*sustainability*

MDPI

*Review*

# A Review on Liquid Hydrogen Storage: Current Status, Challenges and Future Directions

**Ahmad Naquash, Neha Agarwal * and Moonyong Lee ***

School of Chemical Engineering, Yeungnam University, Gyeongsan-si 38541, Gyeongsangbuk-do, Republic of Korea; ahmadnakash@hotmail.com

* Correspondence: cheneha9@gmail.com (N.A.); mynlee@yu.ac.kr (M.L.); Tel.: +82-53-810-2512 (M.L.)

**Abstract:** The growing interest in hydrogen ($H_2$) has motivated process engineers and industrialists to investigate the potential of liquid hydrogen ($LH_2$) storage. $LH_2$ is an essential component in the $H_2$ supply chain. Many researchers have studied $LH_2$ storage from the perspective of tank structure, boil-off losses, insulation schemes, and storage conditions. A few review studies have also been published considering $LH_2$ storage; however, most are simply collections of previous articles. None of these review articles have critically evaluated the research articles. In this review study, recent reports, conceptual studies, and patents have been included and critically discussed. Further, challenges and recommendations have been listed based on the literature review. Our results suggest that the multi-layer insulation scheme and integrated refrigeration system can effectively reduce boil-off losses. However, boil-off losses from storage tanks during transportation are the least discussed and must be addressed. The cost of an $LH_2$ storage tank is high, but it can be reduced with advancements in materials and the utilization of latest technologies. The present challenges and future directions for $LH_2$ storage include minimizing and utilizing boil-off losses, improving insulation schemes, and ensuring cost-effective large-scale $LH_2$ storage. This review study can be fundamental for process engineers and new academic researchers to design energy-efficient and cost-effective $LH_2$ storage systems.

**Keywords:** liquid hydrogen; boil-off rate; $LH_2$ storage; tank insulation; $LH_2$ tank costs

check for updates

**Citation:** Naquash, A.; Agarwal, N.; Lee, M. A Review on Liquid Hydrogen Storage: Current Status, Challenges and Future Directions. *Sustainability* **2024**, *16*, 8270. https://doi.org/10.3390/su16188270

Academic Editor: Pablo García Triviño

Received: 27 August 2024
Revised: 19 September 2024
Accepted: 20 September 2024
Published: 23 September 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Hydrogen ($H_2$) has recently become of fundamental importance in the energy and economics sector because of its clean energy characteristics [1]. Compared to conventional fuels, $H_2$ is a clean energy fuel as it produces only water when burned. $H_2$ is a versatile fuel that can be used in different sectors of life. The increasing importance of $H_2$ paves the way for intercontinental or long-distance transportation. $H_2$ can be transported in different forms, including as a gas or liquid, or with ammonia and liquid organic hydrogen carriers [2]. Among these options, the most cost-effective way to transport high-purity $H_2$ over long distances is in liquid form [3]. In liquid $H_2$ ($LH_2$) transportation, storage is one of the most important considerations. Storing $LH_2$ is very challenging and critical. $LH_2$ exists at −253 °C (1 atm) with a 99% para composition. This is a very low temperature and requires tremendous amount of energy [4]. Similarly, 99% para (1% ortho) at −253 °C is the composition of $LH_2$ at the equilibrium stage [5]. This equilibrium is temperature-dependent and tends to change when the temperature has changed. However, this change is exothermic, which imparts additional heat load on refrigeration [6]. These two challenges make $LH_2$ storage very challenging and critical.

Researchers are working on improving $LH_2$ storage, studying storage conditions, tank structure, insulation material, and boil-off losses to address its associated challenges associated. For instance, Kang et al. [7] worked on the optimization of the insulation thickness of an $LH_2$ storage tank. Their results show that using a vapor cooling shield

(VCS) results in the reduction of layers in the multi-layer insulation (MLI) system. They concluded that the total insulation thickness is reduced by 51.4% with MLI and VCS systems [7]. Jiang et al. [8] conducted an interesting study on the effects of gravity on $LH_2$ storage. They simulated the tank conditions using the computational fluid dynamics (CFD) method. They concluded that the increase in gravitational acceleration leads to an increase in temperature which increases gaseous $H_2$ percentage [8]. Liu et al. [9,10] also studied the thermal performance of $LH_2$ tanks under different gravity levels. Their conclusion suggests that the gravity level is directly proportional to the heat convection. In addition, Liu et al. also studied the thermal performance of insulation in aerospace applications [11] and the thermal stratification of rotating $LH_2$ tanks [12]. Moreover, Xu et al. investigated the design of an $LH_2$ tank for aerospace applications using ANSYS software. Their proposed insulated support structure can reduce heat leakage by 85% [13]. Researchers have also worked on new materials and nanotechnology for $H_2$ storage [14–18]. It has been noted from the literature reviews of research papers that researchers have mainly focused on improving $LH_2$ storage tank insulation schemes.

Similarly, several review studies have also been published in the last few years investigating the work of researchers. For instance, Yartys and Lototsky [19] have published a review on $H_2$ storage methods. They compared $LH_2$ storage with compressed $H_2$ storage and concluded that $LH_2$ storage contains more storage volume because of its higher energy contents. Zuttel [20] has also reviewed $H_2$ storage methods. He presented a brief overview of $LH_2$ storage conditions and characteristics. Eberle et al. [21] also reviewed $H_2$ storage methods. They also presented a brief overview of $LH_2$ storage conditions and insulation characteristics. Moreover, Durbin and Malardier-Jugroot [22] reviewed $H_2$ storage in automobiles. They determined that the main challenge in $LH_2$ automobile storage is controlling boil-off losses. Sharma and Ghoshal [23] reviewed the $H_2$ supply chain, including $LH_2$ storage and transportation. They also summarized challenges associated with $H_2$ and its utilization. Qiu et al. [24] reviewed storage materials for $LH_2$ storage. Stainless steel is widely employed for cryogenic storage tanks [24]. Abdalla et al. [25] briefly explained $LH_2$ storage and transportation and its associated challenges. Furthermore, Andersson and Gronkvist [26] investigated the potential of large-scale storage for $H_2$. They determined that large $LH_2$ storage is an energy-intensive process (6.0 kWh/kg $H_2$) compared to other storage options. Zhang et al. also reviewed $H_2$ liquefaction processes and $LH_2$ storage. They discussed materials used in $LH_2$ storage, insulation types, and its associated challenges. Yatsenko et al. reviewed insulation types and materials for $LH_2$ storage [27]. Aziz [28] recently published a paper reviewing $H_2$ liquefaction, storage, transportation, and safety. He analyzed $LH_2$ storage in detail, considering boil-off losses through sloshing during transportation. Similarly, a few review papers have recently been published presenting a brief overview of $LH_2$ storage methods [29–31].

It has been determined from the literature reviews of review papers that most authors have mainly focused their investigations on $LH_2$ storage conditions, insulation schemes, and boil-off losses. The investigation of $LH_2$ characteristics, the latest research on $LH_2$ storage tanks, and techno-economic analysis are still lacking. This review paper fulfills this knowledge gap by providing a detailed literature review (including reports, patents, and conceptual studies) of $LH_2$ storage and analyzing $LH_2$ storage from a techno-economic perspective. Further, this study shortlists challenges and future directions for process engineers and academic researchers. This review is first-of-its-kind, focusing solely on $LH_2$ storage and prospects.

## 2. Liquid Hydrogen Characteristics

Pure $H_2$ can be stored in gaseous or liquid form [32]. At ambient conditions, $H_2$ exists in gaseous form and the lower heating value (LHV) on a volume basis at these conditions is quite low i.e., 0.01 MJ/L because of the very low density of $H_2$ (0.084 kg/m$^3$) [33]. The pressure of $H_2$ gas is increased up to 690 or 700 bar to increase its density or LHV [33]. At 700 bar, the LHV of compressed gaseous $H_2$ ($CGH_2$) is 4.8 MJ/L with a density of

40.2 kg/m$^3$ [33]. In the case of $LH_2$ (−253 °C and 1 bar), the LHV and density is 8.5 MJ/L and 70.9 kg/m$^3$, respectively [33]. The LHV and density of $LH_2$ are almost double that of $CGH_2$. This shows that $LH_2$ storage is more beneficial in terms of storing more volume compared to $CGH_2$.

The comparison of the basic properties of $CGH_2$ and $LH_2$ is presented in Table 1. These properties are extracted from Aspen Hysys [34] using the Modified Benedict Webb Rubin (MBWR) equation of state as a thermodynamic package [4]. MBWR is a well-known property package and has been widely used for $H_2$ process simulations [4].

**Table 1.** Properties comparison of $CGH_2$ and $LH_2$.

| Properties | $CGH_2$ | $LH_2$ |
|---|---|---|
| Temperature | 25 | −253 |
| Pressure (bar) | 690 | 1 |
| o-$H_2$/p-$H_2$ | 0.75/0.25 | 0.01/0.99 |
| Mass Density (kg/m$^3$) | 38.88 | 70.94 |
| Molar density (kgmole/m$^3$) | 19.29 | 35.19 |
| Mass enthalpy (kJ/kg) | 4639 | −250.2 |
| Mass entropy (kJ/kg°C) | 43.33 | 8.25 |
| Heat of vaporization (kJ/kg) | - | 445.8 |
| Specific Volume (m$^3$/kgmole) | 0.052 | 0.028 |

Table 1 displays the difference in properties of $CGH_2$ and $LH_2$ in storage. The density of $LH_2$ is higher than $CGH_2$ whereas the enthalpy and entropy are lower, mainly because of the very low temperature of $LH_2$. Further, the lower specific volume of $LH_2$ (i.e., 0.028 m$^3$/kgmole) indicates that there is more space to store $H_2$; whereas in the case of $CGH_2$, the higher specific volume (0.052 m$^3$/kgmole) means there is less storage space. This confirms the importance of storing pure $H_2$ in liquid form as opposed to gas.

### *2.1. Ortho-to-Para Conversion*

The $H_2$ molecule exists in two different isomers, i.e., ortho $H_2$ (o-$H_2$) and para $H_2$ (p-$H_2$). The difference between these isomers is the direction of its nuclei spin, resulting in different properties, as shown in Figure 1.

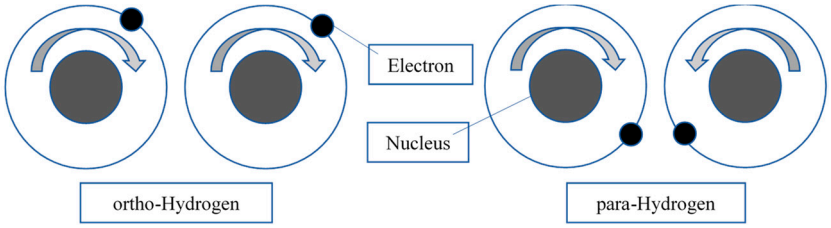



**Figure 1.** Schematic of o-$H_2$ and p-$H_2$ [5,35].

At 25 °C, molecular $H_2$ consists of 75% o-$H_2$ and 25% p-$H_2$, both with opposite nuclei directions [36]. These isomers of $H_2$ have different rotational energies, with o-$H_2$ at the higher energy level. The equilibrium between the two states is temperature-dependent and shifts toward 100% p-$H_2$ as the temperature decreases to −253 °C. This shifting of equilibrium is called ortho-to-para conversion (OPC). The enthalpy of OPC is approximately 527 kJ/kg, and the heat of vaporization of p-$H_2$ is approximately 447 kJ/kg (see Figure 2) [37]. This exothermic enthalpy of conversion is an additional duty that enhances the total reversible work by approximately 15% [38]. This OPC is of vital importance from the perspective of long-term $LH_2$ storage.

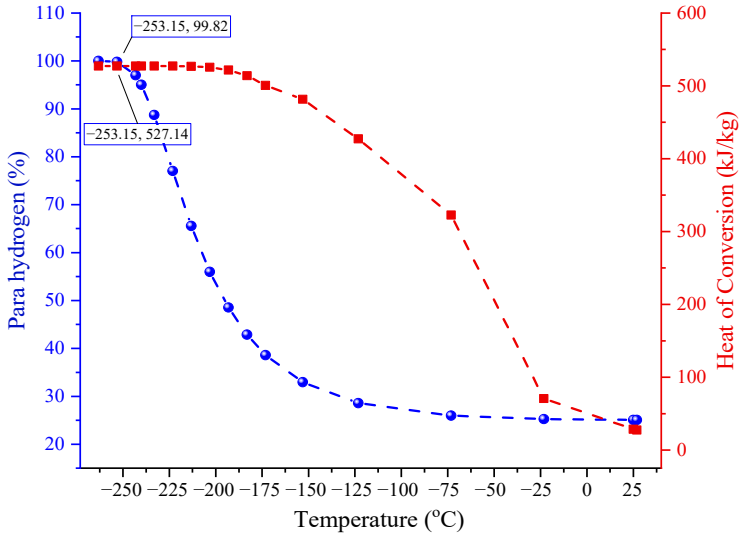



**Figure 2.** OPC and the corresponding heat of conversion to temperature [37].

The OPC in the absence of a catalyst is a second-order reaction [39]. This mode of conversion can also be termed as self-conversion. The rate of conversion is written as (Equation (1)):

$$dx_{ortho}/dt = -K_2 x_{ortho}^2 \quad (1)$$

where $x_{ortho}$ is the mole fraction of o-$H_2$, $K_2$ is the second-order reaction rate constant, and $t$ is the time. If the catalyst is introduced in the OPC, the reaction will approach the first-order reaction for the gaseous phase. The rate of conversion in this case will be (Equation (2)):

$$dx_{ortho}/dt = -K_1 x_{ortho} \quad (2)$$

where $K_1$ is the first-order reaction rate constant. Similarly, the reaction will approach zero-order reaction rate when the catalyst is added in the liquid phase (Equation (3)):

$$dx_{ortho}/dt = -K_0 \quad (3)$$

where $K_0$ is the zero-order reaction rate constant. The second-order reaction rate constant ($K_2$) is equal to 0.0114 $h^{-1}$ [39]. In this case, the time ($t$) required to convert 75% o-$H_2$ can be calculated as (Equation (4)):

$$t = 1/0.0114\left(1/x_{o-H2} - 1/0.75\right) \quad (4)$$

For example, it takes approx. 2 months to convert 75% o-$H_2$ to 5% o-$H_2$ which is a very slow process [39]. Therefore, the OPC is done catalytically to support long-distance transportation or the long-term storage of $LH_2$. (This can also be seen in Figure 3.)

Figure 3 shows the amount of liquid remaining in the storage tank after a certain time with and without OPC. At 80% p-$H_2$ (20% o-$H_2$), the amount of liquid remaining is higher than when compared to the lower percentages of p-$H_2$. Figure 3 demonstrates the necessity of OPC in $LH_2$ storage [39].

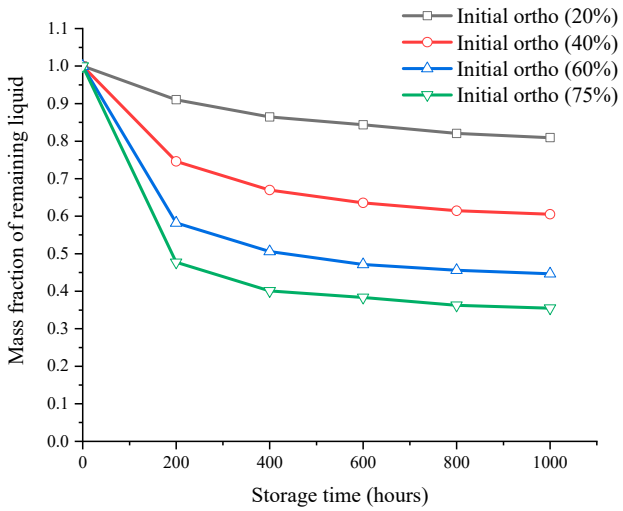



**Figure 3.** Amount of liquid remaining with the passage of time at different o-$H_2$ concentrations [39].

### *2.2. Boil-Off Losses*

Boil-off is the continuous but slow evaporation of liquified gas. Typically, boil-off occurs in the storage tank after exchanging heat with the environment. This boil-off results in a pressure increase inside the storage tank and a loss of liquified gas. In the case of $LH_2$, the boil-off losses are very critical and important, mainly because of the very low temperature (−253 °C) and high energy requirement for $LH_2$ production [40]. The energy consumption for $LH_2$ production is estimated to be 11% of its energy content (i.e., lower heating value (120 MJ/kg)) [5]. At this very low temperature, a small amount of heat exchange will lead to boil-off losses. For typical gases (e.g., carbon dioxide and natural gas), boil-off mainly occurs due to heat leaks, sloshing, and flashing, whereas in the case of $LH_2$, OPC also plays an important role in these boil-off losses.

Heat leaks typically occur due to temperature difference between the liquified gas and its surroundings. This can be minimized by insulating the storage tank or remodeling the storage tank (such as integrated with an refrigeration system) [41]. In addition, the selection of storage tank material plays an important role. The details of storage tank materials are provided in the forthcoming sections. Moreover, sloshing in a liquid storage tank also plays an important role in increasing boil-offs due to the increase in temperature and pressure inside the tank. Typically, sloshing occurs in the moving tank due to the movement of the liquid. The sloshing can be reduced by introducing baffles inside the storage tank, which dissipates the kinetic energy of the fluid. Furthermore, the transfer of $LH_2$ from a high-pressure storage tank (2.4–2.7 bar) to a low-pressure storage tank (1.2 bar) results in vaporization and boil-offs [42]. Storing and transporting $LH_2$ at low pressure can avoid the phenomenon of flashing. Another important factor in boil-offs in $LH_2$ is OPC. As described earlier, OPC is a temperature-dependent equilibrium conversion, and any temperature change will disturb the equilibrium, which will change the $LH_2$ composition and also release the conversion heat. Therefore, the temperature of $LH_2$ should be kept low (~−253 °C) to avoid composition change and boil-off losses.

## 3. Liquid Hydrogen Storage

Storage of $LH_2$ is a complex and challenging process mainly because of the very low temperature requirements (−253 °C) and OPC. $LH_2$ storage has versatile applications [43]. The $LH_2$ storage can be divided into two categories based on its application: stationary storage and mobile storage. Stationary storage includes large-sized storage tanks, especially present at the site of liquefaction plants or space shuttle programs. Mobile storage of $LH_2$ includes small-sized storage tanks, usually used to transport $LH_2$ via trucks or tankers [44]. The applications of $LH_2$ storage vary based on needs, but the important aspect is the storage of high density $H_2$ [45]. Several studies have been published to investigate $LH_2$ storage

from different perspectives, such as OPC in storage conditions, insulation materials, BOG, and the mobilization of $LH_2$ [24,46,47]. Section 3.1 presents a brief discussion of storage tank insulation and materials, whereas Section 3.2 discusses published reports, conceptual studies, and patents related to $LH_2$ storage.

### *3.1. Storage Tank Insulation and Materials*

$LH_2$ storage tanks are critically designed to minimize boil-off losses and maximize the liquified gas in the tank [46,48]. The most common design is double-walled with a vacuum in between these walls. This design reduces heat transfer from the outside and thus minimizes boil-off losses. For example, Kawasaki Heavy Industries, Ltd. (Tokyo, Japan) recently completed the Kobe $LH_2$ Terminal (Hy touch Kobe), the world's first liquefied hydrogen receiving terminal. The Kobe $LH_2$ Terminal consists of a 2500 $m^3$ spherical liquefied hydrogen storage tank with a capacity of 2250 $m^3$ [49]. The tank features a double-shell vacuum-insulation structure, comprising inner and outer shells with a vacuum-sealed layer in between to prevent heat transfer from the outside. Additionally, the tank adopts a spherical design, which is the optimal shape for reducing heat transfer. In some designs, the space between walls is filled with materials (such as aluminum and silica) to minimize any heat transfer through radiations. In addition, the selection of material for storage tank walls is very important, especially in terms of heat capacity and thermal conductivity. Many different materials have been investigated in terms of their ability to withstand the $LH_2$'s extremely low boiling point. For instance, stainless steel is a commonly employed material for low-temperature $LH_2$ storage [27]. However, hydrogen embrittlement is a common issue associated with the use of stainless steel. Stainless steel of different grades has also been tested to evaluate its resistance against embrittlement [24]. Similarly, aluminum can be used for $LH_2$ storage tanks due to its low sensitivity to embrittlement and high specific strength [24]. In addition, titanium and composite materials can also be employed as materials for storage tanks [24,28].

Similarly, insulation plays an equally important role in $LH_2$ storage tank design. There are different types of insulations based on their thermal conductivity (k value) and heat resistance performance. The Table 2 below shows types the pros and cons of different insulation materials used for $LH_2$ storage tanks. Typically, perlite vacuum insulation is used for $LH_2$ storage tanks.

**Table 2.** $LH_2$ storage tank insulations and their characteristics [50].

| Insulation Type | k-Value (300–77 K) W/mK | Pros | Cons |
|---|---|---|---|
| Insulation at atm pressure | 0.020–0.050 | Low weight<br>Inexpensive | High heat load |
| Perlite at $10^{-2}$ mbar | 0.001 | Good performance<br>Standard technology | Needs strong vacuum<br>Heavy structure |
| Multilayer insulation at $10^{-4}$ mbar | $6.5 \times 10^{-6}$–$1.0 \times 10^{-4}$ | Excellent performance | Needs strong vacuum<br>Heavy structure<br>Expensive |

The above table shows that MLI is excellent in reducing boil-off losses (up to 0.01–0.05%/day [50]). MLI is composed of several layers of low-emissivity material with free-volume spaces. MLI is considered the most efficient insulation scheme in cryogenic systems, exhibiting minimal boil-off losses [51]. It consists of multi-layers of reflective materials such as aluminum foil or low conductivity material like fiberglass under high vacuum.

The insulation process can be divided into two types based on thermal protection: passive thermal protection and active thermal protection [44]. Passive thermal protection employs materials such as spray-on foam insulation, fiber-reinforced plastic, aerogel, and

glass bubbles in combination with MLI to reduce heat losses. These materials exhibit low thermal conductivity and good thermal resistance. Further, these materials can be stacked by wrapping materials on the surface of the storage tank and/or can be used in powder form as a filling in the insulation area. Table 3 shows the thermal conductivity and density of common materials [44].

**Table 3.** Thermal conductivity and density of common insulation materials (Reprinted/adapted with permission from [44], 2024, Elsevier Ltd).

| Insulation Material | Density ($kg/m^3$) | k-Value (W/mK) |
|---|---|---|
| **Stacked insulation material (77 K–300 K)** | | |
| Polyurethane | 11 | 0.033 |
| Polystyrene | 39, 46 | 0.026–0.033 |
| Rubber | 80 | 0.036 |
| Silicon | 160 | 0.055 |
| Glass | 140 | 0.035 |
| **Stacked insulation material (90 K–300 K)** | | |
| Perlite | 50, 210 | 0.026–0.044 |
| Aerogel | 80 | 0.019 |
| Vermiculite | 120 | 0.052 |
| Glass fiber | 110 | 0.025 |
| Mineral wool | 160 | 0.035 |
| **Vacuum powder insulation material (77 K–300 K)** | | |
| Perlite | 64, 180 | 0.00095–0.00019 |
| Aerogel | 80 | 0.0016 |
| Glass fiber | 50 | 0.0017 |

Moreover, active thermal protection is the technology utilizing cryogenic chillers to re-condense the evaporated vapors and utilize them to reduce heat transfer and avoid boil-off. This technology provides superior performance and can be used alongside passive thermal protection to provide a better insulation performance. NASA is working on developing and utilizing active and passive thermal protection to minimize boil-offs. For active insulation, an internal refrigeration and storage (IRAS) system can be introduced utilizing helium as a refrigerant and for passive insulation. Glass bubbles have also been assessed as a potential insulation material, exhibiting a better performance than perlite powder [44].

### *3.2. Literature Review*

In this section, a literature review is categorized based on reports, conceptual studies, and patents.

#### 3.2.1. Bibliometric Analysis

The bibliometric analysis of $H_2$ storage was conducted through a Scopus document search [52]. Bibliometric analysis is an efficient tool to analyze research trends in a specific research field. These research trends depict the importance of certain research areas. In this case, the target was to analyze research trends in $LH_2$ storage solutions. To do that, a comprehensive bibliometric analysis was conducted. In the document search, the following keywords were selected: hydrogen storage, hydrogen storage capacities, hydrogen storage materials, hydrogen storage system, liquid hydrogen storage, liquid hydrogen tank. The irrelevant keywords were excluded from the search. This document search resulted in

2594 documents, mainly comprised of articles (1731), conference papers (506), reviews (258), and book chapters (84). These results are shown in Figure 4.

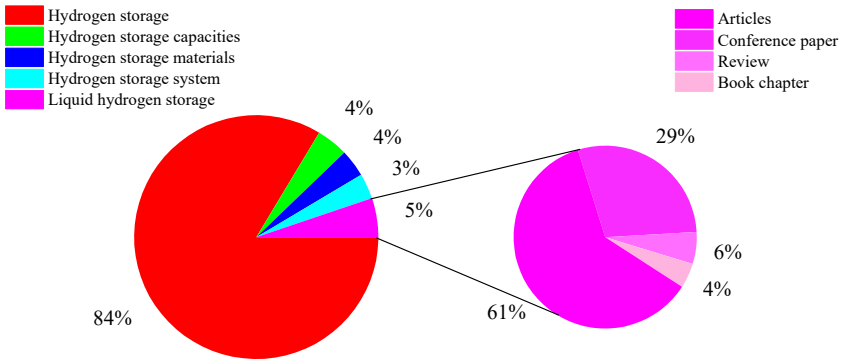



**Figure 4.** Bibliometric analysis results for keyword search: Hydrogen storage, Hydrogen storage capacities, Hydrogen storage materials, Hydrogen storage system, Liquid hydrogen storage, Liquid hydrogen tank.

These results show that the authors mainly used "Hydrogen storage" as a keyword. Nevertheless, this keyword included all kinds of hydrogen storage such as $GH_2$ storage, storage materials, and capacities. To further narrow down the search, the keyword, "Liquid hydrogen storage" was selected. This search showed 159 documents in total, comprising 97 articles (61%), 46 conference papers (29%), 9 reviews (6%), and 7 book chapters (4%). This analysis was further expanded to evaluate the trend of year-wise research in this subject area (see Figure 5).

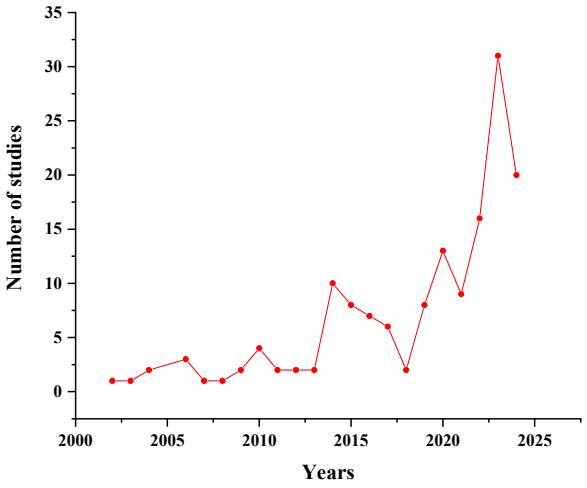



**Figure 5.** Year-wise trend of studies published related to the keyword: Liquid hydrogen storage.

The trend shows that a major boom in the research of $LH_2$ storage has been seen post-2014. This trend is increasing which shows the increasing interest of researchers in developing efficient $LH_2$ storage. Furthermore, this research has mainly been conducted in the research areas of energy and engineering, as can be seen in Figure 6.

Figures 5 and 6 demonstrate research trends and the focus of researchers in $LH_2$ storage research. It can be seen that in recent years, the key focus of researchers has been to improve the energy efficiency of storage by improving the design and tank materials. The main target of researchers is to develop energy-efficient $LH_2$ storage systems. The other research areas include research for space applications, material development, and environmentally friendly applications.

In conclusion, the bibliometric analysis provides an important outlook of importance and current research trends in the field of $LH_2$ storage.

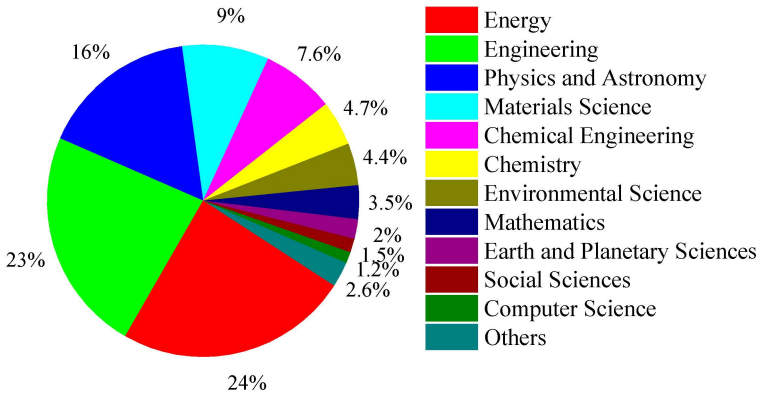



**Figure 6.** Research areas of the research conducted using the keyword: Liquid hydrogen storage.

### 3.2.2. Reports

NASA is the major player in $LH_2$ storage. The world's largest $LH_2$ storage tank belongs to NASA, with a storage capacity of 4732 $m^3$, increasing the total storage capacity to 7950 $m^3$ [53]. The new storage tank is more advanced and efficient regarding the low boil-off rate. The maximum boil-off rate is <1.0% [54], which is much less than that of the old storage tank (>1.0% [50]). The old $LH_2$ storage tank is vacuum jacketed with perlite as insulation. In the new storage tank, a more advanced control system is applied, i.e., a glass bubbles insulation system for passive thermal control and IRAS for active thermal control. The glass bubbles have been proven to be more efficient than perlite, with an associated 44% reduction in boil-off rate [55]. The IRAS system employs a refrigeration system that constantly applies cold energy of helium to stored $LH_2$ in order to minimize the boil-off rate. Figure 7 shows a comparison of an ordinary and an IRAS system storage tank.

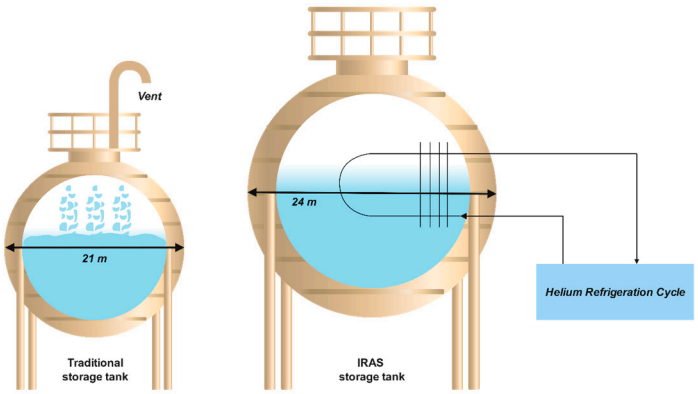



**Figure 7.** Comparison of ordinary and IRAS system storage tanks.

In addition, Kawasaki has developed $LH_2$ storage tanks for JAXA (a Japanese space exploration company) with a storage capacity of 540 $m^3$ and 2250 $m^3$ [56]. Kawasaki has also designed another vacuum-sealed $LH_2$ tank with a storage capacity of 10,000 $m^3$ with a boil-off rate of 0.1% [57]. Similarly, Linde has also developed both small and large-scale storage tanks with a capacity of up to 300 $m^3$ [58]. In addition, NASA also worked on developing efficient insulation systems for $LH_2$ storage tanks [59,60]. The NASA team conducted tests and modeling to study the performance of MLI under different temperature conditions [61]. Similarly, Johnson at NASA [60] worked on optimizing layer densities for MLI systems. He calculated a critical layer density and validated it against test data from a $H_2$ testbed.

### 3.2.3. Conceptual Studies

Several conceptual studies have been published investigating the potential of $LH_2$ storage conditions, tank structure, tank, and insulation materials [62–65].

For instance, Qiu et al. [24] thoroughly reviewed cryogenic materials for $LH_2$ storage and transportation. They concluded that stainless steel is the most common material for storage tanks; however, there are certain issues with stainless steel such as $H_2$ embrittlement [24]. Alloys and composite materials can also be used for tank material. Park et al. studied the mechanical behavior of stainless steel at low temperatures and concluded that the materials are dependent on temperature and strain rate [66]. Similarly, Shultz studied the mechanical, thermal, and electrical properties of composite materials for cryogenic applications [67]. Horiuchi and Ooi [68] also studied the cryogenic properties of composite materials. They investigated carbon fiber-reinforced plastics, aluminum oxide fiber-reinforced plastics, and silicon carbide fiber-reinforced plastics [68]. Further, alloys have also been investigated by researchers and their applications in $H_2$ storage [69,70].

Zheng et al. [71] studied insulation schemes for $LH_2$ storage tanks. They introduced a self-evaporation vapor-cooled shield insulation scheme and compared its performance with other insulation schemes. Similarly, Jiang et al. [72] studied the multi-layer and vapor-cooled shield insulation schemes for $LH_2$ storage tanks. Kang et al. [73] studied $LH_2$ storage tank conditions and insulation schemes for locomotives. They also performed a dynamic study to analyze the effects of structure and insulation systems on boil-off losses. Furthermore, Xu et al. [13] studied the thermal and structural performance of $LH_2$ storage tanks for aerospace applications. They suggested improvements in the support structure of the tank by introducing a point-contact storage support structure, which can reduce heat leakage by 85%. Krenn [74] investigated the abnormal performance of a $LH_2$ storage tank after an increase in boil-off rate. His investigation concluded that this high boil-off was due to a void in perlite filling in the tank, which was later filled [74]. Choi et al. [75] analyzed $LH_2$ tanks in heavy duty trucks based on ISO 13985 standard [76]. The purpose of their study was to analyze the safety of $LH_2$ storage on trucks with respect to structural and thermal performance [75]. Similarly, Ustolin et al. [77] conducted a critical review considering the safety of $H_2$ in the $H_2$ lifecycle. Their review includes the behavior of material such as embrittlement, thermal contraction, and thermal stresses under low-temperature conditions. Fesmire studied the insulation system for nonvacuum cryogenic applications [78]. He proposed a layered composite insulation system, which is suitable for complex systems and can insulate $LH_2$ storage tanks [78]. Wang et al. [79] worked on optimizing the variable density of the MLI system and conducted experimental validation. They demonstrated an improvement of 45% and 54% in the performance of variable density MLI [79]. Yanxing et al. [80] provided a detailed thermodynamic analysis of pure $H_2$ storage. They analyzed the storage density/power consumption for $CGH_2$ storage, cryo-compressed $H_2$ storage, and $LH_2$ storage. According to their analyses, cryo-compressed $H_2$ storage is more advantageous the $LH_2$ storage from a storage density/power consumption perspective [80].

#### 3.2.4. Patents

There are also a few patents published in the field of $LH_2$ storage tanks. Brooks et al. [81,82] patented technologies for cryogenic $LH_2$ storage tanks for aerospace applications. They proposed a cryogenic tank to minimize boil-off losses at high-altitude applications. Similarly, Immel et al. [83] patented a technology that includes a storage tank for $LH_2$. The invention includes a tank that utilizes a common access vacuum tube for different fluid lines in order to minimize obstruction for insulation layers. In another patent, Immel et al. [84] invented a method to suspend the inner tank within the outer tank in order to improve the performance of the cryogenic storage tank. Similarly, Pechtold invented cryogenic storage tank technology to minimize losses during the refilling of $LH_2$ [85]. There are also several other patents published with similar perspectives [86–90].

It has been determined from the literature review (including reports, conceptual studies, and patents) that most studies have focused on analyzing insulation schemes to improve the performance of $LH_2$ storage tanks.

### *3.3. Techno-Economic Analysis*

In this section, the storage of $LH_2$ is evaluated from a technical and economic perspective. The main technical aspect of $LH_2$ storage is the behavior of $H_2$ with respect to temperature and pressure. Therefore, the Pressure–Volume (PV) and Temperature–Volume (TV) diagrams are drawn to analyze the behavior of $H_2$ at different pressures and temperatures. The PV diagram of $H_2$ at different temperatures is shown in Figure 8.

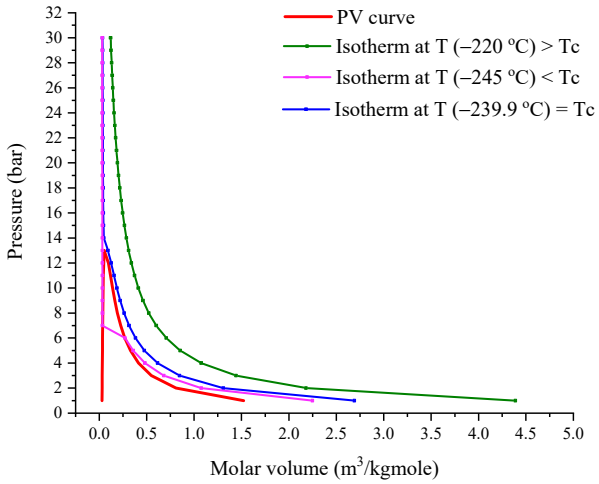



**Figure 8.** PV diagram and isotherm curves drawn from Aspen Hysys employing MBWR EOS.

Figure 8 shows the behavior of $H_2$ at a temperature above the critical temperature (Tc) i.e., −220 °C, below Tc (−245 °C), and equal to Tc (−239.9 °C). $H_2$ above Tc shows no change in phase no matter how much the pressure is increased. However, $H_2$ at Tc shows a change in phase at approx. 6 bar and will remain liquid until the critical pressure (Pc) is reached. A further increase in pressure will lead to a super-critical phase. Similarly, an increase in pressure of $H_2$ gas at Tc (the blue line) shows a similar behavior to the dew point curve. This shows that the $H_2$ at Tc will not liquefy no matter how much pressure is increased.

Moreover, the TV diagrams are also drawn for $H_2$. These TV diagrams show the change in volume of $H_2$ when the temperature is reduced from atmospheric conditions (25 °C) to storage conditions (−253 °C). It must be noted that the TV diagram is drawn using data extracted from Aspen Hysys, whereas the MBWR EOS is used to calculate the $H_2$ properties [6]. Figure 9 shows a TV diagram of $H_2$ and isobars at different pressures.

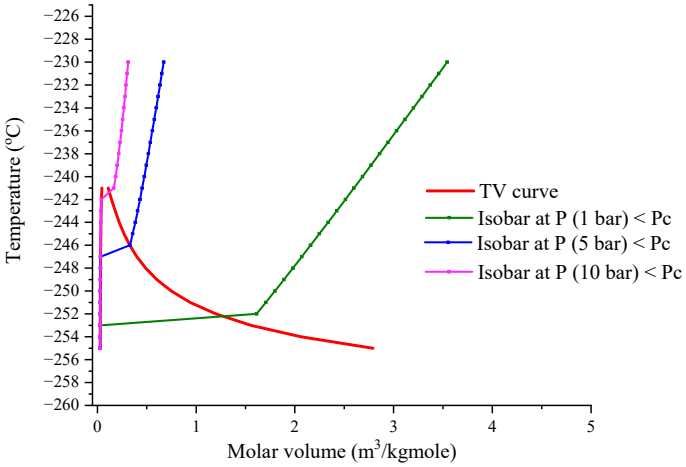



**Figure 9.** TV diagram and isobaric curves drawn from Aspen Hysys employing MBWR EOS.

Figure 9 shows the trend of isobaric curves at different pressures (1 bar, 5 bar, and 10 bar). The considered pressure values are below the critical pressure of $H_2$ (12.8 bar). The isobar at 5 and 10 bar shows a very sharp slope, which means that the volume of $H_2$ is low even at higher temperatures. At atmospheric pressure, the volume of $H_2$ gas is large at higher temperatures. When the temperature is reduced, the volume of $GH_2$ is reduced to the point that $GH_2$ is completely liquefied. To understand the change in volume at different temperatures, Figure 10 is drawn at pressures 1 bar and 10 bar.

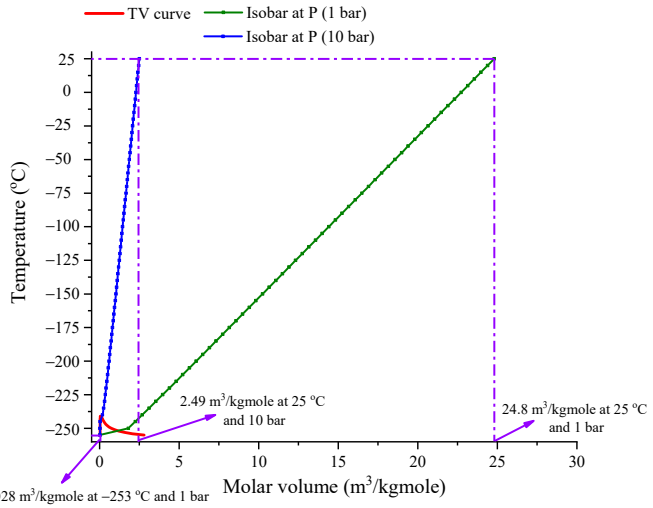



**Figure 10.** TV diagram and isobaric curves are drawn from Aspen Hysys employing MBWR EOS showing volume at atmospheric and storage conditions.

Figure 10 shows that the volume of $H_2$ at 25 °C and 1 bar is 24.8 $m^3$/kgmole. When the temperature is reduced, the volume is reduced linearly till the dew point is reached. At this point, the volume of $H_2$ is approx. 1.5 $m^3$/kgmole. The heat is further removed from the $H_2$ to attain complete liquefaction (till bubble point). The volume of $H_2$ is reduced to 0.028 $m^3$/kgmole when temperature is reduced from 25 to −253 °C. The total change in volume is 24.77 $m^3$/kgmole. This shows that the volume of $H_2$ is reduced 870 times upon liquefaction. This volume reduction is significant compared to conventional fuel (i.e., LNG).

Another important parameter in $LH_2$ storage is the cost of the storage tank. There are many factors that influence $LH_2$ storage tank costs, such as technological advancements, initial investment costs, operating costs, material costs, and maintenance costs. $LH_2$ storage tanks require high heat resistive material that can withstand extremely low temperatures (<−252 °C). These specialized materials have high material and investment costs. High-strength materials and advanced designs like double-walled tanks can also increase the cost. In addition, tank insulation is critical in cryogenic storage. Vacuum or multi-layer insulation significantly adds to the cost. At NASA, Fesmire et al. [91] studied the costs of insulation materials. They compared the costs of perlite powder, glass bubbles, and aerogel beads. Glass bubbles showed the best performance in terms of low thermal conductivity and low boil-off rates. The initial cost of glass bubbles ($ 1.12/$ft^3$) is higher than perlite ($ 2.13/$ft^3$); however, the boil-off costs of glass bubbles are significantly lower (approx. 80%) than the cost of perlite [91]. Further, operating costs play a major role in the overall lifetime costs. Maintenance, replacement, and refurbishment costs increase operating costs.

NREL reported some costs of $LH_2$ storage tanks at different capacities [92]. These costs are shown in Table 4.

**Table 4.** Costs of $LH_2$ storage tanks at different sizes provided by NREL [92].

| Size (kg) | Cost/kg ($/kg) * |
|---|---|
| 8.9–890 | 21–36 (43–74) |
| 0.089–8.9 | 490–700 (1011–1444) |
| 270 | 450 (929) |
| 300,000 | 18 (37) |

* These costs are according to 1995 USD which is converted to the 2024 USD rate (shown in brackets) 1$ (1995) = 2.06 $ (2024).

The values in Table 4 show that larger tanks can be more cost-effective than smaller ones. However, these costings are old, and a lot of technological advancements have been carried out since then. Furthermore, the costs vs. capacity analysis has been carried out using Aspen Hysys and Aspen Process Economic Analyzer (APEA) [34]. In Aspen Hysys, a spherical $LH_2$ (at −253 °C and 1.3 bar) storage tank is simulated, and costs are calculated in APEA. SS304 was selected as a tank material in the analysis. Figure 11 shows the costs of these large-sized tanks at different storage volumes.

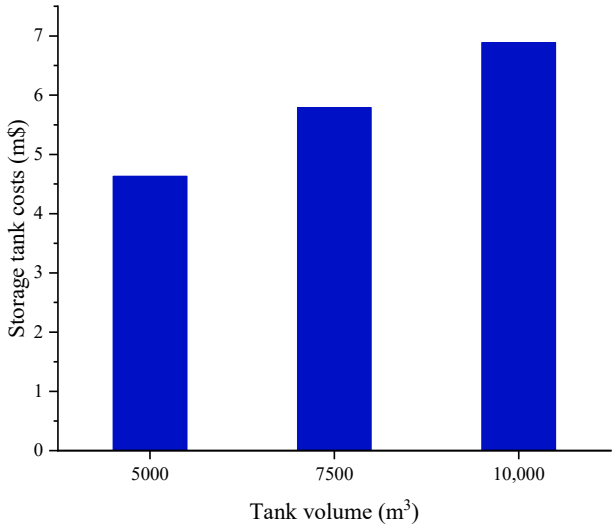



**Figure 11.** $LH_2$ storage tank costs at different capacities calculated by Aspen Hysys and APEA.

It can be seen from Figure 11 that as the capacity increases (5000 $m^3$ to 10,000 $m^3$), the costs of the storage tank increases from 4.6 m$ to 6.8 m$. This increase in cost is mainly because as the tank volume increases, the size of the tank increases, which leads to higher equipment costs. These costs do not include the cost of insulation and auxiliary equipment.

## 4. Challenges and Future Directions

$LH_2$ storage is a critical and challenging issue. The major challenges in $LH_2$ storage are summarized below:

- Insulation plays a key role in keeping $LH_2$ at −253 °C. Commercial $LH_2$ tanks employ perlite insulation with a vacuum to limit the boil-off rate by 1.0% per day. However, this boil-off rate is quite high and needs to be reduced.
- OPC heat of conversion (527 kJ/kg) is higher than heat of vaporization (447 kJ/kg), which leads to a larger heat load and a high boil-off rate. To control and reduce boil-off, a large amount of energy is required. Minimization of this energy is critical for cost-effective $LH_2$ storage.
- Storage at −253 °C requires highly sophisticated equipment and design. In addition, a large amount of energy is required to keep $LH_2$ at −253 °C. The design, equipment,

refrigeration, energy, and other necessities of the $LH_2$ storage tank are cost-intensive. Reducing this cost will be essential for effective long-term $LH_2$ storage.

- During the transportation of $LH_2$, the boil-off rate increases due to sloshing and splashing. To minimize this, the design of the storage tank should be suitable enough to control the pressure built inside the storage tank.
- To improve the energy efficiency of $LH_2$ storage, the design and structure of the storage tank can be improved. The application of an internal integrated refrigeration system (IIRS) by NASA is an attempt in this regard. However, it is very challenging to devise an improvement owing to insulation requirements and low-temperature storage.
- The challenges associated with $LH_2$ storage including tank geometry, tank material, $H_2$ embrittlement, permeation, and process safety must be addressed.

The importance of $LH_2$ storage cannot be denied; however, there are several challenges and limitations for energy-efficient and cost-effective storage. To meet these challenges, future directions and policy implications are listed below:

- Academia and industry are both pillars for the improvement and commercialization of any process. The cooperation of academic and industry research needs to be further strengthened. This can be done by establishing joint research programs to utilize the research expertise of academic researchers and to apply the expertise of industries in commercializing the technology.
- The detailed techno-economic assessment of storage tanks must be considered to compare alternatives with respect to cost and efficiency.
- The energy-efficient $LH_2$ storage can be a game changer. Therefore, government policies and resources should be diverted towards research and applications of $LH_2$ storage.
- Further, research on minimizing and utilizing boil-off losses has to be focused on, and alternatives must be considered. In addition, the research on minimizing the boil-off losses in automobile applications requires further consideration. Similarly, more work needs to be done regarding the insulation of the $LH_2$ storage tank. The studies can focus on insulation materials, insulation types, and their integration with internal refrigeration systems.
- It is necessary to develop a lightweight, compact, strong storage tank.

## 5. Conclusions

Storage of $LH_2$ has become an essential part of the $H_2$ supply chain. This review provides a comprehensive overview of $LH_2$ storage methods by considering reports, conceptual studies, and patents of $LH_2$ storage. This review further analyzes $LH_2$ properties, $LH_2$ behavior at different temperatures and pressures, and the economics of $LH_2$ storage. The conclusions of this study are listed below:

- Owing to its very low liquefaction temperature and ortho-para conversion, the storage of $LH_2$ is critical and challenging.
- Reducing the boil-off rate is an essential and critical part of $LH_2$ storage.
- Improvements in tank insulation can reduce boil-off losses.
- Multi-layer insulation with an internal refrigeration system can reduce boil-offs and improve $LH_2$ storage.
- Utilization of boil-offs can help with the design of efficient storage systems.
- The boil-offs can be used to exchange cold energy and produce power using a small-scale fuel scale.
- Reducing boil-offs during $LH_2$ transportation must be urgently addressed.
- The energy-efficient and cost-effective design of the storage tank is an essential part of the $H_2$ supply chain.
- The economics of $LH_2$ storage can be improved by developing heat-resistive material that can withstand very low temperatures.

**Author Contributions:** Conceptualization, A.N.; methodology, A.N.; formal analysis, A.N.; investigation, A.N.; writing—original draft preparation, A.N.; writing—review and editing, N.A.; visualization, N.A.; Conceptualization and supervision, M.L.; funding acquisition, M.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the National Research Foundation of Korea (NRF), grant funded by the Korea government (MSIT) (2021R1A2C1092152).

**Data Availability Statement:** Data is unavailable due to privacy or ethical restrictions.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Stetson, N.T.; McWhorter, S.; Ahn, C.C. Introduction to hydrogen storage. In *Compendium of Hydrogen Energy*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 3–25. [CrossRef]
2. Peschel, A. Industrial Perspective on Hydrogen Purification, Compression, Storage, and Distribution. *Fuel Cells* **2020**, *20*, 385–393. [CrossRef]
3. Naquash, A.; Riaz, A.; Lee, H.; Qyyum, M.A.; Lee, S.; Lam, S.S.; Lee, M. Hydrofluoroolefin-based mixed refrigerant for enhanced performance of hydrogen liquefaction process. *Int. J. Hydrogen Energy* **2022**, *47*, 41648–41662. [CrossRef]
4. Naquash, A.; Riaz, A.; Qyyum, M.A.; Kim, G.; Lee, M. Process knowledge inspired opportunistic approach for thermodynamically feasible and efficient design of hydrogen liquefaction process. *Int. J. Hydrogen Energy* **2022**, *48*, 26583–26598. [CrossRef]
5. Valenti, G. Hydrogen liquefaction and liquid hydrogen storage. In *Compendium of Hydrogen Energy Volume 2: Hydrogen Storage, Transportation and Infrastructure*; Gupta, R.B., Basile, A., Veziroğlu, T.N., Eds.; Woodhead Publishing: London, UK, 2016; pp. 27–51. [CrossRef]
6. Riaz, A.; Qyyum, M.A.; Hussain, A.; Lee, M. Significance of ortho-para hydrogen conversion in the performance of hydrogen liquefaction process. *Int. J. Hydrogen Energy* **2022**, *48*, 26568–26582. [CrossRef]
7. Kang, D.-H.; An, J.-H.; Lee, C.-J. Numerical modeling and optimization of thermal insulation for liquid hydrogen storage tanks. *Energy* **2024**, *291*, 130143. [CrossRef]
8. Jiang, Y.; Yu, Y.; Wang, Z.; Zhang, S.; Cao, J. CFD simulation of heat transfer and phase change characteristics of the cryogenic liquid hydrogen tank under microgravity conditions. *Int. J. Hydrogen Energy* **2023**, *48*, 7026–7037. [CrossRef]
9. Liu, Z.; Li, Y.; Zhou, G. Study on thermal stratification in liquid hydrogen tank under different gravity levels. *Int. J. Hydrogen Energy* **2018**, *43*, 9369–9378. [CrossRef]
10. Liu, Z.; Zhou, G.; Li, Y.; Gao, P. Thermal performance of liquid hydrogen tank in reduced gravity. *Adv. Space Res.* **2018**, *62*, 957–966. [CrossRef]
11. Liu, Z.; Li, Y.; Xie, F.; Zhou, K. Thermal performance of foam/MLI for cryogenic liquid hydrogen tank during the ascent and on orbit period. *Appl. Therm. Eng.* **2016**, *98*, 430–439. [CrossRef]
12. Liu, Z.; Wang, L.; Jin, Y.; Li, Y. Development of thermal stratification in a rotating cryogenic liquid hydrogen tank. *Int. J. Hydrogen Energy* **2015**, *40*, 15067–15077. [CrossRef]
13. Xu, W.; Li, Q.; Huang, M. Design and analysis of liquid hydrogen storage tank for high-altitude long-endurance remotely-operated aircraft. *Int. J. Hydrogen Energy* **2015**, *40*, 16578–16586. [CrossRef]
14. Tang, S.; Zhang, Z.; Xu, L.; Qin, H.; Dong, J.; Lv, Q.; Han, J.; Song, F. Ultrafine nickel-rhodium nanoparticles anchored on two-dimensional vanadium carbide for high performance hydrous hydrazine decomposition at mild conditions. *J. Colloid Interface Sci.* **2024**, *669*, 228–235. [CrossRef]
15. Zhang, Z.; Tang, S.; Xu, L.; Wang, J.; Li, A.; Jing, M.; Yang, X.; Song, F. Encapsulation of ruthenium oxide nanoparticles in nitrogen-doped porous carbon polyhedral for pH-universal hydrogen evolution electrocatalysis. *Int. J. Hydrogen Energy* **2024**, *74*, 10–16. [CrossRef]
16. Yang, X.; Bulushev, D.A.; Yang, J.; Zhang, Q. New Liquid Chemical Hydrogen Storage Technology. *Energies* **2022**, *15*, 6360. [CrossRef]
17. Yang, X.; Ullah, Z.; Stoddart, J.F.; Yavuz, C.T. Porous Organic Cages. *Chem. Rev.* **2023**, *123*, 4602–4634. [CrossRef]
18. Yang, X.; Chen, L.; Liu, H.; Kurihara, T.; Horike, S.; Xu, Q. Encapsulating Ultrastable Metal Nanoparticles within Reticular Schiff Base Nanospaces for Enhanced Catalytic Performance. *Cell Rep. Phys. Sci.* **2021**, *2*, 100289. [CrossRef]
19. Yartys, V.A.; Lototsky, M.V. An Overview of Hydrogen Storage Methods. *Hydrog. Mater. Sci. Chem. Carbon Nanomater.* **2004**, *172*, 75–104. [CrossRef]
20. Züttel, A. Materials for hydrogen storage. *Mater. Today* **2003**, *6*, 24–33. [CrossRef]
21. Eberle, U.; Felderhoff, M.; Schüth, F. Chemical and physical solutions for hydrogen storage. *Angew. Chem.-Int. Ed.* **2009**, *48*, 6608–6630. [CrossRef]
22. Durbin, D.J.; Malardier-Jugroot, C. Review of hydrogen storage techniques for on board vehicle applications. *Int. J. Hydrogen Energy* **2013**, *38*, 14595–14617. [CrossRef]
23. Sharma, S.; Ghoshal, S.K. Hydrogen the future transportation fuel: From production to applications. *Renew. Sustain. Energy Rev.* **2015**, *43*, 1151–1158. [CrossRef]

24. Qiu, Y.; Yang, H.; Tong, L.; Wang, L. Research Progress of Cryogenic Materials for Storage and Transportation of Liquid Hydrogen. *Metals* **2021**, *11*, 1101. [CrossRef]
25. Abdalla, A.M.; Hossain, S.; Nisfindy, O.B.; Azad, A.T.; Dawood, M.; Azad, A.K. Hydrogen production, storage, transportation and key challenges with applications: A review. *Energy Convers. Manag.* **2018**, *165*, 602–627. [CrossRef]
26. Andersson, J.; Grönkvist, S. Large-scale storage of hydrogen. *Int. J. Hydrogen Energy* **2019**, *44*, 11901–11919. [CrossRef]
27. Yatsenko, E.A.; Goltsman, B.M.; Novikov, Y.V.; Izvarin, A.I.; Rusakevich, I.V. Review on modern ways of insulation of reservoirs for liquid hydrogen storage. *Int. J. Hydrogen Energy* **2022**, *47*, 41046–41054. [CrossRef]
28. Aziz, M. Liquid Hydrogen: A Review on Liquefaction, Storage, Transportation, and Safety. *Energies* **2021**, *14*, 5917. [CrossRef]
29. Kurtz, J.; Sprik, S.; Bradley, T.H. Review of transportation hydrogen infrastructure performance and reliability. *Int. J. Hydrogen Energy* **2019**, *44*, 12010–12023. [CrossRef]
30. Rivard, E.; Trudeau, M.; Zaghib, K. Hydrogen Storage for Mobility: A Review. *Materials* **2019**, *12*, 1973. [CrossRef]
31. Abe, J.O.; Popoola, A.P.I.; Ajenifuja, E.; Popoola, O.M. Hydrogen energy, economy and storage: Review and recommendation. *Int. J. Hydrogen Energy* **2019**, *44*, 15072–15086. [CrossRef]
32. Ghorbani, B.; Zendehboudi, S.; Saady, N.M.C.; Duan, X.; Albayati, T.M. Strategies To Improve the Performance of Hydrogen Storage Systems by Liquefaction Methods: A Comprehensive Review. *ACS Omega* **2023**, *8*, 18358–18399. [CrossRef]
33. Valenti, G. *Hydrogen Liquefaction and Liquid Hydrogen Storage*; Elsevier Ltd.: Amsterdam, The Netherlands, 2016. [CrossRef]
34. Aspentech. Aspen HYSYS 2024. Available online: https://www.aspentech.com/en/products/engineering/aspen-hysys (accessed on 18 September 2024).
35. Naquash, A.; Abdul, M.; Min, S.; Lee, S.; Lee, M. Carbon-dioxide-precooled hydrogen liquefaction process : An innovative approach for performance enhancement—Energy, exergy, and economic perspectives. *Energy Convers. Manag.* **2022**, *251*, 114947. [CrossRef]
36. Harkness, R.W.; Deming, W.E. The Equilibrium of Para and Ortho Hydrogen. *J. Am. Chem. Soc.* **1932**, *54*, 2850–2852. [CrossRef]
37. McCarty, R.D.; Hord, J.; Roder, H.M. *Selected Properties of Hydrogen (Engineering Design Data)*; National Engineering Lab. (NBS): Boulder, CO, USA, 1981.
38. Qyyum, M.A.; Riaz, A.; Naquash, A.; Haider, J.; Qadeer, K.; Nawaz, A.; Lee, H.; Lee, M. 100% saturated liquid hydrogen production: Mixed-refrigerant cascaded process with two-stage ortho-to-para hydrogen conversion. *Energy Convers. Manag.* **2021**, *246*, 114659. [CrossRef]
39. Gursu, S.; Lordgooei, M.; Sherif, S.A.; Veziroğlu, T.N. An optimization study of liquid hydrogen boil-off losses. *Int. J. Hydrogen Energy* **1992**, *17*, 227–236. [CrossRef]
40. Ghaffari-Tabrizi, F.; Haemisch, J.; Lindner, D. Reducing Hydrogen Boil-Off Losses during Fuelling by Pre-Cooling Cryogenic Tank. *Hydrogen* **2022**, *3*, 255–269. [CrossRef]
41. Ratnakar, R.R.; Gupta, N.; Zhang, K.; van Doorne, C.; Fesmire, J.; Dindoruk, B.; Balakotaiah, V. Hydrogen supply chain and challenges in largescale LH2 storage and transportation. *Int. J. Hydrogen Energy* **2021**, *46*, 24149–24168. [CrossRef]
42. Morales-Ospino, R.; Celzard, A.; Fierro, V. Strategies to recover and minimize boil-off losses during liquid hydrogen storage. *Renew. Sustain. Energy Rev.* **2023**, *182*, 113360. [CrossRef]
43. Sarangi, S. Cryogenic Storage of Hydrogen. In *Progress in Hydrogen Energy*; Springer: Dordrecht, The Netherlands, 1987; pp. 123–132. [CrossRef]
44. Yin, L.; Yang, H.; Ju, Y. Review on the key technologies and future development of insulation structure for liquid hydrogen storage tanks. *Int. J. Hydrogen Energy* **2024**, *57*, 1302–1315. [CrossRef]
45. Zohuri, B. Cryogenics and Liquid Hydrogen Storage. In *Hydrogen Energy*; Springer International Publishing: Cham, Switzerland, 2019; pp. 121–139. [CrossRef]
46. Mital, S.K.; Ghekenyesi, J.Z. Review of Current State of the Art and Key Design Issues with Potential Solutions for Liquid Hydrogen Cryogenic Storage Tank Structures for Aircraft Applications. 2006. Available online: https://ntrs.nasa.gov/api/citations/20060056194/downloads/20060056194.pdf (accessed on 26 August 2024).
47. Godula-Jopek, A.; Jehle, W.; Wellnitz, J. *Hydrogen Storage Technologies*; Wiley: Hoboken, NJ, USA, 2012. [CrossRef]
48. Krainz, G. Development of Automotive Liquid Hydrogen Storage Systems. *AIP Conf. Proc.* **2004**, *710*, 35–40. [CrossRef]
49. Green Car Congress. Kawasaki Completes World's First Liquefied Hydrogen Receiving Terminal n.d. Available online: https://www.greencarcongress.com/2021/01/20210123-kobe.html%0A (accessed on 19 July 2024).
50. Derking, H.; van der Togt, L.; Keezer, M. Liquid Hydrogen Storage: Status and Future Perspectives 2019. Available online: https://www.google.com.hk/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.utwente.nl/en/tnw/ems/research/ats/Events/chmt/m13-hendrie-derking-cryoworld-chmt-2019.pdf&ved=2ahUKEwiS29ylkdGIAxVijVYBHYcHCVEQFnoECBQQAQ&usg=AOvVaw2rBUyqZBDsVC0O4J441A2a (accessed on 26 August 2024).
51. Johnson, W.L. *Thermal Performance of Cryogenic Multilayer Insulation at Various Layer Spacings*; University of Central Florida: Orlando, FL, USA, 2010.
52. Scopus. Document Search 2024. Available online: https://www.scopus.com/search/form.uri?display=basic&zone=header&origin=#basic (accessed on 1 July 2024).
53. Swanger, A. World's Largest Liquid Hydrogen Tank Nearing Completion 2022. Available online: https://ntrs.nasa.gov/api/citations/20220004276/downloads/Cold%20Facts_LH2%20Sphere%20Update.pdf (accessed on 31 August 2023).

54. Fesmire, J.; Swanger, A.; Jacobson, J.; Notardonato, W. Energy efficient large-scale storage of liquid hydrogen. *IOP Conf. Ser. Mater. Sci. Eng.* **2022**, *1240*, 012088. [CrossRef]
55. Fesmire, J.; Swanger, A. Overview of the New LH2 Sphere at NASA kennerdy Space Center 2021. Available online: https://ntrs.nasa.gov/citations/20210020920 (accessed on 26 August 2024).
56. Norwegian Centres of Expertise. Norwegian Future Value Chains for Liquid Hydrogen. 2016. Available online: https://maritimecleantech.no/wp-content/uploads/2016/11/Report-liquid-hydrogen.pdf (accessed on 26 August 2024).
57. Kawasaki Heavy Industries Ltd. Liquefied Hydrogen Storage Tank n.d. Available online: https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20201224_8018 (accessed on 2 September 2023).
58. Decker, L. Liquid Hydrogen Distribution Technology 2019. Available online: https://www.google.com.hk/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.sintef.no/globalassets/project/hyper/presentations-day-2/day2_1105_decker_liquid-hydrogen-distribution-technology_linde.pdf&ved=2ahUKEwi8wIGAk9GIAxX-qVYBHaF8KaEQFnoECBIQAQ&usg=AOvVaw0cTTTib4lL_u8vU4VOGqFR (accessed on 26 August 2024).
59. Hedayat, A.; Brown, T.M.; Hastings, L.J.; Martin, J. Variable density multilayer insulation for cryogenic storage. In Proceedings of the 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Las Vegas, NV, USA, 24 July–28 July 2000. [CrossRef]
60. Johnson, W.L. Optimization of layer densities for multilayered insulation systems. *AIP Conf. Proc.* **2010**, *1218*, 804–811. [CrossRef]
61. Hastings, L.J.; Hedayat, A.; Brown, T.M. Analytical Modeling and Test Correlation of Variable Density Multilayer Insulation for Cryogenic Storage. 2004. Available online: https://ntrs.nasa.gov/api/citations/20040121015/downloads/20040121015.pdf (accessed on 26 August 2024).
62. Wang, P.; Ji, L.; Yuan, J.; An, Z.; Yan, K.; Zhang, J. The influence of inner material with different average thermal conductivity on the performance of whole insulation system for liquid hydrogen on orbit storage. *Int. J. Hydrogen Energy* **2021**, *46*, 10913–10923. [CrossRef]
63. Dye, S.; Kopelove, A.; Mills, G.L. Novel load responsive multilayer insulation with high in-atmosphere and on-orbit thermal performance. *Cryogenics* **2012**, *52*, 243–247. [CrossRef]
64. Dye, S.; Johnson, W.L.; Plachta, D.W.; Mills, G.L.; Buchanan, L.; Kopelove, A. Design, fabrication and test of Load Bearing multilayer insulation to support a broad area cooled shield. *Cryogenics* **2014**, *64*, 135–140. [CrossRef]
65. Huerta, F.; Vesovic, V. CFD modelling of the isobaric evaporation of cryogenic liquids in storage tanks. *Int. J. Heat Mass Transf.* **2021**, *176*, 121419. [CrossRef]
66. Park, W.S.; Yoo, S.W.; Kim, M.H.; Lee, J.M. Strain-rate effects on the mechanical behavior of the AISI 300 series of austenitic stainless steel under cryogenic environments. *Mater. Des.* **2010**, *31*, 3630–3640. [CrossRef]
67. Schutz, J. Properties of composite materials for cryogenic applications. *Cryogenics* **1998**, *38*, 3–12. [CrossRef]
68. Horiuchi, T.; Ooi, T. Cryogenic properties of composite materials. *Cryogenics* **1995**, *35*, 677–679. [CrossRef]
69. Zhu, S.; Zhu, C.; Luo, D.; Zhang, X.; Zhou, K. Development of a Low-Density and High-Strength Titanium Alloy. *Metals* **2023**, *13*, 251. [CrossRef]
70. Marinelli, M.; Santarelli, M. Hydrogen storage alloys for stationary applications. *J. Energy Storage* **2020**, *32*, 101864. [CrossRef]
71. Zheng, J.; Chen, L.; Wang, J.; Xi, X.; Zhu, H.; Zhou, Y.; Wang, J. Thermodynamic analysis and comparison of four insulation schemes for liquid hydrogen storage tank. *Energy Convers. Manag.* **2019**, *186*, 526–534. [CrossRef]
72. Jiang, W.; Sun, P.; Li, P.; Zuo, Z.; Huang, Y. Transient thermal behavior of multi-layer insulation coupled with vapor cooled shield used for liquid hydrogen storage tank. *Energy* **2021**, *231*, 120859. [CrossRef]
73. Kang, D.; Yun, S.; Kim, B. Review of the Liquid Hydrogen Storage Tank and Insulation System for the High-Power Locomotive. *Energies* **2022**, *15*, 4357. [CrossRef]
74. Krenn, A.G. Diagnosis of a poorly performing liquid hydrogen bulk storage sphere. *AIP Conf. Proc.* **2012**, *1434*, 376–383. [CrossRef]
75. Choi, Y.; Kim, J.; Park, S.; Park, H.; Chang, D. Design and analysis of liquid hydrogen fuel tank for heavy duty truck. *Int. J. Hydrogen Energy* **2022**, *47*, 14687–14702. [CrossRef]
76. *ISO 13985:2006*; Liquid Hydrogen—Land Vehicle Fuel Tanks. ISO: Geneva, Switzerland, 2006.
77. Ustolin, F.; Paltrinieri, N.; Berto, F. Loss of integrity of hydrogen technologies: A critical review. *Int. J. Hydrogen Energy* **2020**, *45*, 23809–23840. [CrossRef]
78. Fesmire, J.E. Layered composite thermal insulation system for nonvacuum cryogenic applications. *Cryogenics* **2016**, *74*, 154–165. [CrossRef]
79. Wang, B.; Huang, Y.H.; Li, P.; Sun, P.J.; Chen, Z.C.; Wu, J.Y. Optimization of variable density multilayer insulation for cryogenic application and experimental validation. *Cryogenics* **2016**, *80*, 154–163. [CrossRef]
80. Yanxing, Z.; Maoqiong, G.; Yuan, Z.; Xueqiang, D.; Jun, S. Thermodynamics analysis of hydrogen storage based on compressed gaseous hydrogen, liquid hydrogen and cryo-compressed hydrogen. *Int. J. Hydrogen Energy* **2019**, *44*, 16833–16840. [CrossRef]
81. Brooks, A.N.; Hibbs, B.D.; Thompson, D.R. Cryogenic Liquid Tank. U.S. Patent US20180080606 A1, 22 March 2018.
82. Brooks, A.N.; Hibbs, B.D.; Thompson, D.R. Cryogenic Liquid Tank. U.S. Patent US 10584828 B2, 10 March 2020.
83. Immel, R.; Matos Da Silve, J. Liquid Hydrogen Storage Tank with Common-Access Tube as Port for Pipes into the Innervessel. U.S. Patent US007641068B2, 5 January 2010.
84. Immel, R.; Matos Da Silve, J. Suspended Liquid Hydrogen Storage Tank. U.S. Patent 7757882, 20 July 2010.
85. Pechtold, R. Liquid Hydrogen Storage Tank with Reduced Tanking Losses. U.S. Patent US007484540B2, 3 February 2009.

86. Guilhem, J.; Bourgeois, M. Insulated Storage Tank for Liquid or Liquefeed Products. Patent 3896961, 29 July 1975.
87. Rudolf, B. Method of and Apparatus for the Transportation and Storage of Liquefiable Gases. U.S. Patent 3254498, 7 June 1966.
88. Richard, N.H.H. Insulation of Containers for the Storage of Liquids Which Boil at Atmospheric or Slightly Superatmospheric Pressure. U.S. Patent 3110156, 12 November 1963.
89. Rae, R.S. Liquid Storage Tank. Patent 2922287, 26 November 1960.
90. Jingu, J. Liquefied Hydrogen Fuel Tank for Drones and Automobiles. Patent KR102105883B1, 29 April 2020.
91. Fesmire, J.E.; Sass, J.P.; Nagy, Z.; Sojourner, S.J.; Morris, D.L.; Augustynowicz, S.D. Cost-Efficient Storage of Cryogens. 2007. Available online: https://ntrs.nasa.gov/api/citations/20120000651/downloads/20120000651.pdf (accessed on 26 August 2024).
92. NREL. Costs of Storing and Transporting Hydrogen. 1998. Available online: https://www.nrel.gov/docs/fy99osti/25106.pdf (accessed on 26 August 2024).

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.