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Subcooled Liquid Hydrogen Technology for Heavy-Duty Trucks

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Abstract: 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 the complexity of hydrogen refueling stations. In this article, the key technical aspects, advantages, challenges and future developments of sLH2 at vehicle and infrastructure levels will be explored and highlighted.

Keywords: hydrogen mobility; FCEV; heavy-duty trucks; subcooled liquid hydrogen; sLH2; liquid hydrogen; LH2; hydrogen refueling station

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1. Introduction

On the way toward carbon-neutral road transport mobility, heavy-duty trucks (HDTs) are one of the most challenging applications to decarbonize [1]. In this context, truck original equipment manufacturers (OEMs) are exploring a dual technology-open strategy, with both battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) being developed and adopted as complementary solutions [2,3].

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

In an 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 an ambient temperature and pressure. Therefore, in order to reach the mileage targets (as in Figure 1), hydrogen needs to be either stored at a higher pressure or lower temperature. To this end, several potential candidates for onboard hydrogen storages can be considered [5–7], namely the following:

(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 K) and low pressures (<10 bar).

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

While CHG hydrogen can only reach storage densities of up to ~40 kg/m^3 (at 700 bar and 15 °C), subcooled liquid hydrogen (sLH2) can reach up to ~62 kg/m^3 (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/m^3). However, the storage technologies of cryo-compressed hydrogen (CcH2) are more complex and currently have a lower technology readiness level (TRL) compared to the previously mentioned two technologies, as they need to handle both very low temperatures as well as high pressure in both the tank system and the refueling line (pipes, connectors, etc.). Hence, in this paper, we will focus on CHG and LH2.

Figure 1. Technology fit for commercial vehicles based on different use requirements: battery electric trucks, eActros (**left**) and eActros LongHaul (**middle**), and the GenH2 truck using liquid hydrogen in a fuel cell (**right**) (source: Daimler Truck Capital Market Day—November, 2021).

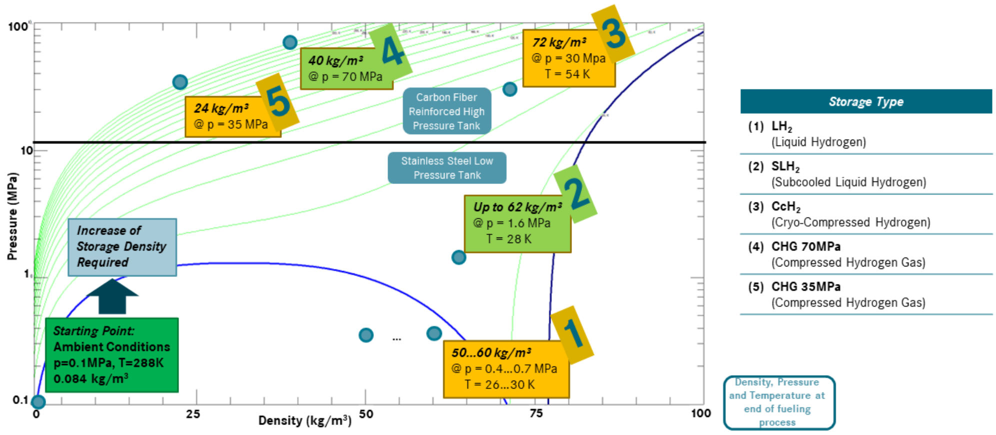


Figure 2. Density vs. pressure diagram for different on-board storage technologies.

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 utmost 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 the complexity of protocols and hardware at the hydrogen refueling stations (HRS) [9]. Some of the key parameters/advantages at the vehicle and HRS levels will be detailed in the following subsections.

2. Vehicle Advantages

The transition of HDT toward zero-emission vehicles implies a profound transformation of vehicle architecture. In FCEVs, one substantial challenge is the integration of large tank systems to achieve range and payload target. Considering sLH2 and CHG70 as the reference technologies for heavy-duty long-haul trucks, the architecture of the respective tank systems, as well as their integration in 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 80% ≈ 130 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)

(1) Assuming 5W heat transfer and depending on operating pressure

Figure 3. Comparison of the main vehicle characteristic of a 4 × 2 HDT equipped with sLH2 and CHG70 tank systems (**left** and **right** respectively); SOC refers to the vehicle state of charge (see details below).

sLH2 has an approximately 50 % higher density (up to 62 kg/m^3 at p = 16 bar and T = 28 K) compared to CHG70 (40 kg/m^3 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].

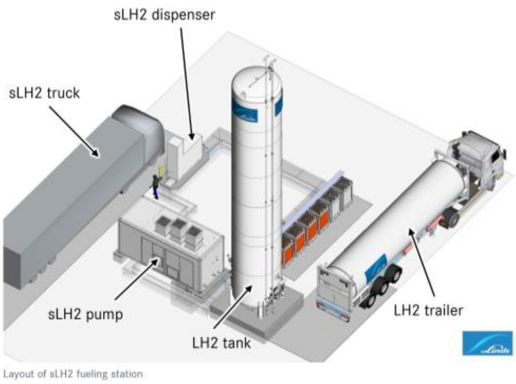
Overall, we conclude that the sLH2 technology has clear advantages in terms of ranges, vehicle investment costs and payloads compared to the more common CHG technology. Furthermore, despite being a novel technology, the necessary know-how to develop sLH2 tanks is quite similar to the wide-spread liquid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

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 10 h if the state of charge (SOC) is 100% and only after more than 160 h when the tank is half empty (~50% SOC). However, considering that HDTs are normally driven on a daily basis, these values suggest that boil-off would be a rather rare event during normal operation.

3. Refueling Protocol and HRS Advantages

The sLH2 refueling process is based on improved LH2 refueling, without back-gas or limitation toward multiple tanks 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 HDTs 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 the example 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	4000 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 the HRS level, beside the smaller footprint, the advantages of sLH2 and liquid delivery are outlined qualitatively in Figure 5.

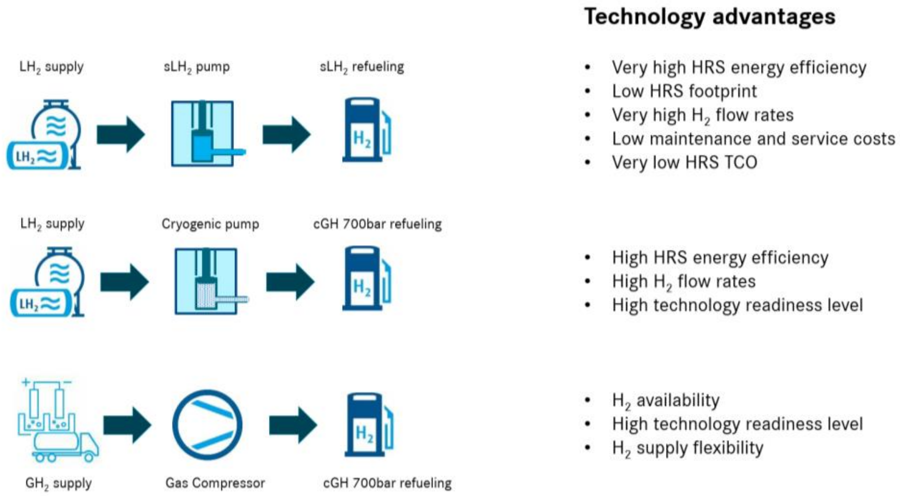


Figure 5. Technology advantages of different fueling technologies (sLH2 on top).

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, also considering the advantages at the 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. Besides the market availability and low cost of liquid hydrogen (a discussion that is out of scope for the current paper), one of the remaining hurdles is the standardization process that will be discussed in the next section.

4. Standardization

Linde and Daimler Truck are not proprietary of the technology and are promoting the advantages of using sLH2 in HDT in order to expand the technology adoption by other OEMs, as well as 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 the ISO level.

The CEP sLH2 white paper activities saw the participation of multiple stakeholders from the trucking and infrastructure sectors, and resulted in two papers being developed:

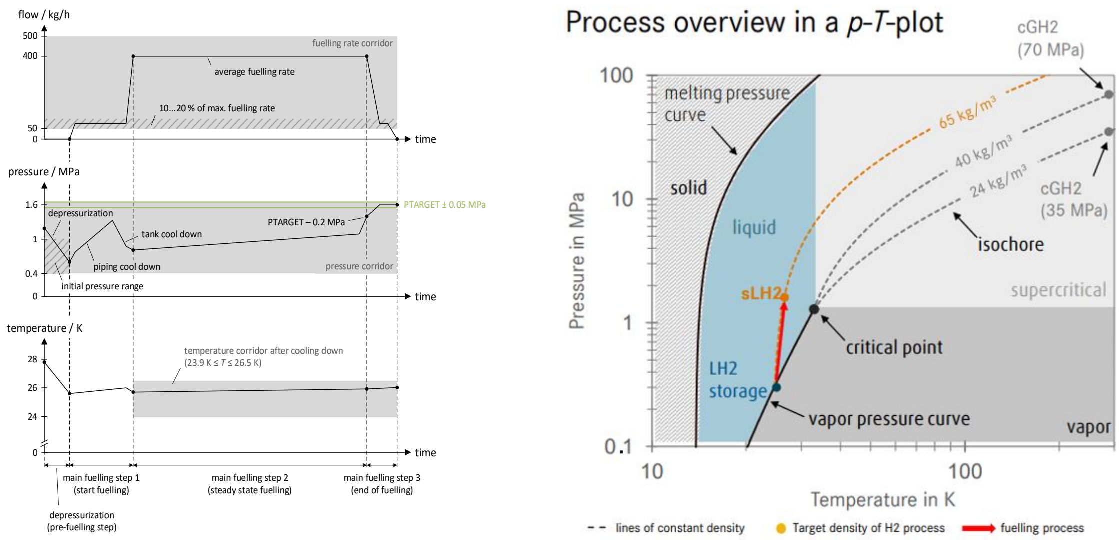
(1) LH2 fueling from the station into the truck is well known from former projects, but has some disadvantages, e.g., gas return from the tank to the fueling station, and fueling

stops only based on signals from the truck. Therefore, the first white paper focuses on sLH2 (subcooled liquified hydrogen) fueling to avoid gas return from the vehicle tank, and defines fueling stops without data communication required. sLH2 fueling is a process in which the liquefied hydrogen is subcooled and can be used in this state to fill the vehicle tank.

The fueling procedure is subdivided into three steps:

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

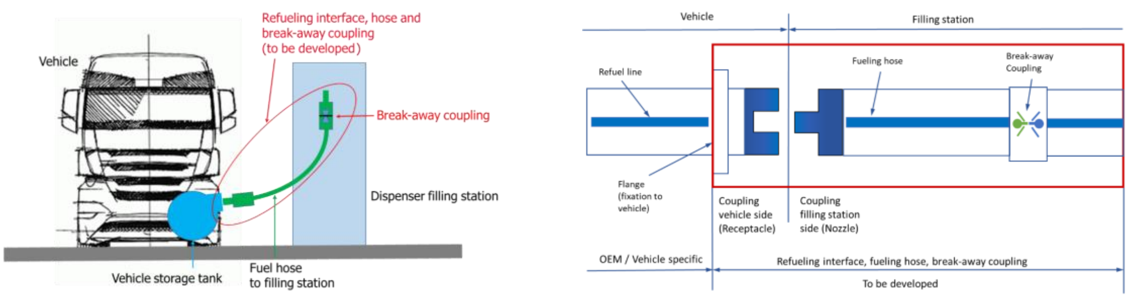
The flow, pressure and temperature profiles during a typical refueling event are shown in Figure 6.



(**a**) (**b**)

Figure 6. (**a**) Exemplarily flow, pressure and temperature profiles during sLH2 fueling; (**b**) p–T plot of hydrogen sLH2.

(2) Furthermore, having the vehicle storage system, connected to the propulsion unit, on one hand and the fueling 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 fueling interface applied in trucks, of which the main hardware components are shown in Figure 7. This coupling component shall be easily reproducible in a series of production process.



(**a**) (**b**)

Figure 7. (**a**) Overview of the fueling interface-components; (**b**) Overview of system boundaries and interface with focus of standardization effort highlighted in red box.

Within the documents, a complete set of information on controlling, testing dimensioning, geometry, design and further requirements (e.g., environmental, electrical, operational) is 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, revision of the following documents has been proposed and is expected to be completed by 2026:

- ISO 13984: liquid H2—land vehicle fueling protocol [13];
- ISO 13985: liquid H2—land vehicle fuel tanks [14];
- ISO 19886: liquid H2—land vehicle fueling connectors [15].

5. Conclusions

In the present paper, the advantages of sLH2 technologies for vehicles as well as refueling stations are shown. Overall, sLH2 features a significant commercial advantage for HDTs and HRSs, while also reducing the space requirements, thanks to the higher energy density of liquid hydrogen and 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 applications.

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