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Comparing hydrogen refueling concepts for heavy-duty vehicles

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ABSTRACT

The objective of this paper is to evaluate hydrogen refueling station (HRS) concepts for heavy-duty vehicles (HDV) based on techno-economic analyses. Considering compressed gaseous (CGH_2), liquid hydrogen (LH_2), and cryo-compressed (CCH_2) refueling concepts, a techno-economic hydrogen refueling station model is extended to incorporate recent development and cost variables. The analysis confirms the high potential of LH_2 based concepts due to hydrogen flow rates, reduced HRS energy demand, station design, significantly lower HRS investment and operational expenditures, resulting in specific hydrogen refueling costs of €0.16–0.58 $/kg_{H2}$ in contrast to €1.02–3.73 $/kg_{H2}$ in the case of gaseous HRS. Liquid hydrogen-based refueling processes have been found to be the most cost-efficient. Furthermore, the technological development of key components, as well as the establishment of standardized filling protocols, were considered important to facilitate rapid infrastructure development.

1. Introduction

The volume of road freight transport in Germany is increasing and there is currently no noticeable trend reversal with respect to reduced greenhouse gas emissions (GHGs), particularly for heavy-duty vehicles (HDVs) [1]. Utilization of alternative fuels for vehicle propulsion from renewable sources provides a significant potential for effective decarbonization. In order to achieve a GHG-neutral vehicle fleet, it is essential to develop and expand the corresponding refueling and charging infrastructure in line with the relevant political, economic, and regulatory frameworks. The highest technical efficiency potential from a well-to-wheel perspective lies within all-electric powertrains and battery storage systems based on 100% primary energy from renewable sources. However, fuel cell systems can offer significant advantages in terms of the temporal and spatial availability of renewable energy and the requirements of HDV operation, particularly in long-haul transport [2]. Therefore, consistent expansion of the hydrogen infrastructure for the energy system will facilitate the growth of intersectoral utilization [3]. The development of onboard storage and refueling technology for HDVs is still in progress. Currently, there is no consistent approach to this technology, as evidenced by the multitude of onboard hydrogen storage concepts that are being tested. The current vanguard role of gaseous pressurized hydrogen storage indicates the highest technology readiness level (TRL) of 9 due to the expanded deployment of this storage option for passenger vehicles. However, despite this, it nevertheless faces significant challenges to the broad establishment of HDV refueling. Conclusive decisions concerning the pressure and temperature levels of hydrogen storage, and thus its thermodynamic phase state, currently remain undetermined. The objective in the field of freight transport is to identify refueling concepts and on-board storage of hydrogen at high densities, by achieving the highest possible economic efficiency.

This paper presents a comprehensive techno-economic comparison of hydrogen refueling station (HRS) concepts for HDVs. The analysis is conducted from a techno-economic perspective. Four concepts for HDV hydrogen refueling are under investigation, which are already in development and have been initiated as part of a standardization process by inherent working groups within ISO[1] or SAE.[2] The concepts include compressed hydrogen (CGH_2) at 35 and 70 MPa at ambient temperatures; liquid hydrogen (LH_2) at low pressure and low temperature levels; and cryo-compressed hydrogen (CCH_2) at 35 MPa and low temperature levels. The identification of the concepts to be considered is preceded by an assessment of their technical feasibility and a stakeholder analysis. The four refueling concepts, which encompass various states of aggregation, temperature, and hydrogen pressure levels, will be evaluated via a techno-economic HRS model based on the Python programming language. The results allow for a critical comparison and evaluation of the refueling technologies, as well as the derivation of the necessary pathways for rapid implementation. This is a mandatory

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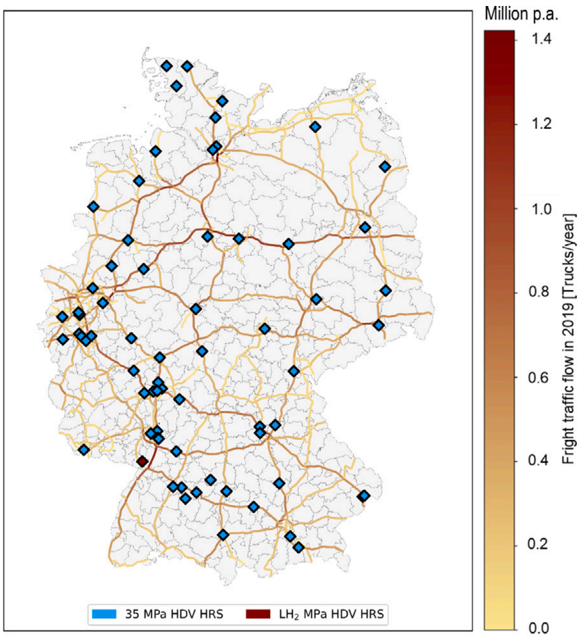

Fig. 1. Public HRS landscape for HDV refueling in Germany (10/2023) [5], including 67 stations (of which 20 are currently in operation and the remaining are in planning up to the commissioning phase) in correlation with the freight traffic flow in Germany along the core Trans-European Transport Network in Germany according to Speth et al. [4].

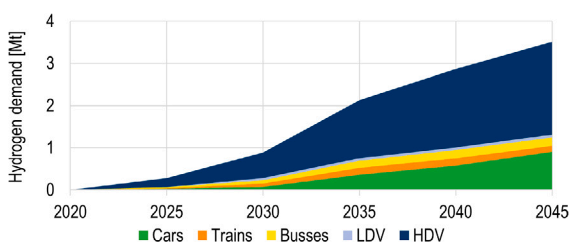

Fig. 2. Hydrogen demand in the transport sector in Germany according to Stolten et al. [6] (LDV: Light-duty vehicle; HDV: Heavy-duty vehicle).

requirement to achieve the climate protection targets and facilitate the technological trajectory decisions for HDVs as outlined by the German government. It is evident that the primary hydrogen infrastructure is undergoing development along the core Trans-European Transport Network and the German highway network, as is illustrated in Fig. 1. It represents the synthetic European road freight transport flow data of HDVs over 12 tons in 2019 as published by Speth et al. in correlation with the actual placement of public HRS for HDVs in Germany [4].

It should be noted that this development is largely confined to 35 MPa gaseous refueling, with a maximum dispensing capacity of 42.5 kilograms per refueling event, as specified in the SAE J2601 refueling protocol. A single public liquid fueling station for HDVs in Wörth am Rhein represents an exception to this pattern. Fig. 2 illustrates the projected cost-opimmal growth in the demand for hydrogen, necessary for the decarbonization of the transportation sector, particularly HDVs, up to the year 2045. The forecast does not yet match the projection in Germany, which is being held back in particular by insufficient infrastructure development, the number of vehicles available, and the political framework.

Literature. The research comprises a conventional literature review of technologies, costs, and regulations of hydrogen refueling. We have also conducted a survey of key stakeholders in the hydrogen refueling sector, including associations, HRS operators, component developers, vehicle manufacturers, and suppliers. In line with the growing recognition of hydrogen's potential to drive carbon emissions reduction in freight transport, research in this field has seen a notable increase in recent years [7]. The publications related to this research fall into six main categories: (i) hydrogen supply chains; (ii) public policies; (iii) environmental impacts; (iv) fuel cell applications; (v) drivetrain technologies; and (vi) storage tank applications [7].

Advanced research aims to enhance on-board storage options for different hydrogen storage states. These include compressed gaseous hydrogen [8–10], liquid hydrogen [11–13] and cryogenic compressed hydrogen [14–21]. The potential for powering multiple vehicle types with a single trailer of compressed gaseous hydrogen and a single trailer of liquid hydrogen was investigated by Cardella et al. Their analysis demonstrates that the significant hydrogen demand for buses, trucks, trains, and ships requires a high hydrogen storage density [22]. Several publications explores the concept of using cryogenic compressed hydrogen as a storage option, mostly for heavy-duty applications. Gangloff and Kast et al. investigated the optimal on-board design of a storage unit in various publications analyzing the boundary conditions of hydrogen usage in HDVs [23–25]. Ahluwalia et al. determined liquid-based on-board storage concepts to be the most cost-effective and with long-term autonomy. They also analyzed HDV storage tanks from a design perspective and outlined the engineering challenges [26]. The current state of development of a wide set of storage methods of hydrogen from the physical and chemical perspectives has been investigated by Usman [27], detached from refueling processes.

On the hydrogen supply chain side, operational challenges of handling liquid hydrogen are examined: including liquefaction [28], transportation [29], pumping [30], boil-off [31], and safety considerations [32]. In a review paper, Zheng et al. [33] identified gaseous hydrogen as the optimal hydrogen refueling for passenger vehicles, given the higher costs and energy demand associated with liquid hydrogen. A study published by Bauer et al. [34] applied a simulation model that considered the real gas behavior in accordance with Helmholtz free energy. They indicated the key impact of energy consumption with respect to the compression of the gaseous CGH_2 refueling of 2.43 $\mathrm{kWh/kg_{H2}}$ and a cooling energy demand of 0.18 $\mathrm{kWh/kg_{H2}}$ for a 70 MPa passenger car refueling technology, as well as significantly lower demand for liquid HRS systems by 0.37 $\mathrm{kWh/kg_{H2}}$. Perna et al. [35] examine the results of techno-economic investigations of on-site HRS supplied by different hydrogen-sourced HRS concepts. In parallel, Nugroho and colleagues conducted a cost analysis of a hydrogen infrastructure for HDVs based on German transport routes under different supply scenarios. Their findings indicated that the centralized scenario yielded cost savings of 18% compared to an on-site one [36]. The work of Gökçeka and Kale on optimal HRS design is primarily concerned with the supply pathways of hydrogen within a single, predefined gaseous HRS concept, rather than with the diverse range of HRS technologies [37]. Drawing on the earlier investigations on refueling with liquid hydrogen, several patents on the handling of LH_2 and the corresponding fueling system have appeared in addition to publications that summarize the conclusions drawn from several test facilities in Germany for the refueling fuel cell electric vehicles (FCEVs) [38].

Several models have been published in the literature focusing on hydrogen supply chain analysis. The hydrogen refueling station analysis model (HRSAM) and the heavy-duty refueling station analysis model (HDRSAM) represent approaches to analyzing hydrogen supply and HRS for HDVs [39,40]. Building upon this modeling approach, Reuß [39] developed an model of hydrogen infrastructure options for supplying the transportation sector with hydrogen. This model enables the identification of applications of technology options independent of regional requirements [41]. Cerniauskas developed a model-based representation of the relevant attributes of a hydrogen infrastructure, incorporating region-specific data on distribution, demand, and energy infrastructures based on Reußs approach [41,42]. Both models consider HRSs for different classes of vehicles using differential supply paths and exclusively the refueling technologies of 70 MPa for passenger vehicles and 35 MPa bar for truck, train, and bus fleets. The potential applications of pipelines and trailers for the transport of gaseous and liquid hydrogen are considered, as are the associated supply chains. This approach also considers corresponding technical and economic requirements within the main components.

Common to all previous studies referenced is that the refueling technologies of LH_2 and CCH_2 have not yet been compared to the established gaseous refueling technologies by means of a techno-economic approach for HDV applications. The research gap that has been identified concerns the interface of hydrogen supply and onboard storage of HDVs within the associated HRS. In this context, numerous authors refer to refueling technologies at pressure levels of 35 MPa, but less so at the 70 MPa level. The latter is assumed in several studies due to their high TRLs for low refueling rates in the passenger car sector and their widespread recognition. Hence, it is therefore imperative to consider additional HRS concepts and to analyze and evaluate potential alternatives as a potentially equitable technology compared to established HRSs. The growing reliance on alternative refueling technologies in the literature is a significant driver of this development. As the demand for refueling HDVs increases, the benefits of these technologies become more apparent, both in terms of the refueling process itself and the economic viability of the operation.

In Germany, this has led to an extension of the funding framework for hydrogen refueling concepts [43]. This study builds on the work of Cerniauskas [41] and aims to identify the potential of individual technologies for HDV hydrogen refueling in Germany. It will provide specific recommendations to determine the technical and economic HRS to pursue for HDV applications. Numerous international, European and German stakeholders have committed to the development of a comprehensive HRS infrastructure. Germany, with its central location with regard to trans-European routes, maintains a central share in the development of such a transport infrastructure [6,44].

2. Methods and data

To determine the optimal HRS concept for HDV refueling, our research examines the technological and economic potential of the four options. Therefore, a model-based techno-economic analysis is conducted taking into account the different HRS concepts, divided into technical and economic investigations of each of the for each of the four refueling technologies (i) 35 MPa CGH_2, (ii) 70 MPa CGH_2, (iii) LH_2 and (iv) CCH_2. Fig. 3 presents a visual flowchart that illustrates the fundamental methodology employed in this study.

(a) Technical analysis

First, the technical potential and limitations of various hydrogen refueling options are analyzed, in order to consider the physical and chemical properties of different hydrogen states as part of a thermodynamic investigation. Table 1 presents the various refueling and storage vessel parameters in terms of temperature, pressure, and phase state for gaseous, liquid, and supercritical hydrogen. The table indicates a wide range of hydrogen conditions for these technologies, which impose separate requirements on its technical handling.

Under standard conditions, hydrogen is in gaseous form and has a low density of 89.88 g/m^3. To ensure efficient utilization in vehicle storage systems, it is essential to significantly increase the volumetric density. This can be achieved by lowering the temperature to 20 K, which allows for an increase of up to 71.91 kg/m^3 at ambient pressure in the case of liquefaction. Alternatively, increasing the pressure to up to 70 MPa enables hydrogen to reach a density of up to 41.69 kg/m^3 at standard temperature in the supercritical phase range. The technologies described in this paper utilize these options in either the case of high-pressure storage (CGH_2) or combine both properties by means of temperature reduction and pressure increase (LH_2, CCH_2) in order to further increase the density, as is shown in Fig. 4.

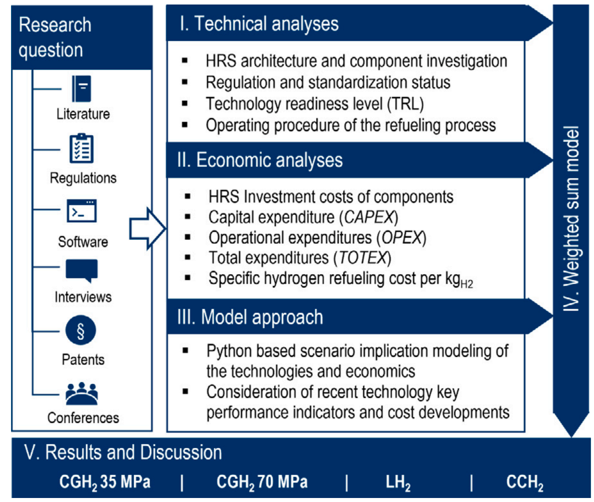

Fig. 3. Schematic of the techno-economic analysis of HRSs employed in this study.

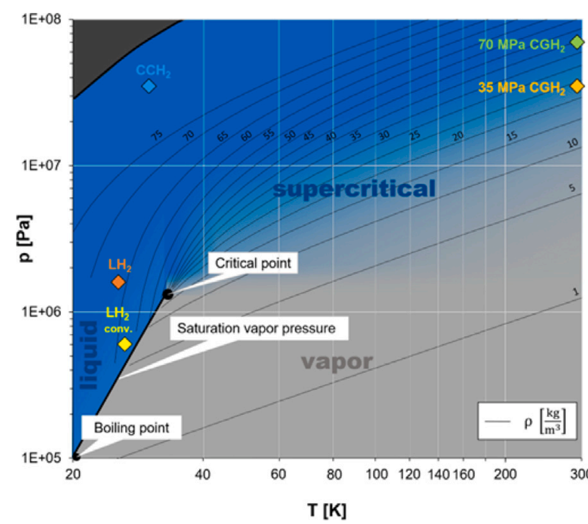

Fig. 4. Phase diagram of hydrogen across different HRS concepts indicating the density and storage states after completion of the refueling process within the on-board storage tank according to [55,56] (LH_2 conv. = conventional liquid hydrogen refueling concept at 0.6 MPa; LH_2 = liquid hydrogen refueling at 1.6 MPa; CCH_2 = cryo compressed hydrogen refueling at 35 MPa; 35 MPa CGH_2 = compressed gaseous hydrogen refueling at 35 MPa; 70 MPa CGH_2 = compressed gaseous hydrogen refueling at 70 MPa).

The data and essential performance metrics for evaluating energy requirements and costs are based on a fundamental dataset from Reuß [39] and Cerniauskas [41], which has been expanded. Energy-intensive processes related to hydrogen handling are examined in the technical literature, considering current hydrogen technologies [8, 47–54]. The technical constraints on the storage, compression, cascade storage, and refueling technologies are considered, as defined by standards and regulations, product specification sheets, manufacturer interviews, and patents. The thermodynamic investigations referenced in this paper utilize the database from the National Institute of Standards and Technology (NIST) [55] and the C++ library for thermodynamic state parameters, coolprop [56]. The thermodynamic state results and changes occurring during the refueling process are outlined in Section 3.

Subsequently, the legal framework and regular requirements for the setup of an HRS are examined in order to evaluate the state of development that is outlined in international standards and which affects the technical parameterization. The refueling concepts are analyzed

Table 1
Thermodynamic characteristic of different hydrogen refueling concepts. (Ref = refueling; EoR = end of refueling; hold = physical state during holding time in the tank; st = standard temperature; sp = standard pressure; Liquid hydrogen refueling (LH2, (conventional)) = First test procedures for vehicle refueling with liquid hydrogen in Germany on low pressure level; Liquid hydrogen refueling (LH2) = Current test procedures for heavy-duty refueling with liquid hydrogen in Germany using increased storage pressures and an adapted process for single-fluid refueling.

	Liquid hydrogen refueling (LH_2) (conventional)	Liquid hydrogen refueling (LH_2)	Cryo compressed hydrogen refueling (CCH_2)	Compressed gaseous hydrogen refueling (CGH_2)
T_{tank_EoR}	22–28 K [38]	23.9–26.5 K [45]	30–340 K [43]	273–358 K [46]
p_{tank_EoR}	0.6 MPa [38]	2.0 MPa [45]	35 MPa [43]	35–70 MPa [46]
$phase_{Ref}$	Liquid/gaseous	Liquid/gaseous	Liquid/gaseous/ supercritical	Gaseous/supercritical
$phase_{EoR}$	Liquid	Liquid	Supercritical	Supercritical
$phase_{hold}$	Liquid/gaseous	Liquid/supercritical	Supercritical	Supercritical
$H_{2,density_{st,sp}}$	71.91 $kg/m^3_{sp,20\ K}$	71.91 $kg/m^3_{sp,20\ K}$	71.91 $kg/m^3_{sp,20\ K}$	41.69 $kg/m^3_{st,70\ MPa}$
$H_{2,density_{EoR}}$	69.58 kg/m^3	70.98 kg/m^3	86.72 kg/m^3	23.31|39.22 kg/m^3

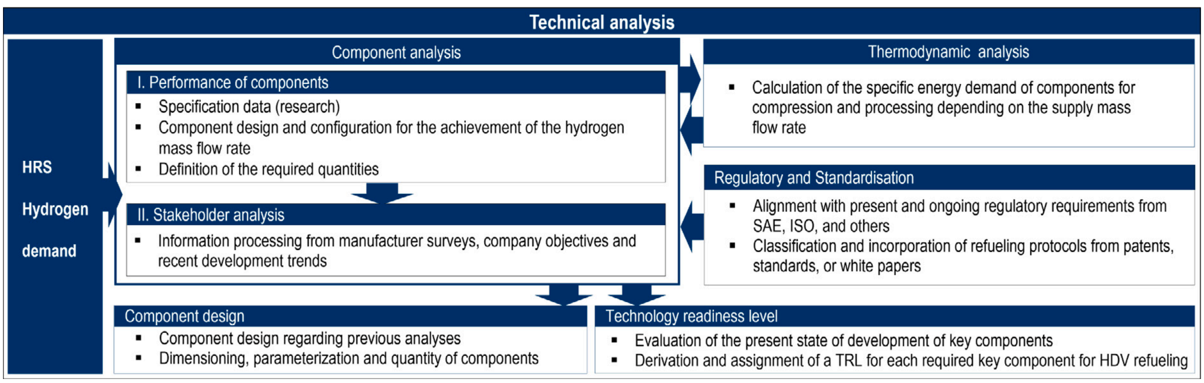

Fig. 5. Methodology of the technical analysis of HRSs.

in the following sections with respect to their structural design and the components required for each concept, with an emphasis on their TRL. This analysis aims to identify potential technical bottlenecks. The technical specifications of the HRS are based on the refueling requirements for HDVs in comparison to passenger car refueling, as outlined in the following chapter [57–59]. This analysis incorporates data from transportation and hydrogen associations, service station operators, and the hydrogen supply industry [46,60–88]. The current technological status of components and ongoing development towards hydrogen carriage in critical states will be evaluated based on the specifications provided by HRS supply industry and manufacturers. In order to facilitate a comparison of the HRS concept developments, each main component was assigned a defined TRL (Technology Readiness Level). The TRL is a standardized measure of a technology's development status, ranging from 0 (basic research) to 9 (system test/launch and operation). Furthermore, recent regulatory and standardization activities related to refueling concepts are examined in the context of HRSs for HDVs. In particular, the potential expansion of existing HRS regulations to accommodate gaseous refueling protocols like the SAE J2601 is investigated. The intricate methodology employed in the technical analysis is delineated in Fig. 5.

(b) Cost analysis

The model structure, as illustrated in Fig. 6 incorporates both the technological and the economic analysis. The economic efficiency calculation was performed using the annuity method according to VDI 2067, Sheet 1 [89] and was conducted as part of a determination of the necessary investment, operating, and maintenance costs for each component based on the selected technological configuration. The purpose of applying the annuity method in this paper is to allocate and account for all capital expenditures associated with the HRS over the period of occupancy. For this purpose, the total investment of all components of the HRS was first determined, followed by conversion of the specific capital expenditure costs (CAPEX) and specific operating and throughput-independent operating costs (fixed and variable OPEX) in the period under consideration into annually-discounted cash flows using a specific interest rate. The sum of the CAPEX, fixed and variable OPEX were used to determine the total expenditure (TOTEX) and thus the specific hydrogen cost. In the context of this study, the initial parameters of the model were revised to facilitate the investigation as electric energy demand and costs for electricity, gas, water, services, equipment, products, and fuel, which are incorporated into the current levelized cost of hydrogen (LCOH) and the current hydrogen price for commercial vehicles of €12.85/kg_{H2} for 35 MPa and €13.85/kg_{H2} for 70 MPa at the dispensers [5].

(c) Model set-up

The results of the techno-economic analysis of each HRS technology were consolidated and the functions of the basic model approach were extended with respect to the different refueling concepts. The underlying model assumptions were predominantly based on the hydrogen infrastructure model of Cerniauskas [41] which includes an extended techno-economic model derived from the HDV refueling station analysis model (HDRSAM) of the Argonne National Laboratory [34]. This model outlines the techno-economic assumptions for the refueling of FCEVs, which have been revised and updated in accordance with the latest technical developments over recent years. For this purpose, the HRS concepts LH_2 and CCH_2 have been included in the code within the thermodynamic extension of the NIST/coolprop tool [55,56]. The corresponding technical configuration and cost functions have been integrated based on the literature research to correspond with the current technologies and cost specifications as detailed in Appendix A1–A7.

(d) Scenario set-up

In order to achieve application-oriented and economical refueling of HDVs, this study defines four HRS scenarios with different hydrogen demand and dispensing rates, assuming the respective operational refueling concept. It is assumed that they correspond to the refueling rate of current diesel refueling stations, from single dispensers at vehicle depots to high-capacity refueling stations on public roads in Germany, as listed in Table 2. For future refueling processes, 80 kg of hydrogen per HDV tank are anticipated to achieve feasible ranges of around 800

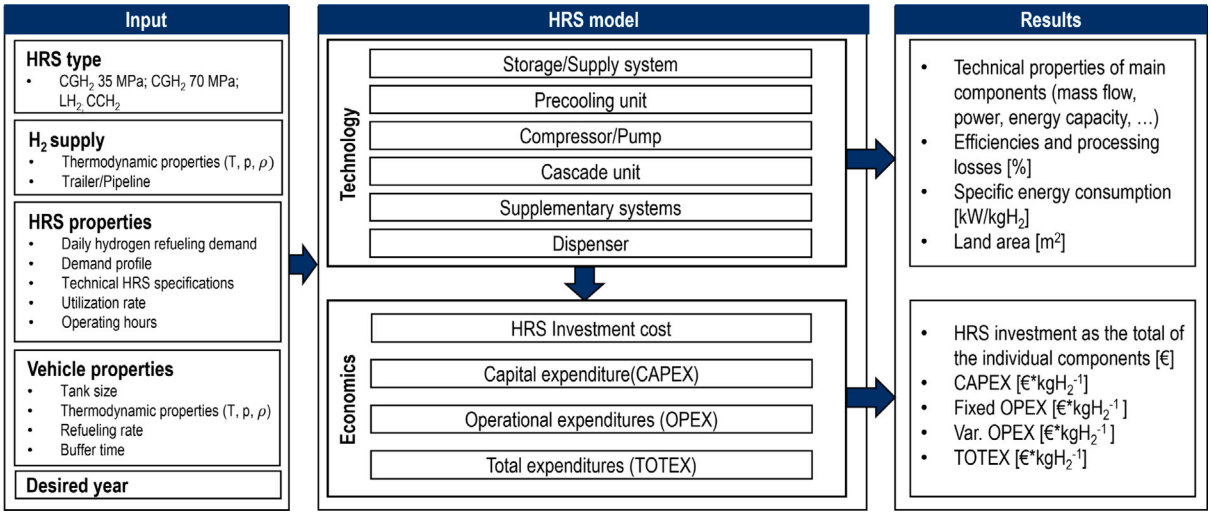

Fig. 6. Schematic of the underlying HRS model setup.

Table 2
Initial parameters of the model characterizing the HRS sizes for HDV refueling.

	2000 kg/day	4000 kg/day	8000 kg/day	16,000 kg/day
Refueling time	11 min (3 min lingering)	11 min (3 min lingering)	11 min (3 min lingering)	11 min (3 min lingering)
Number of dispensers	1	2	4	8
Hydrogen capacity vehicle	80 kg	80 kg	80 kg	80 kg
Mass flow rate	8 kg/min/disp.	8 kg/min/disp.	8 kg/min/disp.	8 kg/min/disp.
Number of vehicles	25/day	50/day	100/day	200/day
Gaseous storage	• CGH_2 35 MPa concept: Cascade, tube trailer/pipeline connection • CGH_2 70 MPa concept: Cascade/booster, tube trailer/pipeline connection			
Liquid storage	• LH_2 concept: LH_2 trailer, LH_2 storage, LH_2 pump • CCH_2 concept: LH_2 trailer, LH_2 storage, LH_2 pump • CGH_2 35 MPa concept: LH_2 trailer, LH_2 storage, evaporator, compressor • CGH_2 70 MPa concept: LH_2 trailer, LH_2 storage, evaporator, compressor			

km [36]. The refueling time corresponds to a refueling process with diesel within a period of less than 15 min, taking into account the technical capabilities required. This considers the time taken for the refueling process, as well as the hydrogen flow rates of 8 kg/min, according to the current standards under development. The four scenarios encompass a range of refueling operations, from the achievement of 25 cycles per day for fleet operators at the depot within one single dispenser to the large-scale refueling of up to eight dispensers at public HRSs, achieving 200 refueling cycles per day.

(e) Weighted sum model

The results of the investigation are evaluated using a Weighted Sum Model, which has been established since the 1960s as part of a Multi-Criteria Decision Analysis. This model is a straightforward approach to the assessment of multiple concepts based on a variety of decision criteria and was selected in order to identify the most appropriate HRS concept for refueling HDVs, in accordance with the research question. The decision criteria for the evaluation include: HRS design, TRL, total cost, supply chain, development status of standards and regulations, as well as the energy requirement. For each concept these are evaluated based on the results of the techno-economic analysis. In order to evaluate the HRS concepts, a set of valuation factors is derived from the results of each criterion by transfer to a defined range according to a linear distribution between the maximum and minimum values. A range from 0 to 10 has been set, with 10 representing the highest possible performance level and 0 indicating the lowest. The total score for each concept is calculated by multiplying the valuation factor by the weighting factor. This score is then used to derive a ranking of concepts. This enables a comparative analysis of the four concepts under consideration. The criteria of total cost, TRL, as well as efficiency and energy demand were assigned the highest weightings, in alignment with the research focus of this study. In the case of the TRL, the results are applied directly and assumed to be constant over the HRS sizes due to a component related TRL. To incorporate the energy demand and the HRS design into the scoring system of the refueling concepts, the specific electric energy demand as well as the expected total land area regarding the required components of the HRS is represented in an equivalent linear form to the TCO valuation factors, but between the minimum and the maximum value. The scoring system incorporates two additional criteria pertaining to the valuation of hydrogen supplies and the implications of regulatory and standardization frameworks. Both of these are crucial in accounting for the differences in the supply of gaseous and liquid hydrogen to HRS, along with the anticipated consolidation of standards and regulations with regard to its realization. Both criteria are considered with a linear dependency on the daily hydrogen dispensing quantity of a HRS.

3. Results and discussion

Technology analysis. The refueling of HDVs represents high engineering challenges for the various HRS concepts, indicating that existing technologies require fundamental modifications while further R&D of novel refueling concepts is essential. The results employed to identify the most techno-economically-appropriate HRS concept are elaborated according to the defined methodology of the technical analysis of HRSs outlined above and provided in the following chapter.

CGH_2 35 MPa — refueling concept. The current HDV fleet in freight transport in Germany is exclusively refueled commercially using HRSs at 35 MPa. The on-board storage systems have been proven and refueling protocols are available up to 42.5 kg capacity. However, for the economical refueling of HDVs, the storage quantity must be approximately duplicated, which requires a revision of several components of the HRS. This encompasses the compressor, particularly with respect to durability, the refrigeration unit, the cascade storage, and the dispenser, as well as the vehicle tanks. Consequently, the technology is predominantly applied in distribution transport, as well as in the light- and medium-duty vehicles and the bus sector. The currently approved refueling rate of 7.2 kg/min is theoretically sufficient to refuel HDVs with up to 80 kg_{H2} in less than 15 min. However, this rate imposes increased requirements on the referenced components, particularly in the case of periodic back-to-back refueling of multiple vehicles, which has not yet been validated and has still not reached maturity. In particular, the heat input into the vehicle tank due to the compression work and Joule–Thomson effect represents a limiting factor that precludes an increased refueling rate of less than 15 min if the 85 °C currently set according to SAE J2601 is maintained without lowering the current precooling temperature of −40 °C of the hydrogen according to SAE. It is anticipated that technical adjustments will be made throughout the upcoming development of SAE J2601. Furthermore, a compressor unit utilizing a diaphragm or reciprocating compressors is required, which is connected upstream of the intermediate storage at the required pressure level in the subsequent cascade storage system [90]. The refueling process should primarily be carried out using real-time data processing control software optimized for refueling HDVs, such as the MC formula from SAE J2601, which is known from the passenger car segment, or alternatively a table-based protocol.

CGH_2 70 MPa — refueling concept. The 70 MPa hydrogen storage previously established in passenger cars is now being pursued and developed by several vehicle manufacturers. This is driven by the 1.6 times higher volumetric energy density of hydrogen to 1.3 kWh/L compared to 35 MPa storage. It draws on the strengths of existing car components that have been developed and tested. The latest revision of the SAE J2601 standard for refueling tanks larger than 10 kg has resulted in today's standardized refueling quantities and rates remaining substantially below the quantities required for refueling HDVs. Thus, it is essential to implement standardized 70 MPa refueling protocols and develop corresponding components to ensure high mass flow rates within an acceptable time frame. This requires higher demands on the safety and availability of corresponding systems compared to 35 MPa HRS. Hydrogen fuel cells require unlubricated compression with respect to reciprocating piston compressors. This imposes additional wear, extra running surface temperatures, and safety requirements. Furthermore, these compressors have thus far only been successfully tested up to 35 MPa. Further developments in pure hydrogen-specific wear materials and seal ring constructions are anticipated to extend this pressure limit and influence the probability of occurrence for gaseous HDV refueling [71]. From an energy consumption perspective, this concept places the highest demands on the energy supply, particularly when supplied by means of a pipeline. In such a case, a 70 MPa HRS requires 3295 MWh (568 MWh at 35 MPa) per year with a high utilization rate for a single dispenser design and up to 25,645 MWh (4512 MWh at 35 MPa) per year of total energy for the largest considered station size. This demand requires a connection to the medium-voltage grid and results in increased operating and maintenance costs, in addition to the already more expensive system.

The reciprocating compressor, as specified by industry experts, is capable of providing a diverse range of mass flows and up to 40 MPa pressure increases. Higher pressures of up to 100 MPa can be achieved by diaphragmatic, hydraulic, and ionic compressors, but these are severely limited in capacity [71]. Further research and development is necessary to meet the requirements of HRSs and comply with the high standards set out in ISO 14687–2 for oil-free lubrication, as well as hydrogen purity thresholds.

LH_2 — refueling concept. Liquefied hydrogen single-flow refueling has rarely been demonstrated due to the challenges of the cryogenic handling of hydrogen, both during refueling and on-board vehicle storage. On the one hand, this is due to the components and materials that come into direct contact with liquid hydrogen; on the other hand, it results from the technically-unavoidable vaporization of liquid hydrogen by heat input. The key motivators for the adoption of LH_2 in the HDV sector are the increased hydrogen demand, the high filling rates, and the on-board storage ratio of the volume to the vessel surface area. In comparison to passenger car applications, these factors have a more favorable impact on the holding time of hydrogen in the HDV. Nowadays, the main emphasis for LH_2 refueling lies on single-flow refueling [67,88]. This can be achieved by strategically leveraging temperature changes through an almost isentropic state transformation in hydrogen processing prior refueling. The objective is to leverage the Joule–Thomson effect, which involves cooling the pressurized liquid phase below a specified pressure threshold during spontaneous expansion. The resultant hydrogen state becomes available for refueling under reduced overpressure, inducing the recondensation of a portion of the gas cushion if the vehicle storage tank achieves sufficient subcooling, thereby leading to a pressure decrease in the tank. This strategy facilitates single-flow refueling under favorable thermodynamic conditions, obviating the need for active supplementary cooling during LH_2 refueling, and is associated with several technical improvements in thermal isolation [38]. As a result of advancements in cryogenic storage technology components, liquid hydrogen can be stored in vehicles at slightly elevated pressures exceeding the critical pressure at 1.3 MPa to a range of 1.6–2.0 MPa [52]. This is achievable in the liquid and supercritical phases with low compression work, allowing for a slightly enhanced storage density using a vacuum-insulated stainless steel tank without resorting to carbon fiber composite storage. The primary challenge in the concept lies in the precise control of the temperature and pressure parameters to ensure successful refueling with the lowest possible pressure losses [38]. Significant inefficiency arising from the low utilization of HRS for the supply of liquid hydrogen, the pre-cooling requirements of components, and the inevitable boil-off in the storage and transportation chain, pose considerable obstacles, particularly in the infrastructure development phase. Except for the requirements for a minimized heat input, the construction is much less complex than for the corresponding high-pressure gas refueling and necessitates significantly fewer components and footprint. From a constructional point of view, the HRS must ensure that the piping carrying liquid hydrogen is designed to be as short as possible, which is often no longer feasible at larger stations due to construction requirements [38]. Nevertheless, under optimal conditions, refueling with liquid hydrogen allows for exceptionally high refueling rates of over 400 kg/h, as well as back-to-back refueling. This is achieved with low energy input by means of a cryogenic pump often designed as a recirculating or centrifugal pump. Currently, these enable reliable process operation at high flow rates and require a significantly lower footprint than gas compressors [90,91]. Accordingly, the HRS architecture is significantly smaller than in the case of CGH_2 concepts and consists essentially of a trailer swap or stationary LH_2 storage, the cryopump, and the dispenser, including super-insulated valves and piping up to the interface of the vehicle. Due to the technical challenges of LH_2 refueling, it is still undergoing research and development and has not yet reached market maturity. The technical analysis indicates that the energy requirement of an LH_2 HRS of 33,819 kWh, at a 100% utilization rate, is just 6% of the energy requirement of a 35 MPa CGH_2-HRS, and 3.4% of the energy requirement of a 70 MPa one for a station with a daily delivery rate of 2 t of hydrogen. The delivery of liquid hydrogen offers several transport advantages, but is currently limited to only three hydrogen production plants in Germany with a total capacity of 25 t LH_2 per day [75].

Table 3
Technology readiness level of different HDV hydrogen refueling concept components (LF = low flow rate ~ 2 kg/min; HF = high flow > 5 kg/min; a TRL ≥ 7 indicates a high development status, with technical solutions leading to market maturity expected in the next few years. In contrast, TRLs < 7 are associated with increased research and developments efforts and significantly delay market maturity) [92].

	Compressed gaseous hydrogen refueling (CGH_2) at 35 MPa		Compressed gaseous hydrogen refueling (CGH_2) at 70 MPa	Liquid hydrogen refueling (LH_2)	Cryo-compressed hydrogen refueling (CCH_2) at 35 MPa
	LF	HF			
Storage tank	TRL 9	TRL 9	TRL 9	TRL 8	TRL 8
Compressor / Cryopump	TRL 8	TRL 6	TRL 5	TRL 8	TRL 7
Valves and piping	TRL 9	TRL 8	TRL 7	TRL 5	TRL 5
Cascade storage	TRL 8	TRL 7	TRL 6		
Booster compressor	TRL 7	TRL 5	TRL 5		
Thermo-management	TRL 8	TRL 5	TRL 5	TRL 6	TRL 6
Dispenser	TRL 9	TRL 8	TRL 8	TRL 6	TRL 6
HRS	TRL 8-9	TRL 5-6	TRL 6	TRL 7	TRL 6

System test, launch & operations	TRL 9 TRL 8
System/ subsystem development	TRL 7
Technology demonstration	TRL 6
Technology development	TRL 5 TRL 4
Research to prove feasibility	TRL 3
Basic technology research	TRL 2 TRL 1

CCH_2 — refueling concept. The concept which enables potentially the highest volumetric energy density in the vehicle tank, operates with hydrogen close to the critical point, requires significantly less energy than gaseous concepts due to its hydrogen state. For compression, reciprocating cryogenic pumps are the preferred technology, currently used extensively in the gas industry. For vehicle refueling, the service life of the cryogenic pump derives benefit from the compression experienced from the initial vehicle pressure up to the maximum pressure. Despite the inability to ascertain the lifetime with any degree of certainty at this time, the research conducted by Petitpas et al. does not reveal any indications of pump degradation following 456 fill cycles at 700 bar [93]. Compared to liquid hydrogen refueling, the additional compression requires a sixfold increase in the energy demand of the HRS, which, however, is only 36% of the energy demand of 35 MPa CGH_2 refueling and 20% of 70 MPa CGH_2 refueling with trailer-swap supply at a daily delivery rate of 2 t of hydrogen. The calculated proportions decrease significantly with increased daily refueling quantities. A significant advantage of the CCH_2 concept over LH_2 refueling is the thermal robustness of the refueling process in terms of external heat input. Due to the increased pressure compensation, the vaporized hydrogen can be further stored in the vehicle tank during the refueling process, for instance through warm system pipes and valves, and does not have to be blown off immediately. This enables more reliable single-flow refueling of a two phase liquid and supercritical phase state. Although this does not lead to recondensation, it nevertheless does lead to increased volumetric density during the refueling process due to passive refrigeration. Consequently, the CCH_2 concept also covers the thermodynamic gap between the CGH_2 and LH_2 concepts, as hydrogen in all intermediate temperature ranges can be held in the vehicle tank to a certain extent. The process results in a lower loss of process-related vaporized hydrogen, as well as time, than with LH_2 technology. Nevertheless, CCH_2 refueling also places high demands on the thermal insulation of the components and achieves maximum storage densities with the lowest possible temperature input. Furthermore, the increased requirements resulting from the combination of high pressure and low temperature place the highest demands on the materials and components utilized, have yet to be demonstrated to be sufficiently durable. Further R&D on these components is therefore required and will determine marketability.

Comparison of refueling concepts. In contrast to passenger car refueling, none of the HRS concepts has reached the development state necessary for the broad roll-out of an infrastructure for refueling HDVs due to the technical challenges entailed. The management of fundamentally different hydrogen phase states requires the application of manifold components. Fig. 7 displays a schematic representation of the component configuration of the individual refueling options, indicating the lower complexity of the liquid-supplied HRS concepts.

A fundamental differentiation characteristic is the definition of the required system pressure level for liquefied or gaseous hydrogen. For gaseous refueling, pressure equalization refueling by means of a cascade system is well-established, with the main compressor reconstituting the target pressure it falls below a specified threshold and is therefore indirectly involved in the refueling process. Liquid hydrogen, however, is refueled directly into the vehicle by a cryogenic pump. As a result, for each dispenser there is a pump required to provide the necessary throughput and pressure according to the refueling protocol. In contrast, in the case of gaseous refueling, a central main compressor can offer multiple dispensers by providing the cascade system pressure, although this is limited by the delivery rates for HDV refueling. The refueling concepts considered and their respective components are analyzed for comparability in terms of their developmental status. For this purpose, a technical analysis of the HRS concepts classifies the components according to their TRL, as is shown in Table 3.

As only the technology of 35 MPa CGH_2 refueling has reached market maturity (for dispensing quantities of up to 42.5 kg), all TRLs are set to "7", "8" and "9", whereas the other refueling concepts feature less mature components. The technological analysis of HRSs for the refueling of HDVs leads to the conclusion that the refueling process places significantly higher demands on the associated components and systems due to the increased refueling rates. This demonstrates a significant advantage of liquid-based refueling in terms of compliance with economic process parameters for refueling, such as refueling duration, refrigeration effort, and preconditioning. Although high-pressure CGH_2 refueling has been established in the passenger car sector, the refueling of HDVs with high mass flows under high pressure levels continues to present significant technical challenges and a pressing need for further development of hydrogen compression components.

Standards and regulations. The majority of hydrogen regulations and standards are aligned with European legislation, whereas they are often international or aligned with global norms. Existing protocols have to be updated to meet the requirements of HDV refueling [44]. Associations as the Society of Automotive Engineers International (SAE) developed a series of standards for hydrogen refueling. Appendix A8-A10 provide a overview of the regulations, standards, approval processes and categorizations of HRSs in Germany. The International Organization for Standardization (ISO) has established a technical committee, ISO/TC 197, with the objective of developing standards for hydrogen technologies that extend beyond the scope of established refueling concepts. Further enhancements to the existing standards are currently being formulated by various working groups (70 MPa CGH_2, LH_2, CCH_2) as illustrated in Fig. 8. It is noteworthy that a revision of numerous approval procedures is imperative when establishing HRS for the refueling of HDV, particularly considering increased refueling rates, higher energy demands and specific location requirements as well as heightened footprints for HRS. Hydrogen fuel cell-based applications impose high requirements on purity. The classification of hydrogen according to its purity is often defined by the percentage or number of nines in a value (e.g., >99.999% or 5.0 N for Polymer Electrolyte Membrane Fuel Cells (PEMFCs)). However, with a focus on specific impurities, it is not sufficient to rely on a percentage as this does not provide adequate information on the specific impurity content. For this reason, standards have been developed that require more detailed information on hydrogen purity, as described in Appendix A8.

Cost analysis. The economic analysis of HRSs reveals significant disparities in the required investment costs, as well as in the OPEX and energy costs for the HDV refueling concepts under investigation in the year 2030. The higher investment in high-pressure gaseous HRS can be attributed to two main factors: increased technical complexity and the requirement for additional components, as outlined above. The

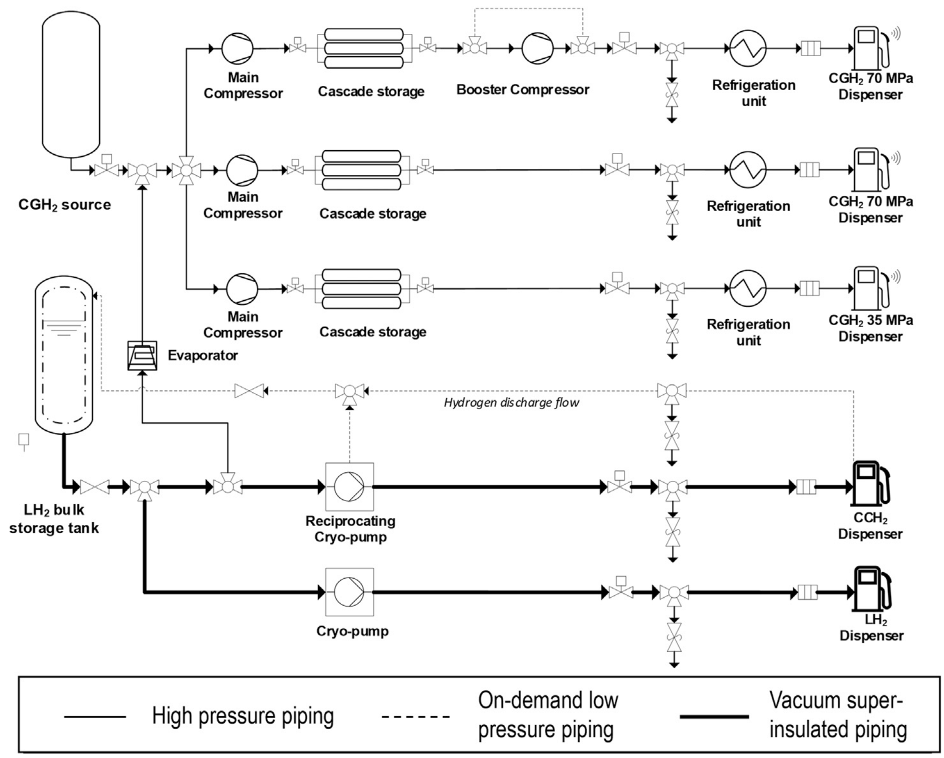

Fig. 7. Hydrogen refueling technologies considered and their components (simplified).

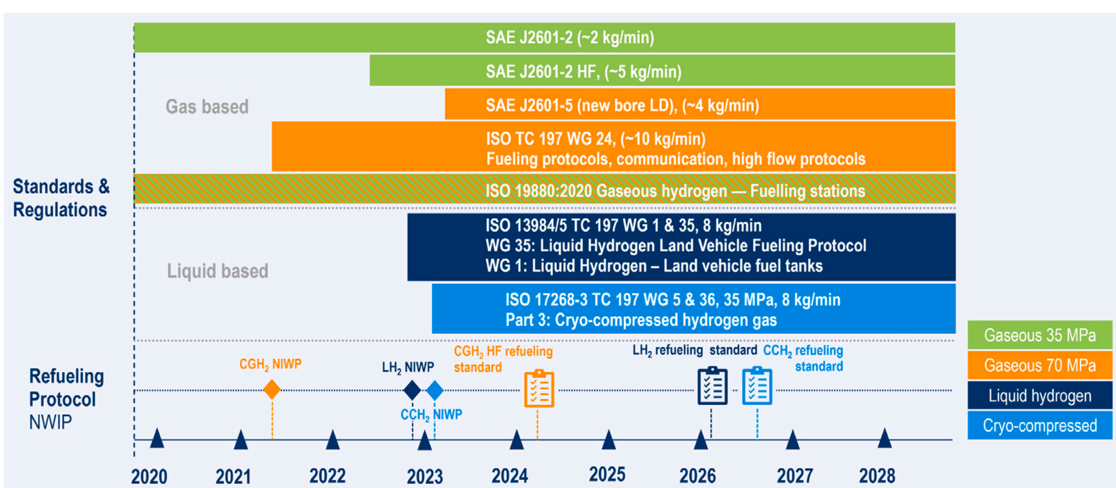

Fig. 8. Regulations and standards for hydrogen refueling concepts.

additional technical effort, in particular for compression and cooling, is reflected in the initial investment costs compared to liquid refueling with reference to Appendix A7.

According to the findings depicted in Fig. 9a, as a detailed examination of the total cost of the various HRS concepts reveals that the investment represents the most significant cost factor. The initial investment in the smallest HRS with an LH_2 concept is equivalent to only one third (33.0%) of the CGH_2 station investment with a trailer supply in the case of 35 MPa and only 16.6% of the initial investment of a 70 MPa station with an equal amount of daily hydrogen dispensing. The additional requirements for compression from the pipeline pressure result in an additional investment of 165% for such an HRS compared to the trailer-swap option. There is a definite increase in investment and operating costs for gaseous HRS, which leads to higher specific hydrogen cost with larger HRS sizes. The costs of the gaseous system exceed the liquid-based HRS for LH_2 and CCH_2 by several times the value of identical refueling rates, as demonstrated in Fig. 9a. The initial investment cost for the smallest HRSs in the context of the LH_2 concept starts at €481,311. For the CCH_2 concept, the investment cost was determined to be €546,197. It is important to note that the investment cost of a 35 MPa CGH_2 HRS with a trailer swap is €1,457,264, while the cost for a 70 MPa CGH_2 HRS is €2,888,450, almost twice as much. It can be determined that for customers such as private operators, without considering the maintenance costs, investment in the HRS already has a significant impact on the choice of concept. This is further enhanced as the HRS scale expands, due to the comparatively lower additional expense of liquid-based refueling concepts that facilitate the delivery of larger quantities of hydrogen. Conversely, the compressor unit of the CGH_2 concepts becomes the most significant cost factor as the station size increases, thereby amplifying the effect of the cost

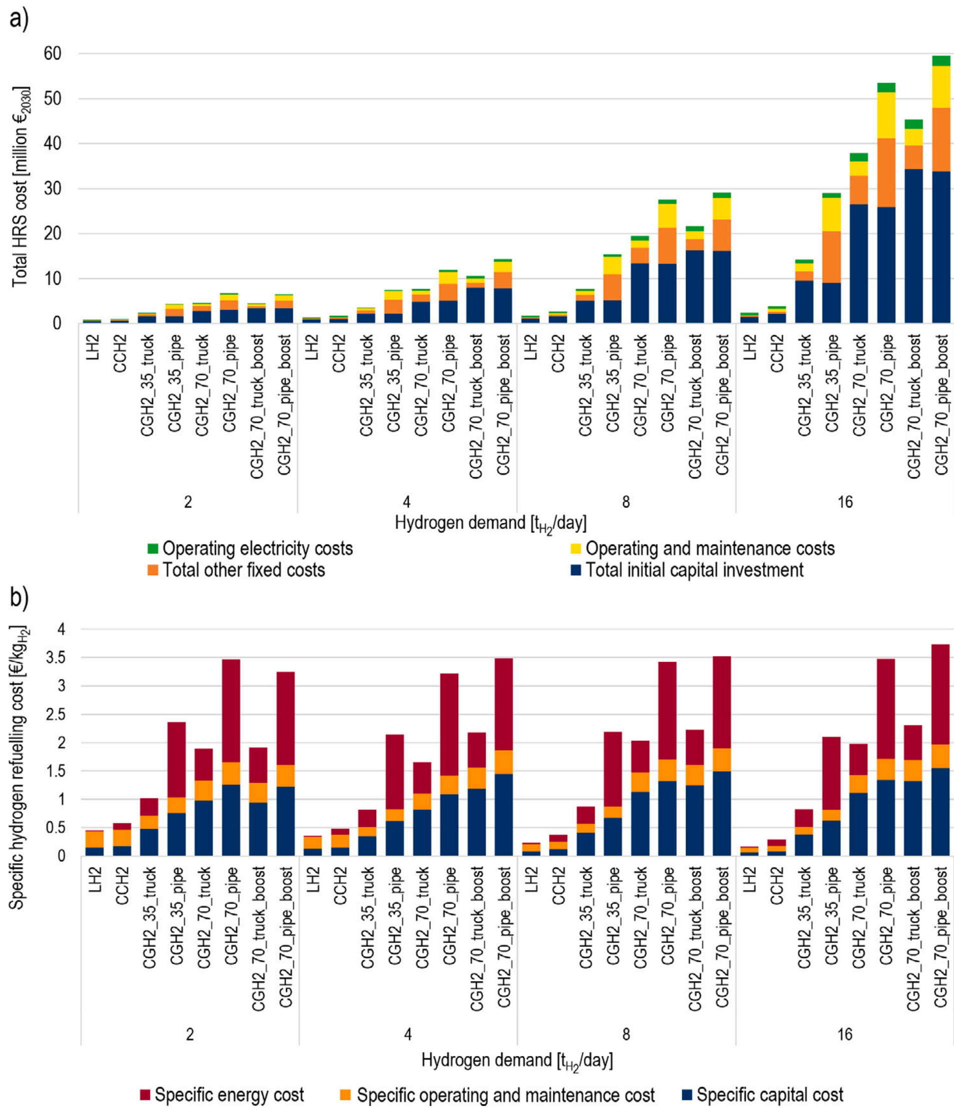

Fig. 9. Cost of different HRS concepts; (a) Total cost of HRSs for different HRS concepts in 2030; (b) Specific hydrogen refueling cost for different HRS concepts in 2030.

differential. In addition, if utilization is less than the assumed 70%, the backup storage requirements for each system will increase, driving up costs due to the high cost of storage.

The disparities between the HRS concepts further increase when maintenance and energy costs are considered, which is to the detriment of the CGH_2 technology. The elevated energy consumption resulting from compression and the corresponding higher cooling demand constitute a significant proportion of the total costs associated with large HRSs. Liquid or cryogenic fueling concepts exhibit a significant energy efficiency advantage at high refueling rates compared to CGH_2 within the system boundaries of the refueling along with the smaller HRS investment. As illustrated in Fig. 9a, it is evident that the energy expenditure associated with compressing hydrogen from the low-pressure levels of a pipeline connection represents the most significant contributor to the specific cost of hydrogen refueling. Furthermore, as the HRS size increases, the fixed CAPEX exerts a negative effect on cost development, given that land use areas, taxes and fixed operating costs tend to increase in parallel with the HRS size. In the case of liquid hydrogen-based concepts, the total costs for all scenarios can be held below €5 million. This is due to the low energy and comparatively low maintenance costs, even for large dispensing amounts, of investment in the components. Fig. 9b reveals that the additional costs incurred by the system as a result of scaling the HRS size are offset by the enhanced hydrogen output. This cost reduction does not occur in the case of the HRS concept with 70 MPa refueling, which is due to the increased energy requirements for compression and refrigeration and the high investment costs for the compressor units. This results in specific hydrogen costs of €0.16–0.45/kg_{H2} for the LH_2 concept, €0.29–0.58/kg_{H2} for CCH_2, €1.02–2.36/kg_{H2} for 35 MPa CGH_2, and €3.21–3.73/kg_{H2} in the case of 70 MPa CGH_2 refueling in 2030. A thorough examination of the technical and economic parameters was conducted to assess the sensitivity of key influencing variables on specific hydrogen costs. A notable impact was identified, for instance, by the evaporation rate of liquid hydrogen, as depicted in Fig. 10. A reduction in hydrogen losses from 0.3% to 0.1% could lead to cost savings of up to 8.1%, while an increase in losses by 0.9% could raise specific hydrogen costs by up to 26.41%, particularly for small HRSs. This highlights the stringent technical requirements for minimizing losses, with sensitivity decreasing with increased daily refueling capacity. Regarding the economic influencing parameters, it was found that the specific costs can only be reduced by 4.43–6.27% if the depreciation period is extended by five years. Conversely, a shortened depreciation period potentially increases costs by up to 5.17%, especially for small HRSs according to Fig. 10.

As previously stated, data on HRSs for HDVs is currently limited. Cost analyses in the literature have primarily been conducted for light-duty FCEVs and have been limited to daily fuel loads of up to 4 tons.

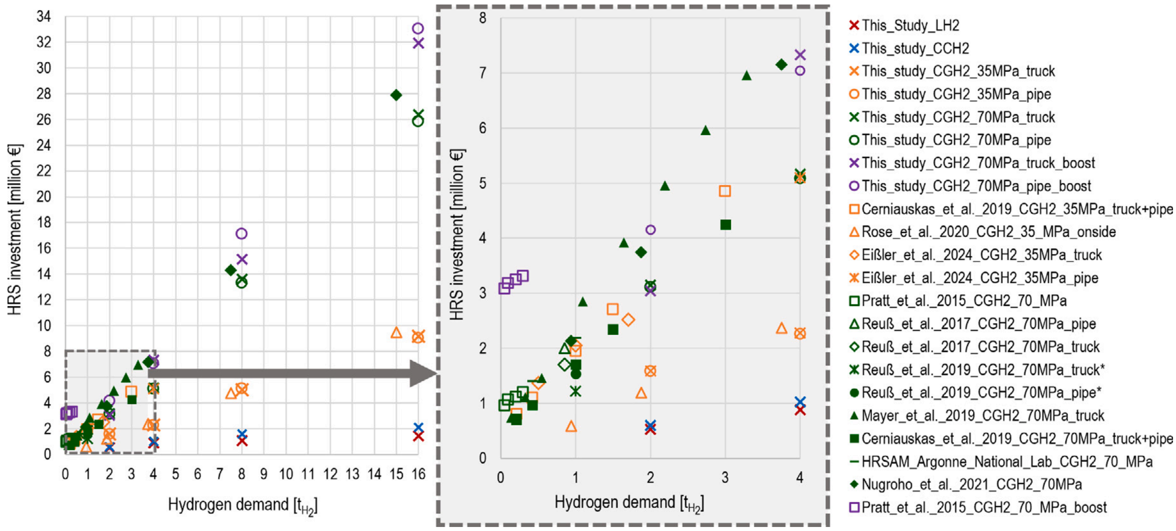

Fig. 10. Comparison of the HRS investment of different HRS sizes with the data from the literature (Cerniauskas et al. [42], Rose et al. [94], Eißler et al. [95], Pratt et al. [96], Reußet al. [39,97], HRSAM Argonne National Lab [98], Nugroho et al. [36]).

The investigation of larger HRS for trucks is conducted by Nugroho et al. and Meyer et al. The findings of these studies align with those of the present study to a considerable extent, assuming comparable conditions. Fig. 11 depicts a proximal increase in investment costs as daily hydrogen demand increases. It is notable that the liquid-based HRS concepts under consideration have a more affordable starting price than gaseous HRS, despite the hydrogen requirement being occasionally considerably higher.

A comparison of the cost intensities of the various concepts with existing literature reveals a correlation between the two. It is evident that the greatest expenditure is incurred by those concepts that involve 70 MPa gaseous refueling with a booster or cascade system. Given the current material and cost-intensive components for compression, no discernible scaling effect can be observed within the considered HRS sizes above 2 tons of hydrogen. Nevertheless, the cost analyses of recent studies indicate a reduction in investment compared to that observed in older studies. This can be attributed to the adoption of more efficient technologies and the market entry and availability of the necessary components. There are currently no sufficient references for CCH_2 and LH_2 for refueling HDVs. The preliminary data yielded from the public HRS concepts is still undergoing assessment. However, the results indicate that the investment and maintenance costs of liquid-based HRS are significantly lower for the same refueling rate. The primary reason for this is the handling of hydrogen, particularly in contrast to compression and pre-cooling efforts in the gaseous state.

Finally, in order to evaluate the results from multiple perspectives and identify the optimal HRS concept for HDV hydrogen refueling across different HRS sizes, the weighted sum model is applied. According to Appendix A11 the six predefined decision criteria: (i) HRS design; (ii) TRL; (iii) total cost; (iv) hydrogen supply; (v) regulation and standardization; and (vi) efficiency and energy demand are defined as outlined in Section 2. The weighted sum model revealed that the liquid hydrogen-based HRS concepts LH_2 and CCH_2 were the most appropriate for meeting the stated requirements, particularly those pertaining to HDV refueling across all station sizes. This is in contrast to the CGH_2 concepts of 35 and 70 MPa, which were deemed to be less appropriate. The advantages are concentrated in the high-weighted decision criteria for HDV applications, namely the lower total cost and lower energy demand in comparison to gaseous HRS. Considering the ongoing technical challenges that remain to be addressed, the presented results are contingent upon the assumption that a fully implementable technology incorporating all concepts will be in place by 2030. This encompasses the difficulties posed by hydrogen at low

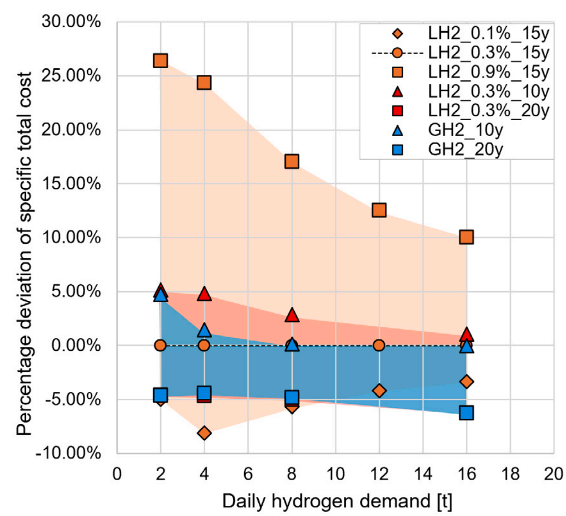

Fig. 11. Sensitivity analysis of the depreciation duration and the boil-off rate of liquid hydrogen storage LH2 = Liquid hydrogen station; GH2 = Gaseous hydrogen station (35/70 MPa; *y* = years).

temperatures, which are further compounded by elevated pressure. Within a assessment of the key decision-makers perspective, involved in the implementation of an HRS, a more refined prioritization of the weighting factors becomes apparent. The chosen stakeholders for this evaluation encompass: (i) fleet operators; (ii) political decision-makers; and (iii) cities and municipalities, as outlined in Table 4. Although the decision criteria are derived from Appendix A11, the weighting factors assigned to the stakeholders will be distinct. This explains the divergent concerns of the stakeholders in each case regarding the evaluation of the four refueling concepts. The primary concerns of fleet operators are the costs associated with the acquisition and maintenance of vehicles, the availability of technology, and the reliability of the vehicles themselves. Cities and municipalities prioritize the hydrogen supply, whereas political decision-makers consider the development level of regulations and standards as influential factors in their decisions. In contrast to the result-based decision criteria, the weighting factors of the selected groups are derived.

The results demonstrate that the prioritized HRS concepts remain consistent with those previously identified. Based on our methodology

Table 4
Decision-makers in the development of the hydrogen infrastructure, their assigned weighting factors, and the prioritized HRS concept based on the evaluation matrix Appendix A11.

Stakeholder \ Criteria	HRS design	TRL	Total cost	Hydrogen supply	Regulation and standardization	Efficiency and energy demand	First-choice HRS technology	Second-choice HRS technology
(1) Fleet operator	8	10	10	3	8	9	LH_2	CCH_2
(2) Policy maker	4	9	8	8	9	7	LH_2	CCH_2
(3) Cities and municipalities	9	7	9	10	8	7	LH_2	CCH_2

we found that the LH_2 and CCH_2 HRS concepts are the preferred options across all interest groups for refueling HDVs. In contrast, the CGH_2 HRS with 70 MPa, whether via pipeline connection or tube truck delivery, emerges as the less favored HRS concept. Differences emerge among stakeholders concerning the rankings of the gaseous HRS. Depending on the institution, the preference for hydrogen supply varies between the connection of a hydrogen pipeline and delivery via tube trucks. However, a clear consensus is observed regarding the arrangement of pressure ranges: the 70 MPa HRSs are the least preferred concepts for HDV across all stakeholders, primarily caused by high investment and energy costs, a low TRL, and a complex system design. The hydrogen supply preference can be attributed to the high priority placed on infrastructure connections through a hydrogen pipeline for a specific location, which outweighs the techno-economic HRS criteria. The connection exerts a positive influence on road traffic, and it also has the potential to have implications for the system integration of energy supply and demand. The comprehensive results of the stakeholder-oriented assessment can be found in the Appendix A12–A14.

4. Conclusion

The findings highlight the necessity of considering concepts beyond gaseous refueling when implementing a hydrogen refueling infrastructure. The scaling of passenger car refueling concepts necessitates a substantial technical investment and causes significant cost increases for maintaining gaseous HRS. Factors hindering the development of a hydrogen infrastructure for HDVs include the complex preconditioning and the high costs associated with larger hydrogen demand and refueling rates. To enable economical refueling of heavy-duty vehicles, it is essential to accelerate the development of the infrastructure through the implementation of techno-economically preferable concepts. This will require increased R&D efforts for components, as well as the harmonization of standardization and the establishment of refueling protocols. In light of the high mass flows required, it is essential to further develop critical components, including compressor units, super-insulated piping, valves, and dispensers, to achieve cost-effective refueling. From a technical standpoint, the energy-intensive compression of gaseous hydrogen, particularly on-site, necessitates compression units capable of providing both, high pressures and high mass flows. The existing technological capacity was found to be ineffective in meeting the required specifications, particularly with regard to the compression and durability of the components involved. Furthermore, the pre-cooling and purification of the hydrogen supplied by pipeline represent a technical hurdle exceeding the capabilities of existing standards. Nevertheless, from the standpoint of thermodynamics, this technical requirement is invariably accompanied by an essential energy requirement in order to be able to provide high gaseous energy densities. Consequently, the development of regulations in particular must be accelerated and completed in a timely manner. While liquid hydrogen based refueling processes show considerable potential, it is essential to demonstrate their reliability in terms of system design under real-world conditions. The technical handling of liquid hydrogen has a strong impact on its economic efficiency. In order to offset the thermodynamic benefits of liquid refueling, compressor technology must evolve to become competitive, particularly given the anticipated provision of higher hydrogen rates by pipeline at low pressure levels. Given the physical limitations for efficient refueling, it is imperative that R&D in liquid and cryogenic hydrogen refueling be continuously pursued. In light of the findings of this study, it is crucial to pursue further research into the techno-economic aspects of the hydrogen supply chain and the on-board storage of hydrogen in heavy-duty vehicles. The potential of hydrogen as an energy carrier for decarbonizing heavy-duty transport, alongside battery electrification, must be rigorously defined prior a definitive pathway. Liquid hydrogen offers an alternative supply concept, characterized by cost-effective and straightforward refueling systems, as well as high purities suitable for fuel cells, if the challenges of boil-off losses during refueling and extensive maintenance requirements can be overcome. The anticipated development of a hydrogen infrastructure for industrial applications is likely to provide gaseous hydrogen with low purity and pressure levels, thereby complicating the integration of the transport infrastructure. Consequently, a thorough evaluation of the hydrogen infrastructure beyond the refueling station system boundary is imperative and will be addressed in a subsequent publication.

CRediT authorship contribution statement

Tobias Otto: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Philip Erhart:** Data curation. **Stefan Kraus:** Software, Data curation. **Thomas Grube:** Supervision, Project administration, Formal analysis, Conceptualization. **Jochen Linßen:** Supervision, Project administration, Formal analysis. **Detlef Stolten:** Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ijhydene.2025.01.498.

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