

Strategic Analysis of Past and Modern Hydrogen Storage Methods and Prospects for Its Future

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Abstract

This research report provides a comprehensive strategic analysis of past and modern hydrogen storage methods and prospects for its future. A literature review was conducted to identify the most promising materials and technologies for hydrogen storage and to compare their properties to current storage methods. The findings suggest that solid-state storage materials, such as metal-organic frameworks (MOFs) and porous carbon materials, show great promise due to their high storage capacities and favorable thermodynamic properties. However, technical challenges such as slow kinetics and low durability need to be addressed to achieve practical application. Furthermore, the integration of hydrogen storage into existing energy infrastructure presents technical and regulatory barriers that need to be overcome, such as pipeline compatibility and safety regulations. Overall, this research sheds light on the prospects and challenges of hydrogen storage and provides insights for future research and development in this field.

Keywords: hydrogen storage, Metal-Organic Frameworks (MOFs), porous carbon materials, energy infrastructure

1. Introduction

Hydrogen has emerged as a promising energy carrier due to its abundance, high energy content, and clean-burning properties. However, the adoption of hydrogen as a widespread energy source is still limited due to the challenges associated with its storage and transportation. Therefore, this report aims to provide a strategic analysis of past and modern hydrogen storage methods and prospects for its future. The report includes a literature review and methodology for conducting the research, as well as findings and discussion based on two research questions. The first research question explores the most promising materials and technologies for hydrogen storage and compares their properties to current storage methods. The second research question investigates how hydrogen storage can be integrated into existing energy infrastructure, and what technical and regulatory barriers need to be addressed. This report aims to provide insights and recommendations that can help drive the advancement of hydrogen storage technology and facilitate the integration of hydrogen into our energy systems.

1.1 Research Aim and Questions

The purpose of this paper is to present and discuss possible solutions to the following two problems: 1) What are the most promising materials and technologies for hydrogen storage, and how do their properties compare to current storage methods? 2) How can hydrogen storage be integrated into existing energy infrastructure, and what are the technical and regulatory barriers to doing so?

2. Literature Review

As the total world population increases, the demand for energy becomes heavier, but fossil fuels such as coal, crude oil and natural gas are non-renewable and very harmful to the environment. Hydrogen is a green energy

source that is both sustainable and environmentally friendly. However, due to its light weight and low density and the gaseous nature of hydrogen itself, it faces several challenges in terms of storage, and the way in which the storage problem is solved is probably the biggest obstacle to the success of hydrogen energy penetration. Hydrogen can be stored by either physical or chemical means. In each storage technique, there are advantages and disadvantages. The subject of this study is to review hydrogen storage strategies and compare the various types of hydrogen storage methods in terms of three aspects: effectiveness, cost and Application.

2.1 Efficiency

Regarding the storage of hydrogen, the efficiency of the storage method is an important consideration that cannot be ignored. Different storage methods lead to different storage efficiencies, and the comparison of the effectiveness of different hydrogen storage methods has been highlighted in many literature (Durbin, D. J., & Malardier-Jugroot, C., 2013).

Compressed Hydrogen: The most widely used method of hydrogen storage is high-pressure hydrogen compression, which is a proven technology. In addition, this method of hydrogen storage requires no energy consumption when releasing hydrogen, however, compressing hydrogen to high pressure consumes approximately 13-18% of the low calorific value of hydrogen (Jensen, J. O., Vestbø, A. P., Li, Q., & Bjerrum, N. J., 2007), which affects the overall economics of the process. The hydrogen is stored in a cylindrical container. Commonly used containers are high-pressure cylinders with a maximum working pressure of 20 MPa. Compressed hydrogen is an efficient method of hydrogen storage, considering that as the volume of the gas increases with pressure, the energy density also increases. However, the target efficiency of the gas depends on the low weight and volume. Therefore, the efficiency of the high-pressure compressed hydrogen method is not the highest among the various types of hydrogen storage methods, but the cost effectiveness is more favorable.

Liquid hydrogen: Liquid hydrogen is obtained by cooling down hydrogen to $-240\text{ }^{\circ}\text{C}$ and can be written as LH 2. The liquid or low temperature form of hydrogen (LH 2) has a higher density and therefore the bulk energy density increases to a great extent. The density of liquid hydrogen reaches about 71 g/L at $-253\text{ }^{\circ}\text{C}$, and its energy density becomes equal to 8 MJ/LH 2. Therefore, it can be said that the 4 cylinders of LH2 are equivalent to 1 gasoline tank. However, taking into account the weight of the insulation material and the weight of the tank, a lower value will be obtained. The critical temperature of hydrogen is $-240\text{ }^{\circ}\text{C}$ (above this temperature hydrogen cannot be liquefied), therefore, hydrogen must be cooled below its critical temperature. Hydrogen is liquefied to $-253\text{ }^{\circ}\text{C}$ (the boiling point of hydrogen) and stored as a liquid. Similar to hydrogen compression, liquid hydrogen storage is a well-established technology. The low adiabatic expansion energy helps to avoid damage in case of a sudden leak of H 2 from the mouth of the container. Since the density of liquid hydrogen is almost 1.5-2 times higher than that of high-pressure compressed (hydrogen Niaz, S., Manzoor, T., & Pandith, A. H., 2015), the size of the storage tank is reduced to an acceptable value. Storage is carried out at low pressure, so rather thin and inexpensive tanks can be used, and liquid hydrogen is noncorrosive, with sufficient insulated stainless steel and aluminum alloy containers available for cryogenic storage (Prabhukhot Prachi, R., Wagh Mahesh, M., & Gangal Aneesh, C., 2016). However, they face a major challenge: LH 2 is extremely sensitive to heat transfer from the environment, resulting in rapid pressurization, which may lead to venting losses opening if the maximum allowable pressure of the vessel and the pressure relief device are reached. In general, liquid hydrogen storage has higher efficiency than compressed hydrogen storage. Other methods: In addition to compression hydrogen storage and liquid hydrogen, there are methods such as metal hydroxides and other hydroxides, physical adsorption, and liquid organic hydrogen carriers.

This literature review pick metal hydroxides as example. For metal hydroxides, it is possible to provide higher hydrogen storage capacity than compression and liquefaction and to store hydrogen at room temperature and natural atmospheric pressure. Metal hydroxides also have a higher safety profile since the constraints of this method are not as severe as those of gas compression and liquefaction. However, the disadvantages of metal hydroxides are the high hydrogen release temperature and the potential formation of impurity gases during hydrogen release.

As a compare, if the cost and Application part been ignored and just compare the storage efficiency, the metal hydroxides are highest, and then liquid hydrogen, lastly compressed hydrogen.

2.2 Cost

The ultimate goal of researching hydrogen storage methods and developing various ways of storing hydrogen is to replace the original fossil energy with hydrogen energy to provide a more environmentally friendly and sustainable energy source for mankind. Therefore, the cost of hydrogen storage is also a key point in hydrogen storage, and storing more hydrogen at a lower cost with guaranteed safety is one of the objectives of hydrogen storage research, with the premise that it can eventually be applied (Usman, M. R., 2022).

Compression hydrogen storage, as the longest developed method of hydrogen storage, already has cost effective

solutions in the choice of materials for containers, such as cast iron. In addition, in this type of method, except for the container, energy is only required for compressing the hydrogen. After the hydrogen is compressed and stored in the container, no additional energy is needed to maintain it and no high percentage of energy is lost when releasing the hydrogen during application. Liquid hydrogen has a higher energy density as well as a smaller volume than compressed hydrogen, but the nature of hydrogen causes it to require very low temperatures to preserve a stable state, and the cost of liquefying hydrogen is high, and therefore the energy used for liquefaction is also high. Another problem is the evaporation phenomenon, which is the loss of hydrogen due to energy input from the surroundings. It is estimated that about 1.5-3% of hydrogen evaporates every day. If evaporation is to be reduced (Zhang, F., Zhao, P., Niu, M., & Maddy, J., 2016), expensive insulation materials and double-layered vacuum vessels are required. For metal-hydrogen compounds, inexpensive mg, etc., can be used as raw material, and for most hydride reactions, not much energy input is required, so if the purpose is only storage, then this method is excellent in terms of cost effectiveness. However, as mentioned in the previous section, the ultimate purpose of hydrogen storage is application, then the cost of metal hydroxides needs to be reconsidered, and extracting the hydrogen from hydroxides requires a container and cannot be used directly as an energy source. Therefore, increasing the time cost for the application of such methods.

2.3 Application

Storage of hydrogen has been the key word in this literature review, and applications, as the focus of hydrogen after being stored, have been important topics. Compressed hydrogen has a similar container to the common energy sources nowadays such as natural gas tanks, on the other hand, pressure tanks have a long history of transportation, heavy trucks and other means of transportation are suitable with tank which storage compressed hydrogen. Although, liquid hydrogen and metal hydroxide are better than compressed hydrogen in terms of energy efficiency for storage, they have obvious disadvantages in terms of transportation (Ahluwalia, R. K., Roh, H. S., Peng, J. K., Papadiaz, D., Baird, A. R., Hecht, E. S., ... & Aceves, S. M., 2023). In the case of liquid hydrogen, the ambient temperature affects the storage quality, and metal hydroxide has a cumbersome process for extracting hydrogen, which shows that both liquid hydrogen and metal hydroxide are good methods when referring specifically to storage, but in combination with practical applications, it is compressed hydrogen that has a higher performance.

3. Methodology

3.1 Introduction

This study conducts a strategic analysis of past and modern hydrogen storage methods and evaluates the prospects for their future development. The research methods employed are a combination of qualitative and quantitative research methods. And which is based on secondary research. Data collection techniques are mainly literature review. Data analysis techniques encompass thematic analysis which will used to answer research questions in the following section. Limitations include the reliance on secondary data sources and the potential for the sample size of the online survey to not be fully representative of the industry. The purpose of this chapter is to provide an overview of the research methods and data collection techniques used, as well as the limitations of the study.

3.2 Research Method

The primary research method utilized in this study is secondary research, which involves the collection and analysis of existing data and information from sources such as academic literature, reports, and online databases. Secondary research is advantageous for its cost-effectiveness, time efficiency, and availability of data from a wide range of sources (Saunders et al., 2018). However, the reliability, relevance, and quality of the data sources used may be limited, thereby affecting the validity of the research findings (Saunders et al., 2018).

For this project, secondary research was considered the most appropriate research method since it enabled a comprehensive analysis of past and modern hydrogen storage methods, and their prospects for the future. By reviewing existing literature and reports, a vast amount of data on hydrogen storage methods that have been previously researched and tested were gathered. Moreover, secondary research facilitated the identification and analysis of trends and patterns in hydrogen storage methods, as well as their prospects. The use of secondary research in this study ensured that data was gathered from a diverse range of sources, and the findings of the study were not limited by the researcher's personal biases or experiences.

The present study utilized mixed methods research, which combined both qualitative and quantitative research methods. This approach allowed for a more comprehensive and holistic understanding of the research questions by triangulating data from multiple sources (Creswell & Poth, 2017). Mixed methods research has been acknowledged as an effective approach to enhance the validity and reliability of research findings by providing a greater depth of understanding and insight into the research topic (Tashakkori & Teddlie, 2010).

Mixed methods research offers various benefits, such as generating both rich and detailed data as well as

quantitative measures of data. Moreover, mixed methods research can help overcome the limitations of using a single research method and provide a more complete picture of the research topic (Creswell & Poth, 2017). However, mixed methods research may be more time-consuming and resource-intensive and requires a greater level of expertise in both qualitative and quantitative research methods. For this study, mixed methods research was chosen as the best method for answering the research questions, as it allowed for a more comprehensive and nuanced analysis of past and modern hydrogen storage methods and their prospects for the future.

3.3 Data Collection

The data collected for this study include secondary data. Secondary data was gathered through a comprehensive literature review of academic journals, reports, and institutional websites. To find relevant sources, various search engines and databases were used, such as Google Scholar, ScienceDirect. Search terms included “hydrogen storage,” “hydrogen energy,” and “renewable energy source”. Relevant sources were determined based on their relevance, reliability, and recency, as well as their ability to address the research questions. The article “Hydrogen storage methods: Review and current status (Usman, M. R., 2022)” serves a critical function in establishing connections and providing context for both the report in its entirety and the title thereof.

3.4 Data Analysis

The qualitative data analysis technique will involve a thematic analysis of the literature review to identify key themes related to hydrogen storage. These themes will be used to develop a conceptual framework that will be used to guide the data analysis process. This approach provides clear and accurate information on the various methods of hydrogen storage. The quantitative data analysis technique will involve statistical analysis of the survey data to identify trends, patterns, and relationships between different variables related to hydrogen storage. This approach helps to set up tables.

3.5 Limitations

While efforts were made to minimize bias and ensure objectivity, there are potential limitations to this study. Firstly, the online database samples may not be fully representative of the hydrogen storage industry. Secondly, secondary data sources may contain bias and outdated information. Finally, the scope of the study may not fully encompass all aspects of hydrogen storage methods and their prospects for the future. Nonetheless, these limitations were acknowledged and considered throughout the research process.

4. Findings and Discussion

4.1 Research Question One

What are the most promising materials and technologies for hydrogen storage, and how do their properties compare to current storage methods?

The development of efficient and economical hydrogen storage devices is critical for the advancement of the hydrogen economy. Numerous materials and technologies, such as metal hydrides, carbon nanotubes, and liquid hydrogen, have been investigated for hydrogen storage. This article reviews the most promising materials and technologies for hydrogen storage and discusses their properties in relation to current storage techniques. By investigating and enhancing the characteristics of these materials, we can identify the most effective and cost-effective hydrogen storage solutions for the hydrogen economy. Table 1 summarizes the properties and characteristics of metal hydrides, carbon nanotubes, and liquid hydrogen as hydrogen storage materials.

Table 1. Properties and Characteristics of Metal Hydrides, Carbon Nanotubes, and Liquid Hydrogen, Adapted from Abdalla et al. (2018), Usman (2022), and Ahluwalia et al. (2023)

Material	Storage capacity	Operating temperature	Storage density	Safety Concerns	Cost
Complex metal hydrides	High	High	Low	High	High
Light metal hydrides	Low	Low	High	Low	Medium
Carbon nanotubes	High	Room temperature	Low	High	High
Liquid hydrogen	High	Low	High	Medium	High

Metal hydrides have been extensively studied for hydrogen storage due to their high hydrogen storage capacity and relatively low operating temperatures. According to Abdalla et al. (2018), metal hydrides are classified into two categories: complex metal hydrides and light metal hydrides. Complex metal hydrides such as sodium alanate and lithium borohydride have shown high hydrogen storage capacity, but their operating temperatures are

too high to be practical. Light metal hydrides such as magnesium hydride and lithium hydride have lower storage capacity but can operate at lower temperatures.

Carbon nanotubes (CNTs) have also been explored as a potential hydrogen storage material due to their high surface area and porosity. Usman (2022) noted that CNTs have shown promise for hydrogen storage, with a storage capacity of up to 9 wt%, but the technology is still in the experimental stage and requires further research and development.

Liquid hydrogen storage is another promising technology for hydrogen storage, with high storage density and relatively low operating temperatures. Ahluwalia et al. (2023) reported that liquid hydrogen storage is suitable for heavy-duty trucks due to its high energy density, but it requires high-pressure tanks and has safety and cost concerns.

4.2 Research Question Two

How can hydrogen storage be integrated into existing energy infrastructure, and what are the technical and regulatory barriers to doing so?

Hydrogen has the potential to play a significant role in the transition to a more sustainable energy future. However, integrating hydrogen into the existing energy infrastructure comes with several technical and regulatory challenges. This section aims to explore the current state of hydrogen storage integration and the associated challenges. Three sources were used to gather information on the topic (Abdalla et al., 2018; Usman, 2022; Ahluwalia et al., 2023).

Table 2. “Comparison of Hydrogen Storage Methods and their Properties” Abdalla et al. (2018), Usman (2022), Ahluwalia et al. (2023)

Topic	Key Findings
Technical barriers	The limited availability of hydrogen storage systems that meet safety standards and can be integrated with existing infrastructure is a significant technical barrier.
Regulatory barriers	The lack of clear regulatory frameworks for hydrogen storage and transportation creates uncertainty for investors and industry stakeholders.
Transportation	Various hydrogen transportation methods are available, including pipeline, truck, and ship transportation, with pipeline transportation being the most widely used.
Storage methods	A range of hydrogen storage methods are available, including compressed gas, liquid, and solid-state storage. Each method has its advantages and disadvantages, and there is no clear consensus on the best method for hydrogen storage.
Infrastructure development	Developing the necessary infrastructure for hydrogen storage, transportation, and distribution is a significant challenge, but several countries are taking steps to promote the development of a hydrogen economy.

The concept of hydrogen storage for energy applications is not a new one and has been the subject of considerable research over time. A successful and economical hydrogen storage mechanism is crucial for the widespread use of hydrogen as a sustainable energy source. To this end, various storage techniques have been developed, with gaseous, liquid, solid-state, and hybrid storage systems being the four primary subtypes of hydrogen storage, as identified by Usman (2022).

Among these storage methods, gaseous storage is the most extensively developed and commonly used, which involves compressing hydrogen gas into high-pressure tanks. On the other hand, liquid hydrogen storage is an effective approach for applications requiring high energy density. While metal hydrides and chemical hydrogen storage are two examples of solid-state storage systems that have shown promising results in laboratory studies, they are still in the developmental stages.

The development of effective hydrogen storage systems is critical for the transition to a sustainable energy future. The use of hydrogen as a clean energy source is gaining momentum, and the practical and affordable storage of hydrogen is a critical challenge that must be addressed. As such, continued research and development in the field of hydrogen storage technologies is essential to pave the way for the widespread adoption of hydrogen as a renewable energy source.

Finally, hybrid storage systems, which combine two or more storage methods, have the potential to overcome the limitations of individual storage methods.

The successful integration of hydrogen into the current energy system requires the development of infrastructure for hydrogen production, transportation, storage, and distribution. Abdalla et al. (2018) highlight that one of the technological challenges associated with hydrogen storage integration is the construction of a reliable and effective storage system. Additionally, optimizing storage capacity and integrating storage systems with other energy systems are also critical technological considerations.

Despite the potential benefits of hydrogen as an energy source, there are substantial technological and legal obstacles to its integration into current energy infrastructure. As noted by Ahluwalia et al. (2023), unclear laws for hydrogen infrastructure pose a significant challenge for the widespread adoption of hydrogen storage technologies.

The integration of hydrogen storage into the current energy infrastructure requires extensive collaboration and cooperation among policymakers, industry leaders, and other stakeholders. Such efforts must address the technological and legal challenges associated with hydrogen storage integration and ensure the development of a robust and reliable infrastructure. With continued investment and research in the field of hydrogen storage technologies, the successful integration of hydrogen into the energy system is within reach, promising a cleaner and more sustainable energy future.

The transportation of hydrogen from its manufacturing site to storage facilities and final consumers presents a significant challenge in the widespread adoption of hydrogen as an energy source. Gaseous hydrogen requires compression for transportation, which can be a costly process. Conversely, the transportation of liquid hydrogen requires cryogenic temperatures and specialized infrastructure, making it challenging and expensive.

In response to these challenges, innovative approaches are being explored to facilitate the transportation of hydrogen. Usman (2022) highlights several potential solutions, including the use of hydrogen pipelines, hydrogen fuel cell vehicles, and hydrogen shipping.

Hydrogen pipelines have the potential to transport large quantities of hydrogen over long distances efficiently. However, the construction of hydrogen pipelines requires significant investment and poses several technological challenges.

Hydrogen fuel cell vehicles are an alternative approach that can transport hydrogen to various locations while also serving as a source of power for transportation. However, the limited availability of hydrogen refueling stations and the cost of fuel cell vehicles remain significant barriers to their widespread adoption.

Hydrogen shipping, particularly for long distances or to remote locations, is another promising approach that can overcome the challenges associated with hydrogen transportation. However, the development of specialized infrastructure and the high cost of shipping remains a significant hurdle to the widespread adoption of this method.

The development of cost-effective and efficient transportation solutions is critical for the integration of hydrogen into the current energy system. Continued research and innovation in hydrogen transportation technologies can pave the way for a more sustainable and cleaner energy future.

5. Conclusion and Recommendation

5.1 Conclusion

This report presents a strategic analysis of past and modern hydrogen storage methods and prospects for its future. The literature review revealed that hydrogen storage remains a critical challenge in the development of a hydrogen-based economy. Several hydrogen storage methods have been proposed, including compressed gas storage, cryogenic storage, and solid-state storage. However, each of these methods has its own advantages and limitations, which depend on various factors such as energy density, efficiency, safety, and cost.

The methodology involved a comprehensive review of the existing literature on hydrogen storage methods, and the findings of the study indicate that hydrogen storage technologies are continuously evolving. Recent developments in hydrogen storage technologies such as nanotechnology, materials science, and innovative designs have opened up new possibilities for the efficient and safe storage of hydrogen.

In conclusion, the findings of this study indicate that hydrogen storage technologies are continuously evolving, and new technologies are emerging that offer promising solutions to the challenges of hydrogen storage. Future research in this area should focus on developing advanced materials and innovative designs that can improve the efficiency and safety of hydrogen storage. Overall, this report provides valuable insights into the current state of hydrogen storage methods and prospects for its future, which can guide policymakers and stakeholders in making informed decisions regarding the development of hydrogen-based technologies.

5.2 Recommendation

Based on the findings and discussions presented in the report, it is recommended that further research and

development be undertaken in the area of hydrogen storage methods to fully realize the potential of hydrogen as a clean energy source. This should include continued efforts to improve the efficiency, safety, and cost-effectiveness of existing hydrogen storage methods, as well as the exploration of new and innovative approaches. And application of hydrogen energy to existing infrastructure.

Also recommended that policymakers and industry stakeholders prioritize the development and deployment of hydrogen infrastructure to support the widespread adoption of hydrogen as a clean energy source. This should include investments in the production, storage, and distribution of hydrogen, as well as incentives to encourage the use of hydrogen in a variety of applications, including transportation, heating, and electricity generation.

References

- Abdalla, A. M., Hossain, S., Nisfindy, O. B., Azad, A. T., Dawood, M., & Azad, A. K., (2018). Hydrogen production, storage, transportation and key challenges with applications: A review. *Energy conversion and management*, 165, 602-627. <https://doi.org/10.1016/j.enconman.2018.03.059>.
- Ahluwalia, R. K., Roh, H. S., Peng, J. K., Papadimas, D., Baird, A. R., Hecht, E. S., ... & Aceves, S. M., (2023). Liquid hydrogen storage system for heavy duty trucks: Configuration, performance, cost, and safety. *International Journal of Hydrogen Energy*. <https://doi.org/10.1016/j.ijhydene.2023.01.176>.
- Creswell, J. W., & Poth, C. N., (2017). Qualitative inquiry and research design: Choosing among five approaches. Sage publications. <https://doi.org/10.4135/9781506335193>.
- Durbin, D. J., & Malardier-Jugroot, C., (2013). Review of hydrogen storage techniques for on board vehicle applications. *International journal of hydrogen energy*, 38(34), 14595-14617. <https://doi.org/10.1016/j.ijhydene.2013.08.095>.
- Erdemir, D., & Dincer, I., (2023). Development and assessment of a novel hydrogen storage unit combined with compressed air energy storage. *Applied Thermal Engineering*, 219, 119524. <https://doi.org/10.1016/j.applthermaleng.2022.117997>.
- Jensen, J. O., Vestbø, A. P., Li, Q., & Bjerrum, N. J., (2007). The energy efficiency of onboard hydrogen storage. *Journal of Alloys and Compounds*, 446, 723-728. <https://doi.org/10.1016/j.jallcom.2007.02.066>.
- Lee, J. W., & Yoon, Y. G., (2019). Carbon materials for hydrogen storage. *Carbon Letters*, 29(1), 1-11. doi: 10.1007/s42823-018-0002-6.
- Niaz, S., Manzoor, T., & Pandith, A. H., (2015). Hydrogen storage: Materials, methods and perspectives. *Renewable and Sustainable Energy Reviews*, 50, 457-469. <https://doi.org/10.1016/j.rser.2015.05.004>.
- Prabhukhot Prachi, R., Wagh Mahesh, M., & Gangal Aneesh, C., (2016). A review on solid state hydrogen storage material. *Adv. Energy Power*, 4(11), 1-8. <https://doi.org/10.4172/2325-9795.1000159>.
- Šarić, M., Grubišić, R., & Omanović, S., (2021). Metal hydrides for hydrogen storage: An overview of recent advances and future prospects. *Renewable and Sustainable Energy Reviews*, 137, 110574. doi: 10.1016/j.rser.2020.110574.
- Saunders, M. N., Lewis, P., & Thornhill, A., (2018). *Research methods for business students*. Pearson Education Limited. <https://doi.org/10.1016/C2016-0-04032-3>.
- Tashakkori, A., & Teddlie, C. (Eds.), (2010). SAGE handbook of mixed methods in social & behavioral research. Sage publications. <https://doi.org/10.4135/9781506335193>.
- Usman, M. R., (2022). Hydrogen storage methods: Review and current status. *Renewable and Sustainable Energy Reviews*, 167, 112743. <https://doi.org/10.1016/j.rser.2020.112743>.
- Zhang, F., Zhao, P., Niu, M., & Maddy, J., (2016). The survey of key technologies in hydrogen energy storage. *International Journal of Hydrogen Energy*, 41(33), 14535-14552. <https://doi.org/10.1016/j.ijhydene.2016.06.145>.
- Züttel, A., (2003). Materials for hydrogen storage. *Materials Today*, 6(9), 24-33. [https://doi.org/10.1016/S1369-7021\(03\)00931-1](https://doi.org/10.1016/S1369-7021(03)00931-1).

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