Large scale of green hydrogen storage: opportunities and challenges

Nan Ma[1], Weihua Zhao[2], Wenzhong Wang[2], Haiqin Zhou[3*]

1 School of Engineering, Lancaster University, Lancaster, LA1 4YW, United Kingdom

2 School of Mechanical Engineering, Beijing Institute of Technology, Beijing, 100081, PR China

3 Chemical and Environmental Engineering, University of Nottingham, Nottingham, NG7 2RD, United Kingdom

Corresponding author: Dr. Haiqin Zhou, e-mail: Haiqin.Zhou1@nottingham.ac.uk

Abstract

The transition from fossil fuels to renewable energy sources is seen as an essential step toward a more sustainable future. Hydrogen is being recognized as a promising renewable energy carrier to address the intermittency issues associated with renewable energy sources. For hydrogen to become the "ideal" low or zero-carbon energy carrier, its storage and transportation shortcomings must be addressed. This paper will provide the current large-scale green hydrogen storage and transportation technologies, including ongoing worldwide projects and policy direction, an assessment of the different storage and transportation methods (compressed hydrogen storage, liquid hydrogen, blending hydrogen into natural gas pipelines, and ammonia as green hydrogen carrier), as well as economic factors that influence the viability of large-scale green hydrogen storage and transportation. The results of our study highlight several significant findings concerning the cost, challenges, and potential advancements in the green hydrogen storage and transportation field. Our analysis demonstrates that the cost associated with storing and transporting green hydrogen is anticipated to decrease over time due to technological advancements and economies of scale being achieved. However, the commercialization of this technology requires addressing challenges related to storage methods, transportation modes, efficiency optimization, and technology adoption. For example, our research highlights the need for thorough technical and economic evaluations of using salt caverns for hydrogen storage. The efficiency of hydrogen storage and transportation utilizing existing infrastructure, such as storage tanks and natural gas pipelines. By elucidating these aspects, our research contributes valuable insights that can guide future endeavors toward achieving a sustainable and economically viable green hydrogen industry.

Keywords: Power-to-gas; Green hydrogen storage and transport; Policy direction of green hydrogen; Economic evaluation

1.Introduction

Fossil fuels, including coal, oil, and gas, have been the world's primary energy source for over a century. According to the International Energy Agency (IEA), in 2020, fossil fuels accounted for approximately 84% of the world's primary energy consumption[1]. However, the widespread use of fossil fuels has led to significant environmental problems, which are responsible for around 78% of global greenhouse gas emissions[2].

As the world becomes more aware of the negative impacts of climate change and the finite nature of fossil fuels, there is increasing recognition of the need to transition to renewable energy sources. According to the IEA, in 2021, renewable energy sources accounted for approximately 12.9% of the world's total final energy consumption. They will to grow rapidly, accounting for about 90% of the increase in global power capacity through 2025[3]. Currently, renewable energy from solar and wind is attracting attention because it has the potential to provide a sustainable, cost-effective, and environmentally friendly power source that can help reduce greenhouse gas emissions and mitigate the impacts of climate change[4]. However, renewable energy from solar and wind are intermittent and are often distant from end-use appliances. They only generate electricity when the sun is shining or the wind is blowing, which can make it challenging to provide a constant supply of electricity to meet the demands of consumers.

Hydrogen is increasingly being recognized as a promising renewable energy carrier that can help to address the intermittency issues associated with renewable energy sources due to its ability to store large amounts of energy for a long time [5-7]. This process of converting excess renewable electricity into hydrogen for storage and later use is known as "power-to-gas" or "power-to-hydrogen"[8]. It provides a way to use renewable energy sources more effectively, enabling a more efficient and reliable transition to a low-carbon energy system. The timeline of significant milestones for the development of the renewable hydrogen application is shown in Figure 1. In the 1970s, hydrogen was proposed as a fuel for transportation and various applications. It took several decades of research, technological development, and policy initiatives to advance the practical applications of hydrogen in multiple sectors, including transportation, industrial processes, and energy storage. However, green hydrogen transportation is still in its early stages of development.

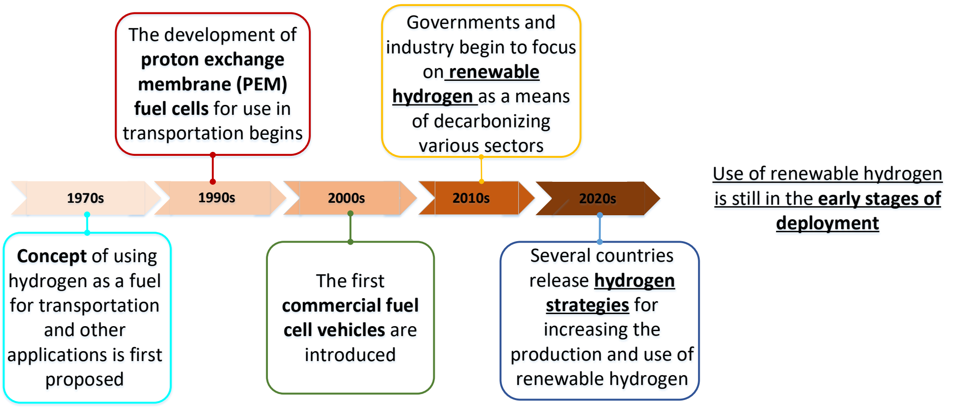

Figure 1. Timeline of important milestones for the development of the renewable hydrogen application

Previous works might not have thoroughly evaluated the scalability of their proposed green hydrogen storage solutions. This could lead to uncertainties about whether the proposed methods can effectively accommodate the demands of large-scale storage applications. In addition, the feasibility and success of large-scale green hydrogen storage are influenced by market dynamics, policy support, and regulatory frameworks. Previous works might not have sufficiently addressed how these external factors could impact the implementation and viability of their proposed solutions. Addressing these limitations in future research will contribute to a more comprehensive understanding of the challenges and opportunities associated with large-scale green hydrogen storage, ultimately leading to more effective and informed decision-making in this critical area.

This work is aimed at a systematic review of large-scale green hydrogen storage and transportation technology. First, it explores the ongoing worldwide projects and policy direction of large-scale green hydrogen storage and transportation technology. Then, the different storage and transportation methods (compressed hydrogen storage, liquid hydrogen, blending hydrogen into natural gas pipelines and ammonia as a large-scale green hydrogen carrier) are analyzed, as well as an evaluation of the challenges and opportunities for large-scale deployment. In addition, this review also includes an analysis of the economic factors that influence the viability of large-scale green hydrogen storage and transportation, including an assessment of the costs associated with different storage and transportation methods.

2. Current developments

2.1 Background

Renewable energy sources are experiencing a period of rapid growth to achieve the target of net-zero CO_2 emissions by 2050. According to the International Energy Agency (IEA), about 30% of the world's electricity comes from renewables, including hydropower, solar, wind and others in 2022[1]. However, renewable energy from solar and wind intermittency, which stems from the dependence on weather conditions and natural variability, presents a notable challenge to their effective integration into the energy grid[9-11]. In addition, the locations of the renewable energy effectively produced are often distant from the end-use appliances[12]. As the world looks to transition to clean energy, a largescale energy storage option is required to operate a renewable energy economy.

Hydrogen is increasingly seen as a promising clean energy carrier that has the potential to help reduce both CO_2 emissions and air pollutants associated with transportation [13, 14]. When excess renewable energy is produced, it can be used to split water into hydrogen and oxygen through electrolysis. The hydrogen produced can then be stored and used later, which provides a way to store large amounts of energy for extended periods[15-17]. Unfortunately, for hydrogen to become the “ideal” low or zero-carbon energy carrier, its shortcomings in storage and transportation need to be addressed, such as transportation of hydrogen[18] and storage of hydrogen[19]. Presently, numerous green hydrogen storage and transportation projects are underway worldwide, focusing on developing large-scale green hydrogen storage technology to support the growth of the renewable energy economy, as shown in Figure 2. No less than 228 large-scale projects have been announced, with 85% located in Europe, Asia, and Australia. And the total investments will reach more than $300 billion in spending through 2030. Next, we will discuss some green hydrogen storage projects underway worldwide.

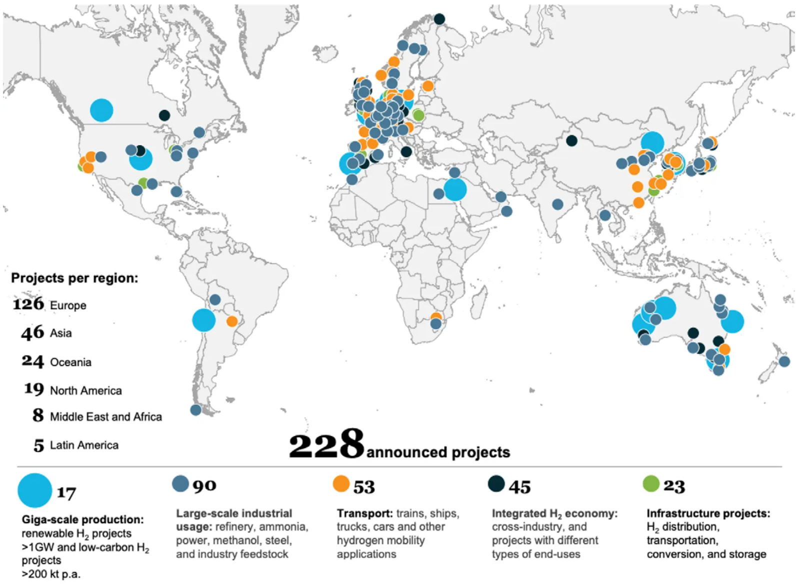

Figure 2. Key hydrogen projects that have been announced globally © Hydrogen Council [20]

2.2 World-wide green hydrogen storage and transportation projects

Several green hydrogen storage projects are underway worldwide, as shown in Table 1. Energiepark Mainz is funded by German Federal Ministry for Economic Affairs and Energy to investigate and demonstrate large-scale hydrogen production from renewable energy for various use cases. The produced hydrogen is compressed by an ionic compressor, stored onsite, filled into trailers and injected into the natural gas grid. They also demonstrate that the hydrogen produced can be stored and converted to electricity later or used for other purposes like mobility, heating, or industrial feedstock. ENERGIX is another project contributing to realizing the government's long-term energy and climate policy but also helps to support other important policy areas such as transport and business development. They compared the energy efficiency, CO_2 footprint and cost of liquefied hydrogen (LH_2) and ammonia as H_2-based energy carriers. They found LH_2 chain is more energy efficient and has a smaller CO_2 footprint (20 and 23 kg-CO_2/MWhth for Europe and Japan, respectively) than the NH_3 chain. Power-to-gas Project (2018) is North America's first multi-megawatt power-to-gas facility using renewably-sourced hydrogen. In this project, renewable hydrogen produced will be injected into the natural gas grid. In 2022, Mitsubishi Power Americas and Magnum Development are set to begin construction on a 300 GWh underground storage facility in the US state of Utah. The innovative project will use Utah’s unique geological salt domes to store the produced green hydrogen underground in two gigantic salt caverns with capacities of 150 GWh. The Aldbrough Hydrogen Storage project, which is supported by SSE Thermal and Equinor in the UK, is the latest being developed to carry out a feasibility study to assess the design of the hydrogen storage caverns at Aldbrough as well as the planned pipeline to transport hydrogen. The France government supports Hydrogen Pilot Storage to contribute to the French regional hydrogen strategy, along with other significant projects, by making possible the development of a local hydrogen hub to reduce atmospheric and noise pollution. Ammonia as a hydrogen carrier, which is supported by the UK’s Department for Business, Energy and Industrial Strategy (BEIS), is to demonstrate how ammonia can act as a profitable hydrogen carrier. From the above projects, it is worth noting that hydrogen stores at high pressure or in liquid form in some technology. In the meantime, natural gas or green ammonia is seen as a less technically challenging and currently commercially viable type of hydrogen transportation project, which is expected to play a critical role in the transition to a more sustainable and low-carbon energy system.

Table 1 Green hydrogen storage projects around the world

Project	Country	Year	Work topic

Energiepark Mainz	Germany	2015	Demonstrate large-scale hydrogen production from renewable energy for a variety of use cases
ENERGIX	EU	2013	Sustainable utilization and efficient consumption of renewable energy resources
Power-to-Gas	America	2018	Build the future of hydrogen with its electrolyzer technology
Underground Hydrogen Storage	America	2022	Creates a hydrogen hub that will store hydrogen which will be used as part of the fuel mixture for a 840 MW hydrogen blend capable gas turbine combined cycle power plant
Aldbrough Hydrogen Storage project	UK	2021	Create a hydrogen storage facility with an initial expected capacity of at least 320 Gigawatt hours (GWh)
Hydrogen Pilot Storage	France	2021	Use salt cavern storage to connect hydrogen injection by electrolysis to industrial and mobility uses.
Ammonia to green hydrogen	UK	2019	Demonstrate a new ammonia cracking technology in producing pure hydrogen
Summary	Hydrogen transportation options: (1) compressed hydrogen gas; (2) liquid hydrogen; (3) hydrogen injected into the natural gas grid; (4) ammonia as a spatial energy vector		

2.3 Policy direction of green hydrogen

As of 2019, hydrogen was being promoted in at least 15 countries (Japan, South Korea, China, the United States, etc.) and the European Union with supporting policies, standardization processes and national strategies[21]. The U.S. Department of Energy launched the "Hydrogen Shot" initiative in 2021 to reduce the cost of clean hydrogen production to make it more competitive with other energy sources and to advance the use of hydrogen as a clean and sustainable energy carrier[22]. The European Commission released the "Hydrogen Strategy for a Climate-Neutral Europe" in 2020 as part of the European Green Deal[23]. The hydrogen strategy plays a pivotal role in this transition by outlining the EU's approach to harnessing the potential of hydrogen as a clean energy carrier. Japan launched the "Basic Hydrogen Strategy" in 2017, aiming to establish a society where hydrogen plays a central role in energy systems[24]. China has integrated hydrogen into its energy and industrial policies, focusing on green hydrogen production and fuel cell applications[25]. South Korea introduced its "Roadmap for Hydrogen Economy" in 2019, with plans to become a leading player in the global hydrogen market[26].

Although governments worldwide are beginning to recognize the potential of green hydrogen as a clean energy source and are starting to develop policies and initiatives to support its growth, significant work remains needed. Most importantly, there is very little legislation that relates explicitly to hydrogen. As the hydrogen economy continues to grow and hydrogen becomes more widely adopted, it is likely that specific regulations and standards will be developed to support its safe and efficient use. And also, each country needs to define the prospects and pathways for future large-scale trading routes, not only from a techno-economic point of view but also to solidify the commercial and political relationships between the countries involved. Second, an Environmental Impact Assessment (EIA) is required to assess the potential environmental impacts if hydrogen is to be stored on-site or if pipelines are carrying hydrogen, which would also consider the potential effects on air quality, water resources, and wildlife habitat. In addition, develop market mechanisms and incentives to encourage the adoption of hydrogen in transportation, industry, and other sectors, such as offering subsidies to companies that produce hydrogen and invest in hydrogen infrastructure development. Governments can help create a green hydrogen market by providing policy incentives and driving innovation in this critical field.

3. Large-scale green hydrogen storage and transportation technology

Large-scale green hydrogen storage and transportation are crucial challenges for developing a sustainable energy economy. However, it faces challenges, including cost-effectiveness[27], efficiency[28], technology development[29], and policy support[30] (In this paper, we consider storing 500 tonnes of hydrogen for one month as a demonstration[31]).

Currently, most hydrogen is produced and used locally. Since the use of hydrogen as a clean energy source becomes more widespread, there will be a need for efficient and cost-effective methods of storing and transporting large quantities of hydrogen over long distances. Various technologies are available, including some that have been applied on a large scale for decades, for example, compressed hydrogen gas, liquid hydrogen, blending hydrogen into natural gas pipelines and ammonia for hydrogen storage, as shown in Figure 3. The coverage for all the above technologies, including the mature and immature ones along with hazards will be provided hereafter.

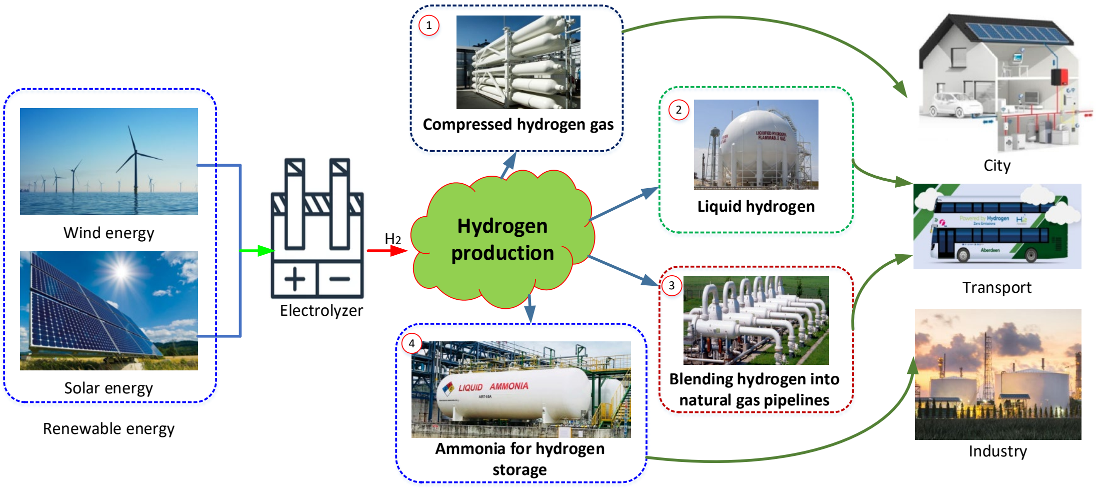

Figure 3 Large-scale green hydrogen storage and transportation technology

3.1 Compressed hydrogen storage

Compressed hydrogen storage involves storing hydrogen gas at high pressure, typically between 350 and 700 bar, which is relatively simple and completed quickly.

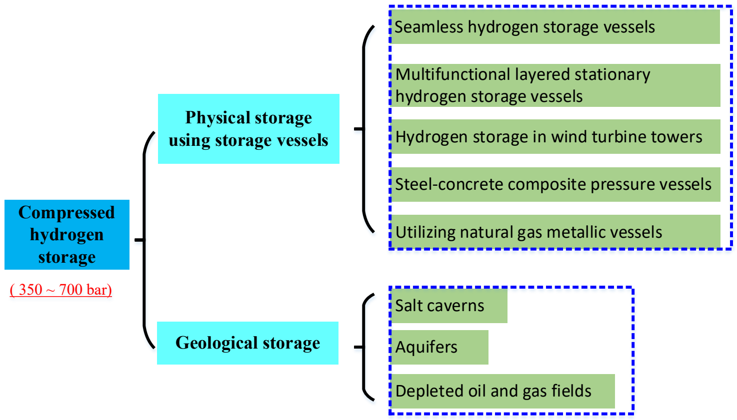

Figure 4 Compressed hydrogen storage technology

It is a technology to buffer energy generated at times of overcapacity for use at another time which means that energy generated during periods of low demand (off-peak) can be utilized to meet high demand (peak load) periods. Currently, two distinct methods exist for compressed hydrogen storage, including physical storage using storage vessels and geological storage, as shown in Figure 4.

3.1.1 Physical storage using storage vessels

Physical storage using storage vessels is the most mature hydrogen storage technology. The technology involves compressing hydrogen gas to high pressures and storing it in high-pressure storage vessels (700 bar), such as seamless hydrogen storage vessels[32], multifunctional layered stationary hydrogen storage vessels[33], hydrogen storage in wind turbine towers[34], steel-concrete composite pressure vessels[35] and utilizing natural gas metallic vessels[36].

Table 2 Physical storage using storage vessels

Physical storage using storage vessels	Application	Disadvantage
Seamless hydrogen storage vessel	Hydrogen fuel stations	Limited storage capacity
Multifunctional layered stationary hydrogen storage vessels	Stationary applications	Limited storage capacity
Hydrogen storage in wind turbine towers	The generated hydrogen can be stored within the wind turbine tower	Structural integrity of wind turbine towers must be carefully evaluated
Steel-concrete composite pressure vessels	Stationary hydrogen storage	Vessels are larger and heavier than other types
Utilizing natural gas metallic vessels	Transportation sector and industrial settings	Evaluate the suitability of the metallic vessels for hydrogen storage
Summary	1. Currently, the demand for high-pressure storage vessels is relatively low 2. As the use of hydrogen continues to grow, particularly for fuel cell vehicles, there may be a shortage of high-pressure storage vessels in the short-term.	

The choice of storage vessel type depends on the specific application, as shown in Table 2. Seamless hydrogen storage vessels are designed to store hydrogen gas at high pressures and these containers are manufactured as a single unit without welded joints, which can enhance structural integrity and safety. They are commonly used in fuel cell vehicles for the advantage of their high strength-to-weight ratio. However, they also have limited storage capacity due to their smaller size [37] (because of the diameter limitation of seamless thick-walled tubes) and be expensive to manufacture[38]. Multifunctional layered stationary hydrogen storage vessels can be designed to meet specific performance requirements, such as high-pressure storage or high-temperature resistance. It is designed to store hydrogen gas for stationary applications while incorporating multiple layers of functionality to optimize efficiency and safety. Currently, the world's first 77 MPa multifunctional layered stationary hydrogen storage vessel with a volume of 2.5 m^3 was developed by Hexagon Purus in 2020[39]. Although it is highly durable and resistant to corrosion, which helps to ensure a long service life, it also has limited storage capacity due to its smaller size[40]. Hydrogen storage in wind turbine towers is a relatively new concept that uses the hollow interior of wind turbine towers to store hydrogen gas. In this process, the excess electricity the wind turbine generates is used to power an electrolyzer that splits water into hydrogen and oxygen. The hydrogen produced is then stored inside the tower, which can serve as a large-scale storage vessel. However, the structural integrity of wind turbine towers, such as modifications to the tower's design to withstand the additional weight and pressure of storing hydrogen gas and material selection, must be carefully evaluated to ensure safety[41]. Steel-concrete composite pressure vessels use steel as the structural component of the vessel and concrete as the protective outer layer, making them suitable for various applications[35, 42]. These vessels can be used for stationary hydrogen storage systems, industrial hydrogen storage, or applications requiring hydrogen as fuel or feedstock. However, steel-concrete composite pressure vessels are typically larger and heavier than others. Utilizing natural gas metallic vessels for hydrogen storage involves repurposing existing natural gas storage infrastructure to store hydrogen gas. This approach uses metallic containers, such as steel or aluminum tanks, initially designed for natural gas storage but can also be used for hydrogen storage with some modifications. It is a relatively low-cost option compared to other types of hydrogen storage vessels. However, it is essential to carefully evaluate the suitability of the metallic vessels for hydrogen storage and to implement appropriate safety measures to prevent accidents or leaks.

The demand for high-pressure storage vessels is relatively low compared to the natural gas industry. However, as the use of hydrogen continues to grow, particularly for fuel cell vehicles (According to the International Energy Agency (IEA), as of 2020, there were approximately 25,000 fuel cell vehicles on the road worldwide[43]), there may be a shortage of high-pressure storage vessels in the short-term. To address this issue, ongoing research and development efforts are focused on developing more efficient and cost-effective manufacturing techniques for high-pressure storage vessels.

3.1.2 Geological storage

Another storage technology uses geological formations such as salt caverns, aquifers, and depleted oil and gas fields to store hydrogen, as shown in Figure 5. The coverage for all the above technologies, including the specific application and disadvantage will be discussed hereafter.

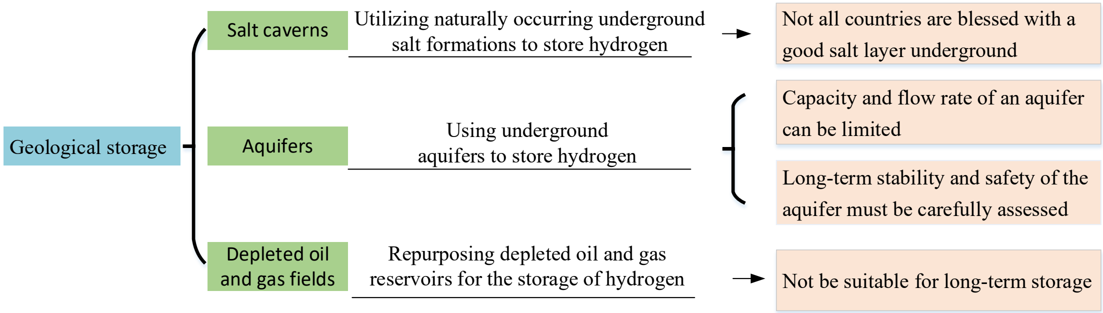

Figure 5 Geological storage technology

(1). Salt caverns

Salt caverns are being considered as a potential storage option for storing large quantities of hydrogen gas. The underground salt deposits in the world are shown in Figure 6. It's worth noting that most of the largest salt deposits are found in North America and Europe. However, only a few large-scale underground salt caverns are currently used for hydrogen storage. For example, in Europe, the EU's Hydrogen Strategy aims to deploy at least 40GW of electrolyzes by 2030 and create a network of hydrogen infrastructure across Europe, including developing underground storage facilities[44]. In the US, the Department of Energy has identified hydrogen storage as a critical technology for the widespread adoption of hydrogen as a fuel and is funding research into developing new storage technologies, including underground storage[45]. In Germany, the AquaPort project in Hamburg aims to convert a former gas reservoir in a salt cavern into a large-scale hydrogen storage facility. The project is part of Germany's efforts to integrate hydrogen into its energy transition strategy[46].

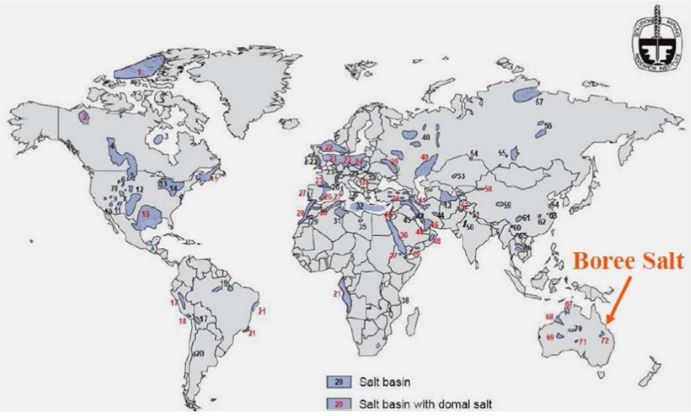

Figure 6 Underground salt deposits in the world[47]

The development of large-scale underground salt caverns for hydrogen storage is a complex process; several challenges need to be addressed before it can be used commercially, as shown in Figure 7. First, where to locate a salt cavern? The location of the salt cavern is an essential factor in determining the feasibility of hydrogen storage. It must have thick layers of salt free of impurities, low water content and be close to hydrogen production to minimize transportation costs and ensure efficient delivery. Second, what is operating pressure? The working pressure for hydrogen storage in salt caverns typically ranges from 700 to 900 bar[48]. The cavern's depth affects the maximum force that can be safely maintained, while the geology of the site can affect the minimum pressure that can be maintained without causing instability or other safety concerns. In addition, higher operating pressures can increase the storage capacity of the cavern but require more energy for compression, which can increase the cost[49, 50]. Overall, selecting the appropriate operating pressure for a salt cavern used for hydrogen storage requires careful consideration of geological, safety and cost to ensure the system can operate safely and efficiently. Third, what cavern volume and what number of caverns? The cavern volume is limited by the thickness of the salt layer, which will vary depending on the location and geological characteristics of the site. And the number of caverns required for hydrogen storage is also limited by the lateral extension of the salt body. In addition, the flow rate for hydrogen injection or withdrawal is also another critical challenge. It will be determined by factors such as the maximum and minimum operating pressures, the cavern's capacity, and the storage system's regulatory requirements. If the flow rate is too high, it can cause damage to the cavern or equipment, while a flow rate that is too low may not meet the demand for hydrogen.

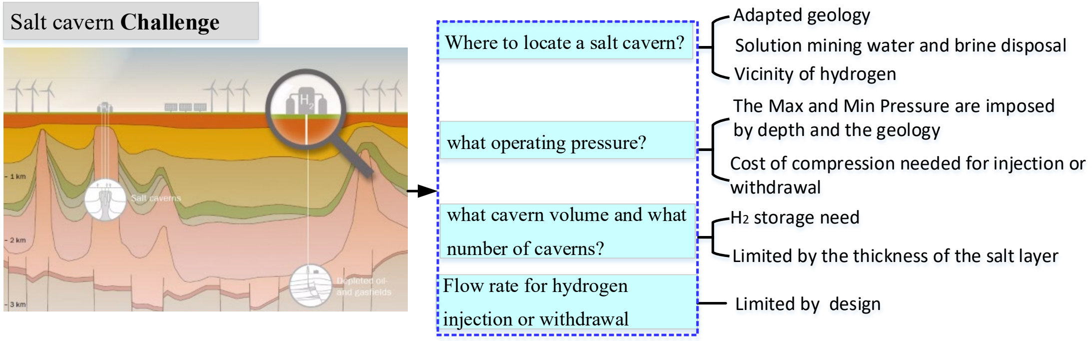

Figure 7 challenges of underground salt caverns for hydrogen storage

However, not all countries are blessed with a good salt layer underground. Aquifers have been identified as a potential storage option for hydrogen, particularly in areas where suitable geological formations for salt caverns are unavailable[51, 52]. The process of using aquifers for hydrogen storage is similar to the method used for natural gas storage, which involves injecting hydrogen into underground water-bearing formations, known as aquifers, and extracting the hydrogen when needed. N. Heinemann found that hydrogen storage in open saline aquifers is a promising alternative to storage in depleted gas fields[53]. Seyed’s research showed that aquifer storage is the most environmentally-friendly type of underground H2 storage and it offers a significant opportunity for cost-effective hydrogen storage[54]. A. Sainz-Garcia illustrated that underground hydrogen storage in saline aquifers can be operated with reasonable recovery ratios. A maximum hydrogen recovery ratio of 78%, representing a global energy efficiency of 30%, has been estimated by a 3D multiphase flow model[55].

However, several challenges must be addressed to make this technology viable at scale. For example, an aquifer's capacity and flow rate can be limited, which may impact the hydrogen storage and extraction rate. Katarzyna found that although the flow of hydrogen decreases with the increase in the length of the first filling period for the development of hydrogen storage, the total capacity of the storage site always rises with the growth of this period length[56]. Additionally, the long-term stability and safety of the aquifer must be carefully assessed to ensure that hydrogen can be stored safely and securely.

Another storage technology is using depleted oil and gas fields, which are considered potential storage options for hydrogen due to a large storage capacity for hydrogen [57]. Maksim's research shows that injecting a 30% hydrogen-formation gas mixture results in a varying hydrogen fraction in the withdrawn gas by injecting pure hydrogen into the gas, oil, and water zones[58]. Mojdeh demonstrated that more lateral spread of the H_2 when compared to CO_2 and natural gas with a need for special containment in H_2 projects and the experience with CO_2 and natural gas storage cannot be simply replicated with H_2[59]. However, using depleted oil and gas fields may not be suitable for long-term storage due to the potential for hydrogen to leak out of the rock formations over time. It is worth noting that the cost of developing and operating underground hydrogen storage facilities can be higher than for above-ground storage options, particularly for smaller facilities. However, the benefits of underground storage, including higher storage capacity and increased safety, make it a promising option for meeting the growing demand for hydrogen as a fuel.

Compressed hydrogen storage offers a range of benefits that make it a promising method of storing hydrogen, such as high energy density and fast refueling times, as shown in Figure 8. However, compressed hydrogen storage can experience energy losses due to various factors. One of the most significant factors is the compression process requires energy to be inputted into the system. This energy input results in an increase in the temperature of the gas, which can lead to heat loss to the surroundings. Similarly, when the compressed hydrogen is released from the storage tank, it also requires energy input, which can result in additional energy losses due to heat transfer to the surroundings. Furthermore, energy losses can be associated with the transportation of compressed hydrogen, as the energy required to transport the heavy and bulky storage tanks can be significant. The overall efficiency of compressed hydrogen storage can range from 70% to 90%[60]. Therefore, more efforts must be made to minimize these energy losses and improve the efficiency of compressed hydrogen storage systems.

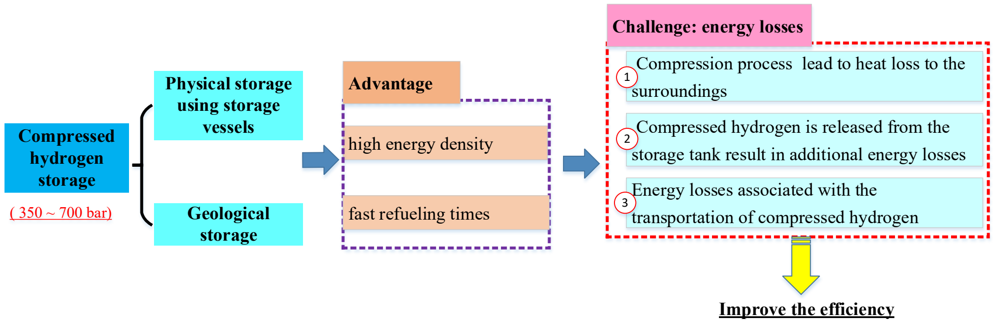

Figure 8 challenges of compressed hydrogen storage for hydrogen storage

3.2 Liquid hydrogen

Among these large-scale green hydrogen storage systems, liquid hydrogen (LH_2) is considered the most promising in terms of several advantages, such as large gravimetric energy density (2.7 times larger than gasoline) and low volumetric densities (3.7 times lower than gasoline). The largest LH_2 storage facility in the world is the Air Liquide hydrogen plant in Kawasaki, Japan, which has a storage capacity of 1,250 tons[61].

To liquefy hydrogen, it must be cooled to cryogenic temperatures (typically below -253°C) through a liquefaction process, as shown in Figure 9. Then the LH_2 is dispensed to delivery trucks and transported to distribution sites where it is vaporized to a high-pressure gaseous product for dispensing. LH_2 has been adopted for commercial use in various industries, including aerospace, automotive, and energy production. Although LH_2 can provide many advantages, its uses are restricted in some parts, such as the energy-efficient liquefaction process, the loss of LH_2 through boil-off during storage and the safety of large-scale green hydrogen storage in liquid form.

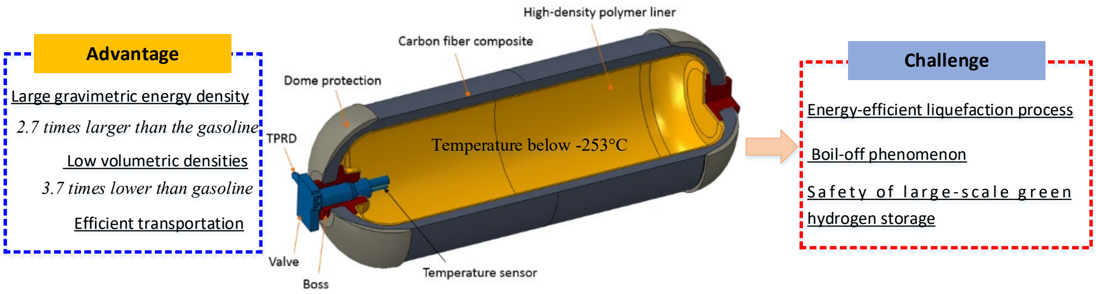

Figure 9 Liquid hydrogen storage technology

The liquefaction of hydrogen requires a lot of energy, as hydrogen has a shallow point of -252.87°C (-423.17°F) and must be cooled to a very low temperature to liquefy[62-64]. Therefore, to allow LH_2 to be successful from the perspective of future energy demands, the specific energy consumption (SEC, which refers to the amount of energy required to produce, transport, and store a unit of LH2) should be reduced, and the exergy efficiency should be increased. Various conceptual designs have been proposed with SEC values in the range of 5 to 8 kWh/kg_{LH_2} and exergy efficiencies are around 40% to 60%. Cardella presents a roadmap for the scale-up of hydrogen liquefaction technology, from state-of-the-art plants to newly developed large-scale liquefaction processes. The results show that SEC between 5.9 and 6.6 kWh per kg LH_2 within five years for a 100 tpd (tons per day) LH_2 plant and specific liquefaction costs were reduced by about 60% by upscaling from 5 to 50 tpd[65]. Yunus developed a novel hydrogen liquefaction process that is based on helium-cooled hydrogen liquefaction cycles. They pointed out that the energy and exergy efficiencies of the liquefaction process are found to be 70.12% and 57.13%, respectively[66]. Shaimaa proposed a novel approach of a large-scale hydrogen liquefaction system combined with geothermal and isobutene power plants. It is found that reducing the hydrogen mass flow rate to 9 kg/s and the high pressure to 20 bar reduces the SEC to 4.7 kWh/kg-LH_2. The SEC, energy and exergy efficiencies are 6.47 kWh/kg-LH_2, 19.8% and 63.7%, respectively[67]. Although efforts to improve the efficiency of conceptual plants have led to the proposal of several modern and more efficient configurations (the Linde-Hampson system, the Brayton cycle liquefaction system), most current liquid hydrogen liquefaction plants still rely on the pre-cooled Claude system, which has not undergone significant improvements in the past 50 years.

Another important challenge related to the storage and transport of LH_2 is the boil-off phenomenon. When the temperature of the LH_2 reaches its boiling point, it begins to evaporate and convert to a gas, which can result in a loss of fuel and a reduction in the pressure and temperature of the system. Currently, efforts have been made to develop the Zero-boil off (ZBO) technology which is designed to reduce or eliminate this boil-off by using a combination of insulation and heat management techniques. Saif developed a novel model which considers the heat transfer from the vapor to the liquid phase to predict self-pressurization and boil-off rates for various scenarios and customizable tank geometries[68]. Gyu-Mok Jeon researched the changes in boil-off gas and thermodynamic attributes due to a cryogenic liquid fuel tank's filling ratio (FR). They found flow and heat transfer characteristics at the bottom of the tank urgent to be improved[69]. Gyu-Mok Jeon researched the changes in boil-off gas and thermodynamic characteristics due to the filling ratio (FR) in a cryogenic liquid fuel tank. The results show that the smaller the FR, the shorter the length at which the vapors generated from the lower support and the temperature sensor reach the interface by buoyancy, so the pressure difference according to the height is small[70]. However, several challenges are associated with the development and implementation of ZBO technology. One is its long-term reliability and performance. The technology may be more challenging to scale up for large-scale storage and their long-term reliability and performance may not be fully understood. Additionally, ZBO technology can be expensive due to the need for advanced insulation materials and refrigeration systems, which may need further investigation to determine the feasibility of its widespread adoption in various industries.

In addition, the safety of large-scale green hydrogen storage in liquid form is also an important consideration, as hydrogen is a highly flammable substance that can ignite spontaneously in the air. There are several measures that can be taken to ensure the safe storage and handling of liquid hydrogen.

1. Liquid hydrogen storage tanks are typically designed with multiple layers of insulation to prevent heat transfer and minimize the risk of ignition. Currently, the world's most extensive multiple layers liquid hydrogen storage tank was built by Chart Industries in collaboration with Shell in Bangalore, India[71]. The tank has a storage capacity of 60,000 liters and is designed to minimize heat transfer and boil-off losses, enabling efficient liquid hydrogen storage at cryogenic temperatures.
2. Hydrogen storage tanks often have safety valves and pressure relief systems to prevent over-pressurization and vent any excess hydrogen in an emergency.
3. Safety protocols and guidelines are in place to ensure that hydrogen storage and handling facilities are operated safely.
4. Hydrogen storage facilities are typically located away from densely populated areas to minimize the potential impact of a hydrogen release or fire.

While there are certainly safety considerations associated with large-scale green hydrogen storage, these risks can be effectively managed through proper design, operation, and maintenance of storage facilities and adherence to safety guidelines and protocols.

3.3 Blending hydrogen into natural gas pipelines

Introducing hydrogen into the natural gas pipeline shows a significant advantage, for the cost of a new hydrogen pipeline infrastructure is expensive and the natural gas pipeline networks already exist. According to data from the International Energy Agency, at least seven countries have more than 50% of households connected to gas grids, including the USA, UK, Italy, and Australia. For this reason, injecting hydrogen into existing natural gas grids is a promising method for utilizing hydrogen as an energy carrier.

As shown in Figure 10, hydrogen is produced from renewable energy sources (solar, wind, etc.) The produced hydrogen is injected into the natural gas pipeline network (partial mixing with natural gas or as a complete conversion to hydrogen) and transported to end-use applications. This process is known as ‘gas power,’ happening in many countries, including the UK, Germany and France.

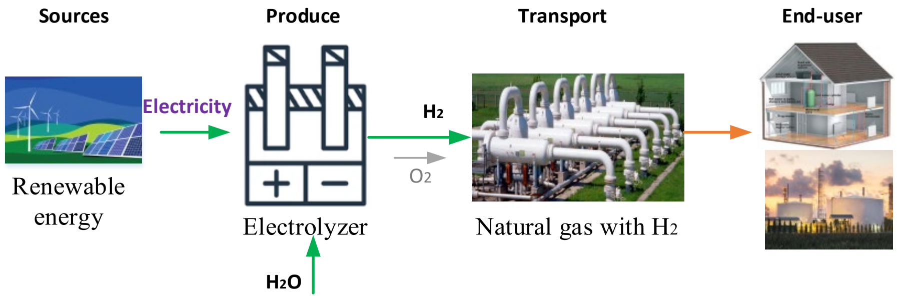

Figure 10. Injecting hydrogen into existing natural gas grids

Injecting green hydrogen into the natural gas grid has several benefits. Firstly, it can provide a cost-effective and safest way to transport hydrogen over long distances with minimal energy loss, as the natural gas infrastructure is already well-established and widely distributed. Secondly, it can help to decarbonize the natural gas supply chain by reducing greenhouse gas emissions associated with the production and consumption of natural gas[72, 73]. Currently, governments worldwide are focusing on renewable hydrogen injection into existing natural gas, which is a way to decrease fossil fuel consumption and reduce greenhouse emissions. In addition, it can improve the scalability of renewable energy sources, which can help to accelerate the transition to a low-carbon energy system and promote the development of renewable energy technologies. However, the existing infrastructures on the market are designed to operate on natural gas. Using the mixture as fuel is challenging due to the significantly different physical and chemical properties between natural gas and hydrogen, as shown in Figure 11.

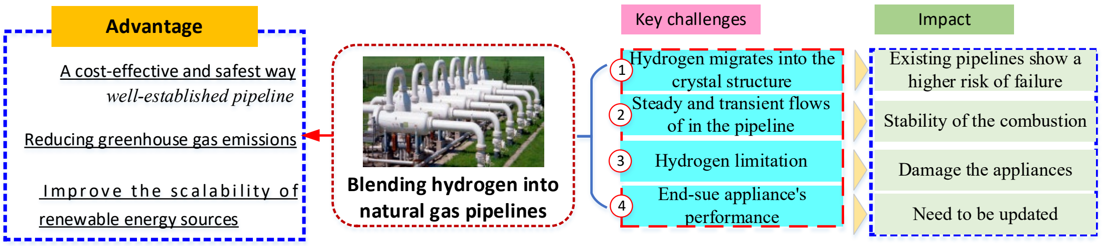

Figure 11 Challenges of hydrogen injected into the natural gas grid

First, studies have shown that existing pipelines can have a higher risk of failure when transporting hydrogen than natural gas due to hydrogen embrittlement. Omar researched the effects of hydrogen embrittlement on the integrity assessment of a cracked steel pipeline[74]. They demonstrated that hydrogen embrittlement of steel pipelines in contact with the hydrogen environment and the transient gas flow and significantly increased transient pressure values. Zahreddine investigates the hydrogen embrittlement of steel pipelines initially designed for natural gas transportation[75]. The results show that fatigue of material and pipeline failure due to overpressure and hydrogen embrittlement must be studied before the replacement of the transported gas. Hryhoriy studied the pipeline durability and integrity issues at hydrogen transport[76]. They showed that dissipated microdamage in the bulk of the pipe wall is distinguished as the main factor of manifestation of hydrogen embrittlement of steel. It is worthwhile mentioning that while the phenomenon of hydrogen-induced embrittlement is well-known and well-documented, the mechanisms are still the subject of ongoing research and debate.

The second issue that needs to be analyzed is the steady and transient flows of the hydrogen-natural gas mixture in the pipeline, which significantly impact the performance and safety of the end-user equipment. Lapo Cheli analyzed the hydrogen and natural gas mixture's main quality indexes and fluid dynamics parameters[77]. They pointed out that pressure in the junctions upstream of the hydrogen injection node increases because velocity and pressure losses in the upstream pipes decrease. Zihang presented a transient analysis model to track the inhomogeneous transient flow of H_2-NG over a real-scale gas network[78]. They reported that blending hydrogen with NG directly impacts the pressure profile across the network, which manifests in a decrease in the line pack. Sami studied the steady and transient state flows of high-pressure hydrogen–natural gas mixtures in looped networks[79]. They found that the transient pressure for hydrogen and hydrogen-natural gas mixtures is higher than for natural gas. To avoided pipeline failures for the sudden changes of gas flow, attention should be paid when mixing hydrogen with natural gas in the existing network pipelines.

In addition, end-use appliances would also be affected by adding hydrogen to natural gas for fuel composition changes. Jones studied the UK's flashback limits for domestic natural gas appliances[80]. They demonstrated that 30 mol% of the natural gas supply may be replaced in the UK without any modification of the devices. Zhao investigated the ignition time of the cooktop burner operating on various hydrogen percentages (up to 20 vol%)[81]. The results show that the ignition time decreases by increasing hydrogen percentage at cold and hot ignition conditions. Riahi conducted an experimental study of natural gas/hydrogen mixture flame in a coaxial burner[82]. They showed that the flame length varies from 56 cm for the enrichment of 20% of oxygen and 15% of hydrogen to 60 cm for the enrichment of 50% of oxygen by volume. Ozturk proposed a novel system integrated with hydrogen and natural gas subsystems on a combi boiler and gas stove. It is stated that hydrogen addition to existing natural gas pipelines would decrease carbon dioxide emissions[83].

Overall, blending hydrogen into natural gas pipelines is a promising technology that can be done using existing infrastructure, which can help reduce the costs and environmental impacts associated with building new hydrogen pipelines. However, some sensitive components in appliances and equipment could be affected by higher levels of hydrogen injection. Equipment replacement or retrofitting may be necessary in such cases, but the overall impact would be smaller than building the new hydrogen pipeline infrastructure.

3.4 Ammonia as large-scale green hydrogen carrier

To realize efficient long-distance hydrogen transportation on large scales, using ammonia (NH_3) as a hydrogen carrier has attracted extensive attention for the advantages of a relatively high volumetric energy density (108 kg-H_2 /m^3 NH_3 at 8.6 bar and 20 °C), gravimetric energy density (17.8 wt%) and providing the only carbon-free chemical energy carrier solution[84]. It is known as power-to-ammonia (P2A). Many countries have recognized the potential of NH_3 as a hydrogen carrier and are investing in research and development programs for ammonia technologies.

In this process, as shown in Figure 12, when excess renewable energy is produced, it can be used to split water into hydrogen and oxygen through a process called electrolysis, followed by the reaction of hydrogen with nitrogen to form NH_3. The N_2 originally comes from the atmosphere (of which it makes up 79%) by a cryogenic process in an air separation unit. It is returned to the atmosphere after the hydrogen has been extracted[85-87]. The produced NH_3 can be stored and transported to or near the point of use. Then the NH_3 decomposes into N_2 and H_2 or is directly used (we will not discuss the NH_3 direct use in this paper).

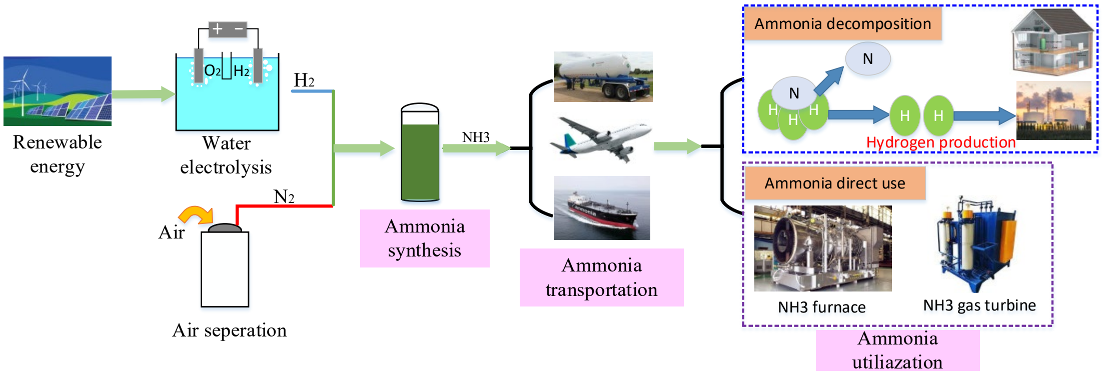

Figure 12 Ammonia as a hydrogen energy carrier

NH_3 has been recognized as a promising alternative hydrogen provider given the following advantages[88]: First, NH_3 has a large weight fraction of hydrogen (17.65%) and a volumetric hydrogen density about 45% higher than liquid hydrogen. Secondly, NH_3 can be decomposed over a catalyst (such as ruthenium, nickel (Ni), platinum (Pt), and palladium (Pd)) to produce the desired H_2 along with N_2-a non-toxic, non-greenhouse gas byproduct. Third, NH_3 is a highly stable chemical, making it less likely to ignite or explode during transportation and storage[89-91], which reduces the risk of accidents and makes it a safer option for hydrogen transport. Moreover, the well-established supply chain for NH_3 makes it easier for production, storage, and transportation, reducing the costs associated with using ammonia as a hydrogen carrier[92-94]. According to the International Fertilizer Association (IFA), world ammonia production in 2020 was estimated to be around 187 million metric tons[95]. Although NH_3 has several desirable characteristics and a mature supply chain that suggests its use as a medium to store hydrogen, The technical challenges associated with NH_3 as a large-scale green hydrogen carrier have been divided into three main areas: NH_3 synthesis, storage and NH_3 cracking technologies, as shown in Figure 13.

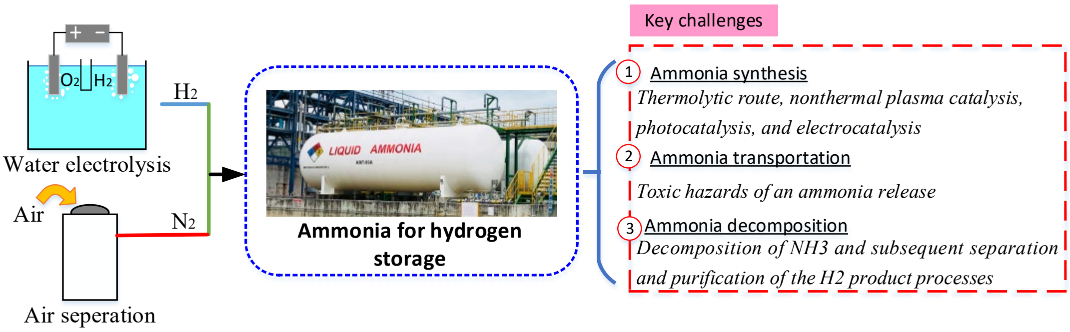

Figure 13 Challenges of ammonia as large-scale green hydrogen carrier

The NH_3 synthesis process is typically carried out at high temperatures with a catalyst, which can require significant energy inputs. The industrial production of NH_3 through the conventional Haber-Bosch process consumes approximately 1-2% of the world's annual energy output. Various strategies have been introduced for achieving nitrogen fixation under mild conditions, such as thermolytic routes, nonthermal plasma catalysis, photocatalysis, and electrocatalysis. The thermolytic route is a well-established method for producing NH_3[96-98]. However, to make nitrogen fixation possible through thermal plasma, the reaction requires high pressure ranging from 20 to 30 atm and temperature above 3000 K. Non-thermal plasma catalysis has emerged as a promising method to significantly reduce the reaction temperature as plasma can activate the reactant at as low as room temperature and atmosphere pressure. However, there is still a limited understanding of how non-thermal plasmas activate nitrogen and hydrogen. Photocatalysis ammonia production is another advanced technology that reduces N_2 to NH_3 without high temperatures and pressures. Additionally, it can use renewable sources of energy, such as sunlight, to drive the reaction, reducing the process's environmental impact. However, there are still challenges, including developing efficient and stable photocatalysts and optimizing the reaction conditions[99-101]. Electrocatalysis ammonia synthesis has drawn much attention from the scientific community owing to its potential to produce NH_3 through a clean and sustainable route, offering a virtually net-zero carbon footprint pathway for NH_3

production. Nevertheless, it is conceptually motivated and still far from practical application due to its low efficiency and ambiguous mechanism[102, 103]. As a result, it is still highly desirable to develop efficient progress in NH_3 synthesis being commercialized.

Another important aspect associated with NH_3 as a green hydrogen carrier is the toxic hazards of ammonia release during production, storage, and transport. Although NH_3 can be easily stored as a liquid at room temperature when a pressure of 8.6 bars is applied, it is a colorless gas with a pungent odor that can cause respiratory irritation and damage to the eyes, skin, and respiratory system at high concentrations. Exposure to high concentrations of NH_3 can also be fatal. J.L. Orozco (2018) quantified the effects of a virtual ammonia release accident from tanks. The results showed that the worse scenario is the toxic cloud of ammonia affecting a vast area with a dense population and causing environmental damage[104]. Prasun investigated the risk analysis for the instantaneous accidental release of NH_3 under different prevalent weather conditions from a pressurized vessel[105]. The release of NH_3 into the atmosphere resulting from the rupture of the storage vessel was identified as the top or unwanted event. Towards this, the transportation of NH_3 is subject to strict safety regulations and guidelines. Additionally, emergency response plans are in place to address any incidents that may occur during transport.

The third barrier is the commercialization of the decomposition of NH_3 and subsequent separation and purification of the H_2 product processes. Massive efforts by academics and industry sectors have also been devoted to researching the activity of the catalysts for NH_3 decomposition. And they most agree that Ru-based catalysts from various metals (Rh, Ni, Co and Fe) are the most active NH_3 decomposition catalyst and likely closest to commercialization. However, commercial Ru-based catalysts are expensive when considering large-scale applications. Since NH_3 decomposition is the equilibrium conversion dependent on the temperature (the concentration of ammonia at equilibrium increases with decreasing temperature)[106, 107], the produced hydrogen is often mixed with other gases, such as N_2 and unreacted NH_3. More recently, technologies have been devoted to the purification of H_2, such as NH_3 absorption and hydrogen-permeable membranes. For NH_3 absorption, it is expensive, which is related to a batch process. A trade-off between selectivity and permeability limits the H_2 permeable membranes. Taking together the above works, it can be seen that the critical areas that future research could focus on in this process are the development of an efficient, affordable catalyst to achieve complete ammonia conversion at low temperatures and also research of advanced technology to purify the H_2 produced from decomposing stored NH_3.

4. Economic evaluation of large scale of green hydrogen storage

Evaluating the economics of large-scale green hydrogen storage ensures the technology provides environmental benefits and the sustainability of the entire supply chain, from production to storage and transportation. Many governments, research institutions, and organizations have supported and conducted research to assess the economic aspects of such storage systems.

4.1 Current world-wide developments

The economic evaluation of large-scale green hydrogen storage was gaining significant attention due to the global push for decarbonization and the advancement of renewable energy technologies, as shown in Table 3. In September 2021, Germany formulated a National Hydrogen Strategy to promote green hydrogen technologies growth. This strategy aimed to establish Germany as a global leader in hydrogen technologies, especially regarding sustainability and economic viability[108]. The EU has been developing the "Hydrogen Backbone," a vision for an integrated hydrogen transportation network across Europe. The project involves economic evaluations of the infrastructure required for transporting green hydrogen across different regions, including pipelines, storage facilities, and production hubs[109]. Saudi Arabia plans to develop the NEOM megacity, which aims to be powered entirely by renewable energy sources, including green hydrogen. Economic evaluations are being conducted to assess the feasibility of producing green hydrogen through renewable energy, storing it, and transporting it via pipelines to crucial demand centers[110]. Japan's Hydrogen Roadmap envisions a significant role for hydrogen in its energy transition strategy. The country has been evaluating the economic feasibility of developing large-scale hydrogen supply chains, including production, storage, and transportation[111]. Australia's National Hydrogen Strategy includes plans for the economic evaluation of large-scale hydrogen projects, including the production, storage, and export of green hydrogen. The strategy aims to leverage Australia's vast renewable energy resources for hydrogen production and explore international partnerships for export[112]. The DOE in the United States has launched various initiatives to evaluate the economics of hydrogen production, storage, and transportation. For instance, the H2@Scale program explores the economic viability of large-scale hydrogen production for various sectors, including transportation, industry, and power generation[113].

Table 3 Economic evaluations of large-scale green hydrogen storage and transportation projects

Project	Country	Year	Work topic
National Hydrogen Strategy	Germany	2021	Establish Germany as a global leader in hydrogen technologies, especially in the context of sustainability and economic viability
Hydrogen Backbone	EU	2022	Economic evaluations of the infrastructure required for transporting green hydrogen across different regions
NEOM	Saudi Arabia	2017	Assess the feasibility of producing green hydrogen through renewable energy
Hydrogen Roadmap	Japan	2017	Evaluating the economic feasibility of developing large-scale hydrogen supply chains
Australia's National Hydrogen Strategy	Australia	2019	Economic evaluation of large-scale hydrogen
H2@Scale program	USA	2016	Explores the economic viability of large-scale hydrogen production

In addition, several studies and research have been conducted on this topic. Jan demonstrated that the most promising early business case for hydrogen energy from large-scale storage is its application as a fuel for the mobility sector[114]. Rodica investigated the economics of a hydrogen production-storage system in the French Pays de la Loire region. They found that hydrogen's production cost is 4.2 €/kg H2 in the most economically exciting case (Hydrogen-to-gas)[115]. Alain analyzes the techno-economic feasibility and business case of large-scale hydrogen underground storage in France[116]. They showed that the hydrogen costs vary from €4.5/kg to €6.6/kg H_2, and the underground mass storage cost remains under 5% of the overall costs. Moritz made a techno-economic assessment of a large-scale point-to-point long-distance overseas hydrogen transport in Australia. They found that the LH_2 pathway might be the best-suited option due to high transport efficiency and only low-grade thermal energy from seawater based on an energetic point of view[117]. Mayrhofer analyzed the additional costs of natural gas/hydrogen blends as fuel for heat treatment furnaces[118]. The results show a significant cost increase from 1.4 to 4.68 for pure hydrogen operation. C. Fúnez developed a technical-economic analysis of ammonia production using hydrogen using electrolysis (carried out with solar, wind, and hydraulic renewable energies)[119]. They concluded that the net present value of the base case is €77,414,525 and 7.62 years of pay-back period were calculated for this green ammonia production plant.

4.2 Current challenge

Although green hydrogen, produced through water electrolysis using renewable energy sources, is considered a promising solution for storing and distributing renewable energy at a large scale. However, for some reasons, the cost of large-scale green hydrogen storage and transportation technology is relatively higher than other sources of energy, such as natural gas. First, the cost of producing green hydrogen depends on the cost of the renewable energy sources used for electrolysis. As the prices of solar and wind energy continue to decrease, the economics of green hydrogen production improve. Second, the infrastructure that can store and transport hydrogen is expensive and still in the early stages of development. For example, hydrogen pipelines must be designed to handle the unique properties of hydrogen, such as its high reactivity and the potential for hydrogen embrittlement of pipeline materials, which can require specialized materials and construction techniques, which can add to the cost of the infrastructure. Third, some technologies, such as compressing hydrogen gas for transportation, require significant energy. This energy consumption can increase the overall cost of hydrogen storage and transport. In addition, government policies, incentives, and regulations play an essential role in shaping the economics of green hydrogen storage. Supportive policies like subsidies and carbon pricing can make green hydrogen more competitive against fossil fuels.

Despite these challenges, the cost of renewable hydrogen is expected to decrease due to technological advancements and economies of scale. Moreover, as countries and industries aim to achieve their decarbonization goals, the environmental benefits of green hydrogen can justify its costs, especially when considering the broader societal and environmental impacts of carbon emissions.

5. Discussion

This article reviewed the current status and challenges of large-scale green hydrogen storage and transportation technology, from underway worldwide projects to policy direction and eventually to hazard and economic evaluation. The results show that many governments worldwide have recognized the potential of green hydrogen as a critical element in their strategies to achieve decarbonization and transition to cleaner energy sources. In addition, large-scale green hydrogen storage technology can help integrate intermittent renewable energy sources and enable the transition to a more sustainable and low-carbon energy system.

However, several technical aspects need to be addressed before this technology becomes commercially viable.

- These government actions collectively contribute to creating an environment conducive to the growth of the green hydrogen sector. However, it's important to note that the level of government support and the specific approaches can vary based on regional priorities, available resources, and existing energy infrastructure.
- Some projects have examined the potential for using salt caverns to store

hydrogen. For example, the "GET H2" project supported by the German government aims to keep excess renewable energy from wind and solar power as hydrogen in salt caverns located in Peine, Lower Saxony. The salt caverns have a storage capacity of up to 130,000 cubic meters of hydrogen, enough to power around 100,000 households for several weeks. The project is expected to be completed by 2025 and has the potential to demonstrate the feasibility of using salt caverns for large-scale hydrogen storage. The Department of Energy's National Energy Technology Laboratory (NETL) in the US is leading a project called "Novel Concepts for Highly Efficient Underground Hydrogen Storage" (NUHES). This project focuses on developing new hydrogen storage methods using salt caverns. However, this research has found that using salt caverns to store hydrogen could be a cost-effective and scalable solution. However, they have typically focused on specific regions or applications, and there is a need for more comprehensive evaluations of the technical and economic feasibility of using salt caverns for hydrogen storage..

- To date, some research has been conducted on the topic of hydrogen carrier ships (liquid hydrogen). One example is the "HySHIP" project, which is being led by a consortium of companies, including Norwegian energy company Equinor, Japanese shipping company Kawasaki Kisen Kaisha (K Line), and German engineering firm ThyssenKrupp. As part of the project, a hydrogen carrier ship (have a capacity of around 23,000 cubic meters) will be developed and built to transport liquid hydrogen from production sites to end users. However, most of these have focused on technical aspects such as safety, storage, and transportation. Few studies have specifically assessed the economic feasibility of large-scale hydrogen carrier ships transporting hydrogen.
- What is hydrogen storage and transportation efficiency using existing infrastructure (such as storage tanks, natural gas pipelines)? There is a

growing interest in using existing infrastructure, such as storage tanks and natural gas pipelines, for hydrogen storage and transportation. Some studies have found that existing storage tanks can be used for hydrogen storage, but additional safety measures may be required to prevent leaks and other hazards. Other studies have suggested that specialized hydrogen storage tanks may be necessary to ensure safe and efficient hydrogen storage. Similarly, the findings of the feasibility of using natural gas pipelines for hydrogen transportation have been mixed. Overall, the findings are still preliminary and more research is needed to fully understand the technical and economic feasibility of this approach.

- There are currently no large-scale ammonia decomposition processes that have been publicly disclosed or widely implemented in the industry. Ammonia decomposition requires high temperatures and pressures to break down the ammonia molecule into its nitrogen and hydrogen constituent elements. However, these conditions also make the process energy-intensive and potentially dangerous due to the high reactivity of hydrogen. While some laboratory-scale methods have been developed, the challenges associated with scaling up the process have made it difficult to implement at a larger scale.

6. Conclusion

Hydrogen is being recognized as a promising renewable energy carrier. However, the transportation of green hydrogen is still in its early stages of development. This paper reviews the current large-scale green hydrogen storage and transportation technologies and the results show that this technology can help integrate intermittent renewable energy sources and enable the transition to a more sustainable and low-carbon energy system. Detailed results can be found below:

1. As the global community continues to focus on addressing climate change and advancing sustainable energy solutions, the role of government support in shaping the development and economic evaluation of large-scale green

hydrogen storage remains crucial.

2. Compressed hydrogen storage (physical storage using storage vessels and geological storage) offers a range of benefits that make it a promising method of storing hydrogen. However, compressed hydrogen storage can experience energy losses which can reduce the overall efficiency.
3. LH_2 has a large gravimetric energy density (2.7 times larger than gasoline) and low volumetric densities (3.7 times lower than gasoline). However, its uses are restricted in some parts, such as the energy-efficient liquefaction process, the loss of LH_2 through boil-off during storage and the safety of large-scale green hydrogen storage in liquid form.
4. Introducing hydrogen into the natural gas pipeline shows a significant advantage for existing natural gas pipeline networks. However, some sensitive components in appliances and equipment could be affected by higher levels of hydrogen percentage.
5. NH_3 as a hydrogen carrier for the advantages of a relatively high volumetric energy density (108 kg-H_2 /m^3 NH_3 at 8.6 bar and 20 °C), gravimetric energy density (17.8 wt%) and providing the only carbon-free chemical energy carrier solution. However, more effect is needed on affordable catalysts to achieve complete ammonia conversion at low temperatures and research advanced technology to purify the H_2 produced from decomposing stored NH_3.
6. Although the cost of storing and transporting green hydrogen is expensive now, it is expected to decrease in the future due to technological advancements and economies of scale being achieved.

Based on the literature survey across time, a variety of progress is demanded in the near future. For example, a novel evaluation method of the technical and economic feasibility of using salt caverns for hydrogen storage needs to be introduced, for current studies have typically focused on specific regions or applications. Second, more research needs to be done about the economic feasibility of large-scale hydrogen carrier ships transporting hydrogen. Third, the efficiency of hydrogen storage and transportation using existing infrastructure (such as storage tanks and natural gas pipelines) needs to be researched for the transformation of fossil fuel-based energy systems into hydrogen-based energy systems. In addition, the challenges associated with scaling up the large-scale ammonia decomposition process must be addressed before this technology can be implemented at a larger scale.

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