*Review*

# Hydrogen Storage in Zeolites: A Mini Review of Structural and Chemical Influences on Adsorption Performance

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**Abstract:** Hydrogen is increasingly being recognized as a clean energy carrier that is vital for decarbonizing industries and integrating renewable energy sources. Efficient hydrogen storage is critical for its widespread adoption and economic viability. Among promising solutions, zeolites have gained attention because of their unique microporous structures, high surface areas, and modifiable chemical properties. These characteristics enable zeolites to effectively adsorb hydrogen molecules, making them suitable for sustainable energy storage and transportation. The exceptional physicochemical properties of zeolites, such as ion exchange and adsorption capacities, allow tailored modifications to enhance their hydrogen storage performance. Techniques such as surface functionalization with amines and ion exchange with specific cations significantly improve adsorption capacity and efficiency. For instance, amine modifications introduce electrostatic interactions, whereas ion exchange optimizes the pore structure and increases the surface charge. Recent studies have highlighted the potential of silver ion-exchanged zeolites for selective hydrogen isotope separation, demonstrating the versatility of these materials. With advancements in zeolite research, the development of scalable, cost-effective, and high-capacity hydrogen storage systems has become increasingly feasible. These innovations position zeolites as key contributors to clean energy transition, supporting the role of hydrogen as a cornerstone of sustainable energy infrastructure.

**Keywords:** hydrogen storage; clean energy carrier; energy sustainability; hydrogen energy sector; decarbonization; renewable energy integration

## 1. Introduction

Energy is a fundamental aspect of modern life and has been essential to human existence since the beginning of civilization [1]. It powers basic needs, such as shelter, transportation, production, and communication, reflecting our ever-growing reliance on energy resources. With advancing technology and a rapidly expanding population, identifying sustainable energy sources and utilizing them efficiently has become critical for preserving the environmental balance and ensuring that future generations can maintain their quality of life. In this context, energy remains indispensable to human progress and well-being [2].

In recent years, the hydrogen energy sector has experienced remarkable growth, driven by the global push for decarbonization and renewable energy integration. Significant investments have been made in hydrogen production technologies, such as green hydrogen prepared via electrolysis, as well as in the infrastructure for storage and distribution [3]. Governments and private enterprises are increasingly prioritizing hydrogen as a versatile energy carrier, with applications ranging from transportation to industrial processes, making it a key pillar in the transition towards a sustainable energy future [4].

As a result of political conflicts, there has been a noticeable increase in the supply of natural gas and the production of hydrogen and hydrogen-based energy as a result of rising unit costs of natural gas. According to the

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Global Hydrogen Review 2023 published by the IEA, hydrogen use is projected to increase by approximately 3 percent in 2022 compared to the previous year, up to 95 Mt per year [5].

The importance of hydrogen transmission and storage is as critical as its production, ensuring its effective use as an energy carrier [6]. The low density of hydrogen requires advanced transportation methods, such as compression, liquefaction, or chemical carriers, to make it feasible over long distances. Similarly, efficient storage solutions are essential for balancing supply and demand, particularly for integrating renewable energy sources with variable outputs. Addressing these challenges is crucial for unlocking the full potential of hydrogen in decarbonizing industries and building resilient energy infrastructure [7]. Innovative storage technologies, such as solid-state storage using metal hydrides or porous materials, such as zeolites, are being explored to enhance safety and efficiency [8]. Additionally, developing a cost-effective and scalable transmission infrastructure is vital to support the global adoption of hydrogen as a cornerstone of the clean energy transition. The efficiency of hydrogen storage technologies is crucial because it directly impacts the practicality and economic viability of hydrogen as a clean energy carrier. Inefficient storage systems can lead to significant energy losses, increased costs, and limited scalability, thereby hindering their widespread adoption. High-efficiency storage solutions enable better energy density, safety, and integration with renewable energy sources, ensuring that hydrogen can be effectively utilized in diverse applications, such as transportation, industry, and grid energy balancing [9]. Ultimately, improving the storage efficiency is key to realizing the potential of hydrogen in achieving a sustainable and low-carbon energy future. Zeolites are promising materials for hydrogen storage, which could eliminate some of the disadvantages of zeolites.

Zeolites are classified into two main categories: natural and synthetic. Natural zeolites form through the hydrothermal alteration of volcanic rocks, and over 40 different types of natural zeolites have been identified globally [10]. Synthetic zeolites, on the other hand, are produced in laboratories by reacting silica and alumina under specific conditions. As of recent reports, there are more than 230 different zeolite structures recognized, and a number that continues to grow as new research uncovers additional varieties.

Zeolite applications are diverse, where natural zeolites are particularly effective in water and wastewater treatment due to their ion-exchange and adsorption properties, and they are also used in agriculture to improve soil conditions [11]. Synthetic zeolites, however, find widespread use in industrial processes such as catalysis, gas separation-adsorbtion, and water softening, making them essential in various sectors, including petrochemical and environmental industries [12].

Zeolites are minerals with a regular, microscopic porous structure composed of aluminium, silicon, and oxygen atoms. This unique structure makes zeolites valuable for various industrial applications, such as gas adsorption, water purification, and catalysis [13]. Owing to their porous nature, zeolites can selectively capture certain molecules, making them particularly important for hydrogen storage and gas separation [14]. Found in both natural and synthetic forms, zeolites offer sustainable solutions with significant environmental and economic potential. By 2030, the size of the zeolite trade and industry is expected to reach approximately $19.2 billion, with a projected growth of 5.2% until 2030 [15]. According to these forecasts, zeolites and the zeolite industry, which have been used as catalysts and adsorbents since the beginning of the 1950s, will continue to grow. The annual growth of the zeolite market is illustrated in Figure 1.

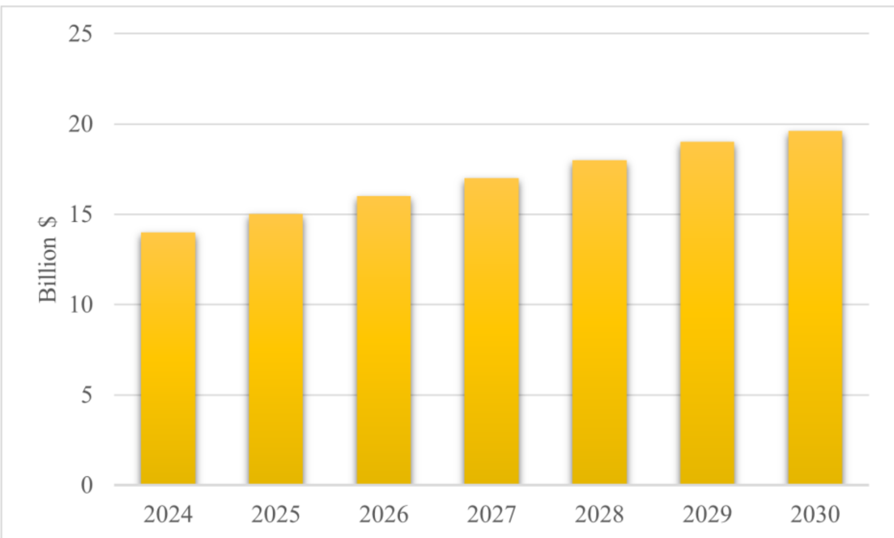


**Figure 1.** Asia-Pacific zeolites market revenue (2024–2030)

Zeolites are composed of micropores and are highly suitable for the absorption of non-polar gases, such as hydrogen, in cages and tunnels. Minimum pressure and low temperature are required for hydrogen to be absorbed into the surface area of the zeolite pores. When these conditions are met, hydrogen is forced onto the zeolite surface and physically absorbed by the zeolite [16].

The prominent advantage of zeolites in hydrogen storage stems from their microporous structure. The structures and micropore systems and sizes of four randomly selected zeolites can be seen in Figure 2. These structures allow them to adsorb hydrogen molecules with high efficiency. Furthermore, the high surface areas and modifiable chemical structures of zeolites increase their hydrogen storage capacity. Zeolites offer a sustainable solution for energy storage and transportation by efficiently sequestering hydrogen at low temperature and high pressure. In addition, zeolites are environmentally friendly and economical, making them an attractive option for hydrogen storage [17].

Zeolites are of interest because their cage and channel sizes can be controlled by utilizing their ion-exchange properties, which modify the valence state and size of exchangeable cations. As a result, the available void space, chemical nature of the potential binding sites, and the ease with which hydrogen molecules access the internal pore structure can be directly adjusted [18].

This review aims to present a comprehensive analysis of the potential of zeolites as efficient materials for hydrogen storage, focusing on their unique structural and chemical properties. The novelty of this review lies in the synthesis of recent advancements in zeolite-based hydrogen storage systems, particularly in their modification through surface functionalization, ion exchange, and the incorporation of hybrid materials. Unlike traditional reviews, this work highlights not only the current capabilities of zeolites but also the challenges that need to be addressed for their large-scale implementation in sustainable energy systems.

The primary objective of this review is to explore the latest research trends, identify the key factors influencing hydrogen adsorption in zeolites, and propose new directions for future research. By addressing the limitations of zeolites, including their low storage capacity at ambient conditions and high regeneration energy costs, this review aims to provide a roadmap for developing more efficient and cost-effective hydrogen storage solutions. Furthermore, this paper seeks to highlight the potential of hybrid zeolite-based materials, combining zeolites with metal-organic frameworks (MOFs), carbon-based materials, and metal oxides, to enhance their adsorption capacity and facilitate the integration of hydrogen storage systems into real-world applications.

## 2. Zeolites, Applicability and Research

Zeolites are widely used in various chemical processes such as gas adsorption, water purification, and wastewater treatment owing to their exceptional physicochemical characteristics such as their ability to exchange cations and their strong adsorption capacity. By predicting the performance of zeolites for specific applications, it becomes possible to save both time and money, as this approach helps in creating the most suitable zeolite with optimized properties [19].

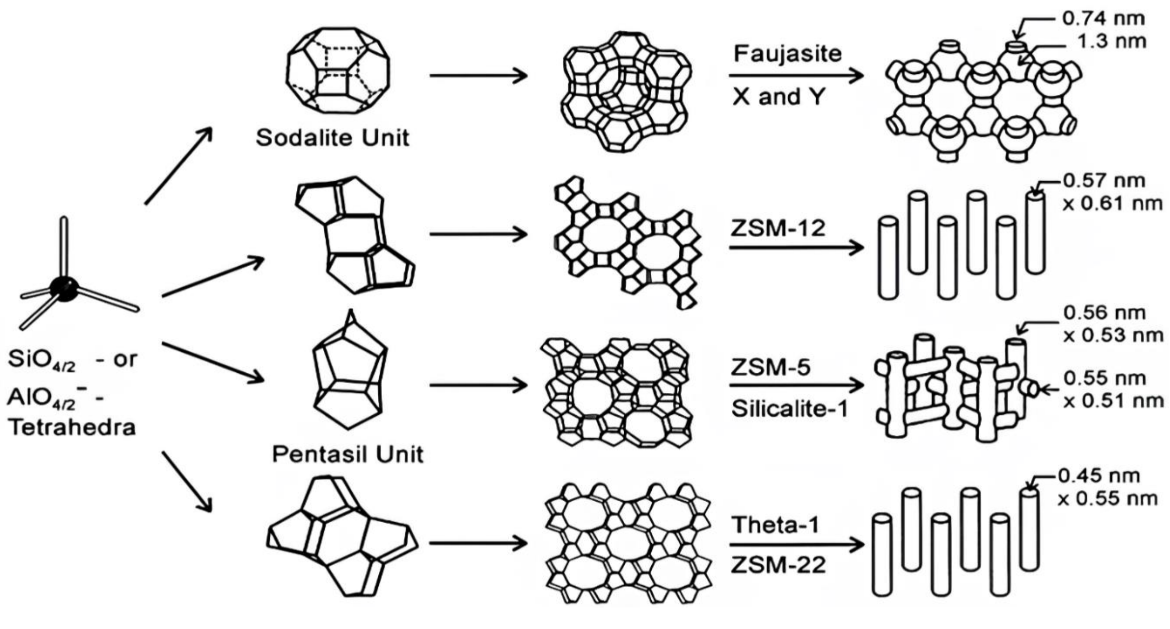


**Figure 2.** Structures and micropore systems and sizes of four selected zeolites.

The porosity and surface area of zeolites play critical roles in their capacity to adsorb molecules, especially hydrogen. Zeolites are microporous materials, with pore sizes generally ranging from 3 to 10 Å [20], making them ideal for adsorbing small molecules such as hydrogen gas. These microporous structures create a large surface area with a small volume, providing many active sites for adsorption can take place.

The high surface area is an important factor in hydrogen storage capacity as this allows zeolites to store significant amounts of hydrogen per mass [21]. For example, zeolites such as ZSM-5 show promising results in hydrogen adsorption owing to their finely tuned microporous structures [22]. Furthermore, zeolites can be selectively modified to optimize adsorption by creating open and well-defined channels and lattices. The narrow pores allow zeolites to establish strong interactions with hydrogen molecules, making them efficient for hydrogen-storage applications.

Several approaches have been studied to increase the adsorption capacity of zeolites, including surface functionalization using amines, ion exchange, polymer modification, and the dispersion of metal oxides [23].

Amines can significantly enhance the adsorption capacities of zeolites by modifying their surface chemical properties. When amine groups bind to the zeolite surface, they interact strongly with the adsorbate molecules through mechanisms such as hydrogen bonding and electrostatic interactions. This improved the ability of zeolites to adsorb gases and liquids. The attachment of amines introduces positive charges on the surface of zeolites, making them more attractive to specific molecules, especially polar and ionized compounds. Additionally, amines can influence the pore structure of zeolites, allowing for more efficient adsorption processes [24].

"4A-zeolit" is a specific type of synthetic zeolite that belongs to the family of A-type zeolites. It is characterized by its three-dimensional, microporous framework composed of silicon, aluminum, and oxygen atoms. The "4A" designation refers to the pore size of the material, which is approximately 4 Ångströms, making it particularly effective for adsorbing small molecules, such as hydrogen, carbon dioxide, and water. Due to its regular pore structure and ion-exchange properties, 4A-zeolite is widely used in gas separation, catalysis, and water purification, as well as in hydrogen storage applications. To optimize the $CO_2$ adsorption capacity of the 4A-zeolite synthesized in the present study by Bahmanzadegan et al. [25], structural modifications with amines were investigated. The zeolite surface was modified using amines such as tetraethylenepentamine (TEPA) and diethanolamine (DEA). These modifications have been were observed to play an important role in enhancing the adsorption capacity of zeolites.

In another study, where the kinetics of the adsorption was observed, it was found that carbon dioxide adsorption increased as a result of amine loading on 13X-DETA-40 for $CO_2$ adsorption and a capacity of 1.054 $mmol_{CO2}$ adsorption per 1 g of zeolite was achieved in a very short time [26].

Ion exchange, another method applied to increase the absorption in zeolites, can significantly affect the capacity of zeolites to adsorb gases such as hydrogen. On account of their ion exchange properties, zeolites can modify their structure and surface properties by exchanging different cations. These changes allow zeolites to adsorb hydrogen gas more efficiently. During ion exchange, the pore structure and surface area of the zeolite can be optimized by replacing large-diameter cations (e.g., $Na^+$, $K^+$) with smaller -diameter cations (e.g., $Ca^{2+}$, $Mg^{2+}$). This optimization allows the hydrogen molecules to bind better to the zeolite surface, thus increasing the adsorption capacity [27]

The effect of ion exchange on hydrogen adsorption depends on the surface charge of the zeolites, pore structure, and arrangement of ions in the zeolite structure. The compounds used in the cation exchange of zeolites play an important role in increasing the adsorption capacities. For example, removing larger ions and replacing them with smaller ions creates a larger surface area and denser pore structure, leading to a greater adsorption of hydrogen [13].

Zhang et al. [28] investigated the efficiency of silver ion-exchanged zeolites in the separation of hydrogen isotopes. When silver ions are integrated into the zeolite structure, the properties are acquired to facilitate more efficient separation of hydrogen isotopes. The addition of silver ions changes the surface structure of zeolites, providing stronger interactions and thus enhancing the selective adsorption of hydrogen isotopes. This study demonstrated that silver-modified zeolites have a significant potential for hydrogen separation and showed that such modifications are useful for the separation of hydrogen and hydrogen isotopes. This method may also be useful for environmental and industrial applications. This study shows how zeolites can be made more efficient for the separation of hydrogen isotopes through ion exchange, especially in energy production and environmental technologies.

Wyszkowski et al. [29] comprehensively studied the properties, synthesis methods, and various applications of zeolites. Zeolites have microporous properties owing to their crystalline structure, which makes them valuable for many industrial applications. This article discusses how modification of zeolites through ion exchange can increase the adsorption capacity of gases such as hydrogen. Ion exchange can change the pore structure, surface area, and chemical properties of zeolites, enabling them to adsorb gases more efficiently. This study also highlights how such modifications can be particularly useful in areas such as hydrogen storage, gas separation and environmental applications. Zeolites have higher adsorption capacities in virtue of these modifications render them suitable for clean energy technologies and environmental cleanup processes. Optimizing the properties of zeolites can make them more efficient in various industrial and environmental applications.

Akyalcin, Akyalcin, and Ertugrul [30] investigated the effects of various cations (for example, $Na^+$, $K^+$, $Ca^{2+}$) on zeolites and how these changes are reflected in the adsorption capacity. The results show that ion exchange plays an important role, especially in the adsorption of hydrogen on the zeolite surface and provides a stronger hydrogen binding. These properties make zeolites more efficient for applications such as energy storage and gas separation. Optimization of ion-exchange to convert zeolites more effective in environmental and industrial applications have also been substantiated in this research study.

Polymer modification can significantly improve the gas-adsorption capacity of zeolites [31]. When the surfaces of zeolites are coated with polymers, the adsorption processes of gases can be improved by changing the pore structure of the zeolite. Polymers can not only increase the adsorption capacity of zeolites, but also impart properties that enable the selective adsorption of gases. In particular, small molecules, such as hydrogen, can be adsorbed more efficiently on polymer-modified zeolites because the polymers optimize the adsorption sites by making the surface of the zeolite smoother and more homogeneous.

Integrating polymers into zeolites leads to changes in the pore size and surface chemistry. This allows the zeolite to hold more gas molecules and to utilize its high surface area more effectively. Furthermore, some polymers can further increase the adsorption power through chemical interactions with small molecules, such as hydrogen. Such modifications can improve the performance of zeolites, especially in areas such as gas separation and energy storage, making them more efficient for environmental and industrial applications [32].

In another study, the ammonia adsorption capacity and selectivity of $Li^+$-modified zeolite 13X were investigated. This study investigated how the modification of the natural structure of zeolites with lithium ions increases their adsorption capacity. The integration of lithium ions into the zeolite pore structure alters the surface properties and adsorption capabilities of the zeolite. This modification enables selective adsorption of gases, especially ammonia. This thesis emphasizes how this modification can be useful in the separation of ammonia and hydrogen, which has significant potential for hydrogen energy production. The optimization of ammonia and hydrogen adsorption demonstrates how such modifications can be used in gas separation and environmentally friendly energy production systems. This study has revealed that lithium-modified zeolites can become more efficient, especially in applications such as gas adsorption and separation [33].

In this research attempt, acidic modification methods were investigated to increase the hydrogen adsorption capacity of natural clinoptilolite zeolite. Improvement studies were carried out to use clinoptilolite more efficiently because of its limited hydrogen storage capacity. This study examined the changes obtained by modifying the clinoptilolite in an acidic environment. Acidic treatment improved the pore structure of the zeolite, allowing more hydrogen molecules to be adsorbed. This treatment increased the surface area of the zeolite and enlarged the voids in its microstructure, allowing the hydrogen to bind with stronger bonds. The zeolite obtained after modification adsorbed hydrogen more efficiently, which enhanced its hydrogen storage capacity. The study has evaluated the strategies how acidic modifications can heighten the properties of clinoptilolite, increasing the potential of zeolite in applications such as environmentally friendly power generation and gas storage [30]. It is also emphasized that such modifications could lead to a wider range of applications in hydrogen storage technologies.

The dispersion of metal oxides has a significant effect on hydrogen adsorption on zeolites. Although zeolites naturally have the capacity to adsorb gases such as hydrogen, modifications with metal oxides can increase this capacity. The diffusion of metal oxides on the surface of zeolites can change the pore structure and chemical properties of the zeolite, thus increasing the adsorption of hydrogen molecules [34].

Metal oxides form active sites on the surface of zeolites, which adsorb gases such as hydrogen more efficiently. Moreover, the integration of metal oxides on the zeolite surface increases the adsorption power by forming stronger interactions with hydrogen molecules [35]. For example, metal oxides, such as titanium oxide ($TiO_2$) or aluminum oxide ($Al_2O_3$), can improve the adsorption properties of zeolites and enable greater adsorption of hydrogen. Such modifications can increase hydrogen storage capacity and thus improve the potential for the use of zeolites in clean energy applications.

The development of safe, affordable, and efficient solutions for energy storage and transportation is one of the challenges to overcome for the use of hydrogen as an alternative energy carrier. Among the proposed solutions, physical adsorption in microporous materials with large surface areas has been included [36].

Physisorption is a process by which gas molecules, especially hydrogen, bind to the surface of a material through weak physical interactions. These interactions are mediated by weak forces of attraction, such as van der

Waals forces. Zeolites have a large surface area because of their microporous structure, and can adsorb hydrogen molecules on these surfaces. Physisorption allows hydrogen to interact with the surface, but these interactions are mediated by weak physical forces (dispersion forces, dipole-dipole interactions, etc.) rather than chemical bonds [37]. Modifications to increase the hydrogen storage capacity of zeolites allow greater physical adsorption of hydrogen by increasing the surface area and improving the pore structure. This process can occur at low temperatures and pressures because physical bonds can be more easily broken and hydrogen gas can be desorbed with lower energy requirements [38]. Thus, the use of zeolites for hydrogen storage offers an efficient and economical energy-storage solution.

A study examining the hydrogen adsorption capacity of zeolites under high pressure provided a comprehensive analysis of hydrogen storage in zeolites [39]. The research modelled the hydrogen adsorption capacity of different types of zeolites using Grand Canonical Monte Carlo (GCMC) simulations. These simulations show that hydrogen is adsorbed by interacting with microporous structures on the zeolite surface, and that physical interactions (such as van der Waals forces) play a role in this process. It was found that under high -pressure conditions, the capacity of zeolites to retain hydrogen molecules had increased. Another study highlights the potential of zeolites in the development of hydrogen storage technologies and provides ideas for improvements that can be made to increase the hydrogen adsorption capacity of zeolites. The hydrogen adsorption performance of zeolites under high pressure has significant potential for energy storage applications and as environmentally friendly energy solutions [40].

Another study investigated the adsorption behaviour of molecular hydrogen on CHA-zeolite using density functional theory (DFT) and molecular dynamics simulations. This research revealed how the adsorption of hydrogen molecules onto the zeolite surface occurs and how these interactions are related to the structural properties of the zeolite [41]. Molecular dynamics simulations illustrated that hydrogen is bound to the microporous structure of zeolite by weak van der Waals forces and that these physical interactions determine the adsorption capacity of hydrogen. Furthermore, the interaction strength of hydrogen at different sites on the zeolite surface was calculated in detail using density functional theory. The results show that the adsorption of hydrogen varies depending on the size and surface properties of the microvoids on the surface of the zeolite, which can significantly affect the hydrogen storage capacity. This study helps to better understand the hydrogen storage potential of zeolites and provides important data for the development of hydrogen storage technologies.

H. C. Bajaj et al. [42] investigated the hydrogen adsorption of zeolite Y exchanged with transition metal ions. Zeolites are capable of adsorbing gases due to their ion exchange capacity and microporous structure. A series of simulations and analyses specifically aimed at understanding the impacts of transition metal ions (e.g., $Ni^{2+}$, $Cu^{2+}$, $Zn^{2+}$, $Zn^{2+}$) on zeolite Y and enhance its hydrogen adsorption capacity have been presented. Using Grand Canonical Monte Carlo (GCMC) simulations, the interactions of different metal ions on the surface of zeolite Y were studied, and the hydrogen binding to these surfaces was determined. The displacement of metal ions increased the adsorption capacity of the zeolite, allowing hydrogen to be retained more efficiently. The results of this study show that by changing the binding properties of metal ions on the zeolite surface, hydrogen adsorption becomes more efficient, and thus, zeolites can be used more effectively in energy storage and environmental applications.

The use of transition metals offers efficient and sustainable energy solutions by increasing the hydrogen storage capacity of zeolites. Another study published in *Microporous and Mesoporous Materials* examines the hydrogen adsorption in transition metal-exchanged zeolite Y. This research has reported that the hydrogen uptake capacity of zeolite Y can be enhanced by exchanging it with transition metal cations, leading to improved hydrogen storage properties [43]. This enhancement is attributed to the increased interaction between hydrogen molecules and the zeolite surface facilitated by the presence of transition metal ions.

Low temperatures (cryogenic conditions) and high pressures significantly affect hydrogen adsorption in zeolites [13]. At low temperatures, hydrogen molecules have less kinetic energy, allowing them to be more easily trapped in zeolite micropores [44]. This results in a higher adsorption capacity because the gas molecules have more time to interact with the surface. Cryogenic conditions also reduce the tendency for desorption, resulting in more stable hydrogen storage. However, high pressures increase the concentration of hydrogen molecules, pushing them into the porous structure of the zeolite, thus improving the adsorption process. However, adsorption is highly dependent on the pore size and surface chemistry of the zeolites [45]. The combination of low temperature and high pressure can maximize the hydrogen storage capacity of zeolites by optimizing the interactions between hydrogen molecules and the zeolite surface. There have also been studies demonstrating the effect of pH on adsorption [46].

A study published by Unk. Özkirim & Yörükoğullari [47] investigated how the hydrogen adsorption capacity of NaY zeolite varies with temperature and pressure conditions. This paper shows that the adsorption of hydrogen occurs most efficiently under low temperature and high pressure. Low temperatures reduce the kinetic energy of hydrogen molecules, allowing them to be retained more efficiently in the microporous structure of zeolites. In addition, the high pressure allows hydrogen molecules to move closer to the zeolite surface, thereby adsorbing more hydrogen. This study emphasizes that the combination of these conditions significantly increases hydrogen storage capacity. These findings provide important insights into the optimization of temperature and pressure conditions for the development of hydrogen storage technologies.

In these studies, the hydrogen adsorption capacity of natural zeolites was evaluated under various temperature and pressure conditions. The results show that temperature and pressure conditions should be optimized to increase the hydrogen storage potential of zeolites [29].

Metal-organic frameworks (MOFs) are porous materials with high surface areas, which are three-dimensional structures formed by metal ions or metal clusters combined with organic bonds [48]. These frameworks are formed by the ordered interconnection of metal ions and organic ligands and can adsorb small molecules such as hydrogen at high capacities [49]. MOFs have great potential for hydrogen storage because their large surface areas and customizable structures enable the physical adsorption of hydrogen, and we can see the mechanism of MOFs for hydrogen storage in Figure 3. [50]. They are also considered to be ideal materials for storing hydrogen at low temperatures and high pressures. MOFs are used in various applications, such as energy storage, gas separation, water purification, and catalysis [51]. These properties make MOFs an effective option for hydrogen energy storage systems, carbon dioxide separation, and environmental cleanup technologies [52].

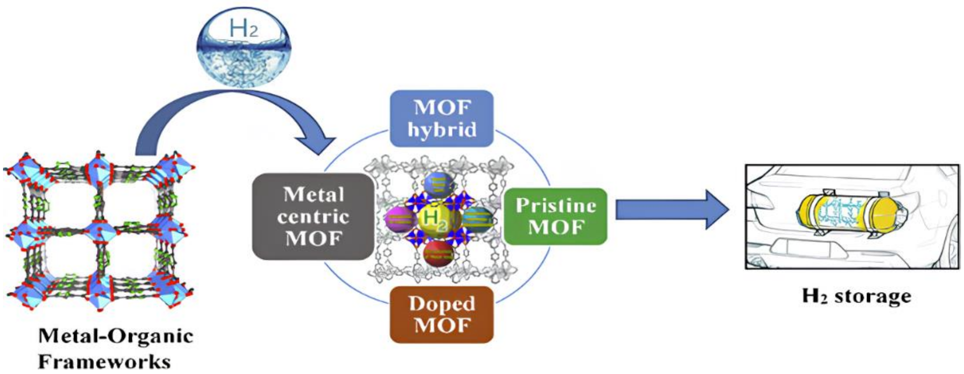


**Figure 3.** MOFs mechanism for Hydrogen storage. "Reprinted with permission from Ref. [50], 2025, Priya, S.S.".

Hydrogen is physically adsorbed onto MOFs via weak van der Waals forces and can be easily desorbed by adjusting the temperature or pressure [53]. Zeolites and Metal-Organic Frameworks (MOFs) play important roles in gas adsorption and storage applications because of their porous nature. Both the materials have advantages and limitations.

MOFs have the capacity to adsorb more gas molecules due to their higher surface areas and larger pore volumes compared to zeolites [54]. This property makes MOFs particularly efficient in the storage of gases such as hydrogen and carbon dioxide. The high surface areas help to increase the adsorption capacity of MOFs, which enables more efficient gas storage [55]. Furthermore, the pore structure of MOFs can be designed to optimize their interactions with molecules, making them more efficient in applications such as gas separation and energy storage [56]. However, despite the wide range of applications of these materials, they also have limitations, such as being more complex to synthesize and incurring higher costs [57].

Another great advantage of MOFs is their capacity to interact with a wide range of gases owing to their flexible structures [58]. Coordination bonds between metal ions and organic linkers allow the structure of MOFs to be changed under various conditions. This flexibility gives MOFs a great advantage in gas storage and separation applications, especially when different gases must be separated from each other [59]. Furthermore, the design of these structures enables them to have high selectivity towards specific gas molecules, which makes them more efficient. On grounds of these flexible structures that increase the surface area, MOFs are also used in applications such as environmentally friendly energy systems and carbon dioxide capture [60]. This elasticity allows them to be employed in a wide range of applications, but also paves way for complexities that need to be considered in the synthesis of these materials [61].

Although MOFs have many advantages, such as high surface area and flexible structure, they also have some limitations. One of the most important limitations is that MOFs generally exhibit poor stability at high temperatures and in acidic environments [62]. This makes their application complicated in some industrial and environmental applications. Furthermore, the synthesis of MOFs is often complex and costly, which is a major obstacle for commercial production [63]. Optimizing the structural stability of these materials can affect their long-term performance, leading to reliability issues in engineering applications. Consequently, the wide availability of MOFs in commercial applications is limited by barriers such as synthesis challenges and stability issues. In order to overcome these limitations, more durable MOF designs and efficient synthesis methods need to be developed [64].

Carbon-based materials, such as zeolites, are two important groups of materials with different advantages and limitations for hydrogen storage applications. Carbon nanotubes offer potential for hydrogen adsorption due to their high surface area and flexible structure [65]. However, the hydrogen storage capacity of carbon nanotubes is generally lower compared to zeolites. This study investigated the efficiency of each material at different temperatures and pressures, and compared hydrogen storage in carbon nanotubes and zeolites. The research concluded that zeolites perform better, especially in cryogenic conditions, while carbon nanotubes offer flexibility in terms of material design and application [66]. Zeolites offer higher hydrogen storage capacities owing to their ordered microporous structures [67]. Zeolite synthesis is complex and costly.

Nicholas M. Musyoka et al. had compared the hydrogen storage capacities of commercial zeolite X and fly ash-derived zeolite X as well as their templated carbon derivatives. They highlighted significant improvements in surface area and hydrogen uptake following the templating process. For commercial zeolite, the surface area increased by 328% from 796 $m^2$/g to 2578 $m^2$/g, whereas for fly ash-derived zeolite, the increase was 275% from 404 $m^2$/g to 1112 $m^2$/g. This enhancement in surface area corresponded to an improved hydrogen uptake capacity, with commercial zeolite-derived templated carbon attaining 2.4 wt% hydrogen uptake, compared to 1.2 wt% in fly ash-derived templated carbon [68]. The significant outcomes of study have demonstrated that the application of fly ash-derived zeolites as template materials for carbon synthesis will definitely offer a cost-effective alternative to commercial zeolites with the potential to scale hydrogen storage technologies. Furthermore, research has underlined the importance of optimizing zeolite-based materials for efficient hydrogen storage in practical applications.

"Advancements in Hydrogen Storage Materials: A Review of Zeolites and Carbon-based Materials" examines the latest advances in hydrogen storage technologies and materials used in this field. This article emphasizes that zeolites have higher stability than carbon-based materials and offer a more reliable option for long-term hydrogen storage applications. They also state that the production processes of carbon-based materials are simpler and more cost-effective, making them advantageous for certain commercial applications [69]. Nevertheless, the pore structures and high adsorption capacities of zeolites make them more efficient in hydrogen storage technologies; however, the flexible structures and portability of carbon-based materials also stand out in important applications.

In recent years, many innovative methods have been developed to increase the hydrogen adsorption capacities of zeolites. Zeolites have important potential for hydrogen storage applications because of their microporous structure and high surface area [70]. However, improvements in the physical and chemical properties of zeolites are required for the effective adsorption of hydrogen. For this purpose, the adsorption capacities of zeolites are increased using various techniques such as customization of pore structures [71], surface modifications [72], and the addition of different additives. These studies aimed to increase the efficiency of zeolites in hydrogen storage applications while simultaneously reducing costs and ensuring long-term stability.

In recent years, several innovative methods have been developed for the structural modification and functionalization of zeolites to enhance their adsorption capacities. Techniques such as metal ion exchange, structural specialization, and framework modification have been widely used to improve the surface properties of zeolites and enhance their gas adsorption performance [73]. Metal ion exchange increases the adsorption capacity of zeolites by altering their chemical and physical properties, whereas structural customization optimizes the pore size and distribution of zeolites, allowing more gas molecules to be adsorbed [74]. Framework modification contributes to the development of more efficient hydrogen storage systems by increasing zeolite stability and selectivity [75]. These modifications increase the adsorption efficiency of zeolites for various gases and offer wider applications, such as energy storage and environmental applications.

The article by Wei Du, Xiubo Xie et al. reviews, the studies on improving the hydrogen storage capacity of $MgH_2$ and ZnO composites are reviewed. Research shows that ZnO doping has positive effects on the hydrogen adsorption and desorption kinetics of $MgH_2$ [76]. ZnO increased the stability of $MgH_2$, enabling the adsorption of hydrogen with a higher capacity and desorption at low temperatures. This study contributes to the development of efficient materials for hydrogen storage, particularly at low pressures and temperatures. Furthermore, the long-term performance testing of these composites promises to provide more reliable and economical solutions for hydrogen storage applications.

Research on the combination of zeolites with other materials is increasing rapidly to develop more efficient materials for hydrogen storage and adsorption applications. Although zeolites have significant potential for hydrogen storage owing to their high surface area and microporous structure, these properties can often be enhanced. In particular, it has been shown that hybrid and composite structures made with different materials such as carbon-based materials, metal oxides and polymers can improve the adsorption capacity of zeolites [77]. Such hybrid and composite materials can improve the structural stability of zeolites, while simultaneously optimizing their adsorption properties and providing more effective hydrogen storage under different conditions. Research in this area has played an important role in the development of next-generation energy-storage systems.

The study of T. Jean Daou et al. investigates the water adsorption capacity of zeolite and polymer composites. In this study, it was shown that the microporous structures of zeolites and the flexible properties of polymers create a synergistic effect on water vapor adsorption, increasing the water-holding capacity [78]. The surface properties of the hybrid materials improve the adsorption of water, indicating the potential use of these materials for environmentally friendly water treatment and aeration applications. Zeolite and polymer combinations offer more sustainable and efficient solutions, particularly in areas such as industrial wastewater treatment and environmental management. Additionally, it is envisaged that these composites can be used in a wide range of applications thanks to their economical and practical production methods.

In another study, the effect of mechanical alloying of various metal hydrides on hydrogen storage performance was discussed. Hydrogen sorption/desorption kinetics can be improved by combining mechanical alloying, surface modification, and alloying techniques [79]. The flexibility of ZIFs can be further improved by surface modification, making them more efficient and suitable for targeted applications. Research shows that ZIFs have high potential for use in environmentally friendly and sustainable energy systems and can play an important role in hydrogen energy storage technologies.

The review, entitled "A Comprehensive Review on Hydrogen Absorption Behavior of Metal Alloys", covers research on improving the hydrogen storage performance of various metal alloys. This study discusses how mechanical alloying methods improve the hydrogen absorption and desorption kinetics by modifying the surface properties of metal hydrides. It is emphasized that metal alloys have great potential, especially in terms of increasing the hydrogen storage capacity, but this improvement requires more complex synthesis processes [80]. Alloying techniques can improve the hydrogen adsorption efficiency through the structural arrangement of metal ions. This study provides important insights into how these alloys can be used to create more efficient hydrogen storage systems. The properties of metal alloys enable storage processes to be accelerated and made more efficient, enabling the wider utilization of hydrogen energy. This study demonstrates the importance of metal alloys in energy storage applications and the development of environmentally friendly energy solutions.

Hydrogen storage remains a critical area for future energy solutions, and zeolites are promising materials for the efficient storage of hydrogen [81]. The hydrogen adsorption capacity of zeolites can increase significantly at low temperatures and high pressures, making zeolites ideal for storing hydrogen under cryogenic conditions [82]. Cryogenic hydrogen storage can significantly reduce storage and transportation costs by enabling hydrogen storage without liquefaction [83]. This method allows the microporous structures and large surface areas of zeolites to adsorb hydrogen molecules more efficiently, thereby improving the energy efficiency. Recent studies have demonstrated how cryogenic temperatures improve the adsorption performance of zeolites, and the potential of this approach in hydrogen storage technologies.

The article of by Gao Q. et al., examines the development and evaluation of nanoporous carbon materials for two important applications: cryogenic hydrogen storage and electrochemical capacitance. The authors synthesized these materials using a two-step casting process and used zeolite 13X as the mold. This method mimics zeolite-like structures in carbon materials, significantly increasing the surface area and pore volume, which is essential for hydrogen adsorption [84].

Another published study dealt with the storage of liquid hydrogen in natural zeolites. The storage of hydrogen poses a significant challenge owing to its low density and explosive properties, particularly in gaseous form. Storage of liquid hydrogen in a high-capacity battery using natural zeolites is proposed as a viable solution to this problem. This study highlights the advantages of the proposed method for the storage and safe maintenance of liquid hydrogen. This system allows for the slow release of gas during long-term storage, while simultaneously making it possible to release the gas when the temperature of the battery increases or restores the hydrogen by re-cooling the storage space [85].

One of the main challenges in hydrogen storage is its inherently low energy density, particularly under ambient conditions [86]. Hydrogen, as a gas, has a very low volumetric energy density at room temperature and atmospheric pressure, which means that large volumes are required to store even small amounts of energy. This makes it difficult to efficiently store hydrogen without compression or liquefaction, both of which require significant energy input [87]. At room temperature, hydrogen gas occupies a large volume, and high pressures (up to 700 bar) or extremely low temperatures (cryogenic conditions) are typically used to increase storage density.

However, these approaches have their own challenges, such as the energy cost of compression or liquefaction and the complexity and safety risks associated with high-pressure systems or cryogenic tanks [88].

Furthermore, materials used for hydrogen storage such as zeolites or MOFs, while promising, often exhibit limited storage capacity at ambient conditions [89]. Their hydrogen adsorption capacity can be significantly lower than that required for practical applications, especially at the temperatures and pressures commonly encountered in everyday environments. This problem is further complicated by the fact that most hydrogen storage materials have relatively low gravimetric densities, meaning that they can only store a small mass of hydrogen per unit weight, further limiting their practical use in transportation and large-scale storage [89]. Consequently, improving the storage capacity of hydrogen materials under ambient conditions remains a major challenge in the development of practical hydrogen storage systems.

Regeneration processes are critical to ensure the reusability of zeolites. However, these processes present significant challenges in terms of energy cost. For example, in an article published by Deng et al. [90], it was reported that the regeneration of zeolites by chemical methods requires the use of high concentrations of salt, which increases costs. The researchers suggested that the alkaline regeneration method at pH 12 can reduce sodium chloride costs tenfold compared to conventional chemical regeneration.

In the study published by Ezzi et al., it is emphasized that zeolite-based desiccants strongly adsorb water vapor molecules, but a significant amount of energy is required for regeneration [91]. These studies have demonstrated that the importance of investigating alternative methods to reduce the energy costs of zeolite regeneration processes.

Zeolites are promising materials for hydrogen storage applications. However, there are some challenges to scaling up these materials for industrial applications and their cost-effectiveness.

In the study titled "Hydrogen storage technologies for stationary and mobile applications", it is emphasized that hydrogen storage systems should be safe, cost-effective and compact. Physical storage systems include compressed gas, liquid, and cryo-compression techniques, whereas material-based systems include adsorbent materials, metal hydrides, and chemical storage materials. In this context, the hydrogen storage capacity and cost-effectiveness of zeolites are critical for industrial applications [92].

Furthermore, In the article published by Manda T. et al. the hydrogen storage performance of zeolites was evaluated using molecular simulations. This approach is important for increasing the storage capacity of zeolites and evaluating their suitability for industrial applications [93]. These studies provide important information for evaluating the potential and industrial scalability of zeolites for hydrogen storage.

Zeolites and MOFs are materials with significant potential in the field of hydrogen storage. Recent research on the combination of these materials and new synthesis techniques offers promising findings for increasing hydrogen storage capacity and improving their suitability for industrial applications.

Recent studies show that the combination of zeolite and MOFs in composite materials for gas adsorption is a viable option to improve the performance of the separation step. Figure 4 shows that when zeolite and MOF are used alone, they have a similar adsorption capacity, while the combination of both materials improves the performance [94].

The combination of zeolites and MOFs can increase the hydrogen storage capacity by combining the advantages of both materials. For example, in the study of Musyoka et al. [89] the combination of ZTC (zeolite templated carbon) and chromium-based MOF (MIL-101) was investigated. This hybrid composite achieved a hydrogen storage capacity of 2.55 wt% at 77 K under a pressure of 1 bar.

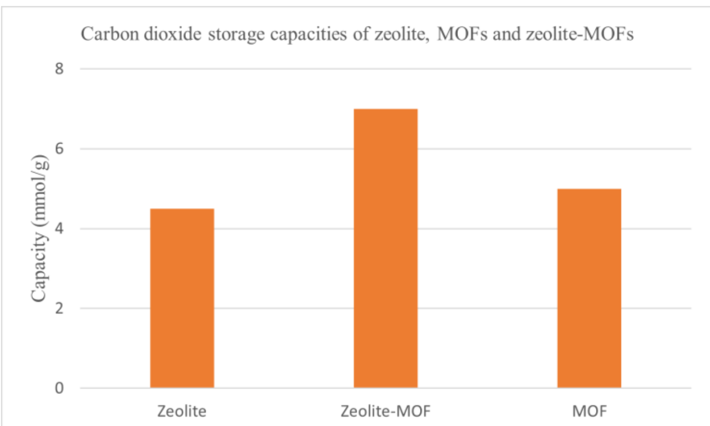


**Figure 4.** Carbon dioxide storage capacities of zeolite, MOFs and zeolite-MOFs

In addition, new synthetic methods are being studied to improve the performance of hydrogen storage materials. In the article published by Wu Z. et al., synthesis strategies of zeolite-encapsulated metal catalysts were discussed. Two main synthesis strategies were identified: post-treatment (ion exchange, interzeolite conversion, and recrystallization) and in situ synthesis (in situ hydrothermal and dry-gel synthesis) [95]. Studies have highlighted the importance of hybrid materials and innovative synthesis techniques for improving the performance of hydrogen storage materials and enhancing their suitability for industrial applications.

Zeolites have attracted attention because of their potential applications in hydrogen storage and clean energy systems. Recent studies have examined the integration of these materials into hydrogen fuel cells and clean energy storage.

The article published by Manda T. et al., examines an approach that uses molecular simulations to evaluate the hydrogen storage capacity of zeolites. This study utilized advanced data analysis methods to improve the accuracy of performance predictions based on zeolite structures. Through molecular simulations, the key structural factors affecting the hydrogen adsorption of zeolites were identified, and potential modifications were proposed to improve the hydrogen storage capacity of these materials. Furthermore, this research discusses how the micro- and macroporous structures of zeolites can improve the efficiency of hydrogen storage. These analyses provide guidelines for zeolites to be used more efficiently in future applications such as hydrogen fuel cells [93]. Such simulations allow for the faster and more efficient development of hydrogen storage materials.

Research has also been conducted on Ammonia Decomposition and Clean Hydrogen Production. Ammonia is a potential carrier for the transportation and storage of hydrogen. In the study titled "Clean hydrogen production from ammonia decomposition over zeolite 13X-supported Ni catalysts," the performance of zeolite 13X-supported nickel catalysts on ammonia decomposition was investigated. This process is effective for hydrogen production [96].

Such studies have signposted the potential applications of zeolites and other materials in hydrogen storage and clean energy systems. In the future, the integration of these materials in a more efficient and economical strategies will contribute to the development of sustainable energy systems.

While zeolites show great promise for hydrogen storage, several challenges still hinder their widespread implementation in practical applications. One of the main difficulties is the relatively low hydrogen storage capacity of zeolites at ambient conditions. Although zeolites are effective in adsorbing hydrogen under cryogenic conditions or high pressure, their storage capacity at room temperature and atmospheric pressure remains insufficient for large-scale applications. This limitation calls for continued research to modify zeolite materials to enhance their hydrogen uptake at more practical conditions.

Furthermore, the regeneration of zeolites after adsorption cycles presents another challenge. Regeneration methods often require high energy input, particularly when chemical treatments or elevated temperatures are involved. This results in higher operational costs and limits the overall efficiency of zeolite-based storage systems. Exploring alternative regeneration techniques that are both energy-efficient and cost-effective will be critical for improving the long-term viability of zeolites as hydrogen storage materials.

Looking ahead, future research should focus on the development of hybrid materials, such as zeolite-metal-organic framework (MOF) composites, which could combine the advantages of both materials—high surface area from MOFs and the stability and affordability of zeolites. By integrating zeolites with other materials like carbon-based compounds, metal oxides, and polymers, researchers may overcome some of the limitations related to surface area, adsorption efficiency, and material stability. Additionally, enhancing the scalability and industrial applicability of zeolite-based hydrogen storage systems will be crucial for their integration into real-world energy systems.

Future studies could also explore the optimization of synthesis techniques, aiming for more cost-effective and environmentally friendly methods to produce zeolite composites with superior hydrogen adsorption properties. Finally, further investigations into the fundamental interactions between hydrogen molecules and zeolite surfaces will provide valuable insights into how modifications can be made to optimize adsorption under various conditions.

## 3. Conclusions

Zeolites have emerged as promising materials for hydrogen storage technologies due to their unique microporous structures, high surface areas, and the potential for chemical modifications to enhance their storage capacities. This review highlights the effectiveness of various techniques, including surface functionalization with amines, ion exchange, and metal oxide dispersion, in improving hydrogen adsorption. These modifications have shown substantial improvements in the performance of zeolites, yet several challenges remain. In particular, increasing the hydrogen storage capacity of zeolites under ambient conditions, as well as reducing the energy costs associated with zeolite regeneration, are critical steps for advancing these technologies to industrial-scale applications.

Moreover, the creation of hybrid materials by combining zeolites with other advanced materials such as metal-organic frameworks (MOFs) presents a promising avenue for further improving hydrogen storage efficiency. Hybrid zeolite-MOF composites, with the high surface area of MOFs and the stability and cost-effectiveness of zeolites, have the potential to significantly increase the adsorption capacity and enhance the overall performance of hydrogen storage systems. Future research should focus on optimizing these hybrid materials and exploring novel synthesis techniques to improve hydrogen storage capacity and expand their industrial applicability.

Additionally, the energy cost associated with the regeneration of zeolites remains a significant challenge. Developing more energy-efficient regeneration methods will be crucial for the long-term viability of zeolites as a material for hydrogen storage. Reducing the energy requirements for regeneration will enhance the overall cost-effectiveness of zeolite-based storage systems, making them more competitive for widespread use.

In conclusion, while zeolites hold significant potential for hydrogen storage, further research is required to address the challenges related to their adsorption capacities and regeneration processes. The integration of hybrid materials, new synthesis methods, and surface modifications presents exciting opportunities for improving the performance of zeolites in hydrogen storage applications. The successful integration of zeolites into hydrogen storage systems will play a pivotal role in the development of sustainable energy infrastructure, contributing to a cleaner, more efficient energy future.

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