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Review

Current Options and Future Trends in Green Fuels Storage

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Abstract

The global transition to renewable energy underscores the urgent need for safe, efficient, and cost-effective storage solutions for green hydrogen and green ammonia. This review critically examines their fundamental characteristics and unique behaviours, emphasising storage, handling, and integration engineering challenges. To identify the influential studies, knowledge gaps and future trends in the research area, a systematic Scopus-based bibliometric and data analysis is conducted. A novel approach is adopted to identify the better green energy storage option between green hydrogen storage and green ammonia storage, combining a risk-mitigation assessment framework, strengths, weaknesses, opportunities, threats (SWOT) analysis, and a multicriteria taxonomy based on the properties and behaviour of hydrogen and ammonia. This study also analysed and reviewed the performance of the hydrogen and ammonia storage system across technical, thermomechanical, safety/risk and economic dimensions. This review further addresses the limitations in technological bottlenecks, unresolved safety concerns and current simulation approaches to evaluate the performance of green hydrogen and green ammonia. The identified limitations open doors to future research priorities in this research area, including the techno-economic viability, standardisation, and modelling accuracy of hydrogen and ammonia storage systems. The evaluation presented by this study allows for precise identification of suitable energy storage based upon various operational and economic contexts.

Keywords: green energy storage; hydrogen storage; ammonia storage; SWOT analysis; risk-mitigation adaptability framework; performance analysis

1. Introduction

Fossil fuels have been the main energy source since they were discovered, but the burning of these fuels vastly contributes to carbon emissions and climate change. Traditional fossil fuels could be replaced by increasing renewable and clean energy sources, which is a meaningful way to achieve decarbonisation [1]. Electricity or power generation through renewable energy sources, such as wind and solar, refers to green energy. Energy curtailment is the most common drawback of such renewable energy sources, which is due to the fluctuation in power generation. This variability in energy generation through renewable energy sources is because of the dependency on the availability of wind and sunlight. Integrating energy storage systems with renewable energy generation units can play a vital role in diminishing energy curtailment. A massive capacity of energy storage systems is required to enhance the stability and security of the energy supply. A large-scale energy storage system would be beneficial to handle the massive energy-generating farms of wind and solar systems [2].

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Academic Editors: Alberto Pettinau and Zhiqiang Xie

Received: 10 March 2026
Revised: 18 April 2026
Accepted: 3 May 2026
Published: 7 May 2026

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Various energy storage systems are practically in use around the globe; each are tailored to the technical requirements and constraints of energy storage. Some energy storage technologies have reached maturity, but others are still in advancement, with a focus on improving their design, optimisation, and management strategies. Traditional methods for storage, like the electrochemical or the mechanical, are beneficial only for limited operation ranges. The conjunction of multiple constraints and limitations with conventional energy storage systems makes them less efficient and reduces their applicability, such as energy density, long-term energy storage, and low ecological footprint [3]. These limitations can be overcome by chemical energy storage (CES), which was fostered by necessity as the technical solution to the interrelated problems of renewable intermittency, long-term energy storage, and carbon abatement. CES redefines space and time scales for storage so that an enormous amount of energy can be stored for times that mechanical flywheels or arrays of lithium-ion batteries can hardly begin to approach [4].

Among various CES, green hydrogen and green ammonia storage systems are potential candidates providing the solution for large-scale and long-term energy storage. Produced from renewable electricity through water electrolysis (for hydrogen) and nitrogen fixation (for ammonia), they facilitate the decarbonisation of difficult-to-electrify sectors like long-distance transport, shipping, and heavy industry [5]. They have high energy density and can be stored for long periods, making them suitable for levelling out intermittent renewables like wind and sunlight and for seasonal and intercontinental storage. Green ammonia, for example, provides transport and handling benefits from its liquid state at moderate conditions, while green hydrogen provides direct use towards industrial processes and fuel cells. Storing excess renewable power in such storable fuels allows us to stabilise the power grid, minimise curtailment, and provide an uninterrupted, continuous energy supply, finally making the global transition to net-zero emissions possible [5].

Hydrogen storage has a range of technologies, including high-pressure gas compression, liquid cryogens, and chemical and physical hydrogen storage, e.g., metal hydrides and organic hydrogen carriers. Similarly, ammonia storage at an industrial scale is mainly accomplished through three large-scale techniques: high-pressure storage, cryogenic refrigeration, and semi-refrigerated systems. All these methods take advantage of the physical properties of liquefied ammonia; however, its use is contingent on various factors such as the desired storage capacity, working parameters, and cost-effectiveness [4].

Compressed green hydrogen and liquefied green ammonia offer promising options for large-scale renewable energy storage but face significant challenges. Compressed hydrogen tanks must withstand very high pressures (up to 700–900 bar) while minimising leakage and hydrogen embrittlement, which weakens metallic alloys and composite materials. Structural integrity is compromised by cyclic pressurisation, permeation through polymer liners, thermal stresses caused by rapid temperature changes, and crack growth in embrittlement conditions, which all threaten long-term durability [6]. The weight is reduced by using carbon-fibre composites, but this raises costs and complicates inspections. Similarly, ammonia storage tanks or vessels for liquefied ammonia, such as atmospheric refrigerated vessels at -33 °C or pressurised tanks at 10–15 bar, are no longer technologically extreme but present unique hazards of toxicity, stress-corrosion cracking (SCC), and boil-off gas handling [5].

Although the production and use of green hydrogen and green ammonia are progressing rapidly, there is a substantial lack of research in the comprehensive evaluation of the storage performance and challenges of both alternatives. The existing literature reviews tend to analyse green hydrogen and ammonia storage separately, with a fragmented focus on storage methods, safety, and/or economic viability, but rarely integrate these perspectives into a unified framework. Tahir et al. [7] recently conducted a review study that

identifies critical technoeconomic challenges, specialised infrastructure for material embrittlement, and safety concerns regarding hydrogen production and storage. Various technical research and review studies provide valuable insights into a single storage method, such as pressurised hydrogen storage tanks; however, there remains a gap in the analysis of the thermodynamic performance, structural dynamics, safety risks, and techno-economic challenges for hydrogen and ammonia side by side.

This review addresses the above-mentioned research gaps by methodically categorising the existing status of green hydrogen and green ammonia storage technologies and critically assessing their technical, thermo-mechanical, safety, and economic dimensions. The subsequent points elucidate the objectives and aims of this study:

- To conduct a comparative analysis, which will allow for determining the suitability of hydrogen or ammonia storage, depending on the primary purposes and features of energy storage requirements.
- To identify potential research trends, influential work, gaps, and future directions of knowledge through an absolute evaluation of the existing literature.
- To perform a systematic analysis of the simulation techniques used to analyse the performance of green hydrogen and green ammonia storage systems with a particular focus on the methodological trends and emergent best practices.
- To identify constraints, obstacles, threats, and technological issues associated with the current storage options of green hydrogen and green ammonia.

This study adopts a holistic approach and provides a decision-making basis for developing highly scalable, safe, and cost-effective infrastructures for storing green hydrogen and ammonia.

2. Review Methodology and Data Analysis

2.1. Literature Search Strategy

The bibliometric analysis process and technique employed in this paper encompasses two stages: (1) data collection and (2) data analysis. This methodology presented the science mapping, content analysis, and keyword cluster prominence to ensure transparency and reproducibility. Figure 1 shows the illustrative overview of the methodological framework employed in this study.

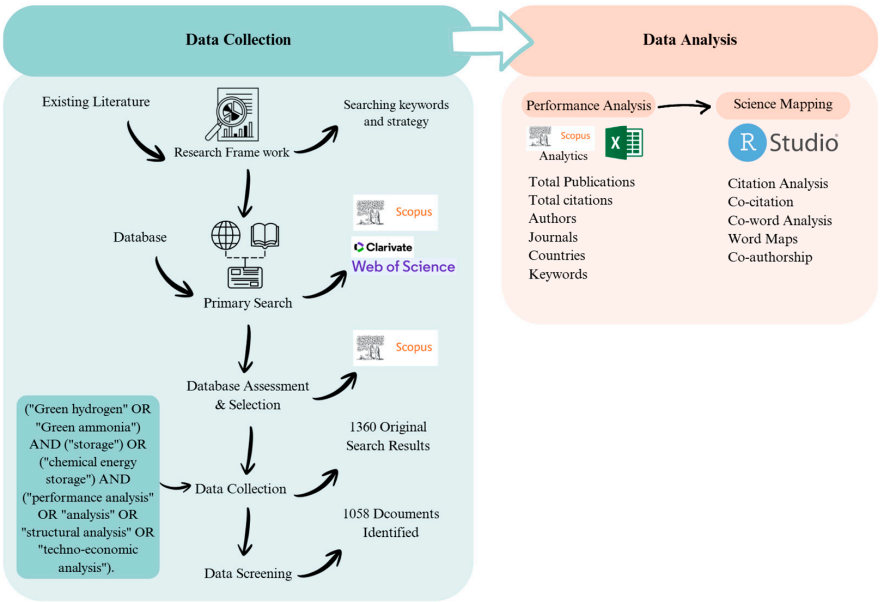

Figure 1. Methodological scheme for a bibliometric study.

Techniques for bibliometric analysis fall into two groups: scientific mapping and performance analysis. The quantitative methods used in this study's approach include citation analysis on bibliometric data, which refers to publication and citation units. In performance analysis, the productivity, effect, and influence of academic publications, researchers, institutions, or nations are assessed and measured using quantitative indicators derived from bibliographic data. To assess research performance, the current study uses three indicators: total publications (TP), total citations (TC), and h-index. The largest number of publications that have gotten at least that number of citations is the h-index, which is a measure of both production and impact.

Science mapping is a method of data analysis and visualisation that investigates bibliographic data to examine the evolution and organisation of scientific subjects. Science maps enable academics to investigate significant research themes, collaborations, and trends in a subject, as well as to spot possible research gaps or new areas of interest by seeing patterns and links among publications, authors, institutions, and keywords. The performance analysis of the green hydrogen and ammonia storage systems is examined in this paper using scientific mapping, which includes the following.

2.2. Search Strings/Key Words

The search strategy combined the keywords related to the green hydrogen and ammonia storage system performance analysis using Boolean operators (AND, OR). The search strings chosen for Scopus and Web of Science (WOS) were themed: ("Green hydrogen" OR "Green ammonia") AND ("storage") OR ("chemical energy storage") AND ("performance analysis" OR "analysis" OR "structural analysis" OR "techno-economic analysis").

2.3. Database Selection

A critical component in determining the accuracy and reliability of bibliometric analysis for research evaluation is the selection and scope of scientific field databases. Scopus, Web of Science, Google Scholar, PubMed, IEEE Explore, and Science Direct are the top databases for scholarly research. Two widely recognised and competitive citation databases that are crucial for the various research objectives covered in this study are WoS and Scopus. Large-scale bibliometric studies have benefited greatly from these databases, with WoS historically serving as the primary source of information for published research until Scopus emerged as a competitive alternative.

2.4. Study Design

All the data presented in this bibliometric analysis were gathered from "Scopus" by Elsevier. Specific Boolean strings were chosen for the Scopus search, which were themed: ("Green hydrogen" OR "Green ammonia") AND ("storage") OR ("chemical energy storage") AND ("performance analysis" OR "analysis" OR "structural analysis" OR "techno-economic analysis"). Microsoft Excel and "R" version 4.3.3 (R Studio) were used to analyse the characteristics of the research publications. The search period selected in Scopus is from the date of first publication until the 18th of August 2025. The results extracted from Scopus are based upon the following, as shown in Figure 2:

- Type of the document and its language.
- Traits of the published document, e.g., total number of citations.
- Performance of the researcher/author.
- Co-citation and collaboration of the research.

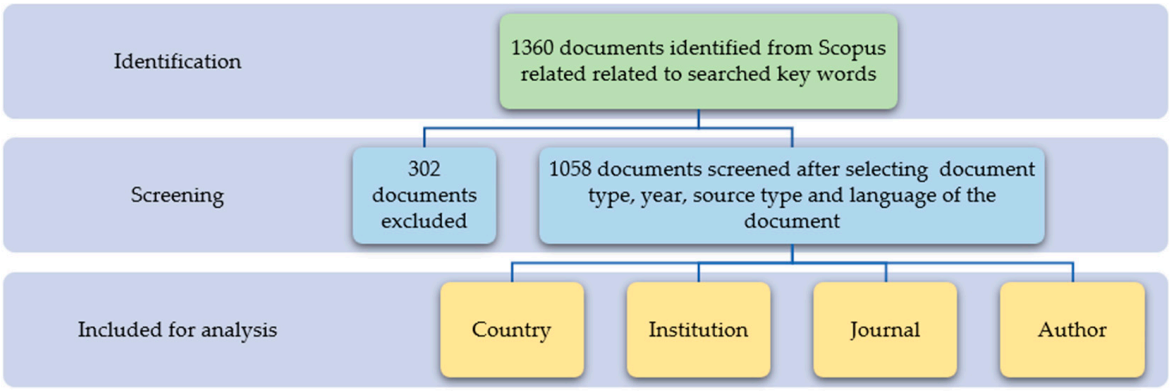

Figure 2. Selection procedure for bibliometric study.

2.5. Data Analysis and Interpretation

Characteristics of Published Documents

A total of 1058 documents published related to green hydrogen and green ammonia storage and their analysis fulfil the selection criteria for this bibliometric analysis. Figure 3 shows the annual publication pattern and the mean total citations per article since the first article was published in 2009. The data included in the analysis is from 2009 to 2025, focusing on published articles from 2020 to 2025, because the years from 2009 to 2020 have very few studies published, most of which are referenced in the recent studies published from 2020 to 2025.

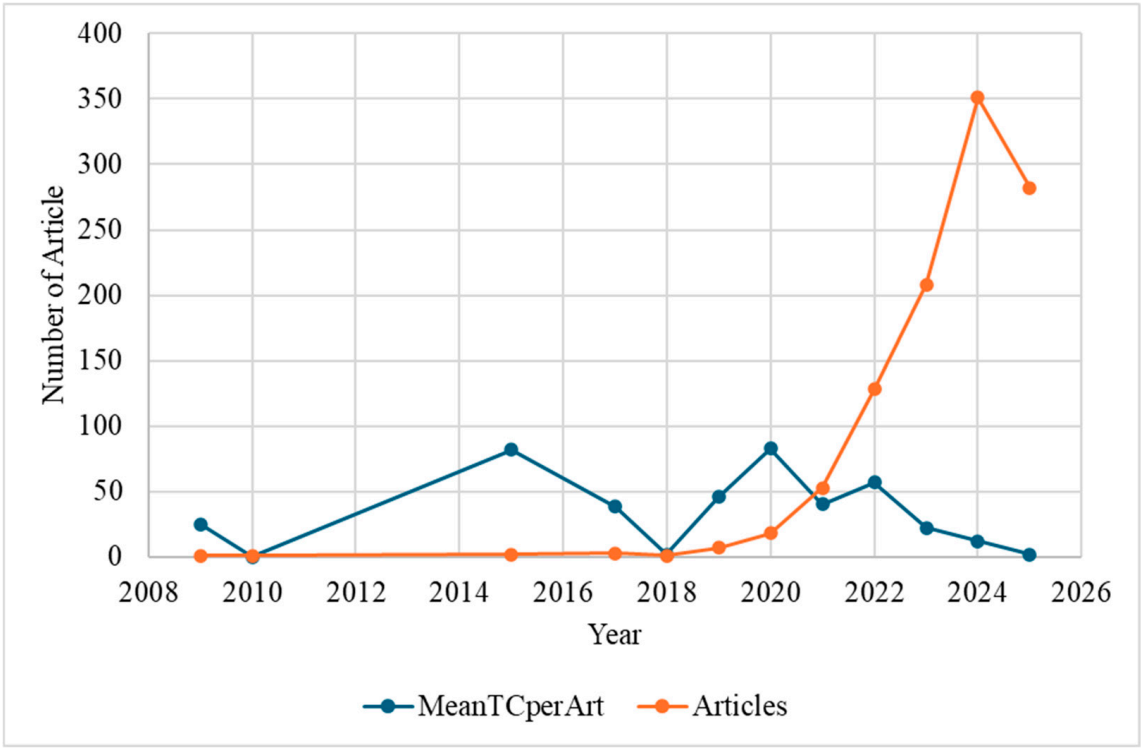

Figure 3. Trend of total publications and mean citation per article yearly.

Similarly, Figure 4 shows the number of published documents concerning the subject area. Most of the research has been published on the subject of "Energy" with 743, followed by the subject of "Engineering" with 419 articles and then "Environmental Sciences" with 243 publications.

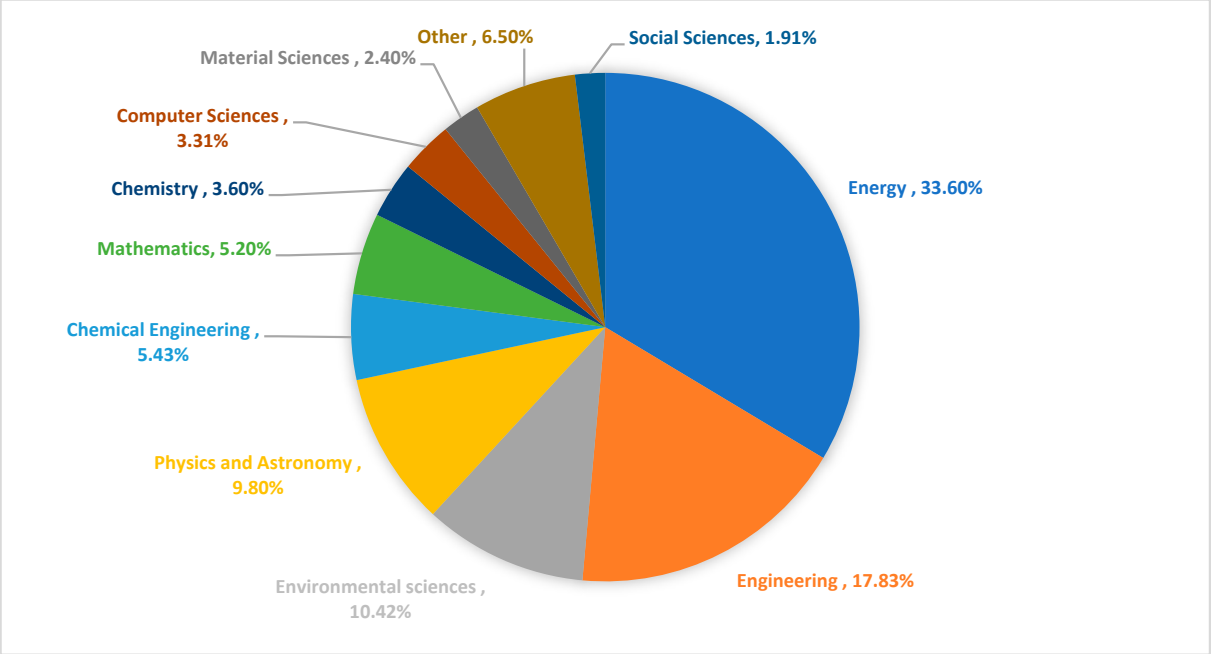

Figure 4. Number of published articles with respect to the subject area.

Table 1 depicts the top 10 journals by number of publications, total citations, and h-index. The *International Journal of Hydrogen Energy*, *Applied Energy*, *Energy Conversion and Management*, and *Energies* have been identified as the best impact journals for documents published on green hydrogen and ammonia storage systems.

Table 1. Impact of the top 10 journals based on the total citations of all the documents since their first publication year.

Element	h_Index	Total Citation	No of Publications	Publication Year Start
International Journal of Hydrogen Energy	41	6366	172	2019
Applied Energy	26	1896	43	2017
Energy Conversion and Management	25	2267	54	2021
Energies	17	1045	60	2019
Journal of Energy Storage	13	551	27	2015
Fuel	10	319	12	2019
Energy	9	291	29	2023
Journal of Cleaner Production	9	323	19	2022
Renewable and Sustainable Energy Reviews	9	781	15	2022
Renewable Energy	8	691	27	2022

There were 2895 authors who worked on green hydrogen and ammonia storage, and three of the documents were single-authored. The top 10 authors with several publications, total citations, and h-index are listed in Table 2.

Table 2. Top 10 authors' impact based on the number of publications and total citations.

Element	h-Index	Total Citation	No of Publication	Publication Year Start
Dincer I	3	1118	4	2021
Crawford CA	2	1067	2	2022
Ishaq H	2	1067	2	2022
Gazzani M	2	663	2	2020
Mazzotti M	2	663	2	2020
Jahirul MI	2	546	3	2022
Rasul MGR	2	546	3	2022
Hazrat MA	2	544	2	2022
Sattar MA	2	523	2	2022
Shearer MJ	1	521	1	2022

Keywords reflect the research trends and knowledge structure within a specific field. A network can be constructed by performing a co-occurrence analysis of keywords, where each node represents a keyword, and each link represents the co-occurrence relationship between two keywords. The co-occurrence network is constructed such that each keyword corresponds to a node, and edges are formed when two keywords co-occur within the same context. A connection of order *n* indicates the strength of co-occurrence between two nodes. As illustrated in Figures 5 and 6, the most frequently occurring keywords in the literature include *hydrogen production*, *hydrogen storage*, *green hydrogen*, *green ammonia*, and *techno-economic analysis*, highlighting the dominant research focus areas in this domain.

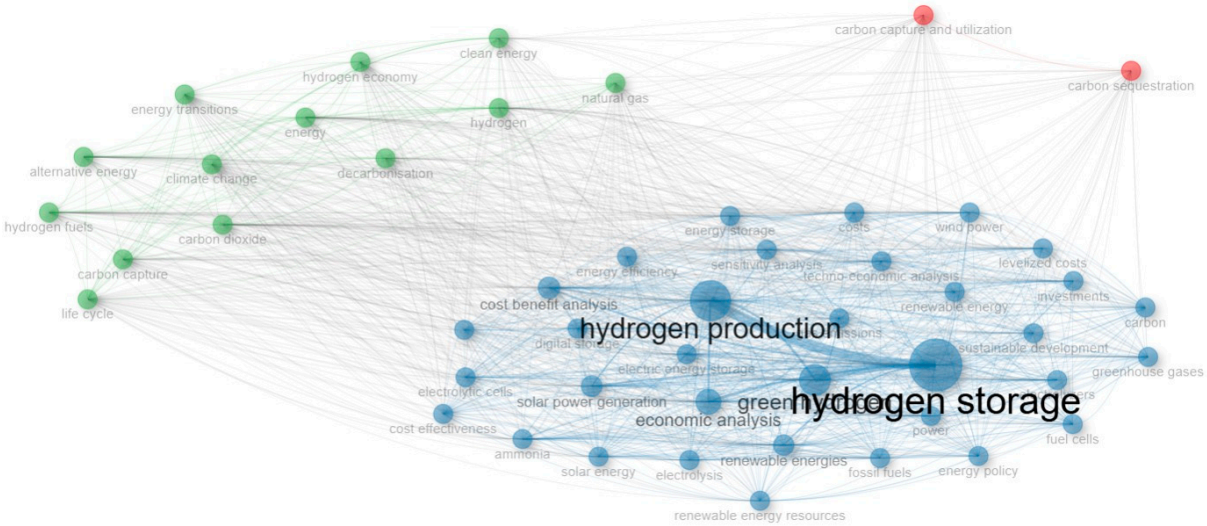

Figure 5. Co-occurrence of the author's keywords.

This bibliometric analysis serves as both an examination of the evolution of research and a data-driven foundation for subsequent analysis and discourse. The bibliometric technique ensures that the review is grounded in a comprehensive and representative dataset by meticulously identifying the most relevant papers, significant research domains, and emerging topics. This bibliometric analysis reveals patterns and deficiencies that directly influence the design of the review, steering attention toward significant yet underexplored topics.

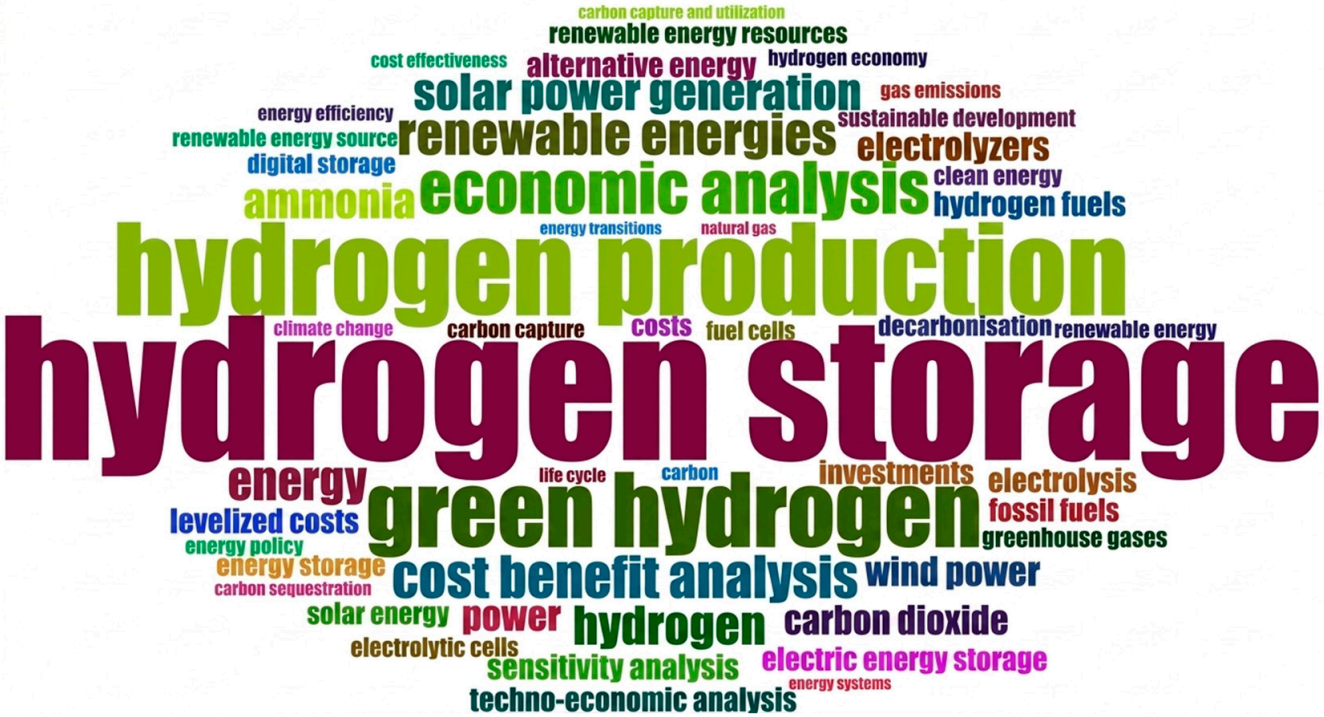

Figure 6. Word map of co-occurrence of authors' keywords.

3. Distinctive Behaviour of Hydrogen and Ammonia

With the footsteps towards the employment of hydrogen and ammonia as clean fuels, we need to know the behaviour of these green fuels in different environments. Both hydrogen and ammonia have unusual properties that lead to strange and sometimes opposite responses. A hydrogen leak, for instance, floats away and vanishes instantly, but is highly flammable. Similarly, ammonia release acts in predictable ways in different environments. The gas can diffuse easily in the air and is highly soluble in water. It will react to form the ammonium ions, and some hydroxide ions can form a corrosive alkaline solution. An ammonia leak behaves differently and sinks, sticking to surfaces and leaving a toxic cloud. The way they react with metals, soil, water, and fire is particularly unorthodox compared to ancient fuels such as gasoline or natural gas. This peculiarity is needed in a manner that enables the establishment of secure storage, transport, and use systems for a clean future. Table 3 shows the peculiar behaviour of hydrogen and ammonia in different environments.

To select appropriate storage systems and identify associated safety issues, it is essential to understand the precise physicochemical properties of hydrogen and ammonia. These qualities dictate their thermodynamic behaviour, interactions with other materials, and modes of failure. The design of storage is not an independent engineering choice but a direct result of constraints imposed by molecular characteristics, such as molecular weight, intermolecular forces, diffusivity, toxicity, and phase equilibrium behaviour. Due to its minimal molecular mass and weak intermolecular forces, hydrogen has a low volumetric energy density, high diffusivity, and significant permeability through standard materials. This necessitates storage under high pressure or freezing conditions, which also presents hazards such as leakage, jet fires, and hydrogen embrittlement in metals. Conversely, ammonia exhibits robust intermolecular hydrogen bonding, enabling it to transition into a liquid state at comparatively low pressures. Nonetheless, it is highly poisonous, corrosive upon contact with water, and emits irritating vapours, which pose distinct safety hazards, including the danger of acute exposure and environmental contamination. It is essential to

understand these fundamental properties immediately, since they directly influence the feasible storage conditions, material compatibility requirements, energy penalties, and safety system design. The absence of this fundamental information may result in the selection of a storage system that yields designs that are inefficient, perilous, or technically unfeasible, particularly in large-scale and offshore energy applications where the consequences of containment failure are far more severe.

Table 3. Distinctive behaviour of hydrogen and ammonia: compatibility in different environments, challenges, and novel insights.

Environment	Ammonia Behaviour and Challenge	Hydrogen Behaviour and Challenge	Novel Insights/Research Gap
Confined Space (e.g., tunnel)	Mixing ammonia with air in a confined environment will be slow, but a small amount can reach a lethal concentration [8].	It will create a homogenous mixture in a confined space such as a tunnel, which will be highly explosive [9].	Development of various sensor network architectures: H_2 sensors must have wide coverage because of explosion hazard; NH_3 sensors must be deployed at the floor level to avoid toxicity.
High-Temperature Environment (Combustion)	Combustion of ammonia in air leads to very high NOx emissions (without using advanced catalysts) [10].	It will produce NO_X when burned in air, a potential pollutant [10].	Summary of current research on ultra-low NOx combustor technology for ammonia and blends of ammonia and hydrogen. This is a critical research frontier.
Atmospheric Leak (Open Air)	Because it is high-density compared to the air, it will form ground-hugging plumes, which are highly toxic and pose an environmental risk [11].	There is a low risk of accumulation at ground because it will move upward rapidly, but it has a high ignition risk [12].	Advancements in CFD models of leak dispersal for these two green fuels in urban, rural, and marine environments. Which is safer, depending upon the context?
Soil and Groundwater (Pipeline Leak)	Ammonia hydrolyses to ammonium and hydroxide ions, leading to a severe alkalinity spike that is devastating for soil and water biology [13].	Minimal chemical interaction will displace oxygen, potentially harming the root system [14].	Development of "self-healing" or "smart" pipelines designed to find and seal leaks for these two green fuels.
Marine Environment (Shipping)	Ammonia is well-soluble in water, so a spill would create a toxic, oxygen-depleting plume that would harm aquatic life [15].	Boil-off gas management is complex due to its low boiling point, which requires venting or reliquification [15].	Compare the environmental effect of an imagined NH_3 spill with the GHG effect of H_2 boil-off venting (if not combusted).
Behaviour with materials (Storage and transportation)	Liquid ammonia caused SCC by attacking high-strength steels and alloys in the presence of a trace amount of water and air [8].	Hydrogen molecules can damage the material properties, leading to surface cracking and catastrophic brittle failure under stress [16].	Finding the material compatibility solutions. Hydrogen in metallurgy: austenitic stainless steels, aluminium alloys, and composites. Ammonia, purity, and inhibitors are the questions: keeping anhydrous and adding chemical additives to passivate the surface.

4. Hydrogen Storage Technologies

Hydrogen has become an important source of energy and will be a key part of the world's plan to reduce carbon emissions. Hydrogen is a promising alternative to fossil fuels due to its high gravimetric energy density as a clean fuel, particularly in regions in which it is hard to electrify robust sectors of transportation and industry, such as steelmaking. A hydrogen-based economy is naturally limited by a severe physical issue, which is that hydrogen is a low-density gas at high pressure. This inherent feature results in low power per unit volume, underscoring the need to develop superior hydrogen storage methods to address the issue of low energy density so it can be used practically. There are physical and material-based methods of hydrogen storage. Both groups have different approaches to hydrogen storage management, and each has advantages and limitations. Figure 7 illustrates the methods of hydrogen storage.

4.1. Compressed Hydrogen (CGH_2)

This method involves holding hydrogen gas at a high pressure, usually 350 bar (5000 psi) or 700 bar (10,000 psi), thereby increasing its volumetric density. For many uses,

including hydrogen tank systems for cars, this method is the easiest and cheapest way to go. Light-duty cars need a lot of hydrogen (5–13 kg) to go a long way, which is why these high-pressure tanks are necessary [17]. Figure 8 shows different kinds of cylinders for storing compressed hydrogen.

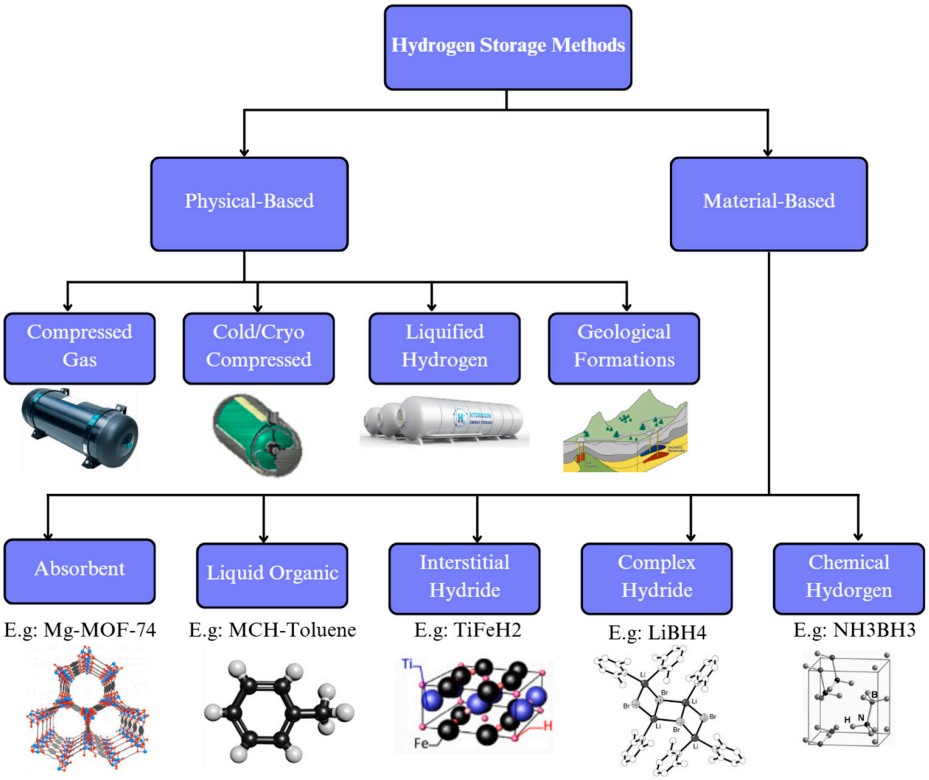

Figure 7. Hydrogen storage methods.

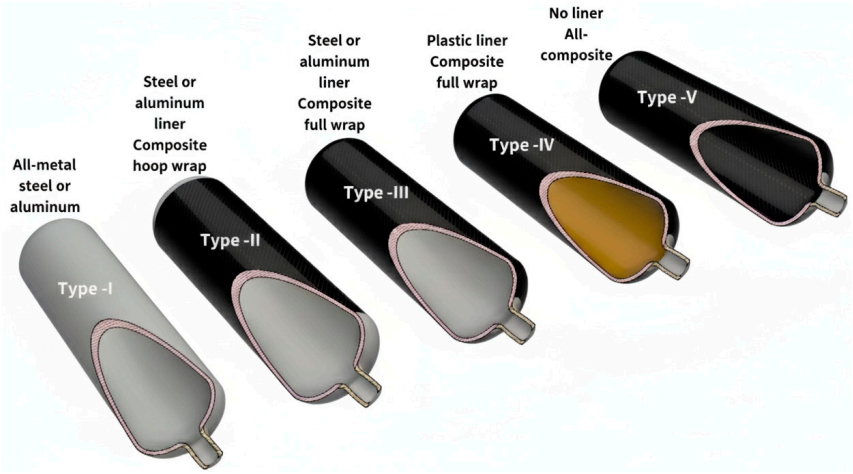

Figure 8. Various types of compressed hydrogen storage cylinders.

Recent engineering advances have aimed to make these high-pressure tanks safer and more efficient. Figure 9 displays the SWOT analysis for storing hydrogen in a compressed form. Compressed hydrogen requires significant energy, thereby affecting the overall storage efficiency. After the compression process, hydrogen remains in the gaseous form; therefore, no cryogenic losses are involved. Compression of hydrogen does not occur because of any chemical reaction, so there are no reaction kinetics involved. Hydrogen molecules, due to their small size, can diffuse into many metallic surfaces, inducing em-

brittlement, but the shift to lighter, more advanced composite cylinders has addressed this penalty.

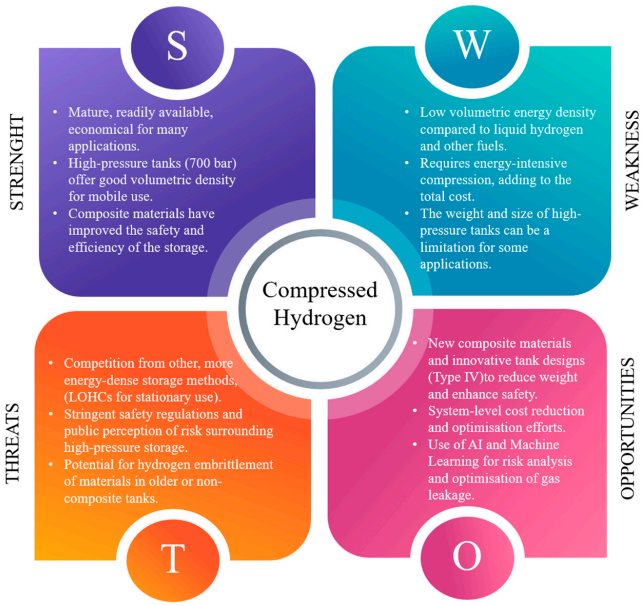

Figure 9. SWOT analysis of compressed hydrogen.

4.2. Liquid Hydrogen (LH_2)

This storage involves cooling hydrogen to cryogenic temperatures, specifically its boiling point of approximately −252.8 °C, at which it transforms into a liquid. This method achieves a significantly higher volumetric energy density than compressed gas, making it a viable option for applications where space is at a premium. A compelling example of systems-level innovation is the cryogenic system for aircraft developed by researchers from Florida universities. This system does not stop at enhancing the tank with liquid hydrogen as the cooling gas for the main energy bearers of the aircraft, including superconducting generators and power electronics. This design is multi-purpose, addressing three issues. This multi-purpose design solves three problems simultaneously: reliable storage, fuel supply, and hardware cooling. Another physical storage method involves cryo-compressed hydrogen (CCH_2) storage, which combines a high pressure and low temperature to achieve an even greater density than either compressed or liquid hydrogen alone. Figure 10 shows the SWOT analysis for liquified hydrogen storage [18].

4.3. Material-Based Storage: (Absorbents and Hydrides)

Material-based storage systems store hydrogen within a solid or liquid material through physisorption or chemisorption. Physisorption involves the physical adsorption of hydrogen molecules onto the surface of a highly porous material through weak Van der Waals forces. This process requires low temperatures and high pressures to be effective. Promising materials for physisorption are zeolites, activated carbons, and metal–organic frameworks (MOFs). Chemisorption is the chemical process of binding the hydrogen atoms onto a material matrix. This is a reversible process; an example is metal hydrides, in which hydrogen is adsorbed into a metal matrix at moderate pressures and temperatures and desorbed by heating. Chemical storage is the storage of hydrogen using chemical bonds with other substances, such as methanol, ammonia, or liquid organic hydrogen carriers (LOHCs) [19]. LOHCs are particularly interesting because they are like oil and can be easily managed and transported through the existing fossil fuel infrastructure. The SWOT analysis of hydrogen storage based on the material is presented in Figure 11. A major limitation of material-based hydrogen storage is the reversible release of hydrogen from

the carrier substance. Most MOFs and hydrides are super expensive, which increases the capital cost of storage. Moreover, structural degradation and capacity fade may occur during repeated daily cycles.

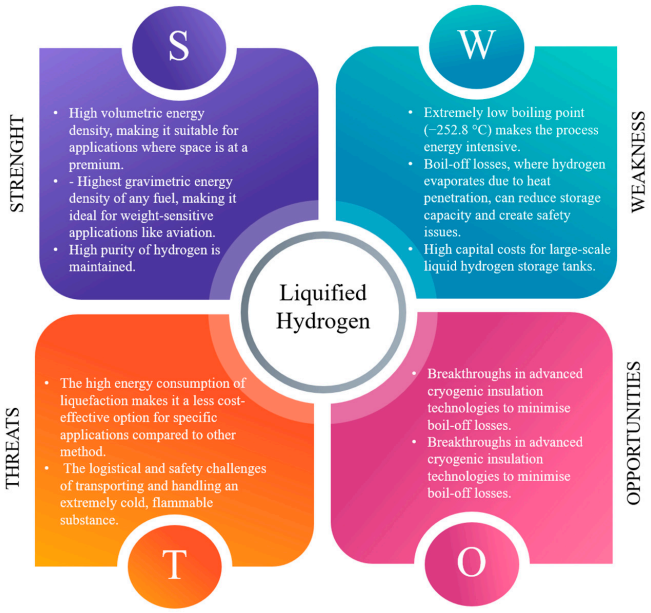

Figure 10. SWOT analysis of liquified hydrogen.

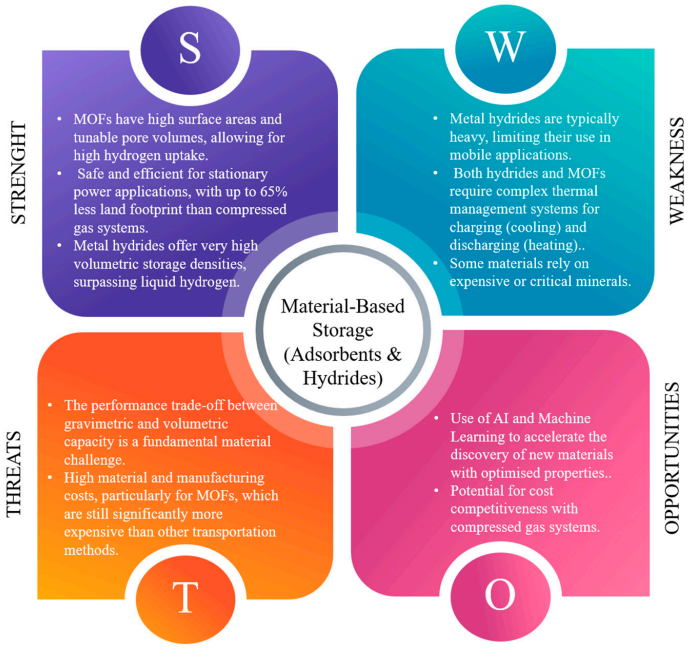

Figure 11. SWOT analysis of material-based hydrogen storage.

4.4. Geological Storage (Hydrogen)

Surface-based systems are insufficient in both capacity and long-term seasonal storage. Geological storage of underground hydrogen storage (UHS) in salt caverns, depleted gas reservoirs, and aquifers can provide a high capacity to offset the intermittency of renewable energy sources. An example is salt caverns, which can store terawatt-hours (TWh) of hydrogen and are therefore suitable for buffering during a long-duration event [20]. The SWOT analysis of geological hydrogen storage is presented in Figure 12.

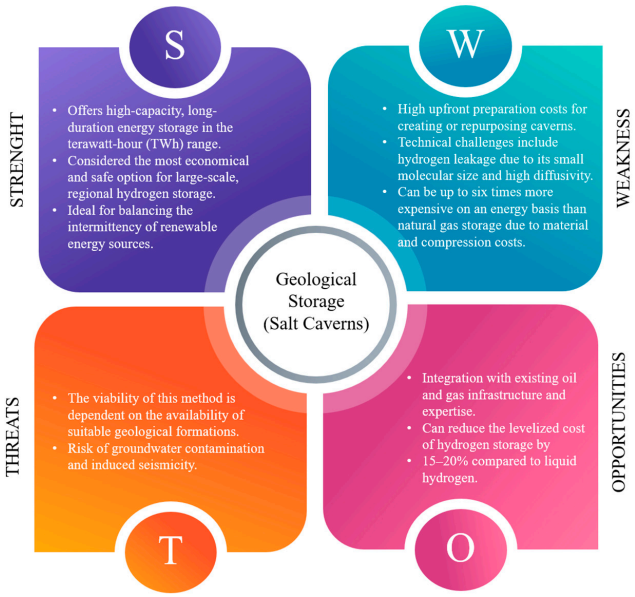

Figure 12. SWOT analysis of geological hydrogen storage.

4.5. Comparative Multicriteria Taxonomy of Hydrogen Storage

Choosing the optimal hydrogen storage technique is a complex challenge, driven by a fundamental physical trade-off. Although hydrogen has a very high gravimetric energy density, its low volumetric density at ambient temperature poses a considerable challenge to its practical storage and transportation. Therefore, there is no single perfect solution, because every technology is characterised by a unique problem set that is specific to its particular use. An example is compressed gas storage, which is an established and easily accessible commodity but, nevertheless, loses volumetric density and automobile range. Techniques such as ammonia and metal hydrides have far higher volumetric efficiency, with the smaller ones shown with smaller icons in Figure 13. Although compact ammonia needs a system to convert it to hydrogen, this is complex and energy intensive. Hydrogen is absorbed within the structure of metal hydrides, making it a safe, compact solution. Nonetheless, they are still prone to issues with weight, cost, and hydrogen release and uptake kinetics. Liquefied hydrogen is smaller than compressed gas, but it requires cryogenic temperatures that require a lot of energy to maintain. LOHCs operate under mild conditions and require a reactor. The most compact systems of hydrogen storage are metal hydrides and cryogenic liquid storage, where one kilogram of hydrogen only requires 25–14 L. Liquid organic hydrogen carriers have the potential to have relatively low volume requirements, which does not include the reactor required to free the hydrogen. The combination of these conflicting issues, including the cycle performance, economics, and safety, makes the decision a multi-dimensional optimisation problem.

Figure 14 presents a radar chart showing trade-offs in hydrogen storage technologies. There are always strengths and weaknesses associated with any system, and thus, there is no best solution for all situations. For example, compressed gas is characterised by a high gravimetric density and stability, but complex safety considerations hold it back. Liquid hydrogen offers the best density for mobile use, but its cryogenic requirements are costly, complex, and hazardous. Being safe and with a higher volumetric density, metal hydrides have a heavy structure, which decreases their gravimetric efficiency and economic feasibility. Likewise, metal–organic frameworks strike a balance between density and simplicity, yet have safety, durability, and cost issues. Liquid organic hydrogen carriers are non-toxic and stable yet have low density, and they require a great deal of energy to release hydrogen. Lastly, the most efficient and secure method for large-scale use is underground

storage, but its practicality depends on certain geological factors. Finally, the graph shows that the ideal hydrogen storage system depends solely on the application's requirements.

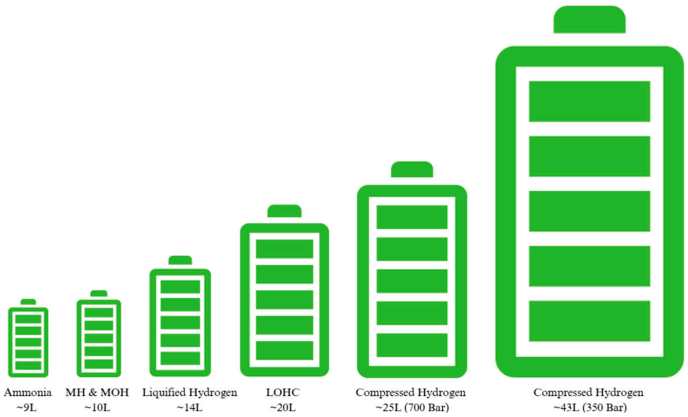

Figure 13. The approximate volume requirement to store one kg of hydrogen using different methods.

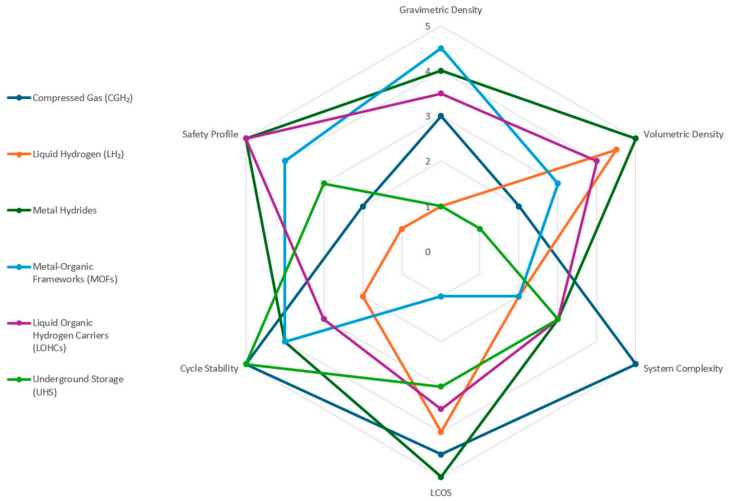

Figure 14. Radar chart comparative analysis of hydrogen storage methods based on economic and environmental factors.

4.6. Risk-Mitigation Adaptability Framework for Hydrogen Storage

The issue of hydrogen storage requires a multi-layered, systematic approach to the sensitive, complex, and interrelated risks. The Risk-Mitigation Adaptability Framework (RMAF) is presented to provide a holistic methodology and systematic measures for the safety assurance of hydrogen storage. It is not merely a checklist of hazards but a system of integrated and dynamic safety management.

Table 4 realises the RMAF philosophy. It also schematically charts the specific risks associated with compressed hydrogen storage against the stacking layers of risk-mitigation controls. Such a structure provides clear, critical information to ensure the safety of storage facilities. It links the practical "what" (the controls) to the strategic "why" (the hazard) and the crucial "how" (the standards and learning loop).

The proposed Risk Mitigation Adaptive Framework (RMAF) is adaptable not due to the incorporation of machine learning or autonomous feedback control, but because it can be systematically reconfigured utilising designated mitigation modules. The framework autonomously aligns risk categories with context-specific control mechanisms, including the operating environment, system scale, and degree of exposure. This ensures that mitigation methods are adaptable for diverse hydrogen and ammonia infrastructure applications while being comprehensible to engineers and accessible to regulators.

Table 4. Risk-Mitigation Adaptability Framework for hydrogen storage systems.

Risk Category and Specific Hazard	Preventive Controls (Engineered and Procedural)	Detection and Continuous Monitoring	Corrective and Emergency Actions	Adaptability and Learning Loop	Governing Codes and Standards
Material Integrity					
Hydrogen Embrittlement in Steel Components (Piping, Valves, Type I Vessels)	Engineered: Material selection per code (e.g., austenitic stainless steels); controlled material processing to minimise residual stress. Procedural: Strict hydrogen purity specifications to limit embrittling contaminants [21].	Acoustic emission (AE) monitoring: Real-time detection of crack initiation and growth. Periodic inspection: Non-destructive testing (NDT), such as advanced ultrasonic testing, is performed during scheduled shutdowns [22].	Automated: Trigger alarm at pre-defined AE activity threshold. Manual: Isolate affected section; conduct detailed inspection; replace component based on condition [23].	Analyse AE data trends to develop predictive maintenance models for component replacement. Conduct failure analysis on any cracked components to validate material selection.	ASME B31.12, ASME Boiler and Pressure Vessel Code [24]
Fatigue Cracking in Composite Overwrapped Pressure Vessels (COPVs)	Engineered: Vessel design validated through extensive pressure cycle testing (e.g., 5000+ cycles) and burst tests per regulations. Procedural: Adherence to specified fill rates and temperature limits to minimise stress [25].	AE monitoring: Continuous monitoring for fibre breakage and delamination events during filling and operation. Embedded Sensors: Integration of strain gauges or fibre optics to monitor structural health [22].	Automated: Activate vehicle dashboard warning or station alarm based on AE signal. Manual: Immediately remove the vessel from service for detailed NDT or replacement [22].	Correlate AE data with operational history (fill cycles, pressures) to refine vessel life prediction models. Share anonymised failure data with manufacturers and standards bodies [26].	FMVSS No. 308, ISO 19885-1 [27]
Operational and Component Hazards					
Leak from High-Pressure Fitting or Seal	Engineered: Use of high-integrity fittings designed for hydrogen service; minimise the number of connections. Procedural: Strict, documented assembly and torquing procedures; leak testing (e.g., with helium) after assembly [26].	Ultrasonic gas leak detection (UGLD): "Hears" the high-frequency sound of a pressurised leak for rapid detection. Electrochemical/catalytic sensors: Detects H_2 concentrations at parts-per-million (ppm) levels in targeted areas [28,29].	Automated: Trigger emergency shutdown system to isolate source; activate ventilation systems; sound alarms. Manual: Site evacuation per emergency plan; approach from upwind [30].	Conduct root cause analysis (RCA) on every leak, regardless of size. Use findings to refine assembly procedures, component selection, or maintenance frequency [31].	NFPA 2, ISO 26142 [32]
Catastrophic Vessel Rupture (e.g., from fire impingement)	Engineered: Installation of thermally activated pressure relief device (TPRD) on vessel. Procedural: Facility layout and siting with adequate separation distances to prevent fire spread [33,34].	UV/IR flame detectors: "Sees" the nearly invisible hydrogen flame. Thermal imaging cameras: Detect heat from fire or vessel impingement [28].	Automated: TPRD activation vents hydrogen to prevent a burst, creating a large jet fire. Activate fire suppression (e.g., water mist) to cool adjacent structures. Manual: Evacuate to a safe distance; coordinate with emergency responders [35].	Analyse fire test data and incident reports to validate TPRD performance and vent stack design. Use QRA to model fire scenarios and optimise facility layout [30].	NFPA 2, FMVSS No. 308 (Fire Test) [36]
Systemic and Human-Factor Risks					
Incorrect Assembly or Maintenance (e.g., wrong part, improper torque)	Engineered: Use of poka-yoke (mistake-proofing) designs, such as unique fittings for different pressures. Procedural: Rigorous management of change (MOC) process; detailed work instructions with verification steps; competency assurance for technicians [37].	Procedural: Independent verification or "double-witness" sign-off for critical assembly steps. Post-maintenance testing: Mandatory leak and function testing before returning to service [26].	Manual: Stop work authority for any personnel who observes a procedural deviation. Isolate the system and correct the error before proceeding.	Investigate all maintenance-related near-misses and incidents. Use findings to improve training, procedures, and component design for easier, error-proof assembly [38].	Internal Safety Management System (SMS)

Table 4. *Cont.*

Risk Category and Specific Hazard	Preventive Controls (Engineered and Procedural)	Detection and Continuous Monitoring	Corrective and Emergency Actions	Adaptability and Learning Loop	Governing Codes and Standards
Formation of Explosive Atmosphere in Confined Space	Engineered: Locate equipment outdoors where possible. For indoor locations, design high-rate ventilation systems (natural or forced) directed upwards. Procedural: Strict ignition source control (e.g., hazardous area classification, intrinsically safe electronics).	Point H_2 sensors: Placed at high points and near potential leak sources to detect accumulation. Ventilation monitoring: Airflow sensors to confirm the ventilation system is operating correctly [29].	Automated: At low H_2 concentration (e.g., 25% of LFL), activate high-rate ventilation and alarms. At high concentration (e.g., 40% of LFL), trigger ESD and de-energise non-rated equipment [28].	Use computational fluid dynamics (CFD) modelling to validate ventilation design and sensor placement. Review and update hazardous area classifications based on operational experience [39].	NFPA 2, IEC 60079-10-1 [40]

The RMAF operates in three phases: (i) identifying and categorising risks, (ii) associating hazards with repositories of mitigation strategies, and (iii) selecting and prioritising controls according to the particulars of each situation. This framework enables identical risks to elicit varied actions for mitigation, which are contingent upon the system's surroundings. Take as an example the adaptability of this RMAF through the demonstration of "urban hydrogen refilling" vs "offshore hydrogen ammonia systems" shown in Figure 15.

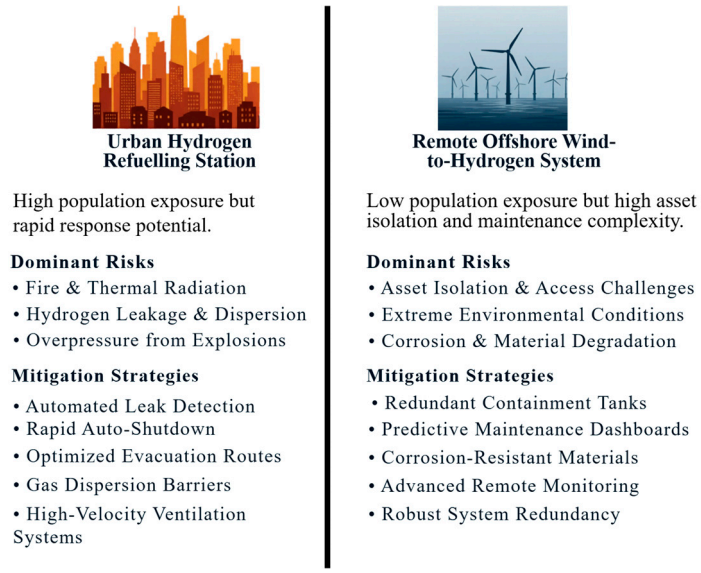

Figure 15. Demonstration of RMAF for urban and offshore hydrogen storage.

5. Ammonia Storage Technologies

The key to the worldwide energy shift lies in developing large-scale, cost-effective storage for renewable energy. As a zero-carbon chemical, green ammonia is becoming a strong and viable energy carrier that will speed up this transition. Any energy storage method needs to be analysed in terms of its strategic landscape, technical maturity, safety, and environmental impact before implementation.

Ammonia has been a silent workhorse of world agriculture for over a century and is traditionally produced by an outdated method (also referred to as grey ammonia), at a high cost in terms of severe environmental impact. This industry is a major source of carbon dioxide emissions, estimated to account for about 1.8 percent of total global emissions, by relying on fossil fuels and a carbon-intensive process called steam methane reforming (SMR). The transition to the world's low-carbon future requires a different strategy to mitigate carbon emissions from ammonia synthesis, and that solution is known

as "green ammonia". It represents a paradigm shift, with renewable electricity powering the entire production process, making it completely carbon-free [41]. Green ammonia is not only a decarbonised form of an industrial chemical but a flexible energy vector with a distinct strategic value proposition in the clean energy ecosystem. To start with, ammonia is a remarkable hydrogen carrier. The technical and economic challenges of storing and transporting hydrogen hinder its widespread adoption as a clean fuel. Ammonia does not face the same difficulties as hydrogen storage. At atmospheric pressure, it can be liquefied at room temperature under a low pressure of about 10 bar and chilled to −33 °C. These requirements are much less than the −253 °C of liquid hydrogen. This makes ammonia a cost-effective and efficient way to store and transport renewable energy [42].

5.1. Technical Taxonomy of Ammonia Storage

There are various forms of ammonia storage, which can be classified into established physical systems that are prevalent in the industry and emerging chemical and geologic storage methods that promise to give the industry a new identity.

5.1.1. Pressurised Storage

This is the process of storing anhydrous ammonia in the liquid state at an ambient temperature in high-pressure containers. In the past, this has encompassed spherical "Horton spheres" and cylindrical "bullets". These are designed to sustain a pressure of 13.5 bar at 38 °C, which occurs when ammonia is stored at a higher temperature. The Horton spheres, characterised by evenly distributed stress and high strength, are employed in medium- and high-pressure containment and can withstand up to 2000 tonnes of ammonia. Contemporary pressure vessels are tailor-made and must meet stringent safety standards, including those established by the American Society of Mechanical Engineers (ASME) and the Occupational Safety and Health Administration (OSHA). The transportation efficiency of pressurised systems is exceptional, but they are not suitable for the utility-scale storage needed for the energy transition, since they are not as safe and cost more capital per unit of volume [43].

5.1.2. Fully Refrigerated (Atmospheric/Cryogenic) Storage

The most common large-scale bulk storage at plant sites and distribution terminals is fully refrigerated storage (often referred to as atmospheric or cryogenic storage). According to this technique, liquid ammonia is kept at −33 °C and atmospheric pressure. This is better, as it is safer and cheaper to install per unit volume; thus, it is the preferred choice for bulk storage [44].

These large-scale tanks have undergone significant design modifications. Old single-wall steel tanks are considered less secure, although cement bunds are still used to contain spills. This industry has since shifted to double-containment tanks, which feature an inner steel tank and an outer tank with perlite insulation. The current best practice, quantitative risk assessment (QRA), recommends the use of two-integrity (DWDI) and double-wall tanks to achieve an as low as reasonably practicable (ALARP) level of risk. These DWDI tanks are designed to hold the entire contents of the inner tank, with the outer tank serving as a secondary line of defence in the event of an initial failure. The safe operation of atmospheric tanks is essential and requires stringent engineering controls. The high concrete slab foundations are piled to avoid frost heave, which can damage the foundation or the tank itself when frozen ground thaws. Other critical components include pressure and vacuum relief valves to prevent overpressure or air ingress, a permanent vaporiser to control pressure, and remote shut-off valves for emergency use. One technical requirement is that ammonia must have a minimum moisture content of 2000 ppm to prevent stress-corrosion cracking (SCC) [45].

5.1.3. Material-Based Solid-State Storage

This new technique is used to store ammonia in solid form through the chemical bonding of the ammonia with a host material. This reversible, non-pressurised process has the potential to address the toxicity and the high-pressure/temperature conditions required by conventional storage. There are two major materials that are good candidates for host materials for bonding ammonia: metal–organic frameworks (MOFs) and metal halide ammines. Metal halide ammonia-based ammines containing cobalt and nickel are promising because they can contain a high ammonia content and can be stored at room temperature. On heating, they can release ammonia on demand, providing a controlled release. On the same note, MOFs are crystalline porous materials that can be designed to exhibit a high ammonia adsorption capacity. Recent work provided a titanium-based MOF that a study found to have an extraordinary ammonia adsorption capacity, signalling the potential of this family of materials as future storage media [46].

5.1.4. Geological Storage (Ammonia)

Geologic storage is a genuinely progressive idea, suggesting that the planet should be utilised as a geochemical reactor to generate and store ammonia. This is carried out by injecting water and a nitrogen source deep into the rock in the deep subsurface that is rich in iron. The pressure and natural heat of the Earth's crust drive a reaction that yields clean hydrogen, which then reacts with nitrogen to produce ammonia. With a low technology readiness level (TRL), this process could avoid the use of large, centralised above-ground plants, thereby reducing the social and regulatory risks of rejection of such projects by the population [47]. Figure 16 compares the radar chart of the ammonia storage methods, including technical factors such as scalability and energy consumption.

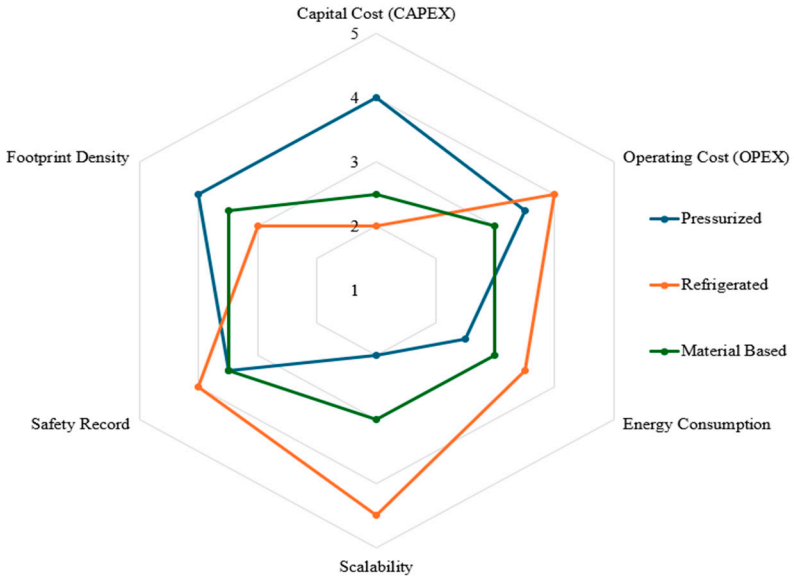

Figure 16. Radar chart comparative analysis of ammonia storage methods based on different technical factors.

5.2. SWOT Analysis for Ammonia Storage

Table 5 presents a strategic SWOT analysis that provides a systematic overview of the forces shaping the future of green ammonia as a clean energy vector, highlighting the main internal strengths and weaknesses, external opportunities, and threats. The framework is important because it provides key insights into the strategic environment and shapes investment and policy decisions. The discussion highlights the advantages and disadvantages of green ammonia, including its higher volumetric energy density than

hydrogen, its long history of international infrastructure, and its significant drawbacks, such as its toxicity, high production costs, and the need for new regulations. Despite the external drivers of its adoption (decarbonisation pressures and favourable government policies), the industry is also facing threats from rival technologies and the substantial capital required to implement a new clean-energy value chain.

Table 5. SWOT analysis of ammonia storage methods.

Category	Factor	Description
Strengths	High Energy Density	Liquid hydrogen's volumetric energy density (12.7 MJ/L) is higher than that of liquid hydrogen, making it an efficient carrier [48].
	Existing Infrastructure	Leverages a century-old global network of storage, transport, and production assets, reducing capital expenditure [49].
	Manageable Storage Conditions	Requires fewer demanding conditions (−33 °C or 10 bar) than cryogenic liquid hydrogen (−253 °C) [50].
	Mature Technology	Large-scale storage tanks are a mature technology with established safety standards like API 620 [51].
Weaknesses	Toxicity and Corrosiveness	Ammonia is a hazardous, toxic chemical that requires extensive safety controls and presents risks to human health and equipment integrity [52].
	High Costs of Storage	Ammonia storage vessels such as Horton spheres and bullets are expensive to fabricate and maintain [53].
	Energy-Intensive Process	Overall efficiency from electricity to ammonia is currently low (45–55%), indicating significant energy losses [54].
	Material Compatibility	Corrosive nature necessitates specific low-temperature carbon–manganese steel and careful material selection to avoid issues like stress corrosion cracking [52].
Opportunities	Policy and Regulatory Support	Governments incentivise green energy adoption through policies and grants (e.g., EU RED III, US IRA) that create a favourable investment climate [54].
	Decarbonisation Pressures	Growing demand for clean fuels in hard-to-abate sectors like the maritime and heavy industries creates a significant new market [55].
	Grid-Scale Energy Storage	Green ammonia's capability for long-duration storage makes it an ideal solution for balancing the intermittency of renewable energy on the grid [56].
Threats	High Capital Investment	Massive upfront capital is required for new facilities, posing a significant financial barrier to project development [57].
	Public Perception	Past incidents and the "dangerous gas" reputation create public opposition, which can stall projects and complicate permitting [58].
	Competition	Green ammonia competes with other clean energy vectors, such as batteries, green methanol, and direct hydrogen, for limited investment and market share [50].
	Fugitive Emissions	Leaks or spills can release ammonia into the environment, causing direct toxic damage to ecosystems and contributing to nitrogen pollution and soil acidification [43].

5.3. Risk-Mitigation Adaptability Framework for Ammonia Storage

The future of green ammonia storage will no longer be characterised by the notion that it is stored, but with a dynamic risk-management strategy. Its large-scale manufacturing, warehousing, and utilisation pose key technical, environmental, and safety concerns, including risks of toxicity and leakage, difficulties in managing the material, and infrastructural limitations. To address them, a Novel Risk Mitigation Adaptability (RMA) Framework is proposed that integrates risk identification, proactive risk mitigation, and adaptive processes in operational scenarios. Furthermore, unlike the conventional approach to safety testing, which focuses on hazard prevention, the RMA framework emphasises flexibility and resilience, enabling ammonia storage and use systems to withstand disruptions

and changes in the technological, legislative, and environmental contexts. This paradigm comprises technological stability, economic viability, and societal acceptance, which is a holistic foundation for the use of ammonia in sustainable energy systems and a high level of safety and flexibility. Table 6 presents the framework for the risk-mitigation adaptability of ammonia storage.

Table 6. Risk Mitigation Adaptability Framework for ammonia storage systems.

Risk Category	Specific Risk	Mitigation Strategy	Adaptability Measure
Technical	Overpressure from overfilling/thermal expansion	Installation of redundant pressure/vacuum relief valves and remote shut-off valves. Use of permanent vaporisers to prevent air ingress. Strict adherence to filling density regulations.	Development of novel synthesis pathways (e.g., electrochemical, geologic) that reduce or eliminate the need for high-pressure storage and transport.
	Vessel failure from material degradation	Use of DWDI tanks and appropriate materials (e.g., impact-tested carbon–manganese steel). Regular inspections via acoustic emission (AE) testing. Maintenance of minimum moisture levels to prevent SCC.	Technological innovation in solid-state storage materials (e.g., metal ammines, MOFs) that are non-pressurised and non-corrosive.
Environmental	Fugitive emissions from leaks	Installation of continuous leak detection systems and sensors. Piped back-up systems route vented ammonia back to the storage tank or to a flare.	Proactive research and development on nitrogen pollution and its impact on biodiversity. Use of closed-loop systems to manage all fugitive emissions and by-products.
	Spills and their ecosystem impact	Robust procedural controls, including emergency response plans and personnel training. Use of water sprays to mitigate gas clouds and contain spills. Elevated foundations and concrete bunds for containment.	Long-term strategy of decentralising production and storage via small-scale plants that can be co-located with end-users (e.g., farms) to reduce transport and logistical risks.
Social	Public opposition due to safety concerns	Transparent communication and public education to address the “dangerous gas” perception. Highlighting the shift to safer DWDI tank designs and modern safety protocols.	The development of underground geologic production and storage to eliminate the visual and perceived risks of extensive, above-ground facilities.
Regulatory	Regulatory uncertainty and fragmentation	Adherence to and promotion of a strong regulatory framework (e.g., API 620, OSHA). Proactive engagement with policymakers to encourage the establishment of clear, harmonised global standards and mandates.	Economic adaptability through using carbon contracts for difference to bridge the cost gap between green and conventional fuels, creating a viable business case despite regulatory delays.

6. Sensitivity Assessment of Hydrogen and Ammonia Storage

The essential value of green ammonia as a better hydrogen carrier and an all-purpose energy vector hinge crucially on its logistical benefits: namely, its high volumetric energy density and an extensive, global storage and distribution system. This legacy infrastructure essentially de-risks the capital investment required to build a new clean energy value chain. The comparison between ammonia and hydrogen storage technologies is presented in Table 7. It gathers the main indicators, including gravimetric, system complexity, cycle stability, safety, and cost. To improve comparability between green hydrogen and green ammonia storage pathways, this study adopts a harmonised analytical framework. Reported performance indicators and cost ranges in the literature often rely on heterogeneous assumptions regarding electricity price, plant capacity factor, storage pressure and temperature, boil-off losses, discount rate, currency year, and energy basis (LHV vs. HHV). Such inconsistencies can lead to misleading conclusions when technologies are compared directly. Therefore, all storage pathways were evaluated using a consistent set of reference assumptions. The functional unit is defined as 1 kg of hydrogen equivalent on a lower-heating-value (LHV) basis. A reference electricity price of 50 USD/MWh, a plant

capacity factor of 70%, and a discount rate of 8% were adopted, with all costs normalised to 2023 USD. Where complete harmonisation was not feasible due to data limitations in the source studies, the original assumptions are explicitly stated to preserve transparency. This structured approach enhances the methodological consistency and strengthens the robustness of comparative assessment.

Table 7. Side-by-side comparison of various hydrogen and ammonia storage technologies based on different factors.

Storage Method	Operating Conditions	Gravimetric Density	Volumetric Density	Round-Trip Efficiency	Levelized Cost of Storage ($/kg$H_2$)
Compressed Gas (CGH_2)	700 bar, Ambient	5–6 wt% H_2	39.8 g/L	30–40%	~$0.25/kg
Pressurised Ammonia Storage	10–15 bar at 20 °C	17.8 wt%	108 g/L 20 °C.	High for short duration	$0.62–0.8/kg
Liquid Organic Hydrogen Carriers (LOHCs)	30–50 bar, 150–200 °C	Different for various LOHCs (5–7 wt% H_2)	Not specified.	60–90% with heat recycling	~$0.65–1.02/kg
Liquid Hydrogen (LH_2) at −253 °C	~1 bar, −253 °C	Highest gravimetric density	70.8 g/L	60–70% of the energy content is lost.	$1.25–1.9/kg
Liquified/ Refrigerated Ammonia Storage	Atmospheric pressure at (−33 °C)	17.8 wt%	121 g/L at −33 °C.	Low	$0.015–0.2/kg
Metal Hydrides	1–10 bar, 25–300 °C	4–8 wt% H_2	Higher than liquid H_2	N/A	~$9–12/kg
Metal–Organic Frameworks (MOFs)	10–100 bar, 25–150 °C	9.1–12.6 wt% H_2 for some MOFs	46.6 g/L for some MOFs	Not specified.	Varies widely, can be high ($11.8–$40/kgH_2)
Underground Geological Storage (Salt Caverns)	50–200 bar, 10–50 °C	Not applicable, measured in TWh	Not applicable, measured in TWh	~40%	~$1.2/kg

This study's comparison analysis is susceptible to economic and operational factors that vary by country, period, and project scale. Table 8 provides a qualitative sensitivity summary to simplify our findings. Changes in seven key factors, including electricity prices, capacity factors, carbon prices, storage lengths, reconversion efficiencies, and transport distances, may determine whether alternative hydrogen and ammonia value chains are feasible. The impact direction (positive or negative) and sensitivity (high, medium, low) are provided for each driver–pathway combination. This shows readers where the conclusions are strongest and most dependent on assumptions.

Table 8. Qualitative sensitivity matrix for hydrogen and ammonia storage.

Key Driver	Compressed H_2	Liquid H_2	LOHC	Ammonia (NH_3)	Impact on Overall Conclusions
Electricity price	✓✓✓	✓✓✓	✓✓✓	✓✓✓	Dominant cost driver for all electrofuel pathways
Renewable capacity factor	✓✓✓	✓✓✓	✓✓	✓✓✓	Strongly affects LCOH/LCOA and asset utilisation
Carbon price	✓✓	✓✓	✓✓	✓✓✓	Particularly shifts ammonia vs fossil benchmarks
Storage duration	✓	✓✓	✓✓✓	✓✓	Favours chemical carriers for long-duration storage
Reconversion efficiency	✓✓	✓✓	✓✓✓	✓✓✓	Critical when electricity regeneration is required
Transport distance	✓	✓✓✓	✓✓	✓✓✓	Long distances favour ammonia and liquid hydrogen

Legend: ✓ = low sensitivity; ✓✓ = medium sensitivity; and ✓✓✓ = high sensitivity.

Selecting the optimal storage technology is a critical decision that is contingent on the application's specific requirements. Table 9 presents a consolidated choice matrix for hy-

drogen and ammonia to facilitate decision-making on storage options. This paradigm links critical applications, such as short-term buffering, seasonal storage, mobility, and industrial use, with the optimal storage solutions for each. It also delineates the primary limits for each coupling, including safety problems, volumetric density, energy losses, system cost, and materials compatibility. This matrix serves as an effective instrument for stakeholders to swiftly identify feasible pathways, discern critical trade-offs, and allocate their development resources towards the most significant technological and economic challenges.

Table 9. Consolidate decision matrix for hydrogen and ammonia storage technologies.

Application	Energy Carrier	Recommended Storage Option	Dominant Constraints
Short-Duration Buffering (e.g., grid stabilisation, daily demand shifts)	Hydrogen	Liquified Hydrogen (LH_2)	✓ Safety (Cryogenic) ☐ Volumetric Density ✓ Losses (Boil-off) ✓ Cost (Liquefaction) ✓ Materials' Compatibility
	Ammonia	Pressurised Storage (small-to-medium)	✓ Safety (Toxicity) ☐ Volumetric Density ☐ Losses ✓ Cost ☐ Materials' Compatibility
Seasonal Storage (e.g., long-term grid balancing, strategic reserves)	Hydrogen	Geological Storage (salt caverns, etc.)	☐ Safety ☐ Volumetric Density ✓ Losses (Leakage/Microbial) ✓ Cost ✓ Materials' Compatibility
	Ammonia	Geological Storage (salt caverns, LRC)	✓ Safety (Toxicity/Env. Safety) ☐ Volumetric Density ☐ Losses ✓ Cost ✓ Materials' Compatibility (SCC risk)
Export/Large-Scale Transport (e.g., intercontinental maritime shipping)	Hydrogen	Compressed Hydrogen (Type I–IV vessels)	☐ Safety ✓ Volumetric Density ☐ Losses ✓ Cost ☐ Materials' Compatibility
	Ammonia	Fully Refrigerated Storage (−33 °C)	✓ Safety (Toxicity) ☐ Volumetric Density ✓ Losses (Refrigeration Energy) ✓ Cost (CAPEX) ✓ Materials' Compatibility
Mobility (On-Board—Light/Heavy Duty) (e.g., FCEVs, trucks, trains)	Hydrogen	Compressed Hydrogen (Type IV, 350/700 bar)	✓ Safety ✓ Volumetric Density ☐ Losses ✓ Cost ☐ Materials' Compatibility
	Ammonia	Fully Refrigerated Storage	✓ Safety (Toxicity/Ammonia Slip) ✓ Volumetric Density ☐ Losses (Boil-off) ✓ Cost ✓ Materials' Compatibility
Industrial Feedstock (e.g., refineries, fertiliser/steel production)	Hydrogen	Geological Storage (large, steady state); Alternatively Compressed/Liquefied	✓ (Geo) or ☐ (Comp) for Safety ☐ Volumetric Density ☐ Losses ✓ Cost ✓ Materials' Compatibility
	Ammonia	Fully Refrigerated (large plants) Alternatively: Pressurised (small depots)	✓ Safety (Toxicity) ☐ Volumetric Density ✓ Losses (Boil-off) ✓ Cost (CAPEX vs. Scale) ✓ Materials' Compatibility

Table 9. *Cont.*

Application	Energy Carrier	Recommended Storage Option	Dominant Constraints
Niche/Specialised Applications (e.g., backup power, portable devices, "battery" replacements)	Hydrogen	Material-Based (Absorbents/Hydrides)	☐ Safety ✓ Volumetric Density ☐ Losses ✓ Cost (Materials) ☐ Materials' Compatibility (Note: Gravimetric Density Is a Key Additional Constraint.)
	Ammonia	Material-Based (Metal Ammine Salts)	✓ Safety (Reduced Vapour Pressure) ✓ Volumetric Density ☐ Losses ✓ Cost (System Complexity) ☐ Materials' Compatibility (Note: Thermal Management Is a Key Additional Constraint.)

Legend: ✓ = primary/dominant factor; ☐ = not dominant (supporting factor).

7. Performance of Hydrogen and Ammonia Storage Systems

Hydrogen and ammonia are at the lead of the international push to decarbonise the energy-intensive industries. Being both a connection between intermittent renewable energy generation and its deployment in numerous end-use forms, such as industrial processes and long-haul transport, they are also known as power-to-X fuels. The thorough analysis of performance is not only an academic endeavour but also the basis for the legitimacy and viability of the massive implementation of a hydrogen-based power economy. This integrated assessment is essential because the performance measures are not isolated; they constitute a critical, interdependent system. The technical efficiency directly controls the total energy losses and, consequently, the system's carbon footprint and sustainability. At the same time, thermomechanical resilience concerns long-term structural integrity and reliability, and material degradation poses a non-trivial threat of catastrophic failure. Moreover, the strong control over safety and intrinsic risks is an unquestionable condition of the population's credibility and acceptance of the regulations. Finally, economic performance, as measured by CAPEX/OPEX and LCOH/LCOA, is the ultimate driver of commercial scalability and competitiveness with existing, traditional fuels. Thus, the deep analysis of performance is not only a yardstick of a system's potential but also a straightforward demonstration of its ability to become a building block of the future energy system.

7.1. Technical Performance

To make the hydrogen economy viable, technical performance is what it all depends on, including the storage performance, boil-off losses, pressure, temperature control, and round-trip efficiency. The low volumetric density of hydrogen is also a major issue, necessitating extreme pressure (up to 700 bar) or cryogenic temperatures (20 K), which demand heavy, costly tanks and subject liquid hydrogen to constant energy and mass loss due to boil-off. In contrast, the high volumetric density of ammonia (1.7 times that of liquid hydrogen) enables it to be stored under significantly less rigorous conditions, whether at 0.99 MPa at room temperature or at −33 C, and simpler, less expensive vessels can be used. A penalty in the energy required to make it an energy carrier, however, is the high round-trip efficiency (RTE) cost, which is 30–40% for hydrogen gas and 20–30% for ammonia. The gaps in the research are in developing better advanced materials and computational models to increase the storage density, and solid-state materials like MOFs and metal hydrides have potential pending issues with thermal conductivity and cost. Further progress should be based on the development of efficient, compact reliquefication or subcooling systems

for hydrogen tanks to remove boil-off, and on new low-temperature catalysts to produce ammonia, thereby enhancing its RTE.

7.2. Thermo-Mechanical Performance

The thermomechanical behaviour of storage systems, especially their stress strain behaviour when subjected to pressure and specific cryogenic temperatures, and their resistance to phenomena such as hydrogen embrittlement and ammonia corrosion influence their long-term durability and safety. Hydrogen embrittlement is a major concern regarding high-strength steel pressure vessels with the diffusion of hydrogen, which can lead to the loss of ductility and an enhanced brittle condition and the probability of catastrophic failure. On the same note, carbon steels exposed to ammonia may develop stress corrosion cracking (SCC), characterised by deep cracks that are difficult to repair. To address these issues, computer-aided tools such as Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) are essential for simulating tank behaviour under stress and for optimising designs. The main gap in the research is the development of effective, long-term testing procedures and deeper insight into the mechanisms of material degradation under complex mechanical and thermal loads. The direction of future research should be to develop improved hydrogen- and ammonia-resistant materials, new alloys, new coatings, and multidisciplinary design optimisation (MDO) frameworks to assess component degradation over their life cycles. The popularisation of best practices, including post-weld heat treatments and the use of water in anhydrous ammonia, is also a significant mitigation measure.

7.3. Safety and Risk Assessment

The safety profiles of hydrogen and ammonia are inherently different: the main risks of hydrogen are its high flammability and explosive nature, whereas the major risks of ammonia are its toxicity and corrosivity. Hydrogen is volatile and highly flammable; however, it disperses rapidly in open spaces due to its low density. Ammonia is not extremely flammable, but it is also toxic and corrosive, and due to its strong smell, it can be detected naturally at very low levels, way below what can cause serious health consequences. Improved leak detection is a key safety measure for both. Because hydrogen is colourless and odourless, the flammable mixtures should be avoided, and this can be achieved with the help of sophisticated sensors. Ammonia has a high vapour pressure, so a leak can reach toxic levels in confined areas within a short time. A good leak detection system is therefore of great importance. The gaps in the research are the development of next-generation sensors, such as MEMS-based or optical sensors, which are capable of providing immediate, location-sensitive detection at low concentrations. The foundation of safety lies in compliance with international codes and standards provided by organisations such as ASME, ISO, and API. But most available codes are based on legacy applications and need to be revised for new, large-scale, and mobile energy applications. The next steps should be product improvement and the standardisation of these standards to address challenges such as hydrogen embrittlement and the complexity of new fuelling stations.

7.4. Economic Performance

The final determinant of commercial viability is economic performance, which is established through capital expenditure (CAPEX), operating expenditure (OPEX), levelized costs, and transport infrastructure costs. In the case of green hydrogen, CAPEX has increased more than expected, owing to real-world complications and macroeconomic factors beyond the price of the electrolyser. The levelized cost of hydrogen (LCOH) is highly sensitive to electricity costs and can account for up to 60% of the total cost. Compared with other fuels, the levelized cost of ammonia (LCOA) is highly dependent on the seasonality

of renewable energy. Although ammonia has a lower round-trip efficiency (20–30%) than hydrogen (30–40%), transporting hydrogen by pipeline or ship is very expensive due to its low volumetric density. It is in this place that the high ammonia density and the already established infrastructure worldwide are major economic benefits, since freight costs over long distances would be significantly lower than for hydrogen. A major gap in research is the lack of standardised, real-world data and techno-economic models that account for the full value chain and regional diversification. Further investigation should focus on developing open-source models that can be easily adjusted to various geographic factors, and on estimating the costs of government subsidies and other support mechanisms. Over the short- and mid-term, ammonia is a key contributor to the hydrogen economy as a carrier fuel due to its low transport costs, enabling the hydrogen economy to get started before specialised hydrogen infrastructure is in place. The evidence-based roadmap presented in Table 10 can be a rapid way to make progress in innovation, and scientific research can be drawn to the most significant obstacles to a hydrogen-based economy, including safety, costs, and energy efficiency. Finally, the experiences from this table will directly contribute to the establishment of viable and sustainable solutions for a cleaner energy future.

Table 10. Critical insights and key findings about hydrogen and ammonia storage in the performance analysis literature.

Purpose of Analysis/Ref.	Key Findings	Expert Comments/Critical Insights	Research Gaps
A structural mechanics analysis of a Type IV hydrogen storage tank to understand deformation, stress, and failure modes during charging and discharging [59].	Cold contraction causes a large stress concentration at low temperatures (−40 °C) and may exceed the yield strength of the inner polyethylene liner. Coupled thermal and pressure loads on the aluminium alloy plugs are most prone to yielding.	The failure may be mostly due to dynamic operating conditions, specifically temperature variations. Thermal stress is not merely a high-pressure load that causes the most critical failure points; rather, it is thermal stress.	Does not experimentally validate stress predictions under dynamic impact loads or real service cycles.
A comparative analysis of impact damage and residual burst pressure (RBP) of Type III and Type IV cylinders [60].	Type IV cylinder exhibited high impact resistance. The Type III and Type IV cylinders decreased the RBP by 10.6 and 6.1 percent, respectively, when impacted with 120 J. Type IV cylinders had a plastic liner that absorbed more energy, resulting in small fibre breakages and matrix fractures, whereas Type III vessels used a rigid metal liner.	The liner of the vessel does not serve the purpose of sealing but enhances the capacity to bear the stress loads. The increased plasticity of the liner provides a critical safety edge in the impact case, allowing the load-bearing composite layers to be severely damaged.	Damage thresholds under service conditions remain unestablished. Does not address long-term fatigue post-impact.
To study the thermal behaviour of Type III and Type IV commercial hydrogen tanks during high-pressure hydrogen cycling (filling and emptying) [61].	The rise in the internal gas temperature during fast fill-up in Type IV tanks was, by a very large margin, greater than in Type III tanks. This is attributed to the polymer liner's low thermal diffusivity, which makes it a thermal insulator. The high thermal diffusivity of the metallic liner in the Type III tank makes it more efficient at dissipating heat.	The material properties of the liner are directly related to the most important results of the operation. The poor thermal performance of Type IV tanks limits safe filling rates and may result in underfilled tanks (low SOC), thereby affecting vehicle range and user experience.	Likely lacks advanced structural coupling with mechanical stress analyses (dynamic analysis, internal temp cycles), given its focus on thermal behaviour.
To investigate pressure and temperature changes during high-pressure filling and to find strategies to suppress temperature rise [62].	Temperature rise is caused by gas compression, conversion of kinetic energy, and the Joule–Thomson effect. Non-adiabatic conditions result in lower temperatures than adiabatic ones due to heat dissipation. A combination of pre-cooling and a controlled filling rate is an effective strategy for temperature management.	The physical mechanisms behind temperature rise and heat transfer cannot be neglected. The development of advanced thermal management strategies shall play a significant role in achieving the controlled mechanism.	The model excludes mechanical deformation, which could influence heat transfer and structural response. Does not extend to transient loading beyond filling (e.g., discharging cycles).

Table 10. *Cont.*

Purpose of Analysis/Ref.	Key Findings	Expert Comments/Critical Insights	Research Gaps
To investigate the influence of various factors (vessel volume, insulation method, pressure, temperature, and geometry) on the gravimetric hydrogen storage density of Type III cryo-compressed hydrogen storage vessels [63].	The optimal pressure for small-volume vessels is 40 MPa, while for large-volume ships, it is 20–30 MPa. Larger volumes and lower temperatures increase the hydrogen storage density. A smaller length-to-diameter ratio and a semi-circular dome cross-section result in superior performance. Polyurethane foam had a higher hydrogen storage density than aerogel, but vacuum insulation provided longer storage times.	A multidimensional, detailed method for optimising cryo-compressed hydrogen storage provides the route towards feasible hydrogen storage. Results are viable and provide clear design parameters for use in both small and large vehicles. Comparisons of various insulation methods are particularly useful because they are not limited to one-factor analysis. The results are validated by earlier research, which further supports the conclusions.	Limited study on synergistic effects of simultaneous factors (structure, insulation, pressure, temperature). Does not integrate composite behaviour differences between Type III and Type IV vessels.
To evaluate a novel reinforcement technique for Type III hydrogen storage tanks that uses carbon fibre strips in axial and radial directions to mitigate stress concentrations in the dome region [64].	Optimally sized carbon fibre strips can reduce axial stress by 29% and hoop stress by 46% around the dome. This improvement is achieved with a minimal 6.5% increase in weight. The reinforcement strips effectively withstand internal pressure and improve the tank's overall durability and safety.	The criteria that are used by Hashin are suitable in composite failure analysis. The main lesson is that a small amount of weight can reduce stress levels. The fact that the simulation is validated against the literature gives it more credibility. The study is a viable, practical way of enhancing the safety and performance of current tank designs.	A completely numerical finite element study needs further experimental validation.
To design and evaluate the fatigue performance of a Type III 35 MPa onboard hydrogen storage cylinder, explicitly considering the effects of autofrettage and dome-thickening treatments [65].	Autofrettage pressure of 74 MPa reduced the average liner stress by 18.7% and enhanced fatigue resistance. The cylinder met design specifications with a minimum fatigue life of 329,715 cycles under working pressure (35 MPa). The liner survived under burst pressure (82.25 MPa), but the composite shell failed, confirming the design's intended failure mechanism. Stress concentrations were identified at the neck region, requiring further optimisation.	The use of autofrettage to improve fatigue resistance is a key design consideration, and the quantified 18.7% reduction in stress is a valuable result. Confirming that the cylinder's failure mode is as intended (the liner survives, the composite fails) is a crucial safety finding. While the findings pertain to a specific cylinder, the methodology and conclusions regarding the stress concentration and autofrettage are broadly applicable.	Limited to a 35 MPa cylinder configuration; applicability to 70 MPa systems is unclear. Does not investigate dynamic loading such as impact, vibration, or fatigue cycles. Thermal effects during refuelling are not integrated with structural analysis.
To provide insights into material development and operational strategies for metal hydride (MH)-based long-duration hydrogen storage facilities by benchmarking them against conventional compressed gas storage systems [66].	MH-based storage systems require up to 65% less land than 170 bar compressed gas storage. These systems can be cost-competitive with 350 bar compressed gas, with one complex MH system costing \$0.38/kWh, which is lower than the \$0.40/kWh for 350 bar compressed gas. The levelized cost of storage (LCOS) can be significantly reduced by extending charging times and increasing operating cycles. Reducing the cost of the MH material to \$10/kg would make MH systems more economically favourable than 350 bar compressed gas storage.	A comprehensive techno-economic framework for evaluating solid-state hydrogen storage is valuable for researchers and policymakers. It highlights the crucial trade-offs between physical footprint, material costs, and operational flexibility. It anchors the technical challenges of metal hydrides within a clear market-driven context.	Limited analysis of system-level integration with renewable energy fluctuations. Does not address structural vessel design constraints compared with high-pressure storage technologies. Lifecycle environmental impacts and material recycling aspects remain insufficiently explored.

Table 10. *Cont.*

Purpose of Analysis/Ref.	Key Findings	Expert Comments/Critical Insights	Research Gaps
The study aims to investigate the influence of hydrogen storage temperature on the hydrogen consumption capacity, hydrogen release capacity, and energy consumption for iron-based thermochemical hydrogen storage technology and identify the optimal temperature range for this technology [67].	The optimal hydrogen storage temperature is 550 °C, resulting in the lowest relative energy demand of 32.30% and a hydrogen consumption capacity that reached the theoretical maximum of 4.8%. Exceeding a temperature of 570 °C makes it "exceedingly difficult" to achieve the theoretical maximum capacity. This is because forming an intermediate phase (wüstite) creates a dense iron layer that impedes the diffusion of oxygen atoms, slowing the reaction.	A deep, multi-scale investigation into a promising thermochemical storage technology is conducted. It successfully identifies a critical temperature threshold and explains the underlying microstructural and kinetic mechanisms that dictate performance, providing a clear and actionable target for process optimisation.	Lacks system-level evaluation comparing thermochemical storage with compressed hydrogen tanks in real infrastructure. Material durability during repeated temperature cycles is not fully explored. Integration with practical storage vessels or reactors remains underdeveloped.
To study the hydrogen refuelling process of a cascade hydrogen storage system (CHSS) at a hydrogen refuelling station (HRS) to reduce operating costs and increase filling capacity. The aim is also to support continuous refuelling of multiple vehicles to improve the user experience [68].	The specific energy consumption (SEC) and hydrogen utilisation rate (HUR) decrease as the ratio of the medium-pressure tank's nominal pressure to the high-pressure tank's increases. The lowest SEC can be found by fixing the HUR and optimising the pressure ratio. For a 600 kg total hydrogen mass and an HUR of at least 12%, the optimal pressures for each level are 50.2 MPa, 65 MPa, and 86.7 MPa. A three-stage CHSS is found to offer a high HUR.	Highly valuable research on optimising the operational parameters of a specific hydrogen infrastructure component, the refuelling station. The findings offer practical, data-driven recommendations to improve efficiency and commercial viability by fine-tuning pressure ratios in a multi-stage storage system.	Limited coupling between thermodynamic station models and detailed structural tank simulations. Does not account for ageing, degradation, or material fatigue in station storage vessels.
To estimate the residual strength (Fitness-for-Service, FFS) of ageing spherical ammonia tanks (St.E460 steel) that exhibited large, critical cracks in the weld heat-affected zone (HAZ) and fusion line [69].	The structural integrity assessment concluded that the observed cracks could be tolerated up to extremely high internal pressures (42–55 bar), primarily due to small weld overmatching that forced cracks to deviate toward the more ductile base metal.	Illustrates the necessity of advanced FFS assessments (J-integral direct measurement technique) over simple prescriptive standards when dealing with large, complex defects. The inherent material properties of the weldment (mismatch/constraint) govern actual failure resistance.	Not specific to hydrogen service; hydrogen embrittlement effects and permeation risks are not addressed. Lack of integration with composite pressure vessel technologies that are widely used in hydrogen mobility.
To explore the technical feasibility and economic viability of producing and storing offshore green hydrogen and ammonia using energy from the UK's Hornsea wind farms, identifying the most effective production and storage scenario [2].	Scenario 3, which combines a direct supply of hydrogen for ammonia synthesis with a storage facility for green hydrogen, is the most appropriate strategy. The levelized cost of hydrogen (LCOH) is estimated between $5.30 and $5.97/kg. The levelized cost of ammonia (LCOA) is estimated between $984.16 and $1197.11/tonne.	This provides a crucial, macro-level perspective on the economic viability of green fuels, anchoring the technical challenges of other papers within a market-driven context. It emphasises that operational flexibility is key to profitability and resilience in the face of renewable energy intermittency.	Does not provide a deep analysis of the engineering design of hydrogen storage vessels. Limited exploration of infrastructure challenges in scaling hydrogen storage. Technoeconomic uncertainties remain for large-scale integration with offshore wind systems.
To develop a lightweight Type IV ammonia pressure vessel for vehicles and analyse the effects of different material combinations (PET/PP liners, CFRP/GFRP composites) and composite stacking sequences on its performance during burst and impact tests [70].	PP-based pressure vessels generated lower stress in the liner than PET-based vessels. CFRP-based vessels showed a higher safety margin and lower stress than GFRP-based vessels. The optimal stacking sequence for a burst test was [90/±30/90]3s (for PP-CFRP) and for an impact test was [90/±θ/90]3s.	The importance of material selection and structural design at the component level is focused research. It confirms the superiority of advanced materials like CFRP and shows that simulation can be used to optimise designs for specific load cases before costly physical prototyping.	Safety implications of ammonia toxicity and leakage have not been fully explored alongside structural analysis. Limited comparison with hydrogen storage tanks under identical operational conditions. Infrastructure compatibility and refuelling considerations are not deeply studied.

Table 10. *Cont.*

Purpose of Analysis/Ref.	Key Findings	Expert Comments/Critical Insights	Research Gaps
To synthesise historical and recent findings on ammonia stress corrosion cracking (SCC) to inform design standards, especially concerning the use of modern high-strength steels in larger tanks [71].	SCC is primarily driven by anodic dissolution (active path corrosion, APC), is strongly correlated with material hardness, and typically exhibits a critical threshold around 200 Hv.	The principles and micro-mechanisms governing film/scale formation and rupture remain ununified and insufficiently studied. This lack of fundamental knowledge directly limits the application of high-strength steel due to highly conservative design rules (e.g., the IGC code's yield stress limit of 370 MPa without PWHT).	Lack of integrated structural modelling linking corrosion mechanisms to tank failure predictions. Limited experimental data under real operational pressures and temperatures. The interaction between ammonia corrosion and composite-reinforced structures remains unexplored.
To propose and verify a numerical model for designing and evaluating hydrogen storage devices using metal hydride (MH) alloys. The model is intended to overcome the challenges and high costs of direct experimentation on large-scale devices [72].	The developed model accurately simulates hydrogen desorption behaviour by establishing a correlation where the reaction rate (R) is a function of temperature (T) and concentration. Heat management and thermal conductivity were found to be critical for system efficiency. The model was validated for various system geometries, scales, and alloy compositions.	A different storage technology (solid-state) but highlights a familiar challenge: the critical link between thermal dynamics and system performance. It reinforces that effective thermal management is a universal challenge in hydrogen storage.	Heat management during hydrogen absorption/desorption cycles requires further investigation. Scaling challenges for large storage capacities remain unresolved.
To assess the structural integrity and determine the thermal operating limits of Type 1, 3, and 4 hydrogen pressure vessels under extreme space conditions (absolute vacuum, extreme temperatures, vibration) to guide selection for future space missions [73].	Type 4 PVs are the lightest (56.2 kg) with a narrow operating range (10–100 °C). Type 3 PVs are heavier (63.7 kg) with a broader range (0–145 °C). Type 1 PVs are the heaviest (106 kg) but offer superior cryogenic performance (−55 to 54 °C). An absolute vacuum has a negligible effect on performance.	An important comparative analysis that clearly spells out the trade-offs that exist between weight, material selection, and thermal stability. It provides a strategic framework for selecting the right storage solution based on application-specific constraints.	Experimental validation of extreme-condition simulations remains limited. Effects of microgravity, radiation, and repeated thermal cycling on composite vessels require further investigation.

8. Discussions and Future Directions

The successful implementation of green hydrogen and green ammonia, which are essential energy vectors for storing and delivering renewable energy, is key to the transition to a decarbonised global energy system. These technologies cannot be assessed by evaluating only their components; rather, they should be evaluated through a detailed analysis of the entire value chains. Despite evidence that system performance is controlled by nonlinear thermos–mechanical–chemical coupling under cyclic and loading conditions, the analysis of green hydrogen and ammonia storage systems and the thorough literature review carried out in this study show that most of the research and advancement occurred in treating material behaviour, structural response, and operational conditions independently.

This emphasises the need for environment-specific material design techniques and fully integrated multi-physical models instead of traditional static characterisation.

Furthermore, performance-based frameworks that incorporate dynamic loading and system-level integration with renewable energy sources must replace the current standards, which were mostly created for static, land-based systems.

These systems are not only highly performing and safe, which is determined by the inherent properties of the system, but are also dictated by the thermomechanical, technical, and safety systems that dictate their use. One of the largest performance issues in hydrogen systems, as in this case, is controlling the large amount of heat generated during the filling of high-pressure storage tanks. The effect of this heat stress is that the mechanical integrity of the composite cylinders may degrade over time, reducing the state of charge. A sufficient performance analysis would therefore entail sophisticated models, validated by applying

computational fluid dynamics (CFD) and finite element analysis (FEA) to effectively chart temperature fields and structural behaviour. The same is true in solid-state hydrogen storage, where the heat released during adsorption and emitted during desorption is essential and must be regulated to enhance the rates of charge and discharge. Table 11 depicts the major bottlenecks hindering the commercial viability of the green hydrogen and ammonia storage systems.

Table 11. Bottlenecks need advancement to de-risk the hydrogen and ammonia storage technology.

Bottleneck	Measurable Targets (2030–2050)	Validation and Pilot Needs
Electrolyser Capital Cost and Materials	Reduce CAPEX to $250–$500/kW [74]; reduce Iridium loading by 10–100x to reach 14–520 GW capacity [75].	Large-scale (MW-scale) demonstration of low-iridium or Ir-free catalysts in PEM systems to ensure durability under intermittent load [74].
Liquefaction Energy Intensity	Reduce specific energy consumption (SEC) from the current 10–13 kWh/kg toward the theoretical limit of 3.9 kWh/kg, targeting 6–8 kWh/kg for large plants [76,77].	Optimisation of helium refrigeration cycles and Claude cycle parameters in industrial-scale pilot plants to verify simulated energy savings [76].
Geological Storage Integrity	Limit leakage to <1% of the stored volume; manage permeability in salt-cavern interlayers (must be $<10^{-17}$ m^2) to prevent a 45% loss over 30 years [78].	Field monitoring at sites like HyPSTER (Etrez cavern) to validate chemical and biological stability against sulphate-reducing bacteria [78].
LOHC Dehydrogenation Efficiency	Achieve hydrogen release yields of >95% at temperatures < 150 °C; extend catalyst life beyond 1500 cycles [79].	Deployment of integrated hydrogenation/dehydrogenation units (e.g., Brunei–Japan supply chain) to test long-term catalyst stability in real-world shipping conditions [75].
Hydride Gravimetric Capacity	Reach US DOE system-level targets of 5.5 wt% gravimetric and 40 kg/m^3 volumetric density by 2025–2030 [75].	Field testing of metal hydride tanks in heavy-duty transport to validate thermal management and refuelling times (<5 min) [75].
Supply Chain and Infrastructure	Expand distribution networks to reduce delivery costs to <$1/kg; ensure 2–5% storage capacity relative to total installed renewables [80].	Multi-sector "hydrogen hubs" to validate the cooperative nature of energy clusters and cross-border trade logistics [80].

The following are some critical suggestions and research gaps to improve the structural performance and make the storage of hydrogen and ammonia feasible:

- The development of new ideas, such as the Modular Adsorbing Tank Insert (MATI), which employs micro-channel cooling and can take advantage of fuel cell waste heat, is a step in the right direction towards the realisation of better systems.
- The creation of new composites that are more thermally stable and conductive to feature the lightweight but fragile Type 4 vessels and the heavy and thermally stable Type 1 vessels. These materials would form a new generation of vessels that can be used in more applications.
- Further studies and safety procedures need to focus on dynamic testing and modelling. Fatigue analysis should be part of the design process for high-cycle applications, with emphasis on interpreting cyclical stress amplitudes, rather than only on peak stress values.
- Multi-physics platforms are being developed to model the entire lifecycle of energy systems, including the long-term structural integrity of hydrogen and ammonia. This method, with experimental data, proved effective for fast, economical design iterations.
- The implementation of a portfolio concerning the storage solution, since neither ammonia nor hydrogen storage technology is ultimate, such as ideal high-pressure hydrogen gas and its long-distance transport, ideal liquid ammonia, ideal solid-state metal hydrides, and ideal stationary grid storage. This approach makes solutions tailored to the market requirements.

Nevertheless, this technological development will not necessarily be the defining factor for the success of these energy carriers; rather, it might pose challenges for the market and policy issues. An example is the maritime industry, which is reluctant to invest in ammonia-fuelled vessels because there is no international bunkering network or comprehensive, up-to-date rules under the IMO. The way forward must involve unified policy, long-term investment, and the development of global standards to build the robust, secure infrastructure of the clean energy future.

9. Conclusions

Hydrogen and ammonia are not the only possible options for the future of clean energy. It is a delicate combination of the two, in which their individual merits are capitalised on to produce a hardy, effective, and genuinely global decarbonised energy infrastructure. The overall comparison of green hydrogen and green ammonia storage demonstrates that it is a simplistic approach to make a binary decision between the two. They should instead be regarded as complementary pillars of a future energy system that has been decarbonised, and the best decision should be made by a case-by-case analysis of the application, geography and economic context. Table 12 presents a comprehensive spatial–temporal map delineating the optimal applications of hydrogen and ammonia across many sectors, elucidating their synergistic interactions. This enhances the system's adaptability to changes in infrastructure and operations. This spatial–temporal discrepancy reinforces the claim that hydrogen and ammonia must be employed synergistically to create a resilient and scalable low-carbon energy system.

- Green hydrogen is the better option for applications where mass is the major limiting factor, such as aviation and some types of ground transportation. The contribution of hydrogen is especially significant in local, high-efficiency applications, where production is local and short-term storage can be reduced by leveraging the existing pipeline infrastructure, thereby minimising the transportation costs.
- Green ammonia's higher volumetric energy density and reduced storage requirements make it a unique solution for transporting energy on a large scale and over long distances, especially in the maritime industry. An established, capital-efficient infrastructure with origins in the fertiliser industry is a potent route to bulk storage and power generation, enabling a quicker transition for select industries with lower capital requirements.
- This symbiotic relationship is the key to a strong energy future: ammonia is the distributor of the global energy storage of long duration and international trade, and hydrogen is the local and effective energy infrastructure.

This combined vision needs to be actualised through a multidimensional strategy that addresses the identified research gaps. Future technological development should focus on new solid-state materials to address challenges in hydrogen storage, such as low energy density and high pressure. There should be immediate advances in increasing efficiency, reducing the cost of ammonia production, and addressing the corrosion issues associated with its use. The development of such material and process innovations must be accompanied by the creation of complex, integrated techno-economic and multi-objective design optimisation (MDO) schemes that accurately model the overall value chain. In addition to that, strategic focus on infrastructure, which identifies and capitalises on the economic advantages of ammonia as an energy carrier in the preliminary phase and coordinated investment in long-term and committed investments in hydrogen infrastructure, is necessary. Lastly, an international initiative to modernise and standardise codes and standards is essential for promoting safety and building market confidence, as the absence of such regulations today is a primary impediment to mass adoption, particularly in the

shipping sector. The future of clean energy is not a black-and-white option, but a more sophisticated, smart combination of hydrogen and ammonia, leveraging their respective advantages towards an energy system that is truly global and decarbonised.

Table 12. Spatial–temporal mapping of hydrogen and ammonia applications.

Scenario	Spatial Condition	Temporal Scale	Preferred Energy Source	Key Rationale
Grid balancing	Local/urban grid	Hours to days	Hydrogen	Fast response, good efficiency
Renewable curtailment (wind/solar)	Generation sites	Hours to days	Hydrogen + Ammonia	H_2 for immediate use, NH_3 for surplus storage
Seasonal energy storage	Continental	Months	Ammonia	Stable, long-duration storage
Offshore wind energy export	Remote offshore/coastal	Weeks to months	Ammonia	Easier transport and global trade
Steel production (DRI)	Inland industrial clusters	Continuous	Hydrogen	Direct reduction chemistry
Fertiliser production	Industrial hubs	Continuous	Ammonia	Feedstock requirement
Industrial heat (high temperature)	Industrial zones	Continuous	Hydrogen	Clean combustion, high reactivity
Maritime shipping (deep sea)	Global routes	Days to weeks	Ammonia	High energy density, easier storage
Short-sea shipping	Coastal regions	Hours to days	Hydrogen/Ammonia	Depends on distance and infrastructure
Heavy-duty transport (trucks)	Regional/national	Daily	Hydrogen	Refuelling speed, infrastructure growth
Rail (non-electrified)	Regional	Daily	Hydrogen	Proven fuel cell systems
Aviation (future fuels)	Global	Long-haul	Hydrogen/Ammonia-derived fuels	Energy density vs. synthesis pathways
Pipeline energy transport	Regional	Continuous	Hydrogen	Efficient short–medium distance transport
Intercontinental energy trade	Global	Weeks to months	Ammonia	Shipping feasibility
Underground bulk storage	Geological formations	Weeks to months	Hydrogen	Low-cost cavern storage
Tank-based storage	Anywhere	Days to months	Ammonia	No geological dependency
Strategic energy reserves	National	Months to years	Ammonia	Stability and scalability
Island energy systems	Isolated regions	Days to months	Ammonia	Transportable, long storage
Off-grid communities	Remote areas	Weeks	Hydrogen + Ammonia	Hybrid flexibility
Backup power systems	Critical infrastructure	Seconds to hours	Hydrogen	Instant response capability
Remote mining operations	Off-grid/remote	Days to months	Ammonia	Easy transport and storage
Petrochemical refining	Industrial zones	Continuous	Hydrogen	Process integration
Hydrogen refuelling stations	Urban/local	Immediate	Hydrogen	Direct use in mobility
Power plant co-firing	Grid-connected plants	Continuous	Ammonia	Easier storage and combustion

Author Contributions: Conceptualisation, M.A.M.; methodology, M.A.M.; software, M.J.R. and Y.C.L.; P.B.R. formal analysis, M.A.M.; investigation, M.A.M.; writing—original draft preparation, M.A.M.; writing—review and editing, M.J.R.; supervision, M.J.R., Y.C.L. and P.B.R.; funding acquisition, M.J.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by School of Engineering, Computing and Mathematics at the University of Plymouth and the EPSRC DTP ORE.

Data Availability Statement: The data presented in this study is available upon request from the corresponding author.

Acknowledgments: The authors gratefully acknowledge the financial support provided by the School of Engineering, Computing and Mathematics at the University of Plymouth and the EPSRC DTP ORE studentship to conduct this research.

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

Abbreviations

H_2	Hydrogen
NH_3	Ammonia
CES	Chemical energy storage
SWOT	Strength, weakness, opportunity, threat
SCC	Stress corrosion cracking
CFD	Computational fluid dynamics
MeanTCperArt	Mean total citations per article
STP	Standard temperature and pressure
MPa	Mega Pascals
PSI	Pounds per square inch
CCH_2	Cryo-compressed hydrogen
MOFs	Metal–organic frameworks
LOHCs	Liquid organic hydrogen carriers
UHS	Underground hydrogen storage
TWh	Terawatt-hours
RMAF	Risk-Mitigation Adaptability framework
AE	Acoustic emissions
NDT	Non-destructive testing
COPV's	Composite overwrapped pressure vessels
ASME	American Society of Mechanical Engineering
ISO	International Standards Organisation
OSHA	Occupational Safety and Health Administration
QRA	Quantitative risk assessment
CAPEX	Capital expenditure
OPEX	Operational expenditure
LCOH	Levelized cost of hydrogen
LCOA	Levelized cost of ammonia
LCOS	Levelized cost of storage
RTE	Round-trip efficiency
FEA	Finite element analysis
TEA	Techno-economic analysis

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