Position Paper

Hydrogen Europe Research

Innovative materials

for low-pressure hydrogen storage

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Abstract

The transition to a hydrogen-based energy system requires safe, efficient, and cost-effective storage technologies. While gaseous and cryogenic hydrogen storage are technologically mature, solid-state storage materials are emerging as a promising alternative for low-pressure applications. This paper reviews the current state and future prospects of innovative materials for hydrogen storage, with a focus on metal hydrides, high-entropy alloys (HEAs), and metal-organic frameworks (MOFs). Metal hydrides offer high volumetric densities and improved safety, but their widespread deployment remains limited by high costs, kinetics, and thermal management challenges. HEAs show potential for exceeding conventional hydrogen-to-metal ratios, yet scale-up and phase stability remain barriers. MOFs provide tunable pore structures and high surface areas, enabling rapid physisorption, though their reliance on cryogenic conditions and complex synthesis limits applicability. The paper highlights life cycle assessment considerations, recycling opportunities, and the role of circular economy approaches in reducing environmental and economic burdens. A research timeline is proposed, outlining pathways from material optimisation and pilot demonstrations to potential niche commercialisation over the next decade. Finally, we discuss the strategic rationale for advancing solid-state hydrogen storage, underlining its contributions to sustainability, energy security, and industrial innovation.

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1

Introduction

Decarbonising the energy sector is a major challenge in the climate crisis. A hydrogen-based economy is seen as a key solution, with significant socio-economic impacts. To support adoption, research not only addresses technical challenges in production, storage, and transport, but also social acceptance. While gaseous and liquid hydrogen storage are well studied, solid-state storage is gaining attention as a promising alternative.

Solid-phase hydrogen storage relies on the ability of certain materials to absorb or bind hydrogen through chemical or physical processes. Materials that can be used for this purpose generally include simple Metal Hydrides [1], High Entropy metal Alloys (HEA) [2], as well as porous materials like Metal-organic frameworks (MOFs) [3] and carbon-based materials, considering the latest studies carried out on carbonaceous matrix materials with insertion of metal catalysts [4]. Among the main advantages of solid-phase hydrogen storage is that they can achieve significantly higher volumetric energy densities (up to 150 kg/m^3) [5] than the gaseous (40 kg/m^3 at 15 °C) or liquid form (70 kg/m^3 at – 253 °C and 1 bar) [6], reducing the need for large reservoirs; they show increased safety as they are less susceptible to accidental leakage and the possibility of explosion compared to the gaseous form, making them safer for use in transport applications; hydrogen can be stored under less extreme conditions (e.g., lower pressure), simplifying the necessary infrastructure; solid-state storage systems can be cycled several times, improving system efficiency; lower environmental impact compared to energy-demanding gas compression at high pressure (i.e. 700 bar) or liquid phase at low temperature (i.e. -256 °C) [7]. Despite its potential, solid-phase hydrogen storage still presents some technological challenges: many hydride materials require high T to absorb or release hydrogen, increasing energy costs limiting their applicability; life cycles and stability: since some materials may degrade during repeated hydrogen loading and unloading cycles, it is necessary to improve the durability and strength of the materials; the speed at which hydrogen can be absorbed or released is another limiting factor, especially in applications that require a rapid response, such as fuel cell vehicles; some of the most promising materials, such as metal hydrides, are still too expensive.

This paper aims to discuss the current state, advances, and limitations in solid-phase hydrogen storage. We highlighted the most remarkable achievements and constraints for different types of materials (i.e., metal hydrides, MOFs, and metal alloys) and the key aspects that still need to be improved, suggesting a timeline for developing and deploying solid-state hydrogen storage technology.


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Metal Hydrides - Current State of Research

Some metals and alloys can reversibly absorb significant amounts of hydrogen, typically by charging with atomic hydrogen supplied from an electrolyser. Their thermodynamic behaviour is described by Pressure–Composition Isotherm (PCI) curves. At a given temperature, hydrogen first dissolves at low concentrations to form a solid solution with the metal or alloy. When hydrogen saturates the first solid solution, the metal hydride formation starts. Such metal hydride formation occurs at a determined equilibrium pressure at the given temperature T. In the so-called pressure plateau region, there is an equilibrium between the hydrogen gas phase, the first solid solution phase, and the hydride phase, and the pressure stays almost constant. At the time of reaching the saturation state of the hydride phase, the pressure starts to increase, notably getting the system out of the plateau region where more hydrogen is supplied to the system and a second solid solution, hydride-hydrogen, is formed. The length of the plateau determines the amount of hydrogen that can be stored reversibly with small pressure changes. The equilibrium pressure strongly depends on T. From the equilibrium pressure and through the van't Hoff equation, it is possible to calculate the enthalpy ΔH and entropy ΔS changes. The enthalpy ΔH provides information on metal and hydrogen bond strength and the entropy ΔS about the change from gas molecular to dissolved solid hydrogen (the standard entropy of hydrogen is approximately 130 J/mo K).

High entropy alloys (HEA), in which five or more elements are mixed in near-equiatomic ratios, offer promising properties as hydrogen storage materials due to their ability to crystallise into simple bcc cubic structures in the presence of large lattice deformations resulting from the different sizes of atoms. Metal hydrides (MHx) represent a promising solution for storing large quantities of hydrogen in a future hydrogen-based energy system. Solid-phase hydrogen storage requires the design of alloys that allow a very high H/M ratio. Transition metal hydrides generally have a maximum H/M ratio of 2, and higher ratios can only be achieved in alloys based on rare earth elements. In this study, Witman et al. demonstrate, for the first time to the best of our knowledge, that a high entropy alloy of TiVZrNbHf [8] can absorb much higher amounts of hydrogen than its constituents and achieve an H/M ratio of 2.5.

The high cost of producing, distributing, and storing green hydrogen remains a major barrier to its large-scale replacement of fossil energy sources. Expenses stem from raw materials, specialised equipment, and energy-intensive production processes. In addition, some high-performance metal hydrides with desirable properties are inherently complex and costly to manufacture, further limiting their use in cost-sensitive energy storage and transport applications. Reducing these costs will require both technological innovation and economies of scale to unlock the full potential of the metal hydride market. Deposition is an example of an advanced synthesis technique that allows precise control over the morphology and properties of materials. Thanks to worldwide government incentives and an increased emphasis on hydrogen storage research, metal hydride research has surged in the past decade. This is because certain metals, such as zirconium, vanadium, niobium, and hafnium, have a high export value. Different metals are combined to create alloys with properties specifically designed for their intended uses. Compared to pure metal hydrides, alloyed metal hydrides have greater stability, better kinetics, and higher hydrogen storage capacity [9].

Recycling metal hydrides presents several environmental, economic, and strategic advantages. Minimising environmental impact is certainly one of the key factors since metal hydrides may contain heavy metals or reactive substances that, if not disposed of properly, can pollute soil and groundwater. Furthermore, reducing mining decreases the need to extract new metals (such as nickel, cobalt, and rare earth elements), activities that have significant ecological impacts. Recovering valuable materials would also lead to lower reservoir production costs, enabling metal hydrides to compete more effectively with other storage technologies in terms of price and to achieve the technology's goal of less than EUR 10 per kg of stored hydrogen. Additionally, while recycling is energy-intensive, it is often less energy-demanding than producing metals from virgin raw materials. Recycling spent metal hydrides also offers considerable strategic advantages by reducing dependence on foreign suppliers from geopolitically unstable regions. In this way, materials are transformed from waste into reuse resources, promoting a more sustainable production and consumption model. Moreover, recent research activities are oriented toward the production of metal hydrides starting from scraps instead of pure metals, enabling a reduction of the costs of the alloys and the environmental burdens and introducing a positive circular economy strategy [9-11].

The use of metal hydrides for hydrogen storage for transport applications is recognised as having significant yet unexplored potential. Indeed, the advantages of advanced metal hydride-based storage systems may outweigh their current disadvantages, especially for selected applications where weight is not a critical factor (e.g., heavy vehicles, tractors of various types, and end-use). A reduction in onboard operating pressure can drastically reduce the complexity and economic cost of the infrastructure, with clear benefits that could boost the hydrogen economy. Adopting (or procuring) advanced materials may also lead to a higher density of onboard storage energy, thus enabling hydrogen-powered vehicles to achieve a better driving range.

Life Cycle Assessment (LCA) is a key tool for evaluating the environmental impact of materials and technologies throughout their entire life cycle, from extraction to disposal. Low-pressure hydrogen storage systems rely on metal hydrides, porous materials, and advanced composites, each with varying environmental impacts and resource availability. LCA is crucial in evaluating these impacts, considering factors like raw material extraction, energy consumption, emissions, and end-of-life disposal. In Europe, the availability of key materials, including magnesium, titanium, and rare earth elements, influences the sustainability and feasibility of storage technologies. While some critical materials are imported mainly, increasing recycling rates and developing alternative materials could enhance resource security and reduce environmental burdens, supporting the EU's transition to a sustainable hydrogen economy. From a LCA and environmental protection perspective, using metal hydrides for hydrogen storage in transport applications offers several potential benefits. By reducing onboard operating pressures, infrastructure complexity, and energy requirements could be minimised, leading to lower environmental impacts on energy consumption and emissions. Furthermore, the increased energy density of hydrogen storage could enable longer driving ranges for hydrogen-powered vehicles, reducing the reliance on fossil fuels and contributing to decarbonization. However, the environmental impact of producing, recycling, and disposing of metal hydrides must be considered in the LCA to assess the full lifecycle sustainability of these technologies. Additionally, the widespread adoption of hydrogen could significantly reduce emissions from the transport sector, helping mitigate climate change [9], [12].

Despite the advantages in terms of gravimetric storage density and operational safety of solid-state hydrogen storage solutions and the fact that the current state of the technology allows for their implementation in certain specific sectors, e.g., use in certain industries, prototypes of hydrogen vehicles or the military sector, their widespread implementation as a mass hydrogen storage solution is not yet technically or economically feasible. Some of these challenges are common for different materials, like the adequate heat management during hydrogen sorption/desorption steps that kinetically limit the hydrogen charge/release operations; the correct balance between gravimetric and volumetric storage densities, although it is dependent on the use of the storage system in a mobile or stationary application; and the development of environmentally and economically sustainable industrial approaches for their large-scale production. The most relevant factors are reducing the carbon footprint and environmental impact during manufacturing and minimizing the critical consumption of raw materials. Also important are the challenges associated with their recycling and after-life treatment. Finally, despite the extensive efforts in measuring the thermodynamic and kinetic properties of the materials used as hydrogen sorbents, the relatively small reproducibility of many scientific measurements of storage capacity and behaviour of sorbent materials hampers the availability of high-quality data to compare and select the best materials for their application. This limitation avoids the escalation of scientific knowledge into standardised technology for solid-state hydrogen storage, except for specific materials used for some projects or prototypes. Developing and establishing harmonised measuring techniques, protocols, and reference materials would help increase the comparability of results from different sources and push up the development of sorbent-based technology [13].

3

Metal-Organic Frameworks (MOFs) - Current State of Research

Metal-organic frameworks, highly porous organic-inorganic hybrid materials formed by coordination bonding between organic ligands and metal ions/clusters, are extensively investigated for gas storage, including hydrogen. Hydrogen is stored in MOFs using physical adsorption of the diatomic molecule, which is different from metal-hydride systems where hydrogen atoms are chemically bonded to metals or occupy interstitial spaces in the metallic matrix. The physical mechanism is faster and fully reversible by pressure and temperature changes due to the lower interaction energy between the physically adsorbed hydrogen and the solids, also involving a smaller amount of heat during operation. However, this smaller energy interaction involves a low operating temperature for adsorption, usually needing cooling agents like liquid nitrogen or similar. Advantages of using MOF materials compared to other porous materials like carbons of covalent organic frameworks (COFs) are the presence of controlled and appropriate pore sizes in the range of micropores (< 2 nm), controllable and defined structure-related properties due to their crystallinity, large surface area per unit of mass and volume for specific MOF structures (gravimetric and volumetric surface areas), and chemical hybridization (organic and metallic) that increases the interaction energy compared to pure organic or carbonaceous materials, with additional advantages due to the easily modifiable surface chemistry.

Various strategies have been employed to improve the H_2 storage capacity of MOFs like ligand functionalization (e.g. modification with -F, $-CF_3$, -OH, -COOH, $-NH_2$), adjustment length of the ligand, replacing the original linker with another one, introduction of unsaturated metal sites e.g. Mn(II), Mg(II) and Ni(ii), interpenetration of framework with another MOF structure, or preparation of hybrid materials (combination of MOFs with carbon materials or metal nanoparticles).

One of the highest H_2 uptakes was determined for MOF-210 (17.6 wt.% at 77K, 80 bar), MOF-177 (7.5 wt.% at 77K, 80 bar), NU-100 (9.95 wt.% at 77K, 70 bar) [14].


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Research Challenges in MOFs, hydrides and HEAs

Some specific limitations affect each type of material used for solid-state hydrogen storage. In the case of MOF materials, the most significant limitation is the high cooling energy consumption due to the weak interaction between hydrogen and the porous structures involved during the physisorption step. This limitation makes using considerable cooling agents like liquid nitrogen necessary to maintain the cryogenic operation. Research efforts have focused on developing structures for increasing the interaction strength, like reducing the pore size of materials still showing a high surface area and pore volume, modifying the chemistry of both metallic and organic secondary-building units, or including metallic nanoparticles to generate preferential sorption sites or promote hybrid physical-/chemical-sorption mechanisms like hydrogen spillover or hydrides nanoconfinement. Besides, since MOFs can be constituted by all the metals in the periodic table and hundreds of organic linkers, their huge chemical and structural variety make selecting the best-performing structures a big challenge. This task includes screening around 100,000 deposited MOF structures and designing and synthesizing new or hypothetical structures by rational approaches, high-throughput experimental or computational screening, and machine learning [15-16]. Finally, improvements in the sustainability and scalability of the synthesis of MOFs are necessary due to non-renewable and diverse metallic and organic precursors and organic solvents used in the specific chemical routes for their synthetic approaches. In this sense, alternative production methods like precipitation in water, electrodeposition, or solvent-free mechanochemical syntheses are under study and in industrial development [17].

For metal-hydride systems, the main challenges are related to the gravimetric storage density due to the high densities of the metallic bulk materials used, the production of alloys without critical raw materials (CRM), and using scraps to move toward a circular economy; the heat management of the storage tanks necessary for hydrogen sorption/desorption that is strictly related to the enhancement of sorption kinetics and thermal conductivity of the metallic powders or pellets used for H_2 storage. It is important to note that the production methods can mainly affect the number of oxides or secondary phases in the metal hydrides, with a possible significant change in sorption properties. This aspect can be critical when alloy production moves from a laboratory scale to an industrial scale with less clean conditions [18]. Finally, challenges are related to the stability and durability of the metal alloys that are measured by cycling the powders, usually for a limited number of cycles. At the same time, the material is expected to be charged/discharged daily for many years in real application storage systems. As pellets are considered, i.e., metallic powders dispersed into binders to avoid tank deformation during cycling, the durability of the polymers used as binders is even more important to consider, as the polymer's degradation can lead to pellet cracks [19].

Similar difficulties also limit the use of high-entropy alloys over traditional metal hydrides. However, they are also limited by the challenges in controlling the hydrogen storage properties due to their complex composition, the stability of their complex metallic phases, which could even change during the hydrogenation/dehydrogenation phases and produce segregation of phases, the lack of a precise understanding of the relationship between composition and the hydrogen storage properties, due to the known as "cocktail effect" basically related to the non-linearity of some properties resulting from mixing different metals, and the difficulties to scale the production of this kind of material further than the gram-scale generally produced in laboratories [20].

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Timeline and Resources

Metal Hydrides – Short-Term Research Priorities

The short-term scenario in 1-3 years will focus on material optimisation, cost reduction, and pilot-scale testing. For Metal Hydrides, it is expected that:

Material Optimisation:

Continued exploration of lightweight hydrides (e.g., Mg-based alloys) and destabilized systems (e.g., MgH_2 + Si) is expected. Computational materials science and AI-driven screening will accelerate discovery, with 5–10 promising new alloy systems likely entering lab-scale validation. The focus will shift toward tuning thermodynamics and kinetics (e.g., through nanostructuring catalysts or composite design). Some systems will reach high TRL (Technology Readiness Level), with reversible storage capacities approaching 6–7 wt% and absorption/desorption temperatures closer to 150–200°C.

Cost Reduction:

Cost remains a barrier due to rare or expensive alloying elements (e.g., Ti, V). Research will aim to replace these with earth-abundant alternatives and simplify synthesis (e.g., mechanochemical processing). Pilot projects will benefit from economies of scale and improved manufacturing methods. Target costs for viable systems could drop to <9.3 €/kWh (hydrogen energy equivalent), nearing competitiveness with compressed or liquefied H_2 storage in select use cases (e.g., stationary, off-grid).

Pilot-Scale Testing:

Early-stage pilot demonstrations will begin in controlled environments (e.g., labs or university-led industrial partnerships), particularly in stationary storage, backup systems, or niche mobility (e.g., drones, submarines). At least 2–3 industrial-scale pilots are expected globally, potentially supported by government hydrogen roadmaps. Emphasis will be on safety, system integration, and cyclic durability (>1000 cycles), with feedback guiding design for full-scale commercialisation.

Metal-Organic Frameworks – Short-Term Research Priorities

Below is a forecast for the next three years for material optimisation, cost reduction, and pilot-scale testing of Metal-Organic Frameworks (MOFs) for hydrogen storage based on current trends and emerging research:

Material Optimisation:

Computational Design & AI Integration: Accelerated discovery using machine learning and high-throughput simulations will significantly reduce trial-and-error synthesis, identifying MOFs with optimal surface area, pore size, and binding enthalpies for hydrogen adsorption.

Enhanced Stability & Recyclability: Efforts will focus on MOFs with improved chemical and thermal stability under practical operating conditions (e.g., temperature, pressure cycling).

Hybrid Materials: Developing MOF composites (e.g., MOF-graphene, MOF-MOF hybrids) will improve performance metrics such as volumetric hydrogen density and mechanical robustness.

Cost Reduction:

Synthesis Scalability: Advances in greener, lower-cost synthesis routes (e.g., mechanochemical synthesis, solvent-free methods) will reduce MOF production costs by 30–50%.

Raw Material Optimization: Using earth-abundant metals (e.g., iron, aluminum) and simpler organic linkers will replace expensive rare metals (e.g., zirconium), cutting material input costs.

Recycling & Reusability: Recyclable MOF production processes and regeneration cycles will become central to cost-effective storage systems.

Pilot-Scale Testing:

From Lab to System Prototypes: More MOFs will move from academic research to TRLs 5–6, undergoing real-world pilot tests in hydrogen-powered vehicles and stationary storage units.

Integration with Storage Tanks: Demonstrations of MOF-based hydrogen storage integrated with Type IV composite tanks will test operational feasibility under SAE standards.

Industry Collaboration: Partnerships among research institutions, startups, and automakers (e.g., Hyundai, Toyota) will yield early-stage demonstration units, targeting 2027–2028 for pre-commercial evaluations.

Metal Hydrides – Medium-Term Research Priorities

Below is a concise 3-5-year forecast (2025-2030) focusing on prototype integration, scalability, and real-world testing of metal hydrides for hydrogen storage:

Prototype Integration:

Metal hydride systems will be integrated into niche prototypes, such as backup power units, portable hydrogen generators, and unmanned vehicles. These prototypes will emphasise compactness, thermal management, and system-level optimisation with fuel cells. Expect broader integration into hybrid energy systems, including renewable-based hydrogen microgrids and small-scale mobile platforms. Designs will move toward modular, plug-and-play formats, simplifying deployment.

Scalability:

Progress will focus on scaling synthesis processes (e.g., ball milling, reactive sintering) for stable, cost-effective materials. Pilot lines for tank fabrication will emerge, targeting batch production for controlled applications. Commercial pre-production may begin for selected markets (e.g., telecom backup, remote energy). Challenges such as heat exchange efficiency, cycle life consistency, and cost per kWh will continue to be refined as production scales.

Real-World Testing:

Testing in controlled operational environments will expand — off-grid sites, research campuses, and defence applications. Performance metrics like hydrogen retention, recharge time, and degradation under cycling will be closely monitored. Field trials in harsh and variable conditions (e.g., desert, arctic, maritime) will gain traction. Regulatory support and funding (e.g., EU Green Deal, US DoE H2@Scale) will boost public-private trials. The first long-term performance datasets will inform certification standards.

Metal Organic Frameworks – Medium-Term Research Priorities

Here's a concise 3–5 years forecast (2025–2030) on Prototype Integration, Scalability, and Real-World Testing of Metal-Organic Frameworks (MOFs) for hydrogen storage:

Prototype Integration:

MOFs with high surface area and volumetric density (e.g., HKUST-1, MOF-5, NU-1501) will be integrated into prototype storage tanks, often in hybrid systems (e.g., MOF + compressed hydrogen). Challenges such as poor thermal conductivity and mechanical stability will be addressed through binder composites or pelletization techniques. Early prototypes move from lab-scale tanks to full-stack systems (e.g., integrated with fuel cells for mobility or backup power). Thermal management and cycling stability will be core focus areas, with system-level integration being tested in controlled demo environments.

Scalability:

Efforts will intensify to scale up MOF synthesis via green, low-cost routes (e.g., water-based synthesis, mechanochemistry). Supply chain maturity remains low, with production mostly limited to kilograms per batch.

Commercial-scale synthesis of at least 2–3 industrially relevant MOFs will be demonstrated, reaching ton-scale output with cost targets <46 €/kg. Adopting continuous flow synthesis and modular production systems will support scalability and reproducibility.

Real-World Testing:

MOF-based systems will be tested in academic-industry collaborations, primarily in stationary and small-scale mobile applications (e.g., drones, UAVs). Testing will focus on durability under humidity, temperature cycling, and mechanical stress. Real-world pilots in cold-chain logistics, off-grid power, and possibly range extenders for electric vehicles. At least one full deployment in a commercial setting (e.g., backup hydrogen storage for telecom towers or data centres) is expected by 2030, depending on policy support and performance data.

Metal Hydrides – Long-Term Research Priorities

The following is a forecast for the next 5-10 years on the full commercialisation, industry adoption, and large-scale storage of metal hydrides for hydrogen storage:

Full Commercialisation:

Metal hydride hydrogen storage is commercialised in niche markets for stationary backup systems and expected to see more and strategic commercialisation by 2030, primarily in applications such as:

Stationary backup power systems (e.g., telecom, remote infrastructure); military and aerospace applications where energy density and safety matter more than cost; Low- to medium-scale hydrogen refuelling stations, especially in regions prioritising solid-state hydrogen safety. Barriers: High cost of hydride materials (e.g., rare-earth alloys), thermal management challenges, and relatively slow kinetics compared to compressed gas systems.

Industry Adoption:

Wider industry adoption will remain application-specific, with automotive and heavy transport sectors likely favouring other storage technologies (like high-pressure tanks or liquid hydrogen) due to weight constraints. Industrial hydrogen users (e.g., semiconductor manufacturing, metal processing) may adopt metal hydrides for on-site storage where space and safety are premium; Hydrogen microgrids or renewable-energy-linked storage (e.g., solar-to-hydrogen) could leverage hydrides for long-duration, seasonal storage. Outlook: Moderate adoption driven by safety and reliability rather than cost-efficiency.

Large-Scale Storage:

Proper large-scale hydrogen storage using metal hydrides (e.g., hundreds of kg to tons of H_2) faces significant hurdles: Mass and cost scale poorly compared to underground or pressurized systems; Thermal management and charging/discharging rates remain a bottleneck. However, modular storage at the community or facility scale (10–100 kg H_2) could be a viable alternative to high-pressure systems where space and safety outweigh throughput needs. Within 10 years: Pilots of metal hydride storage modules for hydrogen hubs and standardised cartridges for off-grid hydrogen storage in specialised sectors.

Metal-Organic Frameworks – Long-Term Research Priorities

The following is a brief forecast of Metal-Organic Frameworks (MOFs) in hydrogen storage over the next 5-10 years, with a focus on full commercialisation, industry adoption, and large-scale storage:

Full Commercialisation:

MOF-based hydrogen storage will remain in the pilot and prototype phase, focusing on materials optimisation, cost reduction, and system integration. Commercial products using MOFs will be limited to high-value, niche markets (e.g., aerospace, defense, portable fuel cells). Commercialisation will expand as synthesis costs drop, stability improves, and performance targets (e.g., US DOE targets for gravimetric and volumetric storage) are approached or met. Early adoption in mobility sectors (e.g., drones, heavy-duty vehicles) and backup power systems are likely.

Industry Adoption:

In the energy and mobility sector, growing interest from hydrogen vehicle manufacturers and energy companies by 2028–2030 and strategic partnerships with MOF developers for on-board storage systems will drive adoption; industrial Gas Supply Chain where MOFs could be adopted for efficient transportation and buffering of hydrogen at ambient or near-ambient pressures and applications in hydrogen refuelling infrastructure may emerge around 2030.

Large-Scale Storage:

In the near term (5 years), grid-level or massive storage is not yet practical due to current scalability and cost issues. The focus will remain on modular, intermediate-scale storage (kg-scale rather than tons). In the long term (10 years), advances in MOF synthesis scalability, cost-efficiency, and thermal management could enable larger-scale storage, and the use in stationary energy storage systems, especially in off-grid or remote areas, may emerge late in this period.

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Rationale for Advancing Research in This Area's Potential Applications

Solid-state hydrogen storage is a promising alternative to conventional compressed gas and cryogenic liquid storage, offering sustainability advantages, societal benefits, economic potential, and alignment with global energy strategies.

Sustainability

Solid-state hydrogen storage materials, such as metal hydrides, complex hydrides, and metal-organic frameworks (MOFs), provide a safer and more energy-efficient storage solution. Unlike high-pressure or cryogenic storage, these materials operate at lower pressures and moderate temperatures, reducing the energy needed for compression and liquefaction. Additionally, certain materials, such as magnesium hydrides, utilise abundant and recyclable elements, further improving their environmental footprint. The adoption of solid-state storage supports the hydrogen economy by facilitating green hydrogen storage from renewable sources.

Societal Benefits

Deploying solid-state hydrogen storage enhances public safety due to its reduced risk of leaks and explosions compared to high-pressure hydrogen tanks. It also supports clean energy transitions by enabling reliable hydrogen storage for fuel cell vehicles, residential energy storage, and backup power systems. Solid-state solutions contribute to energy security and resilience in urban and rural communities by decentralising hydrogen storage and reducing infrastructure risks.

Economic Impact

Solid-state hydrogen storage has the potential to lower costs over time by reducing the need for high-pressure containment and specialised infrastructure. While initial material costs can be high, long-term durability and lower maintenance requirements contribute to overall cost reductions. Additionally, material science and manufacturing advancements are expected to drive down production costs, making solid-state storage more economically viable for automotive, aerospace, and industrial applications. The sector's growth could create jobs in material research, manufacturing, and hydrogen infrastructure development.

Alignment with Strategic Goals

Governments and international organisations increasingly prioritise hydrogen as a key component of their energy transition strategies. Solid-state hydrogen storage aligns with the UN Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy) and Goal 13 (Climate Action) [21]. European hydrogen strategies emphasise the importance of safe, efficient, and scalable hydrogen storage solutions. As global hydrogen demand rises, solid-state storage can be crucial in achieving decarbonization targets and energy security goals.

Applications

Solid-state hydrogen storage is applicable in various sectors, including transportation (fuel cell vehicles, drones, and aircraft), stationary energy storage (grid balancing, residential power), and portable energy systems (hydrogen-powered devices). Its ability to safely store and release hydrogen on demand makes it a key enabler of the hydrogen economy.

Solid-state hydrogen storage presents a sustainable, safe, and economically promising solution for hydrogen storage. Its alignment with global energy strategies and potential for widespread applications make it vital to achieving a cleaner and more resilient energy future.

References

1 Drawer, C. et al. (2024). “Metal hydrides for hydrogen storage – Identification and evaluation of stationary and transportation applications”, Journal of Energy Storage (Vol. 77). https://doi.org/10.1016/j.est.2023.109988

2 Shahi, R. et al. (2023). “Perspectives of high entropy alloys as hydrogen storage materials”. International Journal of Hydrogen Energy, 48(56). https://doi.org/10.1016/j.ijhydene.2022.02.113

3 Yuvaraj, A. R. et al. (2024). “Role of metal-organic framework in hydrogen gas storage: A critical review”. In International Journal of Hydrogen Energy (Vol. 59). https://doi.org/10.1016/j.ijhydene.2024.02.060

4 Carraro, P.M. et al. (2019). “Nanostructured carbons modified with nickel as potential novel reversible hydrogen storage materials: Effects of nickel particle size”. Microporous and Mesoporous Materials (273). https://doi.org/10.1016/j.micromeso.2018.06.057

5 Puszkiel, J.A. et al. (2018). “Emerging Materials for Energy Conversion and Storage”. Ed. Elsevier, USA, DOI: 10.1016/B978-0-12-813794-9.00012-0

6 Bellosta von Colbe, J. et al. (2019). “Application of hydrides in hydrogen storage and compression: Achievements, outlook and perspectives”. Int J Hydrogen Energy 44:7780–808. https://doi.org/10.1016/j.ijhydene.2019.01.104

7 Agostini, A. et al. (2018). “Role of hydrogen tanks in the Life Cycle Assessment of fuel cell-based Auxiliary Power Units”. Applied Energy 215, 1-12; https://doi.org/10.1016/j.apenergy.2018.01.095

8 Witman, M. et al. (2021). Data-Driven Discovery and Synthesis of High Entropy Alloy Hydrides with Targeted Thermodynamic Stability. Chemistry of Materials, 33(11). https://doi.org/10.1021/acs.chemmater.1c00647

9 Puszkiel, J.A. et al. (2025). “On the hydrogen storage properties and life cycle evaluation of a room temperature hydride for scale-up applications: The case of an AB2-alloy”, International Journal of Hydrogen Energy, 118, 482, https://doi.org/10.1016/j.ijhydene.2025.03.161

10 Garelli, F. et al. (2025). “Enhancing TiFe Alloy Activation for Hydrogen Storage Through Al, Cr, Co, and Cu Substitutions as a Step Towards Future Recycling, Condensed Matter, Materials Science, https://doi.org/10.48550/arXiv.2504.06990

11 Yuanyuan, S. et al. (2022). “Developing sustainable FeTi alloys for hydrogen storage by recycling, Communications Materials, 3, 101. 10.1038/s43246-022-00324-5

12 Alves, E.S. et al. (2025). “Life cycle assessment for the determination of the environmental impacts of an advanced large-scale hydrogen storage system from HyCARE EU project”, Journal of Cleaner Production, 515, 145836, https://doi.org/10.1016/j.jclepro.2025.145836.

13 Hirscher, M. et al. (2020). "Materials for hydrogen-based energy storage past, recent progress and future outlook". Journal of Alloys and Compounds 827, 153548, https://doi.org/10.1016/j.jallcom.2019.153548

14 IEA (2023), Global Hydrogen Review 2023, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2023, Licence: CC BY 4.0

15 Furukawa, H. (2010). "Ultrahigh Porosity in Metal-Organic Frameworks, Science, 329 (5990), 424-428

16 Farha, O.K. et al (2010). "De novo synthesis of a metal-organic framework material featuring ultrahigh surface area and gas storage capacities". Nature Chemistry 2 (11), 944-948, https://doi.org/10.1126/science.1192160

17 Dian Zhao, D. et al (2024). "Porous metal–organic frameworks for hydrogen storage". ChenPhys. Chem. Chem. Phys., 2024, 26, 6490 https://doi.org/10.1039/D3CP05540J

18 Julien, P.A. et al. (2017). "Metal–organic frameworks meet scalable and sustainable synthesis". GreenChem.19,2729, https://doi.org/10.1039/c7gc01078h

19 Warfsmann, J. et al. (2023). "Applying wash coating techniques for swelling-induced stress reduction and thermal improvement in metal hydrides". Journal of Alloys and Compounds 950 (2023) 169814. https://doi.org/10.1016/j.jallcom.2023.169814.

20 Barale, J. et al. (2022). "TiFe0.85Mn0.05 alloy produced at industrial level for a hydrogen storage plant". International Journal of Hydrogen Energy 47, 29866 – 29880, https://doi.org/10.1016/j.ijhydene.2022.06.295

21 Marques, F. et al. (2021). "Review and outlook on high-entropy alloys for hydrogen storage". Energy Environ. Sci., 14, 5191, https://doi.org/10.1039/D1EE01543E

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