanks to the higher density of LH2 and the lower required pressure during refueling, the hydrogen delivery as well as the storage and compression at the station, is not only easier compared to gaseous compressed hydrogen but also noticeably more compact as can be seen from an exemplary layout in Figure 4.



HRS characteristics	sLH2 specification
Flow rate	400 – 500 kg/h
Fueling time	10 – 15 min
HRS energy demand	0.05 kWh/kg H_2 dispensed
Station footprint	50 m² w/o dispenser
HRS – vehicle interaction	no data transmission no back-gas
Storage tank size	4,000 kg LH2 – 10 h fueling can be adapted to customer needs
Fueling modes	parallel and back-to-back

Figure 4: Exemplary layout of a small sLH2 HRS with one dispenser

At HRS level, beside the smaller footprint, the advantages of sLH2 and liquid delivery are outlined qualitatively in the following Figure 5:



Technology advantages

- Very high HRS energy efficiency
- Low HRS footprint
- Very high H2 flow rates
- Low maintenance and service costs
- Very low TCO

- High HRS energy efficiency
- High H2 flow rates
- High technology readiness level

- H2 availability
- High technology readiness level
- H2 supply flexibility

Figure 5: Technologies advantages of different fueling technologies (sLH2 on top)

The improved refueling performance with sLH2 fueling leads to a very low TCO for the HRS, as well as a high HRS energy efficiency (0.05 kWh/kg H2) and footprint/complexity reductions are quite remarkable compared to CHG70 [10].

In this respect, and considering also the advantages at vehicle level, sLH2 is a highly attractive technology for customers in the trucking sector and beyond. However, there are still a few steps remaining, before sLH2 becomes widely accepted within the industry. Beside the market availability and low cost of liquid hydrogen (a discussion out of scope for the current paper) one of the remaining hurdles is the standardization process, that will be discussed in the next section.

Standardization

Linde and Daimer Truck are not proprietary of the technology and are promoting the advantages of using sLH2 in HDT, in order to expand the technology adoption to other OEMs as well as towards more infrastructure providers. In order to achieve that, a white paper process was initiated in 2021 [11, 12]. The resulting specifications for the fueling and hardware interface, after the conclusion of the activities within the Clean Energy Partnership (CEP) in 2022, are now under standardization at ISO level.

The CEP sLH2 white paper activities saw the participation of multiple stakeholders from the trucking as well as the infrastructure sector and resulted in two papers:

(1) LH2 fuelling from station into the truck is well known from former projects, but has some disadvantages as e.g., gas return from tank to the fuelling station and fuelling stops only based on the signal from the truck. Therefore, the first white paper focuses on sLH2 (subcooled liquified hydrogen) fuelling to avoid gas return from the vehicle tank and defines fuelling stops without data communication required. sLH2 fuelling is a process in which the liquefied hydrogen is subcooled and can be filled in this state to the vehicle tank.

The fuelling procedure is subdivided into the three steps:

- **Pre-fuelling** (incl. purging and leakage testing, pressure system determination, …),
- **main fueling** (with two fueling steps, one with reduced flow rate for cooldown of piping and storage system and a second with target fueling rate 400 kg/h), and
- **post-fuelling** (after that the p_{target} is reached, further purging and leakage testing needs to be conducted before that the nozzle is disconnected).

The flow, pressure and temperature profile during a typical refueling are shown in Figure 6.

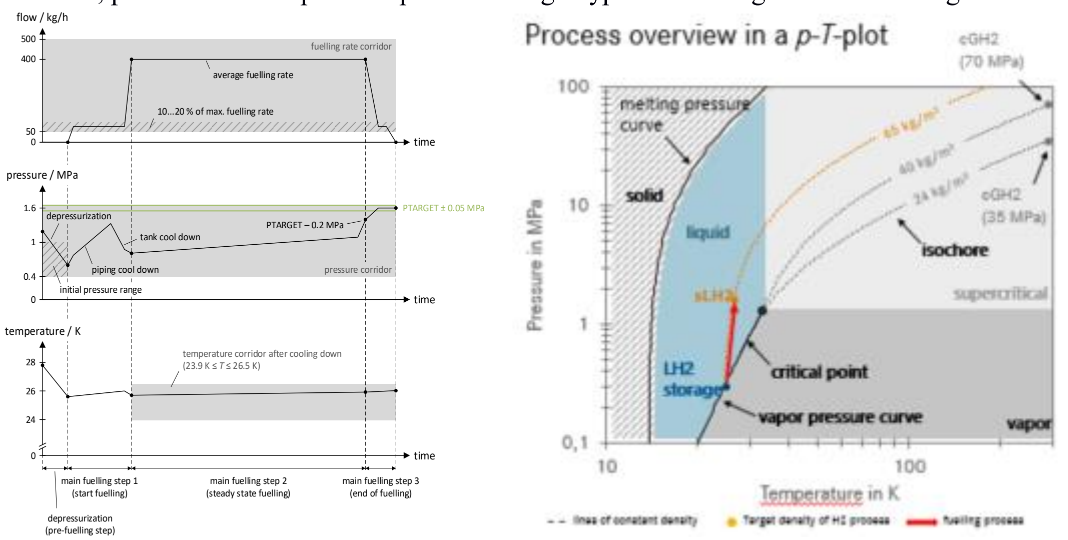


Figure 6: Exemplarily flow, pressure and temperature profiles during sLH2 fuelling (left) and P-T plot (right)

(2) Furthermore, having the vehicle storage system, connected to the propulsion unit, on one hand and the fuelling unit on the other, a component joining both units for hydrogen transfer is required. Therefore, the goal of the second white paper is the development of a subcooled liquid hydrogen fuelling interface applied in trucks, whose main hardware components are shown in Figure 7. This coupling component shall be easily reproducible in a series production process.

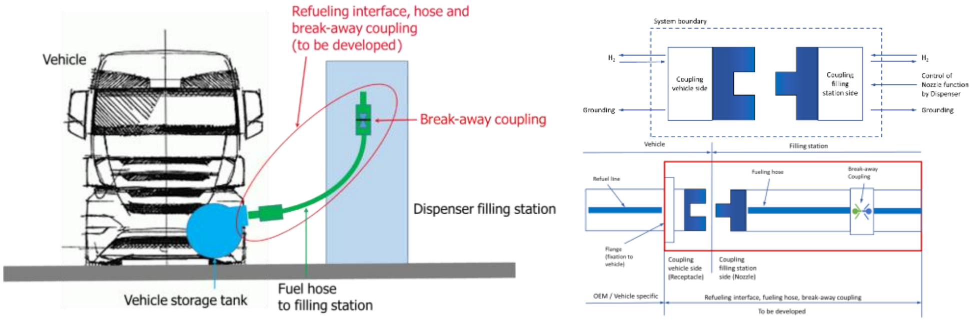


Figure 7*:* Overview of fuelling interface-components and system boundaries (right)

Within the documents, a complete set of information on controlling, testing dimensioning, geometry, design and further requirements (e.g. environmental, electrical, operational …) are provided. Since early 2023, the sLH2 protocol and interface are being discussed within the ISO activities (TC 197 – Hydrogen Technologies) with the target of achieving a global standard. Within these activities the revision of following documents has been proposed and is expected to be completed by 2026:

- ISO 13984 : liquid H2 – land vehicle fuelling protocol

- ISO 13985 : liquid H2 – land vehicle fuel tanks

- ISO 19886 : liquid H2 – land vehicle fuelling connectors

Conclusion

With the present paper, the advantages of sLH2 technologies for vehicles as well as for refueling stations were shown; overall sLH2 features a significant commercial advantage for HDT and HRS, while also reducing the space requirements, thanks to the higher energy density of liquid hydrogen and a reduced amount of equipment. At the same time, the refueling protocol, that is currently undergoing a standardization process, solves some of the critical challenges for fueling vehicles with liquid hydrogen. Considering also the initial positive testing results, we are confident that sLH2 will be a standard solution in the future portfolio of heavy duty road transport and non-road transport applicatio.

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Presenter Biography

Enrico Pizzutilo

Role: Expert Hydrogen Infrastructure Business Solutions at Mercedes Benz Trucks

Topics: Project Lead for H2-Ecosystem strategy in FCEV-Projects; Techno-economic analysis of HRS and H2-Value Chain; Standardization in collaboration with tank R&D

Background: Development and characterization of fuel cell and electrolyzers at Max-Planck-Institut; Energy and decarbonization consultion at Arup; since 2019 at Daimler and since 2022 at Daimler Truck within the hydrogen team.

Christian Will

Role: European Utilities Expert Infrastructure Technology e-Mobility Europe

Background: Christian Will has been working at Mercedes-Benz Cars and Daimler Trucks for seven years. He is responsible for liaising between European utilities and logistics customers as well as enabling the electrification of the transportation sector. Christian obtained a Master's degree in Industrial Engineering and Management at the Karlsruhe Institute of Technology (KIT) and is currently working on his PhD at KIT and the University of California, Davis. His research focuses on electric vehicles and power markets.

Thomas Acher

Role: Head of Process Design & Development at Linde Hydrogen FuelTech; Leading an interdisciplinary team of H2 mobility experts at multiple locations around the globe; Supervision of several H2 test facilities

Topics: Design and enhancement of hydrogen filling station systems from Linde and development of new H2 refueling technologies

Background: Modeling and simulation in process engineering, first in academia, then in large-scale plant design at Linde; since mid-2021 in the field of hydrogen mobility