History, Status, and Future Challenges of Hydrogen Energy in the Transportation Sector

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HISTORY, STATUS, AND FUTURE CHALLENGES OF HYDROGEN ENERGY IN THE TRANSPORTATION SECTOR

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Abstract

In recent years, extreme weather around the world due to climate change has occurred increasingly frequently, and countries globally have gradually realized the harm caused by global warming. All countries are also making efforts to promote less consumption of fossil fuel energy and the use instead of renewable energy technologies that are environmentally friendly and have lower carbon emissions. The transportation sector, as a main contributor to energy consumption and pollution emissions, is receiving increasing attention. At the same time, new energy vehicles are more energy efficient and environmentally friendly than fuel vehicles, making them more prevalent in the automotive market, which is flourishing. Green hydrogen energy can be used as a renewable, clean, and efficient energy source for new energy vehicles and is also gradually being used in transportation to promote the goal of carbon neutrality. This paper reviews the research on hydrogen energy in the transportation field, summarizes the previous research results, and presents the challenges to the future application of hydrogen energy.

Keywords: carbon neutrality, hydrogen, climate change, renewable energy, transportation

JEL Classification: R40

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1. INTRODUCTION

1.1 Background

On 12 December 2015, the Paris Climate Conference reached an agreement on global climate change and set the goal to limit long-term global warming to less than 2 degrees Celsius, and preferably below 1.5 degrees Celsius, compared to preindustrial levels (Masson-Delmotte et al. 2018).

In order to achieve the targets for temperature control proposed in the Paris Agreement, many countries have proposed pathways for carbon neutrality, which has become a common vision and ongoing worldwide action plan. Among the emission reduction measures adopted by many countries and regions, encouraging the development and adoption of renewable energy has become a common choice (News 2022), and there is now a huge and historical opportunity to develop the latter. In the meantime, as a type of renewable and clean energy source, green hydrogen energy has received much attention, and it can play an important role in reducing carbon emissions in the transportation sector, in industrial power, and in other areas that generate large amounts of carbon emissions (Yu et al. 2022). In September 2020, at the 75th session of the United Nations General Assembly, President Xi Jinping announced that the People's Republic of China (PRC) would strive to peak its carbon dioxide (CO_2) emissions by 2030 and achieve carbon neutrality by 2060 (Jinping 2020). Therefore, the research related to hydrogen energy is extremely important and of great significance, but also presents challenges (Zou et al. 2022).

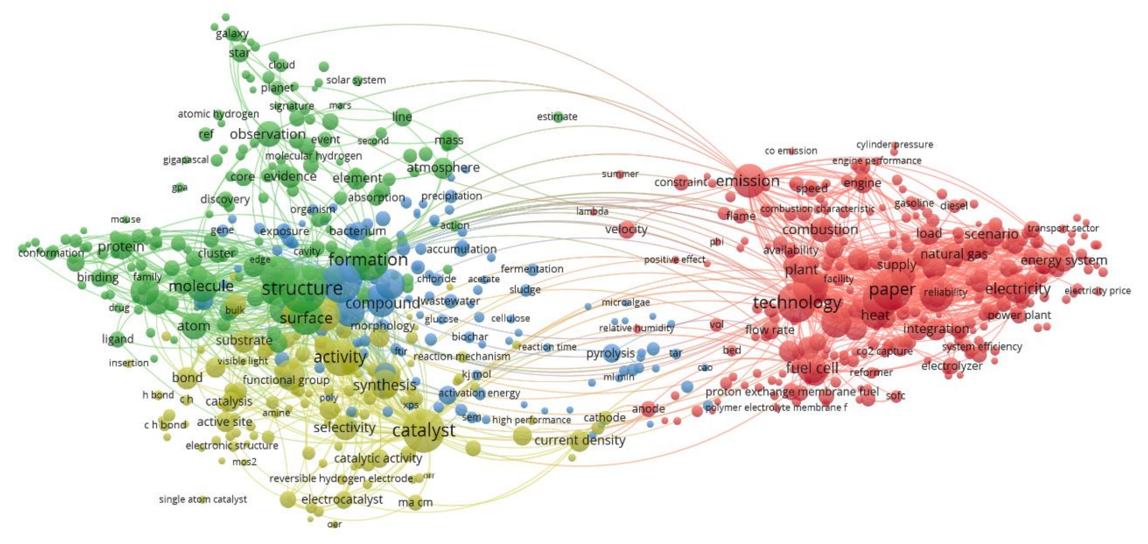
As expected, the research and development of hydrogen energy in the field of transportation keeps increasing. The transportation industry is an important part of our society and underpins the prosperity of the different economies (Selvakkumaran and Limmeechokchai 2015) . However, it is responsible for various types of energy consumption and greenhouse gas emissions, which account for 15% of total carbon emissions (Zhang 2022b). During the current period of the PRC's 14th Five-Year Plan, the Ministry of Transport has released a work plan that includes the implementation of 11 major projects, including the "Green Low Carbon Transport Sustainability Project." Around the overall goal of reducing the carbon intensity of transportation, it is necessary to support the large-scale use of new energy vehicles and ships. Therefore, hydrogen energy plays a more important role in the transportation sector and contributes to sustainable urban development (Bi et al. 2021).

Hydrogen fuel cell vehicles (HFCVs) have been developing rapidly in recent years, and many countries such as the PRC, Germany, and the United States are also accelerating the layout and construction of hydrogen refueling stations for HFCVs so as to vigorously promote the industrialization of hydrogen fuel cells. In addition to HFCVs, aviation and shipping are also actively exploring the application of hydrogen energy (Zhang 2022a). The development of hydrogen energy applications in the transportation sector will undoubtedly greatly facilitate extensive and deep decarbonization in this field.

1.2 Research Status

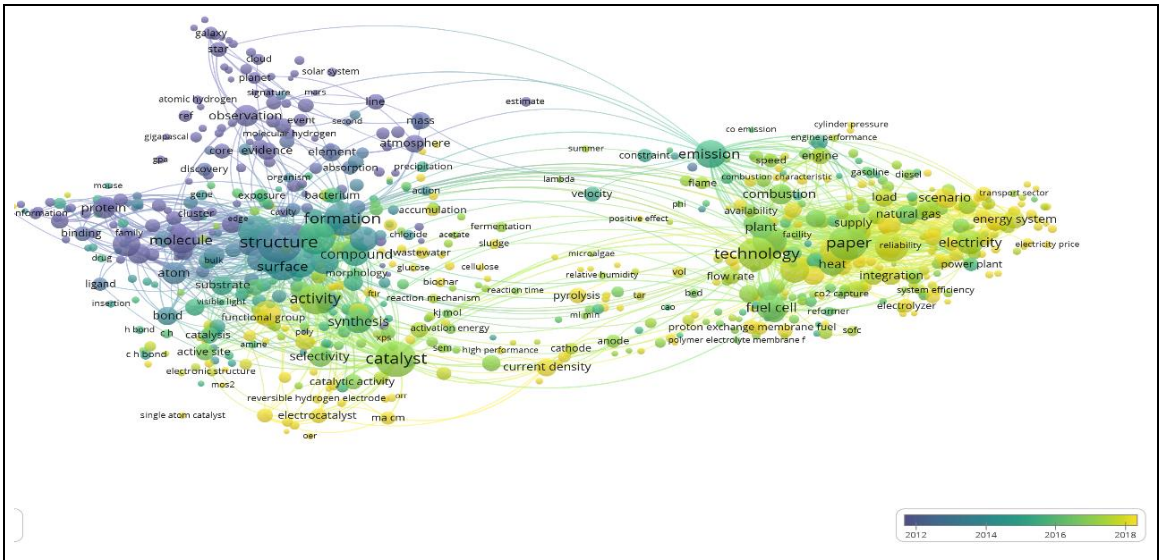
In order to obtain a general understanding of the research status of hydrogen, we searched the Web of Science database with "hydrogen" as the keyword, obtained more than one million related papers, and selected 8,000 from them. The keyword "co-occurrence analysis" was used by VOSviewer software for the above-listed papers. The analysis results are shown in Figures 1.1 and 1.2.

Figure 1.1: Keyword Co-occurrence Analysis Based on Hydrogen



As can be seen in Figure 1.1, the terms "catalyst," "structure," "emission," "molecule," "formation," and "technology" appear most frequently, which indicates that scholars and researchers pay more attention to the production method, production efficiency, and energy structure of hydrogen. In addition, the pollution and emissions generated during the hydrogen production process are also the focus of researchers' attention.

Figure 1.2: Co-occurrence Analysis of Keywords as Time Evolves



The evolution of the research topics over time can be seen in Figure 1.2. According to the above figure, the research topics in the previous years were mainly focused on structure, molecules, formation, catalysts, etc. In recent years, as research has intensified and more attention has been paid to environmental and climate issues, research topics have tended to focus on emissions, power, energy systems, cost, etc.

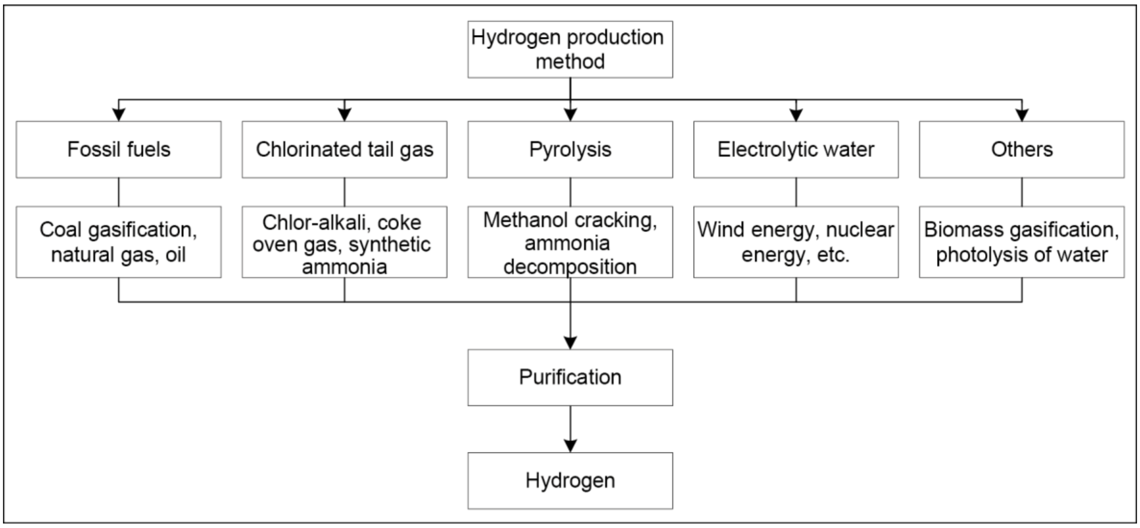
This study first analyzes and summarizes the research background and significance of hydrogen energy, then analyzes and summarizes the current situation and the hot topics of hydrogen energy research by setting keywords to search relevant papers, and, based on this, selects papers related to hydrogen energy in the field of transportation for further analysis. Through a review of the literature, this study briefly introduces the production and manufacturing process of hydrogen energy, the classification of hydrogen energy, and the technologies applied to the transportation field; in addition, the history, current situation, and controversies of its application in the transportation sector are also introduced. Following this, the searched papers are further classified and organized to analyze the application of hydrogen energy. Finally, the challenges of hydrogen energy in the field of transportation in the future are presented.

2. THE APPLICATION OF HYDROGEN ENERGY

2.1 The Hydrogen Energy Production Process

The industry chain of hydrogen energy includes its production, storage, transportation, refueling, and use. Among these processes, hydrogen production technology includes its production from fossil energy, from electrolytic water, from industrial byproducts, and from renewable energy, as shown in Figure 2.1.

Figure 2.1: Methods for Producing Hydrogen Gas



Hydrogen production from fossil energy sources mainly involves the use of fossil fuels to produce hydrogen by chemical pyrolysis or gasification. This technology is relatively mature and inexpensive, and it is currently the main method used for producing hydrogen. To date, hydrogen produced from fossil fuels has been employed mainly as a feedstock for industrial processes such as fertilizers and metallurgy. Since carbon dioxide is produced and emitted during the production of hydrogen, it is called “gray hydrogen” and can be combined with carbon capture and storage (CCS) technology to convert “gray hydrogen” into “blue hydrogen.” The advantage of this technology is that it is suitable for large-scale hydrogen production, but the emissions are high and the gas impurities need to be purified (Zou et al. 2022).

Hydrogen production by electrolysis is the production of hydrogen by decomposing water. This technology allows the use of electricity from renewable sources without emitting carbon dioxide or other toxic substances, and is therefore known as “green hydrogen” in the true sense of the word. Electrolytic water has high theoretical conversion efficiency and the hydrogen obtained is extremely pure. Hydrogen production from electrolytic water can be classified into alkaline electrolytic water, acidic proton exchange membrane electrolytic water, high-temperature solid oxide electrolytic water, and other electrolytic water technologies (Zou et al. 2022). Lei et al. (2019) effectively increased the rate and purity of hydrogen production by developing a technique to produce hydrogen in acid-base two-phase solutions. Dossow et al. (2021) designed a process that can reduce greenhouse gas emissions by 76–78 %. Electrolytic hydrogen generated from offshore wind energy can also contribute to low-carbon systems and effectively reduce carbon emissions (Chen et al. 2021).

The industrial production process, such as in the chlor-alkali industry, will produce a large number of hydrogen byproducts, but the purity of these byproducts is not high, and the purification process requires high-end equipment and a large capital investment. With the continuous advance of the hydrogen energy industry and related scientific technologies, the advantages of industrial byproduct hydrogen gas are expanding. This method has significant advantages, such as its low cost, the wide range of sources, and low-carbon emissions in the recovery process, but the purification process is more complicated (Yang 2022).

Photocatalytic hydrogen production refers to a sustainable, clean, and renewable method of producing hydrogen, and one of the most widely studied and promising technologies is photolytic hydrogen production (Zou et al. 2022). The essence of photolytic hydrogen production technology is the use of semiconductor materials as catalysts to drive the decomposition of water. Microbial hydrogen production technology has emerged as a prospective way to produce hydrogen due to its convenient manufacturing technology and wide availability of sources. Common fermentative hydrogen production microorganisms include various types of hydrogen-producing Clostridium, thermophilic bacteria, and Escherichia coli (Vasconcelos, Leitão, and Santaella 2016; Pugazhendhi, Kumar, and Sivagurunathan 2019). Sadvakasova et al. (2020) investigated the process of producing hydrogen from cyanobacterial cells, and this process is the result of solar energy conversion. They concluded that cyanobacterial gene mutants with great potential for producing hydrogen should be constructed by genetic engineering in order to increase hydrogen production.

2.2 Classification of Hydrogen Energy Applications

The production, manufacture, and application of hydrogen energy is one of the important ways to achieve the goal of carbon neutrality, to guarantee national energy security, and to realize low-carbon transformation (Zhang 2022c). Currently, hydrogen energy is mainly used in energy, iron and steel metallurgy, the petrochemical industry, and so on. Along with the continuous adjustment of national economic policy and the continuous development of hydrogen energy industry technology, hydrogen energy will be applied to a wider range of fields.

2.2.1 Hydrogen Energy Storage

Today we should vigorously develop wind energy and solar photovoltaic power generation and complete the development of renewable energy by producing green hydrogen energy (Cope 2022). However, the intermittent and random nature of wind power and photovoltaic power generation affects the continuity and stability of their grid-connected power supply, and weakens the peak regulation of the power system (Zhou et al. 2022). With the continuous progress and improvement of green hydrogen energy technology, the use of renewable energy to generate electricity and produce green hydrogen is increasingly receiving attention. Meanwhile, the cost of manufacturing green hydrogen is decreasing, and it has further contributed to the pace of the energy transition.

2.2.2 Hydrogen Fuel

As the ultimate energy source for the electric power sector, hydrogen energy transforms chemical energy into electrical and kinetic energy through a series of reactions, providing power for vehicles. At the same time, green hydrogen also has advantages in terms of zero-carbon emissions, and the application in the vehicle industry of batteries based on green hydrogen has become very promising (Zou et al. 2022).

2.2.3 Hydrogen Chemical Raw Materials

The current global demand for hydrogen is mainly used for ammonia synthesis, refinery hydrogenation production, methanol production, and so on (Zou et al. 2022). With the continuous development of relevant technologies, hydrogenation technology will be increasingly used in petroleum refinement and other petrochemical fields. Hydrogenation is also an important technological approach to the manufacture of green oil. Hydrogen is also commonly used for the synthesis of chemical products and compounds containing carbon, such as urea and industrial alcohols. These compounds can be easily stored and transported when liquefied, have high energy density, are less explosive, and can reach nearly zero-carbon emissions as liquid fuels, which makes them a suitable renewable energy source for storage and transportation other than electricity transmission.

2.3 Processes and Technologies for Hydrogen Energy in Transportation

The main application of hydrogen energy in transportation is using hydrogen as an energy source to power vehicles in order to reduce carbon emissions and air pollution caused by transportation vehicles. Since hydrogen energy can power transportation vehicles with zero greenhouse gas emissions (e.g., CO_2 and NOx), many countries are currently accelerating the speed with which they are deploying new energy vehicles such as hydrogen-powered ones. With the rapid development of fuel cell and renewable energy generation technologies, the application of green hydrogen energy in transportation is also gradually increasing (Greene, Ogden and Lin 2020; Bai et al. 2022; Bi et al. 2022; Yang et al. 2022). Rose and Neumann (2020) investigated a network of hydrogen refueling facilities for heavy-duty vehicles by combining an infrastructure location planning model with a power system optimization model that incorporates grid expansion options. The study discussed the interactions between hydrogen refueling stations and the electric power system, and shows that when both are considered systematically and in synergy with multiple sectors it can effectively reduce infrastructure construction costs, which can be a main consideration in building hydrogen refueling stations. Tao et al. (2020) explored the collaborative planning of a distribution network and transportation system for hydrogen fuel cell vehicles. Hydrogen fuel cell vehicles are introduced in the transportation network, and the simulation is performed by planning the location of hydrogen refueling stations, optimizing the ratio of internal combustion engine vehicles, electric vehicles, and fuel cell vehicles, and solving this optimization model using the mixed-integer linear programming and subgradient method. The simulation results show that the proposed model can achieve the lowest emissions due to the good coordination between the power and transportation systems. Pyza, Gołda, and Sendek-Matysiak (2022) studied strategies for the use of hydrogen energy in public transport systems. Through studying the method of hydrogen production and the impact on vehicle operating costs, it was found that the use of hydrogen energy vehicles in public transport systems can be effective in improving air quality as well as optimizing the mobility of the population due to the wide range of hydrogen energy sources. As an alternative energy source in public transportation systems, the use of hydrogen is reasonable and effective. Li and Taghizadeh-Hesary (2022) explored the economic feasibility of green hydrogen fuel cell electric vehicles for road transportation in the PRC and proposed a model to estimate the carbon emissions of the hydrogen supply chain and fuel cells. A balanced hydrogen cost model was also developed to analyze the total cost of supplying hydrogen from renewable energy sources to vehicle hydrogen filling stations, and the cost of fuel cell electric vehicles per kilometer. The results suggest that green hydrogen-fueled vehicles will become increasingly important in the PRC in the long run. Wickham, Hawkes, and Jalil-Vega (2022) studied the optimization of the hydrogen supply chain in the transportation sector. A spatially resolved optimization model was proposed to evaluate the optimal cost configurations of the hydrogen supply chain by 2050, including hydrogen grades and separation and purification technologies. The results show that under given techno-economic assumptions, an optimal configuration of the hydrogen supply chain includes using steam methane reforming with carbon capture and sequestration, the installation of new hydrogen transmission pipelines, modification of the natural gas distribution network to supply hydrogen, and the installation of localized VPS systems at refueling stations. The study found that it was important to include purification technologies in the model. Farahani et al. (2019) proposed an integrated hydrogen-based energy and transport model that facilitates the penetration of intermittent renewable energy sources without compromising the reliability of electricity, heat, and transport energy supplies, while also reducing the cost of the system.

2.4 History, Status, and Controversies of Hydrogen Energy in Transportation

Here we try to investigate the research status of hydrogen energy in the transportation sector, and articles in transportation journals are searched, with the aim of concentrating on the research of hydrogen in the field of transportation. Research literature in the field of transportation was searched using the keywords “hydrogen” and “transport”*, and the keyword “co-occurrence analysis” was used through VOSviewer. The results are shown in the figure below.

Figure 2.2: Keywords Co-occurrence Analysis Based on Hydrogen and Transportation from the Content Dimension

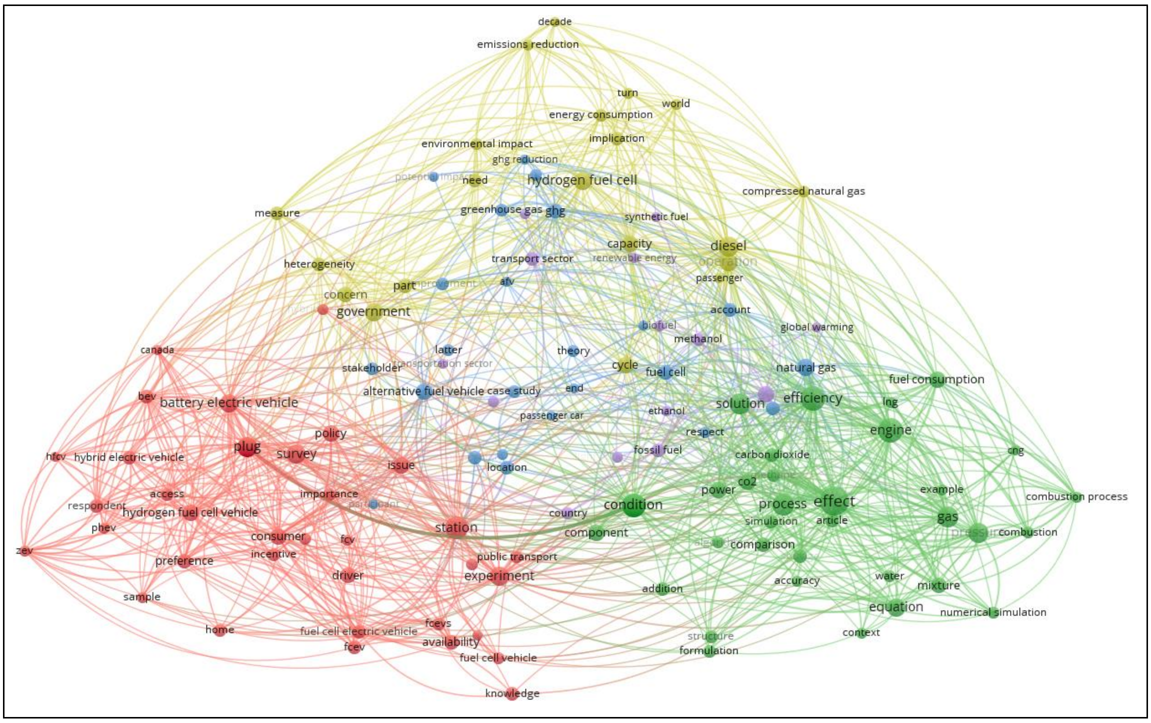
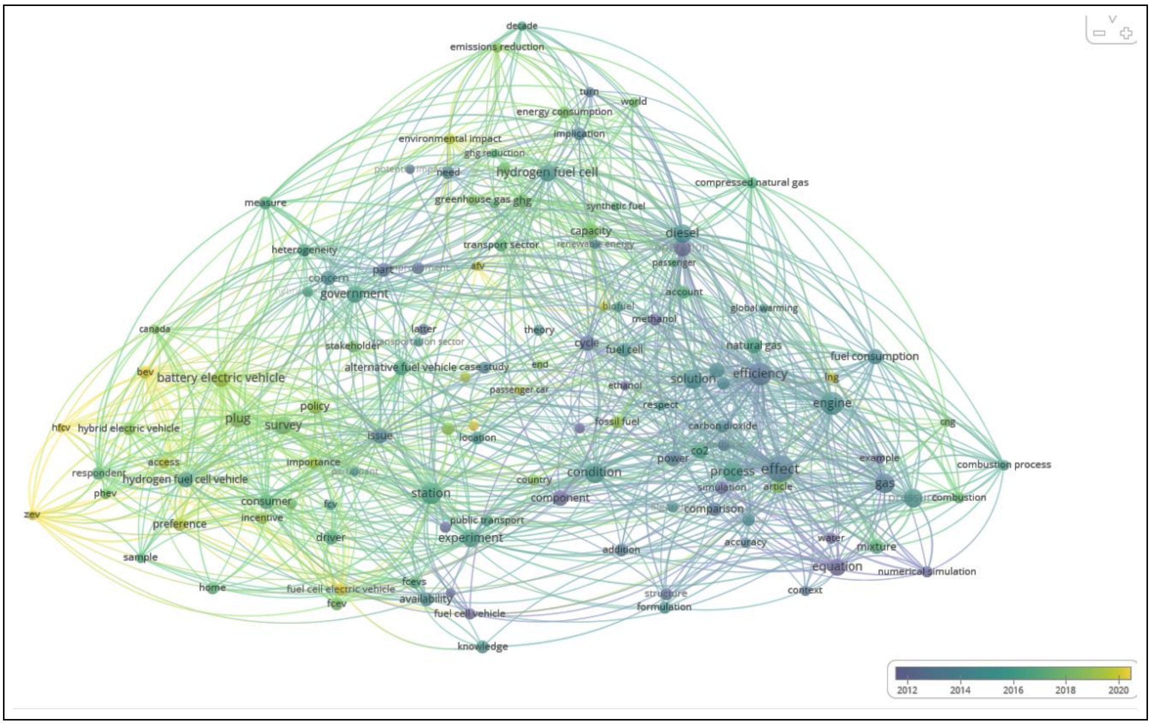


Figure 2.3: Keywords Co-occurrence Analysis Based on Hydrogen and Transportation from the Time Dimension



As shown in Figures 2.2 and 2.3, we can conclude that the hydrogen research in the field of transportation mainly focuses on hydrogen fuel cell vehicles, battery electric vehicles, fuel consumption, process, production, policy, efficiency, stations, and government. In the past few years, scholars have concentrated on the areas of efficiency, components, operation, and process, particularly focusing on the production of hydrogen fuel and the benefits of hydrogen vehicles. In recent years, research has been conducted in the areas of greenhouse gases, hydrogen fuel cell vehicles, battery electric vehicles, government, emission reduction, and preferences, with research directions falling mainly on government policies, fuel vehicles, hydrogen refueling station siting, energy conservation, and emission reduction.

3. LITERATURE SEARCH AND ANALYSIS

In this section, we mainly systematically investigated the literature related to hydrogen and transportation, and these selected papers are analyzed according to the classifications of their research direction.

3.1 Literature Search

In order to conduct a comprehensive review, we first systematically search for papers that concentrate on hydrogen and transportation systems. We conduct a literature search from specific databases and journals due to the difficulty in determining appropriate keywords. The literature search procedure is presented in Figure 3.1. In this review, Web of Science, ScienceDirect, and IEEE Xplore are selected as the search databases. The keywords “hydrogen” and “transport*” are searched in titles, abstracts, and keywords, and the time range is restricted to between 1996 and 2022. All the papers searched from the three databases are integrated together, and after deleting reduplicative and irrelevant papers, 190 papers are obtained.

In addition, the keyword “transport*” is used for searching in three databases, and some papers with the name of specific transportation modes such as “railway,” “road network,” or “aviation” are possibly missed. To cope with this situation, a journal-based literature search is conducted. The search scope is limited to academic journals in the field of transportation. The same selection rules as in the dataset search are applied. Eventually, after the abstract review, 65 more papers are added. Therefore, 148 core papers based on database and journal-based search are obtained.

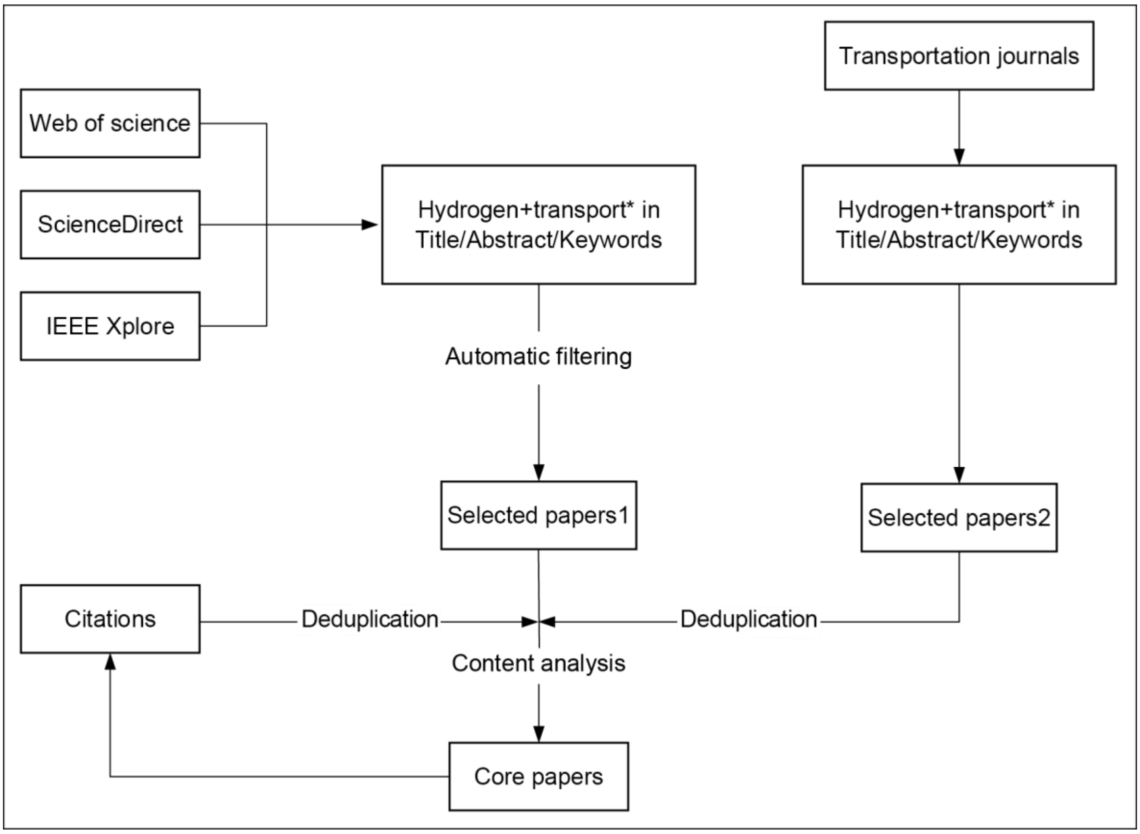
3.2 Literature Analysis

After a comprehensive analysis of the searched literature, the main topics on hydrogen energy in transportation are the problem of locating hydrogen refueling stations, the impacts of hydrogen fuel cells on greenhouse gas emissions, the use of fuel cell vehicles, and the environmental impact on hydrogen fuel cell vehicles. Based on the research focus of selected papers, we divide them into several categories for analyses and discussions.

3.2.1 Problem of Locating Hydrogen Refueling Stations

A reasonable layout of hydrogen refueling stations can reduce users’ refueling time and improve travel convenience (Shang et al. 2022). Scholars have conducted a considerable number of studies on the problem of locating hydrogen refueling stations.

Figure 3.1: Literature Search Procedure



Penev, Zuboy, and Hunter (2019) conducted an economic analysis of high-pressure pipelines within urban areas, and they concluded that pipeline delivery is more advantageous than vehicle transport when the hydrogen demand for fuel cell vehicles in a given area is sufficiently high. In considering the time problem, Fang and Torres (2011) and Brey et al. (2016) conducted optimization studies of the hydrogen refueling station siting and layout problem with a view to reducing travel time. Following this, Zhao et al. (2019) investigated a modeling framework for alternative fuel station system locations based on path and multi-scale scenario planning. It provides effective information for planning hydrogen refueling station infrastructure. Meanwhile, Rose et al. (2020) studied the optimal development of alternative fueling station networks by considering node capacity constraints. Station capacity constraints were found to have a relatively large impact on the number and utilization of stations, and the diversity of station combinations. Coppitters et al. (2022) investigated the optimal design of hydrogen refueling stations under techno-economic and environmental uncertainties. The results show that it achieves good environmental performance but increases the cost of fuel in a hydrogen refueling station for fuel cell electric buses, which could be studied in the future in regard to integration technology with fully electric buses. After this, Tabandeh, Hossain, and Li (2022) studied the planning of hydrogen refueling stations for fuel cell vehicles in combination with renewable energy sources, and established a green model considering on-site hydrogen production capability. The location and size of hydrogen refueling stations can be well determined, and the green production of green hydrogen is also ensured. Bezrodniy, Rezchikov, and Dranko (2021) proposed an algorithm to optimize hydrogen refueling services at hydrogen refueling stations. Kelley et al. (2020) studied the geographic perceptions of early users of hydrogen fuel cells in evaluating a network of gas stations in California. The study suggests that in selecting sites, other factors should also be considered such as land use, population density, and traffic patterns. Reuß et al. (2017) conducted a spatial resolution-based infrastructure assessment by comparing the infrastructure of the hydrogen energy supply chain in Germany. The results show that salt caverns and gas transmission pipelines are the key technologies for future hydrogen infrastructure systems.

Following this, d'Amore-Domenech, Leo, and Pollet (2021) conducted a cost comparison between electrical energy and hydrogen, which considered the scenario of an energy source for large-scale power transmission at sea. The results of the study showed that the transmission of hydrogen by pipeline is cheaper than using electricity in deep-water areas at distances of more than 1000 km, and that transporting liquefied hydrogen by ship is the best option among the various hydrogen transport methods. Alazemi and Andrews (2015) summarized the current status and deployment of hydrogen fueling station networks. They concluded that from an economic, social, and environmental perspective, it is very reasonable to plan a network of hydrogen stations while hydrogen-fueled sales are growing. Chen et al. (2021) used an optimal design and techno-economic evaluation method to assess a low-carbon hydrogen supply chain for refueling stations in Shanghai. The results showed that grid-connected green hydrogen production via a PV-wind hybrid system in a renewable energy-rich area (Qinghai Province, PRC) and delivering to refueling stations in the eastern coastal region of the PRC (Shanghai) via a liquid hydrogen truck are feasible solutions. Xu, Wu, and Dai (2020) analyzed the key barriers to the development of hydrogen refueling stations in the PRC. The high initial capital cost, limited financing channels, immature hydrogen storage technology, imperfect hydrogen transportation technology, a lack of relevant standards, and an imperfect subsidy mechanism were considered the six key factors. Sun and Harrison (2021) proposed a scheme to operate hydrogen fueling stations in renewable energy-rich areas. The electrolyte of the hydrogen fueling stations can be adaptively increased to produce excess electricity, which can convert low-carbon electricity into green hydrogen fuel. Zhao et al. (2021) proposed an optimal scheduling framework for cross-energy systems to evaluate the advantages of the supply chain from water electrolysis, compressed storage, and transportation to the utilization of green hydrogen for fuel cell vehicles. Dijkstra's algorithm is used to search for the shortest path for green hydrogen transportation, and the study shows that it can reduce the operation cost of the trans-energy system and promote the use of renewable energy. Cao et al. (2021) studied the hydrogen-based network microgrid planning problem and proposed an optimal planning model for electro-hydrogen microgrids with renewable green hydrogen production, storage, and refueling facilities. The results show that the computational time can be greatly reduced, and this planning method can also be applied to decarbonization of energy and transportation systems in the future. Bezrodniy and Rezchikov (2021) explored the control of hydrogen supply networks in the transport sector, considering relevant aspects of the hydrogen transport system and providing a method for the optimization of hydrogen supply networks.

Some scholars integrate hydrogen refueling stations with the power grid to study the feasibility of the layout, while others plan hydrogen refueling stations by considering the reduction of travel time. Different scholars take into account the various factors, but all of them tend to resolve the problem concerning the layout of hydrogen refueling stations.

3.2.2 The Impact of Hydrogen Energy on Greenhouse Gas Emissions

The transportation industry has a significant impact on greenhouse gas emissions, and applying hydrogen energy to this sector will have a profound effect on energy conservation and emission reduction in the field of transportation (Liu et al. 2022a).

The application of hydrogen energy in transportation can effectively reduce greenhouse gas emissions (McKenzie and Durango-Cohen 2012; McDonagh et al. 2019; Logan et al. 2020; Navas-Anguita et al. 2020; Benitez et al. 2021). Low-emission alternative fuels are of importance for the low-carbon development of the transport sector, and in their study, Fernández-Dacosta et al. (2019) compared and evaluated alternative fuels in the transport sector. The results showed that green hydrogen production from steam methane reforming is the most economical option, and green hydrogen production from electrolysis using renewable energy sources is the most environmentally friendly one. Moreover, He et al. (2021) analyzed the greenhouse gas, air pollutant emission standards for light-duty fuel cell vehicles in the PRC. The greenhouse gas, volatile organic compound emissions of all fuel cell vehicles were lower than, or comparable to, those of gasoline vehicles, except for the grid electric electrolysis or liquefied hydrogen pathways. Yeh et al. (2006) analyzed the impact of hydrogen energy on transportation, energy use, and air emissions, concluding that although carbon capture and sequestration technologies for their production and renewable technologies for green hydrogen production have the ability to achieve greater CO_2 emission reductions, they are not economically competitive based on their modeling framework. In addition, Sun et al. (2022) proposed and modeled a control strategy based on a hydrogen refueling service charge for the smart city sector to guide the selection of hydrogen refueling stations for hydrogen fuel cell electric vehicles. The results show that promoting hydrogen fuel cell vehicles can help reduce emissions. Li et al. (2022) explored the prospect of applying hydrogen electric-to-gas technology in power and transportation systems and proposed a regional-scale integrated power and transportation system long-term coordination planning model. The results show that the system can effectively reduce CO_2 emissions.

Furthermore, Booto, Aamodt Espegren, and Hancke (2021) explored the environmental impacts of conventional diesel trucks, battery electric trucks, and fuel cell electric trucks in their respective life cycles in terms of energy type, energy source, and production route. The results show that hydrogen fuel cell electric trucks can reduce greenhouse gas emissions by 48% under the same conditions. The application of hydrogen energy as a fuel to vehicles can also significantly increase emission reductions (Frey et al. 2007; Janic 2008; Tittle and Qu 2013; Yazdanie et al. 2016; Booto, Aamodt Espegren, and Hancke 2021; Mingolla and Lu 2021; Chen and Lam 2022). Sundvor et al. (2021) studied alternative ways of powering high-speed passenger ships under a zero-emissions scenario in the context of Norwegian high-speed passenger ships, developing a model based on AIS data. The results suggest that further route optimization and infrastructure improvements are needed to better address greenhouse gas emissions. Following this, Hensher (2021) studied the process of transitioning to a green bus fleet. Along with the increasing demand for energy efficiency and green travel (Liu et al. 2022a), the cost of buses providing green travel is unknown, not only in relation to vehicle technology (especially hydrogen fuel cell technology), but also in terms of the infrastructure for hydrogen energy. The use of clean and renewable energy sources as feedstock for green hydrogen production has become particularly important. Following this, Frey et al. (2007) compared the actual fuel consumption and impact on emissions of diesel- and hydrogen-fueled buses. The effects of speed, acceleration, and road gradient were integrated into a single parameter using the VSP method to analyze fuel consumption changes. The results show that replacing diesel with methane steam reforming to hydrogen increases the fuel cycle and will significantly reduce CO, NOx, and HC emissions.

Janic (2008) explored the potential of liquid hydrogen in “carbon-neutral” air transport and argued that the infrastructure in air transport should be increased. Zhang et al. (2020) studied the cost and greenhouse gas emissions of grid-based electrolytic hydrogen fuel cell vehicles, simulating the time-varying hydrogen fuel replenishment demand for these vehicles. The results show that increasing the flexibility of hydrogen production can reduce the cost of hydrogen and power generation as well as CO_2 emissions. Meanwhile, Liu et al. (2022b) studied the economic and environmental benefits generated by green supply chains. The results showed that under regulation, green supply chains can drive upstream and downstream firms to reduce emissions faster. In addition, Longden et al. (2022) compared the emissions and costs of green hydrogen production from fossil fuels with those from renewable electricity. Comparing the two, the production of green hydrogen using electrolysis and zero-emission electricity does not produce greenhouse gas emissions. Using fossil fuels to produce green hydrogen, even with carbon capture and storage technology, the greenhouse gas emissions would be high. Doll and Wietschel (2008) analyzed the role of hydrogen energy in a sustainable transport vision, concluding that the use of hydrogen can significantly reduce CO_2 emissions in the transport sector, even when tailpipe and upstream emissions and the development of alternative technologies are taken into account.

Kim, Kim, and Lee (2020) studied the issue of greenhouse gas emissions from electric and hydrogen-fueled vehicles and their market share changes. The analysis showed that hydrogen fuel cell vehicles help to reduce greenhouse gas emissions, but affect the market share of electric vehicles, and require optimization of efficient infrastructure. Edwards et al. (2008) analyzed the development of hydrogen energy and fuel cell technologies, concluding that hydrogen fuel cells possess the ability to eliminate CO_2 emissions and trigger a green revolution in transportation. After this, Salvi and Subramanian (2015) proposed measures to control transportation fuel pollution using hydrogen energy systems. The use of hydrogen as a fuel in vehicles was considered to improve energy security and reduce greenhouse gas emissions. Janić (2014) studied the application of hydrogen energy in the aviation sector. Using liquid hydrogen as an aviation fuel, its potential for green commercial air transport to solve problems and the impact of using liquid hydrogen as a fuel on greenhouse gas emissions, especially carbon dioxide, were explored. The results show that the use of liquid hydrogen as aviation transportation fuel can reduce greenhouse gas emissions in the future and that the goal of green commercial air transportation is achievable.

A lot of research on hydrogen energy in terms of greenhouse gas emissions has been conducted, and green hydrogen energy is a good alternative fuel as a clean and renewable energy source. Various transport modes such as highways, water transportation, and aviation can save energy consumption and reduce greenhouse gas emissions significantly if hydrogen energy is used as fuel for transportation (Shang et al. 2021).

3.2.3 Application of Hydrogen Energy in Transportation

Transportation is the main application for hydrogen energy, while the main application of hydrogen energy in transportation is new energy vehicles with fuel cells as power.

There is also a lot of research in this area. Mabit and Fosgerau (2011) studied the demand for alternative fuel vehicles when registration taxes are high, using the example of Denmark, and developed a mixed logistic regression model. Using this model, it was concluded that people would be more likely to choose a more environmentally friendly alternative fuel vehicle over a conventional fuel vehicle, all else being equal. Alavi et al. (2017) proposed a community microgrid for providing car-to-grid power in the case of a scarcity of renewable energy generation, and the remaining renewable energy generation from the microgrid is stored in the form of green hydrogen. By using green hydrogen for transportation and re-electrification, the use of fuel cell vehicles can reduce carbon emissions in the transportation system. Following this, Zhou et al. (2022) investigated the performance of photovoltaic cells and proposed an adaptive differential evolution algorithm based on a dynamic backward learning strategy to effectively improve the identification of photovoltaic cell parameters. Hardman et al. (2017) summarized the barriers to the use of hydrogen fuel cell vehicles through a survey of consumers and suggested corresponding countermeasures, such as pre-deployment of optimized infrastructure. At the same time, they also found that consumers value the range of hydrogen fuel cell vehicles and the ability to provide emergency backup power. Ouchi and Henzie (2017) investigated the feasibility of marine sailboats as energy-harvesting devices to support the production of hydrogen. The results showed that low-cost hydrogen energy can be generated and transported simultaneously, providing a new pathway for the eventual replacement of fossil fuels. After this, Wu et al. (2021) performed an analysis of the application of hydrogen fuel cell vehicles under the carbon neutrality goal according to the characteristics of the PRC. Based on the results, inadequate supporting facilities, hydrogen fuel safety issues, and an insufficient number of manufacturers are the most important issues. Yu, Wang and Chen (2021) proposed the application of a new electric-hydrogen integrated hybrid DC traction power system to a future metro system. Simulation results show that it can effectively utilize renewable energy and regenerative braking energy to achieve energy savings. Moreover, Yi, Jang, and Lee (2021) designed a system for monitoring hydrogen fuel characteristics information on hydrogen fuel buses to respond to the hydrogen consumption and temperature of each component, etc., to determine the safe operation of hydrogen fuel cell buses.

Long et al. (2019) studied the demand for zero-emission vehicles using Canada as an example. The results showed that most people preferred plug-in hybrid and hydrogen fuel cell vehicles as their first choice and conventional or hybrid vehicles as their second choice. After this, Morrison, Stevens, and Joseck (2018) predicted the cost and potential market size issues for battery electric vehicles and hydrogen fuel cell electric vehicles by 2040. The results indicate that hydrogen fuel cell vehicles will cost approximately 71% to 88% less than pure electric vehicles in light vehicle fleets by 2040, and that fuel cell vehicles will have a significant cost advantage for larger models and drivers with longer daily driving ranges. Irdmousa et al. (2010) analyzed energy alternatives in the United States and, under optimistic assumptions, hydrogen energy ranked highest. Melo, Ribau, and Silva (2014) developed an optimized power system for the conversion of city buses to hybrid fuel cells and analyzed the possibility of replacing conventional bus fleets with efficient bus fleets equipped with batteries and hydrogen fuel cells. Subsequently, Durango-Cohen and McKenzie (2018) developed an optimization model applied to the design of bus fleets with different fuel propulsion technologies, taking into account energy consumption, greenhouse gas emissions, particulate matter, etc.

Fan et al. (2022) investigated the operational strategy of hydrogen energy in low-carbon marine transportation. A hybrid propulsion system was proposed, which enables the lowest cost of operation throughout under the greenhouse gas emission limit and further reduces the greenhouse gas emissions. Meanwhile, Ajanovic and Haas (2018) studied the economic prospects and policy framework for hydrogen fuels in the transport sector. It is argued that the prospects of hydrogen energy application in future bus transportation depend on the policy framework, among other things. Ramesohl and Merten (2006) investigated the role of hydrogen energy as an alternative transport fuel in terms of energy systems. They argued that while giving priority to the production of clean hydrogen from renewable energy sources, it is also important to consider how to improve the efficiency of hydrogen fuel cell vehicles. Fu et al. (2019) evaluated two strategies aimed at decarbonizing the transportation sector, electrification, and the use of hydrogen fuel. It was concluded that integrating hydrogen with electric power systems could provide a low-cost alternative energy source, and that the use of advanced hydrogen production technologies could further reduce costs. Singh et al. (2015) analyzed future applications of hydrogen energy in transportation. One of the potential uses of hydrogen is for integrated circuit generators and fuel cell technology in the transportation sector. They concluded that in the future, the energy demand should be adjusted to increase the use of hydrogen as a transportation fuel to provide a clean and green environment for people. Verhelst et al. (2012) studied the use of hydrogen engines and concluded that conversion to hydrogen-powered internal combustion engines could reduce emissions and increase the output power. Rinaldi and Veca (2007) conducted a study on innovative technologies for hydrogen storage using chemical hydrides. The study aimed to evaluate the suitability of polypropylene and low-density polyethene as optimal materials for this purpose. The results indicated that these materials possess exceptional characteristics, including easy recoverability during the hydrogen storage process. Moreover, due to their inherent safety features, these technologies are highly suitable for H2 refuelling stations. Abdelrahman et al. (2016) conducted a feasibility study of hybrid fuel cell and battery railcars. A future hybrid metro system developed in Canada was presented, providing a solution for a hybrid fuel cell train completely independent of grid power, which could save most of the costs and benefit the passengers. Borbujo et al. (2021) reviewed the European legislation and standardization on hydrogen and purely electric buses and heavy-duty trucks. They concluded that the current international safety standards applicable to fuel cells are mainly focused on light-duty vehicles and recommendations were made. Ren and Liang (2017) developed a fuzzy group multicriteria decision-making method to study the sustainability of marine bunker fuels. It was found that green hydrogen is the most sustainable alternative fuel and that it is more socially acceptable as a clean energy carrier without any emissions during the oxidation process.

In the transportation sector, hydrogen fuel cells are increasingly being studied as power facilities. However, there is still a gap between the range of hydrogen fuel cells and other batteries, and further research is needed.

3.2.4 Application of Hydrogen Energy in Policy

The development of an industry is inseparable from the need for necessary support policies, and will in turn provide a scientific basis for policy adjustments.

It has been argued that more comprehensive policies should be developed to stimulate sales of zero-emission vehicles, rather than focusing on charging and refueling infrastructure (Miele et al. 2020). However, Bach et al. (2020) argued that the application of hydrogen technology in the marine sector is currently immature, and therefore priority needs to be given to supporting the research and development of hydrogen production technologies and infrastructure development, etc. Chen and Melaina (2019) and Jones, Genovese, and Tob-Ogu (2020) argued that more attention should be paid to cost policies. Similarly, Gallas and Stobnicki (2022) argued that the main limitation of hydrogen energy applications is the relative cost of hydrogen fuel and that hydrogen production technologies need to be developed to reduce the cost of hydrogen production or that hydrogen production needs to be subsidized. After this, Rottoli et al. (2021) studied alternative pathways for the electrification of light vehicles in the European transport sector. They found that a stronger policy push for fuel cell vehicles is needed, along with the development of good infrastructure. Pinchasik and Hovi (2017) studied CO_2 funds in the transport sector, using Norway as an example, and argued that funds should consider subsidizing renewable technologies such as biogas, electricity, or green hydrogen to promote market demand.

Hydrogen energy should be considered as the direction towards which the energy transition is aiming and its application can become a reality in shipping when hydrogen energy production and demand increase and costs decrease, and it can also achieve carbon emission reduction climate goals. Pomaska and Acciaro (2022) investigated the use of fuel cells and liquefied hydrogen as alternative fuels for ships, with the results of the study suggesting that government policymakers can implement financial incentives to accelerate the development of hydrogen fuels. In addition, Ibrahim et al. (2022) studied three coupled types of dedicated large offshore floating wind farms for hydrogen production. Offshore hydrogen pipelines were considered to be economical for large and remote farms. Their analysis concluded that the decentralized offshore electrolysis approach is a very modular system and provides flexibility while also improving dynamic operation. Mubenga and Stuart (2011) analyzed the feasibility of hydrogen fuel cell electric vehicles transported by hydrogen generated from solar energy. A system was designed to produce hydrogen using solar energy, demonstrating the feasibility of producing hydrogen for transportation using alternative energy technologies. Ehrenstein et al. (2020) studied the optimization of fuel supply chains on a global scale using the case of hydrogen in road transport in the UK. It was found that the generation of hydrogen from electrolytic water powered by wind and nuclear energy and stored in compressed form for distribution by rail is the least impactful for a sustainable fuel supply chain and is a sustainable solution in line with the carrying capacity of the earth.

The application of hydrogen energy requires policy support in terms of infrastructure development, tax incentives, technological advancement, and so on. Hydrogen energy can only work in various fields when there is more support from all sides.

3.2.5 Other Studies Related to Hydrogen Energy

Lakhera, Rajan, and Bernaurdshaw (2021) analyzed the subsurface hydrogen storage capacity of salt mounds and proposed a method for evaluating the hydrogen storage potential of such mounds, taking into account several characteristics such as reservoir size and depth. According to their research method, the hydrogen storage capacity of rock salt can be predicted more accurately. Lee et al. (2022) compared different overseas hydrogen transportation methods from techno-economic and environmental perspectives. The results showed that operation conditions and the use of renewable energy are the main factors in reducing the cost and carbon emissions of the hydrogen supply chain. Liquid hydrogen storage is considered favorable, and improving the energy efficiency of the liquefaction cycle is essential to achieve efficient hydrogen transportation. Robledo et al. (2018) evaluated the application potential of fuel cell vehicles by combining integrated photovoltaic solar panels, residential buildings, and hydrogen fuel cell electric vehicles for power generation to achieve net-zero energy residential building goals. Menanteau et al. (2011) conducted an economic analysis of hydrogen produced by wind power in the transportation industry. The study showed that the variation in hydrogen production costs depends to some extent on the demand involved and that the storage technology of hydrogen is a key variable. In the future, with the development of large geological hydrogen storage facilities in wind farms or small hydrogen storage systems near gas stations, the cost of hydrogen storage may significantly decrease, which will eventually lower the cost of hydrogen for users.

4. FUTURE CHALLENGES

At present, the global hydrogen energy industry is generally in the primary stage of development. Since the energy transition is imminent, many countries in the world are increasing their investment in hydrogen energy. Currently, Europe and the United States are leading in wind power technology, the photovoltaic industry in the PRC is leading the world, and Japan is focused on hydrogen energy (Fastmarkets team 2021). Compared with other energy sources, green hydrogen energy has several significant advantages. First, hydrogen is the most abundant element in the universe, it is easy to obtain, and thus it has great advantages in terms of sustainability. In addition, hydrogen can be produced from water and releases chemical energy through its reaction with oxygen reaction. The whole process only generates water, and no other pollutants are produced, so it is a recyclable closed-loop system (Stock 2021). Second, the high calorific value of hydrogen makes it an ideal substitute for existing fossil fuels. The calorific value of hydrogen is the highest among common fuels, i.e., about three times that of oil and 3.5 times higher than coal. As well as this, with the rapid development of the electric vehicle industry globally and the strong demand for energy storage based on lithium batteries in wind and PV power generation in the future, lithium resources will become a constraint to the development of a new energy industry in the future . Compared with the scarcity of lithium in lithium batteries, a long-term advantage of hydrogen energy can be expected. Hydrogen energy batteries and related technologies can purify the air (Hexun 2022), which is good news for cities with poor air quality. Hydrogen energy will be everywhere in the future owing to its wide range of uses, and it can be used in industrial raw materials, as well as various hydrogen energy vehicles for energy storage.

The largest application of hydrogen energy is in the transportation sector, and the most mature application technology of hydrogen energy and the most promising development in the future are hydrogen fuel cell vehicles in the field of transportation (Agency 2019). The industry chain of hydrogen energy in the transportation sector is extremely complicated, and its potential economic value is huge. The hydrogen energy industry chain in the transportation sector includes hydrogen production, storage and transportation, hydrogen refueling stations, hydrogen fuel cell applications and vehicle integration, and other procedures. Accordingly, the challenges exist in the production, compression, storage, transportation, distribution, and end use of hydrogen (Furfari 2021). The first challenge is how to reduce the cost of green hydrogen production significantly. The development trend of hydrogen energy is from gray to blue hydrogen, and finally to green hydrogen. Although gray hydrogen has pollutants, its cost is low, and it is the main means of hydrogen production in the medium and long term. Hydrogen production by electrolysis of water is an effective way to achieve large-scale production of green hydrogen, but the cost is high, and complete substitution of fossil energy cannot be fully achieved in the short term. In recent years, a lot of work concerning hydrogen production from electrolytic water has been conducted, and very good progress has been made in many aspects. In the future, it will be necessary to continuously improve the hydrogen production process and reduce the cost of green hydrogen production from electrolytic water.

Following this, the second challenge is to decrease the cost of storage and transportation in the most effective way. Hydrogen is chemically active and unstable: If there was a leak, it would be very easy for it to burn and explode, so safety should also be considered. However, compared with security challenges, its cost is the key to hindering the development of hydrogen energy in transportation. There are three main ways to store hydrogen, including gas, liquid, and solid. High-pressure gas-liquid technology has been widely used, and the storage and transportation of liquid hydrogen is technically mature, but the cost of transportation is high, and the risk of leakage and explosion exists, while cryogenic liquid hydrogen storage is costly. Solid-state hydrogen storage is still in the research and development stage. At present, gas transportation for hydrogen is mainly used, supplemented by transportation in a liquid state. Pipeline transportation is suitable for large-scale and long-distance hydrogen transportation with high efficiency, but it requires the construction of pipelines and lots of capital investment at the early stage; liquid transportation also consumes more energy. In the process of storage and transportation, the requirements for materials are very high.

Third, it is a challenge to reduce the cost of key equipment in hydrogen refueling stations and critical components in fuel cells. The core equipment of a hydrogen refueling station includes a hydrogen storage device, compression equipment, and filling equipment, with the compressor being the most costly. Currently, the technical pathways of a hydrogen refueling station can be divided into hydrogen production within the station and external hydrogen supply. Hydrogen production from electrolytic water within stations is the future development direction. In addition, the hydrogen fuel cell is the core component of new energy vehicles based on hydrogen. At the initial stage of industrialization, support policies from government are very much required. The most core part of the hydrogen fuel cell system is the fuel cell, including the fuel cell stack and the air compressor, which are costly and restrict the development of hydrogen fuel cells. The cost of the fuel cell stack accounts for 50% of the hydrogen fuel cell, and the membrane electrode is the core of the stack, accounting for 60% of the cost. Here platinum catalysts have to be mentioned, which are very expensive, and we need to develop low-platinum or platinum-free catalytic technology. Cost reduction is the focus of future development for hydrogen energy in the transportation field.

On top of this, a major challenge for the application of hydrogen energy in the transportation sector lies in whether countries and organizations across the world can cooperate and support each other so as to jointly establish an economic ecosystem of hydrogen energy. Human beings are facing the common problem of global warming, and it is urgent to achieve the goals of carbon neutralization and carbon peak. Some countries have begun to attach great importance to hydrogen energy, and put forward a strategy for the development of hydrogen energy. For example, Japan proposed the 2050 carbon neutrality green growth strategy in December 2020, and the European Union issued the European Green Deal in December 2019, both of them stating clear requirements and expectations for hydrogen energy. As the largest developing country, the PRC is developing hydrogen energy late, but it is expected to account for 10% of the total energy consumption in 2050. The government work report in the PRC in 2019 clearly proposed promoting the construction of infrastructure such as hydrogen refueling stations. In the “14^{th} Five-Year Plan,” the development of hydrogen energy has also been arranged accordingly. In the context of carbon neutrality, all countries and organizations have to work together to negotiate intellectual property rights and patent-sharing mechanisms, establish a market entry mechanism, and jointly promote the establishment of an economic ecosystem based on hydrogen energy that combines hydrogen production, storage, transportation, hydrogenation, hydrogen fuel cell applications, and other procedures into an efficient and low-cost sustainable industry chain system.

The future application of hydrogen has to be studied and developed, the technology for hydrogen production needs to be improved, key equipment and materials are required to reduce the cost, and the safety of hydrogen is also a concern. How to produce hydrogen extremely efficiently, safely, and at low cost is still to be resolved, and the related technical standards also need to be developed with other countries. Only when the technology is mature, the cost is low, and the market tends to accept hydrogen on a large scale can hydrogen energy be widely used in various fields, and then it can promote energy conservation and decarbonization of transportation systems, so as to contribute to the vision of carbon neutrality.

5. CONCLUSION AND POLICY RECOMMENDATIONS

Climate change is one of the biggest challenges of our time (Nations 2022), and promoting green and low-carbon transportation is an important way to cope with this situation. The transportation sector is a major source of greenhouse gas emissions, and there is a growing consensus in many countries to promote green transportation. Based on this, hydrogen energy has received great attention due to its unique advantages, such as zero emissions and high calorific value.

To understand the history, status, and future challenges of hydrogen energy in the transportation sector, we are conducting this review. First, we quickly recap on the background of hydrogen energy in the transportation sector and the research status of hydrogen energy. Following this, the applications of hydrogen energy are reviewed, the production process, processes and technologies for hydrogen energy are introduced, and the history, status, and controversies of hydrogen energy in transportation are also discussed here. Afterward, we conduct a literature search and analysis, and 148 core papers are obtained. The main topics on hydrogen energy in transportation are summarized, that is, the problem of locating hydrogen refueling stations, the impacts of hydrogen fuel cells on greenhouse gas emissions, the use of fuel cell vehicles, and the environmental impact of hydrogen fuel cell vehicles. Based on this, the main challenges are extracted, including reducing the cost of green hydrogen production, decreasing the cost of storage and transportation, reducing the cost of key equipment in hydrogen refueling stations and critical components in fuel cells, and whether countries and organizations across the world can cooperate and support each other.

Compared with new energy vehicles based on lithium batteries, hydrogen fuel cell vehicles have several advantages, such as being free from temperature restrictions, longer mileage, and rapid fuel replenishment. Compared with security challenges, their cost is the key issue hindering the development of hydrogen energy. Today, many scholars are devoted to the study of hydrogen energy applications and development in the transportation sector. All aspects of hydrogen production, storage, transportation, and use have received attention. Currently, the application of hydrogen energy in transportation is mainly in fuel cells, replacing fossil energy with hydrogen energy to play its role in energy conservation and emission reduction. However, the application of hydrogen energy in transportation is also limited by the cost of hydrogen production, transportation efficiency, safety of use, and so on.

Based on current hydrogen technologies and market conditions, urban and surrounding areas are recommended as the priority locations for the deployment of hydrogen refueling stations. These regions are more likely to have a relatively high traffic volume and well-developed public transportation systems, and residents in these regions tend to be more environmentally aware, all of which are conducive to the practical use of hydrogen energy in transportation. In addition, appropriate subsidies should be provided to encourage enterprises or organizations to participate in the construction of hydrogen refueling stations. The government may offer tax reductions or financial grants to encourage investment in station construction as well. Furthermore, hydrogen fuel cell vehicles should be promoted to facilitate the use of hydrogen energy in heavy vehicles such as trucks and buses. Through subsidies, exemption from vehicle purchase taxes, and free tolls, the government can play an important role in promoting the consumption of hydrogen-powered vehicles. Additionally, enterprises/academic organizations should be encouraged to engage in the research and development (R&D) of hydrogen energy technology and promote the industrialization of hydrogen fuel cell vehicles and related equipment, so as to establish a hydrogen energy vehicle industry chain.

In order to ensure the safe use of hydrogen energy in the transportation sector, it is imperative to establish relevant laws, regulations, and safety standards for hydrogen energy. For example, the certification and testing of hydrogen fuel cell vehicles should be strengthened, while the transportation and refueling processes of hydrogen gas need to be regulated. Finally, to better promote the applications of hydrogen energy, publicity and education efforts are also essential, and enhancing intellectual property protection and the environmental awareness of the public will also effectively facilitate the development of hydrogen energy technology in the transportation field.

Although the cost of each aspect is relatively high and the development of hydrogen energy is relatively slow at present, given the abundance of hydrogen and the green characteristics of hydrogen energy, the development of hydrogen energy will be beyond people’s imagination. As a result of this review, we now understand more clearly that the obstacles encountered in the development of hydrogen energy in the transportation sector are not insurmountable. In the context of carbon neutrality, governments and institutions from all countries really need to work together to establish an economic ecosystem that is most suitable for the development of hydrogen energy. In brief, hydrogen energy is on the brink of flourishing.

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