

Hydrogen Storage Technologies: Current Status, Challenges, and Future Prospects

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Abstract: Hydrogen storage is a pivotal enabler of the emerging hydrogen economy, yet its large-scale deployment remains constrained by interconnected challenges spanning materials performance, safety governance, techno-economic viability, power-system integration, and sustainability alignment. This article presents an integrated assessment of hydrogen storage technologies, emphasizing that progress in advanced storage media, such as metal and complex hydrides, liquid organic hydrogen carriers, and nanostructured materials, can improve gravimetric and volumetric densities while reducing operating pressures and temperatures. However, limitations related to kinetics, reversibility, degradation, and scalability persist, requiring multidisciplinary research that links materials innovation with system-level engineering. The study further highlights that safe expansion of hydrogen storage depends on harmonized standards, robust risk-based design practices, and real-time monitoring to address hazards including leakage, embrittlement, boil-off losses, and ignition risks across compressed, liquefied, and solid-state systems. A techno-economic perspective indicates that storage costs and energy efficiency penalties remain decisive barriers to competitiveness, underscoring the need for economies of scale, manufacturing innovation, and strategic integration with renewable hydrogen production. From an energy systems viewpoint, hydrogen storage is positioned as a strategic flexibility resource for high-renewable power networks by enabling long-duration and seasonal storage and sector coupling, despite lower round-trip efficiency relative to batteries. Finally, lifecycle environmental performance and coherent policy frameworks, including subsidies, carbon pricing, and sustained research support, are identified as essential to ensure that hydrogen storage delivers credible decarbonization and sustainability outcomes. Collectively, the findings demonstrate that hydrogen storage must be advanced through coordinated technological innovation, safety regulation, cost-reduction pathways, integrated infrastructure planning, and sustainability-oriented governance to realize its role in resilient, low-carbon energy systems.

Keywords: Hydrogen Storage Technologies; Advanced Storage Materials; Techno-Economic Assessment; Renewable Energy Integration; Energy System Decarbonization.

1. Introduction

Hydrogen storage is widely recognized as a critical enabling technology for the emerging hydrogen economy, supporting applications across power generation, transportation, and industrial decarbonization. At present, the most established hydrogen storage methods include compressed gaseous hydrogen, liquefied hydrogen, and materials-based storage systems [1,2]. Compressed hydrogen storage is technologically mature and commonly used in mobility applications, while liquefied hydrogen offers higher volumetric energy density suitable for long-distance transport and bulk storage. In parallel,

significant research efforts are focused on solid-state and chemical storage pathways, reflecting the growing need for safer, denser, and more flexible storage solutions compatible with large-scale energy systems [3,4]. Figure 1 summarizes how hydrogen (H_2) is stored, grouping technologies into physical-based and material-based approaches. Each pathway balances energy density, operating conditions, safety, and cost.

Hydrogen storage technologies are commonly classified into physical-based and material-based approaches. Physical storage retains hydrogen as H_2 and includes compressed gas (mature and fast to refuel but limited volumetric density and high-pressure requirements), cryo-compressed storage (higher density through combined cooling and compression but with added system complexity), and liquid hydrogen (very high volumetric density but energy-intensive liquefaction, cryogenic handling, and boil-off losses). Material-based storage incorporates hydrogen within a host medium through adsorption in high-surface-area porous materials (often reversible yet typically requiring low temperatures for high capacity), liquid organic hydrogen carriers (LOHCs) (liquid handling at near-ambient conditions but with catalytic and energy penalties for hydrogenation/dehydrogenation), metal/interstitial hydrides (safe, high volumetric density but heavy and heat-management limited), complex hydrides (high gravimetric potential but challenging kinetics and operating temperatures), and chemical carriers (high hydrogen content but by-product handling and regeneration constraints), highlighting that the optimal choice depends on application-specific trade-offs among density, efficiency, cost, safety, and operability [5-10].

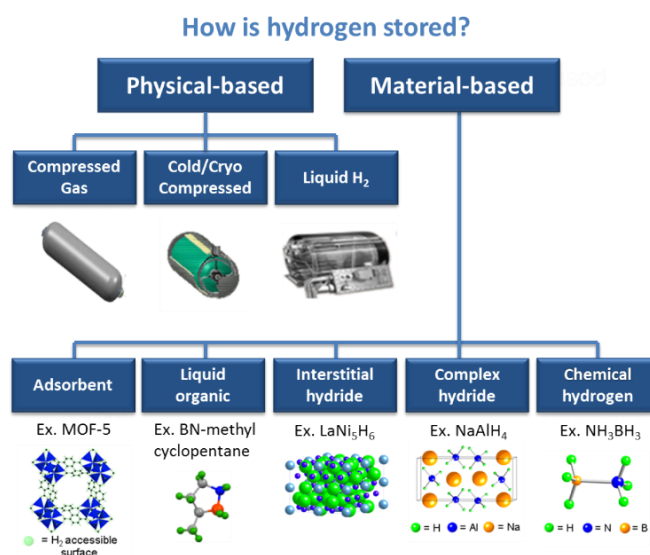


Figure 1. Summarizes how hydrogen (H_2) is stored, grouping technologies into physical-based and material-based approaches.

Despite notable progress, hydrogen storage technologies continue to face substantial technical challenges that limit their widespread adoption. Compressed hydrogen systems require high operating pressures, leading to increased capital costs, energy consumption, and safety concerns related to leakage and vessel integrity. Liquefied hydrogen storage, while advantageous in terms of density, is constrained by the high energy penalty of liquefaction and continuous boil-off losses. Materials-based storage systems, including metal hydrides and liquid organic hydrogen carriers, encounter challenges related to slow kinetics, limited reversibility, thermal management, and material degradation over repeated cycles. These limitations underscore the need for continued innovation across multiple storage pathways [11-13].

Materials innovation plays a pivotal role in addressing the performance constraints of advanced hydrogen storage systems. Recent advances in materials science, such as catalytic doping, nanostructuring, and composite hydride design, have demonstrated the potential to enhance hydrogen absorption and desorption kinetics while reducing operating temperatures and pressures. Liquid organic hydrogen carriers offer an alternative route by enabling hydrogen storage under ambient conditions,

although improvements in catalyst efficiency and system integration are required to reduce energy losses. Progress in these areas suggests that materials engineering, when combined with system-level optimization, can significantly improve the practicality of next-generation hydrogen storage technologies [14,15].

From an economic and systems perspective, the cost of hydrogen storage remains a decisive barrier to market competitiveness. High capital investment, operational energy penalties, and infrastructure requirements vary widely across storage technologies, influencing their suitability for different applications and scales. As a result, no single storage option can be universally applied across all use cases. Future cost reductions are expected to arise from economies of scale, manufacturing standardization, and closer integration with renewable hydrogen production. Strategic deployment that matches storage technologies with appropriate applications, such as short-term grid services or seasonal energy storage, can be essential for improving overall system economics [16,17].

In this direction, hydrogen storage is poised to play a strategic role in future low-carbon energy systems, particularly as renewable energy penetration increases. Its ability to provide long-duration and seasonal energy storage, support grid balancing, and enable sector coupling between electricity, transport, and industry distinguishes hydrogen from other energy storage options. However, realizing this potential will require coordinated advances in technology, safety standards, policy frameworks, and infrastructure planning [18-20]. With sustained research, supportive policies, and integrated system design, hydrogen storage technologies are expected to evolve from niche applications to foundational components of resilient and sustainable energy systems. Several studies have systematically examined hydrogen storage technologies, focusing on their current state of development, key technical and economic challenges, and future prospects, as outlined below:

In [21], Hydrogen storage technologies are fundamental to enabling large-scale renewable energy deployment and improving the flexibility of low-carbon energy systems. Accordingly, a wide range of storage media has been investigated, including hydrogen storage alloys (metal hydrides), inorganic chemical hydrides, carbon-based porous materials, and liquid hydride carriers. Among these options, ammonia (NH_3) is particularly attractive because it can be readily liquefied under mild conditions (≈ 1 MPa at 298 K) and exhibits a very high volumetric hydrogen density (10.7 kg H_2 per 100 L) alongside a high gravimetric hydrogen content (17.8 wt%). Moreover, its theoretical hydrogen conversion efficiency is reported to be approximately 90%. Importantly, NH_3 can be used as a combustible energy carrier without direct CO_2 emissions, reinforcing its potential role as a practical hydrogen vector and renewable energy carrier.

This paper [22] reviews recent advances in applying first-principles (*ab initio*) methods to the design and performance enhancement of key hydrogen storage media, including two-dimensional materials, metal-organic frameworks, alkali-metal-based composite hydrides, and metal-based hydrogen storage systems, with the aim of elucidating underlying storage mechanisms. By calculating electronic structure descriptors, such as band structure, charge density distribution, and lattice vibrational properties, first-principles simulations can predict preferred hydrogen adsorption sites, binding strengths, and diffusion pathways within candidate materials. These insights enable the rational screening and proposal of hypothetical next-generation hydrogen storage materials with improved thermodynamic and kinetic characteristics.

This review article [23] arises from multi-national, multi-institutional collaborative research involving experts in hydrogen energy. Recent advances in artificial intelligence, machine and deep learning, 3D/4D printing, and combinatorial methodologies are increasingly enabling accelerated discovery and engineering of next-generation hydrogen storage materials tailored for PEM fuel cell applications. Building on more than four decades of accumulated knowledge, the review synthesizes a broad spectrum of hydrogen storage systems, including metallic hydrides, functionalized magnesium hydrides, reactive hydride composites, carbonaceous materials and their storage mechanisms, as well as emerging platforms such as metal-organic frameworks, perovskite-based structures, and related materials, highlighting how their fundamental storage behaviors and performance limitations inform current design strategies and future research directions.

This review [24] offers a concise overview of hydrogen production and storage technologies, with particular emphasis on the recent evolution of electrochemical hydrogen storage (EHS) materials. It systematically compares the EHS performance of diverse material classes, including alloys and metal compounds, carbonaceous materials, metal oxides and mixed metal oxides, metal–organic frameworks (MOFs), MXenes, and polymer-based systems. Across the surveyed literature, mixed metal oxides are highlighted as especially promising due to their comparatively high discharge capacities and improved cycling stability. The review further underscores the need to develop next-generation materials that combine large specific surface area, highly active and conductive architectures, and low-cost, scalable synthesis routes.

This article contributes a comprehensive and integrated perspective on hydrogen storage technologies by systematically linking advances in storage materials, safety and standardization frameworks, techno-economic performance, renewable energy integration, and sustainability considerations. It demonstrates that while significant progress has been achieved in compressed, liquefied, and materials-based hydrogen storage systems, their large-scale deployment remains constrained by interrelated challenges involving material durability, safety risks, high costs, and system integration complexities. By synthesizing recent developments and identifying critical cost-reduction and policy-driven enablers, the article positions hydrogen storage as a strategic solution for long-duration energy storage and sector coupling in low-carbon energy systems, while emphasizing that its successful role in the energy transition depends on coordinated technological innovation, harmonized regulations, and alignment with national decarbonization strategies.

2. Materials Innovation and Advanced Storage

Materials innovation represents a central pillar in advancing hydrogen storage technologies, as the intrinsic properties of storage media largely determine system performance, safety, and economic viability [25,26]. Conventional storage approaches based on compressed or liquefied hydrogen face inherent limitations related to low volumetric density, high energy penalties, and stringent safety requirements. Consequently, materials-based hydrogen storage has emerged as a promising alternative, aiming to store hydrogen in solid or liquid carriers with higher densities under moderate temperature and pressure conditions. This paradigm shift places materials science at the forefront of hydrogen storage research, with strong implications for both mobile and stationary energy applications [27,28].

Metal hydrides constitute one of the most extensively studied classes of solid-state hydrogen storage materials due to their high volumetric hydrogen densities and inherent safety advantages. Alloys such as magnesium-based, titanium-based, and rare-earth hydrides can reversibly absorb and desorb hydrogen through chemical bonding mechanisms. However, their practical deployment is constrained by high desorption temperatures, slow absorption–desorption kinetics, and material degradation over repeated cycling. Recent advances, including catalytic doping with transition metals and microstructural refinement, have demonstrated significant improvements in reaction kinetics and thermal stability, bringing metal hydrides closer to practical applicability [29,30].

Complex hydrides, such as alienates, borohydrides, and amides, offer even higher gravimetric hydrogen storage capacities compared to conventional metal hydrides. These materials are particularly attractive for applications where weight is a critical constraint. Nevertheless, their thermodynamic stability often results in high hydrogen release temperatures and incomplete reversibility. Research efforts focusing on composite hydrides, reactive hydride composites, and tailored chemical destabilization have shown promise in lowering operating temperatures and enhancing reversibility [31–34]. Despite these advances, challenges related to synthesis complexity, material cost, and long-term cyclability remain substantial barriers.

Liquid organic hydrogen carriers (LOHCs) provide an alternative materials-based pathway by enabling hydrogen storage in chemically bound liquid form under ambient conditions. LOHC systems benefit from compatibility with existing liquid fuel infrastructure, simplifying transportation and storage logistics. Advances in catalyst development and molecular design have improved hydrogenation and dehydrogenation efficiencies, reducing energy losses and operational costs. However, issues such as

catalyst durability, heat management during hydrogen release, and overall system efficiency continue to limit large-scale adoption, highlighting the need for integrated material–process optimization [35–38].

High-surface-area nanostructured materials, including metal–organic frameworks (MOFs), porous carbons, and graphene-based composites, have attracted significant attention due to their tunable pore structures and high hydrogen adsorption capacities. Nano-confinement effects can enhance hydrogen uptake and improve reaction kinetics when combined with hydrides or catalytic species. While these materials demonstrate excellent performance at cryogenic temperatures, maintaining high storage capacities under near-ambient conditions remains challenging. Addressing scalability, mechanical stability, and cost-effectiveness of nanostructured materials is therefore essential [39–42]. Overall, progress in advanced hydrogen storage materials will require coordinated, multidisciplinary research that integrates materials design, characterization, and system-level engineering to enable practical, efficient, and scalable hydrogen storage solutions.

3. Safety, Standards, and Risk Management Frameworks for Hydrogen Storage

The safe and reliable storage of hydrogen is a fundamental prerequisite for the widespread deployment of hydrogen-based energy systems across transportation, industry, and power sectors. Unlike conventional fuels, hydrogen presents unique safety challenges due to its low ignition energy, wide flammability range, high diffusivity, and material compatibility issues. Base on characteristics necessitate a comprehensive safety framework that integrates robust engineering design, rigorous standards, and proactive risk management practices [43–46]. As hydrogen storage technologies continue to diversify, encompassing compressed gas, liquefied hydrogen, solid-state materials, and liquid organic hydrogen carriers, the complexity of associated safety considerations increases correspondingly. Figure 2 shows storage pathway.

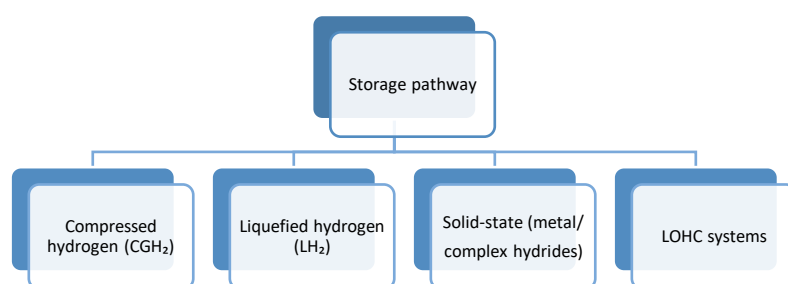


Figure 2. Storage pathway.

In this context, international standards, regulatory codes, and best-practice guidelines play a critical role in ensuring consistency, reliability, and public confidence in hydrogen storage systems. The integration of advanced sensor technologies, real-time monitoring, and risk-based design methodologies has become central to modern hydrogen safety strategies [47–50]. Therefore, a structured assessment of safety risks, applicable standards, and mitigation measures is essential to support informed technology selection, system design, and large-scale deployment. Table 1 presented in this section synthesizes key safety aspects, standards, and risk management approaches across major hydrogen storage pathways, providing a concise reference for researchers, engineers, and policymaker.

Table 1. Safety, standards, and risk management frameworks for hydrogen storage [51–58].

Storage pathway	Operating conditions	Primary hazards	Key risk drivers	Standards / codes	Engineering controls	Risk management methods
Compressed hydrogen (CGH ₂)	350–700 bar, ambient temperature	Leakage, jet fire, vessel rupture	Seal failure, fatigue, ignition sources	ISO 19880-1, NFPA 2, SAE J2601	PRDs, ventilation, shutoff valves	HAZOP, QRA, SIL, emergency plans

Liquefied hydrogen (LH ₂)	~20 K, cryogenic conditions	Boil-off, embrittlement, cryogenic burns	Heat ingress, insulation failure	ISO 21010, EN 13458, NFPA 2	Vacuum insulation, vent systems	Cryogenic HAZOP, vent analysis
Solid-state (metal/complex hydrides)	10–100 bar, 60–400 °C	Thermal runaway, degradation	Poor heat management, cycling	ISO/TR 15916, IEC 60079	Thermal control, containment	FMEA, thermal modeling
LOHC systems	Ambient storage, 200–350 °C release	High-temperature hazards, toxicity	Catalyst aging, heat imbalance	IEC/ATEX, pressure equipment codes	Interlocks, secondary containment	Process HAZOP, LOPA

Table 1 provides a comparative overview of safety risks, standards, and risk management frameworks across the principal hydrogen storage pathways, highlighting both shared safety challenges and technology-specific concerns. A common risk across all storage options is hydrogen leakage, which is particularly critical due to hydrogen’s low ignition energy and wide flammability limits. However, the severity and consequences of leakage differ significantly depending on storage conditions. In compressed hydrogen systems, high operating pressures amplify the risks of jet fires and rapid gas dispersion, whereas in liquefied hydrogen systems, leakage is compounded by cryogenic hazards, boil-off losses, and the potential for oxygen enrichment in the surrounding environment.

The analysis also reveals that operating temperature plays a decisive role in shaping hazard profiles and mitigation strategies. Liquefied hydrogen storage introduces extreme cryogenic conditions that demand specialized materials, insulation systems, and venting strategies to manage thermal stresses and continuous boil-off. In contrast, solid-state hydrogen storage systems, such as metal and complex hydrides, typically operate at moderate pressures but elevated temperatures, shifting the primary safety concern toward thermal management and the prevention of localized overheating or thermal runaway during hydrogen absorption and desorption. LOHC-based systems further extend this thermal challenge by incorporating high-temperature catalytic reactors, which necessitate chemical process safety measures in addition to conventional hydrogen safety controls.

From a regulatory perspective, the table provides the importance of internationally recognized standards in harmonizing safety practices across technologies and jurisdictions. Codes such as ISO 19880-1, NFPA 2, and EN 13458 provide structured guidance on system design, materials selection, pressure relief, and operational procedures. Nevertheless, the diversity of storage technologies means that no single standard can comprehensively address all safety aspects. As a result, effective hydrogen safety management relies on the coordinated application of multiple standards, supplemented by site-specific risk assessments and national regulatory requirements.

The role of monitoring and sensing technologies emerges as a critical enabler of risk reduction across all storage pathways. Continuous hydrogen detection, pressure and temperature monitoring, and real-time system diagnostics allow early identification of abnormal conditions and facilitate rapid intervention. Advanced sensing solutions, when integrated with automated shutdown systems and digital control architectures, significantly enhance the resilience of hydrogen storage installations. This is particularly important for large-scale or remote storage facilities, where early detection can prevent escalation into major incidents.

Overall, the table illustrates that hydrogen storage safety cannot be addressed through isolated technical measures alone. Instead, it requires a holistic, risk-based framework that integrates engineering controls, regulatory compliance, real-time monitoring, and systematic safety assessment tools such as HAZOP, quantitative risk assessment, and lifecycle safety analysis. Such an integrated approach is essential for building public trust, ensuring regulatory approval, and supporting the safe scale-up of hydrogen storage technologies as a cornerstone of future low-carbon energy systems.

4. System Integration with Renewable Energy and Power Networks

The rapid expansion of variable renewable energy sources, particularly wind and solar photovoltaics, is fundamentally transforming the structure and operation of modern power systems. While high renewable penetration is essential for achieving deep decarbonization targets, it also introduces significant challenges related to intermittency, temporal mismatches between supply and demand, and

declining system inertia [59,60]. Conventional flexibility options, such as short-duration battery storage and demand-side management, are effective for managing intra-day variability but are insufficient to address long-duration and seasonal imbalances. In this context, hydrogen storage has emerged as a promising system-level solution capable of complementing existing flexibility resources and enabling reliable, high-renewable power systems [61,62]. Figure 3 illustrates system integration with renewable energy and power networks.

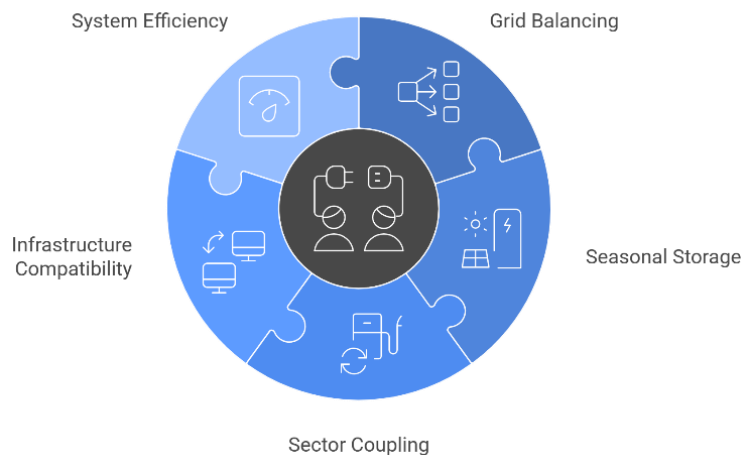


Figure 3. System integration with renewable energy and power networks.

Hydrogen storage provides a unique pathway for integrating renewable electricity with power networks through its ability to convert surplus electricity into a storable energy carrier and to link the power sector with transport, industry, and heating applications. By enabling grid balancing, seasonal energy shifting, and sector coupling, hydrogen storage extends the functional boundaries of power systems beyond electricity alone. However, the integration of hydrogen storage is accompanied by technical, economic, and operational challenges, including infrastructure compatibility, conversion efficiency losses, and the need for advanced control and market mechanisms. This section addresses a system integration perspective, framing hydrogen storage not as a standalone technology but as a strategic component of future low-carbon energy systems [63-68].

A. Hydrogen Storage for Grid Balancing and Flexibility Services

This subsection examines the role of hydrogen storage as a flexibility resource in power systems with high shares of variable renewable energy sources, particularly wind and solar photovoltaics. By converting surplus electricity into hydrogen through electrolysis, hydrogen storage can absorb excess generation during periods of oversupply and provide energy back to the system during demand peaks or renewable shortfalls. The discussion highlights the capability of hydrogen systems to deliver ancillary services such as frequency regulation, reserve provision, and congestion management when appropriately integrated with power electronics and control platforms. Despite lower round-trip efficiency compared to batteries, hydrogen storage offers unique advantages in terms of scale and duration, making it complementary rather than competitive with short-term storage technologies.

B. Seasonal Energy Storage and Long-Duration Applications

This subsection focuses on hydrogen storage as a solution for seasonal and long-duration energy storage, addressing temporal mismatches between renewable energy supply and demand. Unlike electrochemical storage systems, hydrogen storage can retain energy over weeks to months with minimal self-discharge, enabling inter-seasonal shifting of renewable electricity. The addendum discusses applications such as storing excess summer solar generation for winter heating and power needs and balancing prolonged low-wind events. Key technical challenges, including conversion losses, storage capacity requirements, and system sizing, are evaluated to assess the feasibility of hydrogen-based seasonal storage in future power systems.

C. Sector Coupling and Power-to-X Integration Pathways

This subsection explores hydrogen storage as a central element of sector coupling strategies that link electricity, transport, industry, and heating sectors. Through power-to-hydrogen and power-to-X pathways, renewable electricity can be transformed into hydrogen and hydrogen-derived fuels for use in mobility, industrial feedstocks, and high-temperature heat applications. The integration of hydrogen storage across sectors enhances overall system efficiency by expanding demand-side flexibility and reducing renewable curtailment. However, coordination across regulatory frameworks, market structures, and infrastructure planning is identified as a critical requirement for realizing the full benefits of sector coupling.

D. Infrastructure Compatibility and Network Integration Challenges

This subsection critically analyzes the infrastructure and network-level challenges associated with integrating hydrogen storage into existing power and gas systems. Issues such as electrolyzer grid connection, hydrogen pipeline compatibility, blending limits in natural gas networks, and the siting of storage facilities are discussed in detail. The addendum emphasizes that mismatches between electricity network constraints and hydrogen infrastructure availability can limit operational flexibility. Addressing these challenges requires coordinated planning of power grids, hydrogen networks, and storage assets, supported by digitalization, advanced system modeling, and integrated infrastructure investment strategies.

E. System Efficiency, Operational Flexibility, and Future Energy System Design

This subsection evaluates hydrogen storage from a whole-system efficiency and operational flexibility perspective. While hydrogen pathways involve multiple energy conversion steps that reduce round-trip efficiency, their value lies in enabling system-wide optimization rather than maximizing point-to-point efficiency. The addendum argues that future low-carbon energy systems should prioritize resilience, scalability, and flexibility alongside efficiency metrics. By enabling long-duration storage, cross-sector energy flows, and large-scale renewable integration, hydrogen storage is positioned as a strategic enabler of robust and resilient power networks capable of supporting deep decarbonization.

Hydrogen storage occupies a critical role in enabling the large-scale integration of renewable energy into future power networks by providing long-duration and high-capacity flexibility that cannot be achieved by conventional storage technologies alone. Although hydrogen-based pathways exhibit lower round-trip efficiency compared to electrochemical storage, their system-level value lies in their ability to absorb large volumes of surplus renewable electricity, support seasonal energy balancing, and facilitate cross-sector energy exchange. As renewable penetration increases, these attributes become increasingly important for maintaining grid stability, reliability, and resilience.

The analysis underscores that successful integration of hydrogen storage requires coordinated planning across electricity networks, hydrogen infrastructure, and end-use sectors. Technical challenges related to electrolyzer operation, storage siting, and network interoperability must be addressed alongside regulatory and market barriers that currently limit investment and operational flexibility. When integrated through holistic system design and supported by appropriate policy frameworks, hydrogen storage can function as a strategic enabler of renewable-dominated power systems. Ultimately, its contribution extends beyond efficiency metrics, supporting a resilient, scalable, and deeply decarbonized energy system capable of meeting long-term climate and energy security objectives.

5. Environmental, Policy, and Sustainability Implications

The environmental and sustainability implications of hydrogen storage technologies extend beyond their immediate technical performance, encompassing lifecycle emissions, resource use, and systemic interactions with energy and industrial systems [69-72]. As highlighted across the proposed agendas, hydrogen storage can only deliver substantial climate and sustainability benefits if its deployment is guided by rigorous lifecycle assessment, responsible resource management, and alignment with national and international climate targets. Without such considerations, storage technologies risk introducing

new environmental burdens or reinforcing unsustainable supply chains [73-76]. Figure 4 demonstrates environmental, policy, and sustainability implications.

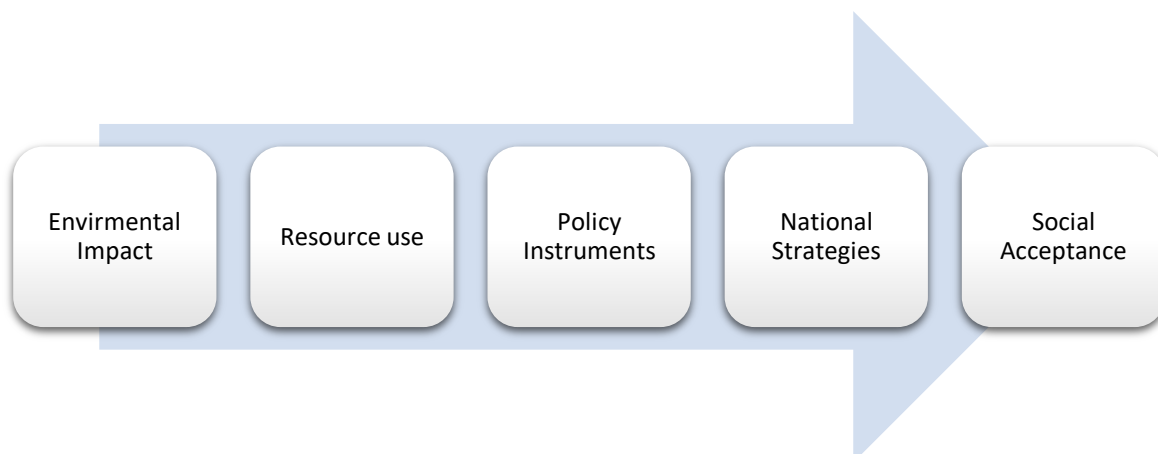


Figure 4. Environmental, policy, and sustainability implications

Effective and well-designed policy frameworks are therefore indispensable for translating hydrogen storage potential into tangible sustainability outcomes. Instruments such as targeted subsidies, carbon pricing, and sustained research and innovation support can accelerate cost reductions while encouraging environmentally optimal technology choices [78-82]. Equally important are governance mechanisms that promote transparency, public acceptance, and adaptive policy learning. When environmental integrity, policy coherence, and sustainability objectives are jointly addressed, hydrogen storage can evolve into a cornerstone of resilient, equitable, and deeply decarbonized energy systems capable of supporting long-term global climate goals.

1) Lifecycle Environmental Impacts of Hydrogen Storage Pathways

This agenda focuses on evaluating hydrogen storage technologies using a lifecycle assessment (LCA) framework. It examines upstream and downstream environmental impacts, including energy consumption, greenhouse gas emissions, water use, and material intensity associated with compressed, liquefied, solid-state, and chemical storage options. Particular attention is given to indirect emissions arising from electricity and heat inputs required for compression, liquefaction, or hydrogen release. The agenda emphasizes the importance of technology-specific LCAs to avoid burden shifting and to ensure that hydrogen storage contributes to net emissions reductions rather than merely displacing environmental impacts across system boundaries.

2) Resource Use, Material Criticality, and Circularity Considerations

This agenda evaluates the sustainability implications of material and resource requirements for hydrogen storage systems. It addresses the use of critical raw materials in high-pressure tanks, catalysts, hydrides, and insulation systems, as well as their supply chain vulnerabilities and recycling potential. The agenda highlights circular economy strategies, including material recovery, reuse, and design for recyclability, as essential measures to reduce environmental footprints and long-term dependency on scarce resources. Integrating circularity principles into hydrogen storage development is presented as a key pathway toward sustainable scale-up.

3) Policy Instruments and Regulatory Frameworks for Deployment

This agenda examines the role of public policy in accelerating the deployment of hydrogen storage technologies. It analyzes the effectiveness of policy instruments such as capital subsidies, investment tax credits, carbon pricing mechanisms, and operational support schemes in reducing financial risks and improving project bankability. The agenda also considers the impact of safety regulations, permitting processes, and standardization on deployment timelines. Coherent and stable policy frameworks are identified as critical for fostering private investment and enabling long-term infrastructure planning.

4) Alignment with National Energy Strategies and Climate Targets

This agenda explores how hydrogen storage development can be aligned with national energy strategies, net-zero commitments, and long-term decarbonization pathways. It emphasizes the need to integrate hydrogen storage into national hydrogen roadmaps, renewable energy plans, and industrial decarbonization strategies. The agenda highlights that misalignment between storage deployment and broader energy system objectives can lead to suboptimal investments and limited emissions benefits. Strategic coordination across sectors and governance levels is therefore essential to maximize the climate impact of hydrogen storage.

5) Social Acceptance, Sustainability Governance, and Long-Term Impacts

This agenda addresses the social and governance dimensions of hydrogen storage deployment, including public acceptance, environmental justice, and stakeholder engagement. It considers how transparent communication, robust safety standards, and inclusive planning processes can enhance societal trust in hydrogen technologies. The agenda also discusses sustainability governance mechanisms, such as environmental reporting, performance monitoring, and adaptive policy design, to ensure that hydrogen storage systems deliver long-term environmental and social benefits. Strengthening governance structures is presented as a prerequisite for the responsible and equitable expansion of hydrogen storage infrastructure.

6. Conclusion

This article has provided a comprehensive and integrated assessment of hydrogen storage technologies, demonstrating that their successful deployment is contingent upon simultaneous progress across materials science, safety governance, techno-economic performance, system integration, and sustainability alignment. Advances in materials innovation and advanced storage media, including metal and complex hydrides, liquid organic hydrogen carriers, and nanostructured materials, highlight the potential to significantly improve gravimetric and volumetric storage densities while lowering operating temperatures and pressures. Nevertheless, persistent challenges related to kinetics, reversibility, material degradation, and large-scale manufacturability underscore that breakthroughs in storage materials must be accompanied by system-level engineering and multidisciplinary research efforts to ensure practical viability.

From a deployment perspective, the analysis of safety, standards, and risk management frameworks reinforces that hydrogen storage cannot scale without robust and harmonized regulatory regimes. The distinct hazard profiles of compressed, liquefied, and solid-state storage pathways necessitate tailored engineering controls, real-time monitoring, and risk-based design methodologies. International standards and best practices, when combined with advanced sensing technologies and structured risk assessment tools, are essential not only for technical safety but also for building public trust and securing regulatory approval for large-scale hydrogen infrastructure.

The techno-economic assessment further reveals that storage costs remain a decisive barrier to hydrogen competitiveness across energy and transport sectors. Capital-intensive components, operational energy penalties, and lifecycle cost sensitivities vary widely among storage options, indicating that no single technology offers a universally optimal solution. Meaningful cost reductions will depend on economies of scale, manufacturing innovation, improved efficiency, and strategic integration with renewable hydrogen production and low-cost energy inputs. Without sustained progress along these pathways, hydrogen storage will continue to impose a significant cost premium on hydrogen value chains.

At the system level, integration with renewable energy and power networks positions hydrogen storage as a uniquely capable enabler of high renewable penetration. While lower round-trip efficiency remains a limitation, hydrogen storage offers unmatched advantages in long-duration and seasonal energy storage, grid balancing, and sector coupling between electricity, transport, and industry. Its value therefore lies in system-wide optimization, resilience, and flexibility rather than isolated efficiency

metrics, making hydrogen storage a complementary asset to short-duration storage technologies in future low-carbon energy systems.

Finally, the environmental, policy, and sustainability analysis emphasizes that hydrogen storage development must be aligned with lifecycle environmental performance, responsible resource use, and coherent policy frameworks. Targeted policy instruments, including subsidies, carbon pricing, and sustained research funding are critical for accelerating innovation while steering deployment toward environmentally preferable pathways. Aligning hydrogen storage strategies with national energy plans and long-term decarbonization objectives is essential to ensure that storage technologies deliver genuine climate and sustainability benefits.

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References

- [1] P. Zhou *et al.*, "Machine learning in solid-state hydrogen storage materials: Challenges and perspectives," *Adv. Mater.*, vol. 37, no. 6, p. e2413430, 2025.
- [2] V. Rahimkhoei, M. Hamadani, and M. Salavati-Niasari, "Sol-gel auto-combustion synthesis and characterization of Eu₂CrMnO₆ nanostructures as a potential electrochemical hydrogen storage material," *Int. J. Hydrogen Energy*, vol. 102, pp. 247–259, 2025.
- [3] J. Gao, Y. Pan, I. P. Jain, F. Yang, and J. Zhu, "Exploring the structure, hydrogen storage capacity and hydrogen storage mechanism of X₃N₃H₆ hydrides for hydrogen storage," *Appl. Mater. Today*, vol. 44, no. 102755, p. 102755, 2025.
- [4] X. Li *et al.*, "Modification strategies of magnesium-based materials originating from other materials for hydrogen storage: A review," *Next Mater.*, vol. 6, no. 100311, p. 100311, 2025.
- [5] S. Rekik, I. Khabbouchi, D. Lounissi, M. Khaleel, D. Richards, and L. Kolsi, "Opportunities and challenges of solar-wind-powered hydrogen in emerging economies: A spatial and techno-economic analysis," in *2025 Global Conference on Sustainable Energy and Net-Zero Emissions (SENZE)*, 2025, pp. 1–6.
- [6] J. O. Fadonougbo *et al.*, "Combinatorial synthesis of solid-state hydrogen storage materials using a modified planetary ball mill," *Int. J. Hydrogen Energy*, vol. 101, pp. 946–958, 2025.
- [7] M. Khaleel, Z. Yusupov, N. Yasser, and H. J. El-Khozondar, "Enhancing Microgrid performance through hybrid energy storage system integration: ANFIS and GA approaches," *ijeess*, vol. 1, no. 2, pp. 38–48, 2023.
- [8] L. Xie *et al.*, "Research on hydrogen storage and its gas sensing modulation of two-dimensional BeN₄ monolayer in relation to concentration, humidity, and metal modification," *Fuel (Lond.)*, vol. 387, no. 134430, p. 134430, 2025.
- [9] E. H. Akarchaou, R. Touti, A. El Mekkaouy, Y. Didi, A. Tahiri, and S. Chtita, "Computational analysis of X₂MgTiH₆ (X =Li, Na, and K) double perovskite hydride materials for hydrogen storage applications," *Int. J. Hydrogen Energy*, vol. 161, no. 150644, p. 150644, 2025.
- [10] M. Khaleel, Z. Yusupov, O. M. Bshina, M. M. Dali, and W. A. Shah, "Toward renewable energy deployment in North African countries: Potential resources, investments, transition scenario, opportunities, challenges, and policy," *Unconventional Resources*, vol. 12, no. 100363, p. 100363, 2026.

- [11] Y. Pan and Y. Zhu, "Theoretical prediction of novel phase, phonon dynamics and physical properties of KAlH₄ hydride for hydrogen storage," *Int. J. Hydrogen Energy*, vol. 131, pp. 221–228, 2025.
- [12] D. Zhou *et al.*, "An overview of RE-Mg-based alloys for hydrogen storage: Structure, properties, progresses and perspectives," *J. Magnes. Alloy.*, vol. 13, no. 1, pp. 41–70, 2025.
- [13] M. Khaleel, I. Imbayah, Y. Nassar, and H. J. El-Khozondar, "Renewable energy transition pathways and net-zero strategies," *IJEES*, pp. 01–16, 2025.
- [14] Y. Wen *et al.*, "Advances in hydrogen storage materials for physical H₂ adsorption," *Int. J. Hydrogen Energy*, vol. 97, pp. 1261–1274, 2025.
- [15] M. Khaleel, Z. Yusupov, and S. Rekik, "Exploring trends and predictions in renewable energy generation," *Energy 360*, vol. 4, no. 100030, p. 100030, 2025.
- [16] M. R. Talukder, "Theoretical insights into novel RbMH₃ (M = Zn, Nb, and Ru) cubic perovskites for hydrogen storage applications: A first-principles DFT Study," *Int. J. Hydrogen Energy*, vol. 113, pp. 550–563, 2025.
- [17] A. Sharma, "Hydrogen storage in platinum loaded single-walled carbon nanotubes," *Int. J. Hydrogen Energy*, vol. 45, no. 44, pp. 23966–23970, 2020.
- [18] B. Hardy, D. Tamburello, and C. Corgnale, "Hydrogen storage adsorbent systems acceptability envelope," *Int. J. Hydrogen Energy*, vol. 43, no. 42, pp. 19528–19539, 2018.
- [19] M. Khaleel, N. El-Naily, H. Alzargi, M. Amer, T. Ghandoori, and A. Abulifa, "Recent progress in synchronization approaches to mitigation voltage sag using HESS D-FACTS," in *2022 International Conference on Emerging Trends in Engineering and Medical Sciences (ICETEMS)*, 2022.
- [20] M. Mohamad and A. Hesri, "Hydrogen storage methods: Opportunities, safety, risk, and compliance assessment," *IJEES*, pp. 17–32, 2025.
- [21] Y. Kojima, "Hydrogen storage materials for hydrogen and energy carriers," *Int. J. Hydrogen Energy*, vol. 44, no. 33, pp. 18179–18192, 2019.
- [22] L. Ruihan, H. Feng, X. Ting, L. Yongzhi, Z. Xin, and Z. Jiaqi, "Progress in the application of first principles to hydrogen storage materials," *Int. J. Hydrogen Energy*, vol. 56, pp. 1079–1091, 2024.
- [23] R. Nagar *et al.*, "Recent developments in state-of-the-art hydrogen energy technologies – Review of hydrogen storage materials," *Solar Compass*, vol. 5, no. 100033, p. 100033, 2023.
- [24] X. Xu, Y. Dong, Q. Hu, N. Si, and C. Zhang, "Electrochemical hydrogen storage materials: State-of-the-art and future perspectives," *Energy Fuels*, vol. 38, no. 9, pp. 7579–7613, 2024.
- [25] V. A. Yartys and M. V. Lototsky, "Laves type intermetallic compounds as hydrogen storage materials: A review," *J. Alloys Compd.*, vol. 916, no. 165219, p. 165219, 2022.
- [26] Z. Jia *et al.*, "Machine learning accelerates design of bilayer-modified graphene hydrogen storage materials," *Sep. Purif. Technol.*, vol. 352, no. 128229, p. 128229, 2025.
- [27] E. Yu and Y. Pan, "Exploring the hydrogen evolution catalytic activity of the orthorhombic and hexagonal borophene as the hydrogen storage material," *Electrochim. Acta*, vol. 435, no. 141391, p. 141391, 2022.
- [28] S. Niaz, T. Manzoor, and A. H. Pandith, "Hydrogen storage: Materials, methods and perspectives," *Renew. Sustain. Energy Rev.*, vol. 50, pp. 457–469, 2015.
- [29] M. Khaleel, Z. Yusupov, M. Guneser, H. El-Khozondar, A. Ahmed, and A. A. Alsharif, "Towards hydrogen sector investments for achieving sustainable electricity generation," *jsesd*, vol. 13, no. 1, pp. 71–96, 2024.
- [30] X.-Q. Duan *et al.*, "Ti₃AlCN MAX for tailoring MgH₂ hydrogen storage material: from performance to mechanism," *Rare Metals*, vol. 42, no. 6, pp. 1923–1934, 2023.
- [31] S. Liu and J. Shui, "Mechanism and properties of emerging nanostructured hydrogen storage materials," *Battery Energy*, vol. 1, no. 4, p. 20220033, 2022.

- [32] M. Khaleel *et al.*, "Harnessing nuclear power for sustainable electricity generation and achieving zero emissions," *Energy Explor. Exploit.*, vol. 43, no. 3, pp. 1126–1148, 2025.
- [33] A. Li, Q. Fang, W. Sun, Z. Yuan, and Y. Han, "Catalytic mechanism of hydrogen absorption and desorption reactions in Mg-based hydrogen storage materials," *J. Alloys Compd.*, vol. 1038, no. 182814, p. 182814, 2025.
- [34] M. M. Khaleel, M. R. Adzman, and S. M. Zali, "An integrated of hydrogen fuel cell to distribution network system: Challenging and opportunity for D-STATCOM," *Energies*, vol. 14, no. 21, p. 7073, 2021.
- [35] Y. Zhang *et al.*, "A review on advances, strategies, and future perspectives of solid-state hydrogen storage materials," *Sustainable Chemistry for Energy Materials*, vol. 2, no. 100014, p. 100014, 2025.
- [36] I. Imbayah, M. Khaleel, and Z. Yusupov, "Optimization of Hybrid Renewable Energy Systems: Classical optimization methods, artificial intelligence, recent trend, and software tools," *IJEES*, pp. 47–69, 2025.
- [37] M. Khaleel, Z. Yusupov, and S. Rekik, "Advancing hydrogen as a key driver for decarbonized power systems," *Unconventional Resources*, vol. 9, no. 100278, p. 100278, 2026.
- [38] M. Khaleel, Z. Yusupov, Y. Nassar, H. J. El-khozondar, A. Ahmed, and A. Alsharif, "Technical challenges and optimization of superconducting magnetic energy storage in electrical power systems," *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 5, no. 100223, p. 100223, 2023.
- [39] V. Mahamiya, A. Shukla, and B. Chakraborty, "Exploring yttrium doped C₂₄ fullerene as a high-capacity reversible hydrogen storage material: DFT investigations," *J. Alloys Compd.*, vol. 897, no. 162797, p. 162797, 2022.
- [40] Q. Yin, G. Bi, R. Wang, Z. Zhao, and K. Ma, "High-capacity hydrogen storage in lithium decorated penta-BN₂: A first-principles study," *J. Power Sources*, vol. 591, no. 233814, p. 233814, 2024.
- [41] M. Khaleel, Z. Yusupov, H. J. El-Khozondar, and A. Alsharif, "Cyber-resilience strategies for smart microgrids: Classification, construction, recent trends, and policy framework," *ijeess*, vol. 3, no. 3, pp. 31–47, 2025.
- [42] R. R. Shahi, A. K. Gupta, and P. Kumari, "Perspectives of high entropy alloys as hydrogen storage materials," *Int. J. Hydrogen Energy*, vol. 48, no. 56, pp. 21412–21428, 2023.
- [43] I. Imbayah, M. Hasan, H. El-Khozondare, M. Khaleel, A. Alsharif, and A. Ahmed, "Review paper on green hydrogen production, storage, and utilization techniques in Libya," *jsesd*, vol. 13, no. 1, pp. 1–21, 2024.
- [44] M. Khaleel *et al.*, "An optimization approaches and control strategies of hydrogen fuel cell systems in EDG-integration based on DVR technology," *J. Eur. Syst. Autom.*, vol. 57, no. 2, pp. 551–565, 2024.
- [45] Y. Xinglin, L. Xiaohui, Z. Jiaqi, H. Quanhui, and Z. Junhu, "Progress in improving hydrogen storage properties of Mg-based materials," *Mater. Today Adv.*, vol. 19, no. 100387, p. 100387, 2023.
- [46] H. H. Bulat, Ö. T. Kaymakçı, and H. İlhan, "Human factors in hydrogen storage: An analysis of safety implications," *Int. J. Hydrogen Energy*, 2024.
- [47] S. Mosleh, C. Schaad, R. Yang, and K. M. Groth, "A methodology for quantitative risk assessment of a high-capacity hydrogen fueling station with liquid hydrogen storage," *Int. J. Hydrogen Energy*, vol. 112, pp. 544–553, 2025.
- [48] M. Shourideh, S. Yasseri, and H. Bahai, "Influence of safety culture on safety outcomes of a hydrogen-CCS plant," *Gases*, vol. 5, no. 1, p. 2, 2025.
- [49] M. Min, C. Yoon, N. Yoo, J. Kim, Y. Yoon, and S. Jung, "Hydrogen risk assessment studies: A review toward environmental sustainability," *Energies*, vol. 18, no. 2, p. 229, 2025.
- [50] G. Li, H. Zhang, S. Li, and C. Zhang, "Risk assessment of hydrogen fuel system leakage in ships based on Noisy-OR Gate model Bayesian network," *J. Mar. Sci. Eng.*, vol. 13, no. 3, p. 523, 2025.

- [51] M. Simonetto, J.-A. Pascoe, and A. Sharpanskykh, "Preliminary safety assessment of a liquid hydrogen storage system for commercial aviation," *Safety (Basel)*, vol. 11, no. 1, p. 27, 2025.
- [52] C. Schaad, S. Mosleh, R. Yang, and K. M. Groth, "Quantitative Risk Assessment of hydrogen releases in a hydrogen fueling station with liquid hydrogen storage," *Int. J. Hydrogen Energy*, vol. 112, pp. 111–120, 2025.
- [53] Y. Yao *et al.*, "Hydrogen energy industry in China: The current status, safety problems, and pathways for future safe and healthy development," *Saf. Sci.*, vol. 186, no. 106808, p. 106808, 2025.
- [54] V. Mahamiya, A. Shukla, and B. Chakraborty, "Scandium decorated C₂₄ fullerene as high capacity reversible hydrogen storage material: Insights from density functional theory simulations," *Appl. Surf. Sci.*, vol. 573, no. 151389, p. 151389, 2022.
- [55] Y. Zhu, Y. Liang, Y. Pu, and J. Xiong, "Investigation for the hydrogen storage properties of XCrH₃ (X=Na, K) and KYH₃ (Y Mo, W) perovskite type hydrides based on first-principles," *Int. J. Hydrogen Energy*, vol. 71, pp. 239–249, 2024.
- [56] Z. Chen, K. O. Kirlikovali, K. B. Idrees, M. C. Wasson, and O. K. Farha, "Porous materials for hydrogen storage," *Chem*, vol. 8, no. 3, pp. 693–716, 2022.
- [57] A. S. Mekonnin, K. Waławiak, M. Humayun, S. Zhang, and H. Ullah, "Hydrogen storage technology, and its challenges: A review," *Catalysts*, vol. 15, no. 3, p. 260, 2025.
- [58] M. R. Kalibek *et al.*, "Solid-state hydrogen storage materials," *Discov. Nano*, vol. 19, no. 1, p. 195, 2024.
- [59] H. Liu *et al.*, "Coordinated planning model for multi-regional ammonia industries leveraging hydrogen supply chain and power grid integration: A case study of Shandong," *Appl. Energy*, vol. 377, no. 124456, p. 124456, 2025.
- [60] H. Liu, Y. Zhang, Q. Xu, W. Han, and J. Shen, "A Carnot battery system integrating Ca(OH)₂/CaO thermochemical energy storage and supercritical CO₂ cycles for long-term energy storage and residential heat supply," *Appl. Energy*, vol. 377, no. 124535, p. 124535, 2025.
- [61] M. Almamoori, M. Almakar, M. Khaleel, F. Mohamed, and A. Elbreki, "Assessing STATCOM-enabled reactive power control in fragile power transmission systems: A case study perspective," *Math. Model. Eng. Probl.*, vol. 11, no. 8, pp. 2019–2028, 2024.
- [62] T. Hai, N. S. S. Singh, and F. Jamal, "Energy management of a microgrid with integration of renewable energy sources considering energy storage systems with electricity price," *J. Energy Storage*, vol. 110, no. 115191, p. 115191, 2025.
- [63] M. Mohamed, Wahab Shah, and Mohamed Amer, "Concentration Dynamics in Solar PV Supply Chains: Lessons for Clean Energy Transitions", *ljsdr*, vol. 1, no. 1, pp. 52–60, Dec. 2025.
- [64] T. Terlouw, N. Savvakis, C. Bauer, R. McKenna, and G. Arampatzis, "Designing multi-energy systems in Mediterranean regions towards energy autonomy," *Appl. Energy*, vol. 377, no. 124458, p. 124458, 2025.
- [65] I. Rai and Suchetha, "Microgrid and grid synchronization: A critical analysis of challenges and opportunities," *Electric Power Syst. Res.*, vol. 242, no. 111434, p. 111434, 2025.
- [66] M. Khaleel, M. R. Adzman, and S. M. Zali, "An integrated of hydrogen fuel cell to distribution network system: Challenging and opportunity for D-STATCOM," *Energies*, vol. 14, no. 21, p. 7073, 2021.
- [67] M. Arun, S. Samal, D. Barik, S. S. R. Chandran, K. Tudu, and S. Praveenkumar, "Integration of energy storage systems and grid modernization for reliable urban power management toward future energy sustainability," *J. Energy Storage*, vol. 131, no. 115830, p. 115830, 2025.
- [68] P. Megantoro *et al.*, "Modeling the uncertainties and active power generation of wind-solar energy with data acquisition from telemetry weather measurement," *Results Eng.*, vol. 25, no. 104392, p. 104392, 2025.

- [69] T. H. Halefom, M. Moglia, C. (andi) Nygaard, and D. Pojani, "Sustainability implications of working-from-home (WFH): A systematic review of the travel behavior literature," *J. Plan. Lit.*, vol. 40, no. 1, pp. 17–31, 2025.
- [70] Muftah Ali and Mohamed Khaleel, "Decarbonizing Buildings at Scale: Energy Codes, Innovation Pathways, and the Net-Zero Transition", *ljsdr*, vol. 1, no. 1, pp. 45–51, Dec. 2025.
- [71] W. Wang, M. Imran, K. Ali, and A. Sattar, "Green policies and financial development in G7 economies: An in-depth analysis of environmental regulations and green economic growth," *Nat. Resour. Forum*, 2024.
- [72] R. Meinhold, C. Wagner, and B. K. Dhar, "Digital sustainability and eco-environmental sustainability: A review of emerging technologies, resource challenges, and policy implications," *Sustain. Dev.*, 2024.
- [73] N. B. Dao, B. Dogan, S. Ghosh, E. Kazemzadeh, and M. Radulescu, "Toward sustainable ecology: how do environmental technologies, green financial policies, energy uncertainties, and natural resources rents matter?," *Clean Technol. Environ. Policy*, 2024.
- [74] M. Khaleel and Z. Yusupov, "Advancing sustainable energy transitions: Insights on finance, policy, infrastructure, and demand-side integration," *Unconventional Resources*, vol. 9, no. 100274, p. 100274, 2026.
- [75] M. M. Khaleel, Z. Yusupov, M. T. Güneşer, A. A. Abulifa, A. A. Ahmed, and A. Alsharif, "The effect of PEMFC on power grid using advanced equilibrium optimizer and particle swarm optimisation for voltage sag mitigation," in *2023 IEEE 3rd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, 2023, pp. 755–760.
- [76] Y. Nassar *et al.*, "Towards green economy: Case of electricity generation sector in Libya," *jsesd*, vol. 14, no. 1, pp. 334–360, 2025.
- [77] D. Çelik, M. A. Khan, N. Khosravi, M. Waseem, and H. Ahmed, "A review of energy storage systems for facilitating large-scale EV charger integration in electric power grid," *J. Energy Storage*, vol. 112, no. 115496, p. 115496, 2025.
- [78] M. Khaleel *et al.*, "Battery technologies In electrical power Systems: Pioneering secure energy transitions," *J. Power Sources*, vol. 653, no. 237709, p. 237709, 2025.
- [79] F. E. Abukhres, A. Algaddaf, and M. Ouadi, "Investigation and development the modelling of intermediate temperature PEM fuel cell for transport applications," *IJEES*, pp. 61–82, 2025.
- [80] Mohamed Khaleel and Ali Hesri, "Improving Power System Reliability Using Hydrogen Fuel Cell-Integrated D-FACTS for Power Quality Enhancement", *ljsdr*, vol. 1, no. 1, pp. 01–16, Nov. 2025, Accessed: May 13, 2026.
- [81] A. Afaq, L. Gaur, G. Singh, M. Erben, and A. Ferraris, "A critical insight into the intersection of sustainability and technology," *Int. J. Contemp. Hosp. Manag.*, 2024.
- [82] J. Shand, E. Glakpe, and C. Ivey, "Policy implications of implementing residential PV solar energy systems in developing regions," *Energy Policy*, vol. 196, no. 114414, p. 114414, 2025.



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