MULTI-DIMENSIONAL COMPARATIVE STUDY OF HYDROGEN STORAGE TECHNOLOGY BASED ON VEHICLE FUEL STORAGE SCENARIOS

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Philosophy

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CERTIFICATE OF ORIGINALITY

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________________________ (Signed)

_____YE LING HE________ (Name of student)

Abstract

Facing greenhouse gas emissions problems, the application of hydrogen energy systems to current vehicles, such as family sedans, is of great importance for alleviating and reducing greenhouse gas emissions and global warming. However, in the field of transportation, the application of hydrogen energy is currently facing hydrogen storage difficulties, which limits the use of hydrogen energy in transportation and its role in solving the problem of carbon emissions. To cope with the deteriorating environmental trend, we need to evaluate the current mature hydrogen storage technology.

The thesis aims to evaluate the mature hydrogen storage technologies, e.g. high-pressure storage (which includes two-generation storage vessels: Type 3 and Type 4 and cryogenic storage technologies, mainly based on Type 3 high-pressure vessels, under the application of fuel cell vehicles/sedans' fuel tank with multi-dimension of environment and economy. In terms of the environment, the LCA model (Life Cycle Assessment model) is used to establish the inventory in the manufacturing process of hydrogen storage containers, and the environmental impact is calculated according to the CML-IA(Centrum voor Milieuwetenschappen-Impact Assessment) database. The economic aspect is a cost-benefit analysis, which evaluates the cost of manufacturing and hydrogen storage monetization environment to derive its performance in the market.

Recent research has shown that Type 4 high-pressured vessel manufacture has the minimum Greenhouse Gas (GHG) emission with 5539 kgCO_2 eq. This result is lower than Type 3 high-pressured vessels of 7219 kgCO_2 eq and cryogenic vessels of 135000 kgCO_2 eq in their whole life cycle. Over 80% of CO_2 emissions is caused by carbon fiber's production. Furthermore, it present that electricity covers 6% sources of CO_2 emission, for the hierarchy of power generation. The result of human toxicity potential showed the that Type 4 high-pressure storage vessel shows the lowest level of human toxicity with1500 kg 1,4-DB eq, which is lower than the 2140 kg 1,4-DB eq of cryogenic vessel and 2580 kg 1,4-DB eq of Type 3 high-pressure vessel. Carbon fiber as the main material contributes 83% of the human toxicity impact of Type 4 high-pressure vessels.

Economic analysis reveals that Type 4 high-pressure vessels cost 10.4 US dollars per kilogram of hydrogen and use 5.2 kWh per kilogram, which is less than Type 3 high-pressure vessels and cryogenic vessels. Cryogenic vessels require an additional 724 kWh/kgH2 of energy to maintain functioning conditions. The Type4 high-pressure hydrogen storage vessel has the most potential for use in the Sedan since it has the lowest energy and financial costs per unit of hydrogen.

Based on the evaluation result above, this study come out with the policy analysis, which refer to the previous hydrogen policies worldwide. Investment in the technologies developments and basic infrastructure is still necessary. The other key measure is in the establishment of the social system, including the stricter environmental regulation and more efficiency market leverage mechanism design to promote the relevant industry of hydrogen and its storages.

With this study, we can have clarification in the characteristics of the existing mature hydrogen storage technologies applied in the light-duty vehicles and make the policy suggestions. According to the assessment, the Type 4 high-pressure vessel will be a suitable option for hydrogen mobility on the Sedan in terms of its economic and environmental performance. Sedans as important parts of the road transportation have their own role in hydrogen industry development. The commercial nature of hydrogen fuel cell vehicles, especially the light-duty vehicle, which is the sedan for family using and easier for people to understand, is a pathway for most of people to access and trust the hydrogen energy technologies. This research will have a completed recognition of the Sedan's hydrogen storage system and play the role as a roadmap of hydrogen utilization in the transportation field with applicable policy suggestions. This will promote the hydrogen storage development and hydrogen fuel cell vehicles, which will lead to the development of whole hydrogen industry.

Publications arising from the thesis

Journal Paper

[1] **Ye, L.,** Lu L., Environmental and economic evaluation of the high-pressured and cryogenic vessels for hydrogen storage on the sedan, *International Journal of Low-Carbon Technologies*, 2023,18: p.144–149.

Conference Paper

[1] **Ye, L.,** Lu L., Environmental evaluation of human toxicity for production of common hydrogen storage device on the sedans, International Conference on Energy Storage and Saving, 2022, Xi'an, China.

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I would also like to thank other teachers, colleagues and friends who supported and encouraged me throughout the research process, as well as my family. You have given me love and support on my journey of seeking knowledge, and you have given me tolerance and encouragement. This is an important reason why I can persist and achieve the results described in this article. Thank you for always walking side by side with me.

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Chapter 1 Introduction

1.1 Research background and significance

With the swift development of industrial society, burning fossil fuels plays a great role as contributor to greenhouse gas and nitrogen oxide emissions[1], around estimated to be responsible for 75% and 66% of these pollutants, respectively[2, 3]. For China, the emission world share of CO_2 in 2019 was 29.5%[4], which is a huge number of pollution. Regarding final oil consumption, over 60% of energy cost was from transportation (including road, railway, navigation and aviation) and is the largest final consumption of oil in 2019[4]. The fossil fuel system is still the primary choice for transportation, which makes the reform in energy source became a necessary measure to counter the tendency.

From another perspective, the world's efficiency in energy utilization is still inadequate. Currently, mainstream internal combustion engines have an energy conversion efficiency of less than 30%, while electric motors can achieve up to 80%, but their energy storage and charging are greatly limited. This makes the balance between obtaining higher energy conversion efficiency and achieving more efficient energy storage and charging processes a major research which focus on the energy technology.

As one of the green energy sources of world attention, the application of hydrogen in the mobility power is a response to the environmental challenges caused by the long-term use of fossil fuels. Hydrogen as clean energy is believed to be the efficacious solution to the current problem of its characteristics, including green neutrality, high energy density, and obvious renewability[5, 6]. In all respects, hydrogen energy technology is of great interest because of its own advantages. In terms of the current technological level, hydrogen's biggest advantage lies in its characteristics as an energy storage medium. Especially with the maturation of fuel cell technology, hydrogen's energy storage and refueling efficiency are higher than that of pure electric systems, and it is also suitable for areas without grid connections. While hydrogen energy technology development has traditionally focused on power supply in remote communities and portable energy sources, it has also become a significant technology project in road traffic, second only to electric battery mobility[7, 8] .

The first hydrogen-powered fuel cell mobility came out in 1991 and the available vehicles for sale include Honda, Hyundai, and Toyota productions[9]. Suprava and Santanu found that hydrogen-power fuel cell mobility has the lowest cost in 200 miles among all the electric cars in 2035 and 2050[10]. This informs that hydrogen-powered fuel cell mobility has better performance in the future. In the aspect of environment, Daniele and Antonio found that the hydrogen-power fuel cell has good performance for its lower emission level under GWP standard[11]. Wang and Ou proposed an energy-saving simulation model for fuel cell vehicles to study the energy consumption of the entire vehicle. They discovered a quantifiable correlation between the reduction of hydrogen consumption and the improvement of fuel cell and motor efficiency, as well as the decrease in the total vehicle mass[12]). Another study by Haruki found that hydrogen-power fuel cell vehicles have more environmental benefit potential when it combines with rooftop photovoltaics technology and will have 40% less in hydrogen consumption and CO_2 emission than normal fuel cell vehicles[13]. In addition, regarding hydrogen energy supply, Thomas informed an available & affordable hydrogen supply project based on the factory-built electrolyzers and small scale steam reformer, which is applicable and necessary for planning for the hydrogen infrastructures[14].

In brief, as a power reforming solution to the worldwide Greenhouse effect problem, hydrogen application in the mobility area with fuel cell power systems has strong potential. Moreover, the successful application of hydrogen energy technology has significant implications for changing the current fossil fuel-based energy utilization structure. Not only can it achieve low emissions while providing high energy supply, but it also provides a viable medium for storing and accessing more renewable clean energy sources (such as connecting winding electricity to hydrogen storage[15], which simultaneously promotes the development of renewable clean energy systems. However, in the process of large-scale application of hydrogen energy technology, there is another problem that cannot be ignored: hydrogen storage.

Despite the very promising green energy source, the development of hydrogen energy still faces significant challenges. Especially in hydrogen energy applications, hydrogen perform as an energy carrier to achieve energy conversion. As we mentioned earlier, hydrogen has its unique advantages as an energy storage medium. However, other characteristics of hydrogen severely limit its development and application. The low energy density is a difficult problem, which causes severe storage difficulty for hydrogen storage [16]. Additionally, hydrogen has serious hydrogen embrittlement problems and explosion risks[17, 18]. Therefore, current research should focus on developing storage solutions with higher energy density and security to address these challenges. The development of such solutions will be crucial for the success of hydrogen fuel cell vehicles, which have the potential to bring about significant changes in the field of transportation energy[19, 20] .

In addition to further exploring hydrogen storage technology to address its existing problems, it is also necessary to analyze and evaluate existing technologies and seek possible applications and improvement plans, in order to quickly put them into production and use, thereby accelerating the reform of the energy structure. Hydrogen energy technology has undergone hundreds of years of theoretical development and technological iteration, which is also a large and complex system. Some hydrogen storage technologies are still undergoing experimental tests, while others have a long history of application. Selecting which hydrogen storage technology to develop has gone beyond the scope of pure technology and also concerns market and policy guidance. At a higher level, the significance of this study also contributes to new industrial policy recommendations for the changing environmental energy landscape and the changing international situation in the world today. As an emerging technology, the significance of hydrogen energy has already surpassed its original expectations. Hydrogen energy technology itself and the emerging hydrogen-based economy not only symbolize a possibility for the future development of human civilization but also need to be tested in practice to optimize their composition in the present. This requires us to conduct targeted evaluation, research, and comparison of existing technologies in specific application scenarios.

Based on this approach, the next part is to explore the most important directions for hydrogen energy economy and technology from a high-level perspective, in order to determine the direction of subsequent research. We need to start from the national strategic level, gradually delve into the concentrated practical areas of hydrogen energy policy guidance, explore the core technological needs and challenges, and come up with corresponding work plans for our subsequent research. This requires analyzing and interpreting the hydrogen energy industry development policies that different countries have developed in their different ecological niches in the international market.

1.2 Organization of the thesis

This thesis has of 6 chapters and presents the results of analytical research on hydrogen storage technologies in the context of vehicle applications. Chapter 1 makes a brief statement on the research topic and content value. The content of this paper is organized in the following chapters.

Chapter 2 reviews and analyzes the current environment and energy background, the cognition and layout of hydrogen energy technology and industry in many regions around the world, the development status and problems of hydrogen energy technology from multiple levels. It focuses on reviewing the transportation application of hydrogen energy and the current status of hydrogen storage technology. This chapter also clarifies the objectives, methodology and workflow of this research.

Chapter 3 focuses on the impact of the environmental field, and based on the life cycle assessment model, analyzes the parameters and environmental impact of three hydrogen storage systems with relatively mature applications. The evaluative analysis in this part will consider the environmental impact of hydrogen storage devices in the manufacturing process and application. Based on the overall results of the evaluation, a basic judgment is made on decision-making of hydrogen storage technology from an environmental perspective.

Chapter 4 analyzes the application performance of different hydrogen storage technologies in fuel cell vehicles from an economic dimension. Based on the research method of benefit-cost analysis, this chapter evaluates various application scenarios of fuel cell vehicles in the future, so as to more comprehensively analyze the performance of hydrogen storage technology in the field of fuel cell vehicles from an economic point of view.

Chapter 5 analyzes the industrial policies related to hydrogen storage technology based on the evaluation results of the previous two chapters. This chapter makes a comparative analysis of policy cases around the world, and at the same time predicts future policy trends, so as to design policies for the hydrogen storage technology industry.

Chapter 6 summarizes the research results presented in this thesis, and at the same time puts forward some suggestions for future work based on previous research.

Chapter 2 Literature review

2.1 Research statues of multi-dimensional comparative study of hydrogen storage technology

2.1.1 Research status of the hydrogen economy

There is an important premise for the evaluation of the development and application of hydrogen energy technology, which is to base this work on the future form of the hydrogen economy. Indeed, the hydrogen economy is the ultimate result of the development of hydrogen technology. The concept of the hydrogen-based economy was firstly proposed by Appleby in 1972[21] and supported by many researchers, including Agarwal[22], and Florin[23]. This concept is not only beyond the scope of pure technical efficiency, but more importantly, hydrogen energy technology's development has been raised to a level of important strategic significance. The evolution and usage of hydrogen energy technology in many regions are not only based on the problems of current and future environmental degradation and energy shortages but also to promote domestic economic and technological development, thus gaining advantages in future international competition and translating technological advantages into bargaining chips in the political and economic fields[24]. As the Figure 2.1 shown, the world's major economies have all taken measures in the competition for hydrogen energy technology[25]. However, as can be seen from the Figure 2.1, the roles and goals sought by each country in the future hydrogen energy system are not consistent due to differences in national conditions and international division of labor responsibilities, resulting in different development philosophies and policy ideas[23]. As an important aspect in effectively evaluating and comparing the existing technologies and policies of hydrogen energy technologies, the different perspectives and priorities of different countries should be understood, and develop targeted solutions for specific application scenarios.

Since the formation and development of the world market division of labor after the end of the Cold War, as the Figure 2.1 shown, developed countries and developing countries have occupied different niches in the world market, which has also affected the cooperation and competition among countries in the field of hydrogen economy. Developed countries have started their research on hydrogen energy relatively early and have more sufficient scientific research and manufacturing capabilities. At the same time, their application market and capital will also greatly influence the relevant market of hydrogen energy technologies (such as the hydrogen technology consumer market), placing them at the top of the triangle relationships. The latecomer industrial countries and petroleum-producing countries often play the role of followers in the international division of labor order dominated by developed countries. Among them, the latecomer industrial countries themselves also have certain scientific research and manufacturing capabilities, and have a more extensive market for hydrogen technology applications due to their population size.

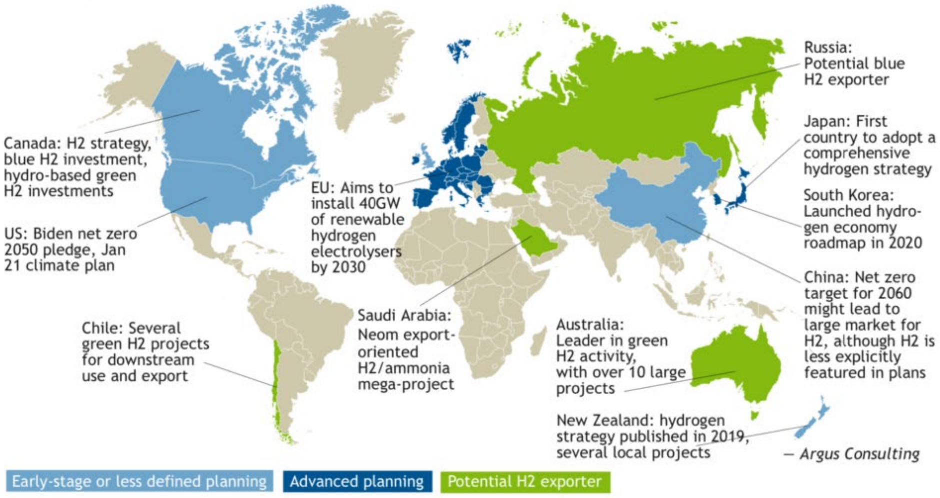


Fig. 2.1. The map of the worldwide hydrogen industrial policies.

They maintain a global position in the hydrogen economy by supplying components, equipment processing and assembly, and limited development and application of hydrogen energy technologies. Their main disadvantage lies in the lack of control over cutting-edge hydrogen technology and hydrogen raw material supply. The ecological niche of petroleum-producing countries is even more special. Their role is a major influencing side in the supply of petroleum resources and the hydrogen market. This is because the current hydrogen industry is still dominated by gray hydrogen, that is, hydrogen production based on petroleum resources. Therefore, these countries can still participate in international competition based on petroleum resources and exert influence based on their reserves. However, their disadvantage lies in their long-term reliance on resource exploitation, narrow domestic market, and single industrial structure, and they are severely constrained by external countries in both technology and market fields. Furthermore, the development of green hydrogen technology (low-pollution hydrogen produced based on renewable energy) is fatal to their existing ecological niche. Besides, de-industrialization policies and population decline have also led to the problem of shrinking new energy markets in developed countries despite their front-end technology capabilities. In addition, the rise of some developing countries (such as BRICS countries) has directly challenged the dominant position of developed countries in the field of hydrogen energy application. The strengths and weaknesses of these three types of countries have led to a pattern of both competition and cooperation in the international hydrogen energy market today as Figure 2.2, which also provides us with a model for analyzing the principles of hydrogen energy policies in various countries.

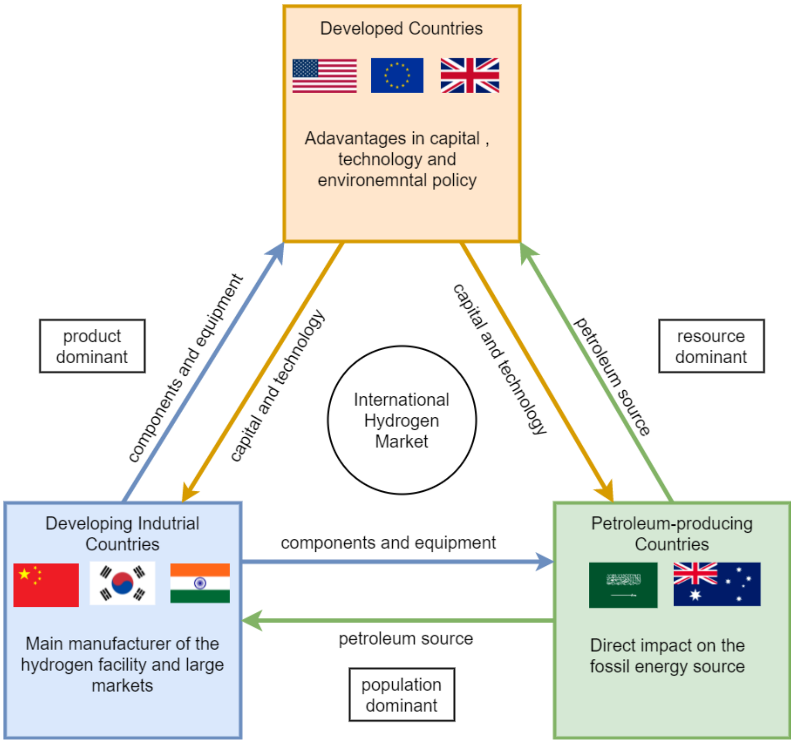
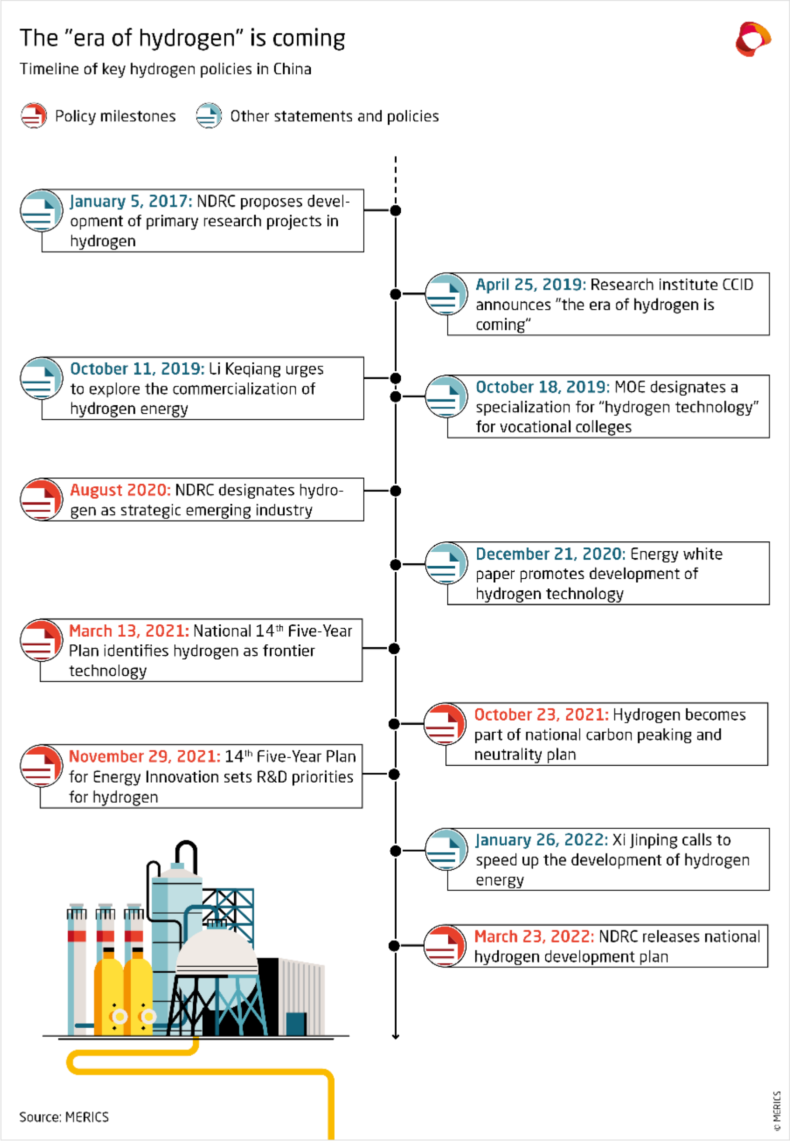


Fig. 2.2. International hydrogen market.

As a late-developing industrial country, China's development path for hydrogen energy is focused on developing petrochemical alternative energy as the core, improving the technology of the entire industrial chain, and catching up with advanced international levels. As shown in Figure 2.3, the Chinese government has invested heavily in politic measures to promote domestic technological research and development and the development of related industries in the field of hydrogen energy. China plans to achieve an annual production of 100,000 to 200,000 tons of green hydrogen by 2025, and gradually reach carbon neutrality in the energy part. As mentioned earlier, the storage and transportation of hydrogen energy are identified as the current technology's weakness and key research direction. To address this, China is investing heavily in the development of new storage and transportation technologies, including the development of high-pressure hydrogen storage tanks and the exploration of cryogenic hydrogen storage technologies[26-28] . Similar to China, India's designated hydrogen energy industrial policy aims at increasing the utilization of hydrogen energy in the production field, particularly in the transportation industry[29, 30] . Other late-developing industrial countries, such as South Korea[31] and Japan[30, 32-34], also have national-level integration and planning for the hydrogen industry.



The "era of hydrogen" is coming

Timeline of key hydrogen policies in China

🟥 Policy milestones 🟦 Other statements and policies

January 5, 2017: NDRC proposes development of primary research projects in hydrogen

April 25, 2019: Research institute CCID announces "the era of hydrogen is coming"

October 11, 2019: Li Keqiang urges to explore the commercialization of hydrogen energy

October 18, 2019: MOE designates a specialization for "hydrogen technology" for vocational colleges

August 2020: NDRC designates hydrogen as strategic emerging industry

December 21, 2020: Energy white paper promotes development of hydrogen technology

March 13, 2021: National 14th Five-Year Plan identifies hydrogen as frontier technology

October 23, 2021: Hydrogen becomes part of national carbon peaking and neutrality plan

November 29, 2021: 14th Five-Year Plan for Energy Innovation sets R&D priorities for hydrogen

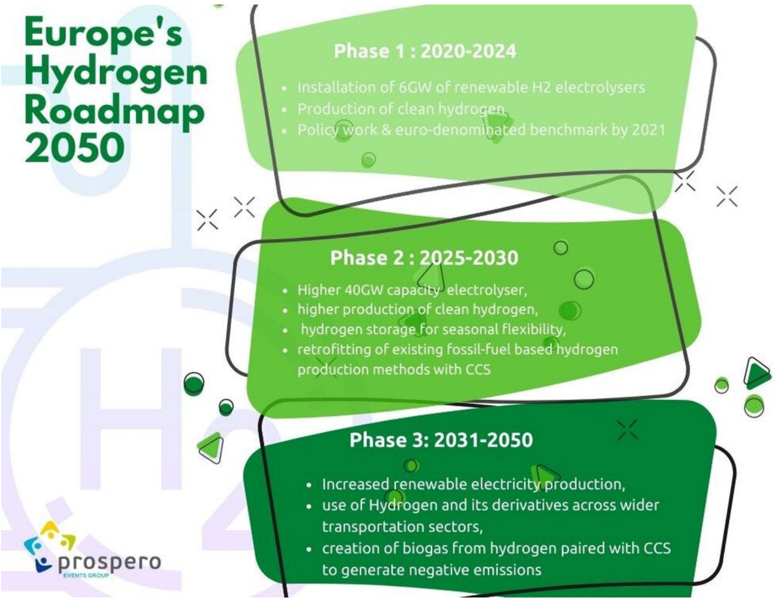
January 26, 2022: Xi Jinping calls to speed up the development of hydrogen energy

March 23, 2022: NDRC releases national hydrogen development plan

Source: MERICS

Fig. 2.3. The timeline of hydrogen policy in China.

Late-developing industrial countries attach significance to the form in hydrogen economy. Because according to the "backward advantage " theory[35](Vu & Asongu,2020)[35], which was firstly proposed by Alexander Gerschenkron in 1952 ,the application of hydrogen energy technology and the development of concerned industries will be effective measures for these countries to achieve industrial upgrading, strengthen the country's economic status, improve employment and the environment, and even constitute advantages for traditional developed countries[36]. The transformation of the energy mix will establish a new role in the international market. Especially in the current context of growing energy and environmental concerns, achieving a clean energy transition is even more necessary, which is why so many developing countries with industrial capacity are actively deploying hydrogen energy strategies.



Europe's Hydrogen Roadmap 2050

Phase 1 : 2020-2024

- Installation of 6GW of renewable H2 electrolysers
- Production of clean hydrogen
- Policy work & euro-denominated benchmark by 2021

Phase 2 : 2025-2030

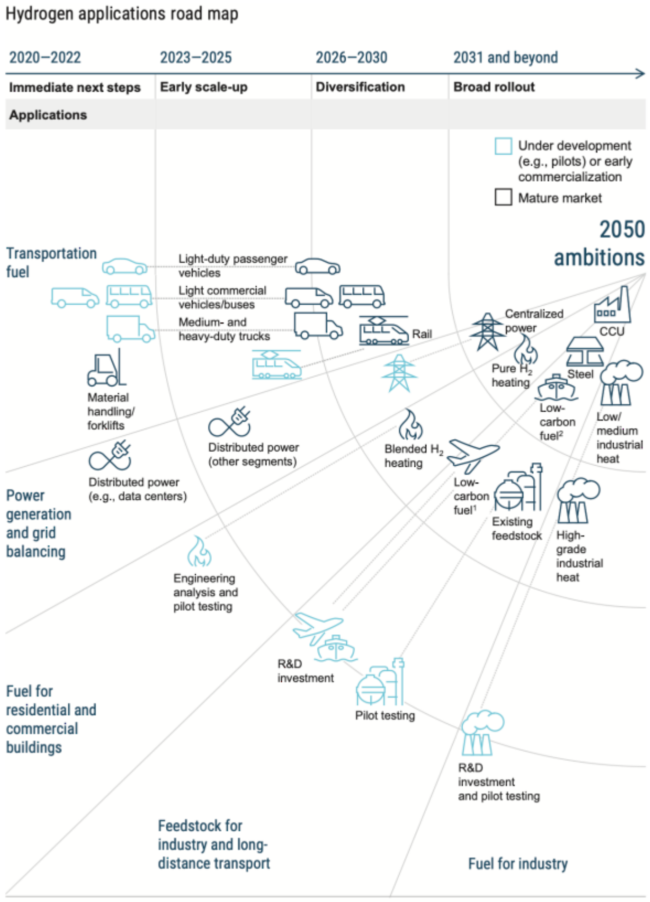
- Higher 40GW capacity electrolyser,
- higher production of clean hydrogen,
- hydrogen storage for seasonal flexibility,
- retrofitting of existing fossil-fuel based hydrogen production methods with CCS

Phase 3: 2031-2050

- Increased renewable electricity production,
- use of Hydrogen and its derivatives across wider transportation sectors,
- creation of biogas from hydrogen paired with CCS to generate negative emissions

Fig. 2.4. The roadmap of EU in hydrogen to 2050.

For developed countries, the first-mover advantage and expansion in hydrogen energy are more obvious. The EU's strategic planning in the field of hydrogen is very representative, which is shown in Figure 2.4. The European Union's hydrogen energy application policy is an important part of its realization of circular economy, and the European Union has three advantages in funding, policy orientation and technology in this field, and has put forward clear tasks[37] . The United Kingdom has given a ambitious plan for the establishment of the hydrogen system in road transportation and the energy supply of most buildings, as a part of the clear growth strategy. [38] As a country that invested in hydrogen energy technology research and industrial application earlier, the United States released a relevant policy roadmap as early as 2002. [39] According to the Figure 2.5, by around 2030, the United States will realize hydrogen energy on the platform of small and medium-sized vehicles, such as cars and small and medium-sized trucks. Moreover, by 2050, a larger-scale application of hydrogen energy in the energy field will be realized and it will satisfy 14% total final energy demand [40].



¹ Carbon capture and utilization (for chemicals production)
² Biofuel, synfuel, ammonia

Fig.2.5. Hydrogen applications road map.

As a country with abundant natural resources and strong environmental awareness, Australia's project focuses on establishing a hydrogen production network to meet domestic development needs while enhancing its hydrogen supply capacity for future important hydrogen markets , such as Japan and South Korea[41]. Poland's policies show similar characteristics, but the development of its hydrogen energy industry is limited by the conditions of domestic facilities[42]. Another interesting example is the view of the Persian Gulf Country, like Qatar and Iran, in which fossil energy producing countries have a very special role in the overall economic system. Since an important source of hydrogen production is fossil energy (like oil, natural gas, and coal), even under the background of the hydrogen economy, the resource output of these countries will directly affect the world's energy market, and even cause extremely far-reaching consequences, just as OPEC causing by the oil crisis during the third Middle East war by oil embargo[1]. Therefore, the industrial of hydrogen like blue hydrogen facility has the role of evolution in the domestic industry of these countries, which is the main direction of these oil source productions countries’ development[43]. These fossil energy producing countries have similar industrial upgrading and environmental protection needs as the late industrial countries, and there are also important economic ties between the two. But at the same time, the relevant manufacturing and scientific research capabilities of these countries are not well developed, which has caused them to be extremely limited to developed industrialized countries in terms of hydrogen energy technology. Under the innovation in hydrogen energy technology, the status of fossil energy producing countries is actually threatened. This is also the core factor for fossil energy producing countries, such as the Gulf countries shown in Figure 2.6 [44], to consider the layout of the hydrogen energy industry under the current background.

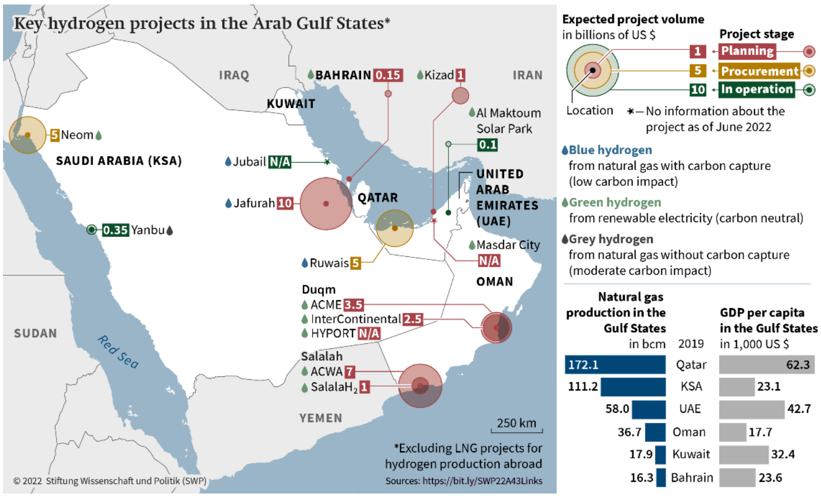


Fig. 2.6. The map of key hydrogen project in Gulf states.

Due to the long distance for the hydrogen supply sources and final consumption markets, the international cooperation necessary. Based on this goal, the ASEAN developed an evaluation tool: HEART for the hydrogen supply chain improvement, which has great reference value[45]. This provides a good example for the construction of hydrogen industry chain and the development of hydrogen economy under the cooperation of transnational integrated market as Figure 2.7. ASEAN includes various economies ranging from least developed countries to developed countries. At the same time, the industrial division covers developed industrial countries (Singapore)[46], late industrial countries (Malaysia, Indonesia, Thailand, etc.), and petrochemical resource producing countries (Malaysia, Indonesia, Brunei, etc.). At the same time, ASEAN has a very close relationship with the world's major economies, and it is also an important petroleum resource transportation center and refining center. As a regional transnational cooperation system, ASEAN's hydrogen economy market trend is of great importance to China's energy construction in the Belt and Road projects (such as industrial cooperation with petroleum resource producing countries in Central Asia and West Asia), and even the establishment of hydrogen energy systems around the world.

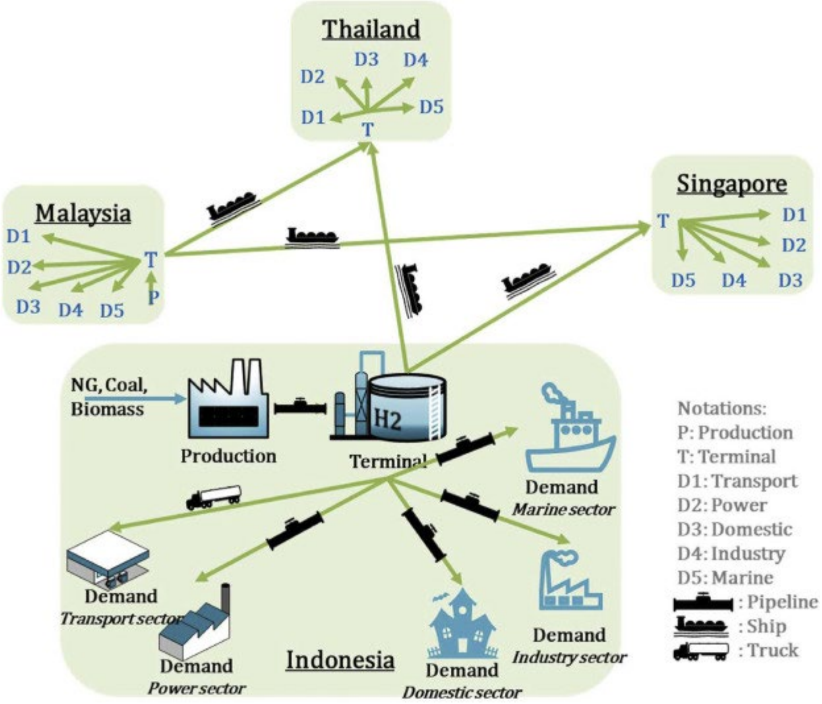


Fig. 2.7. Supply chain of hydrogen in ASEAN[45].

Compared with other countries, China has unique superiority in the field of hydrogen energy development, which also makes China's hydrogen energy development path present some particularities. China's own fossil resource reserves (mainly coal) and overall power generation are very impressive, especially the renewable electricity[47]. At the same time, there is a strong demand for energy, and there is also a drive to promote the application of clean energy under the guidance of policies[48]. Moreover, China has certain research and development capabilities in the hydrogen energy technology, thus laying the foundation for the implementation of hydrogen energy policy. Therefore, the development trend and overall strategy of China's hydrogen energy industry are more similar to the combination of developed countries and late industrial countries, and have some common characteristics of these two types of countries.

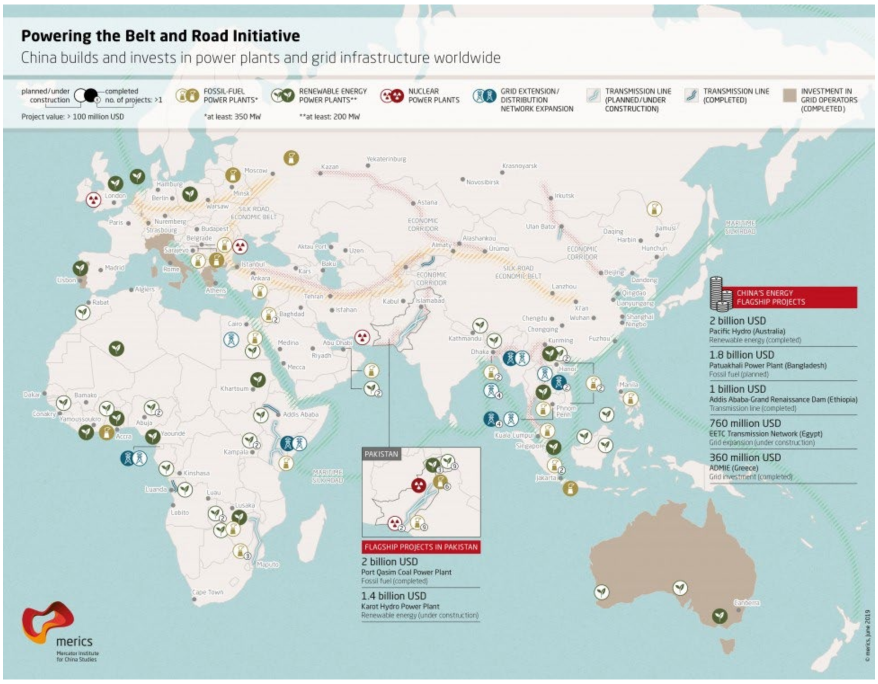


Fig. 2.8. Powering project of the Belt and Road Initiative[49].

Firstly, China's huge energy demand has aroused domestic concerns about energy security and the ecological environment. This makes hydrogen energy not only a pure technological innovation in China's energy policy, but also an industrial technology system related to national security [50]. Secondly, within China's energy system, there are also differences in the distribution of energy production and consumption markets. This has led China to use hydrogen as a regulation of domestic energy, extending the value chain of the petrochemical industry for the central and western areas while improving the environment of eastern area[50]. In addition, the transfer from grey hydrogen to green hydrogen is an important parts of the policy in China, which is directly related to China's international performance in the field of hydrogen energy[51]. In the context of China's foreign policy, particularly under the Belt and Road Initiative, China's trade investment and technology exports to developing countries are significant. The development of hydrogen energy technology and industry, as a clean energy source and a means to achieve industrial upgrading, is of great benefit to energy-exporting countries along the Belt and Road, such as Gulf countries and Central Asian countries, as well as to China itself[49, 52]. This will further enhance China's energy security, promote industrial upgrading and environmental improvement in countries along the Belt and Road, and make China's emphasis on hydrogen energy technology go beyond traditional domestic economic and technological development. The development of hydrogen energy also provides opportunities for China to play a leading role in the global energy transition and to promote international cooperation in the field of clean energy.

Regardless of the strategies adopted by countries for the development of hydrogen energy, any industrial development model has its early practices as a reference for subsequent policies, especially for emerging forms such as hydrogen technology and hydrogen-based economy. Therefore, we need to understand where hydrogen energy policies currently stand in the industrial development of various countries, which areas are given priority for the development and application of hydrogen energy technology, and what results are achieved from these efforts.

2.1.2 Research statues of hydrogen technology in transportation industry

Due to the differences in the conditions of each country and the differences in the industrial structure, the differences and complementarities shown in the hydrogen economy policy still obey the current international division of labor in the world economy[23]. But at the same time, due to the strong intrinsic need of hydrogen energy development and the expectations of various countries to achieve industrial upgrading and even occupy the advantages of the fourth industrial revolution, there are certain commonalities in the policies of various countries. Among these, the strategies displayed by various countries in the part of hydrogen energy development are inseparable from the utilization of hydrogen energy technology in the transportation industry. In other words, the transportation industry is regarded as the entrance of hydrogen energy substitution in the overall industrial chain[53, 54] .

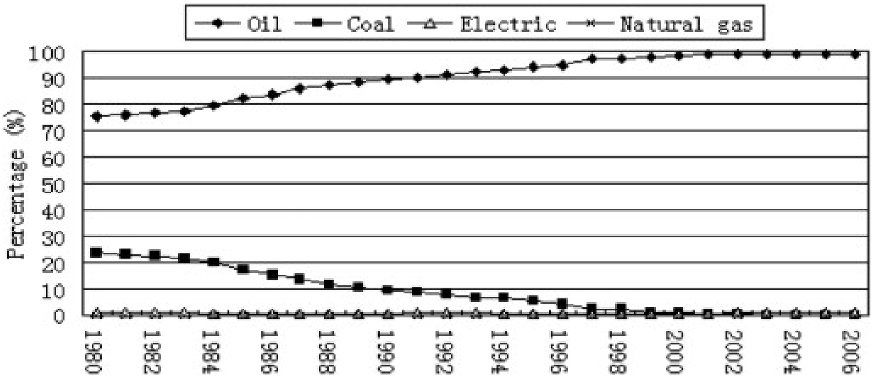


Fig. 2.9. The percentages of the fuel type in total energy consumption[55].

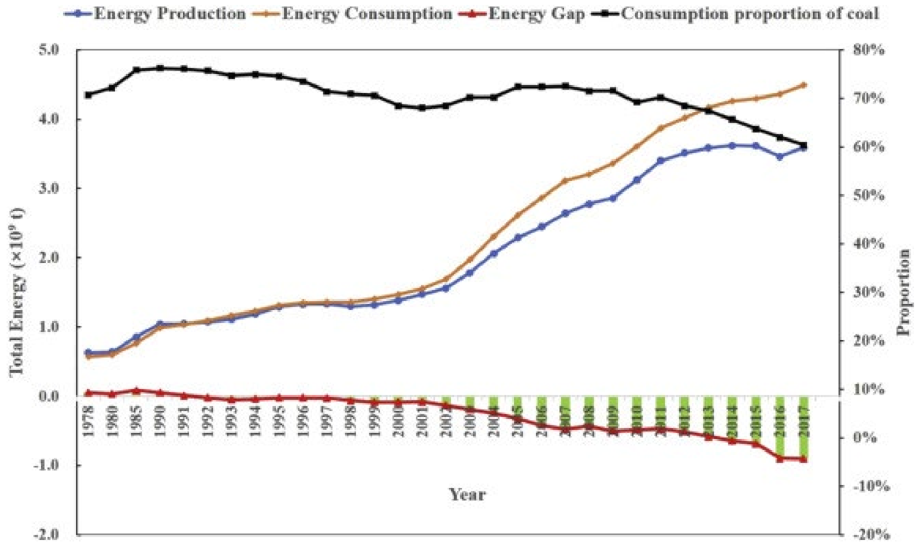


Fig. 2.10. Energy production, consumption, gap and the proportion of coal in the energy consumption of China[21].

There are reasons for choosing the field of transportation as an experimental scenario and a priority research and development area for hydrogen energy applications. The transportation industry is a bridge that communicates the entire industry and market. It is also a sector that accounts for a large share of carbon emissions in the entire industrial system, in which the scale of energy consumption is negatively correlated with the efficiency of utilization. For example , China's transportation industry accounted for 49.6% of the total oil consumption in 2006[55], and accounted for 57.7% in 2017.[56]The emission of transportation part has 10% share in CO_2 emission and 15% total energy cost in 2010[21]. This illustrates that a high resource utilization rate in the transportation sector is not always desirable, as increasing resource inputs can lead to a decrease in energy efficiency. In fact, China's transportation industry's disproportionately high share in the energy structure is a severe problem that urgently needs to be addressed. From a higher level, the construction of the international hydrogen energy economic chain, the hydrogen economy in different regions within the country, and even the hydrogen energy industry in the region all need the support of the transportation industry. Therefore, no matter in terms of the environmental and economic goals of using hydrogen energy technology, or the path and technical requirements for the development of hydrogen energy industry, it is an important idea to use the transportation industry as the entry point for hydrogen energy application. Therefore, from all aspects, it is a very necessary practice and development direction for the energy structure conversion of hydrogen energy in the transportation industry.

The performance of the hydrogen energy economy in the transportation industry actually involves two aspects, namely, the construction of hydrogen energy logistics network and the transformation of hydrogen energy structure in transportation and traditional transportation. The former mainly focuses on the construction of hydrogen energy supply network, and more involves infrastructure construction, such as large-scale hydrogen storage facilities, transportation nodes, industrial vehicles and hydrogen refueling stations. It will also involve some research on road, rail, and waterway transportation modes. The latter mainly studies the hydrogen power of existing vehicles, such as vehicles and railways, and more involves the research and development and evaluation of mobile hydrogen storage systems and fuel cell systems.

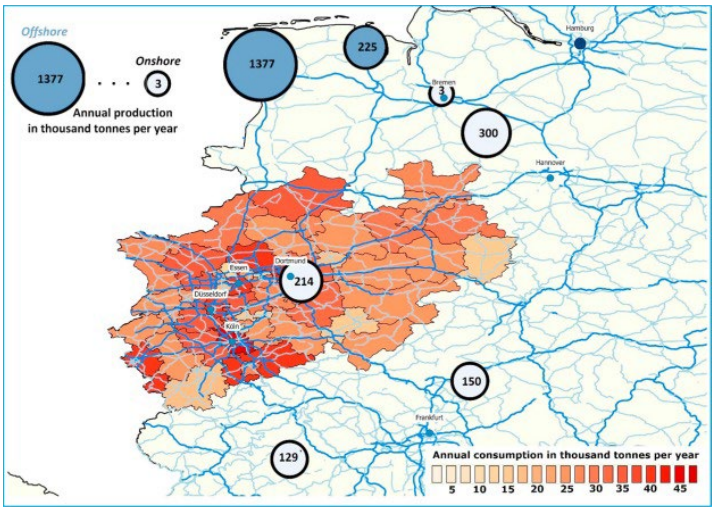
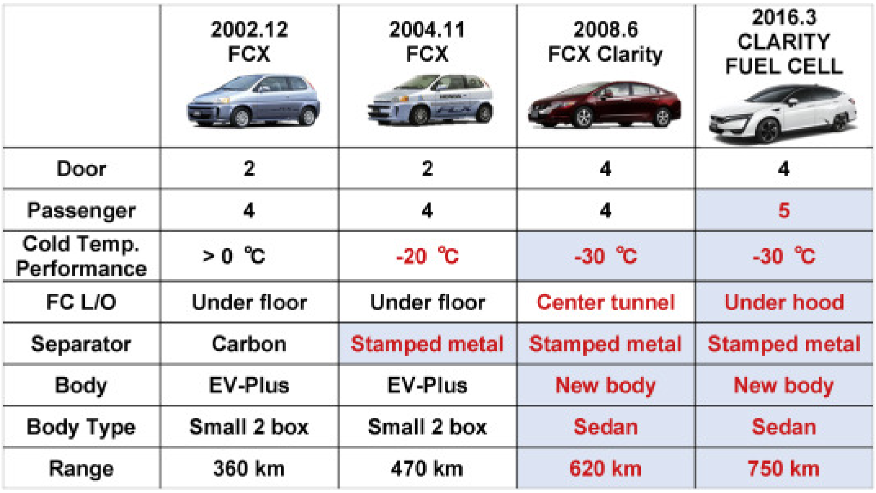


Fig. 2.1. Hydrogen production and consumption in NRW region by 2050.

For the construction of hydrogen energy logistics network, Hanif and Aditya conducted the LCA analysis on the delivery of hydrogen and comparative analysis with pipeline delivery, which shows the huge cost of energy in the production of the FCVs' onboard hydrogen tank[57]. Sahraie and Kamwa developed a hydrogen transportation system to fit the urban traffic system , which use the vehicle routine problem to improve the hydrogen tube trucks' work[58]. Another analysis on this was made by Lahnaoui and wulf, who proposed a plan in the minimization of hydrogen transportation cost and system improvement for the future hydrogen supply in North Rhine-Westphalia[59]. Considering the close connection between hydrogen production and other energy sources and the chemical industry, it is an important idea to coordinate power grid and other systems with the hydrogen energy supply chain. Wang and Bo have proposed a cooperation planning model to design the electricity and hydrogen supply network for the optimistic system in decline energy waste in the transferring process[60].



	2002.12 FCX	2004.11 FCX	2008.6 FCX Clarity	2016.3 CLARITY FUEL CELL
Door	2	2	4	4
Passenger	4	4	4	5
Cold Temp. Performance	> 0 ℃	-20 ℃	-30 ℃	-30 ℃
FC L/O	Under floor	Under floor	Center tunnel	Under hood
Separator	Carbon	Stamped metal	Stamped metal	Stamped metal
Body	EV-Plus	EV-Plus	New body	New body
Body Type	Small 2 box	Small 2 box	Sedan	Sedan
Range	360 km	470 km	620 km	750 km

Fig. 2.2. Evolution of Honda FCV.

For the performance of the hydrogen in the transportation, the analysis and evaluation on the fuel cell vehicles is currently the main research topic. This research trend largely depends on the strategies developed by many countries (completely abolish the sales and operation of fossil fuel vehicles by the middle of this century), which makes FCVs attract attention as a next-generation alternative[61]. The commercial FCV made by Honda was an important sign in the history of hydrogen application[62]. The fuel cell vehicle developed by Honda Motor Corporation symbolizes the transition of fuel cell vehicles from concept cars and technology demonstrations to formal commercial application as Figure 2.2 shown. This has epoch-making significance for the development of hydrogen energy technology and transportation industry. Alessandro and Valeria have the LCA evaluation on the PEM fuel cell and found that fuel cell has lower efficiency loss at around 150,000 km working distance[63]. For the built hydrogen energy transportation system, Iceland's hydrogen energy bus practice is more representative[64].

For the future performance of the application of fuel cell, Ralf and Janos evaluated a variety of possible energy options in future long-distance road transportation. Daniele and Antonio had the LCA comparative evaluation in hydrogen fueled vehicles and points out that the mix energy system of hydrogen and petrol or nature gas will be a good choice in the short-term[11]. Among them, the overall performance of hydrogen fuel cells vehicle is second only to electric vehicles. However, the technology at this stage still needs to be iterated to fully meet market demand[65]. Kim have the evaluation on the hydrogen energy system in the road transportation and found that hydrogen will have the 76% share under the high tax rate and high petrol price scenario[66]. Sandum and Kasun proposed that the FCVs has the long-term advantage compared to the electricity trucks under the LCA view, but the lack of infrastructure and security in the hydrogen supply chain will be the problem.[67]. You and Kim conducted a special comparative analysis is about the transportation cost of liquid hydrogen, LNG and liquid ammonia in international shipping. This work also investigated the future energy marine transportation system using emerging energy sources was verified and compared[68].

In addition, since the material epitaxy of current hydrogen technology is no longer limited to pure hydrogen energy storage-production technology, the technical models of various hydrogen carriers should be paid attention to. Ogden and Amy discussed the role of nature gas in the hydrogen transportation[69]. Otto analyzed and compared a wider range of hydrogen carriers and hydrocarbons, which clearly pointed out the positive effects that low-temperature hydrogen and ammonia can produce in the fields of transportation and power generation. Shi and Chen compared the achievements of several countries in the hydrogen and ammonia storage and transportation technology route, and believed that hydrogen and ammonia, as emerging energy sources to replace fossil fuels, have complementary characteristics in themselves, which will be of great importance in the future research and application in the field of transportation[70].

In general, for the exploration of the field of transportation under the background of hydrogen economy, the application and analysis of hydrogen and hydrogen carriers have achieved certain results. The current core issue of the hydrogen energy technology system is also gradually emerging—that is, whether the environmental performance, efficiency, and durability of related equipment surrounding hydrogen energy can meet human standards. Among them, fuel cell vehicles are a research field that involves both the establishment of hydrogen energy networks and the hydrogenation of transportation equipment, and its research progress is directly related to the construction of the future hydrogen energy economy. For fuel cell vehicles, in addition to the application dilemma caused by the less infrastructure, the higher cost of fuel cell vehicles' own functions and energy storage than fuel vehicles is also a serious problem. Therefore, it is necessary to provide a systematic review of hydrogen storage technologies in fuel cell vehicles in subsequent analyses to better guide the development of efficient on-board hydrogen storage systems.

2.1.3 Research status of hydrogen storage

In the previous section, we have reviewed the current development of hydrogen energy in the transportation sector, and we have found that hydrogen-powered transportation is still constrained by the storage of hydrogen, which has led to overall performance that cannot yet replace traditional fossil fuels. As the most significant issue in the process of hydrogen energy application, if the changes and breakthroughs in the field of hydrogen storage can be realized will directly affect the subsequent technology application and industrial construction, and even the future development of hydrogen energy economy[71].

Hydrogen has a wide range of application scenarios in the future, which has led to the various classification standards in hydrogen storage, including fixed and mobile, physical hydrogen storage and chemical (material) hydrogen storage, pure hydrogen and hydrogen carriers, etc.[71].

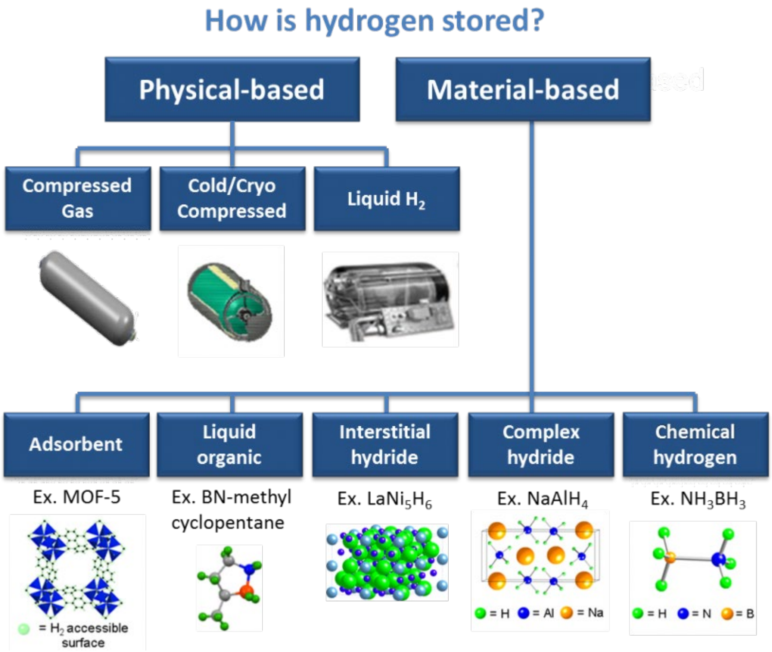


Fig. 2.3. The different pattern of hydrogen storage.

If we classify from the technical path of hydrogen storage, we will get two technical fields of physical hydrogen storage and chemical hydrogen storage. The main principle of physical hydrogen storage is to change the form of hydrogen fuel (generally pure hydrogen). The most traditional technical means include pressurization and cryogenic liquefaction (or both), more advanced methods may use porous materials (such as activated carbon[72]) to absorb hydrogen, but in general, this type of hydrogen storage The patterns themselves do not involve material changes.

High-pressure hydrogen storage has become the most widely used hydrogen storage method at the moment in the fields of chemical industry and hydrogen energy, with the most mature technology and a complete industrial chain. This hydrogen storage method originates from the pressurized storage of gas in the chemical industry. Usually, hydrogen will be pressurized to a pressure of 35MPa or 70MPa[73] and stored in a container with a composite structure. At present, this kind of container has been developed to the fourth generation technology (Type 4 Vessel)[74-76]. The main body and the third generation container (Type 3 Vessel) are both composite winding carbon fiber structures[77-79], which are responsible for bearing internal and external pressure[80, 81]. The biggest difference in the structure of the two generations of containers is the material of the inner lining. The third generation of containers is made of aluminum alloy to deal with hydrogen embrittlement and hydrogen leakage, while the fourth generation of containers is made of polymers.

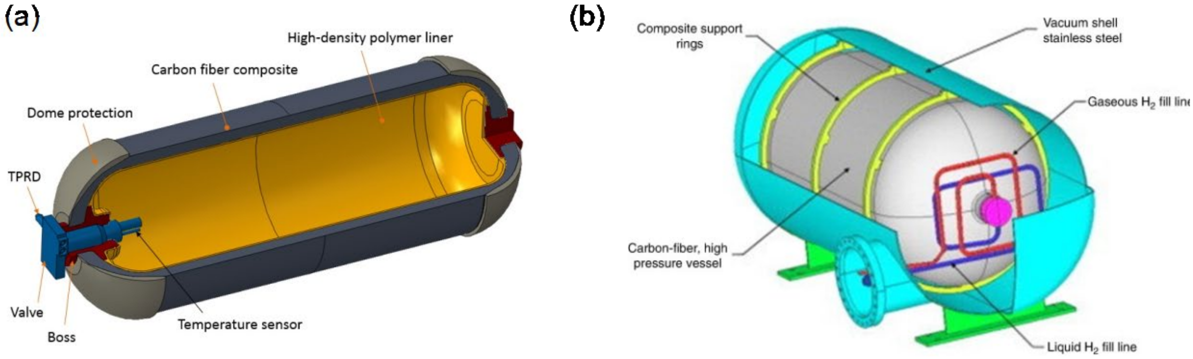


Fig. 2.4. (a) Type 4 high-pressured vessel[82]; (b) cryogenic vessel[79].

Another type of physical storage is cryogenic storage or liquefaction storage. The boiling point of hydrogen is -252.8 degrees Celsius, cryogenic storage needs to lower the temperature of hydrogen to its liquefaction to obtain higher storage density, and this temperature needs to be maintained during storage. Cryogenic storage now often involves a pressurization process for better storage results[83]. Storage containers are based on pressure vessels with an insulating layer and a temperature control device added. However, this device needs to be kept in operation for a long time to maintain a liquid state[84].

The above two physical storage methods are relatively mature hydrogen storage models. However, as the requirements for hydrogen storage continue to increase, the defects of physical hydrogen storage are gradually exposed, while chemical hydrogen storage has also become the focus of current research.

The technical path of chemical hydrogen storage mainly lies in the development of hydrogen storage materials. The storage of hydrogen depends on chemical properties and reactions, so it is also called material hydrogen storage. Chemical hydrogen storage often involves the selection of hydrogen carriers, the conversion between hydrogen and carriers, and the development of carrier containers. The efficiency and loss of hydrogen carriers, and the safety during storage are all issues that will be involved in the technical evaluation of chemical hydrogen storage.

Hydrogen storage carriers include the following categories: ammonia, organic liquid hydrogen carrier (LOHC)[85], formic acid, metal hydride, etc. Among those to focus on are ammonia, methanol, and metal solid hydrides.

Ammonia has obvious advantages as a hydrogen carrier. Ammonia itself does not contain carbon, so it produces no carbon emissions when it reacts in the fuel cell. The storage conditions of ammonia are simpler than that of pure hydrogen, and the safety requirements for containers are lower. Ammonia has a high hydrogen loading capacity, and at the same time[86], the ammonia industry has mature technology and can be mass-produced[87-89]. Whether it is used as a carrier of pure hydrogen or directly used for energy supply, there are technical reserves, so ammonia is considered to be an ideal choice in material hydrogen storage.

Methanol, another type of hydrogen carrier, is produced in the chemical industry based on the reaction of pure hydrogen and carbon dioxide[90]. Although methanol will generate carbon emissions in the transfer, the production process of methanol itself can be co-produced with the carbon capture system, so that the carbon cycle can be added to the energy system to reduce carbon emissions. At the same time, methanol is in a liquid state at room temperature, and its storage container does not need to meet the storage standards of hydrogen or ammonia, which is also lower in cost and more conducive to large-scale transportation and application. Therefore, methanol, as a kind of hydrogen carrier, has its unique advantages[91].

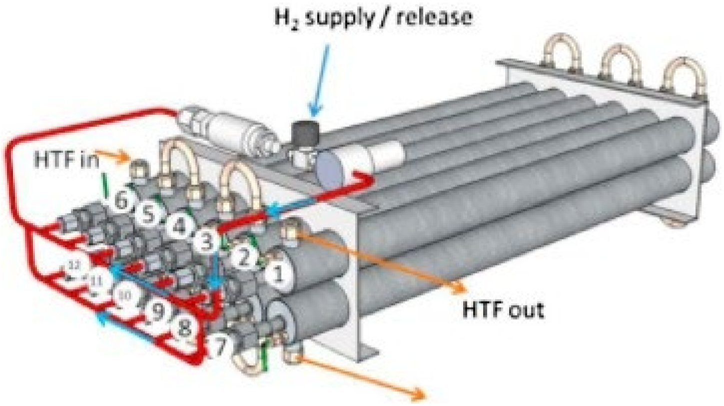


Fig. 2.5. Scheme of the structural part of the solid-state hydrogen storage tank of the SSH2S APU.

Metal hydride is the technical field that is currently focused on the development of solid-state hydrogen storage systems. The metal hydride itself has the characteristic of adsorption, and it will absorb and release hydrogen gas with the change of temperature, so as to play a storage effect[72, 92, 93]. One example is the SSH2S project shown by Figure 2.5, which contains intermetallic compound in 12 vessels and coupled with PEM fuel cell.

Since the application of hydrogen energy in the transportation field is still in its infancy and the scope is extremely limited, there are still not enough cases to analyze the overall technology application situation. The most important application scenario for mobile hydrogen storage is the family car without a fixed working environment, especially the most common four-seater or five-seater car. For example, Honda's FCX series fuel cell vehicles are the world's first commercial fuel cell vehicles, which use the 35MPa high-pressure hydrogen storage technology. Due to its simple and mature structure, high-pressure hydrogen storage technology is also the mainstream hydrogen storage technology solution for existing fuel cell vehicle cases. Since there is no fixed application scenario for family cars, this also represents the upper limit of the versatility of the fuel cell vehicle technology in practical applications, and in turn represents the upper limit of the versatility of the mobile hydrogen storage equipment equipped with it.

In summary, although the development of hydrogen storage technologies has achieved the above results, it is still necessary to evaluate these technologies to determine their improvement direction and application prospects. In particular, the mobile hydrogen storage technology based on the application of fuel cell cars has actually become a key research topic in the field of hydrogen energy applications. Therefore, it is necessary to evaluate hydrogen storage technologies in different dimensions, especially to fully reflect the evaluation of characteristics in mobile hydrogen storage scenarios, which is also the core of this study.

2.1.4 Research status of multi-dimensional comparative method for hydrogen storage technology

When considering the real-world application of a technology, we often need to consider its performance from multiple dimensions, such as efficiency, cost, safety, and environmental impact. This also requires us to evaluate and analyze the various hydrogen storage technologies from different perspectives, as there are many types of technologies expected to be widely applied. The evaluation and analysis of hydrogen storage technology in different environments and application scenarios constitute the basis for our judgment on technology performance and selection.

For mature storage technology, like pressurized and liquefied storage, the evaluation concentrates on the storage efficiency, environment impact and security test. Juan and Damien had the simulation and experiment on the burst of 70MPa high pressure hydrogen vessel to clarify the structure system of polymer[75]. Bie and Li evaluated the fatigue life of the high pressure storage vessel[94]. Mohammad and Sergii provides a kind of risk evaluation method for the onboard hydrogen storage of vehicle[95]. Fowler and Orifici evaluated the optimization and risk assessment of a composite structure annular vessel for high-pressure fuel gas storage. This configuration provides a broader idea for the future design of FCVs[96]. Ahuwalia and Hua evaluated the performance of cryogenic pressure vessels and observed their performance in hydrogen vehicles[83].

There has been a significant shift in the evaluation models for different material storage. Taking ammonia storage as an example, the effect of storing ammonia directly for use in ammonia fuel cells versus using it as a hydrogen carrier to produce hydrogen for use in hydrogen fuel cells can be quite different. Andrea had evaluated the life cycle of ammonia as a source of electricity and found that ammonia as an energy source has good environmental potential[97].

Judging from the overall literature performance, for traditional hydrogen storage technology, the main problem is still the optimization and safety of the structure. Environmental impact, especially in the field of equipment manufacturing, is still under-researched. Compared with the emphasis on technical requirements for physical hydrogen storage, the current material hydrogen storage is still in the verification stage, and there are not many corresponding industrial practice cases. Alessandro and Nadia had the environmental and technical evaluation between the pressure storage and solid storage applied on the automobile. The result shows that solid storage is still limited by its cots and needs improvement[93] Other storage materials, such as ammonia and methanol, have relatively low storage requirements. Other storage materials, such as ammonia and methanol, have relatively low storage requirements. The main dilemma lies in the efficiency and environmental impact of the hydrogen conversion process (such as energy consumption and carbon emissions in the process of ammonia electrolysis for hydrogen production)[86, 98].

Through this series of studies, we will find that the extension of application scenarios has brought more demands for hydrogen storage technology, and has made the evaluation, research, and comparison of hydrogen storage technologies more diversified. However, at least for the foreseeable future, the application of hydrogen storage technologies in the transportation sector will still be the focus of development. This requires us to consider what hydrogen storage technologies need to achieve for the complex field of transportation and what we can do to achieve these goals.

2.2 Research gap

In the literature review section, we found that the current hydrogen energy technology and industry are restricted by the development level of hydrogen storage technology. The practice of hydrogen energy in the transportation field also urgently needs the further development of hydrogen storage technology. Therefore, in this case, establishing a reasonable hydrogen storage technology evaluation system and realizing a linkage mechanism with industrial policies is a very critical idea. From this we can find the following research gap:

(1) The application scenario analysis of hydrogen storage technology devices is

still insufficient. The actual application performance of the hydrogen storage technology device should be used as an important basis for evaluating its performance, which is a relatively lacking part of the original research. The improvement and optimization of hydrogen storage technology should be combined with its future application direction, so it is necessary to analyze the application scenarios of hydrogen storage devices in the transportation field.

(2) The environmental assessment of hydrogen storage technology should involve more dimensions of environmental impact. Hydrogen storage technology at this stage is mainly used in the field of transportation. The characteristics of this field determine that hydrogen storage technology will have a wider environmental impact area than general energy storage. In this case, it is not enough to objectively evaluate the environmental performance of hydrogen storage technology based on a single environmental assessment dimension, so more aspects need to be analyzed.

(3) The economic evaluation of hydrogen storage technologies still lacks analysis for more diverse scenarios. The hydrogen storage system applied to fuel cell vehicles needs to face complex road conditions, which also means that the pure technical index analysis is not enough to support the analysis of the economic benefits of the hydrogen storage system, so a more comprehensive evaluation system is needed.

(4) At present, hydrogen storage technology and industry still lack relevant

industrial policy design. We will find that all countries regard the development of hydrogen storage technology as an important part of hydrogen policy, but there is a lack of specific policy design for hydrogen storage technology and industry. Based on the comprehensive evaluation model in this paper and the original policy case guidance, we will provide suggestions for future hydrogen storage technology and industrial policies.

2.3 Research Objects and Methodology

Based on the aforementioned research gap, this study formulated the following research objectives:

(1) In order to establish the scenario basis for the subsequent evaluation and analysis, we need to calculate the technical parameters of the hydrogen storage device in the application scenario of fuel cell vehicles

(2) In order to have a comprehensive analysis of the environmental impact of the hydrogen storage device in the application scenario of fuel cell vehicles, the environmental impact of the hydrogen storage device in production and application is evaluated from multiple dimensions based on the life cycle assessment.

(3) Based on a variety of fuel cell vehicle application scenarios, conduct a cost-benefit analysis of hydrogen storage devices to obtain corresponding economic performance.

(4) In order to provide suggestions for future hydrogen storage technology and

related industries, this study will design corresponding industrial policies based on evaluation results and historical cases.

The flowchart of research methodology is below:

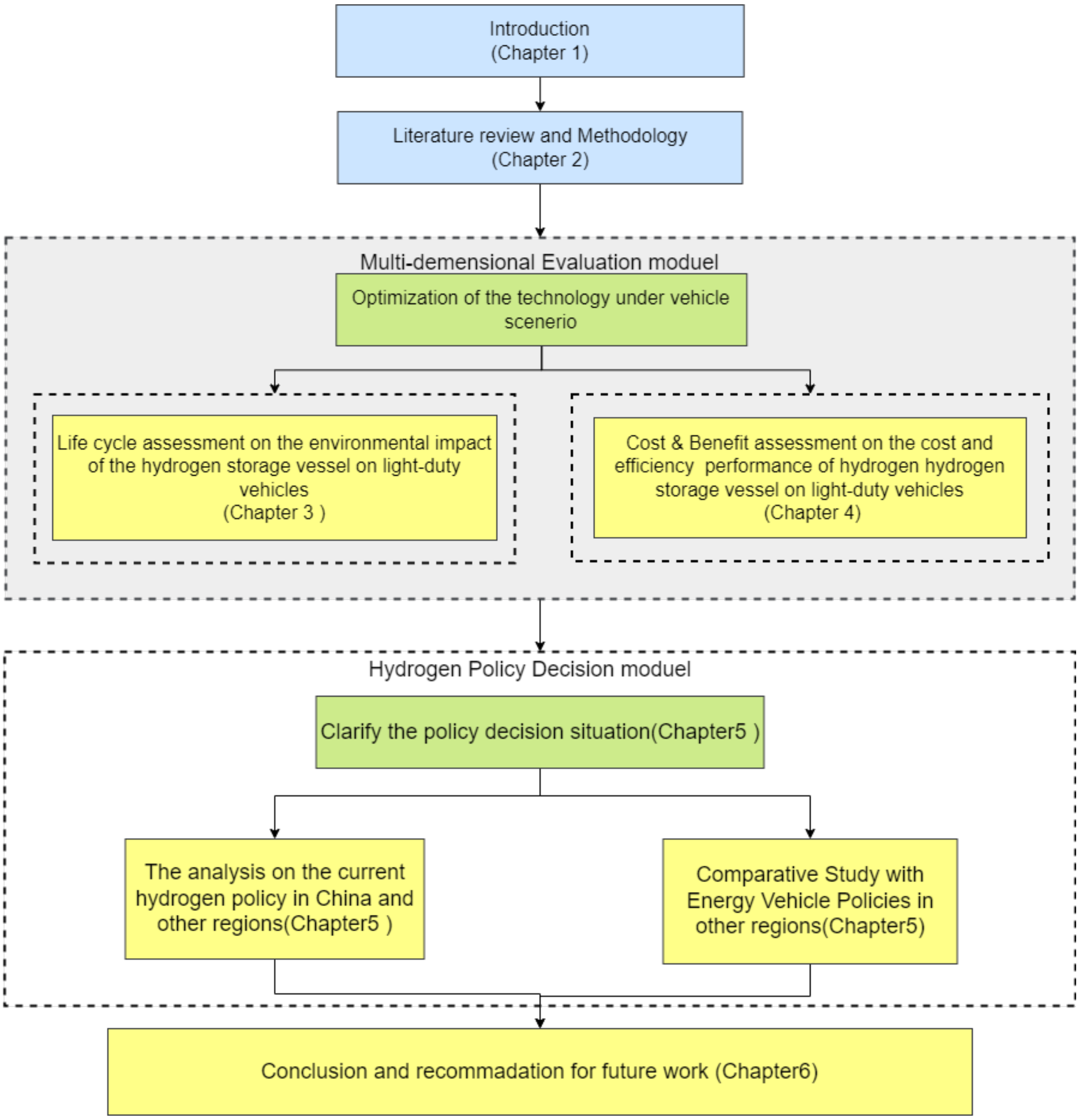


Fig.2.6. The flowchart of research methodology.

Chapter 3 Environmental analysis of hydrogen storage technology

Based on the life cycle assessment (LCA) methodology, different hydrogen storage technologies are evaluated as the assessment objects to quantify the environmental burdens and benefits generated throughout the life cycle of hydrogen storage tanks, including resource consumption, energy use, and pollutant emissions. This evaluation follows the basic steps outlined in the LCA research framework defined by the International Organization for Standardization (ISO), specifically ISO 14040[99] and ISO 14044[100]. These standards provide guidelines for conducting LCA studies, ensuring consistency and reliability in the assessment process[99].

3.1 Goal and scope definition

This section describes the LCA study object and rationale, while also determining the scope and boundaries of the life cycle assessment for hydrogen storage systems.

3.1.1 Determining the research object and purpose

This study selected three hydrogen storage technologies for life cycle assessment research. The chosen three evaluation objects are as follows:

high-pressure hydrogen storage system - Type3 vessel (HHSS-Type3)
high-pressure hydrogen storage system - Type4 vessel (HHSS-Type4)
the cryogenic hydrogen storage system- Type3 vessel (CHSS-Type3)

3.1.2 Functional unit

The functional unit (FU) is a qualitative or quantitative description of the function of a product system and is commonly used as a benchmark unit in research. For this study, the functional unit of the hydrogen storage system is defined as delivering 1 kg of usable hydrogen. The hydrogen storage tanks investigated in this study are categorized into Type 3 and Type 4, both with an expected lifespan of around 10 years[101, 102]. Assuming one refueling cycle per year, the total number of refueling cycles over their lifespan would be 3650 cycles. To meet the functional unit, the reference flow is 2.74×10^{-4} of either Type 3 or Type 4 hydrogen storage tank.

3.1.3 system boundaries and evaluation model

The system boundary for this study is defined from the point where hydrogen enters the hydrogen storage tank until it is transported to the application end. The production of hydrogen and the disposal of the hydrogen storage system are not within the scope of this study. Based on the functional unit defined in this study, the capacity of the three different hydrogen storage systems is 1 kg of hydrogen. Although there may be variations in the materials and components of the different hydrogen storage systems, their function remains the same. The system boundaries for the three hydrogen storage systems are depicted in Figure 3.1, Figure 3.2, and Figure 3.3.

3.1.3.1 high-pressure hydrogen storage system - Type3 vessel and Type4 vessel

In this study, the entire high-pressure hydrogen storage system is seperated into two parts: the hydrogen storage tank and the Balance of Plant (BoP) components[101, 103]. BoP components refer to the auxiliary materials required to ensure the proper operation of the high-pressure hydrogen storage system, including pipelines, valves, electronics, infrastructure, etc. The main difference between Type 3 and Type 4 hydrogen storage tanks lies in their materials. The inner liner of a Type 3 hydrogen storage tank is made of aluminum alloy, while the inner liner of a Type 4 hydrogen storage tank is made of High-Density Polyethylene (HDPE). Table 3.1 presents the main materials included in each category of Type 3 and Type 4 hydrogen storage tanks.

Table 3.1. Main Materials and Components of High-Pressure Hydrogen Storage System.

Component		HHSS-Type3 Main Materials	HHSS-Type4 Main Materials
Hydrogen storage tank		Carbon fiber, resin, aluminum alloy	Carbon fiber, HDPE, resin
Framework		Steel	Steel
BOP	pipeline	stainless steel	stainless steel
	Valves	Stainless steel, aluminum alloy	Stainless steel, aluminum alloy
	Electronic components	Silicon	Silicon
	Infrastructure	Stainless steel, aluminum alloy	Stainless steel, aluminum alloy

Figure 3.1 and Figure 3.2 respectively depict the system boundaries of the lifecycle processes and sub-components for HHSS-Type3 and HHSS-Type4. All components are composed of a variety of different materials. These materials undergo different manufacturing processes and are then assembled during the production stage to form the hydrogen storage system.

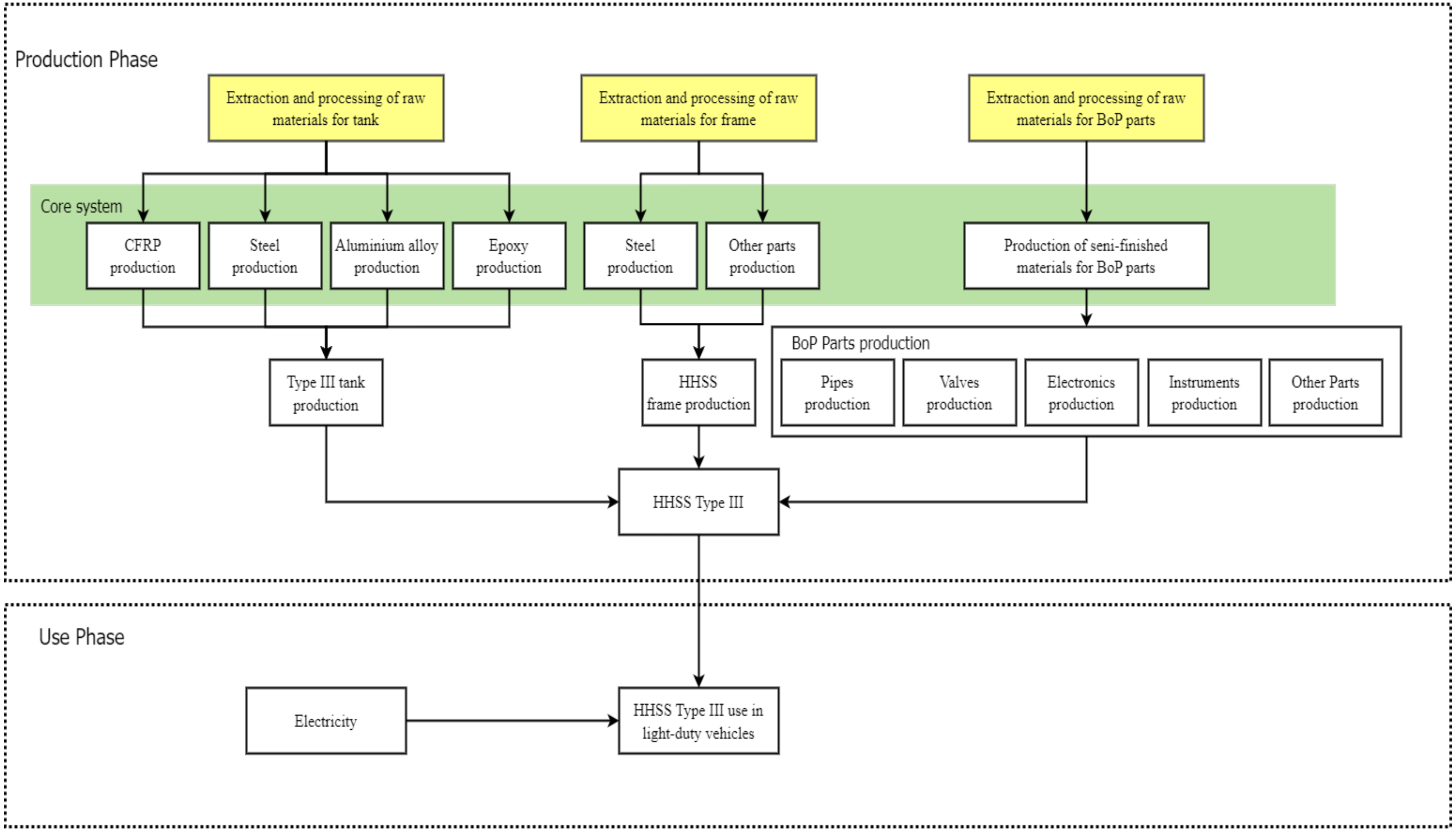


Fig. 3.1. HHSS-Type3 system boundaries.

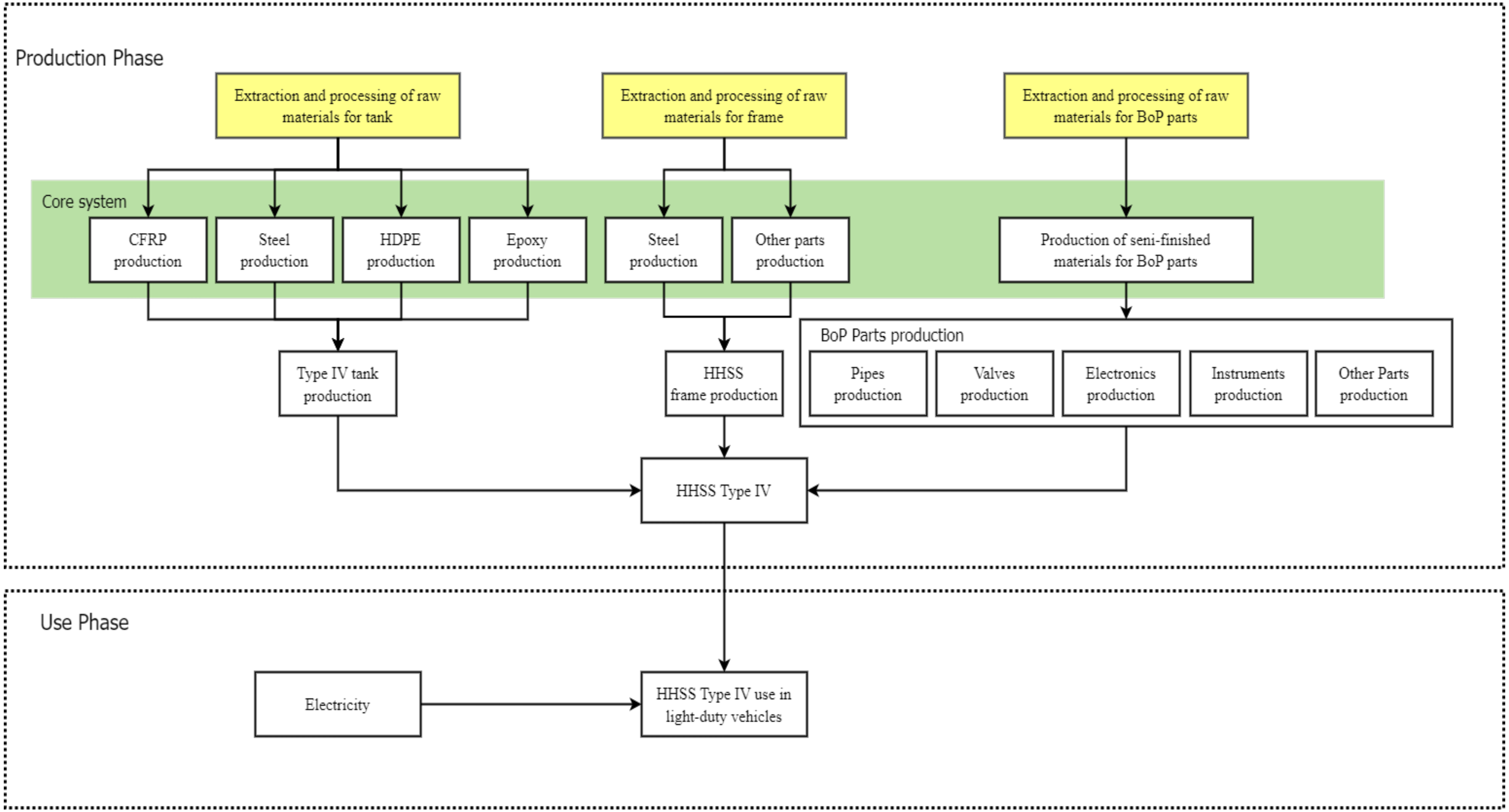


Fig. 3.2. HHSS-Type4 system boundaries.

3.1.3.2 The cryogenic hydrogen storage system- Type3 vessel

A low-temperature hydrogen storage system can also be divided into three parts: the hydrogen tank, the frame, and the Balance of Plant (BoP) components. The inner liner of the tank in the low-temperature system is made of aluminum alloy, while the outer layer is wrapped in carbon fiber. A stainless-steel bracket serves as a fixed support for the outer container, which is also made of stainless steel. There is a hollow layer between the inner and outer containers[101]. The BoP components of the low-temperature hydrogen storage system primarily consist of control modules, valves, heat exchangers, and pipelines, among others. Table 3.2 presents the main components and raw materials of the low-temperature hydrogen storage system.

Table 3.2. Main Materials and Components of the Low-Temperature Hydrogen Storage System.

Component		CHSS-Type3 Main Materials
Hydrogen storage tank		Carbon fiber, Stainless steel, aluminum alloy
BOP	Control modules	Silicon
	Valves	Stainless steel, aluminum alloy
	Electronic components	Silicon
	Infrastructure	Stainless steel, aluminum alloy

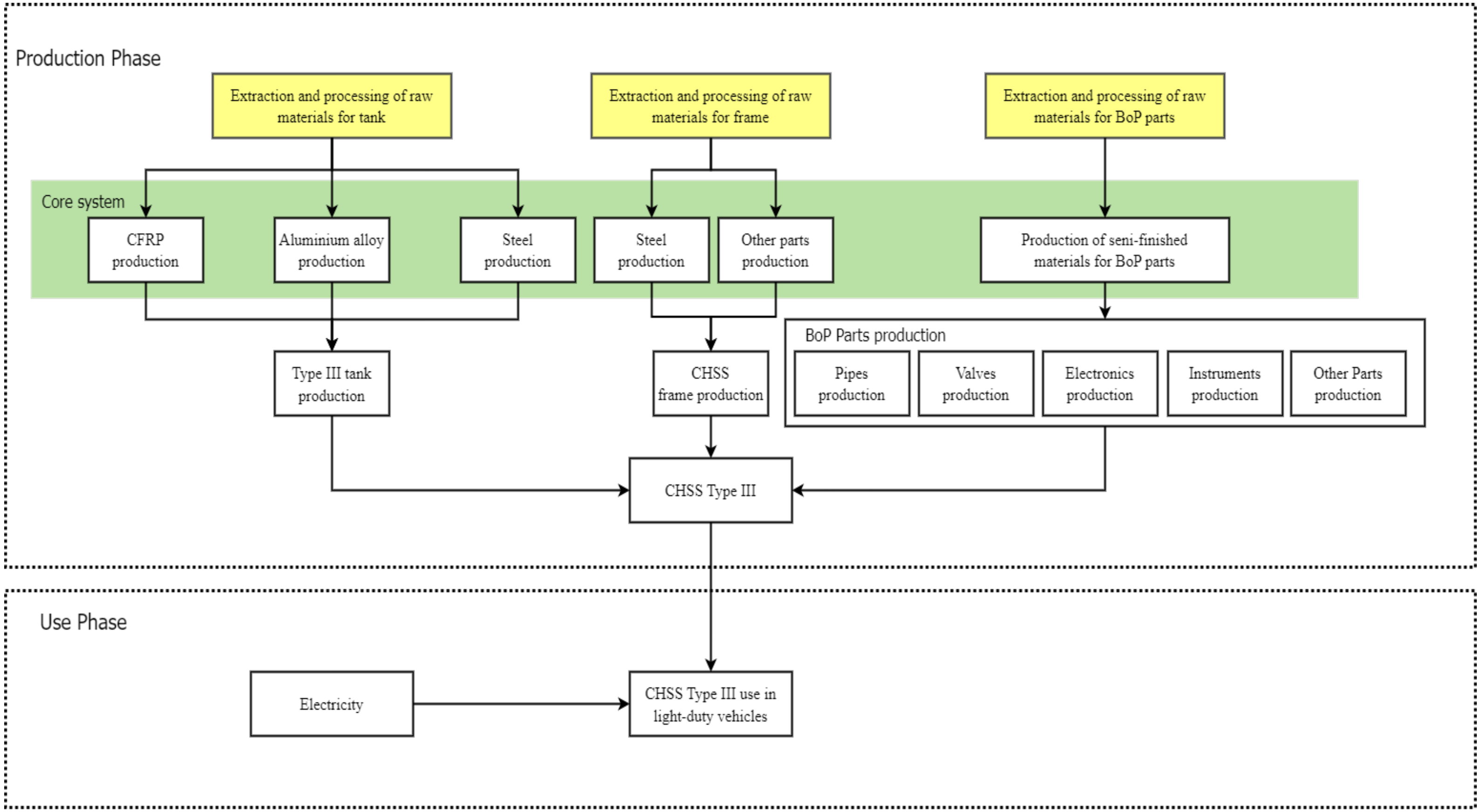


Fig. 3.3. CHSS-Type3 system boundaries.

3.1.4 Assessment method and impact categories

The evaluation method used in this study is ReCiPe 2016 Midpoint. This method focuses on three areas: ecosystem quality, human health, and resource depletion[102].

These three impact areas encompass a total of 18 impact categories. The selected impact categories for this study are as follows:

Climate change：The global warming potential (GWP) is a commonly used midpoint characterization factor for assessing the impact of greenhouse gases (GHGs) on climate change. It measures the integrated infrared radiative forcing increase caused by a GHG and is expressed in kilograms of carbon dioxide equivalent (kg CO2-eq).[103].

Stratospheric ozone depletion：The ozone-depleting potential (ODP) is another commonly used midpoint characterization factor, which is expressed in kilograms of chlorofluorocarbon-11 (CFC-11) equivalents. ODP measures the time-integrated decrease in stratospheric ozone concentration caused by a substance over an infinite time horizon.[104].

Terrestrial acidification：The acidification potential (AP) is a midpoint characterization factor expressed in kilograms of sulfur dioxide (SO2) equivalents. To determine changes in acid deposition resulting from variations in air emissions of nitrogen oxides (NOx), ammonia (NH3), and SO2, researchers used the GEOS-Chem model. They then used the geochemical steady-state model PROFILE to estimate the corresponding changes in soil acidity resulting from the altered acid deposition.[105].

Fossil resource scarcity: The Fossil Fuel Potential (FFP) is a commonly used midpoint indicator for assessing the impact of fossil resource use. The ratio between a fossil resource's higher heating value and crude oil's energy content is measured in kilograms of oil equivalent (kg oil-eq).[106].

3.2 Life Cycle Inventory (LCI) analysis

This section discusses the life cycle inventory and models of the production and use stages of the three hydrogen storage systems. Data on material consumption, energy consumption, and pollutant emissions during the production and use stages of the hydrogen storage systems are sourced from industry studies and literature. Background data for materials are obtained from the Ecoinvent 3.8 database, and modeling analysis is conducted using SimaPro 9.1 software.

3.2.1 Production Stage

This section describes the inventory and modeling of hydrogen storage system production. The production of the hydrogen storage system primarily involves the assembly of its sub-components. The activities in the production stage include the production of auxiliary materials, hydrogen storage system sub-components, and their assembly. For modeling convenience, the sub-components of the hydrogen storage system are divided into three categories: storage tank, framework, and BoP components.

3.2.1.1 The Production of the storage tank

The high-pressure storage tank consists of an inner liner, bosses, and an external protective layer. The inner liner of HHSS-Type3 is made of 6061 aluminum alloy, while HHSS-Type4 uses an HDPE injection-molded liner. The bosses are typically made of 316 stainless steel[93]. For the storage tank, the largest quantity is allocated to the outer layer of CFRP (Carbon Fiber Reinforced Polymer). The CFRP and epoxy resin are combined through a process of circumferential and longitudinal winding to encapsulate the inner liner.

The production data for carbon fiber is referenced from Benitez et al.[107] and ELSA WEISZFLOG[103], and the carbon fiber production process is modeled in SimaPro. The data is from T700 carbon fiber and includes the production of carbon fiber precursor, heat treatment, and final processing. However, carbon fiber production can vary significantly depending on factors such as precursor materials, treatment methods, or temperature variations during production. The inventory data for 1 kg of carbon fiber is presented in Table 3.3.

The inventory data for HHSS-Type3 storage tank is based on the research by Alessandro Agostini et al.[93], with an operating pressure of 35 MPa and a storage capacity of 35 L, which is equivalent to 0.805 kg of hydrogen. Due to the lack of data for a 70 MPa Type3 storage tank, the input-output inventory for Type3 storage tank in this study is estimated based on the 35 MPa storage tank. Alessandro Agostini did not specify the energy consumption data during the production process of HHSS-Type3 storage tank, so the energy consumption data in this study is assumed to be the same as HHSS-Type4 storage tank. The inventory data for HHSS-Type3 storage tank (storing 1 kg of hydrogen) is presented in Table 3.4.

The inventory data for HHSS-Type4 storage tank is based on the research by Alicia Benitez [107] et al., with a similar framework to HHSS-Type3 storage tank. The operating pressure of this storage tank is 70 MPa, and it can store 5.6 kg of hydrogen. Alicia Benitez did not specify the material of the bosses in her research, so this study assumes that the bosses are made of 316 stainless steels. The auxiliary materials and energy consumption during the processing of bosses are referenced from the Ecoinvent database. The inventory data for HHSS-Type4 hydrogen storage tank (storing 1 kg of hydrogen) can be found in Table 3.5.

The inventory data for CHSS-Type3 storage tank is based on the research by Salvador M. Aceves [79] and R.K. Ahluwalia[83].The operating pressure of this storage tank is 34 MPa, and it can store 10.7 kg of hydrogen. The inventory data for CHSS-Type3 storage tank (storing 1 kg of hydrogen) is presented in Table 3.6.

Table 3.3. The inventory data for T700 carbon fiber input and output.

Flow	Value	Unit	Secondary datasets
Inputs			
ammonium bicarbonate	9.0691	kg	Ammonium bicarbonate {RoW}| market for ammonium bicarbonate | APOS, S
nitrogen, liquid	9.2679	kg	Nitrogen, liquid {RoW}| market for | APOS, S
natural gas liquids	0.2339	kg	Natural gas liquids {GLO}| market for | APOS, S
silicone product	0.2679	kg	Silicone product {RoW}| market for silicone product | APOS, S
dimethyl sulfoxide	0.509	kg	Dimethyl sulfoxide {GLO}| market for | APOS, S
methyl acrylate	3.425	kg	Methyl acrylate {GLO}| market for | APOS, S
acrylonitrile	3.1983	kg	Acrylonitrile {GLO}| market for | APOS, S
acrylic acid	0.0283	kg	Acrylic acid {RoW}| market for acrylic acid | APOS, S
epoxy resin insulator, SiO2	0.0102	kg	Epoxy resin insulator, SiO2 {GLO}| market for | APOS, S
ethylene glycol	0.0307478	kg	Diethylene glycol {GLO}| market for | APOS, S
compressed air,1000 kPa gauge	1.496412	Nm^3	Compressed air, 1000 kPa gauge {RoW}| market for compressed air, 1000 kPa gauge | APOS, S
electricity	44.1408	kWh	Electricity, low voltage {CN}| market group for | APOS, S
steam, in chemical industry	23.9936	kg	Steam, in chemical industry {RoW}| market for steam, in chemical industry | APOS, S
steam, in chemical industry	39.1	kWh	Heat, from steam, in chemical industry {RoW}| market for heat, from steam, in chemical industry | APOS, S
water, deionized	50.8500996	kg	Water, deionized {RoW}| market for water, deionized | APOS, S
Outputs			
Carbon fiber	1	kg	Product flows
Carbon dioxide	7.57E+00	kg	Element flows
Nitrogen oxides	1.08E-01	kg	Element flows

Table 3.4. HHSS-Type3 The inventory data for the storage tank input and output for a capacity of 1 kg of hydrogen.

Flow	Value	Unit	Secondary datasets
Inputs			
Aluminum alloy	18.6335	kg	Aluminum alloy, AlMg3 {GLO}| market for | APOS, S
	18.6335	kg	Metal working, average for aluminum product manufacturing {GLO}| market for | APOS, S
Carbon fiber	15.6522	kg	/
Epoxy resin	10.4348	kg	Epoxy resin insulator, SiO2 {GLO}| market for | APOS, S
Stainless steel 316	0.6211	kg	Steel, unalloyed {GLO}| market for | APOS, S
	0.6211	kg	Metal working, average for steel product manufacturing {GLO}| market for | APOS, S
Electricity, low voltage	152.2650	MJ	Electricity, low voltage {CN}| market group for | APOS, S
Compressed air, 1000 kPa gauge	0.0266	m^3	Compressed air, 1000 kPa gauge {RoW}| market for compressed air, 1000 kPa gauge | APOS, S
Outputs			
HHSS-Type3 hydrogen storage vessel	1	Item	Product flows

Table 3.5. HHSS-Type4 The inventory data for the storage tank input and output for a capacity of 1 kg of hydrogen.

Flow	Value	Unit	Secondary datasets
Inputs			
HDPE	1.3473	kg	Polyethylene, high density, granulate {GLO}| market for | APOS, S
	1.3473	kg	Polyethylene, high density, granulate {GLO}| market for | APOS, S
Carbon fiber	13.5595	kg	/
Epoxy resin	4.6548	kg	Epoxy resin insulator, SiO2 {GLO}| market for | APOS, S
Stainless steel 316	0.1710	kg	Steel, unalloyed {GLO}| market for | APOS, S
	0.1710	kg	Metal working, average for steel product manufacturing {GLO}| market for | APOS, S
Electricity, low voltage	152.2650	MJ	Electricity, low voltage {CN}| market group for | APOS, S
Compressed air, 100 kPa gauge	0.0266	m^3	Compressed air, 1000 kPa gauge {RoW}| market for compressed air, 1000 kPa gauge | APOS, S
Outputs			
HHSS-Type4 hydrogen storage vessel	1	Item	Product flows

Table 3.6. CHSS-Type3 The inventory data for the storage tank input and output for a capacity of 1 kg of hydrogen.

Flow	Value	Unit	Secondary datasets
Inputs			
Aluminum liner	5.8318	kg	Aluminum alloy, AlMg3 {GLO}| market for | APOS, S
	5.8318	kg	Metal working, average for aluminum product manufacturing {GLO}| market for | APOS, S
Carbon fiber	2.1215	kg	/
Stainless steel 316	4.6075	kg	Steel, unalloyed {GLO}| market for | APOS, S
	4.6075	kg	Metal working, average for steel product manufacturing {GLO}| market for | APOS, S
Electricity, low voltage	18.5000	mj	Electricity, low voltage {CN}| market group for | APOS, S
Compressed air, 100 kPa gauge	0.0032	m^3	Compressed air, 1000 kPa gauge {RoW}| market for compressed air, 1000 kPa gauge | APOS, S
Outputs			
CHSS-Type3 hydrogen storage vessel	1	Item	Product flows

Table 3.7. The inventory data for the frame of different hydrogen storage systems with a capacity of 1 kg of hydrogen.

Hydrogen storage system	Cost, kg	Secondary datasets
HHSS-Type3	14	Steel, unalloyed {GLO}| market for | APOS, S
	14	Metal working, average for steel product manufacturing {GLO}| market for | APOS, S
HHSS-Type4	14	Steel, unalloyed {GLO}| market for | APOS, S
	14	Metal working, average for steel product manufacturing {GLO}| market for | APOS, S
CHSS-Type3	6	Steel, unalloyed {GLO}| market for | APOS, S
	6	Metal working, average for steel product manufacturing {GLO}| market for | APOS, S

Table 3.8. The inventory data for the Balance of Plant (BoP) components of the HHSS system with a capacity of 1 kg of hydrogen.

Flow	Value	Unit	Secondary datasets
Inputs			
Pipes	0.4488	kg	Steel, unalloyed {GLO}| market for | APOS, S
	0.4488	kg	Metal working, average for steel product manufacturing {GLO}| market for | APOS, S
Electronics	0.0749	kg	Electronics, for control units {GLO}| market for | APOS, S
Valves	0.1144	kg	Aluminum alloy, AlMg3 {GLO}| market for | APOS, S
	0.1144	kg	Metal working, average for aluminum product manufacturing {GLO}| market for | APOS, S
	0.3431	kg	Steel, unalloyed {GLO}| market for | APOS, S
	0.3431	kg	Metal working, average for steel product manufacturing {GLO}| market for | APOS, S
Instruments	0.0069	kg	Aluminum alloy, AlMg3 {GLO}| market for | APOS, S
	0.0069	kg	Metal working, average for aluminum product manufacturing {GLO}| market for | APOS, S
	0.0179	kg	Steel, unalloyed {GLO}| market for | APOS, S
	0.0179	kg	Metal working, average for steel product manufacturing {GLO}| market for | APOS, S
Outputs			
HHSS BoP components	1	Item	Product flows

Table 3.9. CHSS BoP (Balance of Plant) components input-output inventory data for a capacity of 1 kg of hydrogen.

Flow	Value	Unit	Secondary datasets
Inputs			
Electronics	0.2243	kg	Electronics, for control units {GLO}| market for | APOS, S
Valves	0.1612	kg	Aluminum alloy, AlMg3 {GLO}| market for | APOS, S
	0.1612	kg	Metal working, average for aluminum product manufacturing {GLO}| market for | APOS, S
	0.4837	kg	Steel, unalloyed {GLO}| market for | APOS, S
	0.4837	kg	Metal working, average for steel product manufacturing {GLO}| market for | APOS, S
Heat exchanger	0.1402	kg	Steel, unalloyed {GLO}| market for | APOS, S
	0.1402	kg	Metal working, average for steel product manufacturing {GLO}| market for | APOS, S
Pipes	0.3738	kg	Steel, unalloyed {GLO}| market for | APOS, S
	0.3738	kg	Metal working, average for steel product manufacturing {GLO}| market for | APOS, S
Instruments	0.0069	kg	Aluminum alloy, AlMg3 {GLO}| market for | APOS, S
	0.0069	kg	Metal working, average for aluminum product manufacturing {GLO}| market for | APOS, S
	0.0179	kg	Steel, unalloyed {GLO}| market for | APOS, S
	0.0179	kg	Metal working, average for steel product manufacturing {GLO}| market for | APOS, S
Outputs			
CHSS BoP components	1	Item	Product flows

3.2.1.2 The production of the framework

The framework production models for all hydrogen storage systems are similar. The framework is made of S355 steel, which is a low-carbon steel with galvanized and powder-coated finish. However, the specific type of steel used in each framework differs. Since background data for S355 steel is not available in the Ecoinvent database, a substitute non-alloy steel is selected. The consumption quantities of the framework for different hydrogen storage systems are shown in Table 3.6.

3.2.1.3 The production of Balance of Plant (BoP) components

The BoP components for HHSS-Type3 and HHSS-Type4 are similar, consisting primarily of valves, pipes, electronic components, and infrastructure. Due to limited research and data availability on BoP components for hydrogen storage systems, it is assumed that the material consumption for BoP components in HHSS-Type3 and HHSS-Type4 is the same. The production inventory for BoP components in HHSS-Type3 and HHSS-Type4 is presented in Table 3.7. For the BoP components of CHSS-Type3 hydrogen storage system, the reference is the study conducted by R. K. Ahluwalia and others[83]. The consumption data for infrastructure is assumed to be consistent with that of high-pressure hydrogen storage systems. The production inventory for BoP components in CHSS-Type3 is provided in Table 3.8.

3.2.2 The use phase

The use phase involves the compression or liquefaction of hydrogen for storage purposes. Common mature methods of hydrogen storage include high-pressure storage and cryogenic liquefaction. In the use phase, the focus is mainly on the energy requirements for compressing or liquefying hydrogen.

For high-pressure hydrogen storage systems, the hydrogen is compressed to a pressure of 70 MPa and pre-cooled to -40°C. Assuming the initial state of hydrogen is 0.2 MPa, the theoretical energy required for isothermal compression from 0.2 MPa to 70 MPa is 1.36 kWh/kg.H_2[108]. The efficiency of hydrogen compression is typically around 75%, so the actual energy consumption for the compression process is 1.81 kWh/kg H_2. Additional energy of 0.2 kWh/kg.H_2 is required for cooling the hydrogen to -40°C.

For cryogenic hydrogen storage systems, the hydrogen needs to be liquefied, but compression may not be necessary. The minimum theoretical energy for liquefying hydrogen at (300 K, 1.01 bar) is 3.3 kWh/kg.LH_2[109]. However, the actual energy requirement for liquefaction is much higher, typically ranging from 10 to 13 kWh/kg. LH2, depending on the scale of the liquefaction operation. For this study, a value of 13 kWh/kg L H_2[110] is used.

3.3 Life Cycle Impact Assessment and Interpretation of Results

The chapter analyzes the environmental impacts of three types of hydrogen storage tanks and compares the environmental performance of different hydrogen storage systems throughout their life cycle to deliver 1 kg of hydrogen. Sensitivity analysis is used to measure the impact of variations in electricity consumption due to different countries of production and use, as well as the compression or liquefaction of hydrogen. The overall environmental impact results of the hydrogen storage systems are provided in the appendix.

3.3.1 Environmental Impact Analysis of Hydrogen Storage Tanks

Based on the inputs and outputs of the three types of hydrogen storage tanks, a life cycle assessment (LCA) model of the storage tanks can be established in SimaPro software. The ReCiPe method can be used to assess the environmental impacts of the storage tanks in four impact categories: Global warming, Stratospheric ozone depletion, Terrestrial acidification, and Fossil resource scarcity.

3.3.1.1 Global warming

The environmental burdens in terms of the greenhouse effect impact category for the three hydrogen storage systems are shown in Figure 3.4. According to the analysis results, the HHSS-Type3 storage tank exhibits the highest environmental burden, while the CHSS-Type3 storage tank has the lowest environmental burden. The greenhouse effect contributions of HHSS-Type3 and HHSS-Type4 storage tanks are 1871 kg CO_2eq and 1381 kg CO_2eq, respectively. The carbon emissions are primarily attributed to CFRP (carbon fiber reinforced polymer), accounting for 84% and 96% of the total emissions for HHSS-Type3 and HHSS-Type4 tanks, respectively. For HHSS-Type3 tank, the environmental burden associated with the aluminum alloy liner accounts for 12%, which is significantly higher than the HDPE liner used in HHSS-Type4 tank. The major environmental burden for CHSS-Type3 tank also comes from CFRP, followed by the aluminum alloy. The energy consumption during the production process of CHSS-Type3 tank is relatively low compared to HHSS tanks, resulting in a lower contribution of these processes to the environmental burden.

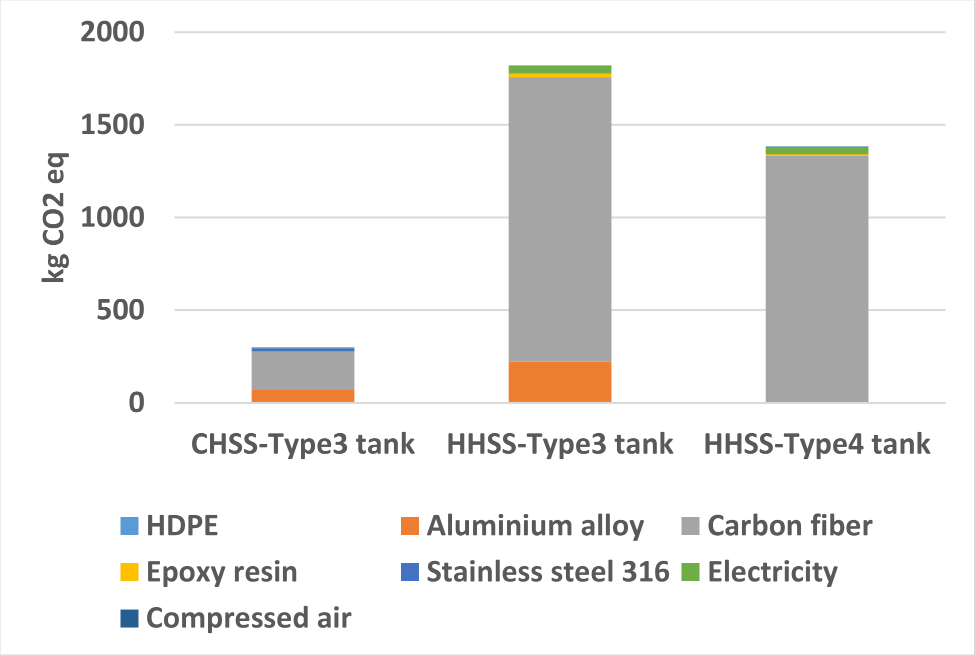


Fig. 3.4. LCIA results of tank for Global warming.

3.3.1.2 Stratospheric ozone depletion

The environmental burdens in terms of the Stratospheric ozone depletion impact category for the three hydrogen storage systems are shown in Figure 3.5. According to the analysis results, the HHSS-Type3 storage tank exhibits the highest environmental burden, while the CHSS-Type3 storage tank has the lowest environmental burden. The Stratospheric ozone depletion contribution of HHSS-Type3 storage tank is 6.66E-04 kg CFC11 eq, which is 5.5 times higher than that of CHSS-Type3 storage tank. The environmental burdens of HHSS-Type3, HHSS-Type4, and CHSS-Type3 storage tanks are primarily attributed to the aluminum alloy and CFRP materials, as well as the electricity consumption during the assembly process of the hydrogen storage system. CFRP accounts for 75%, 95%, and 56% of the total environmental burdens for HHSS-Type3, HHSS-Type4, and CHSS-Type3 tanks, respectively. The environmental burdens associated with aluminum alloy for HHSS-Type3 and CHSS-Type3 tanks are 1.40E-04 kg CFC11 eq and 4.39E-05 kg CFC11 eq, respectively.

3.3.1.3 Terrestrial acidification

The environmental burdens in terms of the Terrestrial acidification impact category for the three hydrogen storage systems are shown in Figure 3.5. According to the analysis results, the HHSS-Type3 storage tank exhibits the highest environmental burden, while the CHSS-Type3 storage tank has the lowest environmental burden.

The environmental burden of the CHSS-Type3 storage tank is 1.21E+00 kg SO_2 eq, primarily attributed to CFRP (66%), aluminum alloy (29%), and stainless steel 316 (3.9%). For the HHSS-Type3 storage tank, CFRP is the material with the highest environmental burden in terms of Terrestrial acidification, accounting for 5.85E+00 kg SO2 eq, which represents 81% of the total Terrestrial acidification burden of HHSS-Type3 tank. The Terrestrial acidification contribution from electricity consumption during the production process of HHSS-Type3 tank is 2.2% of the product's total burden.

The environmental burden of HHSS-Type4 storage tank in terms of Terrestrial acidification is 5.27E+00 kg SO2 eq, with CFRP being the main contributor, accounting for 96% of the burden.

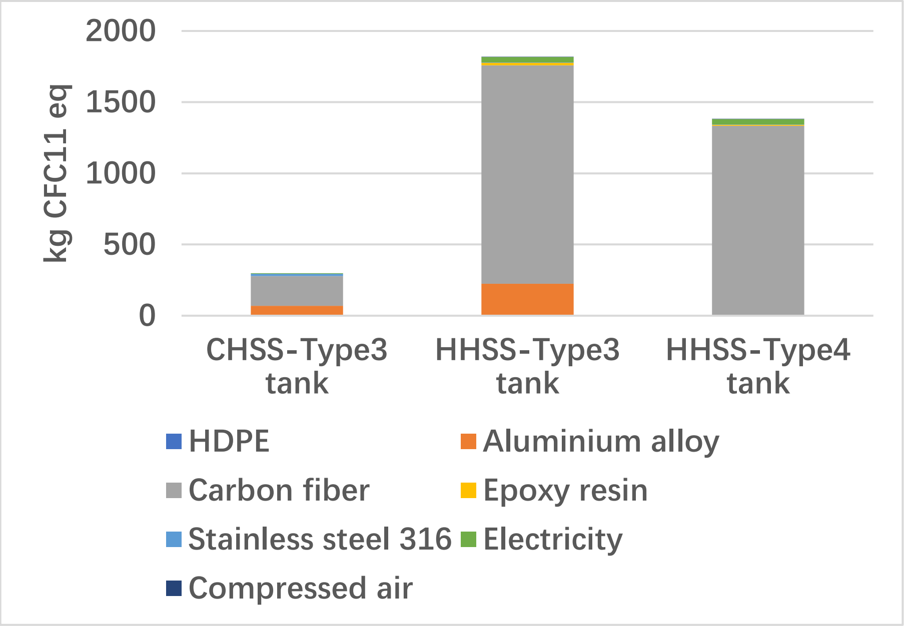


Fig. 3.5. LCIA results of tank for Stratospheric ozone depletion.

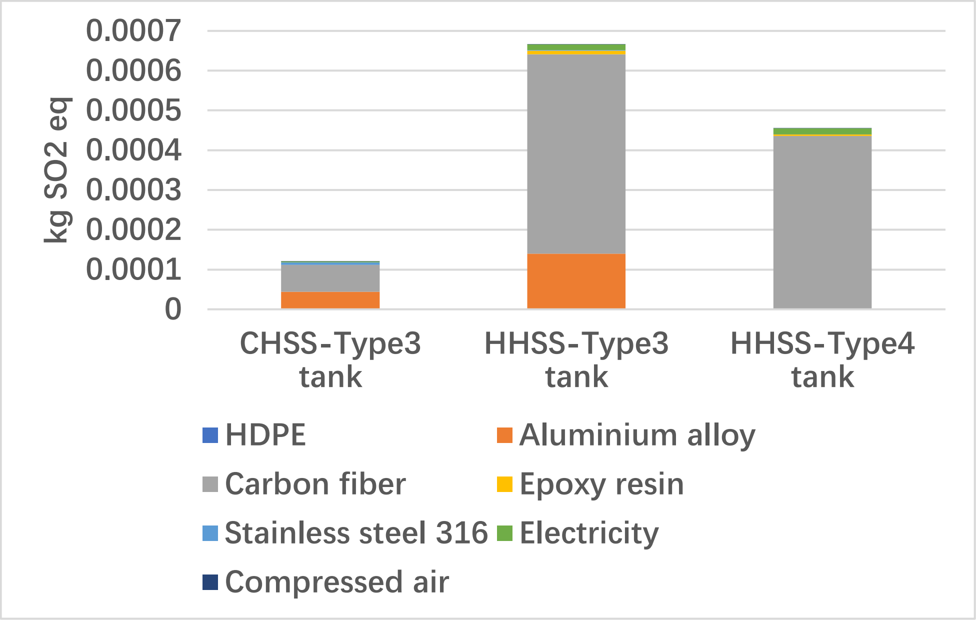


Fig. 3.6. LCIA results of tank for Terrestrial acidification.

3.3.1.4 Mineral resource scarcity

The environmental burdens in terms of the Mineral resource scarcity impact category for the three hydrogen storage systems are shown in Figure 3.7. According to the analysis results, the HHSS-Type3 storage tank exhibits the highest environmental burden, followed by the HHSS-Type3 storage tank, and the CHSS-Type3 storage tank has the lowest environmental burden. The environmental burdens for the three storage tanks are 5.48E+02 kg Cu eq, 4.16E+02 kg Cu eq, and 8.89E+01 kg Cu eq, respectively. The material with the highest contribution to the environmental burden for all three storage tanks is CFRP, followed by aluminum alloy and electricity consumption during the production process.

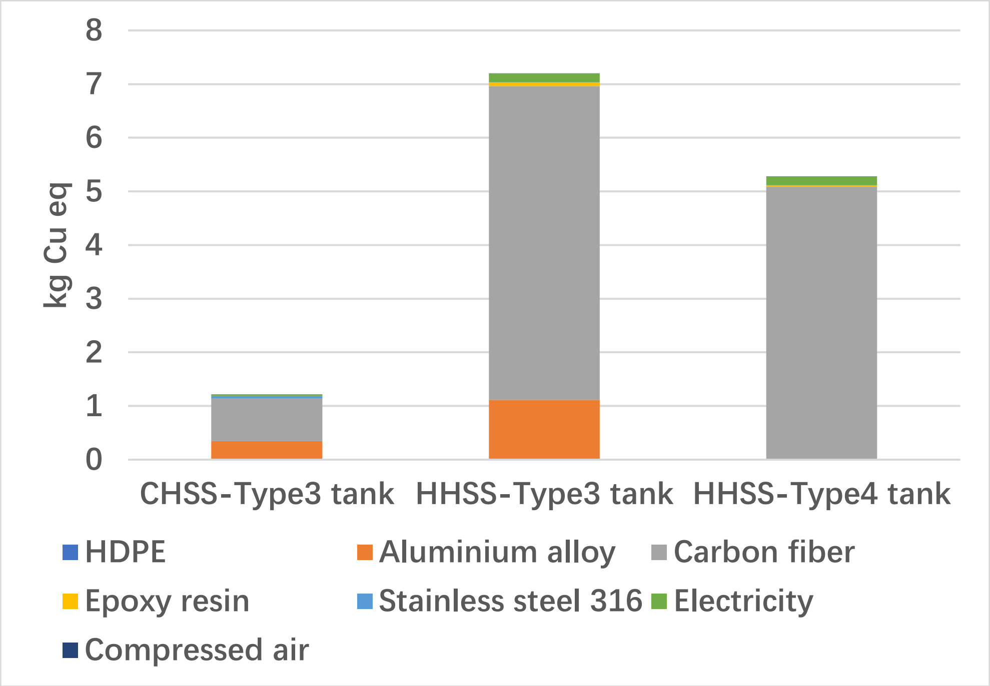


Fig. 3.7. LCIA results of tank for Mineral resource scarcity.

3.3.2 Environmental Impact Analysis of Hydrogen Storage Systems

The chapter analyzes the environmental burdens of hydrogen storage systems in different impact categories when delivering 1 kg of hydrogen. The environmental burdens during the production stage are attributed to the hydrogen storage tanks, frames, and Balance of Plant (BoP) components. The environmental burdens during the usage stage arise from the electricity consumption for hydrogen compression or liquefaction.

3.3.2.1 Global warming

The environmental burdens of the three hydrogen storage systems in the Global warming impact category are shown in Figure 3.8. The CHSS-Type3 hydrogen storage system exhibits the highest environmental burden, followed by the HHSS-Type3 system, while the HHSS-Type4 system has the lowest environmental burden. The environmental burden of the CHSS-Type3 system is 12.12 kg CO2 eq, with electricity consumption accounting for 99% of the total burden. The environmental burdens of the CHSS-Type3 and CHSS-Type4 systems are similar, at 2.37 kg CO2 eq and 2.25 kg CO2 eq, respectively, with usage stage accounting for approximately 80% of the environmental burdens for both hydrogen storage systems.

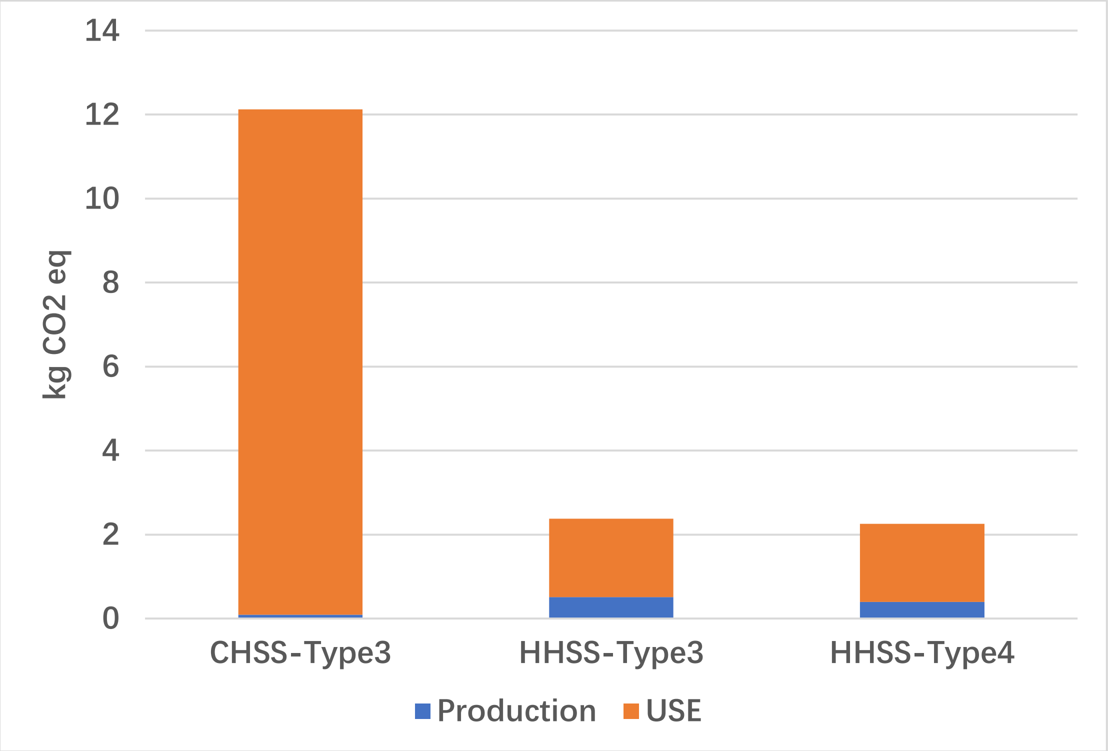


Fig. 3.8. LCIA results of hydrogen storage system for Global warming.

3.3.2.2 Stratospheric ozone depletion

The environmental burdens of the three hydrogen storage systems in the Stratospheric ozone depletion impact category are shown in Figure 3.9. The CHSS-Type3 hydrogen storage system exhibits the highest environmental burden, followed by the HHSS-Type3 system, while the HHSS-Type4 system has the lowest environmental burden. The environmental burdens for the three hydrogen storage systems are 4.65E-06 kg CFC11 eq, 9.02E-07 kg CFC11 eq, and 8.44E-07 kg CFC11 eq, respectively. The largest impactor to the environmental burden is the electricity consumption during the usage stage, accounting for 99%, 79%, and 84% of the total burden for the CHSS-Type3, HHSS-Type3, and HHSS-Type4 systems, respectively.

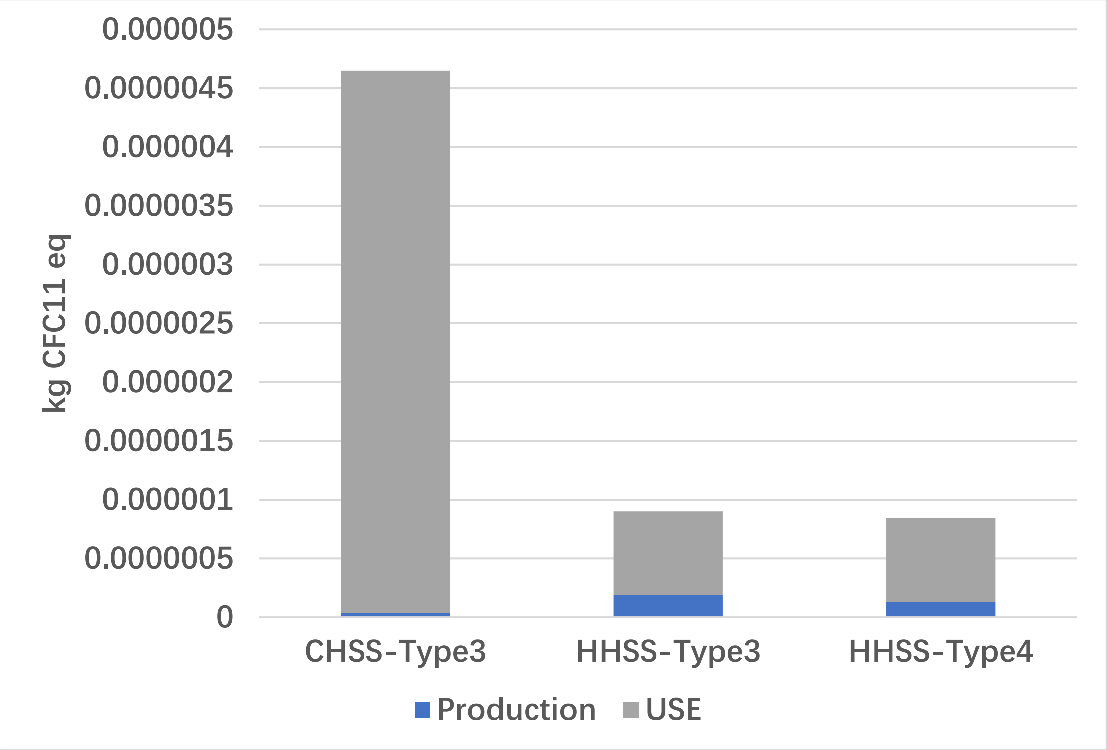


Fig. 3.9. LCIA results of hydrogen storage system for Stratospheric ozone depletion.

3.3.2.3 Terrestrial acidification

The environmental burdens of the three hydrogen storage systems in the Terrestrial acidification impact category are shown in Figure 3.10. The CHSS-Type3 hydrogen storage system exhibits the highest environmental burden, followed by the HHSS-Type3 system, while the HHSS-Type4 system has the lowest environmental burden. The environmental burden for the CHSS-Type3 system is 4.99E-02 kg SO_2 eq, with almost all of the burden stemming from electricity consumption during the usage stage. The environmental burdens for the HHSS-Type3 and HHSS-Type4 systems are 9.67E-03 kg SO_2 eq and 9.15E-03 kg SO_2 eq, respectively.

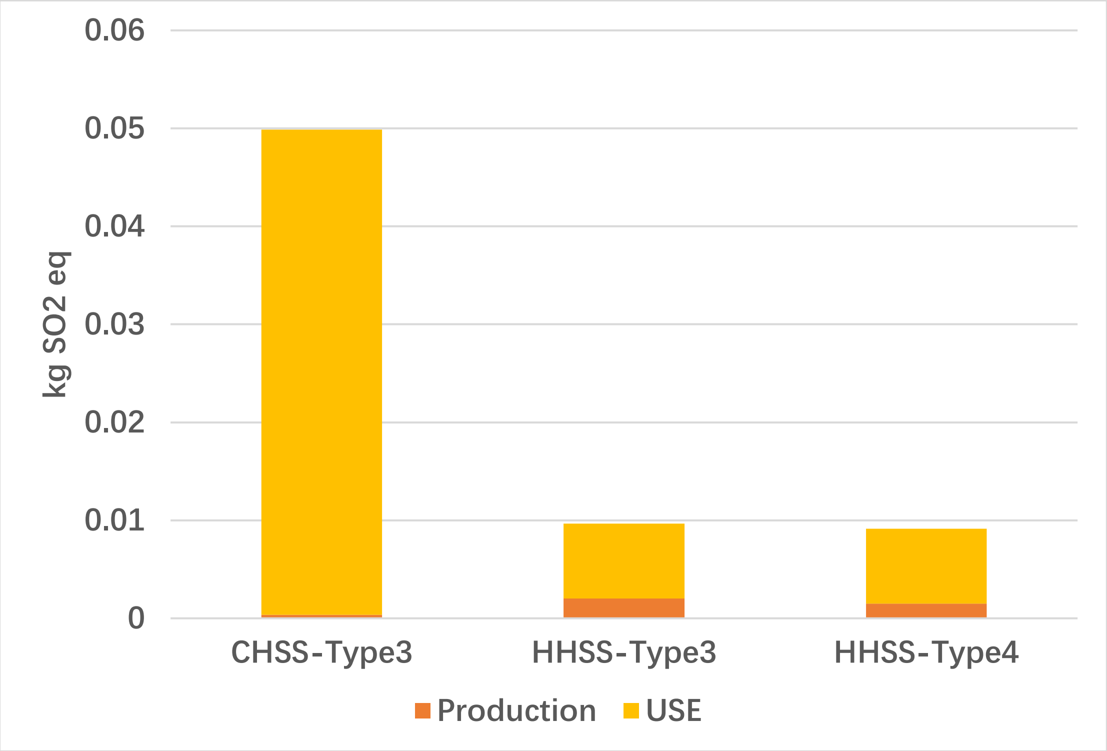


Fig. 3.10. LCIA results of hydrogen storage system for Terrestrial acidification.

3.3.2.4 Mineral resource scarcity

The environmental burdens of the three hydrogen storage systems in the Terrestrial acidification impact category are shown in Figure 3.11. The CHSS-Type3 hydrogen storage system exhibits the highest environmental burden, followed by the HHSS-Type3 system, while the HHSS-Type4 system has the lowest environmental burden. For the CHSS-Type3 system, the environmental burden is 9.79E-03 kg Cu eq, with the usage stage being the largest contributor. On the other hand, for the HHSS-Type3 system, the production stage has the highest environmental burden. The environmental burden for the HHSS-Type3 system is 3.17E-03 kg Cu eq, with the production stage accounting for 55% of the total burden. This is primarily due to the consumption of CFRP and aluminum alloy materials during the production of the hydrogen storage tank. The environmental burden for the HHSS-Type4 system is 2.35E-03 kg Cu eq.

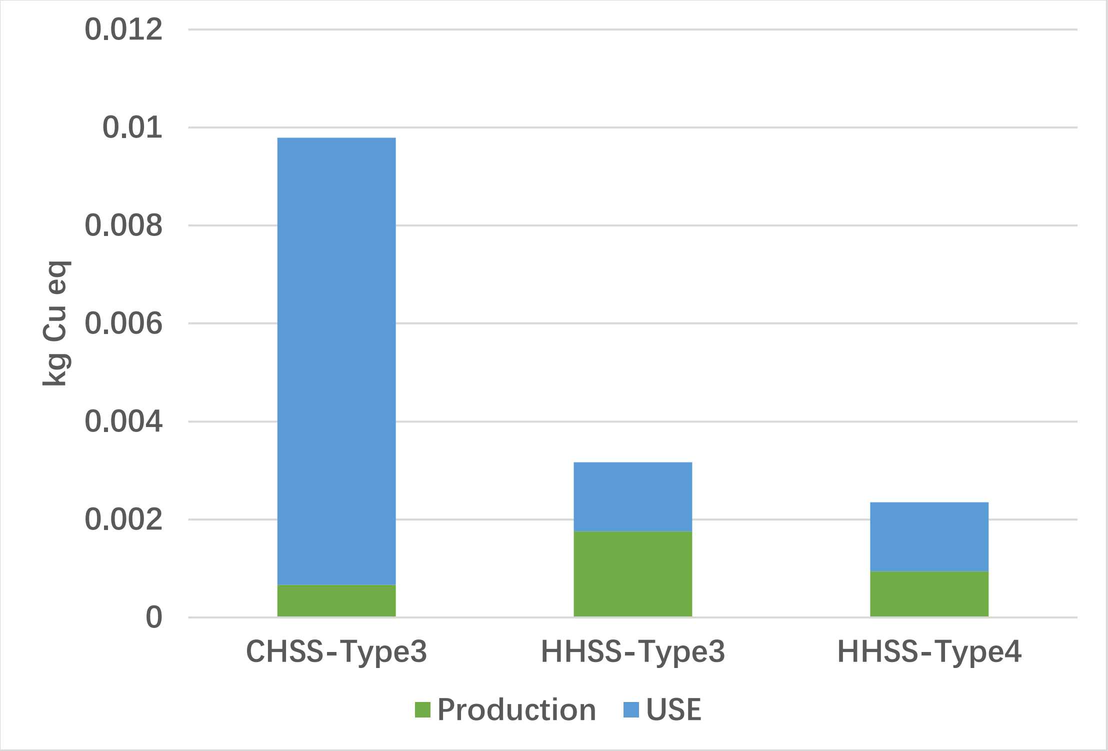


Fig. 3.11. LCIA results of hydrogen storage system for Mineral resource scarcity.

3.3.3 Sensitivity analysis

The baseline scenario for this study is in China. According to the analysis results, the main environmental burdens stem from the electricity consumption during CFRP production and the energy consumption during hydrogen compression and liquefaction processes. This chapter discusses the variations in environmental impacts of hydrogen storage system production and usage in different regions, including China (baseline scenario), the United States, Europe, and Japan.

3.3.3.1 HHSS-Type3 sensitivity analysis of different regions

Sensitivity analysis was conducted from four aspects: Global Warming, Stratospheric ozone depletion, Terrestrial acidification, and Mineral resource scarcity. For the HHSS-Type3 system, China shows higher sensitivity in Global Warming, Stratospheric ozone depletion, and Terrestrial acidification compared to the EU, JP, and US. Particularly, in the case of Terrestrial acidification, the sensitivity of China is twice as high as that of the other three countries. However, in terms of Mineral resource scarcity, the sensitivity of the other three countries is higher than that of China, with JP having the highest sensitivity at 130%.

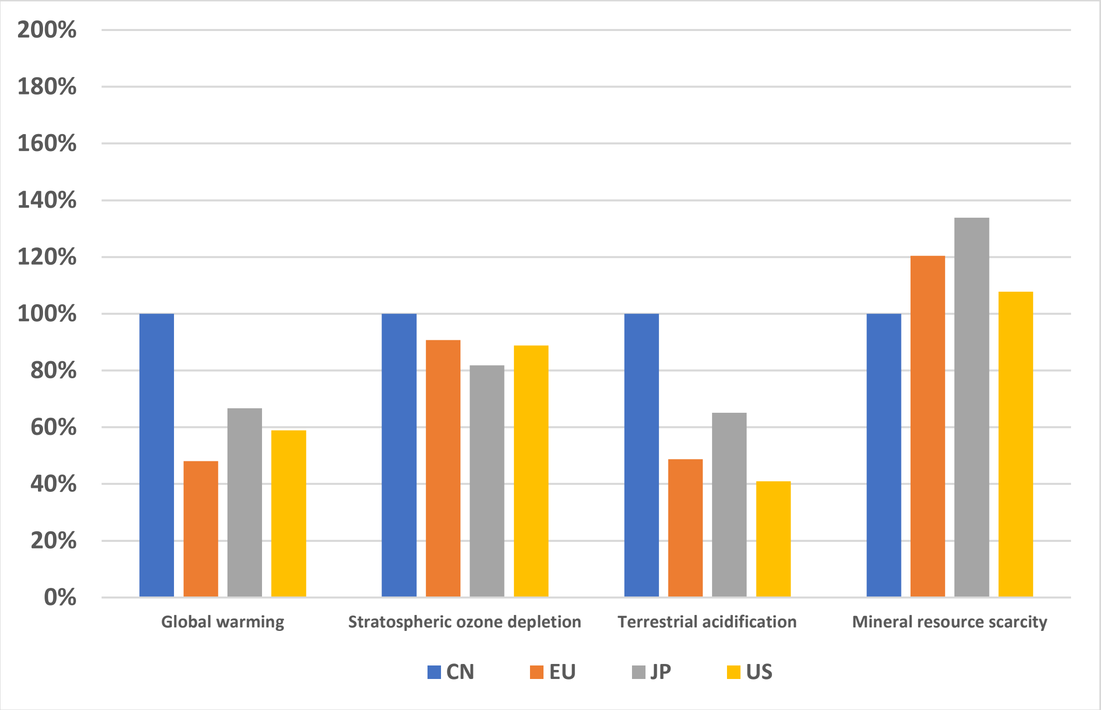


Fig. 3.12. HHSS-Type3 sensitivity analysis of different regions.

3.3.3.2 HHSS-Type4 sensitivity analysis of different regions

In the case of the HHSS-Type4 system, the sensitivity ranking in Global Warming is as follows: China, JP, US, and EU. For Stratospheric ozone depletion, the ranking is China, EU, US, and JP. In terms of Terrestrial acidification, the ranking is China, JP, EU, and US. Similarly, Japan exhibits the highest sensitivity in Mineral resource scarcity, at approximately 145%, while China has the lowest sensitivity in this aspect.

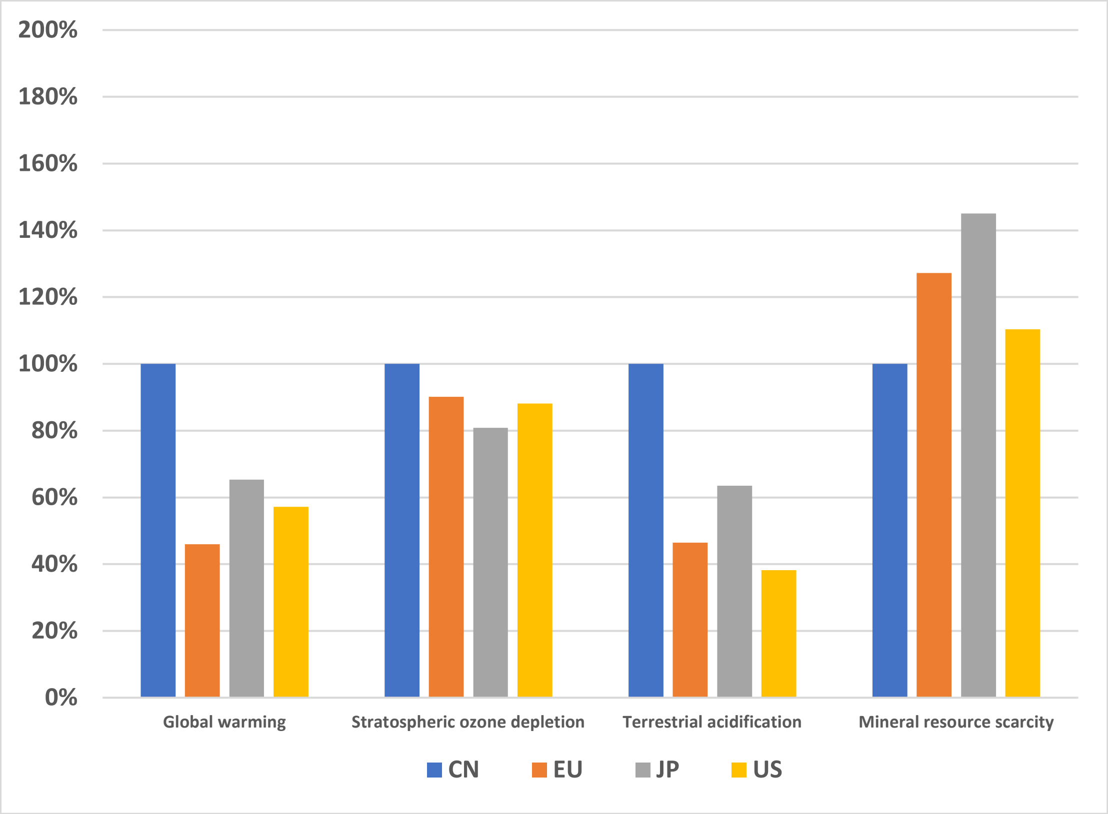


Fig. 3.13. HHSS-Type4 sensitivity analysis of different regions.

3.3.3.3 CHSS-Type3 sensitivity analysis of different regions

The same trend is also observed in the CHSS-Type3 system, with slight variations in the proportions among the countries for each factor. This indicates that the sensitivity of different systems to electricity is very similar across countries.

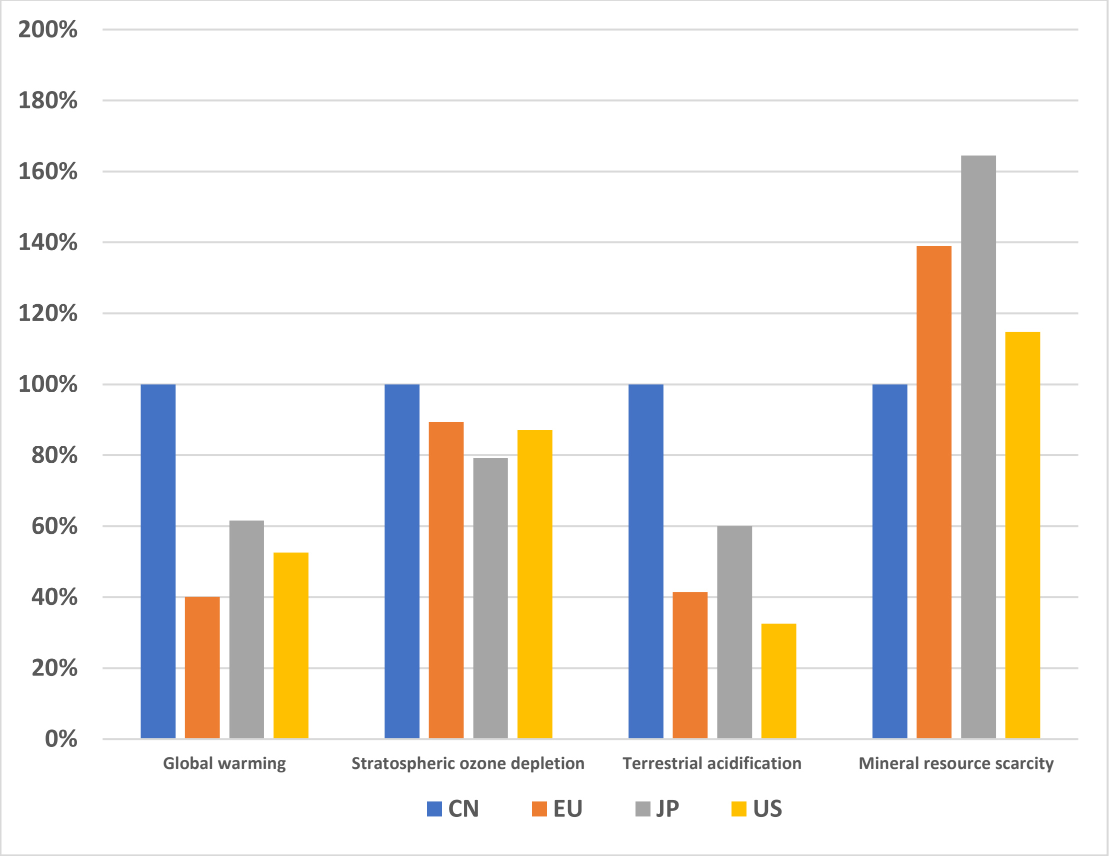


Fig. 3.14. CHSS-Type3 Sensitivity Analysis of Different Regions.

3.4 Summary

In this part, the LCA model is used to establish the inventory in the manufacturing process of hydrogen storage containers, and the environmental impact is calculated according to the CML-IA database. It is found that:

1. For the production of hydrogen storage tanks, the HHSS-Type3 hydrogen storage tank has the highest environmental impact, followed by the HHSS-Type4 hydrogen storage tank, while the CHSS-Type3 hydrogen storage tank has the lowest environmental impact. The environmental impact mainly arises from the production of CFRP and aluminum alloy materials, while the environmental impact from other materials and processes is relatively small, accounting for less than 1%.

2. For hydrogen storage systems, the CHSS-Type3 hydrogen storage tank has the highest environmental impact when transferring 1 kg of hydrogen, followed by the HHSS-Type3 hydrogen storage tank, while the HHSS-Type4 hydrogen storage tank has the lowest environmental impact. The environmental impact of hydrogen storage systems mainly comes from the electricity consumption during the compression or liquefaction of hydrogen.

3. According to the sensitivity analysis results, the electricity sources in different regions have a significant impact on the environmental burden of hydrogen storage systems. This is because the main environmental burden of hydrogen storage systems comes from the electricity consumption during the usage phase. In addition, the environmental burden of CFRP production process is responsible for nearly 50% of the overall environmental impact, and CFRP materials are important contributors to the environmental burden of hydrogen storage systems.

Chapter 4 Economic analysis of hydrogen storage technology

High-pressure and liquid hydrogen are two common hydrogen storage technologies for vehicles. Among them, the common high-pressure hydrogen storage bottles for vehicles can be divided into Type III bottles and Type IV bottles according to the inner core composition of the container. Among them, the common hydrogen storage pressure of type III bottles is 35MPa, and the common hydrogen storage pressure of type IV bottles is 70MPa. At present, high-pressure hydrogen storage technology is comparatively mature, and it is the most widely used in vehicles because hydrogen compression consumes less energy. However, high-pressure hydrogen storage also brings problems of low hydrogen storage density and high transportation costs. The transportation cost and storage cost of liquid hydrogen technology are lower, but the energy spending in hydrogen liquefaction process is higher, and the technical maturity of liquid hydrogen technology is lower than that of high-pressure gas hydrogen. Therefore, high-pressure hydrogen storage and liquid hydrogen technology routes have different technical advantages, and may reflect different economic benefits in a specific scenario, which needs to be analyzed according to the scenario. The main content of this chapter is to analyze the economics of hydrogen storage for vehicles in different scenarios, mainly including type III bottles, type IV bottles and liquid hydrogen storage.

4.1 Economic evaluation of high-pressure and low-temperature hydrogen storage containers benefits for cars

4.1.1The hydrogen storage benefits of high-pressure and low-temperature hydrogen storage technology

High pressure and low temperature hydrogen storage technology are two common hydrogen storage technologies, of which high pressure vessel This paper focuses on Type 3 high-pressure vessel and Type 4 high-pressure vessel, and there are certain differences in their hydrogen storage benefits. The hydrogen storage benefits of Type 3 and Type 4 high-pressure and low-temperature hydrogen storage technologies are described in detail below.

High-pressure hydrogen storage technology compresses hydrogen into a high-pressure state and then stores it in a hydrogen storage tank. Compared with low-temperature hydrogen storage technology, the hydrogen storage benefits of high-pressure hydrogen storage technology are mainly declared in the following aspects:

(1) High hydrogen storage density: high-pressure hydrogen storage technology can compress hydrogen to a high-pressure state, so that the volume of hydrogen becomes smaller and the hydrogen storage density is higher. This means that high-pressure hydrogen storage technology can store more hydrogen for the same tank volume [111]·

(2) Low hydrogen storage cost: Compared with low-temperature hydrogen storage technology, high-pressure hydrogen storage technology has a lower hydrogen storage cost. This is because high-pressure hydrogen storage technology uses storage tanks that

are less expensive and do not require liquid hydrogen storage tanks. Figure 4.1 shows the Type 3 high-pressure hydrogen storage tank and its internal structure

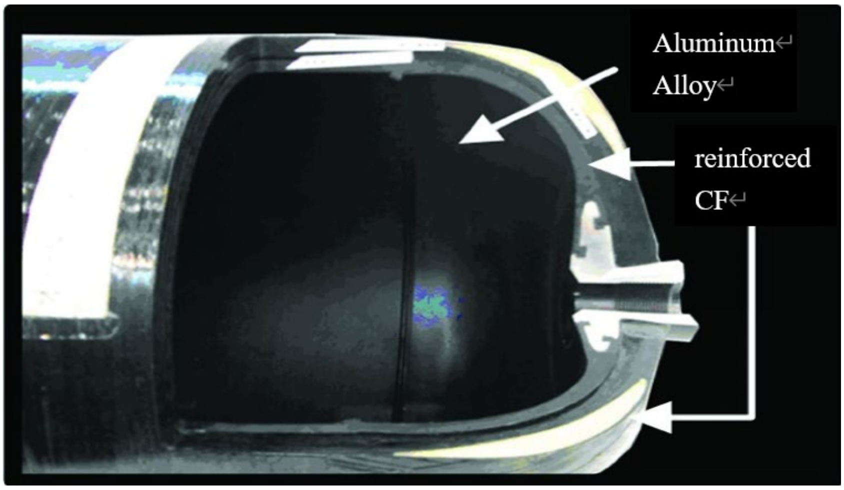


Fig. 4.1. High-pressure hydrogen storage tank and its internal structure (inner layer is aluminum alloy inner tank, outer layer is wound reinforced carbon fiber.

(3) Wide range of application: high-pressure hydrogen storage technology is suitable for application scenarios that require short-term storage of hydrogen, such as hydrogen fuel cell vehicles. This is because high-pressure hydrogen storage technology can quickly compress hydrogen into a high-pressure state, thus meeting the demand for a short period of time.

4.1.2 The cost of hydrogen storage of high-pressure and low-temperature hydrogen storage technology

At present, the storage of hydrogen energy is mainly through high-pressure storage tanks and cryogenic storage technology, and there are certain differences in their hydrogen storage costs. The hydrogen storage costs of high-pressure and low-temperature hydrogen storage technologies will be elaborated in detail below.

4.1.2.1 Hydrogen storage cost of high-pressure hydrogen storage technology

High-pressure hydrogen storage technology is a technology that compresses hydrogen into a high-pressure state for storage. It is a common hydrogen storage technology and is widely used in the field of hydrogen energy. Hydrogen storage costs refer to the cost required to store hydrogen at a specific pressure. The following will analyze the hydrogen storage cost of high-pressure hydrogen storage technology from the following aspects.

(1) Compress equipment costs

High-pressure hydrogen storage technology requires the use of compression equipment to compress hydrogen into a high-pressure state for storage. The cost of these devices depends on their compression capacity and compression ratio. In general, the cost of compression equipment increases as the compression ratio increases, as shown in Figure 4.2. In addition, the energy consumption of compression equipment also affects the cost of hydrogen storage. Therefore, the cost of compression equipment is an important part of the cost of hydrogen storage in high-pressure hydrogen storage technology[112].

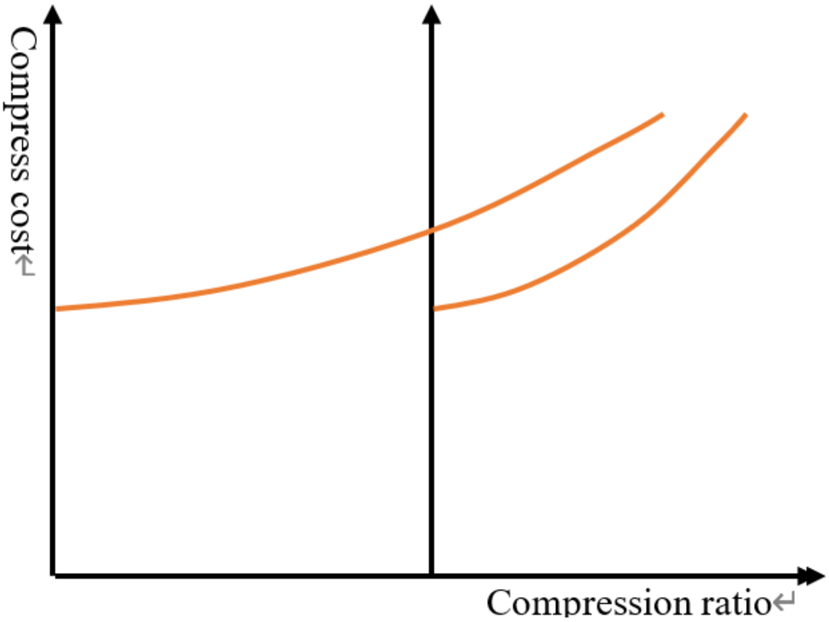


Fig. 4.2. Compression cost vs. compression ratio.

(2) The cost of hydrogen storage containers

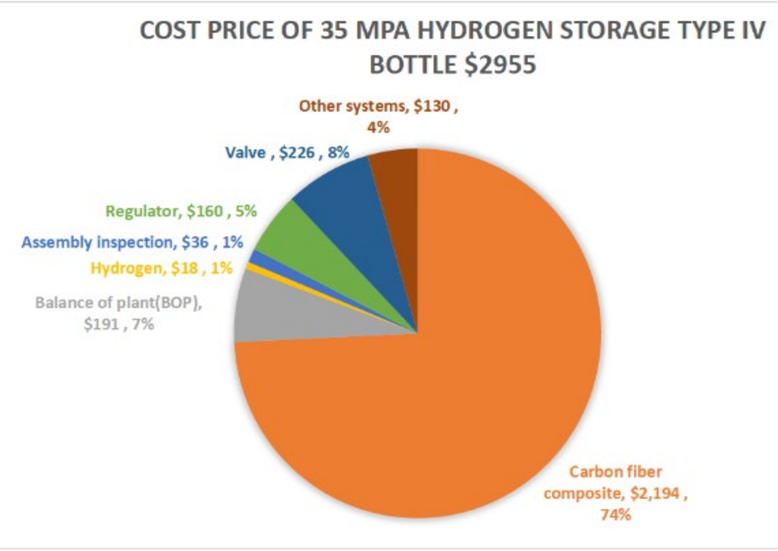
High-pressure hydrogen storage technology requires the use of high-pressure vessels to store hydrogen. The cost of these containers depends on their material, pressure class, and capacity. In general, the cost of high-pressure vessels increases with increasing capacity and pressure rating. In addition, the material of the high-pressure vessel will also affect its cost, for example, the carbon fiber hydrogen storage container is lighter than the steel hydrogen storage container, but it is also more expensive, of which the carbon fiber quantity of the Type 3 high-pressure vessel is higher than that of the Type 4 container by 20 kg, so its cost is slightly higher than that of the Type 4 high-pressure vessel[113]. Therefore, the cost of high-pressure vessels is another important component of the cost of hydrogen storage in high-pressure hydrogen storage technology.

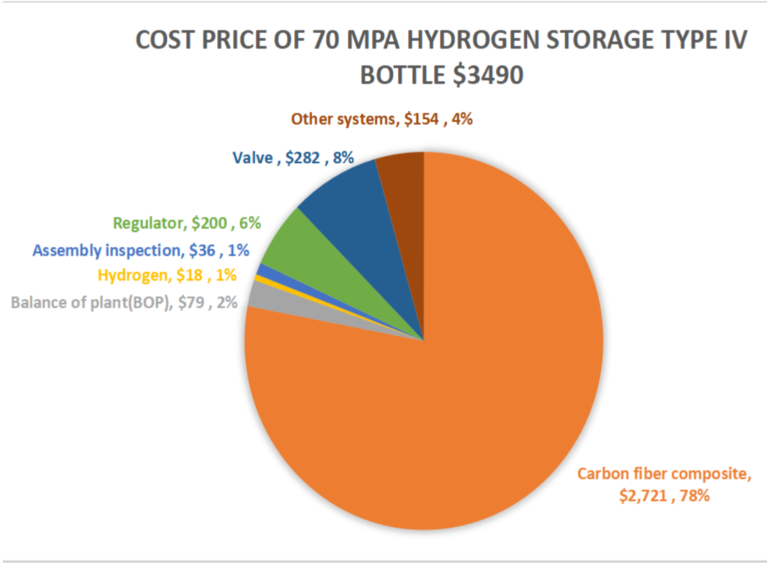
Table 4.1. Materials used in Type 3 high-pressure vessels.

Material	Quantity	Unit	Price（￥\kg）
6061 Aluminum Alloy	26	kg	21.4
T700 Carbon Fiber	96	kg	200
Epoxy	64	kg	64

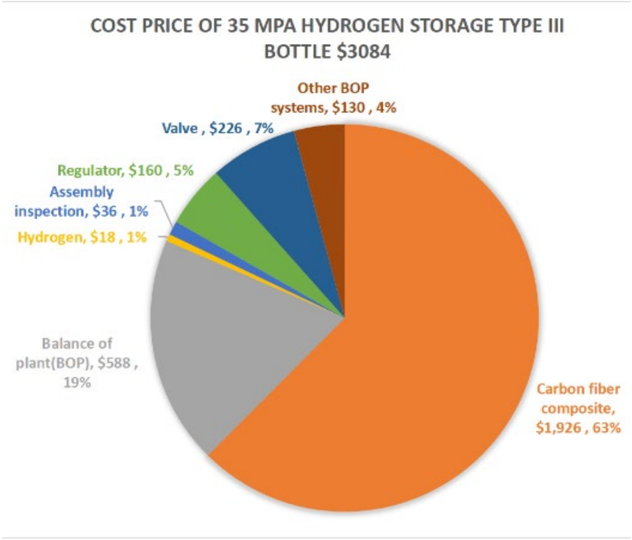
Table 4.2. Materials used in Type 4 high-pressure vessels.

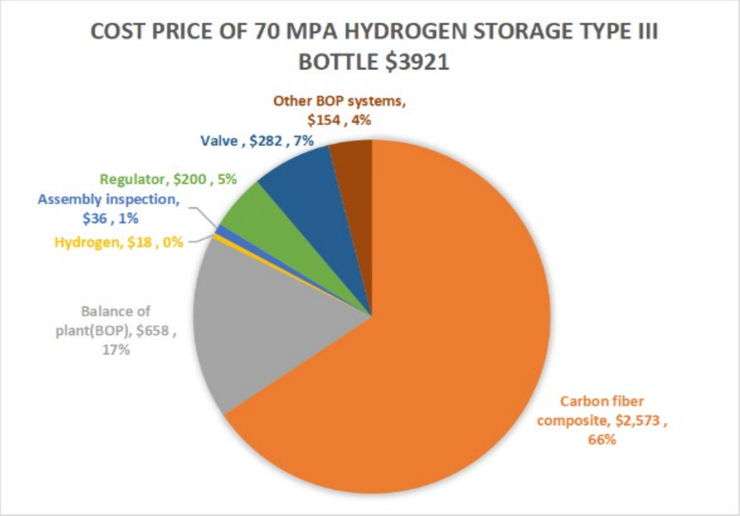
Material	Quantity	Unit	Price（￥\kg）
HDPE	7.5	kg	9.0
T700 Carbon Fiber	76	kg	200
Epoxy	26	kg	64




COST PRICE OF 70 MPA HYDROGEN STORAGE TYPE IV BOTTLE $3490
Other systems, $154 , 4%
Valve , $282 , 8%
Regulator, $200 , 6%
Assembly inspection, $36 , 1%
Hydrogen, $18 , 1%
Balance of plant(BOP), $79 , 2%
Carbon fiber composite, $2,721 , 78%

a


COST PRICE OF 35 MPA HYDROGEN STORAGE TYPE III BOTTLE $3084
Other BOP systems, $130 , 4%
Valve , $226 , 7%
Regulator, $160 , 5%
Assembly inspection, $36 , 1%
Hydrogen, $18 , 1%
Balance of plant(BOP), $588 , 19%
Carbon fiber composite, $1,926 , 63%



b

Fig. 4.3. (a) Cost of Type 4 high-pressure hydrogen storage vessel and (b)Cost of Type 3 high-pressure hydrogen storage container.

(3) Hydrogen storage loss cost

In high-pressure hydrogen storage technology, hydrogen may be lost during storage and use. These losses can come from hydrogen leaks, container leaks, leaks, etc. These losses lead to an increase in the cost of hydrogen storage, as more hydrogen is needed to compensate for the losses. Therefore, reducing hydrogen storage losses is a way to reduce the cost of hydrogen storage in high-pressure hydrogen storage technology.

(4) Transportation costs

In high-pressure hydrogen storage technology, hydrogen needs to be transported from the place of production to the point of use. Transportation costs include the cost of hydrogen transportation vehicles, fuel costs, and labor costs. In addition, hydrogen leakage may occur during transportation, which will also increase transportation costs. Different modes of transportation also incur different costs, but the overall cost shows a decreasing or stable trend with the increase of transportation distance, as shown in

Figure 4.4.

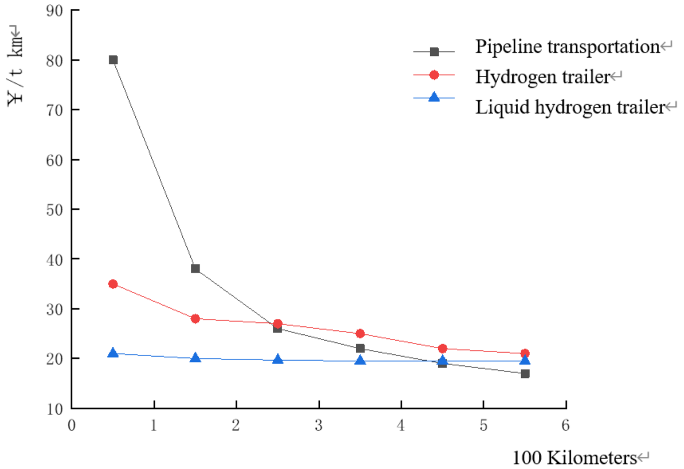


Fig. 4.4. Comparison of different modes of transportation.

In short, the hydrogen storage cost of high-pressure hydrogen storage technology is affected by many factors, including the cost of compression equipment, the cost of hydrogen storage containers, the cost of hydrogen storage loss and transportation costs. Ways to reduce these costs include improving the efficiency of compression equipment and hydrogen storage vessels, reducing hydrogen storage losses, and optimizing transportation routes and modes.

4.1.2.2 Hydrogen storage cost of cryogenic hydrogen storage technology

Cryogenic hydrogen storage technology is to cool hydrogen to a very low temperature, turn it into liquid hydrogen, and then store it in a liquid hydrogen storage tank. The hydrogen storage cost of low-temperature hydrogen storage technology is mostly manifested in the following areas when compared to high-pressure hydrogen storage technology:

(1) Liquefaction equipment cost

Cryogenic hydrogen storage technology requires the use of liquefaction equipment to liquefy hydrogen for storage. The cost of these devices depends on their liquefaction capacity and liquefaction efficiency. The energy consumption of liquefaction equipment also affects the cost of hydrogen storage. Therefore, the cost of liquefaction equipment is an important part of the cost of hydrogen storage in cryogenic hydrogen storage technology.

(2) The cost of hydrogen storage containers

Cryogenic hydrogen storage technology requires the use of cryogenic vessels to store liquid hydrogen. The cost of these containers depends on their material, capacity and pressure rating. In general, the cost of cryogenic vessels increases with increasing capacity and pressure rating. In addition, the material of the cryogenic container also affects its cost. For example, carbon fiber hydrogen storage containers are lighter than steel hydrogen storage containers, but they are also more expensive. Therefore, the cost of cryogenic vessels is another important component of the cost of hydrogen storage in cryogenic hydrogen storage technology.

(3) Hydrogen storage loss cost

In cryogenic hydrogen storage technology, liquid hydrogen may be lost during storage and use. These losses can come from leaks, leaks, etc. These losses lead to an increase in the cost of hydrogen storage, as more hydrogen is needed to compensate for the losses. Therefore, reducing hydrogen storage losses is a way to reduce the cost of hydrogen storage in low-temperature hydrogen storage technology. Figure 4.5 shows the LLNL low-temperature and high-pressure hydrogen storage vessel, and the specific parameters of the hydrogen storage system are shown in Table 4.3. The vessel is installed on a hydrogen hybrid vehicle and can last for 2 weeks without evaporation loss.

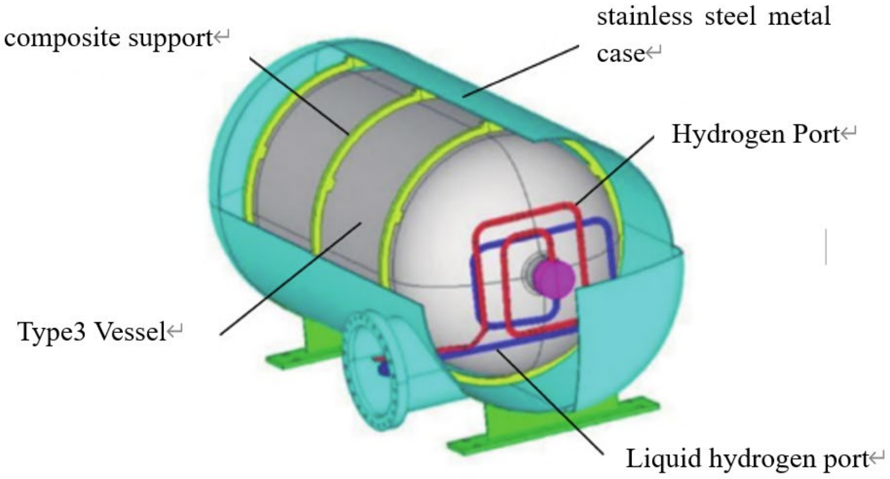


Fig. 4.5. Structure of low-temperature and high-pressure hydrogen storage vessel.

Table 4.3. Parameters of low-temperature and high-pressure hydrogen storage system

serial number	Project	Data
1	Water volume \L	151
2	Total contour volume \L	235
3	Design pressure \MPa	27.2
4	The inner plate aluminum gallbladder is thick \mm	9.5
5	Outer container stainless	3

	steel \mm	
6	The insulation structure is thick \mm	17
7	Mass hydrogen storage density\%	7.4
8	Volume hydrogen storage density\(kg· L^{-1})	0.45
9	No discharge storage time\h	192

(4) Transportation costs

In cryogenic hydrogen storage technology, liquid hydrogen needs to be transported from the place of production to the place of use. Transportation costs include the cost of hydrogen transportation vehicles, fuel costs, and labor costs. In addition, hydrogen leakage may occur during transportation, which will also increase transportation costs. Therefore, reducing the transportation distance and transportation time can reduce the cost of hydrogen storage for cryogenic hydrogen storage technology.

The hydrogen storage cost of cryogenic hydrogen storage technology is affected by many factors, including the cost of liquefaction equipment, the cost of hydrogen storage containers, the cost of hydrogen storage loss and transportation costs. Ways to reduce these costs include improving the efficiency of liquefaction equipment and hydrogen storage vessels, reducing hydrogen storage losses, and optimizing transportation routes and modes.

4.2 Analyze the results of economic evaluation under different scenarios

In addition to the benefits and costs of the above analysis, the actual driving conditions of the vehicle will also put forward other requirements for the on-board hydrogen storage system, hydrogen fuel cell car economy is related to the driving state of the car, long-distance driving hope that the hydrogen storage system can continue to supply hydrogen stably, when parking, it should stop supplying hydrogen in time, which requires the on-board hydrogen storage system to have continuous and good response performance, Table 4.4 is the U.S. Department of Energy on the 2015-2020 on-board hydrogen storage system technical and economic indicators[114].

Table 4.4. U.S. Department of Energy's technical and economic indicators for on-board hydrogen storage systems from 2015 to 2020.

Hydrogen storage system parameters	2010	2015	2020
Weight energy density (kWh/kg)	2.0	2.5	3.0
System weight(kg)	111	85	55.6
Hydrogen storage density(wt.%)	4.5	5.9	9.0
Volumetric energy density (kWh/L)	1.2	1.5	2.7
System Volume(L)	139	111	62
System Energy Cost	6	4	2

(USD/kWh)			
System Cost (USD)	1000	666	333
Hydrogen filling rate (kg/min)	1.5	2.0	2.5
Hydrogen filling time (min)	10	3.3	2.5

4.2.1 The economy of high-pressure hydrogen storage vehicles during long-distance driving

The economy of using high-pressure hydrogen storage technology in cars under long-distance driving conditions mainly depends on the following aspects:

(1) Fuel efficiency of vehicles: High-pressure hydrogen storage technology can provide higher energy density, so that vehicles can travel longer distances when driving. However, vehicles are generally less fuel-efficient over long distances, so more hydrogen is needed to provide the same range. Figure 4.6 shows the change curve of fuel efficiency between hydrogen-powered vehicles and fuel vehicles with the distance traveled, which may lead to more frequent hydrogenation, thereby increasing the cost of use.

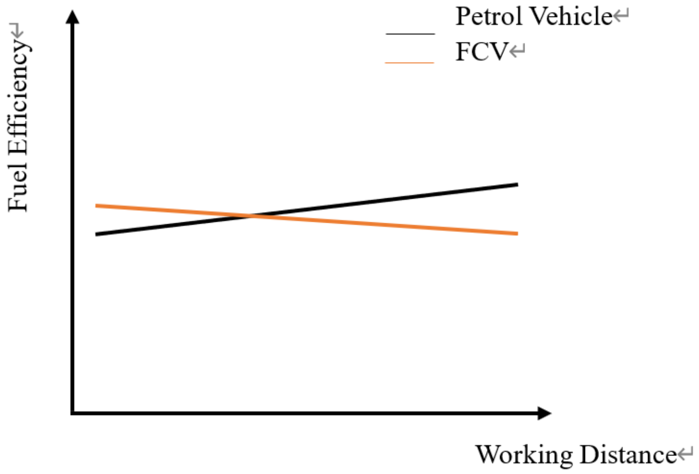


Fig. 4.6. The fuel efficiency of the two models varies with distance traveled.

(2) The cost of hydrogen: The cost of hydrogen is an important factor in the economy of high-pressure hydrogen storage technology. At present, the production and supply costs of hydrogen are relatively high, which may lead to higher costs for the use of high-pressure hydrogen storage technology. In addition, the cost of hydrogen is also affected by factors, such as the balance of supply and demand, production costs and policy support.

(3) Availability of hydrogen storage facilities: High-pressure hydrogen storage technology requires special hydrogen storage facilities to store hydrogen, and the availability and cost of these facilities will also affect the economics of high-pressure hydrogen storage technology. If the construction and maintenance costs of hydrogen storage facilities are high, the cost of using high-pressure hydrogen storage technology will also increase accordingly.

(4) Purchase cost of vehicles: High-pressure hydrogen storage technology requires special hydrogen storage tanks and fuel systems, which may lead to higher purchase

costs of vehicles. In addition, due to the small scale of production of hydrogen fuel cell vehicles, the production cost of vehicles is also relatively high.

.4.2.2 The economy of cryogenic hydrogen storage vehicles during long-distance driving

Low-temperature hydrogen storage vehicles refer to vehicles that use liquid hydrogen as fuel, and their hydrogen storage system adopts low-temperature hydrogen storage technology to store hydrogen in the state of liquid hydrogen. The economy of low-temperature hydrogen storage vehicles during long-distance driving can be analyzed from the following aspects:

(1) Energy efficiency: The fuel cell system of low-temperature hydrogen storage vehicles has the characteristics of high efficiency, and its energy transfering efficiency can reach more than 50%, which is much higher than that of traditional fuel vehicles. Cryogenic hydrogen storage vehicles are more efficient in their energy use during long journeys because their fuel cell systems can convert liquid hydrogen into electricity faster, providing a stronger power output.

(2) Energy cost: The fuel cost of low-temperature hydrogen storage vehicles is relatively high, but when driving at high speed, its energy cost is relatively low. This is because fuel cell systems require more energy output when driving long distances, and liquid hydrogen has a much higher energy density than pure electric cars, as shown in Table 4.5. Therefore, at the same driving distance, the fuel cost of low-temperature hydrogen storage vehicles will be lower.

Table 4.3. Performance comparison of hydrogen fuel cell vehicles and pure electric vehicles.

	Pure electric sedan	Hydrogen fuel cell car
Power density performance	1-1.5KW/L	3-4KW/L
Energy density performance	~170Wh/kg (lithium iron phosphate battery)	>500Wh/kg
Battery life	200-300km (standard: 300-400KWH power)	~400 km (Equipped with: 110KW hydrogen fuel system + 100KWH lithium battery) > 35 MPa*8 standard gas tank: ~400 km> 70 MPa*8 standard gas tank: 600-700 km Liquid hydrogen storage tank: ~1000 km
Service life	~30,000 hours	1.5-20,000 hours

(3) Environmental pollution: low-temperature hydrogen storage vehicles use hydrogen as fuel, and their emissions are mainly water vapor, which will not produce harmful exhaust emissions and have very little environmental pollution. During long-distance driving, low-temperature hydrogen-storage vehicles emit less emissions

because their fuel cell systems can convert liquid hydrogen into electricity faster, reducing combustion emissions[2].

To sum up, the economics of using high-pressure hydrogen storage technology for cars under long-distance driving is affected by many factors. Although high-pressure hydrogen storage technology can provide higher energy density, the fuel efficiency of vehicles usually decreases during long-distance driving, thereby increasing the cost of use. In addition, the cost of hydrogen, the availability of hydrogen storage facilities, and the purchase cost of vehicles also affect the economics of high-pressure hydrogen storage technologies. Low-temperature hydrogen storage vehicles are relatively economical for long-distance driving, with high energy efficiency, low energy costs, and low environmental pollution. However, it should be noted that the hydrogen storage system of low-temperature hydrogen storage vehicles is relatively complex and requires high costs, and the current production and storage technology of liquid hydrogen is not mature enough, and further research and development are needed. Therefore, when choosing a hydrogen storage technology, conducting a thorough economic analysis and taking into account all relevant elements is essential.

4.2.3 The economy of high-pressure hydrogen storage technology for cars when driving short distances

The economy of cars using high-pressure hydrogen storage technology when driving short distances may be affected by a variety of factors. Here are some factors you might want to consider:

(1) High cost of hydrogen storage facilities: High-pressure hydrogen storage technology requires special hydrogen storage facilities, and the construction and maintenance costs of these facilities are high. These costs may be passed on to the price of hydrogen, increasing the operating costs of the vehicle.

(2) High fuel cost: The cost of hydrogen as fuel is also high. Hydrogen is more expensive to produce and transport than conventional fuel fuels, which may increase the operating costs of vehicles[3]. In addition, hydrogen has a relatively low energy density and requires more frequent hydrogenation, which also increases the operating costs of the vehicle.

Table 4.4. Cost estimates by logistics and transportation mode in 2022.

	Hydrogen energy cars	Traditional fuel cars	Pure electric sedan
Fixed cost: Depreciation	8.97	2.38	4.50
Price (10,000 RMB/unit)	110	20	40
Subsidy (10,000 yuan/vehicle)	22	0	3.96
Depreciation period (years)	8	8	8
Salvage rate	5%	5%	0%
Initial purchase cost (million	34	15	20

yuan)			
Variable costs: O&M	6.70	10.64	3.63
Fuel cost (10,000 yuan/year)	4.70	8.64	1.63
Daily mileage	160	160	160
Energy consumption per 100 km (kg.L.kWh/100km)	2.8	20	50
Energy price (8kg.yuan/L, yuan/kWh)	35	9	0.68
Number of days in operation per year (days)	300	300	300
Other expenses (10,000 yuan/year)	2	2	2
Total annual operating cost	15.49	13.02	8.13

(3) Mileage limit: Cars with high-pressure hydrogen storage technology may be subject to mileage restrictions. Due to the relatively low energy density of hydrogen, the range of vehicles may be limited. This means that car owners need to hydrogenate

more frequently, which increases operating costs.

(4) Market maturity: The car market for high-pressure hydrogen storage technology is not yet fully mature. This can affect vehicle availability and repair costs. Due to the small market share of hydrogen fuel cell vehicles, repair and maintenance costs are likely to be higher.

(5) Environmental advantages: Although the economy of high-pressure hydrogen storage technology cars may be limited when driving short distances, this technology has environmental advantages. The emissions of hydrogen fuel cell vehicles are only water, and do not produce harmful gases and particulate matter. This makes hydrogen fuel cell vehicles an environmentally friendly mode of transportation[115].

In general, the economy of high-pressure hydrogen storage technology cars may be somewhat limited when driving short distances. However, as the technology continues to evolve and the market matures, these limitations may gradually decrease. At the same time, hydrogen fuel cell vehicles have environmental advantages, which is one of the reasons why they have attracted attention.

4.2.4 The economy of cryogenic hydrogen storage technology for cars when driving short distances

The economy of low-temperature hydrogen storage technology vehicles in the process of short-distance driving is mainly reflected in the following aspects:

(1) Low energy cost: Cryogenic hydrogen storage technology vehicles use hydrogen as fuel, and the cost of hydrogen is lower than that of traditional fuel vehicles.

In addition, low-temperature hydrogen storage technology vehicles are highly energy-efficient and can use hydrogen more efficiently, thereby reducing energy costs.

(2) Low maintenance cost: The hydrogen storage system of low-temperature hydrogen storage technology cars is made of high-strength materials, which has good corrosion resistance and wear resistance, which can ensure the long-term use of the car. In addition, low-temperature hydrogen storage technology vehicles have fewer engine components and relatively low maintenance costs.

(3) Policy support: in order to promote clean energy vehicles, the government has given certain subsidies and preferential policies to low-temperature hydrogen storage technology vehicles, such as car purchase subsidies, free parking, etc., which can reduce the purchase and use costs of low-temperature hydrogen storage technology vehicles.

(4) High long-term return on investment: The purchase cost of low-temperature hydrogen storage technology vehicles is relatively high, but with the continuous development of technology and the promotion of application, its cost will gradually decrease. In addition, low-temperature hydrogen storage technology vehicles have the characteristics of high long-term return on investment, because of their long service life, low energy costs, low maintenance costs, and can bring long-term economic benefits to users[116].

In summary, low-temperature hydrogen storage technology vehicles have high economy during short-distance driving, which can bring users low energy costs, maintenance costs and long-term return on investment.

4.2.5 The economy of cars using high-pressure hydrogen storage technology when driving in mountainous areas

When driving in mountainous areas, the economy of cars using high-pressure hydrogen storage technology will be affected by many factors. Here are some possible factors:

(1) Energy density: High-pressure hydrogen storage technology can provide higher energy density, which means that vehicles can get more energy in less time. This can be even more important when driving in mountainous areas, as vehicles require more energy to climb hills and cope with more complex road conditions. Vehicles using high-pressure hydrogen storage technology can obtain the required energy faster, thereby improving the economy of the vehicle[6].

(2) Fuel efficiency: Vehicles using high-pressure hydrogen storage technology generally have higher fuel efficiency because hydrogen fuel cells can convert hydrogen into electricity without producing any emissions. This means that vehicles can be driven more economically because they do not need to be refueled frequently. When driving in mountainous areas, vehicles require more energy to climb hills and cope with more complex road conditions, so vehicles using high-pressure hydrogen storage technology can drive more economically.

(3) Hydrogen storage facilities: When driving in mountainous areas, you may find that the availability of hydrogen storage facilities varies. If there are not enough hydrogen storage stations, then vehicles may take longer to hydrogenate or need to be refueled more frequently. This can affect the economy of the vehicle. If the hydrogen

storage site is available, vehicles using high-pressure hydrogen storage technology can be driven more economically.

(4) Maintenance costs: Vehicles using high-pressure hydrogen storage technology usually require less maintenance because hydrogen fuel cells have no mechanical parts and therefore require less maintenance. This reduces the maintenance costs of the vehicle and thus improves the economy of the vehicle.

In summary, the economy of a car using high-pressure hydrogen storage technology when driving in mountainous areas can be affected by a variety of factors. If hydrogen storage sites are well available, vehicles using high-pressure hydrogen storage technology can provide higher fuel efficiency and better energy density, resulting in improved vehicle economics. In addition, vehicles using high-pressure hydrogen storage technology often require less maintenance, which can reduce the maintenance cost of the vehicle, thus further improving the economy of the vehicle.

4.2.6 The economy of using cryogenic hydrogen storage technology for cars when driving in mountainous areas

First, cryogenic hydrogen storage technology can increase the storage density of hydrogen, thereby reducing the space and weight required for hydrogen storage. This makes hydrogen-powered cars lighter when driving in mountainous areas, reducing energy consumption and improving energy efficiency. In addition, cryogenic hydrogen storage technology can also improve the stability and safety of hydrogen, reduce the risk of hydrogen leakage and explosion, thereby reducing the safety risk and maintenance cost of hydrogen-powered cars when driving in mountainous areas [117].

Secondly, hydrogen-powered cars use low-temperature hydrogen storage technology to achieve zero emissions and reduce environmental pollution. When driving in mountainous areas, hydrogen-powered cars can better adapt to complex terrain and climatic conditions, reducing damage and impact on the natural environment. In addition, hydrogen-powered cars can also achieve energy recovery and reuse through technologies such as recovery of braking energy, improving energy efficiency and economy.

Third, hydrogen-powered cars use low-temperature hydrogen storage technology to achieve rapid hydrogenation and improve the convenience and flexibility of driving. When driving in mountainous areas, hydrogen-powered cars can respond more flexibly to road and traffic conditions, reducing travel time and energy consumption. In addition, hydrogen-powered cars can also achieve energy management and optimization through intelligent control systems, improving economy and reliability.

In summary, hydrogen-powered cars using low-temperature hydrogen storage technology have high economy when driving in mountainous areas, which can reduce energy consumption and environmental pollution, and improve the convenience and flexibility of driving. With the continuous development and maturity of hydrogen energy technology, hydrogen-powered cars will become one of the important choices for sustainable development in the future.

4.3 Summary

Economic evaluation is a method of assessing economic activity or policies that can help decision-makers understand the costs, benefits, and impacts of a policy or activity. However, the reliability of economic evaluation results is an important issue, as unreliable results can lead to wrong decisions.

Here are a few aspects of the reliability of economic evaluation results:

(1) Data source and quality: Economic evaluation requires a large amount of data to support analysis and calculation. Therefore, the source and quality of the data are critical to the reliability of the evaluation results. If the data source is unreliable or of poor quality, the results of the evaluation will be affected.

(2) Assumptions and models: Economic evaluations are often based on assumptions and models that may not be fully in line with reality. If the assumptions and models are inaccurate, the evaluation results will be distorted.

(3) Analytical methods: Economic evaluation uses a variety of analytical methods to calculate costs, benefits, and impacts. The choice and use of these methods may affect the reliability of the review results. If the methodology is inappropriate or used incorrectly, the results of the evaluation will be affected.

(4) Uncertainty and sensitivity analysis: Economic evaluation results are usually accompanied by certain uncertainties. Therefore, uncertainty and sensitivity analyses are required to assess the reliability of the results. If the uncertainty and sensitivity analysis is inadequate or inaccurate, the results of the assessment are affected.

(5) Evaluator's bias and conflicts of interest: Evaluator's bias and conflicts of

interest may affect the reliability of evaluation results. Evaluators should be as objective and neutral as possible, avoiding bias and conflicts of interest.

In summary, the reliability of the evaluation results depends on several factors such as data source and quality, assumptions and models, analytical methods, uncertainty and sensitivity analysis, and evaluator's bias and conflict of interest. Evaluators should be as objective and neutral as possible, use appropriate methods and models, and conduct adequate uncertainty and sensitivity analyses to ensure the reliability of evaluation results.

Economic evaluation is the process of economic analysis of a policy, project, or decision. In this process, evaluators use a variety of methods and models to estimate the costs, benefits, and impacts of a policy or program. However, these estimates are often subject to some uncertainty, which may affect the final evaluation results.

Here are some factors that can contribute to uncertainty in the outcome of an economic evaluation:

(1) Data uncertainty: Economic evaluation usually requires the use of a large amount of data to analyze, but these data may have errors, omissions or inaccuracies, which will lead to uncertainty in the evaluation results.

(2) Model uncertainty: Economic evaluation often uses various economic models to estimate the impact of policies or projects, but these models have their own limitations and assumptions, which can lead to uncertainty in the evaluation results.

(3) Assumption uncertainty: Economic evaluation usually requires some assumptions, such as predictions of future market trends, changes in people's behavior

after policy implementation, etc., which may not be consistent with the actual situation, resulting in uncertainty in the evaluation results.

(4) Uncertainty of evaluation methods: Economic evaluation can use a variety of methods, such as cost-benefit analysis, cost-utility analysis, etc., which also have some limitations and assumptions, which will lead to uncertainty in evaluation results.

(5) Uncertainty of the external environment: The results of economic evaluation may be affected by the external environment, such as policy changes, economic fluctuations, etc., which will also lead to uncertainty in the evaluation results.

To reduce the uncertainty of economic evaluation results, evaluators can take the following measures:

(1) Collect more accurate data, validate and calibrate the data.

(2) Analyze using multiple models and perform sensitivity analysis on the models to determine the robustness of the evaluation results.

(3) Conduct a sensitivity analysis of the hypothesis and consider the evaluation results under different assumptions.

(4) Analyze using multiple evaluation methods, compare and validate evaluation methods.

Consider the impact of the external environment, and conduct risk analysis and prediction of evaluation results.

Economic evaluation is a method used to evaluate a policy, project or decision with the aim of determining its economic and cost-effectiveness. However, the limitations of economic evaluation results are also obvious, and here are some common limitations:

(1) Limitations of assumptions: Economic evaluations are usually based on assumptions such as market behavior, technological progress, and the impact of policy implementation. These assumptions may be inaccurate or incomplete, so the results of the review may be affected by limitations of the assumptions.

(2) Data limitations: Economic evaluation requires a large amount of data to support its analysis and conclusions. However, data may be incomplete or inaccurate, which may lead to inaccuracies in the results of the review.

(3) Time limitations: Economic evaluations are usually based on data and assumptions over a certain time frame. However, the market, technological and policy environment may change over time, which may affect the accuracy of the evaluation results.

(4) Limitations of values: Economic evaluations are usually based on values and preferences, such as social equity, environmental protection, and economic growth. However, these values and preferences may vary from person to person, so evaluation results may be influenced by different values and preferences.

(5) Limitations of externalities: Economic evaluations often struggle to consider certain externalities, such as environmental impacts, social impacts, and political impacts. These externalities may have an important impact on evaluation results, but are difficult to quantify and consider.

In summary, the limitations of economic evaluation results are unavoidable, so it is necessary to carefully consider these limitations when conducting economic evaluation, and try to use a variety of methods and data to verify the accuracy and reliability of evaluation results.

In general, both high-pressure and low-temperature hydrogen storage technologies require the use of high-quality materials and equipment, as well as regular inspection and maintenance to ensure their safety. In addition, appropriate measures must be taken to prevent hydrogen leakage and storage tank explosions.

High-pressure hydrogen storage technology and low-temperature hydrogen storage technology are both methods of storing hydrogen, but their costs and benefits are different.

High-pressure hydrogen storage technology compresses hydrogen into a high-pressure state, usually between 350-700 bar. j In addition, high-pressure hydrogen storage technology carries the risk of hydrogen leakage, which can lead to safety issues.

Cryogenic hydrogen storage technology is the cooling of hydrogen to extremely low temperatures (usually below -253°C) to turn it into liquid hydrogen. The advantage of this technology is that the hydrogen storage density is higher, and more hydrogen can be stored in less space. In addition, liquid hydrogen is much smaller in volume than gaseous hydrogen, so it can be delivered more easily. However, cryogenic hydrogen storage technology requires expensive cooling equipment and hydrogen storage vessels, which increases costs. In addition, liquid hydrogen needs to be stored and transported at extremely low temperatures, which increases operational and safety risks.

In general, high-pressure hydrogen storage technology and low-temperature hydrogen storage technology have their advantages and disadvantages. High-pressure hydrogen storage technology is suitable for applications that need to store hydrogen in a smaller space, while cryogenic hydrogen storage technology is suitable for applications that need to store more hydrogen in a smaller space. In terms of cost and benefit, both technologies require expensive equipment and vessels, but high-pressure hydrogen storage technology may be cheaper. However, cryogenic hydrogen storage technologies may be safer because liquid hydrogen is less prone to leakage.

Chapter 5 Policy analysis of hydrogen storage technology

As the global shift towards a hydrogen economy intensifies, the understanding of the policy landscape becomes increasingly critical[118]. Policies at various levels can significantly influence the trajectory of these technologies[119, 120]. Therefore，this section delves into the intricate relationship between policy and the development, implementation, and adoption of hydrogen storage technologies.

Firstly, this discussion starts with an overview of current policies. This encompasses policies at the national, local, and international levels. National policies often provide the broad framework and set the tone for the development of hydrogen technologies. Local policies can offer more specific guidelines and incentives, tailored to the unique needs and resources of a particular region. International policies and agreements can drive global cooperation and set shared goals for hydrogen technology development[121].

In the second part of this section the impact of these policies on hydrogen storage technology were analyzed. Policies could shape the direction of technological development, influence market dynamics, and create opportunities or challenges for different stakeholders. They could also have significant implications for the environmental and economic viability of hydrogen storage technologies.

Also, case studies were carried to illustrate the real-world implications of these policies. These case studies provide concrete examples of how policies have influenced the development and deployment of hydrogen storage technologies in different contexts.

In the second part of this, the future policy trends were discussed. Based on the current policy environment and the development trajectory of hydrogen storage technologies, potential policy changes were predicted and their likely impacts were discussed.

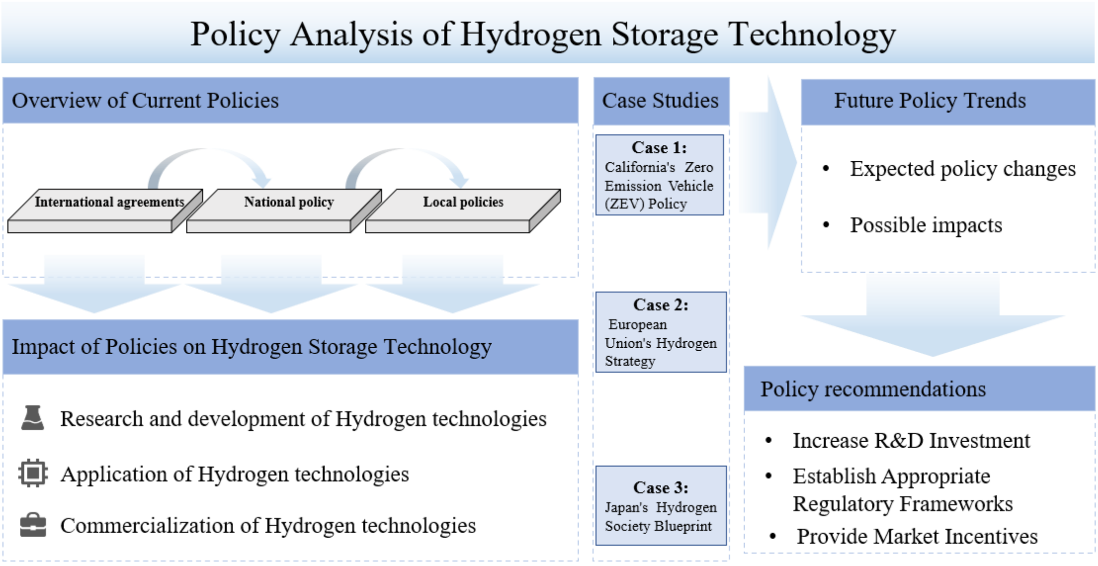


Fig. 5.1. The research framework diagram of policy analysis of hydrogen storage technology.

Finally, policy recommendations were offered. Based on the research findings, policies that could further promote the development and adoption of hydrogen storage technologies are proposed.

Through this policy analysis, a comprehensive understanding of the policy landscape for hydrogen storage technology were provided, offering insights that can guide future policy-making and technological development.

5.1 Overview of Current Policies

As the world transitions towards cleaner and more sustainable energy sources, hydrogen energy is emerging as a promising solution due to its high energy content and the fact that its only byproduct is water[122]. However, the adoption of hydrogen energy is not without challenges, and policy plays a crucial role in driving the development and deployment of hydrogen energy technologies[123].

5.1.1 National Policies

At the national level, several countries have begun implementing policies to promote the development of hydrogen energy. Japan was the first country to develop a national hydrogen strategy in 2017, focusing on its application across transportation, industry, power production, and more[124, 125]. The strategy encompasses the broadening of applications to include ships, trains, trucks, and other transportation modes, and the development of a comprehensive hydrogen ecosystem. The goal is to make hydrogen affordable through the creation of a global supply chain and the construction of onsite storage facilities.

In 2020, China announced its Technology roadmap for hydrogen energy and fuel cell vehicles, with the goal of reaching 1 million fuel cell vehicles by 2030, and establishing 15 hydrogen energy demonstration cities to promote the development of hydrogen energy in the future[126-128]. At present, the adoption and development of hydrogen fuel cells are mainly concentrated in Beijing Tianjin Hebei, Yangtze River Delta, Pearl River Delta and Shandong. There are economic conditions, industrial development conditions and strategic opportunities corresponding to the development conditions of this place. Beijing takes the 2022 Winter Olympics as an opportunity to demonstrate Hydrogen fuel cell vehicles. According to the official statement, pure electricity will be used in plains and fuel cells will be used in mountains during the Winter Olympics, basically speaking, we are further demonstrating the feasibility of using fuel cell vehicles in mountainous or alpine areas.

Table 5.1. Overall Technology Roadmap for Hydrogen Fuel Cell Vehicles in China.

		2020	**2025**	**2030**
Total Objects		Small-scale demonstration application in the field of public service vehicles in specific areas, scale of 10,000 vehicles	Large-scale application in the fields of urban private vehicles and public service vehicles, with a scale of 100,000 vehicles	Realize large-scale commercial promotion in the field of private passenger cars and large commercial vehicles, with a scale of one million vehicles
		Fuel cell system production capacity exceeds 1,000 sets/enterprise	Fuel cell system production capacity exceeds 10,000 sets/enterprise	
Hydrogen Fuel cell vehicle	**Function requirement**	The cold start temperature reaches -30°C, the configuration design of the power system is optimized, and the overall cost is comparable to that of a pure electric vehicle	The cold start temperature reaches -40°C, and mass production reduces the purchase cost of the whole vehicle, which is equivalent to that of hybrid electric vehicles of the same level	The performance of the whole vehicle is equivalent to that of traditional vehicles, and it has a considerable product competitive advantage
	Commercial Vehicle	Maximum speed≥80 km/h; cost≤1.5 million	Maximum speed≥80km/h; cost≤1 million	Maximum speed≥80km/h; cost≤0.6 million
	Transport Vehicle	Maximum speed≥180 km/h; Duration	Maximum speed≥180 km/h; Duration	Maximum speed≥180 km/h; Duration

		reaches 0.2 million km; Cost≤0.3 million	reaches 0.25 million km; Cost≤0.2 million	reaches 0.3 million km; Cost≤0.2 million
Common Key technology	**Fuel Cell Stack Technology**	The cold start temperature＜ -30℃, Mass specific power 2 kW/kg Volume power density 2kW/L	The cold start temperature＜ -40℃, Mass specific power 2.5 kW/kg Duration reaches over 5000h	Duration reaches over 8000h
	Basic Material Technology	High-performance membrane materials, low-platinum catalysts and metal bipolar plate technology	High Reliability Membrane, Catalyst and Bipolar Plate Technology	Low cost membrane electrode, bipolar plate technology
	Control Technology	Fuel Cell Optimal Control Technology	Fuel Cell Reliability Control Technology	Fuel cell low cost, highly integrated control technology
	Hydrogen Storage Technology	Development technology of key parts of the supply system, high-pressure hydrogen storage technology, hydrogen safety technology	High reliability technology for key parts of supply system, reliability technology for hydrogen storage system	Low-cost technology for key parts of the supply system, low-cost technology for hydrogen storage systems
Key Component technology		The performance of key system accessories such as high-speed oil-free air compressor, hydrogen circulation system, and 70MPa hydrogen storage tank meets the requirements of vehicle indicators		System cost＜200￥/kW
Hydrogen basic facility	**Hydrogen Supply**	Renewable energy distributed hydrogen production, low-energy alkaline electrolysis water distributed technology, coke oven gas and other by-product hydrogen production/high-efficiency and		Renewable energy distributed hydrogen production

		low-cost hydrogen separation and purification technology		
	Hydrogen Delivery	High pressure gaseous hydrogen storage and transportation	Cryogenic liquid hydrogen transportation	High pressure and high density organic liquid hydrogen storage and transportation
	Hydrogen Refueling Station	60 sets	350 sets	1000 sets

India's national hydrogen energy mission was launched in 2021. Indian Prime Minister Narendra Modi officially announced the launch of the national hydrogen mission on June 13, 2021 to accelerate the plan of producing carbon free fuel from renewable energy[129]. He set the goal for India to achieve energy self-reliance by 2047. Currently, all hydrogen consumed in India comes from fossil fuels. By 2050, it is expected that three-quarters of hydrogen will be green, generated by renewable electricity and electrolysis. In response to the government's attention to hydrogen, both private and public sector companies have announced ambitious hydrogen projects. Intended to contribute to the 2030 clean energy agenda by increasing the use of hydrogen energy.

Germany's hydrogen energy strategy was released in 2020, with the core being to view hydrogen energy as the main pillar of energy transformation. A policy framework has been established for the future production, transportation, and use of hydrogen energy in Germany[6]. Through this strategy, the German federal government proposes to create favorable conditions for the market growth of hydrogen energy technology, explore domestic hydrogen production and utilization markets, and utilize international markets to ensure the safety of German energy supply through renewable energy hydrogen production, while enhancing Germany's industrial competitiveness in hydrogen energy technology. The new coalition government, which took office in 2019, hopes to advance the deadline for phasing out coal-fired power from 2038 to 2030. By 2030, 70 billion euros will be invested in hydrogen energy and achieve the goal of net zero greenhouse gas emissions by 2045.

The development of hydrogen energy policy is still in its early stages, and only a few countries and regions have set out detailed hydrogen strategies. There is a pressing need for more in-depth research into this area to guide the future development of hydrogen energy. This includes understanding how best to build a hydrogen supply chain, considering the creation of infrastructure, and exploring the potential applications of hydrogen energy. Policymakers should also consider how to incentivize investment in hydrogen technologies, possibly through subsidies, tax incentives, or other financial support mechanisms.

In conclusion, while there are promising signs of progress in the development of hydrogen energy policy, much work remains to be done. It is hoped that with continued research and policy innovation, hydrogen energy can play a key role in the world's transition to a future with sustainable energy.

5.1.2 Local Policies

At the local level, many cities and regions are also promoting the development of hydrogen energy.

For example, the city of Los Angeles has pledged to establish a public transportation system fully running on hydrogen energy by 2025 [130]. This commitment has led to increased investment in hydrogen storage and distribution infrastructure. The Los Angeles City Council voted in February 2023 to convert a natural gas power plant into a new hydrogen system. This proposal is part of the "Green New Deal" passed by Eric Garcetti, the former mayor. It aims to close three natural gas plants and support "renewable" energy. The city's goal is to produce 100% "clean" electricity by 2035, which is more radical than the state's goal of 100% renewable energy by 2045, although recent state analysis shows that there is no plan to achieve this goal.

The California Energy Commission has released a roadmap for the deployment and expansion of renewable energy hydrogen plants to support policy decisions[131]. The roadmap also defines the actions completed by renewable hydrogen power plants to meet growing demand. According to this study, "the analysis predicts that factory costs will decrease from the current level of approximately $16 per kilogram (excluding subsidies and credit) to a median estimate of $6 by 2025, and to below $5 by 2050, ultimately estimated at $4 per kilogram." [132] Long et al.,20111) 1322] "The biggest factor is the cost reduction caused by increased station utilization (full allocation accounts for a portion of total capacity), while economies of scale and technological progress also contribute.

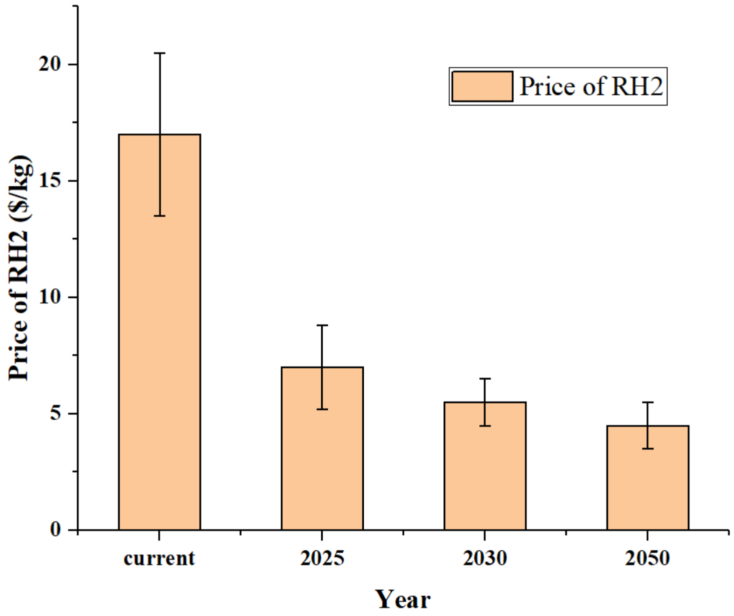


Fig. 5.2. The analysis predicts that factory costs of H_2

The research results highlighted nine market development recommendations:

1. Expand the support of hydrogen infrastructure to the entire supply chain (expanding the focus of the current plan to the production, processing, and transportation of renewable hydrogen). Focus on attracting forms of support from private capital (such as loan guarantees).

2. Adopt stable policies to support stable expansion of production capacity and avoid boom/bust cycles, while establishing a strong competitive market by improving market transparency and targeted incentive measures.

3. Reducing Developmental disorder in California: California Environmental Quality Act (CEQA), regulations and standards, costs (including taxes) and local issues.

4. Develop a tariff structure dedicated to Renewable fuels facilities (e.g. electrolyzers and liquefaction facilities) connected to transmission, such as overall electricity market access and transmission costs.

5. Promote the use of natural gas systems for the transportation and storage of renewable hydrogen - establish hybrid restrictions and interconnection requirements.

6. Take steps to ensure that the mixed gas/liquid supply chain does not pose obstacles to market access. For example, encouraging the development of open access points in supply chains such as gas or liquid terminal facilities.

7. By minimizing employment opportunities in disadvantaged communities while minimizing negative impacts such as transportation, noise, visual impact, and air emissions, we ensure the development of renewable hydrogen to promote social development.

8. Take action to ensure program eligibility, environmental accounting, and lack of definition are not obstacles to the development of renewable hydrogen.

As of last month, California has more than 8000 fuel cell electric vehicles operating in the state, and 41 Hydrogen station are in operation[133]. It is expected that this number will grow rapidly in the coming months and years.

In Germany, regions like **North Rhine-Westphalia** have begun constructing hydrogen energy infrastructure, including hydrogen fueling stations and hydrogen storage facilities[134](Di Molfetta,2022)[134]. North Rhine-Westphalia actively promotes its transformation to a modern climate neutral region, and hopes to create the largest hydrogen energy ecosystem in Europe covering innovation, production and infrastructure by 2030.

Cities and regions worldwide are demonstrating significant enthusiasm for hydrogen energy, with corresponding policies being implemented. For instance, Los

Angeles has committed to a hydrogen-powered public transportation system by 2025, leading to increased investment in hydrogen storage and distribution infrastructure. The city also plans to convert a natural gas power plant into a hydrogen system. Similarly, North Rhine-Westphalia in Germany is constructing hydrogen energy infrastructure, aiming to create Europe's largest hydrogen energy ecosystem by 2030. However, while these policies reflect a growing interest in hydrogen energy, they often lack specific provisions for hydrogen storage. This gap highlights the need for more comprehensive policies that address all aspects of the hydrogen energy supply chain, including storage.

5.1.3 International Policies

According to data from the European Commission, hydrogen energy currently accounts for less than 2% of Europe's energy consumption. 96% of hydrogen energy is generated through natural gas, and the production capacity of renewable energy for hydrogen production is relatively small[135]. The industrial scale and economy of hydrogen energy need to be improved. However, in recent years, the European Union has high hopes for the development of hydrogen energy, believing that hydrogen energy will bring significant changes to energy use in industries, transportation, construction, and other fields, and help adjust energy structure, drive investment and employment.

In July 2020, the European Union proposed a hydrogen energy strategy and announced the establishment of a clean hydrogen energy alliance[136]. Currently, 15 EU countries have included hydrogen energy in their economic recovery plans. After the crisis in Ukraine, hydrogen energy has become an important part of the EU's energy transformation strategy.

The European Energy Supply Adjustment Plan was announced in May 2022, with the goal of producing 10 million tons of renewable hydrogen in the European Union and importing 10 million tons of renewable hydrogen by 2030. The European Union has also established the "European Hydrogen Bank" to increase investment in the hydrogen energy market.

At the same time, the EU's vision of achieving energy structure transformation through hydrogen energy is facing challenges. In the current situation where technology is still immature and costs are relatively high, the research and promotion of hydrogen energy will inevitably be affected. The transportation and storage of hydrogen energy also need to be further improved, and it is still time for large-scale commercial applications.

Analysts point out that although the EU has announced a large number of hydrogen energy projects, many of them involve hydrogen energy generated by natural gas, which may generate significant carbon emissions like natural gas, oil, and coal.

In addition, the production of renewable hydrogen requires a large amount of electricity, which is a test for the EU, which currently faces tight electricity supply and rising prices. The main economies of the European Union, France and Germany, also have differences in regulations on "low-carbon" hydrogen energy, further complicating the introduction of hydrogen energy regulations by the EU.

At the international level, the European Union has released a hydrogen strategy aimed at expanding the use of hydrogen energy to a portion of all energy consumption by 2030 (European Commission, 2020). This strategy includes support for the research and commercialization of hydrogen storage technology. Furthermore, the Paris Agreement under the United Nations Framework Convention on Climate Change encourages countries to develop and use hydrogen energy to reduce greenhouse gas emissions (UNFCCC, 2015).

5.2 Impact of Policies on Hydrogen Storage Technology

Policies significantly influence the development and adoption of hydrogen storage technologies, affecting technological innovation, market dynamics, and environmental and economic viability.

5.2.1 Technological Innovation

Policies play a crucial role in the development and deployment of new technologies, and can stimulate or hinder technological innovation in hydrogen storage. For instance, the U.S. Department of Energy's Hydrogen and Fuel Cells Program has provided more than $1 billion in funding since 2004 to research, develop, and demonstrate a wide range of technologies, including hydrogen storage. This policy has led to significant advancements, such as the development of novel materials that can store hydrogen more efficiently.

Conversely, policies that favor certain technologies can create barriers to innovation. For example, in countries where policies heavily favor battery electric vehicles, like Norway, the development of hydrogen storage technologies for fuel cell vehicles may be hindered due to a lack of comparable support.

5.2.2 Market Dynamics

Market-based policies can influence the competitiveness of hydrogen storage technologies. For example, in regions with high carbon pricing, such as the European Union with its Emissions Trading System, hydrogen storage can become more attractive compared to fossil fuel-based energy storage technologies. In 2021, the carbon price in the EU reached a record high of over €50 per tonne, making low-carbon technologies like hydrogen storage increasingly competitive.

On the other hand, policies that subsidize competing technologies can distort market dynamics. For instance, generous subsidies for lithium-ion batteries in China have led to a rapid expansion of the battery industry, potentially crowding out investment in alternative storage technologies like hydrogen.

5.2.3 Environmental and Economic Viability

Policies can also affect the environmental and economic viability of hydrogen storage technologies. In California, strict emission standards and the Low Carbon Fuel Standard, which provides credits for low-carbon fuels, have made hydrogen storage an attractive option for energy companies. As a result, the state has seen a significant increase in the deployment of hydrogen storage systems.

Economic policies can also improve the viability of hydrogen storage. In Germany, feed-in tariffs guarantee a fixed price for electricity generated from renewable sources, including hydrogen. This policy has made the production and storage of hydrogen a more economically viable option for energy companies, leading to an increase in the number of hydrogen storage projects in the country.

In conclusion, policies at various levels have a significant impact on hydrogen storage technology. Understanding these impacts is crucial for policymakers, researchers, and industry stakeholders to navigate the policy landscape and promote the development and adoption of hydrogen storage technologies.

5.3 Case Studies

In this section, the impact of policies on hydrogen storage technologies is illustrated through representative case studies. These cases highlight how specific policies have either facilitated or hindered the development and application of these technologies in different regions.

5.3.1 Case Study 1: California's Low Carbon Fuel Standard

California's Low Carbon Fuel Standard (LCFS) is a policy that aims to reduce the carbon intensity of transportation fuels[137]. This program, established by the California Air Resources Board (CARB), aims to declien the carbon intensity of transportation fuels used in California by 20% by 2030, is a key policy in California that encourages the use of cleaner, low-carbon fuels, and it has had a significant impact on the growth of hydrogen refueling infrastructure.

The low-carbon fuel standards in California have driven the early development momentum of green hydrogen in the United States, and the US government has made the development of hydrogen energy a key factor in addressing climate change. The LCFS has been instrumental in promoting the development and adoption of hydrogen storage technologies in the state. Under the LCFS, hydrogen producers can generate credits by producing and dispensing hydrogen for use in fuel cell electric vehicles. These credits can be sold to other parties, providing an additional revenue stream for hydrogen producers.

In California, hydrogen powered vehicles (FCEVs) play an important role in reducing greenhouse gas and smoke emissions as zero emission vehicles[138]. California's latest clean car program encourages the rapid deployment of ZEV technologies, including Hydrogen fuel cells and battery electric vehicles. In addition, the California government has also passed Assembly Bill 8, acknowledging that providing sufficient hydrogen refueling facilities for the upcoming ZEV fleet is a necessary first step, and has coordinated and cooperated in this regard. These policies have led to a obvious increase in the number of hydrogens refueling stations in California, from just a handful in 2015 to over 40 by 2023.

5.3.2 Case Study 2: Germany's National Hydrogen Strategy

Germany's National Hydrogen Strategy, launched in 2020, sets out a comprehensive roadmap for the development of a sustainable hydrogen economy. The strategy includes specific targets for the installation of electrolysis capacity for hydrogen production, as well as measures to promote the use of hydrogen in various sectors[139].

This policy has spurred significant investment in hydrogen storage technologies, with several large-scale projects currently underway. For example, the GET H2 project in Lower Saxony aims to create a cross-sector hydrogen economy, with hydrogen storage playing a key role. In recent years, the demand for Hydrogen fuel battery driven electric vehicles in Germany is growing. The strategy predicts that by 2050, the demand for Hydrogen fuel in Germany will increase to 110 tWh to 380 tWh[140].

5.3.3 Case Study 3: Lack of Supportive Policies in Australia

In contrast to the previous cases, the lack of supportive policies in Australia has been a barrier to the development of hydrogen storage technologies. Despite having abundant renewable energy resources, which could be harnessed for hydrogen production, Australia has been slow to develop a hydrogen economy. The absence of a national hydrogen strategy or similar policy framework has resulted in a lack of direction and certainty for potential investors. As a result, the development and deployment of hydrogen storage technologies have been limited compared to other countries[141].

These case studies highlight the significant impact that policies can have on the development and adoption of hydrogen storage technologies. They underscore the need for well-designed policies that provide clear direction and support for this emerging field.

5.4 Summary

Based on the current policy environment and the careful analysis of the development track of Hydrogen technologies, it can be expected that there will be several trends in the policy prospect of the vehicle fuel storage scenario.

(1) Increased Support for Research and Development

Given the ongoing technological advancements in hydrogen storage, it is likely that policies will increasingly support research and development in this field. Governments may provide more funding for R&D initiatives, establish research partnerships with industry, and offer incentives for private sector innovation. These policies could accelerate the development of more efficient, cost-effective, and scalable hydrogen storage solutions.

(2) Greater Emphasis on Infrastructure Development

As the adoption of hydrogen fuel cell vehicles grows, there will be a greater need for hydrogen infrastructure, including production facilities, refueling stations, and storage systems. Policies may therefore shift towards supporting the development of this infrastructure, such as through public-private partnerships or infrastructure funding programs. This could facilitate the wider adoption of hydrogen as a vehicle fuel[142].

(3) Stricter Environmental Regulations

With increasing global focus on climate change, policies may impose stricter environmental standards that favor low-carbon technologies like hydrogen[143]. This could include tighter emission standards for vehicles, higher carbon pricing, and stricter regulations on fossil fuel-based energy sources. These policies could enhance the competitiveness of hydrogen storage technologies compared to carbon-intensive alternatives.

(4) Market-Based Policies

Future policies may also increasingly leverage market mechanisms to promote hydrogen storage technologies. This could include feed-in tariffs for hydrogen energy, carbon credits for hydrogen producers, or cap-and-trade systems that incentivize low-carbon technologies. These market-based policies could create a more favorable economic environment for hydrogen storage.

In conclusion, future policy trends are likely to further support the development and adoption of hydrogen storage technologies. However, the specific impacts of these policies will depend on their design and implementation, as well as the broader economic, technological, and environmental context.

Based on the research findings, several policy recommendations can be proposed to further promote the development and adoption of hydrogen storage technologies for vehicle fuel storage scenarios.

(1) Enhance Policy Support for Research and Development

Governments should increase funding for research and development in hydrogen storage technologies. This could involve direct funding for research institutions, tax incentives for private sector R&D, and support for collaborative research initiatives. Such policies can accelerate technological advancements and help bring new solutions to market more quickly.

(2) Improve the Policy Environment for Infrastructure Development

Policies should facilitate the development of hydrogen facilities, including production facilities, refueling stations, and storage systems. This could involve public-private partnerships, infrastructure funding programs, and regulatory measures that streamline the approval process for new infrastructure projects. A robust hydrogen infrastructure is crucial for the wider adoption of hydrogen as a vehicle fuel.

(3) Implement Stricter Environmental Regulations

Governments should implement stricter environmental regulations that favor low-carbon technologies like hydrogen. This could include tighter emission standards for vehicles, higher carbon pricing, and stricter regulations on fossil fuel-based energy sources. Such policies can make hydrogen storage technologies more competitive and drive their adoption.

(4) Leverage Market-Based Policies

Policies should leverage market mechanisms to promote hydrogen storage technologies. This could include feed-in tariffs for hydrogen energy, carbon credits for hydrogen producers, or cap-and-trade systems that incentivize low-carbon technologies. Market-based policies can create a favorable economic environment for hydrogen storage and drive investment in this field.

In conclusion, well-designed policies can play a crucial role in promoting the development and adoption of hydrogen storage technologies. Policymakers should consider these recommendations in their efforts to support a transition to a hydrogen economy.

Chapter 6 Conclusion and recommendations for future work

6.1 Conclusion of the study

With the growing problem of global warming, it is increasingly important to make a clean energy transition for the energy mix. As a low-carbon emission green energy, hydrogen energy is expected to replace fossil fuels as an important part of clean fuel and achieve efficient emission reduction in the automotive sector.

Although hydrogen energy itself has the advantage of green and clean energy and hydrogen-fueled vehicles have been industrialized, it still faces some technical limitations when it is really applied in the field of family cars, especially in the field of hydrogen storage, such as difficult compression, easy explosion and obvious container embrittlement effect. Therefore, this study firstly conducts a multidimensional literature review on the current background of hydrogen storage technology. Secondly, based on the LCA model, CML-IA database and monetized environmental assessment, the current hydrogen storage technology under fuel cell vehicle/car tank application is systematically evaluated from environmental and economic perspectives using a common 5-seater domestic car in China as the evaluation scenario, and finally some suggestions are provided for the future energy industry transformation and policy level based on the evaluation results.

In terms of environmental analysis, the carbon footprint analysis under the whole life cycle of different hydrogen storage containers was carried out for the hydrogen storage process. The carbon emission of the manufacturing process of the Type 4 of high-pressure vessel is the lowest (5539 kgCO_2 eq), which is lower than that of the Type 3 of high-pressure vessel (7219 kgCO_2 eq) and cryogenic vessel (135000 kgCO_2 eq), and more than 80% of CO_2 emission comes from the production process of carbon fiber. At the same time, human toxicity potential analysis was conducted for the hydrogen storage process, and the human toxicity level of the Type 4 of high-pressure vessel was also the lowest, at 1,500 kg 1,4-DB eq, also lower than the Type 3 of high-pressure vessel (2,140 kg 1,4-DB eq) and cryogenic vessel (2,580 kg 1,4-DB eq), in which the toxicity impact of carbon fiber accounted for 83%. In terms of carbon emissions and human toxicity, the Type 4 of high-pressure vessels has more significant environmental advantages.

From the results of economic analysis, the coin cost and energy consumption per unit of hydrogen of Type 4 high pressure vessel are the lowest, 10.4 US$/kg.$H_2$ and 5.2 kWh/kgH_2, respectively, compared to Type 3 high pressure vessel and cryogenic vessel, which consume more energy, especially the latter consumes about 724 kWh/kgH_2. it can be seen that Type 4 high pressure vessel has more potential to be used in the car industry.

In view of the evaluation performance of hydrogen storage technology, this study believes that it is an important and practical policy formulation idea to strengthen the research and development investment of hydrogen storage technology, specify more serious technical and environmental regulations, and guide the overall industrial development with the demand of market theme. The policy design for hydrogen storage should always develop in the direction of technical practice.

In summary, this study concludes that the Type 4 high-pressure vessel as a hydrogen storage unit has more environmental and economic advantages for use in hydrogen-fueled cars, and functional departments can pay more attention to the application of this hydrogen storage technology in the automotive industry and hydrogen energy policy. The guiding results of this study will also lead to a more systematic understanding of the hydrogen storage system for cars and contribute to the blueprint planning of future hydrogen energy utilization.

6.2 Recommendation for future work

Under the background of the ‘carbon emission reduction’ in the world, hydrogen energy, as a sustainable and clean energy source, is attracting the attention of various countries. With the development of water electrolysis technology and the operation of hydrogen fuel-cell cars, the development of ‘hydrogen production’ and ‘hydrogen utilization’ has also made the issue of ‘hydrogen storage’ more prominent. In the scientific and industrial communities, numerous studies have been carried out in the field of hydrogen storage, including physical and chemical hydrogen storage techniques. However, hydrogen energy companies still face many complex problems in choosing specific storage methods, such as cost, carbon emission and safety risks due to the diversity of routes. Moreover, the lack of evaluation system for hydrogen storage technology is also not conducive to the integration of the whole hydrogen energy industry chain. Therefore, the overall goal of this project is to develop a unified evaluation system for multiple hydrogen storage technologies under the same life cycle, so as to meet the needs of the hydrogen energy-related enterprises and policy-making department in each country to optimize the industry chain. Based on this main goal, the following are the recommended work to the future development:

(1) To conduct research on the current technical status of the mainstream physical storage and chemical storage technologies in the industry, and form a detailed industrial development report, so as to bridge the gap in industrial awareness of hydrogen storage field.

(2) To analyze the energy consumption and material loss of each route and compare them with the relevant industry data on the basis of the development status of different hydrogen storage technology routes, so as to provide model data support for the establishment of the subsequent evaluation system.

(3) Conduct carbon footprint analysis based on the whole process of raw material extraction, manufacturing, transportation, distribution, use and final disposal of each hydrogen storage technology route, and optimize the technology route from the perspective of ‘carbon emission reduction’ by using various carbon footprint calculation methods.

(4) Safety evaluation of different hydrogen storage technologies for the safety hazards, and provide the safety evaluation standards for hydrogen storage technologies.

(5) Based on the above evaluation results, analyze the technical characteristics and future development focus of the hydrogen storage field, and further promote the design of relevant policies and the planning of the industrial chain.

Based on the above evaluation results, analyze the technical characteristics and future development focus of the hydrogen storage field, and further promote the design of relevant policies and the planning of the industrial chain.

Reference

1. Lattin, W.C., et al., *Transition to hydrogen economy in the United States: A 2006 status report.* International Journal of Hydrogen Energy, 2007. **32**(15): p. 3230-3237.
2. Shen, N., et al., *Renewable Energy Green Innovation, Fossil Energy Consumption, and Air Pollution—Spatial Empirical Analysis Based on China.* Sustainability, 2020. **12**(16): p. 6397.
3. Ebhota, W.S., et al., *The place of small hydropower electrification scheme in socioeconomic stimulation of Nigeria.* International Journal of Low-Carbon Technologies, 2018. **13**(4): p. 311-319.
4. IEA, *Key World Energy Statistics 2021*. 2021, International Energy Agency.
5. Jain, I.P., *Hydrogen the fuel for 21st century.* International Journal of Hydrogen Energy, 2009. **34**(17): p. 7368-7378.
6. Li, Z., et al., *Development of renewable energy multi-energy complementary hydrogen energy system (A Case Study in China): A review.* Energy Exploration & Exploitation, 2020. **38**(6): p. 2099-2127.
7. Sadeghzadeh, M., et al., *A novel exergy-based assessment on a multi-production plant of power, heat and hydrogen: integration of solid oxide fuel cell, solid oxide electrolyzer cell and Rankine steam cycle.* International Journal of Low-Carbon Technologies, 2021. **16**(3): p. 798-813.
8. Bethoux, O., *Hydrogen Fuel Cell Road Vehicles and Their Infrastructure: An*

Option towards an Environmentally Friendly Energy Transition. Energies, 2020. **13**(22): p. 6132.

9. Gurz, M., et al., *The meeting of hydrogen and automotive: A review.* International Journal of Hydrogen Energy, 2017. **42**(36): p. 23334-23346.

10. Chakraborty, S., et al., *Hydrogen Energy as Future of Sustainable Mobility.* Frontiers in Energy Research, 2022. **10**.

11. Candelaresi, D., et al., *Comparative life cycle assessment of hydrogen-fuelled passenger cars.* International Journal of Hydrogen Energy, 2021. **46**(72): p. 35961-35973.

12. Wang, W., et al., *Prediction and Analysis of Energy Saving Potential for Fuel Cell Vehicles*. IEEE.

13. Tsuchiya, H., *Innovative renewable energy solutions for hydrogen vehicles.* International Journal of Energy Research, 2008. **32**(5): p. 427-435.

14. Thomas, C., *Affordable hydrogen supply pathways for fuel cell vehicles.* International Journal of Hydrogen Energy, 1998. **23**(6): p. 507-516.

15. Seo, Y., et al., *Design concepts of hydrogen supply chain to bring consumers offshore green hydrogen.* International Journal of Hydrogen Energy, 2023. **48**(40): p. 15126-15142.

16. Zhang, F., et al., *The survey of key technologies in hydrogen energy storage.* International Journal of Hydrogen Energy, 2016. **41**(33): p. 14535-14552.

17. Li, X., et al., *Review of Hydrogen Embrittlement in Metals: Hydrogen Diffusion, Hydrogen Characterization, Hydrogen Embrittlement Mechanism and*

Prevention. Acta Metallurgica Sinica (English Letters), 2020. **33**(6): p. 759-773.

18. Xiao, H.H., et al., *Premixed flame propagation in hydrogen explosions.* Renewable & Sustainable Energy Reviews, 2018. **81**: p. 1988-2001.

19. Mohan, M., et al., *Hydrogen storage in carbon materials—A review.* Energy Storage, 2019. **1**(2): p. e35.

20. Rivard, E., et al., *Hydrogen Storage for Mobility: A Review.* Materials, 2019. **12**(12): p. 1973.

21. Ren, X., et al., *Challenges towards hydrogen economy in China.* International Journal of Hydrogen Energy, 2020. **45**(59): p. 34326-34345.

22. Agarwal, R., *Transition to a Hydrogen-Based Economy: Possibilities and Challenges.* Sustainability, 2022. **14**(23): p. 15975.

23. Bonciu, F., *The Dawn of a Geopolitics of a Hydrogen-based Economy. The Place of European Union.* Romanian Journal of European Affairs, 2021. **21**(2): p. 95-113.

24. Blanchette, S., *A hydrogen economy and its impact on the world as we know it.* Energy Policy, 2008. **36**(2): p. 522-530.

25. sro, C. *The development of hydrogen energy*. 2021; Available from: https://cepconsult.com/publications/the-development-of-hydrogen-energy/.

26. Baohua MAO., et al., *On Development Path of Hydrogen Energy Technology in China's Transportation System Under Carbon Neutrality Goal.* Journal of Transportation Systems Engineering and Information Technology, 2021. **21**(06): p. 234-243.

27. Alexander Brown, N.G. *China's nascent green hydrogen sector: How policy, research and business are forging a new industry*. 2022 [cited 2023 10th June]; Available from: https://merics.org/en/report/chinas-nascent-green-hydrogen-sector-how-policy-research-and-business-are-forging-new.

28. Alexander Brown, N.G. *China's nascent green hydrogen sector: How policy, research and business are forging a new industry*. 2022; Available from: https://merics.org/en/report/chinas-nascent-green-hydrogen-sector-how-policy-research-and-business-are-forging-new.

29. Kar, S.K., et al., *Hydrogen economy in India: A status review.* WIREs Energy and Environment, 2023. **12**(1).

30. Otaki, T., et al., *The Potential of Collaboration between India and Japan in the Hydrogen Sector.* Energies, 2023. **16**(8): p. 3596.

31. Lee, D.Y., et al., *Research and Development Investment and Collaboration Framework for the Hydrogen Economy in South Korea.* Sustainability, 2021. **13**(19): p. 10686.

32. Khan, U., et al., *Consumer preferences for hydrogen fuel cell vehicles in Japan.* Transportation Research Part D-Transport and Environment, 2020. **87**.

33. Salimi, M., et al., *The Role of Clean Hydrogen Value Chain in a Successful Energy Transition of Japan.* Energies, 2022. **15**(16): p. 6064.

34. Burandt, T., *Analyzing the necessity of hydrogen imports for net-zero emission scenarios in Japan.* Applied Energy, 2021. **298**.

35. Vu, K.M., et al., *Backwardness advantage and economic growth in the*

information age: A cross-country empirical study. Technological Forecasting and Social Change, 2020. **159**: p. 120197.

36. Wen, H., et al., *Green Technological Progress and the Backwardness Advantage of Green Development: Taking the Sustainable Development Strategy of Central and Western China as an Example.* Sustainability, 2021. **13**(14): p. 7567.

37. Bonciu, F.F., *The european union hydrogen strategy as a significant step towards a circular economy.* Romanian Journal of European Affairs, 2020. **20**(2): p. 36-48.

38. Edwards, R.L., et al., *The status of hydrogen technologies in the UK: A multi-disciplinary review.* Sustainable Energy Technologies and Assessments, 2021. **43**.

39. Author, N.G., *A national vision of America's transition to a hydrogen economy. To 2030 and beyond*. 2002, Office of Scientific and Technical Information (OSTI).

40. Association, F.C.H.E. *ROAD MAP TO A US HYDROGEN ECONOMY*. 2020.

41. Kar, S.K., et al., *Overview of hydrogen economy in Australia.* WIREs Energy and Environment, 2023. **12**(1).

42. Murray, M., et al., *Stakeholder perceptions towards the transition to a hydrogen economy in Poland.* International Journal of Hydrogen Energy, 2008. **33**(1): p. 20-27.

43. Safari, A., et al., *Petroleum Sector-Driven Roadmap for Future Hydrogen Economy.* Applied Sciences, 2021. **11**(21): p. 10389.

44. Ansari, D., *The Hydrogen Ambitions of the Gulf States*. 2022.

45. Hong, X., et al., *Hydrogen Economy Assessment & Resource Tool (HEART): A python-based tool for ASEAN H2 roadmap study.* International Journal of Hydrogen Energy, 2022. **47**(52): p. 21897-21907.

46. Hong, X., et al., *Techno-enviro-economic analyses of hydrogen supply chains with an ASEAN case study.* International Journal of Hydrogen Energy, 2021. **46**(65): p. 32914-32928.

47. Liu, R., et al.,, *An Analysis of Renewable Energy Sources for Developing a Sustainable and Low-Carbon Hydrogen Economy in China.* Processes, 2023. **11**(4).

48. Ren, J., et al., *Hydrogen economy in China: Strengths–weaknesses–opportunities–threats analysis and strategies prioritization.* Renewable and Sustainable Energy Reviews, 2015. **41**: p. 1230-1243.

49. Thomas S. Eder , J.M., *Powering the Belt and Road China supports its energy companies' global expansion and prepares the ground for potential new supply chains.* 2019.

50. Lu, J., et al., *Building the hydrogen economy in China: Drivers, resources and technologies.* Renewable and Sustainable Energy Reviews, 2013. **23**: p. 543-556.

51. Zhang, M., et al., *The Regulatory Perspectives to China's Emerging Hydrogen Economy: Characteristics, Challenges, and Solutions.* Sustainability, 2022. **14**(15).

52. Green, R., *Opportunities with the Green Belt and Road Initative(BRI)-Building a Hydrogen Economy*. 2022.

53. Demirbas, A., *Future hydrogen economy and policy.* Energy Sources, Part B: Economics, Planning, and Policy, 2017. **12**(2): p. 172-181.

54. Mulder, G., et al., *Towards a sustainable hydrogen economy: Hydrogen pathways and infrastructure.* International Journal of Hydrogen Energy, 2007. **32**(10-11): p. 1324-1331.

55. Zhang, M., et al., *Decomposition analysis of energy consumption in Chinese transportation sector.* Applied Energy, 2011. **88**(6): p. 2279-2285.

56. Group, O.C.R.P., *China's total oil consumption control path and implementation roadmap.* China Coal, 2020. **46**(2): p. 28-34.

57. Tayarani, H., et al., *Life Cycle Assessment of Hydrogen Transportation Pathways via Pipelines and Truck Trailers: Implications as a Low Carbon Fuel.* Sustainability, 2022. **14**(19).

58. Sahraie, E., et al., *A Flexible System-level Hydrogen Transportation System Operating Structure Interacting with Urban Transportation System*. IEEE.

59. Lahnaoui, A., et al., *Optimizing hydrogen transportation system for mobility by minimizing the cost of transportation via compressed gas truck in North Rhine-Westphalia.* Applied Energy, 2018. **223**: p. 317-328.

60. Wang, S., et al., *Joint Planning of Electricity Transmission and Hydrogen Transportation Networks.* IEEE Transactions on Industry Applications, 2022. **58**(2): p. 2887-2897.

61. Pramuanjaroenkij, A., et al., *The fuel cell electric vehicles: The highlight review.* International Journal of Hydrogen Energy, 2023. **48**(25): p. 9401-9425.

62. Tanaka, S., et al., *Fuel cell system for Honda CLARITY fuel cell.* eTransportation, 2020. **3**.

63. Arrigoni, A., et al., *Greenhouse Gas Implications of Extending the Service Life of PEM Fuel Cells for Automotive Applications: A Life Cycle Assessment.* Clean Technologies, 2022. **4**(1): p. 132-148.

64. Dalrymple, C.A. *EU Funds for Hydrogen Buses In Iceland.* 2018; Available from: https://grapevine.is/news/2018/10/10/eu-funds-for-hydrogen-buses-in-iceland/.

65. Peters, R., et al., *Future Power Train Solutions for Long-Haul Trucks.* Sustainability, 2021. **13**(4): p. 2225.

66. Kim, J., et al., *The role of hydrogen in the road transportation sector for a sustainable energy system: A case study of Korea.* International Journal of Hydrogen Energy, 2008. **33**(24): p. 7326-7337.

67. Wanniarachchi, S., et al., *Transforming road freight transportation from fossils to hydrogen: Opportunities and challenges.* International Journal of Sustainable Transportation, 2023. **17**(5): p. 552-572.

68. You, Y., et al., *Comparative study on ammonia and liquid hydrogen transportation costs in comparison to LNG.* International Journal of Naval Architecture and Ocean Engineering, 2023. **15**.

69. Ogden, J., et al., *Natural gas as a bridge to hydrogen transportation fuel:*

Insights from the literature. Energy Policy, 2018. **115**: p. 317-329.

70. Shi, R., et al., *The State-of-the-Art Progress on the Forms and Modes of Hydrogen and Ammonia Energy Utilization in Road Transportation.* Sustainability, 2022. **14**(19): p. 11904.

71. Barthélémy, H., *Hydrogen storage – Industrial prospectives.* International Journal of Hydrogen Energy, 2012. **37**(22): p. 17364-17372.

72. Nazir, G., et al., *Recent Advances and Reliable Assessment of Solid-State Materials for Hydrogen Storage: A Step Forward toward a Sustainable H ₂ Economy.* Advanced Sustainable Systems, 2022. **6**(11): p. 2200276.

73. Hong, J.-H., et al., Chang, *Safety evaluation of 70MPa-capacity type III hydrogen pressure vessel considering material degradation of composites due to temperature rise.* Composite Structures, 2014. **113**: p. 127-133.

74. Zhang, Q., et al., *Design of a 70 MPa type IV hydrogen storage vessel using accurate modeling techniques for dome thickness prediction.* Composite Structures, 2020. **236**: p. 111915.

75. Berro Ramirez, J.P., et al., *700 bar type IV high pressure hydrogen storage vessel burst – Simulation and experimental validation.* International Journal of Hydrogen Energy, 2015. **40**(38): p. 13183-13192.

76. Eberle, U., et al., *Chemical and physical solutions for hydrogen storage.* Angewandte Chemie International Edition, 2009. **48**(36): p. 6608-6630.

77. Ghouaoula, A., et al., *Analytical Prediction of Damage in the Composite Part*

of a Type-3 Hydrogen Storage Vessel. Mechanics of Composite Materials, 2012. **48**(1): p. 77-88.

78. Son, D.-S., et al., *Evaluation of modeling techniques for a type III hydrogen pressure vessel (70 MPa) made of an aluminum liner and a thick carbon/epoxy composite for fuel cell vehicles.* International Journal of Hydrogen Energy, 2012. **37**(3): p. 2353-2369.

79. Aceves, S.M., et al., *High-density automotive hydrogen storage with cryogenic capable pressure vessels.* International Journal of Hydrogen Energy, 2010. **35**(3): p. 1219-1226.

80. Lin, D.T.W., et al., *Optimal design of a composite laminate hydrogen storage vessel.* International Journal of Energy Research, 2013. **37**(7): p. 761-768.

81. P.F.Liua., et al., *Numerical simulation and optimal design for composite high-pressure hydrogen storage vessel: A review.* Renewable and Sustainable Energy Reviews, 2012: p. 1817-1827.

82. Acar, C., *A comprehensive evaluation of energy storage options for better sustainability.* International Journal of Energy Research, 2018. **42**(12): p. 3732-3746.

83. Ahluwalia, R.K., et al., *Technical assessment of cryo-compressed hydrogen storage tank systems for automotive applications.* International Journal of Hydrogen Energy, 2010. **35**(9): p. 4171-4184.

84. Wijayanta, A.T., et al., *Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: Comparison review.* International Journal of

Hydrogen Energy, 2019. **44**(29): p. 15026-15044.

85. Li, L., et al., *Hydrogen storage and release from a new promising Liquid Organic Hydrogen Storage Carrier (LOHC): 2-methylindole.* International Journal of Hydrogen Energy, 2016. **41**(36): p. 16129-16134.

86. Aziz, M., et al., *Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization.* Energies, 2020. **13**(12): p. 3062.

87. Boulamanti., et al., *Production costs of the chemical industry in the EU and other countries: Ammonia, methanol and light olefins.* Renewable and Sustainable Energy Reviews, 2017. **68**: p. 1205-1212.

88. Campion, N., et al., *Techno-economic assessment of green ammonia production with different wind and solar potentials.* Renewable and Sustainable Energy Reviews, 2023. **173**.

89. Gezerman, A.O., *A Critical Assessment of Green Ammonia Production and Ammonia Production Technologies.* Kemija u industriji, 2022(1-2).

90. Deka, T.J., et al., *Methanol fuel production, utilization, and techno-economy: a review.* Environmental Chemistry Letters, 2022. **20**(6): p. 3525-3554.

91. Gulden, J., et al., *New means of hydrogen storage - the potentials of methanol as energy storage for excessive windpower in North Germany.* 17th International Conference Heat Transfer and Renewable Sources of Energy (Htrse-2018), 2018. **70**.

92. Chen, Z.W., et al., *Development of Ti-Cr-Mn-Fe based alloys with high hydrogen desorption pressures for hybrid hydrogen storage vessel application.*

International Journal of Hydrogen Energy, 2013. **38**(29): p. 12803-12810.

93. Agostini, A., et al., *Role of hydrogen tanks in the life cycle assessment of fuel cell-based auxiliary power units.* Applied Energy, 2018. **215**: p. 1-12.

94. Bie, H.Y., et al., *Fatigue life evaluation of high pressure hydrogen storage vessel.* International Journal of Hydrogen Energy, 2010. **35**(7): p. 2633-2636.

95. Dadashzadeh, M., et al., *Risk assessment methodology for onboard hydrogen storage.* International Journal of Hydrogen Energy, 2018. **43**(12): p. 6462-6475.

96. Fowler, C.P., et al., *A review of toroidal composite pressure vessel optimisation and damage tolerant design for high pressure gaseous fuel storage.* International Journal of Hydrogen Energy, 2016. **41**(47): p. 22067-22089.

97. Boero, A.J., et al., *Environmental Life Cycle Assessment of Ammonia-Based Electricity.* Energies, 2021. **14**(20).

98. Al-Zareer, M., et al., *Transient thermodynamic analysis of a novel integrated ammonia production, storage and hydrogen production system.* International Journal of Hydrogen Energy, 2019. **44**(33): p. 18214-18224.

99. Standardization, I.O.f., *ISO: 14040 Environmental management — Life cycle assessment — Principles and framework*. 2006.

100. G, I.S.O., *ISO14044 Environmental management-Life cycle assessment-Requirements and guidelines*. 2006.

101. Joos, F., et al., *Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis.* Atmospheric Chemistry and Physics, 2013. **13**(5): p. 2793-2825.

102. AWOE. *Life Cycle Analysis of hydrogen storage tanks*. 2020; Available from: http://www.awoe.net/Hydrogen-Storage-LCA.html.

103. ELsa Weiszflog, M.A., *Life Cycle Assessment of Hydrogen Storage Systems for Trucks : An assessment of environmental impacts and recycling flows of carbon fiber*, in *DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS*. 2022, CHALMERS UNIVERSITY OF TECHNOLOGY: Sweden.

104. Organization, W.M. *Global Ozone Research and Monitoring Project—Report No. 52 : Scientific Assessment of ozone Depletion: 2010*. 2010.

105. Roy, P.-O., et al., *Life Cycle Impact Assessment of Terrestrial Acidification: Modeling Spatially Explicit Soil Sensitivity at the Global Scale.* Environmental Science & Technology, 2012. **46**(15): p. 8270-8278.

106. Roland Hischier, B.W. *Implementation of Life Cycle Impact Assessment Methods*. 2010.

107. Benitez, A., et al., *Ecological assessment of fuel cell electric vehicles with special focus on type IV carbon fiber hydrogen tank.* Journal of Cleaner Production, 2021. **278**.

108. Gardiner, M. *Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs*. 2009.

109. *NIST Chemistry WebBook*, in *NIST Standard Reference Database Number 69*. 2023.

110. *H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional*

Pathway Options Analysis Results. 2012.

111. *Beijing Hydrogen Energy Industry Development Implementation Plan (2021-2025).* 2021; Available from: https://www.ncsti.gov.cn/zcfg/zcwj/202108/t20210816_38829.html.

112. Commission, N.D.a.R. *Medium and long-term plan for the development of hydrogen energy industry (2021-2035).* 2022; Available from: https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/t20220323_1320038.html.

113. China, S.o.A.E.o., *Energy-saving and new energy vehicle technology roadmap 2.0.* 2020.

114. 张媛媛, 赵., 鲁锡兰, 张德祥, *有机液体储氢材料的研究进展.* 化工进展, 2016. **35**(09): p. 2869-2874.

115. Farias, C.B.B., et al., *Use of Hydrogen as Fuel: A Trend of the 21st Century.* Energies, 2022. **15**(1): p. 311.

116. Wolf, J., *Liquid-Hydrogen Technology for Vehicles.* MRS Bulletin, 2002. **27**(9): p. 684-687.

117. Milad Sadeghzadeh, M.M., et al., *A novel exergy-based assessment on a multi-production plant of power, heat and hydrogen: integration of solid oxide fuel cell, solid oxide electrolyzer cell and Rankine steam cycle.* International Journal of Low-Carbon Technologies, 2021. **16**(3): p. 798–813.

118. Falcone, P.M., et al., *Hydrogen economy and sustainable development goals: Review and policy insights.* Current Opinion in Green and Sustainable Chemistry, 2021. **31**: p. 100506.

119. Liu, W., et al., *Trends and future challenges in hydrogen production and storage research.* Environmental Science and Pollution Research, 2020. **27**(25): p. 31092-31104.

120. Yuan, K., et al., *Hydrogen in China: Policy, program and progress.* International Journal of Hydrogen Energy, 2010. **35**(7): p. 3110-3113.

121. Johnston, B., et al., *Hydrogen: the energy source for the 21st century.* Technovation, 2005. **25**(6): p. 569-585.

122. Yue, M., et al., *Hydrogen energy systems: A critical review of technologies, applications, trends and challenges.* Renewable and Sustainable Energy Reviews, 2021. **146**: p. 111180.

123. Solomon, B.D., et al., *A global survey of hydrogen energy research, development and policy.* Energy Policy, 2006. **34**(7): p. 781-792.

124. Cheng, W., et al., *How Green Are the National Hydrogen Strategies?* Sustainability, 2022. **14**, DOI: 10.3390/su14031930.

125. Nagashima, M., *Japan's hydrogen strategy and its economic and geopolitical implications*. 2018: Ifri Paris, France.

126. Li, Y., et al., *The economic feasibility of green hydrogen and fuel cell electric vehicles for road transport in China.* Energy Policy, 2022. **160**: p. 112703.

127. Yunzhe, J., et al., *Research on Hydrogen Energy and Fuel Cell Vehicle Roadmap in Various Countries.* IOP Conference Series: Earth and Environmental Science, 2020. **512**(1): p. 012136.

128. Wu, Y., et al., *Obstacle identification, analysis and solutions of hydrogen fuel*

cell vehicles for application in China under the carbon neutrality target. Energy Policy, 2021. **159**: p. 112643.

129. Kar, S.K., et al., *Hydrogen economy in India: A status review.* WIREs Energy and Environment, 2023. **12**(1): p. e459.

130. Lord, A.S., et al., *Geologic storage of hydrogen: Scaling up to meet city transportation demands.* International Journal of Hydrogen Energy, 2014. **39**(28): p. 15570-15582.

131. Ogden, J.M., *Developing an infrastructure for hydrogen vehicles: a Southern California case study.* International Journal of Hydrogen Energy, 1999. **24**(8): p. 709-730.

132. Long, J., et al., *California's Energy Future-The View to 2050*. 2011.

133. Vijayakumar, V., et al., *Modeling future hydrogen supply chains in the western United States under uncertainties: an optimization-based approach focusing on California as a hydrogen hub.* Sustainable Energy & Fuels, 2023. **7**(5): p. 1223-1244.

134. Di Molfetta, R., *Strategies for regional deployment of hydrogen infrastructure: The case of North Rhine-Westphalia, Germany*. 2022.

135. Nuñez-Jimenez, A., et al., *Competitive and secure renewable hydrogen markets: Three strategic scenarios for the European Union.* International Journal of Hydrogen Energy, 2022. **47**(84): p. 35553-35570.

136. Bonciu, F., *The European Union Hydrogen Strategy as a significant step towards a circular economy.* Romanian Journal of European Affairs, 2020.

20(2): p. 36-48.

137. Sanchez, D.L., et al., *Policy Options for Deep Decarbonization and Wood Utilization in California's Low Carbon Fuel Standard.* Frontiers in Climate, 2021. **3**.

138. Trencher, G., *Strategies to accelerate the production and diffusion of fuel cell electric vehicles: Experiences from California.* Energy Reports, 2020. **6**: p. 2503-2519.

139. Westphal, K., et al., *The international dimensions of Germany's hydrogen policy.* 2020.

140. Stamm, A., et al., *Green Hydrogen: Implications for International Cooperation.*

141. Kar, S.K., et al., *Overview of hydrogen economy in Australia.* Wiley Interdisciplinary Reviews: Energy and Environment, 2023. **12**(1): p. e457.

142. Park, C., et al., *How much hydrogen should be supplied in the transportation market? Focusing on hydrogen fuel cell vehicle demand in South Korea: Hydrogen demand and fuel cell vehicles in South Korea.* Technological Forecasting and Social Change, 2022. **181**: p. 121750.

143. Dechezleprêtre, A., et al., *Climate change policy, innovation and growth*, in *Handbook on green growth*. 2019, Edward Elgar Publishing. p. 217-239.