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Review

The alternative path for fossil oil: Electric vehicles or hydrogen fuel cell vehicles?

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ABSTRACT

New energy vehicles are accelerating to substitute for internal combustion engine vehicles (ICEVs) and fossil oil. Although most literature acknowledges this trend, few compare two specific substitutable paths in terms of the operation system, namely electric vehicles (EVs) and hydrogen fuel cell vehicles (HFCVs). This paper makes a comparative analysis of EVs and HFCVs in power sources, fuel storage and transportation, fuel supply infrastructure construction, and the cost and use of vehicles. Our findings indicate that electric passenger vehicles have more advantages in economy, safety, and environmental impact, in comparison with hydrogen fuel cell passenger vehicles. Nevertheless, great efforts should still be made to develop advanced rapid charging technology, shorten charging time, and accelerate charging infrastructure construction. Then, it is just around the corner for EVs to gradually take over from traditional motor vehicles driven by oil. In contrast, popularizing hydrogen fuel cell passenger vehicles faces several insurmountable obstacles in the short run, such as the high hydrogen production price, complicated storage process, and expensive hydrogen refueling station infrastructure. However, hydrogen fuel cell commercial vehicles have unique application scenarios. The dislocation and complementarity principle in different scenarios of EVs and HFCVs is supposed to be firmly grasped.

1. Introduction

The communications and transportation industry is a major consumer of energy resources (Nowotny et al., 2018; Zhu and Li, 2017) and accounts for the largest shares (about 70%) of oil consumption on a global scale (BP, 2021; Zhu et al., 2021). Moreover, the transport industry, as the world's second-largest carbon emission sector and the critical driver of global warming, is responsible for about 26% of global carbon emissions in 2020 according to International Energy Agency (IEA) (Gnann and Pltz, 2015). Meanwhile, road transport takes the most significant proportion of oil consumption and greenhouse gases emissions in the transportation sector, and China is no exception (Wu et al., 2021; Chai et al., 2012). Therefore, China needs to take measures to directly reduce motor vehicle use or indirectly reduce fossil energy consumption.

Reducing vehicle use is not feasible. Consumers' demands for cars have been continuously increasing with prolonged boom and living standards improvement. It leads the world's largest automobile consumer market in China (Liu et al., 2020). Nevertheless, car ownership per thousand people in China is relatively low, which only owns 173 and ranks 17th based on the data for 20 countries released by the World Bank in 2019. China is not only inferior to developed economies in North America and Europe but lower than some developing economies (178 vehicles per thousand people in Iran and 174 vehicles per thousand people in South Africa), indicating a tremendous growth potential for auto vehicles in China. However, the driving power of traditional motor vehicles comes from oil resources which mainly rely on imports. Specifically, China's dependence on foreign oil even climbed to 73% in 2020, posing severe challenges to energy security (Chen et al., 2022; Wang et al., 2021; China Petroleum Enterprise Association, 2020). Therefore, high oil consumption proportion and poor oil self-sufficiency induce a prominent contradiction between oil supply and demand. It urgently encourages China to seek alternatives for fossil oil and fuel vehicles to achieve national energy security and carbon neutrality, that

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is, contributing to a transition from conventionally fueled vehicles to greener transportation (Guo et al., 2021a; Zhang et al., 2020).

Some countries are at the forefront of carrying out top-level planning to find substitutes for fossil oil in the transportation sector. This could trace back to the Arab oil embargo in 1973 that triggered the first oil crisis (Ju et al., 2015). The soaring oil prices and gasoline shortage were blasting fuses as a prelude to exploring the alternative paths of oil in the United States, Japan, and other developed economies. (1) The United States. The United States Congress passed the Electric and Hybrid Vehicle Research, Development, and Demonstration Law in 1976. Many car manufacturers began to seek substitutes for traditional fuel vehicles at roughly the same time. For example, General Motors (GM) developed a prototype of urban electric vehicles exhibited at the first low-pollution powertrain development seminar organized by the U.S. Environmental Protection Agency (EPA) in 1973. (2) Japan. Japan implemented the mid-and-long term plans containing the “Sunshine Plan” aiming at new energy technologies and the “Moonlight Plan” focusing on energy-saving technologies since 1974, which attributed to over-reliance on imported oil and high international oil prices. Fuel cell and solar cell technologies made leaps and bounds among various new energy and energy-saving technologies studied in two plans. Meanwhile, battery manufacturing costs were also significantly reduced. When came to the 1990s, Japan and South Korea came from behind, and the research and development (R&D) of hydrogen-fueled vehicles were taken over by Honda, Toyota, and Hyundai. Japan and South Korea have successively released achievements on hydrogen-powered vehicles since 2013, such as Hyundai Tucson and Toyota Mirai. It could be seen that the countries mentioned above took new energy extensions used by vehicles as a crucial method to replace oil.

The rapid progress in new energy vehicles such as battery electric vehicles (BEVs or EVs) and hydrogen fuel cell vehicles (HFCVs) are generally regarded as two promising ways to effectively replace internal combustion engine vehicles (ICEVs) and fossil fuel consumption at this stage (Vinoth Kanna and Paturu, 2020; Shi et al., 2020). Firstly, popularizing EVs is one of the transportation electrification ways to advance the substitution of renewable energy for oil and environmental protection (Lin and Xu, 2021; Qi et al., 2018). EVs have a lower global warming potential in usage by comparison with ICEVs (Moro and Lonza, 2018; Hawkins et al., 2013). Secondly, some scholars also believe that hydrogen, as a substitute for diminishing fossil fuel supply in the communications and transportation industry, is the most widely recognized clean energy source (Nowotny et al., 2018; Vinoth Kanna and Paturu, 2020). These statements are in line with those of Jacobson et al. (2005) and Zhang et al. (2019) who argue that fuel cell vehicles supplied with hydrogen can be regarded as an alternative to on-road vehicles. As pointed out by Lajunen and Lipman (2016) and Mierlo et al. (2006), HFCVs usually tend to own shorter refueling time and longer endurance than EVs. However, large-scale uptake of HFCVs is still bottlenecked by a series of barriers. A major barrier is the high purchase prices of HFCVs compared to EVs (Brey et al., 2018; Manoharan et al., 2019). The costly fuel cell systems and rising component costs due to the lack of economies of scale are principal considerations for higher purchase costs of HFCVs. Moreover, some research clearly states that high hydrogen production prices, complicated storage and transport process, and expensive hydrogen refueling station all increase the operating costs of an HFCV system (Apostolou and Xydis, 2019; Michalski et al., 2011). According to Hardman et al. (2017) and Roche et al. (2010), the marketization promotion of HFCVs confronts obstacles consisting of benefits uncertainties, safety concerns, and short of refueling infrastructure.

Facing the current academic controversy on optimal substitutes of fossil oil in transportation, this literature aims to provide an overview of the superiority and inferior strengths of battery electric passenger cars and hydrogen fuel cell passenger cars from the perspectives of economy, safety, and environmental impact in the operation system. It runs along the operation chains of EVs and HFCVs and puts forward differences in comprehensively considering power sources, fuel storage and transportation, and auxiliary infrastructure construction. As for alternatives to motor passenger vehicles, the comparison results referring to existing research indicate that EVs are more suitable than HFCVs. However, further promoting EVs still faces several weaknesses, for instance, user anxiety originated from endurance capability, over-long charging, and inadequate charging infrastructure (Metais et al., 2022; Skippon et al., 2016). The way forward could develop rapid charging technology and increase public charging piles to better meet charging demand (Shao et al., 2019; Kong et al., 2012).

The rest of this paper is structured as below. Section 2 explains the necessities and feasibilities of urgently seeking a substitutable path to fossil oil in China. Section 3 presents the operation system’s composition of EVs and HFCVs. Section 4 compares the advantages and disadvantages of EVs and HFCVs regarding power generation and hydrogen production, electricity transmission and hydrogen transportation, and the construction of charging stations and hydrogen refueling stations. Section 5 then introduces methods to enable EVs’ large-scale adoption, and Section 6 summarizes the main conclusions and summary.

2. Motives to find substitutes for fossil oil in China

Regarding new energy vehicles as an alternative to fossil oil and fuel passenger vehicles in China is determined under the following framework. (1) Signals that the transportation industry urgently needs oil substitutes are becoming increasingly clear and definite. It reflects in policy incentives for new energy vehicles, which has laid a policy foundation for petroleum replacement in-depth implementation and automotive powerhouse construction. (2) Meanwhile, new energy vehicles, especially EVs in production, marketing, and export, have conspicuous results, making the new energy vehicle industrial foundation deeply rooted in China. It provides a realistic basis and feasible conditions for new energy vehicles to replace oil and “traditional” motor vehicles’ in-depth implementation. As a result, developing EVs is of uppermost priority to China’s automobile industry in the future, which is also a promising pathway to alleviate dependence on oil, reduce pollutant emissions, and set off a new energy revolution (Shao et al., 2019; Yuan et al., 2015; Li et al., 2014).

2.1. *Signals for urgent needs to replace oil in the transportation industry*

China’s 31 provinces, autonomous regions and municipalities directly under the central government have successively issued a series of policies for accelerating green transportation system construction and supporting new energy vehicles to replace traditional motor vehicles since China officially put forward carbon peaking and carbon neutrality goals on September 22, 2020. Different provinces have various focal points on the plannings of green transportation and new energy vehicles and set objectives on issuing policies that mainly focus on four aspects as below. The first is to popularize power infrastructure, such as charging piles, power exchange stations, and hydrogen refueling stations. Second, it is supposed to optimize technologies related to the whole industry chain of new energy vehicles on research and development. Third, the local government usually provides fiscal and financial support for promoting and applying new energy vehicles. Fourth, new energy scenario applications and demonstration projects are advanced. The main policy details of provinces to advance new energy vehicles are shown in Appendix 1.

Driven by previous policies, provincial action measures on EVs and HFCVs have also made considerable progress. In summary, the technical breakthrough in carbon dioxide emission reduction and low-carbon fuel substitution (WRI, 2019) is the route one must take to achieve carbon dioxide emissions from “peak” to “neutralization” in road traffic. In this sense, developing new energy vehicles provides a supplementary solution for coupling renewable energy utilization and road transport electrification.

2.2. *Revitalization status of the new energy vehicle industry*

China's new energy vehicle industry has been booming with the largest front-end electric vehicle market worldwide, which provides an essential prerequisite and industrial base for exploring substitutes for fossil oil (Crabtree, 2019). There are two main technology paths for new energy vehicles to take the place of fuel vehicles. One is to vigorously popularize electric vehicles (Kong et al., 2014; Moro and Lonza, 2018), and the other is to promote fuel cell vehicles driven by hydrogen (Apostolou and Xydis, 2019; Ajanovic and Haas, 2018). Once new energy vehicles coupled with low-carbon electricity production systems can efficiently replace oil, a great energy transformation and automobile industry revolution will achieve (Metais et al., 2022).

China's electric vehicle industry has entered a mature stage of rapid development with large-scale production and marketing (Wen et al., 2021). Specifically, the production and sales volume were 3.02 million and 2.99 million from January to November in 2021, which owed an increase of 1.7 times year-on-year and made a giant leap in comparison with previous years (Fig. 1). Annual Report on the Development of China's Automobile Industry 2021 published by the Ministry of Industry and Information Technology demonstrates that the sales of new energy vehicles in China have ranked first worldwide for six years running. In addition, the amount of EVs production and sales achieved 2.504 and 2.466 million with a year-on-year increase of 1.8 and 1.7 times compared to the same period in 2020, while those of HFCVs was only 1000.

The production and sales of EVs have reached 2504 times and 2466 times than that of HFCVs according to the Chinese Association of Automobile Manufacturers. Although China has advantages in hydrogen production, HFCVs, of which the sales are concentrated in commercial vehicles (buses account for 98% and trucks account for 2%), are relatively lagging. China is not in exceptional circumstances. HFCVs have developed faster abroad, such as in the U.S., Japan, and South Korea compared with China. Nevertheless, the volume of HFCVs is also minimal in the embryonic stage around the world.

3. The fundamental process of EVs' and HFCVs' operation systems

3.1. *The EVs' operation system*

New energy vehicles play a crucial role in the total carbon emission controls of the automotive industry. Batteries are divided into two types: storage batteries and fuel cells. As the only power source of the vehicle drive system, storage batteries are suitable for pure electric vehicles. Renewable energy power generation, power grid transmission, and charging infrastructure must go through the EVs' operation system (Fig. 2).

3.1.1. *Electric power generation*

Whether EVs or HFCVs contributing to carbon neutralization depends on power sources. If the power source is fossil energy, such as coal and oil, the above vehicles in two types cannot play a role in emission reduction but improve local air quality in urban cities. Only by taking renewable energy including light energy, wind energy, and hydropower, as the final power source of new energy vehicles, can we achieve real emission reduction and greener transportation (Shao et al., 2019; Bellocchi et al., 2018).

3.1.2. *Power transmission*

The direct power source of an electric vehicle charging pile is the power grid (Yang et al., 2021). With explosive growth, enormous EVs connected to the power grid simultaneously may have unfavorable effects on power demand balance, grid security, and power quality. Given this, the regional distribution transformer overload and the charging coordinated control need to be considered carefully. Further, disorderly grid-connected charging is supposed to be avoided as far as possible, especially during electric load peak-hour (Li et al., 2021).

3.1.3. *Charging infrastructure*

The charging infrastructure downstream in the electric vehicle industry chain is a link that cannot be lightly dismissed. The charging infrastructure as one of the urban new infrastructure construction contents refers to facilities that provide power supply for EVs. The number of charging piles in China had reached 2.617 million by the end of 2021.

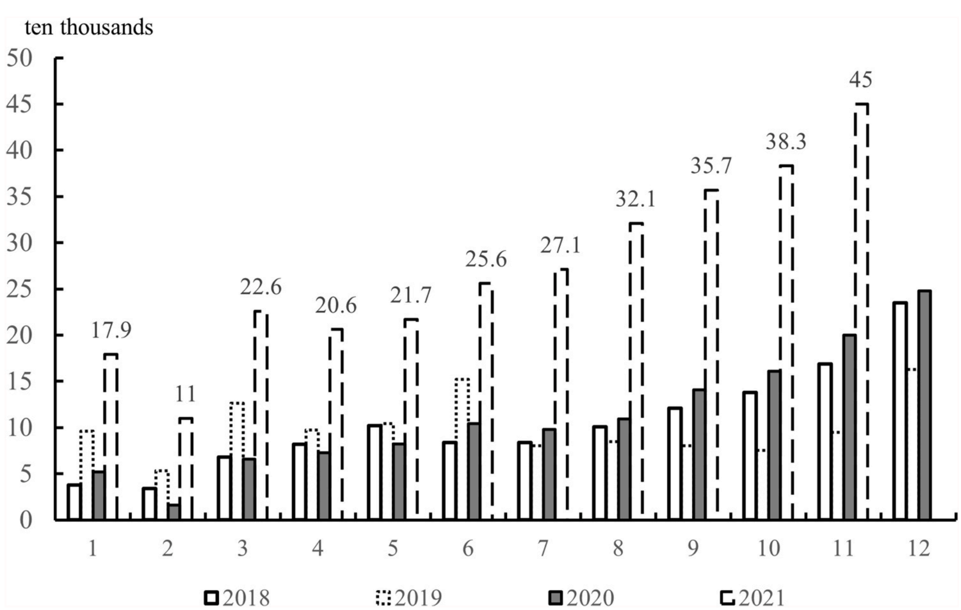

Fig. 1. The monthly sales volume of new energy vehicles from 2018 to 2021
Notes: The horizontal axis represents the month and the vertical axis indicates the monthly sales volume of new energy vehicles. The data source is the Chinese Association of Automobile Manufacturers.

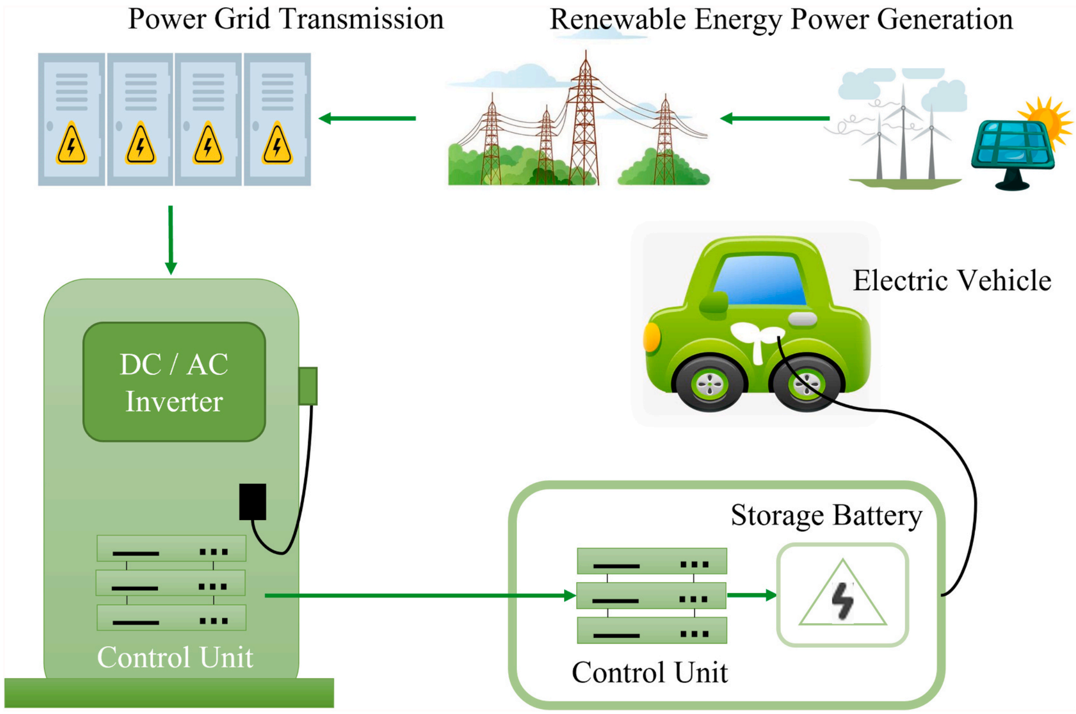

Fig. 2. The fundamental process of the EVs' operation system.

Among them, the number of public charging piles is 1.147 million, which is composed of 0.47 million DC charging piles, 0.677 million AC charging piles, and 589 AC/DC integrated charging piles. In contrast, the number of private charging piles built with the vehicle reached 1.4701 million. The specific contents of the upstream, midstream, and downstream of the charging infrastructure industry chain are shown in Appendix 2.

3.2. The HFCVs' operation system

HFCVs are an emerging industry involved in hydrogen supply and application (Rahil et al., 2018; Zheng et al., 2013). A fuel cell vehicle mainly uses hydrogen as fuel and takes the power generated by the onboard fuel cell device as endurance power, supplemented by a traditional battery as an instantaneous high-power generation. The

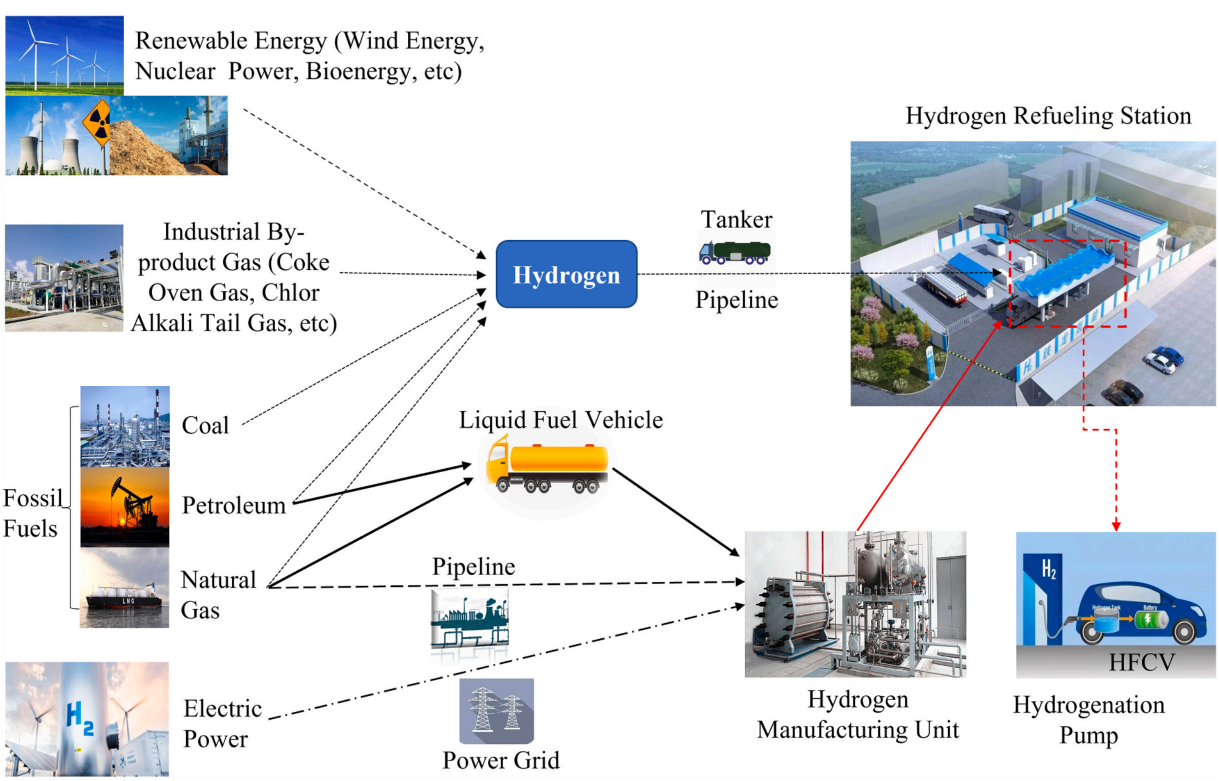

Fig. 3. The fundamental process of the HFCVs' operation system.

HFCVs' operation system also involves many links such as hydrogen preparation, storage and transportation, hydrogen refueling, and fuel cell application (Fig. 3).

3.2.1. Hydrogen production

Hydrogen does not exist independently in nature. It can only be extracted or prepared from other substances. At present, there are three relatively mature extraction methods for hydrogen. The first method of hydrogen production is from fossil energy, such as coal and natural gas. The second method uses industrial by-products to produce hydrogen on a large scale, of which raw materials involve coke oven gas and Chlor alkali tail gas. This process is highly energy-intensive, resulting ineffectively in an energy shortage crisis and leading to disadvantages of being "less environmentally friendly" and "less energy-efficient" (Li and Taghizadeh-Hesary, 2022). The third method is water electrolysis. It is suitable for small-scale production and has a long tradition with a relatively straightforward process, of which conversion efficiency can reach 75%–85%.

Most scientists have turned their attention to solar energy. Although this kind of hydrogen production technology is making progress, it is still in the laboratory stage, such as solar-driven production from water using particulate photocatalysts (Guo et al., 2021b). Additionally, new methods, such as Microwave-Driven Hydrogen Production (MDHP) from water and activated carbons (Horikoshi et al., 2021) and production from wastewater (Aydin et al., 2021), need to be verified in the commercial market promotion.

3.2.2. Hydrogen storage and transportation

High-pressure gaseous state. Hydrogen is extremely high in mass-energy density, but very low in volume energy density, storing it in compression. Compressed gas storage with high pressure (35 or 70 MPa) is considered the most effective transport mode on account of technical simplicity, promising reliability, and elevated energy efficiency (Li et al., 2021). When the transportation volume is small, gaseous hydrogen can be transported by a high-pressure long tube trailer. If hydrogen is transported over a long distance (generally more than 500 km) and on a large scale, only pipelines could be selected as the most economical means of transportation (Gu et al., 2020).

Cryogenic liquid state. The storage and transportation in the liquid state usually rely on (railway) liquid hydrogen tankers. Hydrogen needs to be cooled to −253 °C in the low-temperature mode and then stored in a special highly vacuum-insulated container; otherwise, it will vaporize and evaporate (Niaz et al., 2015). The most ideal insulating container is dewar. However, high costs make it unable to be widely used. At present, liquid hydrogen is mainly used in aerospace and military fields.

Solid-state. Metal alloys are the most mature storage materials, generally composed of two parts. Compared with high-pressure gaseous and liquid hydrogen storage, solid hydrogen storage has the advantages of high density, low working pressure, and good safety performance. However, this method is still in the laboratory stage.

3.2.3. Hydrogen refueling

A hydrogen refueling station provides power for HFCVs. The earliest station may be traced back to Los Alamos, the U.S., in the 1980s. At that time, the American Alamos National Laboratory built the station to verify the feasibility of liquid hydrogen. And then, several hydrogen refueling stations were gradually built. Nevertheless, the number of infrastructure network facilities such as hydrogen refueling stations is extremely few nowadays and merely increases from 214 to 685 in the past seven years with an average annual growth rate of 21.53% (Fig. 4). There were only 218 stations in China by the end of 2021.

4. Comparison of the superiority and inferiority between EVs and HFCVs

This section compares the power source, fuel storage and transportation, and auxiliary infrastructure construction of EVs and HFCVs, aiming at exploring the way more economical, efficient, secure, and applicable.

4.1. Power source: power generation and hydrogen production

The power sources of EVs and HFCVs ought to be electricity and hydrogen coupled with clean energy electricity production systems respectively. Cost determines technological progress in hydrogen production (Li and Taghizadeh-Hesary, 2022). For example, the leading production cost drivers under hydrogen production by electrolysis embody purchase costs concerning manufacturing facilities and energy costs dominated by power production. (1) Purchase costs. Domestic technology in producing hydrogen by water electrolysis has been relatively mature, but it has yet to be fully implemented in the pivotal device localization, core cell components especially. The proton exchange membrane mainly relies on imports (and is costly). Furthermore, there still exists a wide gap in membrane and electrode technology from overseas giant enterprises (Rahil and Gammon, 2017). (2) Energy costs. The production cost of water electrolysis is greatly impacted by

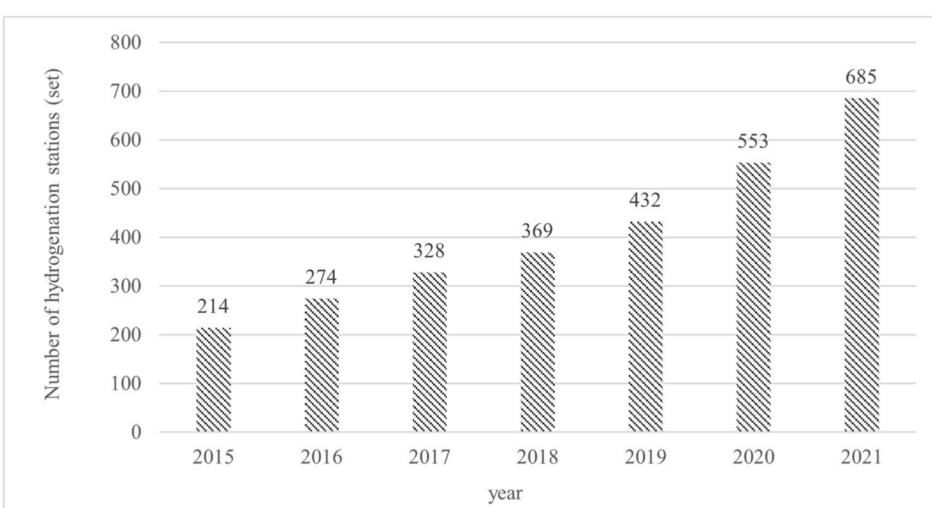

Fig. 4. The quantity of global hydrogen refueling stations from 2015 to 2021
Data sources: H2stations.org by LBST.

electricity price, accounting for more than 70% of the total cost, while the unit energy consumption is up to 4–6 kWh/m^3. The International Energy Agency estimates the cost of several hydrogen production methods in China (Birol, 2019). The cost is about US $3.0/kg for electrolytic hydrogen production from renewable energy. Hydrogen production from coal and natural gas reforming costs US $1.1/kg and US $1.8/kg, respectively. If carbon capture and storage (CCS) is adopted, the cost would increase by about US $0.5/kg. In conclusion, HFCVs powered by hydrogen are not suitable for large-scale production and use considering the cost. After all, the new methods are still in the experimental research phase and actual operation needs to be verified in the commercial market promotion. The layout of large hydrogen production plants around the city has become possible with hydrogen production technology improvement, that is, to provide distributed hydrogen sources. However, the production cost of distributed hydrogen production is much higher than that of centralized mass production (Li and Taghizadeh-Hesary, 2022). The motor energy of EVs comes from the battery and ultimately the power grid supplied by wind power generation, photovoltaic power generation, hydropower, nuclear power, etc. The power supply technology of EVs is relatively mature compared with HFCVs. In addition, the direct use of electricity leaps over the link where "electricity" is also needed to produce hydrogen.

4.2. Storage and transport: electricity and hydrogen

Storage and transport infrastructure networks are critical components of the hydrogen supply chain, nevertheless, the shortcomings in economy and safety are concomitant. First, pipelines are a means for gaseous hydrogen. There are special requirements for the materials in storage and transportation to prevent hydrogen corrosion and embrittlement. At present, stainless steel is generally used as a container material in China. Supposing that pipelines of more than thousands of kilometers are made of stainless steel, they would face one-time exorbitant costs. Hence, how to reduce pipeline material costs and eliminate hidden dangers are other obstacles to the large-scale application of such transportation methods. Second, liquid hydrogen units own high initial investments and liquefaction costs, and high energy consumption in the liquefaction. There are evaporation losses during storage (Nazir et al., 2020; Brown et al., 2013), confronting a regeneration challenge. It brings about a noticeable increase in costs and losses concerned with hydrogen conversion and pollutant emissions, such as nitrogen oxides and carbon dioxide (Ratnakar et al., 2021).

Aside from the above potential safety hazards relevant to storage and transport, hydrogen itself is dangerous, such as permeation, leakage, and explosion (Najjar and Mashareh, 2019; Zhang et al., 2021a). The main reasons are: first, hydrogen is a colorless, tasteless, and non-toxic gas. Tasteless hydrogen is more difficult to detect than gasoline and gas with a peculiar odor in case of leakage, making storage and transport more dangerous (Ma et al., 2021). Second, hydrogen is the most minor dense gas known to nature, which is easy to diffuse in the air after leakage. The minimum explosible concentration is much higher than that of gasoline and natural gas. It is for this reason that hydrogen is safe and controllable in an open space. However, hydrogen can accumulate to the lowest concentration of explosion and accidental explosions can occur in the confined space with poor ventilation, such as underground garages, tunnels, roofed buildings, etc (Zhang et al., 2021b). This has also hindered hydrogen refueling station construction.

In summary, hydrogen goes through multiple links of storage and transportation from transferring between different stations, transporting to the refueling station, and then importing into vehicles for use. Only under the condition of safe storage, fuel cell technology can become a promising method of using renewable energy (Asadnia et al., 2017). By contrast, the biggest superiority of EVs is that the power source is electricity generated and used at any time. On one hand, it can be directly transmitted to the electric terminal of electric vehicles through the power grids, omitting the intermediate storage segment. On the other hand, power grid transmission is more mature, safe, efficient, economical, and convenient than hydrogen transmission modes in various forms. However, the drawback is that damaged power lines and malfunctions in electric chargers may cause wildfires, electrocution, etc.

4.3. Fuel supply infrastructure construction: charging equipment and hydrogen refueling infrastructure

A hydrogen refueling station (HRS) is the infrastructure for fuel supply, which is specially used to fill hydrogen into HFCVs. Köhler et al. (2010) believe that only by firmly convincing consumers that there are sufficient fuel supply facilities will they purchase HFCVs. Yet, hydrogen refueling infrastructure construction is one of the major impediments to commercialization in the current period (Brey et al., 2018; Hardman and Tal, 2018). Plötz (2022) also indicates the reason that HFCVs cannot be commercialized is too few refueling stations in a manner of fuel supply. It in essence attributes to high cost and high risk of construction and operation. First of all, it costs 1.86 million U.S. dollars to build a hydrogen refueling station (about three times than that of traditional gas stations) with a daily capacity of 500 kilos and a filling pressure of 35 PMA in China regardless of land cost (Alliance, 2019). Consequently, operating a hydrogen station costs great expense including special equipment maintenance, operation, labor, and tax with a daily average of 1–1.4 thousand U.S. dollars. Secondly, the refueling station site selection faces the controversy of whether they are distributed in communities or cities as large as gas stations. For one thing, hydrogen leakage is likely to occur in storage tanks, production facilities, and distributors. Since a large amount of hydrogen needs to be stored under high pressure, it is necessary to monitor concentration distribution around hydrogen filling and take specific measures to prevent its leakage (Tsunemi et al., 2019). For another, attention should be paid to the safety of rapid hydrogen charging, mainly because it may rapidly increase storage tank internal temperature. It would not only negatively affect the tank charging state, increase energy consumption, and cause a greater cost burden, but bring potential safety hazards (Wang et al., 2014).

Electric vehicle charging infrastructure, namely charging piles, considers multiple advantages of low cost, safety, flexibility, and convenience by comparison. Firstly, a charging pile's purchase and installation cost is quite low. (1) The purchase cost of a charging pile. Deilami and Muyeen (2020) point out that charging infrastructure has three charging rates: slow charging pile (10–13 h for complete charging), class I fast charging pile (1–3 h for complete charging), and class II fast charging pile (30–100 min for full charging). Among them, the purchase cost of a slow-charging pile is generally $310 to $465 while that of a fast pile has a bearing on its power. A rapid-charging pile with power between 10kw and 300kw is usually 1.55 thousand to 46.5 thousand U.S. dollars. An ordinary charging station construction only costs about 155 thousand U.S. dollars, and even Tesla's supercharging station only costs twice as much. (2) The installation and prime land cost. On one hand, the power line relating to the distance and installation requirements is usually between 155 and 31 thousand U.S. dollars. On the other hand, the prime land cost is not high because the space occupied by the charging pile is very small and the layout is flexible. It highlights supremacy over construction costs compared to hydrogen refueling stations and traditional gas stations. Secondly, the charging pile owns advantages in flexible installation, convenient use, and small floor space because it can be fixed on the ground or wall. Taking accessibility into consideration, charging piles can be divided into public and private piles. Public piles that are open to all users can install in public buildings, such as entertainment and shopping centers, municipal parking lots, etc. (Palanca et al., 2020). Electric vehicle owners can also equip their private parking spaces with charging facilities for a family. It is preferred to use slow charging piles after work at night for owners who have installed private charging piles due to similar daily routines (Fridgen et al., 2021). Sun et al. (2020) also suggest that almost 90% of daily trips can be completed by recharging overnight at home. However, most electric vehicle owners can only rely on public charging piles in some large cities given limited private charging facilities (Perera et al., 2020). Thirdly, the charging pile is more convenient which is closely connected with artificial intelligence and big data technology. Electric vehicle consumers can use a specific charging card to swipe on the man-machine interactive operation interface provided by the charging pile. In contrast, the charging pile display screen can display data such as charging amount, cost, and power supply time.

4.4. Cost of vehicles: EVs and HFCVs

Purchase the vehicle. The price range of EVs is relatively wide, as low as ten or twenty thousand U.S. dollars and as high as millions of U.S. dollars. Appendix 3 lists models, manufacturers, price range, and pure electric endurance mileage of some pure battery electric vehicles in six grades. This reveals that although some EVs in purchase price has reached $0.155 million, there are many models with different prices that consumers can choose from. On the contrary, the acquisition cost of HFCVs is quite high, with few models to choose from (Muthukumar et al., 2021). For example, the relatively mature second-generation Toyota Mirai HFCV listed on December 9, 2020, costs about $68.976 thousand to $78.276 thousand, which can be in comparison with BMW I4 or Mercedes Benz E-class EVs.

Operating cost. The superiority of EVs is decided by low operating and charging costs concerning energy consumption expenses per hundred kilometers and energy conversion efficiency (Ruffini and Wei, 2018). For one thing, EVs cost less per 100 km. As for Tesla Model 3, for instance, the average power consumption per hundred kilometers is about 17 kWh and only costs $3.72 to $4.74 based on the super-fast charging. Instead, the operating cost of an HFCV is higher. According to the international hydrogen network (https://www.in-en.com/), the current price of hydrogen is about $11.53/kg in Germany, $16.48/kg in the United States, $10.85/kg in Japan, and $9.3/kg to $10.85/kg in China. According to Schiebahn et al. (2015), an HFCV consumes 1 kg of hydrogen per hundred kilometers, an HFCV costs $9.3 to $10.85 per hundred kilometers in China. As a result, the operating cost of HFCVs is much higher than that of EVs. This reflects the side that it takes a heavy burden and embarks on a long road of HFCVs for ICEVs. For another, the lower final efficiency of hydrogen fuel cells leads to increased use costs. Regarding energy conversion, the final efficiency of HFCVs is only 25%–35%, while that of EVs can reach 70%–90% (Plötz, 2022). On balance, hydrogen is not suitable for large-scale use as the power raw material of fuel cell vehicles. It causes HFCVs unable to replace fuel vehicles.

4.5. Use of vehicles: EVs and HFCVs

Power supply time and endurance. HFCVs have comparative dominant positions in shorter power supply time and more extended endurance than EVs. If a pure electric vehicle (ordinary battery capacity) is completely discharged, it takes 8–10 h to fill with AC charging pile, and 1.5–3 h with DC fast charging pile. Even Tesla's supercharging pile still takes 80 min to fill. In contrast, HFCVs only need to be charged for a few minutes to endurance for hundreds of kilometers. For instance, Hyundai's hydrogen-powered SUV NEXO could go 609 km between refueling for only 5 min. The alpha 0 hydrogen fuel cell prototype vehicle launched by the French Hopium company in June 2021 has a single endurance of more than one thousand kilometers. However, EVs' power supply infrastructure construction has made rapid progress, making it possible to remedy shortcomings comprised of a long time for power supply and short mileage to a certain extent. Based upon the purchase price range and endurance mileage of different types of electric vehicles in Appendix 3, an electric vehicle with a similar price compared to the Honda FCV can also reach 500–700 km. Moreover, there is a large inventory of charging piles to power EVs. The ownership of public charging piles in China had reached 1.147 million by the end of 2021. Four or five hundred kilometers endurance capacity is adequate in the areas with concentrated public charging infrastructure, such as Guangdong (181800), Shanghai (103,200), Jiangsu (97,300), and Beijing (96,800), hence the endurance mileage and battery life of EVs in urban driving cannot constitute serious disadvantages.

Environmental impact. Pure electric vehicles and hydrogen fuel cell vehicles produce little pollution and emissions during driving. However, such emissions transfer to vehicle and power production. EVs' carbon emissions mainly depend on the power generation structure. The proportion of clean energy power generation in China has increased year by year, which exceed 43% in 2020. According to Rietmann et al. (2020), China's CO2 emission per 1 kWh of electricity is 0.711 kg. Generally, an EV use 10-15 kWh of electricity per hundred kilometers means 7.11 kg–10.67 kg CO2 emissions per hundred kilometers. By comparison, an HFCV's CO2 emissions per 100 km calculate 16.96 kg according to China's hydrogen production structure (Zhang et al., 2020). Furthermore, using HFCVs needs to undergo the conversion from electricity to hydrogen and then to electricity in view of the energy vector conversion, resulting in lower final efficiency and greater energy loss of HFCVs than EVs (Plötz, 2022). This means that the number of wind turbines to produce the same amount of raw electricity needed by HFCVs is more than that of EVs, even three times (Jacobson, 2009). Therefore, the production of wind turbines would slightly increase pollution for HFCVs compared with EVs. In general, EVs may provide more environmental benefits in the future.

Power grid stability. Hydrogen can help power grid stability because hydrogen energy storage power generation technology is a potential solution to balance the supply and demand of the power grid with a high installed capacity of renewable energy (Bennoua et al., 2015). Hydrogen is an intermediate carrier. For one thing, the surplus electricity not on-grid could produce hydrogen. It means converting wind and solar energy with strong fluctuation characteristics into hydrogen energy. The storage of hydrogen has high energy density, low costs for operation and maintenance, and long storage time. For another, when the power load increases, the stored hydrogen could generate electricity and supply power to the grid. This can achieve peak shaving and valley filling in the power grid, promote the stable grid connection of new energy, and improve the security and flexibility of the power system. However, it is worth noting that HFCVs in China own a low base, only reaching about 1000 in 2020. Therefore, the effects of HFCVs on the stability of the power grid are barely measurable. Similarly, EVs are also conducive to maintaining power grid stability (Jacobson et al., 2015, 2022). Gandhi and White (2021) propose the concept of making vehicle-to-grid systems work. First, electric vehicle batteries are charged during off-peak hours, usually at midnight. Second, users commuting to work only consume a small amount of electricity. Third, idle cars could be connected to the power grid during peak hours when users are working. If the grid operator needs it, the power would be sold back.

Precautions for daily use. As for EVs, first, it is necessary to consider that the charging time is inadvisable to be too long. For example, overcharging, over-discharging, and under-charging would shorten the battery life. Second, an EV needs to be charged before parking for a long time. Batteries stored in power loss may cause sulfation, resulting in lead sulfate crystals adhering to the electrode plate, which is extremely harmful to the battery. Third, preventing exposure to extreme hot and cold environments is necessary. Prolonged exposure to the sun would increase the internal pressure of the battery with water loss and then accelerate plate aging. While, a prolonged standstill in a cold environment would lead to a sharp decline in endurance. Besides, the biggest obstacle to the widespread use of HFCVs lies in fuel availability, because of the lack of hydrogen fuel station infrastructure and related on-site storage facilities.

5. Further discussion on the routes to better promote EVs

Developing electric vehicles in China still needs the following improvements. First, a renewable energy power supply system as the initial power supply shall be established according to local conditions. Second, as for fuel supply facilities, strengthening public and private charging infrastructure construction is warranted. Third, it is necessary to continuously boost technological progress in improving endurance mileage and shortening power supply time.

5.1. Promote renewable energy power supply according to local conditions

China's renewable energy resource endowments are unevenly distributed geographically. Hydroelectric resources are mainly concentrated in the southwest while photovoltaic and wind energy are in the northwest (Wang et al., 2021). Wind power and photovoltaic installations in the west region are higher than that in the east region. Relatively, power demand in the west region is significantly lower than that in the east region owing to significant differences in economic levels (Bai et al., 2019). Thus, the northwest and southwest regions are often rich in renewable energy but backward in economy and energy consumption, creating a gap between production and consumption of renewable energy power. It leads to surplus water, wind power curtailment, and light abandonment, which causes renewable energy wastage (Xu et al., 2022; Reichenberg et al., 2018).

Vigorously spreading EVs becomes an essential channel to absorb renewable energy according to local conditions. For one thing, a dedicated distributed power grid is built for surplus renewable energy power unable absorbed in the western areas which could be used exclusively for charging stations and lithium batteries. It can fully utilize local renewable energy and provide consumers with cheap automobile power. For another, renewable energy supply is also closely related to the season. In winter, hydroelectric and photovoltaic resources are both in short supply. For example, photovoltaic power stations can only be shut down due to cold winter and heavy snow in northwest China. Instead, Hainan is located in the tropical region with plenty of sunshine. It has unique conditions to drive EVs with photovoltaic power generation on the whole island.

5.2. Strengthen charging infrastructure construction

The first method for strengthening charging infrastructure is to accelerate public charging piles construction, and the second is to speed up the individual charging piles.

First, optimizing public charging infrastructure deployment is conducive to making up for a deficiency in charging short boards (Anjos et al., 2020; Gan et al., 2020). The key is to assure public charging and battery-swapping network construction in urban and rural areas (Napoli et al., 2020; Bryden et al., 2018) because it provides fundamental guarantees for eliminating mileage anxiety by users and improving accessibility for long-distance travel (Palomino and Parvania, 2019; Vassileva and Campillo, 2017). The data revealed by the China Charging Union demonstrated that the vehicle-pile ratio was about 3.1:1 by June 2021 with 6.03 million domestic new energy vehicles and 1.947 million charging piles consisting of 1.024 million private piles and only 0.923 million public piles. It leads to curb EVs' promotion and application caused by insufficient public infrastructure (Haustein and Jensen, 2018). Another key point is accelerating the effective coverage of expressway rapid charging networks. Tesla China tweeted that China's longest supercharging station line was completed in June 2021. This line which starts from Zhoushan and extends to Horgosest has a total length of 5 thousand kilometers. The distance between supercharging stations is about 100 km–300 km. Besides, charging for 15 min can supply for an endurance of 250 km.

Second, speeding up personal charging piles is another way to provide assistance for personal EVs promotion. Numerous solutions have been introduced in different places, which can provide inspiration and references for personal charging piles' infrastructure construction. For example, Xiamen launched a pilot project called "Networking" to resolve puzzles containing long pile construction time, cumbersome processes, and severe potential safety hazards, which opened up the whole pile construction process. Specifically, "Networking" is integrating property management, power department meter installation, and new energy vehicle sales, which accelerates the power sales and piles installation to proceed in parallel with the power connection process. This would materialize customer information flows and charging facility power connection business all in one network. And then, new energy owners only need to submit applications through the online platform. Furthermore, Sichuan adopts the "unified construction and operation" mode to standardize chaotic charging piles, potential safety hazards, and high-power expansion costs.

5.3. Shorten power supply time and enhance endurance

Technological progress in charging is one of the critical factors in enhancing the comprehensive application and popularization of EVs (Ma et al., 2021; Kumar and Revankar, 2017). A great deal of R&D investment flows to improve battery energy density and recovery efficiency and optimize the battery management system (Tian et al., 2018; Zhang et al., 2015; Borgstedt et al., 2017). The way forward is shortening the power supply time to better meet the demand and increasing battery capacity to enhance endurance (Metais et al., 2022).

First, it ought to shorten power supply time. Related infrastructure construction for EVs has been relatively perfected to support long-distance driving, but long power supply time remains a critical factor restricting marketing promotion (Xiao et al., 2020; Noel et al., 2019). Thus, the vital means to shorten charging time are renewing rapid charging technologies (Deilami and Muyeen, 2020) or swapping out a battery (Vassileva and Campillo, 2017; Barreras et al., 2016). (1) As for rapid charging technologies, for one, some materials need to be developed for output power improvements of electric vehicle charging equipment, such as wide bandgap devices (Li et al., 2021). For another, enhancing rapid charging of electric vehicle batteries is needed, which requires by increasing the average power of DC chargers' modules. (2) As for directly replacing a battery, the specific method is changing an empty storage battery with a fully charged battery at a battery-swapping station that is capable of automatically replacing, charging, storing, and maintaining batteries (Schmidt, 2021). This process has an advantage in saving time compared to charging (Revankar and Kalkhambkar, 2021). In addition, the battery swapping method requires more equipment investment costs, land occupation, and manpower in contrast with rapid charging technologies.

Second, improving endurance mileage is necessary. The main concern that some consumers cannot accept EVs comes from user anxiety originating from endurance. It is noteworthy that the endurance of EVs has been significantly improved, roughly the same as traditional ICEVs. Appendix 3 lists the corresponding endurance mileage of EVs at each price range. The results display that the endurance capability of EVs generally reaches 300–700 km while the endurance of ICEVs with 2.0 exhaust capacity and 60–70L fuel tank size is also 600–700 km.

6. Conclusions and summary

Based on the comparative analysis of EVs and HFCVs regarding power source, storage, transport, fuel supply infrastructure, and the purchase and use of vehicles from the consensus of previous studies, this paper concludes that adopting EVs is more effective instead of HFCVs. The specific reasons are as follows. First, wind and photovoltaic power generation as power sources of EVs have been relatively mature, of which the cost is low. In contrast, hydrogen production by electrolysis owns high purchase costs of manufacturing facilities and high energy costs dominated by power production. In the meantime, hydrogen has risks of permeation, leakage, and explosion. Second, grid transmission has matured for the storage and transport of EVs. By comparison, the one-time investments and construction costs of materials and devices for transporting hydrogen are both high, such as gaseous hydrogen transported by pipelines made of stainless steel. Third, as for fuel supply infrastructure, a charging pile owns low purchase and installation costs with characteristics including flexible installation, convenient use, and small floor space, while such situations are the opposite for the hydrogen refueling station. Fourth, EVs have a larger purchase cost range and lower energy consumption costs than HFCVs. As a result, HFCVs have increasingly prominent defects in economy and security. The premise of developing HFCVs is to re-establish an enormous power production, storage, and transport system and to supplement the shortcomings of the operation system (Shi et al., 2020; Ajanovic and Haas, 2018; Hua et al., 2014). Therefore, EVs are predictably the mainstream substitute for ICEVs. The new energy and automobile industry revolution in China will point to the day and wait for it with rapid development in the EV industry.

We should pay attention to actualizing EVs in place of ICEVs. The key lies in the market-oriented promotion of EVs.. Consumer preference, determined by the purchase and fuel price of a vehicle and travel convenience, directly affects the market penetration of new energy vehicles in a country (Huijts et al., 2012; Oliveira et al., 2019). The critical points for increasing the consumer preference and acceptance of EVs are to improve two power supplement methods consisting of rapid charging and battery swapping (Deilami and Muyeen, 2020; Vassileva and Campillo, 2017; Barreras et al., 2016) and to accelerate charging infrastructure construction, public charging piles in particular (Palomino and Parvania, 2019). It will overcome difficulties such as endurance anxiety caused by over-long power supply time in long-distance travel.

Although we hold the view that giving priority to EVs' development is advisable, it does not totally deny HFCVs. It is supposed to grasp the principle of dislocation and complementary of EVs and HFCVs in different scenarios, bringing HFCVs into full play and finding suitable application scenarios. More particularly, first, HFCVs possess a strong superiority in super low-temperature operation, which is precisely the insufficient strength or position of EVs. HFCVs can start at −30 °C, and the fuel cell performance changes a little before and after startup.[1] Second, HFCVs could be used as medium- and heavy-duty vehicles and applied in alpine areas. Further, the potential to transition military vehicles to hydrogen fuel cell systems has also been widely discussed. For example, Baroutaji et al. (2019) regard hydrogen fuel applications as unique in aviation and spacecraft consisting of rockets, missiles, etc. Katalenich and Jacobson (2022) appoint the equivalence and improvement of ground combat vehicles using commercial hydrogen fuel cell technologies. China's liquid hydrogen has been successfully used in aerospace engineering, but hydrogen as aviation fuel requires further research in terms of safety, cost, and feasibility (Ratnakar et al., 2021).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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