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# Hydrogen Storage Methods: Opportunities, Safety, Risk, and Compliance Assessment

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**Abstract:** Hydrogen storage is a central enabling element for the large-scale deployment of hydrogen as a low-carbon energy carrier, directly shaping the feasibility, cost, safety, and regulatory acceptability of hydrogen supply chains. This article synthesizes the principal hydrogen storage methods, compressed gaseous hydrogen ($CGH_2$), liquefied hydrogen ($LH_2$), cryocompressed hydrogen ($CcH_2$), physically adsorbed hydrogen in porous media, metal and complex hydrides, and liquid organic hydrogen carriers (LOHC), and evaluates their deployment relevance through an integrated opportunity–risk–compliance lens. First, the study summarizes the operating principles and system-level trade-offs of each pathway, emphasizing application-dependent performance constraints in volumetric/gravimetric density, refueling dynamics, thermal management, and infrastructure compatibility. Second, it maps sectoral opportunities across mobility, industrial hubs, maritime and aviation logistics, power-system balancing, and long-duration/seasonal storage, demonstrating that technology suitability is strongly conditioned by duty cycle, utilization rate, footprint constraints, and the availability of heat and cryogenic logistics. Third, the article develops a structured safety, risk, and compliance assessment framework that consolidates key hazard domains, high-pressure failure modes, cryogenic exposure and boil-off governance, hydrogen embrittlement and leakage/dispersion risks, thermally coupled reaction hazards in materials and carriers, and emergency venting and fire escalation control into a unified safety case aligned with codes, standards, and local permitting pathways. The integrated assessment supports robust technology screening and project bankability by linking sector-specific value propositions to verifiable safeguard strategies and compliance deliverables, thereby advancing safer and more scalable hydrogen storage deployment.

**Keywords:** Hydrogen Storage, Compressed Hydrogen, Liquid Hydrogen, LOHC, Safety Case, Risk Assessment, Permitting and Compliance.

## 1.Introduction

The $CO_2$ impact of hydrogen storage methods is primarily an indirect, life-cycle effect driven by the additional energy and materials required to condition, store, and deliver hydrogen, rather than by emissions from hydrogen itself. Compressed storage increases $CO_2$ through electricity use for compression (and associated cooling), with emissions scaling with pressure level and the carbon intensity of the grid supplying the compressors [1,2]. Liquefied and cryocompressed storage typically impose a larger $CO_2$ burden because liquefaction and cryogenic thermal management are energy intensive; moreover, boil-off losses and any venting can raise the effective $CO_2$ per kilogram of delivered hydrogen by reducing utilization. Material and carrier pathways shift the $CO_2$ contribution toward process heat and supply chains: metal/complex hydrides require thermal energy for absorption/desorption and may carry embodied emissions from alloy production, while LOHC systems add $CO_2$ via hydrogenation/dehydrogenation heat demand, catalyst manufacture, and carrier handling, although these impacts can be substantially mitigated when low-carbon electricity and waste heat integration are available. Therefore, comparing storage options on $CO_2$ grounds requires an application-specific life-cycle assessment that accounts for energy inputs (electricity/heat), duty cycle and dwell time, losses (especially for $LH_2$), and embodied emissions in tanks, insulation, catalysts, and carrier materials [3,4].

Hydrogen storage constitutes a pivotal enabling layer within the hydrogen value chain, governing not only the technical feasibility of production–transport–end-use integration but also the economic and spatial viability of deployment across mobility, industrial, and power-system contexts [5,6]. The principal storage pathways compressed and cryogenic physical storage ($CGH_2$, $LH_2$, and cryocompressed systems), material-based storage (metal and complex hydrides), liquid organic hydrogen carriers (LOHC), and adsorption-based concepts, exhibit markedly different performance envelopes in gravimetric/volumetric density, discharge dynamics, autonomy duration, and infrastructure compatibility [7-9]. It worthy to mention that, as renewable energy generation expands, the imperative for large-capacity hydrogen storage is becoming increasingly pronounced. In this context, underground hydrogen storage, implemented across a range of geological formations and engineered subsurface repositories as illustrated in Figure 1, presents a particularly compelling set of options for achieving scalable, long-duration hydrogen storage.

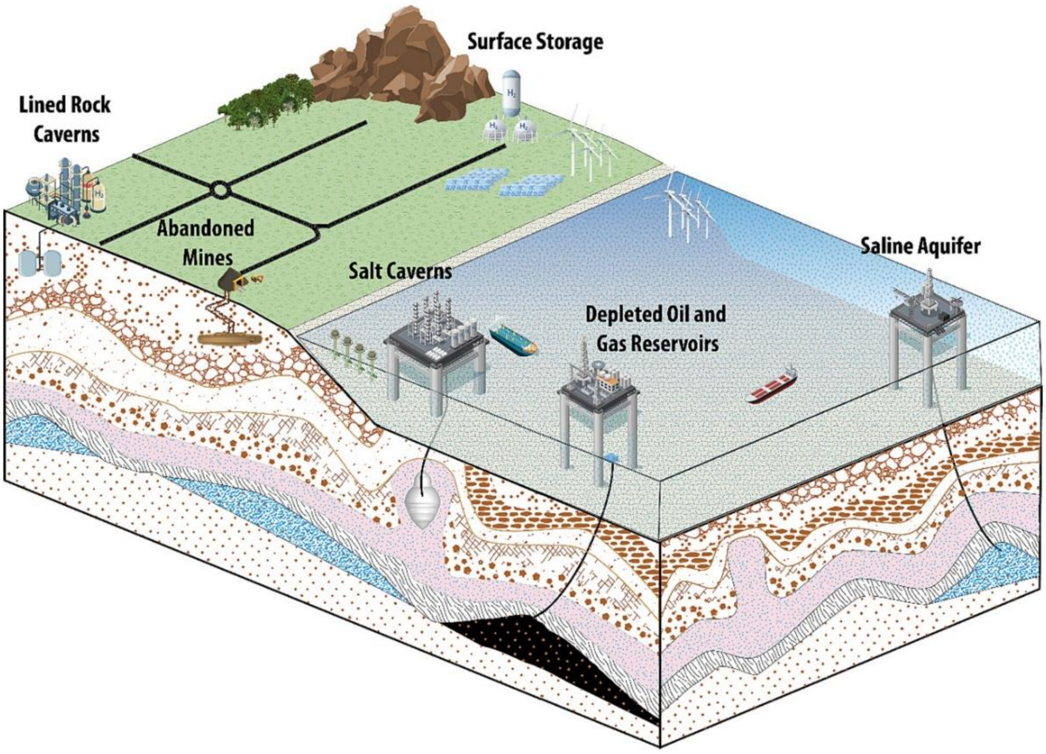


**Figure 1**. A particularly compelling set of options for achieving scalable, long-duration hydrogen storage [10].

Consequently, the opportunity landscape is intrinsically application contingent: compressed storage remains advantageous for fast-response buffering and refueling station architectures; liquefaction supports high-throughput hubs and long-distance logistics where volumetric compactness is decisive; hydrides and LOHC are strategically attractive for safety-sensitive and long-duration storage scenarios due to their low-pressure or ambient-condition handling characteristics; and adsorption/advanced hydrides remain promising yet conditional options whose competitiveness hinges on breakthroughs in materials performance and system integration [11-13].

A rigorous assessment of these opportunities must be complemented by an integrated safety and risk framework that treats hazards as system-level phenomena rather than isolated component issues.

Physical storage methods are dominated by high-pressure and cryogenic hazards, where credible scenarios include overpressure during fast filling, vessel rupture, rapid decompression, insulation failure, oxygen condensation, and boil-off gas (BOG) accumulation and venting [14-16]. In parallel, cross-cutting integrity risks, hydrogen embrittlement, permeation-driven leakage, and ignition/dispersion behavior, necessitate conservative materials selection, lifecycle mechanical integrity management, and facility-level controls such as hazardous area classification, ventilation design, and high-point detection [17,18]. For hydrides and LOHC systems, the principal risk signatures shift toward thermally coupled reaction hazards, including exothermic heat release during absorption/hydrogenation, endothermic heat demand for desorption/dehydrogenation, catalyst hot spots, and upset-driven excursions, thereby aligning these pathways with the methodological requirements of chemical process safety.

From a compliance standpoint, the decisive requirement is the development of a unified safety case that explicitly maps hazard scenarios to engineered safeguards, operational controls, verification evidence, and the local permitting pathway. This entails codifying pressure-relief and emergency venting philosophies (including dispersion-informed vent stack siting and cryogenic anti-icing provisions), documenting commissioning and proof testing, and establishing auditable inspection regimes (NDT schedules, traceability records, and fitness-for-service criteria) [19-21].

Several studies have investigated hydrogen storage methods, as summarized as follows. According to [22], intensifying concern regarding greenhouse gas (GHG) emissions and their climatic consequences has accelerated the search for low-carbon energy alternatives, thereby elevating hydrogen's prominence as an abundant, environmentally benign, and versatile secondary energy carrier. Notwithstanding its exceptionally high gravimetric energy density ($\approx$120 $MJ\cdot kg^{-1}$), hydrogen exhibits a pronounced limitation in terms of volumetric energy density ($\approx$0.01079 $MJ\cdot L^{-1}$), underscoring the central importance of effective storage and densification strategies for practical deployment.

Article [23] provides investigation on hydrogen storage technologies and associated materials, encompassing physical storage (e.g., compressed gas), physisorption-based storage employing porous sorbents (including carbonaceous materials, metal–organic frameworks (MOFs), and related high-surface-area structures), and chemical storage routes such as ammonia, methanol, formic acid, liquid organic hydrogen carriers (LOHCs), and metal hydrides, in addition to emerging two-dimensional MXene-derived materials. The study critically synthesizes the merits of these storage mechanisms, particularly with respect to capacity, reversibility, kinetics, and operating conditions, while also delineating key barriers to practical deployment, including energy penalties, thermal management constraints, materials stability, safety considerations, and infrastructure compatibility.

In work [24], the authors comprehensively review hydrogen storage across gaseous, liquid, and solid-state modalities, synthesizing the principal storage strategies and critically appraising recent technical advances in materials, system architectures, and process integration. In addition, the study examines the storage and utilization of carbon-free hydrogen vectors, notably ammonia and selected metal-alloy hydrides, with emphasis on their thermodynamic characteristics, kinetic behavior, and practical implications for large-scale deployment

This study [25] proposes a novel solid–gas coupled hydrogen storage architecture that integrates a metal hydride–phase change material (MH–PCM) composite to enhance storage kinetics and thermal regulation. First, the authors formulate and analyze a vertical MH–PCM solid-storage model that explicitly accounts for natural convection, thereby capturing buoyancy-driven heat transfer effects that are often neglected in simplified conduction-dominant formulations. Building on this framework, the MH–PCM unit is subsequently embedded within a solid–gas coupling storage configuration and integrated into a photovoltaic-driven hydrogen production system to assess end-to-end storage performance under realistic operating conditions. The results indicate that incorporating natural convection increases the average storage rate by approximately 12.7%, albeit at the cost of a more spatially heterogeneous and temporally uneven charging process, highlighting a performance trade-off between accelerated uptake and uniformity of storage progression.

This paper [26] presents a comprehensive review of prevalent on-board hydrogen storage tank technologies, systematically examining typical failure mechanisms, dominant manufacturing routes, and prospective development trajectories. It classifies hydrogen tanks into five principal types based on constituent materials, noting that vehicular applications are currently concentrated on Type III (metallic liner overwrapped with a fiber-reinforced composite) and Type IV (polymeric liner overwrapped with a fiber-reinforced composite) configurations due to their favorable strength-to-weight characteristics and packaging suitability. With specific emphasis on Type III systems, the study highlights that metallic liners are commonly fabricated from aluminium alloys, and it critically surveys and contrasts key manufacturing processes, including roll forming, deep drawing and ironing, and backward extrusion, with respect to their implications for liner integrity, dimensional tolerance, defect formation, and overall tank reliability.

This article advances the hydrogen storage literature by delivering a unified, deployment-oriented assessment that integrates technology fundamentals, sectoral opportunity mapping, and safety–risk–compliance requirements within a single analytical framework. Specifically, it (i) synthesizes the operational principles and system-level trade-offs of the principal storage pathways ($CGH_2$, $LH_2$, $CcH_2$, adsorption-based storage, metal/complex hydrides, and LOHC), (ii) translates these trade-offs into a sector-specific suitability matrix spanning mobility, industrial hubs, maritime/aviation logistics, grid balancing, and seasonal storage, and (iii) formalizes a modular safety case structure that links dominant hazard domains to verifiable safeguards and permitting deliverables aligned with codes and local approval processes. By coupling performance-driven technology screening with explicit compliance pathways, the study provides a defensible basis for project bankability, reduces permitting ambiguity, and supports safer and more scalable hydrogen storage deployment across diverse applications.

## 2.Hydrogen Storage Methods

Hydrogen storage is a cornerstone of the hydrogen value chain because it determines how efficiently hydrogen can be produced, transported, distributed, and ultimately utilized in mobility, industry, and power systems. Since hydrogen has low volumetric energy density under ambient conditions, practical deployment requires engineered storage pathways that increase density, improve handling logistics, and meet safety and cost constraints [27-31]. Accordingly, multiple storage methods have been developed and are commonly classified into physical storage (compressed, liquefied, cryocompressed), surface-based storage (physical adsorption), and material/chemical storage (metal hydrides, complex hydrides, and liquid organic hydrogen carriers, LOHC). Figure 2 illustrates hydrogen storage methods. Table 1 summarizes these principal options and highlights their operating regimes, benefits, limitations, and typical application domains of hydrogen storage methods.

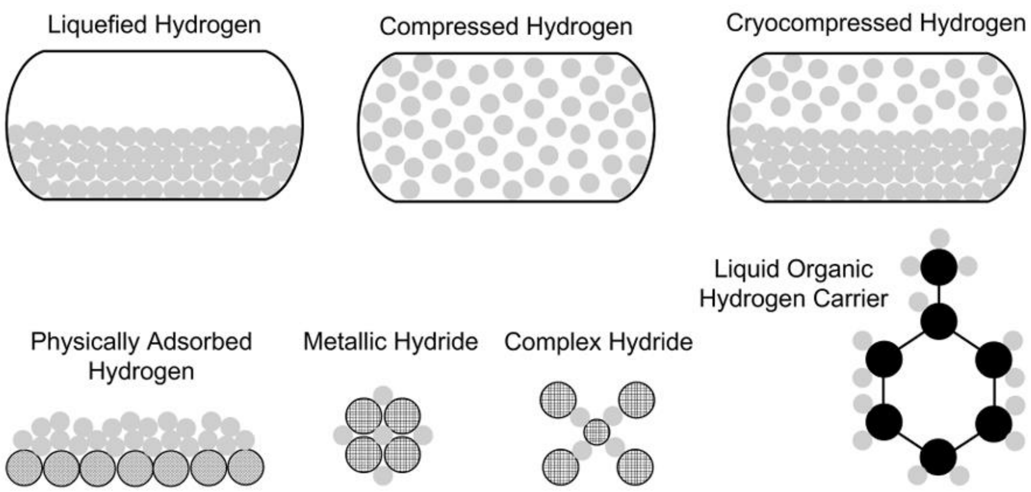


**Figure 2.** Concept of Hydrogen Storage Methods [32]

**Table 1.** Recent trends of hydrogen storage methods [33-52].

| Hydrogen storage method | Storage principle / medium | Typical conditions (indicative) | advantages | challenges | Common applications / maturity |
|---|---|---|---|---|---|
| Compressed hydrogen ($CGH_2$) | Hydrogen stored as a high-pressure gas in cylinders | Approx. 350–700 bar; ambient temperature | Mature and widely deployed; | Lower volumetric density than liquid; heavy/expensive tanks; | Fuel-cell vehicles (350/700 bar), tube trailers, station buffers |
| Liquefied hydrogen ($LH_2$) | Hydrogen stored as a cryogenic liquid in vacuum-insulated tanks | Approx. 20 K (-253 °C); near 1–10 bar | High volumetric density; suited to long-range transport | Liquefaction energy penalty; boil-off losses; cryogenic materials/insulation; complex handling | Space/aerospace, emerging heavy transport and supply chains; medium–high maturity |
| Cryocompressed hydrogen ($CcH_2$) | Cold, pressurized hydrogen combining cryogenic temperature with elevated pressure | Cryogenic (~20–80 K) and pressurized (often 100–350+ bar) | Higher density than $CGH_2$; reduced boil-off vs $LH_2$; flexible operating window | Complex tank design (cryogenic + pressure); thermal management; cost and system integration | Demonstrations for vehicles and high-performance storage; demonstration/emerging |
| Physically adsorbed hydrogen | $H_2$ stored by physisorption on high-surface-area materials (e.g., activated carbon, MOFs) | Often requires low temperature (e.g., 77 K) | Potentially high gravimetric capacity in optimized materials; | Typically needs cryogenic cooling for practical capacity | R&D and pilots; niche cryogenic adsorption concepts; research–pilot |
| Metal hydrides | Hydrogen stored as reversible metal–hydrogen compounds (e.g., $LaNi_5H_6$, $TiFeH_x$) | Moderate pressures; temperatures vary by alloy; heat exchange required | High volumetric density; low operating pressure) | Heavy systems (lower gravimetric capacity); heat management during charge/discharge | Stationary buffering, portable power, niche mobility; medium maturity |
| Complex hydrides | Hydrogen stored in complex ionic/covalent hydrides | Often elevated temperature for release; may need catalysts | Very high theoretical hydrogen content | High desorption temperatures/slow kinetics; challenging regeneration pathways | Primarily R&D; limited field use; research |
| Liquid Organic Hydrogen Carriers (LOHC) / Liquid organic hydrides | Hydrogen stored via reversible hydrogenation/ dehydrogenation of organic liquids, methylcyclohexane/toluene) | Near-ambient storage/transport; dehydrogenation typically ~200–350 °C with catalysts | Uses liquid-fuel logistics (tanks, pipelines); low pressure; scalable transport and storage | Energy and heat demand for dehydrogenation; catalyst cost/deactivation; round-trip efficiency and purity management | Large-scale storage/transport concepts, import/export chains; pilot–early commercial |

A. *Compressed hydrogen ($CGH_2$)*

Compressed storage keeps hydrogen as a high-pressure gas in cylinders or composite tanks, making it the most operationally mature option for mobility and station buffering. Its main strengths are straightforward fueling/defueling, fast response, and broad code-and-standards experience; therefore, it is widely adopted in refueling infrastructure and fuel-cell vehicles. The principal drawbacks are comparatively low volumetric density at ambient temperature, the need for heavy and costly pressure vessels, and the energy penalty associated with multi-stage compression and thermal control during rapid filling. From a system-design perspective, safety and durability considerations, such as leak detection, pressure relief, and hydrogen embrittlement in metals, are central to reliable deployment [38,39].

B. *Liquefied hydrogen ($LH_2$)*

Liquefaction stores hydrogen as a cryogenic liquid, substantially increasing volumetric density and enabling compact storage and long-distance transport with higher payload per shipment. This pathway is particularly attractive for centralized production, export/import corridors, and high-throughput distribution hubs where space and logistics dominate. However, liquefaction is energy intensive and requires sophisticated cryogenic tanks with vacuum insulation, while unavoidable heat ingress leads to boil-off gas that must be vented, reliquefied, or utilized, each carrying cost and efficiency implications. Consequently, $LH_2$ systems are most effective when designed around high utilization rates, minimized idle storage time, and robust boil-off management strategies [40,41].

C. *Cryocompressed hydrogen ($CcH_2$)*

Cryocompressed storage combines low temperature with elevated pressure, aiming to bridge the density benefits of liquid hydrogen and the operational flexibility of compressed gas. By storing hydrogen cold and pressurized, it can achieve higher density than ambient compressed storage and, under certain duty cycles, reduce boil-off sensitivity relative to pure $LH_2$ by allowing pressure to rise without immediate venting. The trade-off is increased tank and system complexity: vessels must be both cryogenic-capable and pressure-rated, with advanced insulation, liners, and carefully engineered pressure relief and thermal management [42,43]. As a result, cryocompressed concepts remain more common in demonstrations and specialized applications than in broad commercial deployment.

D. *Physically adsorbed hydrogen.*

Physical adsorption stores hydrogen on high-surface-area porous materials (e.g., activated carbons or metal–organic frameworks), offering rapid kinetics and reversibility that can be advantageous for frequent cycling. In practice, competitive storage capacity typically requires low temperatures (often near liquid-nitrogen conditions) and sometimes moderate pressures, because room-temperature adsorption is generally insufficient for many real-world volumetric targets [44,45]. Key challenges include the need for cryogenic integration, material cost and stability, packing density, and heat effects during adsorption/desorption. Accordingly, adsorption-based storage is best viewed as an emerging pathway with potential in niche systems where cooling is feasible and safety or rapid response is prioritized.

E. *Metal hydrides.*

Metal hydrides store hydrogen within a solid metal lattice, enabling relatively low-pressure operation and high volumetric density with strong safety characteristics because hydrogen is stored in a bound form. These attributes make metal hydrides attractive for stationary buffering, portable power, and applications where high pressure or cryogenic handling is undesirable. The main limitations are system mass (lower gravimetric capacity at the tank level), sensitivity to heat-transfer constraints, and the requirement for effective thermal management because absorption releases heat while desorption requires heat input. Material cost, impurity tolerance, and cycling durability also influence performance, so practical designs often integrate heat exchangers and, where possible, leverage waste heat sources to drive hydrogen release [46,47].

*F. Complex hydrides.*

Complex hydrides (such as alanates, borohydrides, and amide-based systems) are notable for very high theoretical hydrogen content, which motivates continued research into compact storage solutions. Despite this promise, many complex hydrides require elevated temperatures for hydrogen release, exhibit slower kinetics, and depend on catalysts or tailored reaction pathways to achieve practical reversibility. Some systems also face challenging regeneration requirements, shifting the concept toward a fuel-like model where spent material is processed off-board [48,49]. For these reasons, complex hydrides are largely at the research-to-pilot stage, with progress closely tied to advances in catalysis, thermodynamic tuning, and cost-effective regeneration.

*G. Liquid Organic Hydrogen Carriers (LOHC)*

LOHC systems store hydrogen chemically in liquid organic compounds via hydrogenation and release it via catalytic dehydrogenation, allowing hydrogen to be handled using liquid-fuel-like infrastructure at near-ambient conditions. This logistic compatibility can be a decisive advantage for large-scale storage and transport, especially where safety, simplicity of handling, and existing liquid logistics networks outweighs efficiency concerns. The principal challenges are the energy and heat demand for dehydrogenation, catalyst cost and deactivation over time, and the need to maintain hydrogen purity depending on the carrier and process configuration. LOHCs are therefore most compelling in integrated industrial settings where low-cost heat is available and where the value of simplified transport and storage can offset the efficiency and equipment complexity penalties [50-52].

The study demonstrates that hydrogen storage is inherently a multi-objective engineering choice shaped by density requirements, efficiency, safety, cost, and infrastructure compatibility. Compressed hydrogen remains the most commercially established solution due to its simplicity and fast dynamics, yet it is constrained by limited volumetric density and high-pressure vessel demands. Liquefied hydrogen offers superior compactness for large-scale distribution and long-distance transport, but it introduces significant liquefaction energy penalties and cryogenic boil-off management challenges, while cryocompressed storage provides an intermediate pathway at the expense of greater tank and system complexity. Advanced material-based routes reveal distinct strategic advantages: physisorption can enable rapid reversible storage but typically relies on low temperatures for practical capacity; metal hydrides improve safety and volumetric packing under low pressures but suffer from mass and thermal-management constraints; and complex hydrides promise high theoretical capacities yet remain limited by kinetics, high release temperatures, and regeneration burdens. Finally, LOHCs stand out for ambient-condition handling and liquid-fuel logistics, although their competitiveness depends on efficient catalytic dehydrogenation and access to suitable heat integration. Overall, the comparative evidence supports a portfolio approach in which near-term deployment is anchored by compressed and liquid storage, while hydrides and LOHCs are scaled selectively where their safety and logistics benefits justify energy and cost trade-offs, and adsorption/complex hydrides continue to mature toward broader applicability.

## 3.Opportunities of Hydrogen Storage Methods

This section provides a sector-oriented perspective on hydrogen storage by mapping the principal storage pathways, compressed hydrogen ($CGH_2$), liquefied hydrogen ($LH_2$), cryocompressed hydrogen ($CcH_2$), hydride-based storage (metal and complex hydrides), liquid organic hydrogen carriers (LOHC), and adsorption-based systems, against major end-use contexts. Because hydrogen storage performance is strongly application dependent, the table frames "opportunity" as a function of practical constraints (volumetric/gravimetric density, discharge dynamics, safety profile, autonomy duration, infrastructure readiness, and cost) and the operational realities of each sector (refueling speed, logistics, siting, and integration with heat and power) [53,54]. The resulting matrix supports technology screening by identifying where each storage method can deliver the highest near- to mid-term value and where limitations remain dominant. **Table 2** shows opportunities of hydrogen storage methods by sector.

**Table 2.** Opportunities of hydrogen storage methods by sector [55-64]

| Sector / Use case | $CGH_2$ | $LH_2$ (Liquid) | $CcH_2$ | Hydrides | LOHC |
|---|---|---|---|---|---|
| Light-duty mobility (passenger cars) | High – mature 700 bar tanks and fast refueling | Low–Med – cryogenic complexity; niche concepts | Med – density gains, but complexity limits rollout | Low – mass/thermal constraints for vehicles | Low – onboard dehydrogenation not practical |
| Heavy-duty road transport (buses/trucks) | Med–High – 350 bar common; range may be limiting | High – strong for range/throughput corridors | Med – promising, still emerging | Low–Med – niche where safety/low pressure dominates | Low–Med – better for logistics than onboard |
| Rail / off-road (mining, construction) | High – robust, modular, easier field service | Med – where centralized fueling exists | Med – specialized deployments | Med – safety and low pressure can help | Med – site logistics advantage if heat available |
| Maritime bunkering and shipping fuels supply | Low–Med – bulky at scale | High – strong logistics for ports and hubs | Med – possible in niche high-performance cases | Low – mass and kinetics | High – liquid handling aligns with port infrastructure |
| Aviation (future $H_2$ aircraft / airports) | Low – volume constraints | High – $LH_2$ is the leading pathway for aviation concepts | Med – potential onboard density/operational flexibility | Low | Low–Med – more suited to ground logistics than onboard |
| Industrial hubs (steel, refining, chemicals) | High – buffering and short-term storage | High – large throughput distribution | Med – emerging option | Med – site-integrated heat can support hydrides | High – strong where waste heat enables dehydrogenation |
| Power grid balancing (hours–days) | High – fast response, proven hardware | Med – feasible but boil-off penalizes long idle | Med – depends on duty cycle | High (metal) – safe and stable for cycling if heat managed; Med (complex) | Med–High – good if round-trip efficiency acceptable and heat integration exists |
| Seasonal / long-duration storage (weeks–months) | Med – feasible but space/cost heavy at scale | Low–Med – boil-off challenges for long duration | Low–Med – still cryogenic losses/complexity | High (metal) – minimal losses; Med (complex) if regeneration is viable | High – excellent logistics and stable storage |
| Remote microgrids / telecom backup | High – straightforward and serviceable | Low – cryogenic impractical in remote settings | Low – complexity | High (metal) – safe, low-pressure, low-loss storage | Med – viable if heat/power is available for dehydrogenation |
| Hydrogen refueling stations (on-site storage buffers) | High – cascade storage is standard | Med – for high-throughput stations | Med – specialized station concepts | Low–Med – niche buffering | Low–Med – more for supply chain than station buffer |

Legend (opportunity level): High = strong near-/mid-term fit; Med = application- and context-dependent; Low = generally unfavorable with today's constraints.

Table 2 indicates that $CGH_2$ has the broadest near-term applicability, especially in light-duty mobility and refueling stations, where fast filling, established standards, and mature supply chains enable high deployment readiness. Its "high" opportunity in passenger cars and station buffering reflects strong compatibility with existing station architectures (cascade storage and compression systems) and predictable operational behavior. However, the opportunity rating drops toward “medium” in heavy-duty transport and long-duration storage because $CGH_2$’s lower volumetric density and high-pressure vessel requirements can become limiting as range, onboard space, or storage scale increases. In contrast, $LH_2$ is strongly positioned for logistics-intensive and high-throughput sectors, including heavy-duty corridors, maritime bunkering, aviation ecosystems, and industrial hubs. The consistently high opportunity in these domains is driven by superior volumetric density and transport efficiency, which are decisive where large quantities must be moved and stored compactly. Nonetheless, the t article’s more moderate ratings for stationary, remote, or long-idle applications implicitly reflect $LH_2$’s central constraint: cryogenic complexity and boil-off management, which can penalize systems with low utilization or extended storage durations.

Cryocompressed hydrogen ($CcH_2$) appears as an intermediate opportunity, often “medium”, across several sectors, reflecting its technical promise to enhance density relative to $CGH_2$ while providing operational flexibility that can mitigate some $LH_2$ boil-off constraints under certain duty cycles. Table 2 also suggests why $CcH_2$ remains less dominant: the need for pressure-rated cryogenic tanks and robust thermal–pressure transient control increases complexity and cost, making it more suitable for specialized deployments and demonstrations than for broad near-term rollouts. Moreover, the article highlights that hydride-based storage offers particularly strong opportunities in stationary and remote contexts, such as microgrids, telecom backup, and potentially seasonal storage. These “high” opportunities are consistent with hydrides’ low-pressure, solid-state safety advantages and minimal self-discharge over long durations, which are valuable where maintenance access is limited, and risk tolerance is low. At the same time, hydrides are rated lower for mobility and high-flow fueling because system-level gravimetric penalties and heat-transfer limitations can restrict onboard practicality and fast transient response unless carefully engineered with advanced thermal management.

LOHC systems show high opportunity in maritime logistics, industrial hubs, and seasonal storage, reflecting their major strategic advantage: ambient-condition handling using liquid-fuel-like infrastructure. This is particularly attractive for large-scale transport and long-duration storage, where pressure vessels or cryogenic systems impose significant costs or operational burdens. The study’s lower ratings for onboard mobility primarily stem from LOHC dehydrogenation requirements, high-temperature reactors, catalysts, and heat integration, which are difficult to accommodate in compact vehicle platforms but can be viable in industrial settings with waste heat or centralized processing. Finally, adsorption-based storage is generally rated low to medium, indicating that its opportunity is presently niche and highly conditional. Where cold utilities or cryogenic integration is feasible, adsorption may support rapid reversible storage and potentially improved safety relative to extreme pressures; however, the article implies that practical capacity at ambient conditions and the complexity of achieving competitive system-level performance remain barriers to wide deployment.

## 4. Safety, Risk, and Compliance Assessment

Safety, risk, and compliance are decisive factors in determining whether hydrogen storage projects can be permitted, insured, constructed, and operated reliably at scale [65,66]. Because hydrogen storage spans multiple hazard classes, high pressure ($CGH_2$/$CcH_2$), cryogenic exposure and boil-off ($LH_2$/$CcH_2$), and reactive materials/process hazards (hydrides and LOHC), a fragmented approach to risk management often results in design gaps, permitting delays, and elevated operational risk [67,68]. The safety, risk, and compliance assessment Table 3 therefore structures a unified safety case into coherent modules that cover the full hazard spectrum, from prevention and detection to emergency response and regulatory documentation [69,70]. This modular approach aligns technical controls with evidence requirements and the local permitting pathway, enabling consistent evaluation across storage technologies and project contexts.

**Table 3.** Safety, Risk, and Compliance Assessment for Hydrogen Storage Methods [65-74].

| Safety case module | Storage methods most impacted | Risk scenario set | Evidence to include in the safety case | Compliance & permitting pathway deliverables |
|---|---|---|---|---|
| Pressure hazards | $CGH_2$, $CcH_2$, some adsorption (if pressurized) | Overpressure during filling; vessel rupture; PRD lift; rapid decompression; compressor discharge excursions | Pressure vessel certifications; PRD sizing calculations; fill protocol/thermal analysis | Pressure equipment compliance; station siting setbacks; hazardous area classification |
| Cryogenic hazards | $LH_2$, $CcH_2$, cryogenic adsorption | Cryogenic burns; brittle fracture at low temperature; oxygen condensation; insulation/vacuum failure; cold spills; ice blockage | Cryogenic design specification; vacuum integrity test reports; transfer procedures | Cryogenic storage provisions in fire code; liquid/gas handling permits; operator training records; emergency response coordination with local authorities |
| Boil-off gas (BOG) handling | $LH_2$, some $CcH_2$ | Pressure rise from heat ingress; routine/abnormal venting; BOG compressor/recondensation failure; flammable cloud at vent | Boil-off rate estimates; vent/stack dispersion modeling; BOG system PFD/P&IDs | Vent-stack siting approval; environmental/venting conditions (if applicable); AHJ review of routine release philosophy |
| Embrittlement & materials compatibility | All (metal components), especially high-pressure and cryogenic | Hydrogen-assisted cracking; fatigue under cycling; seal/permeation issues; weld degradation | Materials selection basis; welding/QC records; NDT schedule and baseline results | Pressure system QA/QC documentation; integrity management plan accepted by regulator/insurer |
| Leakage, dispersion, ignition | All | Small leaks to jet releases; indoor accumulation; ignition from electrical/hot surfaces; invisible flame hazards | Area classification drawings; detector layout and setpoints; ventilation calculations | Hazardous area compliance (ATEX/IECEx/NFPA as applicable); building/fire permitting; |
| Thermal runaway / reaction hazards (materials & carriers) | Hydrides (absorption heat), LOHC (reactors), complex hydrides | Exothermic heat release during charging/hydrogenation; hot spots; uncontrolled temperature rise; decomposition/by-products | HAZOP/LOPA; reactor/bed thermal model; instrumented safeguard design; catalyst data and lifecycle | Process safety compliance; chemical handling/storage permits (carriers); occupational safety requirements; documented MOC (management of change) |
| Emergency venting & pressure relief | All (critical for $CGH_2$/$LH_2$/ $CcH_2$) | PRD failure or undersizing; vent discharge hazards; ice blockage (cryo); backpressure; vent ignition | PRD datasheets and sizing; vent routing drawings; dispersion/thermal radiation checks | AHJ review of vent locations; setbacks and exclusion zones; emergency response plan approval/coordination |
| Fire/explosion escalation control | All | Jet fire exposure; confined deflagration; domino effects; responder access | Fire scenarios and consequence modeling; layout/siting rationale | Fire authority sign-off; insurer risk engineering review; site emergency plan and communication protocols |

| | | | | |
|---|---|---|---|---|
| Unified compliance dossier & permitting strategy | All | Gaps between design intent and regulatory expectations; documentation completeness; operational readiness | Complete dossier: PFD/P&IDs, HAZID/HAZOP, QRA, SOPs, maintenance plans, training records, audit findings | Permitting roadmap (who approves what, when); submission pack for AHJ; commissioning/acceptance test plan; compliance matrix mapping requirements to evidence |

Note: AHJ = Authority Having Jurisdiction; PRD = Pressure Relief Device; QRA = Quantitative Risk Assessment; HAZOP/LOPA = process hazard studies.

Table 3 shows that an effective safety case begins with pressure hazards, which dominate compressed and cryocompressed storage systems and can also apply to pressurized adsorption concepts. Overpressure during filling, rapid decompression, and component fatigue are not only design issues but also operational ones; hence, the article emphasizes the pairing of engineered safeguards (pressure-rated components, conservative margins, PRDs, isolation) with procedural controls (temperature-compensated filling, inspection and NDT programs). Importantly, the evidence package, certifications, PRD sizing calculations, commissioning tests, and integrity plans, translates engineering intent into auditable compliance artifacts required by authorities and insurers.

For cryogenic hazards, the article highlights that $LH_2$ and $CcH_2$ introduce distinct failure modes, including low-temperature brittle fracture, oxygen condensation, insulation/vacuum degradation, and cold spills. These are mitigated through qualified cryogenic materials, vacuum-jacketed transfer systems, rigorous insulation QA, and disciplined purging and transfer procedures. The discussion implied by the article is that cryogenic safety is highly dependent on maintaining thermal integrity over time; therefore, vacuum integrity testing, documented operating procedures, and emergency response coordination become critical permitting enablers, not optional add-ons.

A core differentiator for liquid storage pathways is boil-off gas (BOG) handling, which the article treats as its own safety module. BOG is both a performance and safety challenge because heat ingress inevitably produces pressure rise and potential vented releases. The article links risk reduction to a clear "BOG philosophy": engineered vent routing, PRDs sized for credible heat-leak and upset scenarios, and a defined strategy to utilize, compress, or recondense boil-off. Dispersion modeling for vent stacks and an explicit abnormal operating procedure set are particularly important for satisfying fire authorities and local siting requirements, especially in populated or industrially congested areas.

The article then addresses embrittlement and materials compatibility as a cross-cutting integrity risk affecting essentially all hydrogen storage systems due to hydrogen–metal interactions and cyclic loading. The critical point is that materials selection must be coupled to traceable QA/QC and lifecycle integrity management. Welding qualification, procurement traceability, baseline NDT, and periodic inspections are treated as primary evidence because they demonstrate ongoing control of degradation mechanisms that may not be visible during normal operations but can govern long-term risk.

Leakage, dispersion, and ignition is presented as a universal module, reflecting that even low-probability leaks can become high-consequence events when accumulation occurs, particularly indoors or under canopies. The article emphasis on hazardous area classification, ventilation design, and detector placement recognizes that risk reduction is frequently achieved through layout and facility engineering rather than equipment selection alone. Deliverables such as area classification drawings, detector setpoints, and dispersion/QRA outputs are also central to permitting because they justify separation distances and electrical equipment ratings.

For materials and carrier-based storage, the article distinguishes thermal runaway and reaction hazards, which are most relevant to hydrides and LOHC processes. In these systems, safe performance depends on thermal management and process safeguards: rate-limited charging, heat exchanger design, temperature control loops, and interlocked shutdown logic. The article inclusion of HAZOP/LOPA and instrumented safeguard design indicates that permitting expectations often mirror chemical process safety practice, requiring formal hazard studies and documented management of change, especially where reactors, catalysts, and heated circuits are involved.

## 5.Conclusion

This study confirms that hydrogen storage is not a purely technical subsystem but a determining constraint on the scalability, cost structure, safety performance, and regulatory viability of hydrogen-based energy transitions. Comparative synthesis of the principal storage pathways indicates that no single option optimizes all decision criteria; rather, storage selection must be explicitly matched to application requirements and operational duty cycles. Compressed storage retains a near-term advantage where rapid refueling, modular buffering, and mature infrastructure are decisive, whereas liquid and cryocompressed approaches become increasingly compelling for high-throughput logistics and space-constrained applications, albeit with substantial cryogenic complexity and boil-off governance requirements. In parallel, adsorption-based systems, hydrides, and LOHCs provide strategically important alternatives for safety-sensitive and long-duration use cases, yet their competitiveness depends on mitigating thermal-management constraints, conversion energy penalties, materials durability limitations, and purity assurance at the point of use.

The sectoral opportunity mapping further demonstrates that storage technologies should be evaluated at the system level, accounting for utilization rate, footprint constraints, heat availability, and the practicality of cryogenic supply chains. Importantly, the proposed safety, risk, and compliance framework establishes a defensible pathway from hazard identification to engineered safeguards and auditable evidence, consolidating pressure and cryogenic hazards, embrittlement and leakage/dispersion phenomena, reaction-coupled thermal risks, and emergency venting and escalation control into a unified safety case aligned with codes, standards, and local permitting expectations. By explicitly linking sector-specific value propositions to verification-ready safeguards and compliance deliverables, the integrated opportunity–risk–compliance perspective strengthens technology screening rigor, reduces permitting uncertainty, and enhances project bankability. Collectively, these contributions provide a practical basis for accelerating safe, reliable, and scalable deployment of hydrogen storage infrastructure across mobility, industrial, logistics, and power-system applications.

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