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An Extensive Review on Hydrogen Storage Technologies and its Challenges

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Abstract: This research paper presented a review of different types of hydrogen storage technologies, current gaps and challenges of the hydrogen storage system. Transportation of hydrogen is the biggest task that has been involved in adoption of hydrogen as an import and export of clean energy. It has been categorized into three different approaches to describe the current hydrogen storage technologies i.e. compressed gas storage, solid-state storage and liquid hydrogen storage, and while liquid hydrogen storage relies on freezing temperatures to preserve hydrogen in liquid form, compressed gas storage involves large concentrations of pressurized hydrogen. Higher energy densities and lower operating pressures are potential benefits of solid-state storage, which is made up of metal hydrides, chemical hydrides, and porous materials. This review paper combines a comprehensive study of hydrogen storage technologies and approaches from various research studies. Furthermore, discuss on current gaps, challenges in hydrogen storage and comparing the results, methodologies, and conclusions of several significant papers related to Hydrogen Storage Technologies.

Keywords: *Solid-State Storage, Liquid Hydrogen Storage, Compressed Gas Storage.*

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I. INTRODUCTION

Global energy consumption is accelerating rapidly, driven by the growth of the global population, ongoing industrialization, and urban expansion [1]. Presently, over 85% of global energy requirements are satisfied by fossil fuels, including coal, oil, and natural gas. This heavy reliance contributes significantly to environmental issues—including global warming—as well as economic and geopolitical instability [2]. These non-renewable energy sources are becoming increasingly scarce, leading to rising costs and long-term sustainability concerns.

One of the major challenges facing the world today is reducing dependence on these finite fossil fuel resources to ensure a secure and sustainable energy future. In response, the global focus has shifted toward renewable energy sources due to their long-term environmental and economic benefits [2]. This transition is driven by the urgent need to find abundant, clean, and renewable alternatives that can meet future energy demands while mitigating the effects of climate change. Various renewable energy technologies, such as wind, solar, and nuclear power, have been widely studied to address this need [1]. However, their output is often limited by factors like weather variability and geographic location, making them insufficient on their own to fully support a global green economy [1].

Hydrogen is emerging as a promising solution and known as "fuel of the future" due to higher energy efficiency and environmental clean profile [3]. As the most abundant element in the universe, hydrogen offers a versatile energy carrier that can store and deliver electricity through chemical processes, rather than combustion [3]. It can be utilized in a broad range of applications, from home heating to powering electric vehicles [4]. Importantly, hydrogen combustion produces only water and heat, making it a zero-emission fuel. With an energy content of 120 MJ/kg, hydrogen surpasses gasoline in terms of energy per unit mass [4][5].

However, hydrogen does not naturally exist as a free gas and must be produced from other sources. Its production requires primary energy input, which comes from either non-renewable sources. For hydrogen to be a practical and sustainable solution, it must be produced in a cost-effective and environmentally friendly manner. As nations work toward achieving net-zero carbon emissions by 2050, the production of renewable hydrogen is anticipated to be crucial in the transition to a cleaner, more sustainable energy system [5].

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Hydrogen storage is essential for facilitating its utilization in diverse applications, including stationary power generation, transportation, and portable energy systems.

To support the development of a clean hydrogen economy, highly efficient and dependable storage technologies are essential. On the other hand, material-based storage relies on hydrogen's interaction with materials and is further divided into two subtypes: **physisorption** (physical sorption) and **chemisorption** (chemical sorption) [6].

II. LITERATURE REVIEW

➢ *Hydrogen Storage Background*

Zhang et al. (2016) emphasized the significant role hydrogen plays in the overall energy landscape. It influences various aspects of energy generation, such as grid reliability, effective use of renewables, fossil fuel conservation, and environmental sustainability. This is because the energy input required for producing hydrogen is often greater than the energy it releases during use.

Despite this, hydrogen is considered an efficient energy carrier due to its ability to be stored and transported with relative ease. Zhang also pointed out the critical need for the development of storage methods that are safe, cost-effective, and reliable—an essential step toward building a sustainable hydrogen economy. The primary storage techniques include compressing hydrogen gas, cooling it into a liquid form (cryogenic storage), and embedding it in solid materials (solid-state storage). In more recent studies, Kumar et al. (2022) projected that hydrogen would evolve into a more efficient and environmentally friendly energy carrier.

Earlier, Mori et al. (2009) noted that to match the performance of gasoline-powered vehicles. Building on this, Wei et al. (2017) suggested that a comprehensive evaluation of storage technologies should consider the entire energy lifecycle—from generation to consumption. Anna et al. (2014) also emphasized the significance of infrastructure, particularly highlighting the potential of geological hydrogen storage, similar to the systems used for natural gas, to reduce costs and meet growing energy demands.

➢ *Creation of Hydrogen Storage materials*

Malleswararao et al. (2022) highlighted that metal hydrides (MHs) have attracted significant interest as materials for hydrogen storage due to their environmental friendliness, ability to operate with low-grade thermal energy, and high volumetric hydrogen storage capabilities under moderate pressure conditions [7].

In a separate study, Hirscher et al. (2020) discussed the long-standing use of porous materials like activated carbon and zeolites for hydrogen storage via physisorption. According to their analysis, the effectiveness of these materials is strongly influenced by the available surface area that can interact with hydrogen molecules [8]. They also introduced a newer category of materials—coordination polymers or Metal-Organic Frameworks (MOFs)—which have shown promising performance in hydrogen uptake. Notably, these materials have demonstrated hydrogen storage capacities up to 4.5 weight percent at pressures below 1 bar and a temperature of 77 K [8].

Marinelli et al. (2020) explored additional hydrogen storage mechanisms, emphasizing that hydrogen can be stored either on the surface of materials (through adsorption) or inside metal matrices (via absorption). Their research revealed that certain metal hydrides are capable of reversible hydrogen storage under near-ambient conditions. This led to the discovery of intermetallic compounds, also referred to as hydrogen storage alloys, which enable efficient hydrogen absorption and release cycles [9].

Additionally, Hermosilla-Lara (2007) emphasized the safety benefits of using solid-state materials such as metal hydrides for hydrogen storage. The chemisorption process involved allows for hydrogen to be stored at much lower pressures compared to conventional compressed gas storage methods, making the system inherently safer [10].

➢ *Methods and Technologies for Hydrogen Storage*

Zhang et al. (2016) highlighted that hydrogen can be stored in compressed form within specialized cylinders, storage tanks, or even underground facilities, typically at pressures reaching up to 700 bar. The authors classified high-pressure hydrogen storage vessels into three main categories: stationary, vehicular, and those used for bulk transport. Compared to compressed gas storage, storing hydrogen in its liquid state offers a higher volumetric energy density, enabling more energy to be stored within a smaller space.

This technique holds significant promise because it allows a large amount of hydrogen to be stored in compact volumes. According to Zhang et al. (2016), both compressed gas and liquid hydrogen storage methods are widely adopted in industry. However, increasing the gravimetric density—essential for mobile applications—[12] has led to growing interest in material-based solutions. In these systems, hydrogen can adhere to material surfaces or be absorbed into their crystal lattices. The performance of such storage technologies largely depends on the development of new materials capable of efficiently storing and releasing hydrogen at feasible temperatures and pressures.

➢ *Different Types of Hydrogen Storage*

Ramin et al. (2019) emphasized that hydrogen storage is a critical component in any hydrogen-based energy infrastructure, especially for its expansion at scale. Ensuring reliable and efficient storage options tailored to various applications is essential to meet both present and future energy needs [11].

- *Gaseous Hydrogen Storage*

As the lightest element, hydrogen occupies a large volume at standard temperature and pressure, making its storage and transportation a technical challenge. To

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overcome this, hydrogen is commonly compressed to reduce its volume, allowing for more practical handling and use. Gaseous hydrogen storage remains one of the most straightforward and widely employed methods. Today, a variety of technologies are used to store hydrogen gas effectively, depending on the intended application and performance requirements.

- *Storage of Compressed Hydrogen*

One of the most common ways to store hydrogen is to use cylindrical or conformable tanks with strong walls made of materials with high strength, which contribute to their robustness and long service life. Despite their durability, current tank designs are not fully optimized, often resulting in excessive weight and inefficient material usage, which also limits the vessel's operational lifespan [13]. Hydrogen storage tanks are divided into four types. Among these, the most advanced are composite tanks that utilize either non-load-bearing metallic liners (Type III) or plastic liners (Type IV), which are reinforced with resin-impregnated continuous fiber wraps for added strength [14]. Faye et al. noted that traditional high-pressure steel cylinders, typically operating at around 200 bar, are widely used for hydrogen storage [15]. However, to achieve higher storage density, modern lightweight composite tanks have been developed to withstand pressures up to 800 bar, enhancing hydrogen density to around 36 kg/m³—approximately half that of liquid hydrogen at its boiling point of −252.87°C [16].

- *Applications of Compressed Hydrogen*

Numerous automotive manufacturers are actively engaged in the development of compressed hydrogen storage systems. For example, Dynetek Industries is focused on Type II cylinder development, while other companies such as EADS Group, Faber, CEA, Ullit, and COMAT are pioneering Type IV cylinders. Japanese automakers are also heavily involved in research and innovation related to Fuel Cell Vehicles (FCVs). Recently, Dynetek Industries reported testing of advanced cylinders capable of handling pressures up to 825 bar, intended for stationary hydrogen storage applications [17]. These high-pressure tanks are made from aerospace-grade aluminum, offering excellent sealing properties. Additionally, Quantum Technologies, in collaboration with General Motors, has developed a 700 bar composite hydrogen tank designed to extend driving ranges of FCVs up to 270 kilometers. These tanks also enable rapid refueling—typically within five minutes [17].

- *Benefits and Limitations*

Despite advancements, Faye et al. argue that traditional hydrogen storage technologies—such as high-pressure gas tanks and liquid storage systems—require further improvements to match the efficiency and range of conventional gasoline vehicles. One key advantage of compressed gaseous hydrogen is its relatively low cost, especially when stored at pressures around 200 bar. However, this method offers limited storage capacity at such pressures. Efforts to enhance high-pressure storage systems are ongoing to address these capacity limitations [15].

- *Challenges in Compressed Hydrogen Storage*

The development of cost-effective and safe compressed hydrogen storage still faces several hurdles. These include the need for affordable materials that can store hydrogen at lower pressures while minimizing leakage, innovations in manufacturing processes to enable the large-scale production of high-pressure tanks at reduced costs, and advancements in sensor technologies to reliably detect hydrogen leaks. Additionally, there is a pressing need to establish standardized codes and regulations to ensure safety and compatibility across applications [15].

➢ *Liquid Hydrogen Storage*

According to Faye et al., storing hydrogen in liquid form is a viable option to significantly increase its energy density. One major benefit of liquefaction is that it allows hydrogen to be stored at atmospheric pressure with high density—about 70 kg/m³ at 1 bar. The two primary liquefaction processes employed are the Linde cycle and the Joule-Thomson expansion method [16]. However, this storage method presents notable challenges. The evaporation or boil-off of hydrogen due to thermal heat transfer is a persistent issue, along with the risk of leakage. To reduce energy losses during liquefaction, highly efficient refrigeration systems and well-insulated containers are essential.

➢ *Methods and Technologies for Hydrogen Storage*

Zhang et al. (2016) highlighted that hydrogen can be stored by compression in pressurized containers, including high-pressure cylinders and even underground reservoirs, at pressures reaching up to 700 bar. According to Zhang, three primary forms of high-pressure hydrogen storage vessels are commonly used: stationary, mobile (vehicular), and bulk transport containers. Storing hydrogen in liquid form enables a greater storage density than compressed gas, allowing more energy to be held per unit volume. Material-based storage methods involve binding hydrogen to solid materials, either through physical or chemical means, which makes it one of the most promising storage approaches due to its compactness and high capacity. Zhang et al. concluded that although compressed gas and liquid hydrogen storage are widely adopted in industry, there is a growing interest in material-based solutions due to their potential to offer high gravimetric densities suitable for mobile applications. However, their effectiveness hinges on the advancement of novel materials that can efficiently store and release hydrogen under moderate conditions.

➢ *Classification of Hydrogen Storage Methods*

Ramin et al. (2019) emphasized that hydrogen storage plays a pivotal role in ensuring the feasibility and scalability of hydrogen energy systems, especially in large-scale applications. A diverse range of storage methods tailored to specific applications is essential for supporting the evolving hydrogen economy.

- *Gaseous Hydrogen Storage*

Being the lightest element, hydrogen occupies a large volume at standard conditions. To store it efficiently, it must be compressed to significantly reduce its volume. Gaseous

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storage is among the most commonly used and technologically straightforward methods today.

- *Compressed Hydrogen Storage*

Hydrogen is often stored in robust, high-strength cylindrical tanks made from composite materials. Despite their reliability, many tanks remain oversized with suboptimal material utilization and limited service life. The European Integrated Hydrogen Project (EIHP) classifies compressed hydrogen storage tanks into four types, with the most advanced being composite tanks (Type III and IV) featuring metallic or polymer liners reinforced with continuous fiber wrap. Faye et al. [16] noted that conventional steel cylinders operate around 200 bar, but newer composite designs can withstand up to 800 bar, achieving hydrogen densities up to 36 kg/m³—around half the density of liquid hydrogen at −252.87°C.

- *Applications of Compressed Hydrogen*

Several automotive and aerospace companies are developing advanced hydrogen storage solutions. For instance, Dynetek Industries is focusing on Type II cylinders, while companies like Faber and CEA are working on Type IV variants. In collaboration with General Motors, Quantum Technologies developed a 700-bar composite tank capable of extending vehicle range up to 270 km, with refueling times as short as five minutes.

- *Advantages and Limitations*

Compressed hydrogen storage is cost-effective and relatively simple, especially at pressures around 200 bar. However, the quantity of hydrogen stored at such pressures is limited, and performance in automotive applications is still lagging compared to gasoline vehicles.

- *Research Challenges*

Key challenges include the need for cost-effective materials to prevent hydrogen leakage, improved manufacturing processes for high-pressure tanks, reliable sensors for leak detection, and the establishment of safety standards and regulations for end-user applications.

➢ *Liquid Hydrogen Storage*

Faye et al. [16] reported that liquefying hydrogen significantly increases its energy density, with saturated liquid hydrogen reaching densities of 70 kg/m³ at 1 bar. Liquefaction relies on cycles such as Linde and Joule-Thomson. Despite the advantage in storage density, liquid hydrogen systems face issues like boil-off and hydrogen leakage, necessitating insulated containers and refrigeration to minimize energy losses.

➢ *Storage of Cryocompressed Hydrogen*

Cryo-compression combines the benefits of cryogenic and pressurized storage by storing hydrogen at low temperatures (using insulation) and high pressures (250–350 atm). According to Faye et al., this method offers improved safety through dual-layer vacuum enclosures that protect the hydrogen from external influences, ensuring better storage conditions.

➢ *Hydrogen Storage in Salt Caverns*

Richard et al. describe how salt caverns—created by leaching naturally occurring salt deposits—provide a stable underground storage solution. These formations, typically located 500 to 1500 meters below ground, offer self-sealing and low-permeability environments ideal for hydrogen containment. The first salt cavern hydrogen storage facility began operation in Cologne, Germany, in 1971. Research by Chen et al. revealed that storage effectiveness can be compromised by lithological variations in salt beds, affecting porosity, permeability, and ultimately, the integrity of the cavern.

➢ *Aquifer-Based Hydrogen Storage*

Richard et al. (2021) proposed that aquifers—naturally porous rock formations in sedimentary basins—can store hydrogen by displacing the water within pore spaces using controlled injection pressures. This technique could support seasonal or large-scale hydrogen storage needs where surface storage methods are impractical.

- *Saline Aquifers*

Deep saline aquifers offer the potential for large-scale hydrogen storage due to their extensive distribution and capacity. Despite this potential, practical implementation is hindered by uncertainties related to seal integrity, flow rate limitations, and challenges such as viscous fingering. Heinemann et al. [21] highlighted the role of cushion gas and reservoir properties in determining injectivity, productivity, and storage capacity.

- *Benefits and Challenges*

Underground hydrogen storage offers flexibility in operation, potentially allowing storage at pressures up to 200 bar. However, issues such as chemical reactivity with reservoir water, gas purity concerns, and geographical constraints need to be resolved. Frequent cycling of injection and withdrawal is essential for evaluating system performance and reliability.

➢ *Storage of Hydrogen in Depleted Gas and Oil Fields*

Richard et al. (2021) noted that using abandoned oil and gas reservoirs for hydrogen storage presents economic advantages due to existing infrastructure. These sites are geographically widespread and have low cushion gas requirements, making them one of the most cost-effective geological storage options.

- *Geological Storage Strategies*

According to Thiyagarajan et al. (2022) [23], geological formations used for underground hydrogen storage include porous media (e.g., sandstones) and solution-mined caverns. Proper selection of geological parameters, including injection pressures and fracture resistance, is crucial for successful storage.

- *Technical Challenges*

Several challenges are associated with underground hydrogen storage: geochemical reactions (e.g., H_2S formation), microbial activity, seal integrity, and potential changes in reservoir rock properties. These complications

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can lead to hydrogen loss, reduced injectivity, and gas contamination. Advanced modeling of interfacial properties—like wettability and capillary forces—is required to optimize injection and withdrawal processes. Thiyagarajan et al. also identified additional issues such as fault reactivation, mineral precipitation, and hydrogen diffusion, all of which must be addressed to ensure long-term stability and efficiency of underground storage systems.

III. METHODOLOGY

This research adopts a comprehensive methodology to assess various hydrogen storage technologies based on key parameters such as energy efficiency, energy density, system longevity, and associated energy costs. In addition to these performance metrics, a detailed quantitative risk and reliability assessment will be conducted, incorporating transportation strategies for each storage technique. The aim is to systematically identify the most viable hydrogen storage solution tailored to specific application needs. By comparing different storage methods—such as liquefaction, underground reservoirs, and others—this study intends to propose the most promising approach for large-scale and cost-effective hydrogen storage.

➢ *Quantitative Analysis*

A comparative quantitative evaluation serves as the foundation for understanding the efficiency and feasibility of hydrogen storage techniques. One commonly used method in the **storage of compressed gas** is to store hydrogen under high pressure in durable containment vessels. Historical studies indicate that although traditional metal vessels used for this purpose tend to have low strength-to-weight ratios, they remain cost-effective. Modern compressed hydrogen tanks are fabricated using advanced filament-winding processes, typically involving high-strength carbon/epoxy composites reinforced around a metallic (Type III) or polymer (Type IV) liner.

Type IV composite overwrapped pressure vessels (COPVs) are particularly notable for their superior storage density, lightweight construction, and resistance to corrosion. These vessels are capable of withstanding pressures up to 70 MPa, thereby significantly increasing storage capacity. While their mechanical properties—such as gas impermeability and impact resistance—are advantageous, the limited gravimetric energy density and relatively high production costs present ongoing challenges.

In contrast, **metal hydride storage systems** involve chemically bonding hydrogen with specific metals to form solid hydrides. When heat is applied, these hydrides release hydrogen gas through a reversible reaction. One limitation of this method is the difficulty in selecting optimal metal alloys that maximize hydrogen uptake and release efficiency. Ideally, metal hydrides should store at least 10% of their weight in hydrogen. For instance, 50 grams of an appropriate metal could potentially absorb up to 15 liters of hydrogen gas. Despite this, the cycle life is generally short, with some alloys—such as magnesium hydrides modified with $LaNi_3$—offering up to 2000 hours of effective usage. Energy-wise, metal hydride systems can achieve around 69% efficiency for hydrogen input and release but only about 17% efficiency when the total electrical input and output is considered.

Liquid hydrogen storage (LHS) requires hydrogen to be cooled to cryogenic temperatures near −253°C and stored in specialized vacuum-insulated containers. Though this method allows for high volumetric storage, it faces technical and economic challenges. Liquefaction is energy-intensive, often consuming energy equivalent to one-third the value of the hydrogen produced. Other concerns include boil-off losses, ortho-para conversion, thermal leakage, and sloshing during transit. Boil-off rates of 0.2–0.3% per day are typical, though modern insulation methods can help mitigate such losses. Anti-slosh mechanisms are essential during transport to reduce risks associated with fluid movement.

While the above methods are typically deployed above ground, **underground hydrogen storage (UHS)** offers a scalable solution, particularly for balancing intermittent renewable energy sources. Storage in geological formations like salt caverns allows for large-scale hydrogen containment with promising energy efficiency figures—ranging from 60% to 89% in various studies. The energy density of UHS can reach up to 300 kWh/m³, which is comparable to that of lithium-ion batteries. In fact, a group of 20 salt caverns could theoretically store up to 1700 GWh of energy, supporting an output of approximately 14 GW.

➢ *Evaluating the Practicality of Hydrogen Storage Methods*

Several established methods for hydrogen storage exist, each operating under different physical conditions and environments. These approaches include metal hydride systems, cryogenic liquid hydrogen storage, high-pressure composite cylinders (e.g., Type IV vessels), and subterranean storage within geological formations. Each option varies significantly in terms of material requirements, cost, storage capacity, and long-term reliability.

Metal hydride systems rely on hydrogen absorption into specialized metal alloys. Although this technique allows for reversible hydrogen storage, it is currently limited by high material costs, uncertain lifespan, and unrefined technology. **Liquid hydrogen storage**, on the other hand, demands cryogenic conditions maintained in vacuum-insulated containers. Despite high storage density and lower initial cost, the process suffers from low energy efficiency and reduced service life, limiting its practicality for large-scale applications.

Type IV pressure vessels, built using carbon fiber-reinforced polymers (CFRP) and metallic components, provide excellent strength-to-weight ratios and significant hydrogen capacity in the gas phase. However, they are expensive to produce, and their composite materials are difficult to recycle or refurbish. Furthermore, exposure to hydrogen over time can cause embrittlement of metallic parts, weaken mechanical properties, and result in gas

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permeation through the polymer liner, potentially leading to leaks.

In contrast, **underground hydrogen storage (UHS)**—especially within salt caverns—presents a promising solution for long-term, industrial-scale hydrogen retention. This method offers high capacity, minimal environmental impact, and relatively low land usage. Among geological options such as aquifers, depleted hydrocarbon reservoirs, and salt caverns, the latter stands out due to its physical advantages. Salt formations are dense, have low porosity and permeability, and demonstrate self-healing characteristics that minimize hydrogen leakage.

➢ *Hydrogen Storage Evaluation Based on Delivery Mechanisms*

Hydrogen's storage efficiency must be considered alongside its delivery processes, particularly as they influence the overall cost, energy consumption, and emissions footprint. When hydrogen is produced at centralized locations, two major logistical stages occur: **Transmission**, which transports hydrogen to city gates, and **Distribution**, which delivers it from those entry points to fuelling stations or end users.

The method of delivery often depends on the form in which hydrogen is stored. There are three primary hydrogen delivery systems:

- Gaseous Hydrogen Delivery
- Cryogenic Liquid Hydrogen Delivery
- Carrier-Based Hydrogen Delivery

➢ *Delivery of Gaseous Hydrogen*

Hydrogen stored in its gaseous form is typically delivered using high-pressure vessels mounted on trailers or through dedicated hydrogen pipelines. In the United States, a network of about 2,600 kilometers of hydrogen pipelines serves large-scale consumers such as ammonia production plants and oil refineries. Though creating custom pipeline infrastructure is costly, increasing efforts are being made to retrofit existing natural gas pipelines to accommodate hydrogen.

Tube trailers are a practical solution, operating at around 250 bar and storing hydrogen that amounts to approximately 7% of the total trailer weight. These trailers are advantageous due to relatively low hydrogen loss and minimal compression requirements at distribution points—sometimes cutting costs by up to 60% compared to liquid hydrogen systems. For safety assurance, these systems undergo stringent testing such as pressure cycling, hydrostatic bursting, and penetration resistance evaluations.

➢ *Delivery of Liquid Hydrogen*

Liquid hydrogen becomes more cost-effective when daily demand exceeds 500 kg, particularly for medium-range transport distances. Its higher volumetric density makes it well-suited for fuel stations. Cryogenic delivery involves liquefaction, low-temperature storage, and insulated transport to end users. The viability of this method depends heavily on advancements in liquefaction technologies, such as reduced energy consumption, increased efficiency, and lower capital costs [18].

- *Delivery Using Hydrogen Carriers*

Hydrogen can also be transported using carrier materials, such as liquid organic hydrogen carriers (LOHCs) or chemical compounds like ammonia. These systems offer enhanced safety due to operation under ambient temperature and pressure conditions, along with manageable physical properties. Despite their promise, they are not yet suitable for supplying large-scale hydrogen demands due to technological limitations and energy inefficiencies.

➢ *Risk and Reliability Assessment of Hydrogen Storage Solutions*

Several technical and operational challenges could impair system performance, from material degradation to leakage risks and pressure management failures. Alongside these reliability concerns are safety-related risks tied to storage, transportation, and handling, all of which must be addressed for practical deployment [25-29].

IV. CONCLUSIONS

This study has explored the current landscape of hydrogen storage technologies and identified key insights from existing research. Among the available methods, **cryogenic storage and high-pressure compression** are the most mature and widely adopted. However, the **inherent low density of hydrogen** presents a major limitation, particularly for compressed gas storage, which demands substantial volumes and suffers from relatively low energy efficiency.

Material-based storage approaches, such as chemical and solid-state systems, are still in the experimental or developmental phase. These methods hold potential but require further advancement and validation before they can be considered viable for long-term and industrial-scale applications.

For instance, **metal hydride storage systems** involve introducing hydrogen gas under high pressure into a tank containing reactive metals, forming **solid hydride compounds**. While this offers a promising solid-state solution, technical and economic barriers remain. On the other hand, **underground hydrogen storage (UHS)** has proven to be a more scalable and cost-effective option, particularly for **long-duration and large-volume energy storage**.

In comparative terms, **compressed hydrogen storage remains the most cost-efficient** in terms of infrastructure and deployment. However, due to limitations such as energy loss and material degradation, it may not be suitable for all scenarios [22].

Taking into account performance parameters such as **system lifespan, economic feasibility, environmental footprint, and scalability**, **underground hydrogen**

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storage—especially in **salt caverns**—emerges as the most promising solution for **industrial-scale, long-term hydrogen storage**. It combines maturity, safety, and storage density in a way that makes it a strategic choice for supporting a future hydrogen economy.

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