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HYDROGEN STORAGE AND DELIVERY: RECENT DEVELOPMENTS AND INDUSTRIAL PERSPECTIVES

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ABSTRACT

As hydrogen can be generated without using fossil fuels, transitioning toward such an economy holds promise for reducing greenhouse gas emissions and enhancing energy security. 1-2 For using hydrogen as a greener alternative, the development of safe and affordable methods for hydrogen storage and transportation is highly required.3 The key components of the hydrogen economy (HE) are hydrogen production, storage, delivery, and utilization. Hydrogen can be stored through various methods, including compression, liquefaction at low temperatures, or by employing hydrides.4

This report will give an overview of hydrogen storage technologies and discuss the challenges and limitations associated with material performance in hydrogen-rich environments, and conditions representative of hydrogen energy uses. Furthermore, safety and reliability analysis for hydrogen storage and delivery technologies will also be discussed since the safety and reliability of hydrogen infrastructure is a vital prerequisite for gaining public acceptance of these technologies. Finally, suggestions are made to support safe, reliable operations to help provide a foundation for future risk and reliability analysis.

NOMENCLATURE

HE	hydrogen economy
LHV	lower Heating Value
HDPE	High-Density Polyethylene
DOE	Department of Energy
LOHC	Liquid Organic Hydrogen Carriers
MOF	Metal-Organic Frameworks
COPV	Composite Overwrapped Pressure Vessels
CARB	The California Air Resources Board
FRP	Fiber Reinforced Polymer
SRNL	Savannah River National Laboratory
TPRD	Thermally Activated Pressure Relief Devices
BN	Bayesian Networks
HIAD	Hydrogen Incident and Accident Database
QRA	Quantitative Risk Assessment
P2G	Power-to-Gas
FAR	Fatal Accident Rate
AIR	Average Individual Risk
PLL	Potential Loss of Life

1. INTRODUCTION

Hydrogen is emerging as a key player in the realm of clean energy, offering a promising alternative for both transportation and energy storage. Boasting the highest energy density by weight, hydrogen's use in fuel cells makes water the sole byproduct. Its storage versatility, on both large and small scales, adds to its appeal. Moreover, hydrogen production from various energy sources enhances its role in energy storage and contributes significantly to the energy security of the U.S. [1]. As a low-emission fuel, hydrogen's applications are diverse - from powering vehicles to heating and cooling systems, and even storing surplus electricity. This can potentially lead to integrated transport and power sectors. Envision a city like Fukuoka, Japan, thriving on hydrogen with negligible pollution - a testament to hydrogen's transformative potential in creating a Hydrogen Economy (HE) [2].

The global hydrogen market is already substantial, projected to reach a value of $154.74 billion by 2022 [3]. Its widespread use in various industries, including refineries, agriculture, and food processing, lays a solid foundation. This existing market familiarity with hydrogen, coupled with some infrastructure already in place, is advantageous for further expansion.

For the Hydrogen Economy to materialize, ensuring the safety and reliability of the necessary infrastructure is paramount. System designs must be robust and demonstrably as safe, if not safer, than current technologies. Being in the nascent stages, hydrogen technology may face initial setbacks or 'infant mortality' failures [4]. Public perception of hydrogen is also influenced by historical incidents like the Hindenburg fire (1937) and the Fukushima nuclear plant hydrogen explosion (2011) [5]. Even minor mishaps in hydrogen systems, such as fuel stations or storage facilities, could hinder the progress, deployment, and public acceptance of hydrogen technologies. Early years marked by safe, reliable operations can foster public trust, which significantly influences policy decisions [6]. Therefore, guaranteeing safety and reliability in hydrogen systems is not just a necessity but a catalyst for the advancement and widespread adoption of hydrogen technologies.

This study delves into the latest advancements and methodologies in risk and reliability analysis specific to hydrogen technologies, aiming to pinpoint and highlight areas where further research is essential to maintain and enhance the safety and reliability of these technologies. The focus is on two critical aspects of the hydrogen economy: the delivery and storage of hydrogen. The discussion on hydrogen storage acknowledges the necessity for diverse storage capacities and varying operational conditions to meet the demands of consumers. The importance of hydrogen delivery is explored as a key element in making this eco-friendly energy source widely available. The structure of this study is designed to systematically examine the areas of hydrogen storage and delivery, with a threefold focus. Describing the various technologies used in hydrogen storage and delivery, as explored in sections titled 'Hydrogen Storage Technologies' and 'Hydrogen Delivery Technologies.

The review synthesizes information from a range of authoritative sources, including journal articles, reports from the US Department of Energy, and relevant industry literature. The focus is on the most recent findings, primarily those published in the past five years, to ensure the relevance and timeliness of the insights provided.

2. ADVANCES IN HYDROGEN STORAGE TECHNOLOGIES

Hydrogen storage plays a pivotal role in the functionality of hydrogen energy systems, particularly for large-scale applications. To cater to the current and future demands of the hydrogen energy market, the development of robust and reliable storage solutions tailored for specific applications is crucial. The applications of hydrogen storage within the hydrogen economy framework are illustrated in Fig. 1, categorized into stationary and mobile applications. Stationary storage predominantly serves on-site storage needs, both at production sites and usage points, as well as for stationary power generation. In contrast, mobile applications focus on the transportation of hydrogen to storage points or its utilization in vehicles.

Considering hydrogen's relatively low energy density by volume compared to fossil fuels (9.9MJ/m³ LHV [Lower Heating Value] [7]), the challenge is to avoid excessively large storage vessels. This necessitates employing at least one of the following strategies: high storage pressure, low storage temperature, or utilization of materials capable of attracting a significant quantity of hydrogen molecules. It's important to note that large-scale storage is not the primary focus of this study and will only be briefly addressed in the section 'Large Scale H_2 Storage.'

Hydrogen storage technologies can be broadly classified into two categories: physical-based and material-based, as delineated in Fig. 2. Physical-based storage encompasses methods such as compressed gas storage, cold/cryo-compressed storage, and liquid hydrogen storage. Material-based storage is further divided into chemical sorption/chemisorption and physical sorption/physisorption [8].

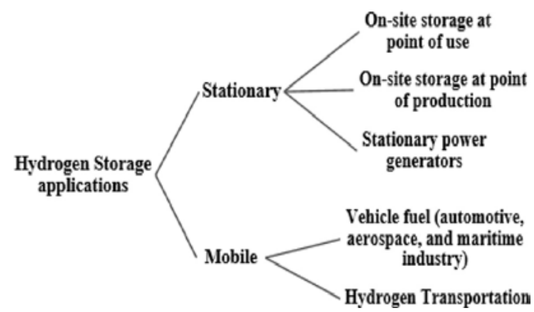

FIGURE 1 TYPES OF HYDROGEN STORAGE APPLICATIONS.

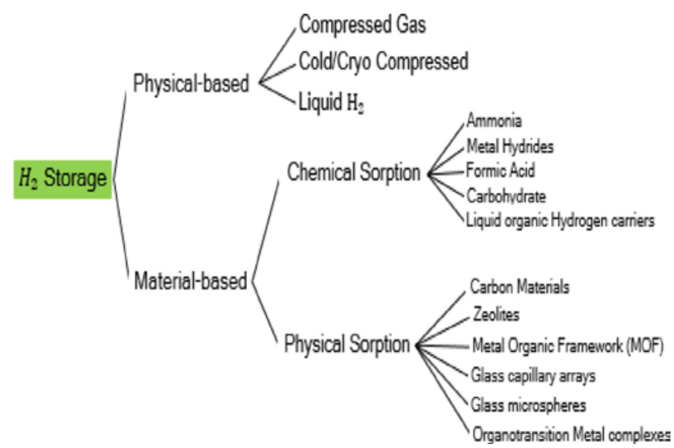

FIGURE 2 HYDROGEN STORAGE METHODS.

Physical-Based Hydrogen Storage Methods

Compressed H_2 Storage: There are four types of pressure vessels for storing hydrogen [9]

- Type I: Fully metallic pressure vessels, the most traditional and cost-effective, yet heaviest, typically made from aluminum or steel, accommodating pressures up to 50 MPa.
- Type II: Steel pressure vessel with a glass fiber composite overwrap, sharing the structural load equally between steel and composite. Manufacturing costs are approximately 50% higher than Type I, but these vessels are 30-40% lighter and have the highest pressure tolerance.

- Type III: Features a full composite wrap with a metal liner. The composite structure (often carbon fiber composite) bears the majority of the structural load, with the metal liner (usually aluminum) used for sealing. Type III vessels are reliable at 45 MPa working pressure but face challenges in aging tests at 70 MPa [9]. They offer a weight reduction of 0.75-1 lb/L, about half of Type II, but at double the cost.
- Type IV: Fully composite vessels with a polymer liner (commonly High-Density Polyethylene, HDPE) and carbon fiber or carbon-glass composites for structural support. These are the lightest, albeit costly, and can withstand pressures up to 100 MPa.

A novel development is the liner-less, full composite pressure vessel (Type V), still in the pre-commercial stage. First developed in 2010 by Composites Technology Development Inc., its inaugural model was 20% lighter than similar Type IV vessels, with an operational pressure of 1.37 MPa [10], which is currently insufficient for storing hydrogen at required pressures outside of laboratory settings.

Liquid and Cryogenic Hydrogen Storage Systems

Liquefying hydrogen is achieved at extremely low temperatures (around -250°C), with maintaining such low temperatures being the primary challenge in cryogenic hydrogen storage. The liquefaction process is both time-intensive and energy-consuming, with up to 40% of the hydrogen's energy content potentially lost during this process, compared to approximately 10% energy loss in compressed hydrogen storage [9]. Consequently, this method of storage is predominantly utilized for medium to large-scale applications, such as truck delivery and intercontinental hydrogen shipping, as depicted in Fig. 3. A typical cryogenic tanker can transport approximately 5000 kg of hydrogen, which is around five times the capacity of compressed hydrogen gas tube trailers.

In terms of safety, cryogenic vessels incorporate an additional layer of protection, such as a vacuum jacket, to mitigate risks in the event of accidents. Additionally, hydrogen possesses low adiabatic expansion energy at cryogenic temperatures [12], which reduces the likelihood of severe explosions in case of leakage or tanker rupture, unless an ignition source is present. However, the extremely low temperature of leaked hydrogen gas can compromise the functionality of adjacent valves or pressure relief devices not rated for such conditions. This was exemplified in a 2016 incident at a cryogenic hydrogen lab, where a pressure relief valve failed to operate at its set point due to exposure to unexpected cryogenic temperatures, indicating the valve was not appropriately rated for such conditions [13].

FIGURE 3 LEFT: KAWASAKI HEAVY INDUSTRY CONCEPT DESIGN FOR LIQUID HYDROGEN CARRIERS AND ON THE RIGHT: CRYOGENIC TRAILER [11].

Cryo-Compressed Hydrogen Storage Solutions

The cryo-compressed hydrogen storage method, initially introduced by Aceves et al. [14], represents a significant advancement in hydrogen storage technology. This method involves storing hydrogen as a supercritical cryogenic gas, where it is compressed at approximately -233°C without undergoing liquefaction. This approach has demonstrated promise in terms of storage efficiency and safety. Cryo-compressed storage offers a high storage density (approximately 80 g/L, which is about 10 g/L more than traditional cryogenic storage), rapid and efficient refueling capabilities, and enhanced safety due to the incorporation of a vacuum enclosure [15].

A comprehensive technical assessment conducted by Ahluwalia et al. concluded that cryo-compressed hydrogen storage has the potential to meet the ultimate targets set by the Department of Energy (DOE) for system gravimetric capacity, system volumetric capacity, and minimal hydrogen loss during periods of dormancy [16]. As a technology with substantial potential for widespread application, its inclusion in ongoing research and development efforts is crucial. Nonetheless, the primary challenges associated with cryo-compressed hydrogen storage remain the availability and cost of the necessary infrastructure.

Material-Based Hydrogen Storage Technologies

In the realm of hydrogen storage, both chemical and physical sorption methods utilize base materials that often start in powder form, with some exceptions like liquid organic hydrogen carriers. During the charging and discharging of hydrogen, heat is either produced or absorbed, and powdery substances are not the most efficient for heat transfer. Consequently, these base materials undergo various preprocessing techniques, as outlined by Ren et al. [35], including casting, templating, foaming, coating, and uniaxial pressing. The processed materials are then placed into a containment unit. Typically, these containment units are designed with embedded heat exchangers for thermal management, along with connections for controlling hydrogen flow and filtering the input and output hydrogen gas, as demonstrated by Lototskyy et al. [36]. Jehan and Fruchart [37] have proposed a design suitable for fueling station-scale hydrogen storage as a proof of concept. However, as noted, the commercial implementation of these methods remains uncertain, with the reasons discussed in subsequent sections (refer to Fig. 4).

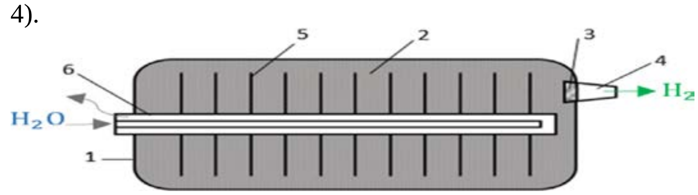

FIGURE 4 SAMPLE DESIGN FOR A MATERIAL-BASED STORAGE UNIT [36].

Chemical Sorption Hydrogen Storage

Chemical sorption involves the splitting of hydrogen molecules into atoms, which are then integrated into the material's chemical structure. Metal hydrides are the most notable materials for chemical sorption. Comprehensive information and references about metal hydrides are available in Refs. [35,38]. The primary challenges for chemical sorption materials include reducing cost and weight, lowering operating temperatures, improving charge-discharge kinetics, and controlling the formation of unwanted gases during desorption.

It's important to mention that Liquid Organic Hydrogen Carriers (LOHCs) are emerging as promising options. In LOHC systems, hydrogen is stored by chemically bonding with hydrogen-lean molecules and released through catalytic dehydrogenation [26]. These systems offer ease of management under ambient conditions, carbon-free storage and release processes, and the ability to reuse the carrier liquid. Additionally, these carriers are non-toxic, non-corrosive, and operate under low storage pressure. However, their low hydrogen storage capacity (maximum reported value of 7.2% wt. as per Table 1) limits the application of LOHCs [27].

Table 1- Maximum storage capacities (percentage of weight %wt) reported for several different physical and chemical hydrogen storage methods.

	Material-based Storage Method	***Max Reported storage capacity(wt %)***	***References***
Chemical	Ammonia Borane	19.4	[17,18]
	Metal Hydrides	12.6	[19,20]
	Alanates	9.3	[21,22]
	Formic Acid	4.4	[23,24]
	Carbohydrate	14.8	[25]
	Liquid Organic Hydrogen Carrie	7.2	[26,27]
Physical	Carbon Materials	8	[28,29]
	Zeolites	9.2	[30,31]
	Glass Capillary Arrays	10	[32,33]
	Glass Microspheres	14	[34]

Physical Sorption Hydrogen Storage

Porous material-based storage systems, such as Metal-Organic Frameworks (MOFs) and porous carbon materials, are recognized for their potential to achieve high-capacity and reliable storage [28,39]. This method offers a high surface area, low hydrogen binding energy, rapid kinetics in charge and discharge processes, and lower material costs. Physical absorption might also address thermal management issues during the storage unit's charge and discharge cycles. Nonetheless, challenges with this method include the weight of carrier materials, the necessity for low temperature and high pressure during storage, and inadequate gravimetric and volumetric hydrogen densities [40]. Currently, physical sorption technologies are not yet ready for widespread use, as all experiments have been conducted on a small scale, and the performance criteria (such as volumetric/gravimetric hydrogen density, pressure, and temperature requirements) have not met the desired standards.

Large-Scale Hydrogen Storage Solutions

In this research, the term "large-scale storage" is specifically applied in the context of grid-scale energy storage. For industrially advanced nations like Germany, this scale equates to storing energy in the double-figure terawatt range. In the envisioned hydrogen economy, such large-scale storage would be pivotal for accumulating excess energy from the grid and supplying hydrogen to a vast consumer base, or potentially a combination of both. The predominant method for this purpose involves utilizing artificially constructed salt caverns for hydrogen gas storage. Salt caverns are an optimal choice due to the inert nature of salt, which does not react with hydrogen. Approximately 170 caverns are currently used in Germany for natural gas storage, with additional caverns in Texas, the US, and the UK. Thus, substantial technical expertise in this domain already exists. However, the feasibility of this method is geographically constrained. Typically, these caverns have a volume of about 700,000 m^3 and can operate at a maximum pressure of 20 MPa. An alternative approach is the utilization of depleted natural gas reservoirs or natural aquifer formations. Nonetheless, the potential reactions of hydrogen with microorganisms and minerals in these structures warrant further investigation [41,42].

Underground storage of hydrogen offers enhanced safety compared to above-ground methods, attributable to the substantial wall thickness and lower operating pressures. However, this method raises ecological and environmental concerns, particularly regarding the potential impact of hydrogen leakage on adjacent areas, including local flora and fauna. These aspects necessitate careful consideration and assessment.

3. ADVANCEMENTS IN HYDROGEN DELIVERY SYSTEMS

Hydrogen delivery significantly influences the cost, energy use, and emissions associated with hydrogen pathways. In scenarios involving centralized hydrogen production, the delivery process to end-users encompasses two main phases: Transmission, which involves the delivery of hydrogen from production plants to city gates, and Distribution, which covers the delivery from city gates to fueling stations or end-users. There are three primary delivery pathways, each depending on the chosen storage method:

A. Gaseous Hydrogen Delivery
B. Liquid Hydrogen Delivery
C. Material-Based Hydrogen Carriers

The selection of a delivery method is contingent upon specific geographic and market characteristics, such as target population and consumption behavior, population density, size of refueling stations, and market penetration of fuel cell vehicles and other hydrogen-consuming units.

A. Gaseous Hydrogen Delivery

Gaseous hydrogen can be transported using compressed H_2 pressure vessels (refer to the 'Hydrogen Storage Technologies' section) arranged in tube trailers, or via gas pipelines.

A.1. Pipelines for Gaseous Hydrogen Transportation

The United States has approximately 2600 km of hydrogen pipelines, primarily located near major hydrogen consumers like refineries and ammonia plants [43]. To extend pipeline usage for hydrogen delivery across the U.S., a substantial expansion of dedicated hydrogen pipelines is necessary [44]. Consequently, the feasibility of utilizing the existing natural gas pipeline infrastructure for hydrogen distribution is being explored by researchers and policymakers.

A.2. Tube Trailers for Gaseous Hydrogen Transportation

Transportation of hydrogen gas via tube trailers has been a focus of the Department of Energy (DOE) and its collaborators for several years. HEXAGON Lincoln's report [45] outlines the development of a high-pressure tube trailer named TITAN, with an operating pressure of 250 bar and a total hydrogen capacity of 616 kg, given that the mass of hydrogen stored is approximately 7% of the tank weight. Tube trailers offer a relatively simple infrastructure requirement and leverage the extensive knowledge gained from the gaseous storage and transportation of other gases. Another advantage is the minimal hydrogen loss and lower compression costs at fueling stations, which, according to Elgowainy et al. [46], can be reduced by 60% compared to liquid hydrogen transportation. However, challenges such as liner blistering at high pressures, high manufacturing costs of Composite Overwrapped Pressure Vessels (COPVs), limited storage capacity, and regulatory constraints on dimensions and tank pressures exist.

B. Liquid Hydrogen Transportation Systems

Despite the previously mentioned energy losses, liquid hydrogen delivery is considered economical for high demands (above 500 kg/day) and mid-range distances [47]. The California Air Resources Board (CARB) [48] predicts that hydrogen fueling stations will likely be supplied by liquid hydrogen by 2020-2025 due to its higher storage capacity. Cryogenic hydrogen delivery involves three stages: liquefaction, storage (as discussed in the 'Compressed H_2 Storage' section), and transportation using cryogenic tanks. North America currently has eight liquefaction plants with a daily production capacity of 5-10 metric tons. To meet future market demands, the development of liquefaction plants with higher production rates, reduced specific energy consumption, lower capital costs, and increased efficiency is required. Cardella et al. [49,50] have explored optimized approaches for large-scale, economically viable liquefaction processes. Additionally, Asadnia and Mehrpooya [51] proposed a new large-scale liquefaction method with an energy consumption of 7.69 kWh/kgL H_2, compared to the current range of 12.5 to 15 kWh/kgL H_2 in existing plants.

C. Hydrogen carriers (material based)

Material-based hydrogen delivery presents an opportunity to enhance safety standards in hydrogen transportation. This method typically involves lower storage pressures and exhibits manageable properties under ambient conditions. Additionally, it offers favorable gravimetric density compared to gaseous storage, where, as noted in the context of tube trailers, the weight of hydrogen constitutes only 7% of the tank's total weight. However, material-based delivery systems may not be suitable for high-demand scenarios. For a more comprehensive analysis of this method, including its limitations and advantages, refer to the section titled 'Material-Based H_2 Storage.'

4. RISK AND RELIABILITY ASSESSMENT IN HYDROGEN SYSTEMS

This section of the study undertakes a comprehensive assessment of the risk and reliability factors impacting hydrogen storage and delivery systems. It categorizes and elucidates factors that could adversely affect these systems' reliability (as detailed in Table 2), discusses the estimation of remaining useful life as a measure of component-level reliability, and reviews quantitative risk and reliability assessment studies pertinent to hydrogen systems. Moreover, it addresses the challenges in conducting reliability analysis of hydrogen systems and introduces recommendations for improvements

Table 2: List of factors that can negatively impact the reliability of hydrogen systems

Material properties-related issues	Hydrogen handling-related issues
Hydrogen impact on materials	Temperature variation
Liner blistering	Compression process
Damage mechanisms of carbon fibers	Pressure fluctuation
Fire encounter of COPVs	Hydrogen leakage
	Contamination

FIGURE 5 FRP PIPELINE INSTALLATION [62].

5. CRITICAL ISSUES AND RELATED STUDIES IN MATERIAL PROPERTIES

Effects of Hydrogen on Material Properties

The phenomenon of hydrogen embrittlement is a significant concern in steel materials. Various studies have explored this issue in different steel types. For instance, Siddiqui and Abdullah [52] demonstrated an increase in ductility reduction in 0.31% carbon steel with prolonged hydrogenation. Hardie et al. [53] assessed the susceptibility of X60, X80, and X100 steel types to hydrogen embrittlement under the influence of cathodic protection systems. Their findings indicated a notable difference in embrittlement susceptibility at charging current densities above 0.44 mA/mm². Capelle et al. [54] conducted burst tests on notched X52 pipes exposed to hydrogen, identifying a critical hydrogen concentration that significantly reduces local fracture resistance. Further, Amaro et al. [55] formulated the fatigue crack growth in X100 steel, and Nanninga et al. [56] compared the embrittlement behaviors of X52, X65, and X100 steel under high-pressure hydrogen gas, concluding that embrittlement susceptibility increases with hydrogen pressure and alloy strength.

Alternative Material Solutions

One strategy to mitigate the impact of hydrogen on pipeline steel is the utilization of Fiber Reinforced Polymer (FRP) materials. A DOE-funded project by Savannah River National Laboratory (SRNL), in collaboration with FRP pipe manufacturers like Fiber Spar Line Pipe, LLC [58], has been investigating the use of FRP pipelines since 2006. FRP, commonly used in the upstream oil and gas industry, offers advantageous mechanical properties and installation benefits. According to Rawles et al. [58], FRP pipelines can significantly reduce installation costs and have been accepted into the ASME B31.12 (Hydrogen Piping and Pipelines Code) for service up to 170 bar. Additionally, the study by Sandia and Oak Ridge National Laboratories [59] examined the behavior of steel pipeline welds in the presence of hydrogen gas.

Considerations for End-User Impact

The impact of hydrogen on end users, such as natural gas turbines and gas-fueled engines, remains a subject of ongoing research, with projects like NATURALHY [60] and $H_2$1 [61] providing some insights. However, there is still a lack of extensive operational data to fully assess this impact. An alternative approach involves extracting hydrogen from natural gas pipelines at city gates and then distributing it within cities using different methods. This strategy could address end-user concerns but necessitates thorough reliability and economic assessments of the extraction units, along with optimization of their locations based on cost, risk, and safety considerations

Liner Blistering in Composite Overwrapped Pressure Vessels (COPVs)

In COPVs, a polymer liner, integrated with a metallic boss and wrapped in carbon fiber composites, ensures vessel sealing. However, under high pressure, this plastic liner can absorb hydrogen gas, leading to blistering if depressurization occurs too rapidly, preventing the trapped gas from diffusing out. Yersak et al. [63] developed a model to predict liner blistering based on liner thickness and depressurization rate. Pepin et al. [64] constructed a test rig to replicate liner blistering on small samples through explosive decompression, bypassing the need for full-scale cylinder testing. This innovative approach accelerates the understanding of liner failure. Factors influencing blistering include liner permeability under varying pressures and temperatures, liner thickness, maximum cylinder pressure, residual pressure post-emptying, and the rate of depressurization. The effect of blistering on pressure vessel leakage and appropriate materials and manufacturing processes for prevention are areas requiring further investigation (refer to Fig. 6)

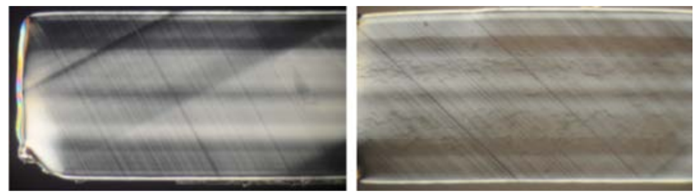

FIGURE 6 HDPE LINER BEFORE (ON THE LEFT) AND AFTER (ON THE RIGHT) HYDROGEN CYCLING [45].

Damage Mechanisms in Carbon Fiber Composites

Composite pressure vessels are complex structures whose properties depend on numerous parameters. Understanding the physics behind fiber breaks, delamination, matrix cracking, dome geometry's impact on burst pressure, and resistance to various types of impacts is crucial for designing reliable storage vessels. Ramirez et al. [65] accurately predicted burst pressure in a 700-bar type IV hydrogen vessel with a 7.74% error margin. Wu et al. [66] analyzed damage mechanisms in carbon fibers under various impact conditions, and Demir et al. [67] observed a 47% decrease in burst pressure due to single and repetitive impacts on glass fiber-reinforced composite pressure vessels. Given the variability in composite material properties based on stacking procedures and fiber density, accurately predicting these properties is challenging. Probabilistic approaches, as suggested by Ref. [65], may provide a feasible path forward in predicting fiber failures

Resistance to Fire and High Temperatures in Storage Vessels

The use of resins and polymers in storage vessels raises concerns about their operational temperature limits, as they are generally more susceptible to high temperatures than metallic materials. Understanding composite materials' behavior in fire, especially for onboard applications, is critical due to the varied locations and conditions a vehicle might encounter. Ruban et al. [68] conducted fire tests on fully composite hydrogen storage vessels, finding minimal pressure increase before bursting and a burst delay time of 6-12 minutes, which may be inadequate. Saldi and Wen [69] successfully simulated a Type IV cylinder's response to fire, predicting burst delay accurately. However, current designs still face challenges in fire resistance. Common protection methods include Thermally Activated Pressure Relief Devices (TPRDs), which release vessel contents at elevated temperatures to prevent explosions. Modifications in TPRD design, as proposed by Ruban et al., could significantly reduce hydrogen flame length. Applying intumescent paints on vessel exteriors, as studied by Kim et al. [70], can also enhance fire resistance. Additionally, Kuroki et al. [71] demonstrated the efficacy of container walls in reducing radiative heat flux from nearby fires, suggesting multiple strategies for improving the fire resistance of hydrogen storage tanks, including protective containers, TPRDs, and improved design and material properties

Hydrogen Handling-Related Issues: Temperature Variation

Temperature fluctuations within tanks during filling and emptying, as well as in fueling station nozzles, pumps, and compressors handling hydrogen, are critical factors for material and design selection. CFD simulations and experimental measurements during these processes [74-76] are vital for understanding the optimal placement of measurement devices, particularly in onboard applications. External temperature monitoring as a proxy for internal tank temperature is being explored for its convenience but requires extensive calibration. Long-term temperature variations can affect the lifespan of storage vessels, underscoring the need for design enhancements.

Hydrogen Leakage in Storage and Delivery Systems

Hydrogen molecules, due to their small size and light-weightness, have a propensity to permeate materials and penetrate seals. Comparative studies have shown that the volume leakage rate of hydrogen in steel and ductile gas distribution systems is approximately three times that of natural gas. This becomes increasingly significant in long-distance pipeline systems featuring thousands of weld lines, numerous valves, pumps, and several compressor stations. An analysis of Germany's natural gas pipeline indicated a 0.00005% gas leakage rate for a 17% hydrogen-natural gas blend [77]. This necessitates further research and empirical data to better estimate gas loss, particularly in on-board applications where composite materials offer lower weights compared to metallic vessels. Research is currently focused on the crack and cycling behavior of liner-less full-composite COPVs and cryogenic fuel storage systems [78-80]. The study of gas leakage from elastomeric seals and joints in hydrogen systems, such as the behavior of plastic and rubber seals in high-pressure hydrogen environments [81-83], is also crucial. Detection of hydrogen leaks, particularly in enclosed areas, is a critical safety concern. Advances in sensor technology for detecting odorless and colorless hydrogen are discussed in detail by Hubert et al. [84].

Contamination Risks in Hydrogen Transportation

If existing natural gas pipelines are repurposed for hydrogen transport, the presence of corroded spots could lead to hydrogen contamination. This would necessitate purification processes, particularly for applications like fuel cells. Lubricating oils in pumps and compressors, as well as water degassing from polymer liners in composite storage vessels, are additional contamination sources. Studies like those reviewed by Cheng et al. [85] have explored how contamination affects fuel cell performance, but further research is needed to evaluate potential contamination sources and compensation methods.

Compression Process Challenges

The compression and pumping power required for hydrogen gas is higher than that for natural gas due to hydrogen's lower molar mass and one-third volume energy density compared to natural gas. This necessitates more compression power, leading to higher tip speeds in compressors, accelerated degradation, shorter maintenance periods, and other reliability concerns, unless compensated for by design modifications.

Pressure Fluctuations in Hydrogen Pipelines

Whether using existing natural gas pipelines or dedicated hydrogen pipelines, pressure fluctuations are inevitable due to variable renewable energy production rates and fluctuating hydrogen demand. Yu et al. [86] demonstrated that pressure cycles can significantly accelerate corrosion crack propagation in X60 steel pipes. This finding underscores the need for detailed analyses of pressure fluctuation impacts on pipeline integrity. Pellegrino et al. [87] modeled green gas injection into the natural gas network and concluded that bulk storage facilities are necessary to balance system input and output fluctuations in Power-to-Gas (P2G) concepts. This highlights the importance of developing durable and reliable large storage vessels, a relatively unexplored research area. Further studies are required to estimate fluctuation amplitudes, characterize impacts, and design control scenarios.

6. REMAINING USEFUL LIFE ESTIMATION IN HYDROGEN SYSTEMS

Concept and Importance

Remaining Useful Life (RUL) estimation is a critical element in the lifecycle management of components and systems, particularly in the context of hydrogen economy applications. It refers to the predicted duration a component or system can effectively serve its intended purpose before requiring replacement. RUL estimation can be derived from direct observations such as condition and health monitoring, inspection data, average lifespan estimates of similar components or systems, or hybrid methodologies combining these approaches [88]. This estimation is integral to condition-based maintenance prognostics and health management, influencing safety evaluations, budgeting, and maintenance strategies.

Application in Hydrogen Economy

Components and systems within the hydrogen economy can be categorized into two groups: those with extensive in-field data (e.g., methane reforming production plants, cryogenic storage vessels) and those relatively new with limited field experience (e.g., Composite Overwrapped Pressure Vessels (COPVs), hydrogen fueling station systems). The latter group's limited operational history necessitates extensive simulations, experiments, and field tests to inform development strategies for the hydrogen economy (HE). Fuel cells, for instance, have seen considerable research and accurate analysis regarding RUL estimation, leveraging advanced prognostics and estimation methods [89-91]. This research intensity has enabled the commercial availability of fuel-cell vehicles. Similar attention and research efforts are imperative for other new HE subsystems.

7. QUANTITATIVE RISK AND RELIABILITY ASSESSMENT IN HYDROGEN INFRASTRUCTURE

Role and Process

Quantitative Risk Assessment (QRA) is a tool designed to inform decision-making processes about a system, without being a decision-maker itself. It typically involves evaluating whether the risk level in a system is As Low as Reasonably Practicable (ALARP). The common steps in conducting a QRA are outlined in Fig. 7 [92].

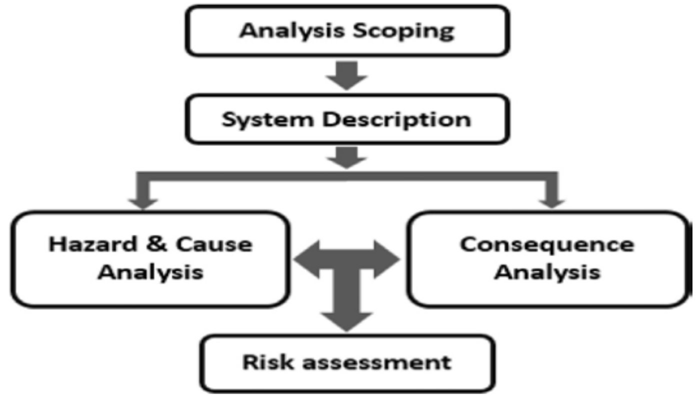

FIGURE 7 MAIN STEPS OF THE QRA PROCESS.

Challenges in Hydrogen Infrastructure

Hydrogen infrastructure, particularly in the transportation sector, lacks the depth of historical data characteristic of natural gas systems, posing a challenge to credible QRA. Despite these challenges, several studies have attempted to advance this field. For example, Zhiyong et al. [93] performed a QRA on a hydrogen refueling station in Shanghai, assessing safety distances based on $EIHP_2$ criteria. Jafari et al. [94] conducted a comprehensive QRA for a hydrogen generation unit, identifying high-risk areas and safety parameters. Kikukawa et al. [95] applied risk assessment techniques to a liquid hydrogen fueling station, creating risk matrices and implementing safety measures. However, the diversity in assumptions and methodologies across these studies makes it challenging to develop a uniform guideline for designing hydrogen systems for the envisioned hydrogen economy.

Summary of Challenges and Gaps

The risk and reliability analysis of hydrogen systems face several challenges and gaps, including:

- Scarcity of data on degradation, failure, and accidents
- Need for detailed and validated probability models for hydrogen gas ignition
- Accuracy and modeling challenges in flame and gas detection
- Complexity in comprehensive Computational Fluid Dynamics (CFD), Finite Element (FE) simulations, or their combination
- The need to factor in environmental and human impacts
- Variability in analysis outcomes due to differing assumptions.

Addressing these challenges is essential for advancing the reliability and safety of hydrogen systems within the broader context of the hydrogen economy.

8. RECOMMENDATIONS AND FUTURE RESEARCH DIRECTIONS IN HYDROGEN SYSTEMS

Data Collection and Modularization

Enhancing the quality of risk assessment in hydrogen systems necessitates the establishment of a comprehensive, accessible database and the development of widely accepted physics-based formulations and probability models, integrated with established risk analysis tools and methods. Notable efforts, such as the Hydrogen Incident and Accident Database (HIAD) [98] and ARIA [99], are underway, gathering and categorizing data essential for risk assessment. The general categorization of Quantitative Risk Assessment (QRA) data in hydrogen systems is depicted in Fig. 8. To accurately assess risks and predict consequences of various scenarios, detailed knowledge of hydrogen's physical behavior under different conditions and its interaction with materials is required. Initiatives like Sandia National Lab's HyRAM tool [100] are instrumental in this regard. HyRAM incorporates failure probabilities for hydrogen system components, ignition probabilities, and models for assessing the impact of heat flux and pressure on humans and structures. It also models hydrogen release and flame behavior, facilitating faster consequence analysis by reducing the need for comprehensive CFD modeling. HyRAM calculates risk metrics such as Fatal Accident Rate (FAR), Average Individual Risk (AIR), and Potential Loss of Life (PLL), and has built-in models for the physical behavior of hydrogen jets, jet fires, and deflagrations.

Expanding Bayesian Networks Application

Bayesian Networks (BNs) are increasingly used in risk and reliability assessments due to their ability to incorporate diverse information sources and support decision-making processes. BNs can handle a wide range of complex systems, from single components to entire fueling stations or production plants. The flexibility of BNs in integrating new information to refine models and reduce uncertainties is particularly advantageous. Recent studies have demonstrated BNs' effectiveness in various industrial systems, including chemical process plants and natural gas fueling stations, which share similarities with hydrogen systems. For example, Haugom and Friis-Hanse [117] successfully applied BN to reevaluate the risks of a hydrogen fueling station. Pasman and Rogers [118] used BN to compare risks between liquid and gaseous hydrogen fueling stations, finding that compressed hydrogen fueling stations with truck delivery pose the lowest risk. Despite its potential, BN's application to large systems faces challenges due to computational complexity and memory requirements. Innovations like compression algorithms [119] are addressing these issues, but further research is needed.

Higher-Level Reliability and Feasibility Analysis

Addressing large-scale utilization of hydrogen as an energy source raises critical questions about distributed production protocols, maintenance, safety regulations, permissible impurity levels, and measurement errors. While exact analysis might be challenging, lessons from large-scale natural gas utilization can provide insights. Research on the operation of extensive, interconnected hydrogen production, storage, and delivery networks is crucial for hydrogen's widespread adoption as an energy carrier.

9. CONCLUSION

This paper has meticulously examined the evolving landscape of hydrogen storage and delivery, highlighting significant strides in material compatibility, storage capacities, and simulation accuracy, while also acknowledging persisting challenges. Despite advancements in technologies like cryogenic and compressed storage, issues like energy inefficiency and large-volume requirements pose constraints. Composite storage vessels and material-based storage methods are promising but require further research to enhance reliability and ascertain long-term viability. Gaseous delivery using tube trailers faces economic limitations, making liquid hydrogen tankers and pipelines more viable for extensive demands.

The selection of an appropriate delivery method must consider regional characteristics, demand, and economic factors, with the centralization or distribution of hydrogen production playing a critical role in this decision. A glaring gap in this field is the scarcity of comprehensive experimental data, especially at the system level. To bridge this gap, systematic data collection and analysis are imperative. The integration of advanced modeling techniques, like quantitative risk assessments and Bayesian analysis, is essential for robust, system-level evaluations and safety assessments. The hydrogen safety community should also capitalize on the latest sensor technologies and predictive maintenance methods to advance safety and maintenance practices.

Overall, this analysis emphasizes the necessity for ongoing research and development in hydrogen storage and delivery, focusing on enhancing safety, reliability, and economic viability to realize the full potential of this vital energy resource.

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