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Hydrogen Fuel Cell Vehicle Development in China: An Industry Chain Perspective

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Hydrogen fuel cell vehicle (FCV) technology has significant implications on energy security and environmental protection. In the past decade, China has made great progress in the hydrogen and FCV industry considering both the government's policy issuances and enterprises' production. However, there are still some technological and cost challenges obstructing the commercialization of FCVs. Herein, the status of China's hydrogen FCV industry is analyzed comprehensively from three perspectives: policy support, market application, and technology readiness level. The unique characteristics and key issues in each part of the industry chain are emphasized. Furthermore, the energy, environmental, and economic performances of FCV in the life-cycle perspective are reviewed and summarized based on pre-existing literature and reports. The life-cycle analysis of hydrogen and FCV indicates that the energy and environmental impacts of FCVs are highly related to the sources of hydrogen. With the combination of industry status and technology performances, it is highlighted that technology advancements in hydrogen production and fuel cells and the optimization of the manufacturing processes for fuel cell systems are equally essential in the development of hydrogen FCVs.

1. Introduction

Energy security and climate change have become increasingly important concerns in recent years, and the transport sector plays an important role in global energy consumption and greenhouse gas (GHG) emissions. According to the International Energy Agency (IEA), the transport sector accounted for 29%[1] of worldwide energy consumption in 2017 and 25%[2] of global CO_2 emissions in 2016. As the world's largest emitter of GHGs, China released 34.74 Gt of CO_2 in 2017, accounting for 28% of the global total,[3] and it has pledged to lower the carbon intensity per GDP by 60–65% below the 2005 level by 2030.[4] China has been the world's largest automobile market for 10 consecutive years.[5] In 2019, the annual production and sales of automobiles in China both reached 25.7 million. With the rapid growth in vehicle stock, the transport sector is an important source of GHG emissions in China. With the recent advances in fuel cell technologies and the unprecedented pressure to mitigate climate change, hydrogen fuel cell vehicles (FCVs) have regained momentum as an alternative vehicle technology[6] that may contribute significantly to improve air quality and address climate concerns in the future.[7] China's annual hydrogen production reached 21 million tons in 2018, making it the largest hydrogen producer in the world[8] and therefore laying a solid foundation for the development of the hydrogen economy. China's rich hydrogen resources and large vehicle market provide great potential for the rapid deployment of hydrogen FCVs. FCVs will be strategically important for China in transition to energy independence and sustainable mobility.

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The development of an industry is closely related to the relevant policies, technology development, and application. In this article, as shown in **Figure 1**, the hydrogen industry and FCV industry are, respectively, evaluated from three perspectives to give a comprehensive picture of the whole hydrogen FCV industry in China.

A well-to-wheel (WTW) analysis is required to comprehensively assess the environmental impact of a vehicle technology, especially FCVs. Compared with electricity, the power source of battery electric vehicles (BEVs), the hydrogen supply, is much more complicated and diversified, which requires advanced production, purification, transport, and storage technologies. The FCV industry chain and the hydrogen industry chain must be developed simultaneously for the deployment of hydrogen FCVs. As shown in **Figure 2**, both the hydrogen and FCV industry chains were analyzed in this study. The hydrogen industry chain includes four parts: production, distribution, refueling, and application. The FCV industry chain was studied covering both upstream and downstream, which includes manufacturing of components, system assembly, and vehicle integration. The complex interdependence between the two industry chains makes it even more challenging to commercialize FCVs.

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2. Worldwide Policy Analysis of Hydrogen FCV Industry

2.1. China

The FCV market in China is mainly policy driven. Since the late 1990s, research and demonstration programs have been initiated in China.[9] The FCV industry has recently become a hotspot, and central and local governments have successively issued policies to promote the development of FCVs.

2.1.1. Supportive Policies

In recent years, the State Council and central government ministries have issued a large number of policies to guide the development of hydrogen and FCVs, including macro comprehensive policies, industry management, promotion and application, tax incentives, scientific/technology innovation, and infrastructure development, as shown in **Table 1**. From the 10th Five Year Plan to the 13th Five Year Plan, the Ministry of Science and Technology of China took the lead in launching a series of

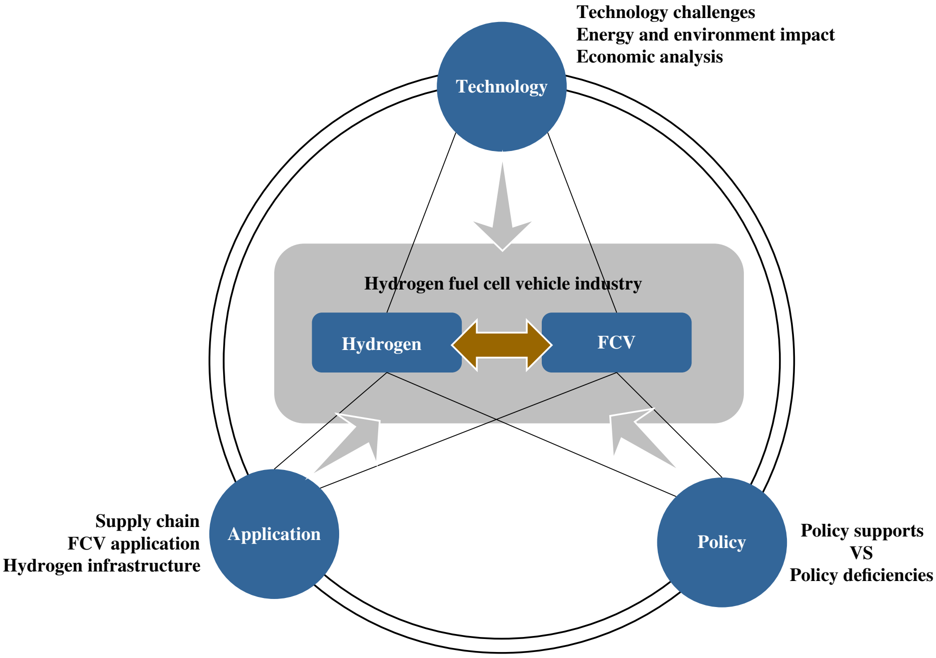


Figure 1. The hydrogen FCV industry's development evaluation framework.

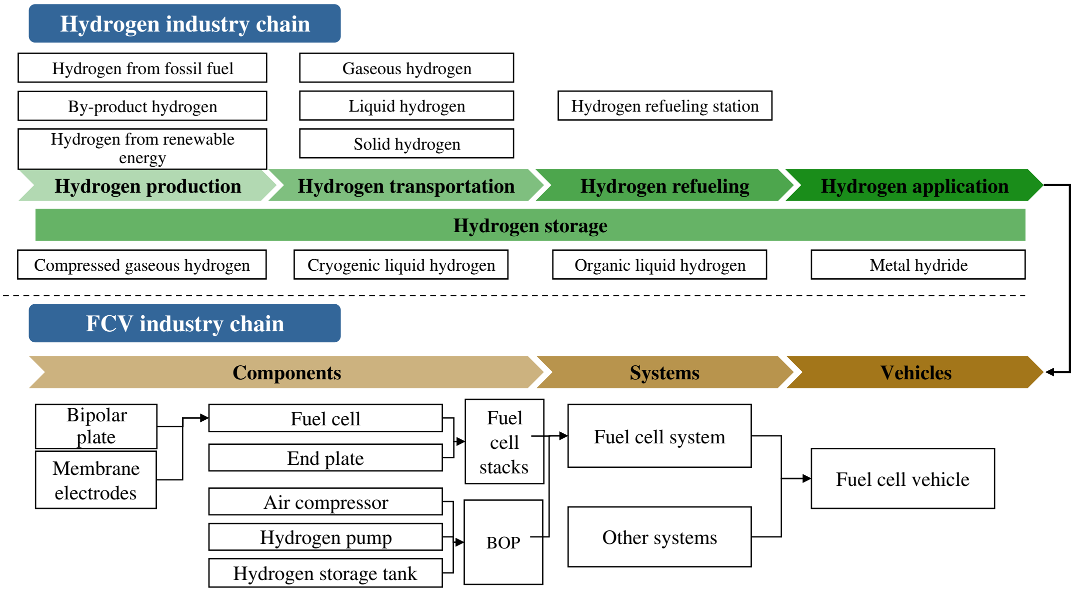


Figure 2. Overview of the hydrogen FCV industry chain.

scientific and technological projects on hydrogen and FCVs. Four ministries jointly introduced fiscal subsidy policies for FCVs and promised that the subsidies will not be phased out after 2020,[10] which will benefit the deployment of FCVs after the elimination of subsidies for BEVs in 2020. Meanwhile, with the phasing out of subsidies, the new-energy vehicle (NEV) credit regulation[11] was promulgated in 2018, which mandates automakers to produce BEVs, plug-in hybrid electric vehicles (PHEVs), or FCVs. Per-vehicle NEV credit is specified depending on vehicle performance including electric range and rated power of fuel cell systems. In the new Dual Credits Measurements,[12] the maximum NEV credit per vehicle for FCV increased from 5 to 6, whereas the maximum credit for BEV decreased from 5 to 3.4, encouraging automakers to produce FCVs in their NEV fleet portfolios to achieve higher NEV credits. Furthermore, the NEV credit regulation could also be implemented for commercial vehicles (CVs) starting 2026,[13] which will promote the deployment of FCVs due to their advantages over BEVs for commercial applications.

Encouraged by the technology breakthroughs and national supportive policies, some local governments also issued supportive policies. Up to now, development plans for the hydrogen FCV industries have been explicitly proposed in Shanghai,[42] Wuhan,[43] Suzhou,[44] etc. In other provinces and cities such as Shandong,[45] Guangdong,[46,47] Zhangjiakou,[48] and Datong,[49] similar supportive documents have been issued to stimulate the development of hydrogen FCV industry. Due to the unprecedented policy support from both central and local governments, it is projected that the hydrogen FCV industry in China will take off starting 2025.

2.1.2. Underdeveloped Policies

However, even with strong central and local government policy support, the development of hydrogen FCV industry still faces major problems in terms of standards and regulations for the hydrogen industry.[50]

Hydrogen has long been classified as a hazardous chemical rather than a type of fuel, making it difficult for the public to accept hydrogen as a conventional fuel like natural gas or gasoline.[51] In fact, although there can be safety risks during the delivery, storage, and dispensing of hydrogen, the risks can be well managed if handled appropriately.[51]

Because hydrogen is classified as a hazardous chemical, its production, transportation, refueling, and storage are strictly regulated. According to the current regulations, hydrogen production is restricted to chemical industry zones, which greatly hinders the development of on-site hydrogen refueling stations (HRSs) and hence leads to high hydrogen transportation costs.

For road transport, the working pressure of tube trailers for hydrogen transportation is limited to 20 MPa, resulting in low transportation efficiency and high cost. China does not have a standardized approval process for the construction of HRSs, resulting in long construction times for HRSs. For on-board hydrogen storage, type IV vessels are not permitted, resulting in low hydrogen storage densities.

2.1.3. Analysis of FCV Policies in China

An NEV policy analysis framework[52] is adopted to analyze FCV policies in China, as shown in **Figure 3**. The X-axis represents the industry innovation level, which includes three parts: public research and development (R&D) and demonstration, commercialization, and marketing. The Y-axis stands for the "supply–demand" policy measures. The policies promoting R&D and production are categorized as "supply-side" policies, and those stimulating market formation and product consumption are categorized as "demand-side" policies.

Table 1. List of policies promoting the development of hydrogen and FCVs in China.

Year	Policy	Highlights
Macrocomprehensive policy		
2006	State's long-term scientific and technological development plan[14]	Hydrogen and fuel cell technology was included.
2012	Energy Saving and New Energy Vehicles Industry Development Plan (2012–2020)[15]	Technological targets of FCVs were planned for the first time.
2014	Program of action for the energy development strategy (2014–2020)[16]	Hydrogen and fuel cell technology was formally considered as an energy technology innovation direction.
2015	Made in China 2025[17]	The FCV development was planned into three phases.
2016	Innovation action plan of energy technology revolution (2016–2030)[18]	Hydrogen and fuel cell technology innovation was considered as one of the major tasks.
2016	The 13th Five Year National Plan for the Development of Strategic Emerging Industries[19]	The plan was issued to develop energy technology for hydrogen and fuel cells, and massive production and scalable demonstration will be realized by 2020.
2016	The 13th Five Year Plan on Energy Development[20]	Focus on new high-efficiency energy storage and hydrogen and fuel cell technology and increased financial and policy support for scalable energy storage and hydrogen production.
2017	The medium- and long-term development plan on automotive industry[21]	Strengthen R&D on FCVs and develop a roadmap for hydrogen FCVs.
2019	Catalogue for Guiding Industry Restructuring[22]	Hydrogen and fuel cell technology was included in the Catalogue of Industries Encouraged.
Industry management policy		
2017	Provisions on the Access Administration of New Energy Vehicle Manufacturers and Products[23]	Access administration of FCVs was included.
2017	Catalogue of Industries for Guiding Foreign Investment[24]	Foreign investment for FCV components was encouraged.
2017	Opinions on improving investment project management of automotive industry[25]	Investment project management of FCVs could be referred to as that of BEV.
2017	Measures for the Parallel Administration of the Average Fuel Consumption and New-Energy Vehicle Credits of Passenger Vehicle Enterprises[11]	Fuel cell passenger cars were included in the NEV credit system and had a ceiling of five credits.
2017	Catalogue of Technologies and Products Encouraged for Import[26]	FCV component production technology, test equipment of high-power FC stack and system were listed in the catalogue.
2018	Special Administrative Measures (Negative List) for the Access of Foreign Investment[27]	Restrictions on the proportion of foreign equity were eased in foreign investment projects on FCVs.
2019	Provisions on the Administration of Investments in the Automotive Industry[28]	Provisions on the Administration of Investments for FCVs were included.
Promotion and application		
2009	Fiscal subsidization fund management interim measures of energy saving and NEV demonstration and extension[29]	Fuel cell passenger cars and buses were subsidized for 250 and 600 000 yuan per vehicle, respectively, in demonstration cities for the first time.
2014	Guiding Opinions on Accelerating Promotion and Application of New-Energy Vehicles[30]	Financial subsidies, tax exemption, and R&D support were specified.
2015	Notice on financial support policies for the promotion of NEVs in 2016–2020[10]	Financial support for FCVs was clarified and would remain the same in 2017–2020.
2018	Notice on improving the Fiscal Subsidy Policies for the Promotion and Application of New-Energy Vehicles[31]	Financial support for FCVs was improved.
2019	Notice on further improving the Fiscal Subsidy Policies for the Promotion and Application of New-Energy Vehicles[32]	Financial support for FCVs will be transferred to infrastructure after 2020.
Tax incentive		
2011	Vehicle and Vessel Tax Law of the People's Republic of China[33]	Vehicle and Vessel Tax should be exempted for FCVs.
2014	Announcement on the Exemption of Vehicle Purchase Tax on New-Energy Vehicles[34]	Purchase tax on FCVs should be exempted.
2017	Announcement on the Exemption of Vehicle Purchase Tax on New-Energy Vehicles[35]	Purchase tax on FCVs should be exempted.
Science, technology, and innovation policy		
2001	Electric vehicle key project of 863 program[36]	
2006	Energy-saving and new-energy vehicle key project of 863 program[37]	

Table 1. Continued.

Year	Policy	Highlights
2012	Special plan for electric vehicle technology development during the 12th Five Year Plan[38]	
2015	Implementation plan of the new-energy vehicle key project of major national research and development plans[39]	
Infrastructure policy		
2014	Rewards of NEV charging facilities[40]	The reward for newly built HRSs was specified.
2016	Blue Book on China Hydrogen Energy Industry Infrastructure Development[41]	A hydrogen roadmap was proposed for the first time, addressing short-, mid-, and long-term targets.

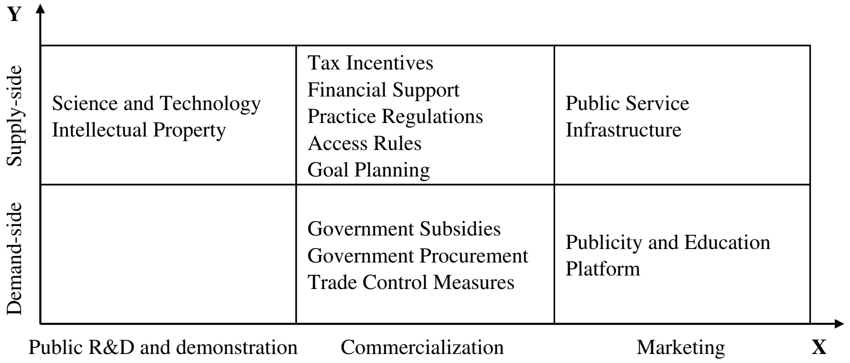


Figure 3. Analysis framework of FCV policies. Reproduced with permission.[52] Copyright 2016, The Authors. Published by Elsevier Ltd.

The policies in Table 1 are classified according to the analysis framework and **Figure 4** shows the results. The majority of China's FCV policies mainly focus on commercialization, whereas the policies about marketing is the least. At present, the supply-side policies significantly out-number the demand side. There are 27 supply-side policies whereas only five policies are demand side. On the supply side, China has introduced many policies in planning, industry management, and demonstration. Demand-side policy involves fewer policies and mainly focuses on commercialization.

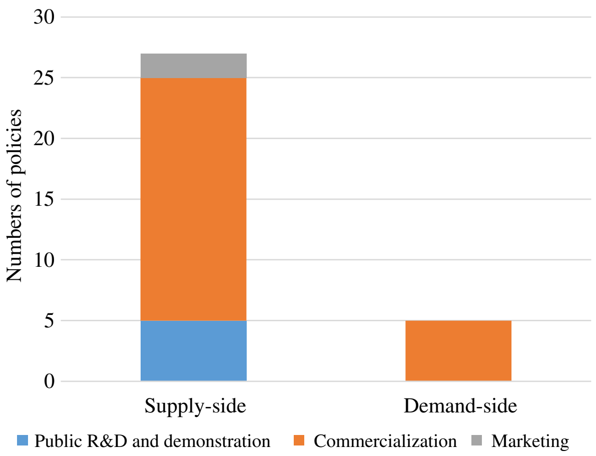


Figure 4. Analysis of China's FCV policies.

2.2. Other Countries and Regions

Because of the demand for rising energy consumption and low emissions, hydrogen and fuel cell industry has been developed and facilitated in many other countries and regions,[53,54] some of which, such as the United States,[55] Japan,[56] and European Commission,[57] have implemented relatively comprehensive supports through investment in R&D, tax exemption for FCVs, strategic plans, and so on. The policies facilitating the introduction of hydrogen and FCVs in these major three countries and regions are shown in **Table 2**.

2.2.1. The USA

The USA was the first country to develop a hydrogen economy. As the world's second-largest primary energy consumer,[58] the USA has consumed more energy than it produced for a very long time, leading to serious energy safety concerns. Therefore, reducing dependence on foreign oil has been one of the most important government policies. The energy crisis was a fuse that detonated the development of the hydrogen economy. In the 1970s, the US National Foundation was authorized to issue hydrogen energy projects.[59] In 2005, the US government published its energy policy,[60] which considered hydrogen as an important type of energy to ensure future jobs and instructed programs and funds to develop the hydrogen economy. Since then, the USA has formed a comprehensive scheme of incentives, laws, regulations, and programs to develop a hydrogen-based energy system.[61] According to the Hydrogen

Table 2. Policies to develop hydrogen and FCVs in the USA, Japan, and EU.[59,64]

Year	The USA	Japan	EU
1973	The establishment of the International Association for Hydrogen		
1974		Sunshine Project	
1976	Electric and Hybrid Vehicle Research, Development, and Demonstration Act		
1978		Moonlight Project	
1987	Electric and hybrid vehicles program		
1990	Hydrogen Research, Development, and Demonstration Act of 1990		
1992	Energy Policy Act (EPAct) of 1992		
1993		Research and development based on the hydrogen energy system	
1996	Hydrogen Future Act		
1997		Special Measures Law for Promoting the Use of New Energy	
2000			Hydrogen R&D and Demonstration Strategy
2001	National energy policy: Reliable, Affordable, and Environmentally Sound Energy for America's Future		5th Framework Program
	National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond		
2002	Founding Agreement for FreedomCAR and Fuel Partnership	Special Measures Law for Promoting the Use of New Energy Revised	6th Framework Program
	National Hydrogen Energy Roadmap	Japan Hydrogen and Fuel Cell (JHFC) Demonstration Project	
2003	The US Hydrogen Fuel Initiative		Hydrogen energy and fuel cells: A vision of our future
2004	Action Plan to develop Hydrogen/Fuel Cell GTR(s)		
	Basic research needs for the hydrogen economy		
	FreedomCAR and Fuel Partnership Plan		
	Hydrogen Posture Plan		
2005	Energy Policy Act (EPAct) of 2005		
2007			7th Framework Program
2008		Commercialization of fuel cell vehicles and hydrogen stations to commence in 2015	
2009	American Recovery and Reinvestment Act of 2009	Eco-Car Tax Break and Subsidies for Vehicles	Regulation (EC)No.79/2009
	Tax credits		
2010		Strategic Energy Plan	
2011	The DOE Hydrogen and Fuel Cells Program Plan		H2moves Scandinavia
			Clean Hydrogen in European Cities Project
2013		Japan Revitalization Strategy	Horizon 2020
		Subsidies for HRSs	CPT Project
2014		Hydrogen Energy White Paper	Fuel cell and hydrogen implementation plan
		4th Strategic Energy Plan	
		Promotion strategies for hydrogen fuel cell vehicle	
		Strategic Road Map for Hydrogen and Fuel Cells	
		Subsidies for fuel cell vehicles	
2015	Tax credits revised	Budget and subsidy	

Table 2. Continued.

Year	The USA	Japan	EU
2016		Strategic Roadmap for Hydrogen and Fuel Cells (Revised Edition)	Renewable energy directive
2017		Basic Hydrogen Strategy	
2018	Tax credits revised	5th Strategic Energy Plan	H_2 Bus Europe Project
2019	Roadmap to a US Hydrogen Economy	New standard for HRS The Strategic Road Map for Hydrogen and Fuel Cells	Hydrogen Roadmap Europe

Posture Plan,[62] the development of hydrogen technology and market transformation are divided into four stages: technology development (from 2000 to 2030), initial market penetration (from 2010 to 2025), expansion of markets and infrastructure (from 2015 to 2035), and fully developed markets and infrastructure (from 2025 to 2040).

2.2.2. Japan

Formulating a proper energy strategy is crucial for Japan's long-term development because of its small land area, dense population, and scarce resources. Hydrogen has been considered as the strategic energy in the Japan Revitalization Strategy[63] and the Strategic Energy Plan[64] released by the Japanese Cabinet, with the hope of solving domestic energy problems through the deployment of advanced hydrogen technologies and the development of a hydrogen society. The Japanese government has formulated specific standards and regulations for hydrogen and FCVs, providing strong support for their commercialization. In summary, Japan has formed a well-planned industry–academia–government cooperation, making it a global technological leader. However, due to the limited size of the domestic market, the deployment of hydrogen and FCVs will inevitably reach a bottleneck if focusing on the Japan market only.

2.2.3. European Union

The European Commission is one of the most positive propellers to solve the problems of energy depletion and environmental deterioration, with a focus on renewable energy applications. The proportion of renewable energy sources (RESs) in the electricity generation is increasing every year and electricity generation from RESs contributed 32.3% to total gross electricity generation in 2018.[65] Hydrogen and fuel cells are regarded as key technologies to address the challenges of energy and climate change and the energy-storage problem in the European Union (EU), whose framework programs have continuously supported hydrogen and fuel cell R&D since the second Framework Program (FP2) in 1986.[66] The EU has a relatively complete hydrogen-related legal system, which benefits the enforcement of regulations. Research and demonstration projects have been successively conducted based on its frame projects, which provide explicit development progress and targets for the commercialization of hydrogen and FCVs in EU.

3. Analysis of Current Hydrogen and FCV Deployment in China

The hydrogen FCV industry in China started relatively late and has lagged behind other major countries in terms of technology and commercialization readiness levels. For hydrogen and FCV, it is crucial to form a complete industry chain, which can considerably affect the performance, reliability, and cost of FCV products.

3.1. The Integrity Analysis of Hydrogen Industry Chain

The world has seen the transition of energy systems from one form to another since the 19th century, i.e., from wood to coal to oil to natural gas, revealing the increase in the ratio of hydrogen to carbon in the successive dominant fuel.[67,68] Therefore, it is widely accepted that hydrogen has the potential to become a major fuel in the future. Some of the state-owned traditional energy giants, such as China Energy and Sinopec, have formed a strategic plan for the hydrogen industry in China. With enterprises working on each key sector, the hydrogen industry chain began to take shape, as shown in **Figure 5**.

3.1.1. Hydrogen Production

Hydrogen production is the foundation for the development of the hydrogen economy. Hydrogen can be generated from various energy sources, but the production pathways should be prioritized from economic, environmental, technical, and social–political aspects.[69] Hydrogen is currently produced from coal gasification, industrial off-gases, and water electrolysis in China.[8] Because China is rich in coal and poor in oil and gas, coal gasification accounts for the largest proportion of hydrogen production and will continue to play an important role in the future. The chlor–alkali industry is the second-largest source of hydrogen,[8,70] in which hydrogen is usually considered as a byproduct. Although there is no large-scale hydrogen production from water electrolysis due to its high cost at the current stage, hydrogen from water electrolysis could be the most environmentally friendly pathway and will play an increasingly important role in the future.

Figure 6 shows the development prioritization of hydrogen production technologies for FCVs. Currently, ≈10 million tons of hydrogen are produced annually from industrial off-gases (coke oven gas, synthetic ammonia, methanol, chlor–alkali). With mature pressure swing adsorption (PSA) technology, the

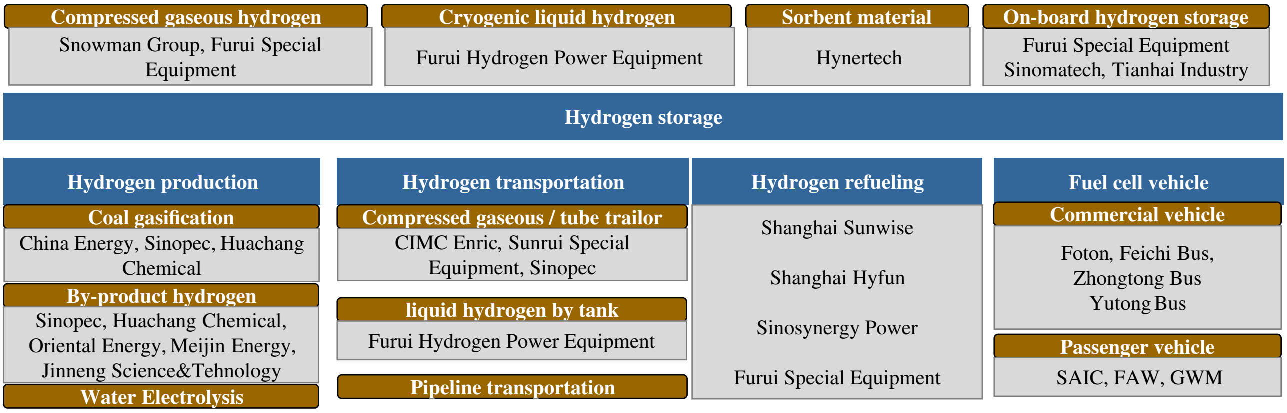
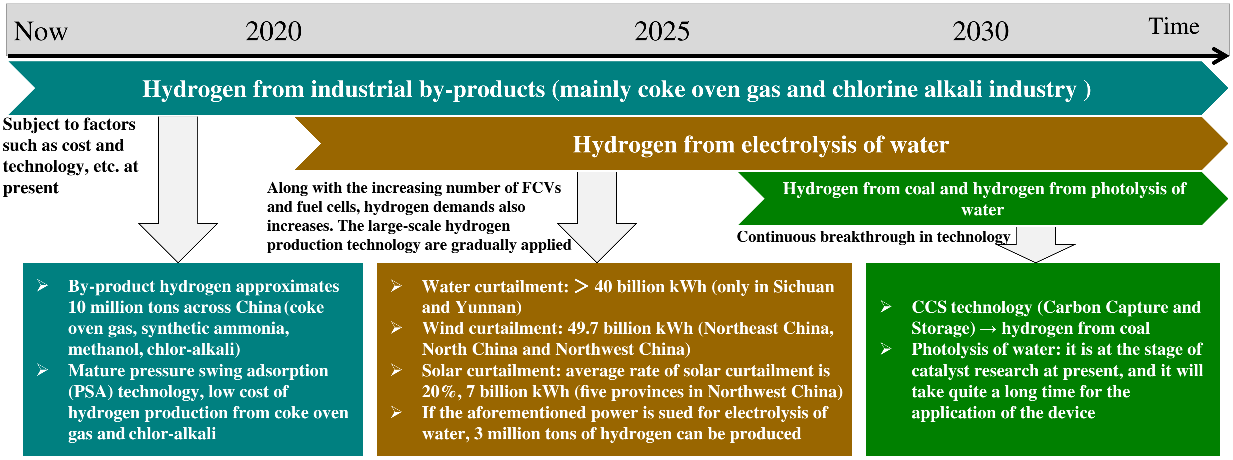


Figure 5. Main enterprises in each sector of the hydrogen industry chain.



Subject to factors such as cost and technology, etc. at present

Along with the increasing number of FCVs and fuel cells, hydrogen demands also increases. The large-scale hydrogen production technology are gradually applied

- By-product hydrogen approximates 10 million tons across China (coke oven gas, synthetic ammonia, methanol, chlor-alkali)
- Mature pressure swing adsorption (PSA) technology, low cost of hydrogen production from coke oven gas and chlor-alkali

- Water curtailment: > 40 billion kWh (only in Sichuan and Yunnan)
- Wind curtailment: 49.7 billion kWh (Northeast China, North China and Northwest China)
- Solar curtailment: average rate of solar curtailment is 20%, 7 billion kWh (five provinces in Northwest China)
- If the aforementioned power is sued for electrolysis of water, 3 million tons of hydrogen can be produced

- CCS technology (Carbon Capture and Storage) → hydrogen from coal
- Photolysis of water: it is at the stage of catalyst research at present, and it will take quite a long time for the application of the device

Figure 6. Projections for hydrogen production in the future.

costs of producing hydrogen from industrial off-gases are relatively low compared with other production pathways. Thus, based on the cost and technology readiness level, it is and will be a dominant hydrogen source for FCVs. The curtailment of renewable electricity is a huge problem and waste in China. For example, the curtailed hydroelectricity in Sichuan and Yunnan is over 40 billion kWh per year. Producing hydrogen using the curtailed electricity is the most environmentally friendly production pathway. China has abundant coal reserves, and it is crucial to develop clean coal technologies. With the advancements in emission control technologies (carbon capture and storage, etc.), hydrogen from coal will also contribute to the development of the hydrogen economy in China.

3.1.2. Hydrogen Storage and Delivery

Hydrogen storage and delivery are the key factors in the hydrogen economy, and they affect the energy efficiency and cost. There are three main methods to deliver hydrogen from a centralized factory to a refueling station: compressed hydrogen, cryogenic liquid hydrogen, and solid-state hydrogen. Compressed and cryogenic hydrogen storage are technically mature. Magnesium hydride is one of the most promising materials for solid-state hydrogen storage. All of them, however, still face challenges of low energy efficiency and high cost.[71]

Compressed hydrogen via tube trailers is the most common method of hydrogen delivery in China, partially because of the standards and regulation restrictions. Due to its low-cost and mature technology, compressed hydrogen will continue to be the most common form of hydrogen delivery, on-board hydrogen storage, and hydrogen storage at HRSs in the short-to-medium term. Although liquid hydrogen has not been permitted for civil use, it is widely accepted that liquid hydrogen, due to its high density, is a preferred form for medium-distance hydrogen transportation and high-volume storage. Some enterprises in China have already developed hydrogen liquefaction technology and products. Material-based hydrogen storage shows great advantage in terms of volumetric density, making it have great potential for short-distance and small-scale hydrogen storage and delivery in the future. The three methods above are suitable for short-to medium-distance transportation. When it comes to long-distance transportation, however, pipeline transportation is a better choice for a nationwide hydrogen society. For now,

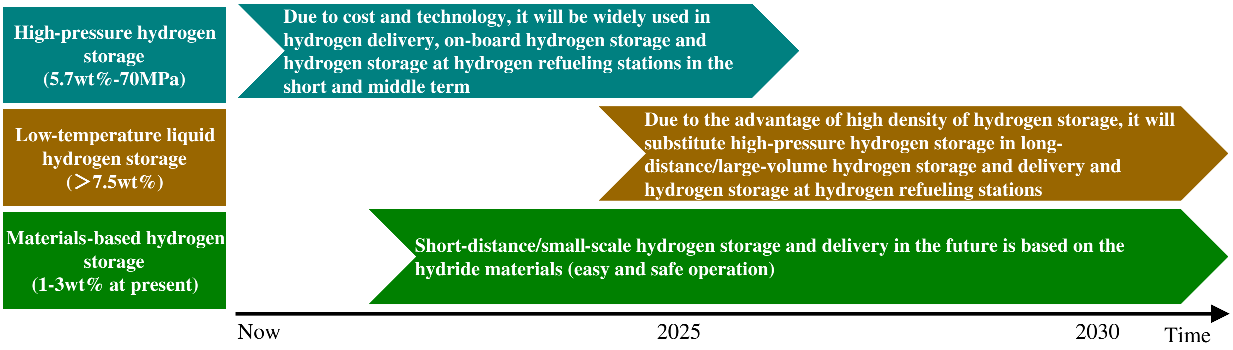


Figure 7. Future application scenarios of hydrogen storage.

only 100 km of pipelines have been laid in China[8] for demonstration purpose (**Figure 7**).

3.1.3. Hydrogen Refueling

HRSs are pivotal connections between hydrogen supplies and hydrogen applications. HRSs can be categorized into two types according to the hydrogen sources: off-site HRSs, in which the hydrogen is produced in a centralized hydrogen production factory, and on-site HRSs, in which the hydrogen is produced inside the station. The development of HRS is mainly subject to the construction cost, the economics of the operation, and the floor space required. The hydrogen cost varies tremendously depending on the HRS type and scale. On-site hydrogen production can result in a lower hydrogen cost.[72] Currently, on-site hydrogen production is not allowed in commercial HRSs in China according to the existing regulations.

3.2. The Integrity Analysis of FCV Industry Chain

Supported by the government demonstration projects, FCVs could be firstly deployed in CV fleets. Some bus original equipment manufacturers (OEMs), such as Foton, Feichi, Zhongtong, and Yutong, have already completed the R&D of a series of fuel cell bus models, and the fuel cell buses have come into operation in commercial bus lines in some regions in China. In terms of passenger vehicles (PVs), the Shanghai Automotive Industry Corporation (SAIC) has formed two vehicle platforms, and Great Wall Motors (GWM) and First Automotive Workshop (FAW) released their R&D plans. With the large market of logistics and public transport in China, CVs will be the preferred sector to deploy FCVs in the short term due to their lower cost sensitivity and easy-to-manage centralized hydrogen refueling.

Due to the lag in stack performance and the development of balance of plant (BOP) components, there are substantial gaps in the technology readiness level of fuel cell systems between China and foreign countries. As shown in **Figure 8**, companies in China have grasped the key technologies of fuel cell systems but still lag behind foreign companies in fuel cell performance and durability. Several representative fuel cell system companies, such as SinoHytec and Sunrise Power, have mature technologies in system integration. For the upstream, however, the domestic component enterprises are relatively small in scale. Some core parts such as bipolar plates are still in the R&D stage. There are still no mature products for key BOPs in China, for example, air compressors and hydrogen circulating pumps, which are crucial to the power density of the fuel cell system. The high technical requirements for compressors and circulating pumps as well as the great difficulties in making breakthroughs in core technologies hindered the development of fuel cell systems. As a result, the foreign hydrogen and fuel cell technologies are necessary for the development of the Chinese FCV industry.

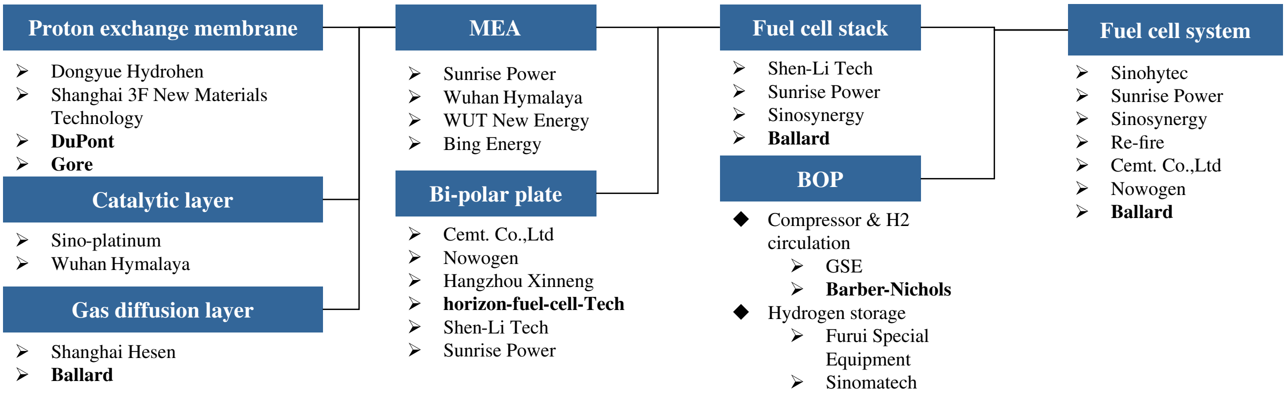


Figure 8. Main enterprises in each sector of the fuel cell industry chain.

3.3. Key Issues in the Development of the Hydrogen FCV Industry

3.3.1. Hydrogen Infrastructure Operation Analysis

The lack of hydrogen infrastructure is one of the key factors that hinders the commercialization of FCVs. By the end of 2018, there were 23 HRSs in operation in China,[8] located in four hydrogen energy clusters: Beijing–Tianjin–Hebei, the Yangtze River Delta, the Pearl River Delta, and Central China. Despite the high increasing rate of HRSs, the hydrogen supply is far behind the demands of FCVs. The popularization of HRSs is mainly restricted by the construction cost, the economics of operation, and the management policies. The high cost of HRS is mainly due to the high price of refueling equipment, small station capacity, a lack of economy of scale, and low utilization of the refueling capacity,[73] which is a major problem for the hydrogen industry worldwide. At present, the development of FCVs in China is in the initial stage, and most of the refueling services are provided for fuel cell buses for limited demonstration purposes, resulting in the poor economy of HRSs. The imperfections of management policies throughout construction and operation also impede the development of hydrogen infrastructure in China. In fact, it is incredibly difficult to obtain approvals for land, construction, and operation because of the ambiguous governing authorities, regulations, and standards. Considering the national energy strategy, it is also very challenging to develop three independent sets of infrastructures (gasoline stations, charging stations, and hydrogen stations) due to the high investment and limited land resources (**Figure 9**).

The development of hydrogen infrastructure should be planned systematically and gradually. Restricted by the limited hydrogen availability and the current low efficiency of hydrogen transportation, the establishment of hydrogen refueling infrastructure should start in areas with sufficient hydrogen sources. The development of hydrogen energy infrastructure should also consider the local hydrogen production technology and FCV technology, and these three should be coordinated to avoid mutual constraints between the development of infrastructure and FCVs.

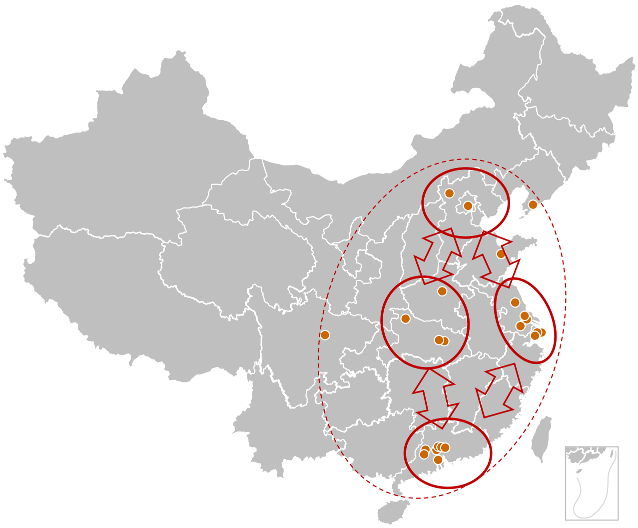


Figure 9. HRSs in China by the end of 2018.

3.3.2. FCV Application Analysis

Because of the limited refueling infrastructure, high cost, and technical challenges, the fuel cell technologies are mostly on the demonstration stage or early stage of commercialization. Compared with PVs, CVs are less cost sensitive and less dependent on infrastructure due to their relatively fixed driving routes. Therefore, the commercialization of FCVs could start in the CV sector in China.[74] The characteristics of the operation of CVs have determined that FCVs will be more practical than BEVs, and the introduction of an NEV credit policy for CVs will play a key role in promoting the application of fuel cell CVs in the future. As **Figure 10** shows, fuel cell buses and special vehicles (mainly trucks) dominate the FCV market in China.[75] Fuel cell CVs have entered the market, starting from city buses and logistics vehicles, and will gradually extend to heavy-duty CVs.

Although commercial FCVs have been sold in the Chinese market, the number of FCVs in operation is still very small because of the limited HRSs, the high cost of hydrogen, and the imperfect regulations on hydrogen FCVs. FCVs also have the advantages of a high driving range and short refueling time. With the improvement of the industry chain and infrastructure, FCVs will gradually penetrate into the passenger car market. Technology breakthroughs and cost reduction are necessary for the large-scale commercialization of FCVs. Overall, FCVs are still in the early stage of market penetration with numerous demonstration projects guided by central and local governments. FCVs have tremendous market potential in China.

4. Hydrogen and FCV Technology Evaluation

4.1. Potential for Energy Saving and Emissions Reduction

The life cycle assessment of FCV can scientifically measure to what extent FCs are energy efficient and environmentally sound, thus guiding the policymaking of governments and vehicle production of enterprises.[76] The application of FCVs should contribute to the improvement of energy efficiency and decrease GHG emissions. Although FCVs exhibit advantages over internal combustion engine vehicles (ICEVs) on energy efficiency and

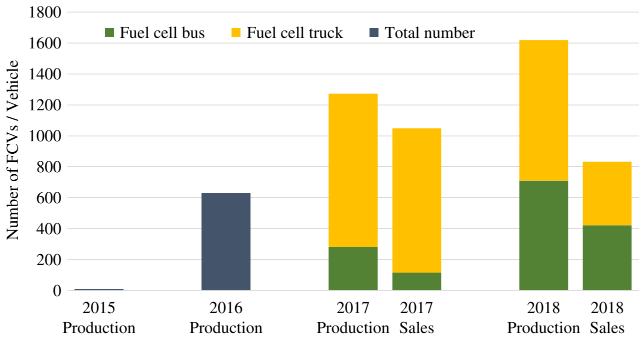


Figure 10. Production and sale volume of FCVs in China.[78]

GHG emissions in the pump-to-wheel (PTW) stage, this is not always the case from a life cycle perspective.

Both the vehicle cycle and fuel cycle should be taken into consideration. From the vehicle life cycle perspective, the energy consumption and GHG emissions are unlikely favorable to FCVs when compared with ICEVs due to the system complexity when considering available techniques and technology readiness levels.[77,78] The components in a proton-exchange membrane fuel cells (PEMFC) vehicle are shown in **Figure 11**. Drivetrain, especially the fuel cell system, accounts for the largest proportion of total energy consumption and GHG emissions in vehicle life cycle.[79,80] The fuel cell system is composed of fuel cell stack and BOP. Fuel cell stack is the core part of the fuel cell system, whose structure is relatively complex. BOPs include air compressor, hydrogen circulation pump, and other parts. The production processes of fuel cell systems, hydrogen tanks, and other related components consume a variety of polymer materials, carbon-fiber-reinforced plastics (CFRP), metals, and so on, most of which have a relatively high GHG emission density based on the current technical level, resulting in a high energy consumption and GHG emissions.[81]

Though the energy and environmental performance of FCV has a disadvantage compared with ICEV and BEV in vehicle life cycle, it can still improve its whole life cycle performance through the uses of clean hydrogen in fuel life cycle.[82] As Figure 11 shows, the life cycle energy consumption and GHG emissions show a rather pronounced variation with the energy structure, vehicle technologies, and driving patterns.[83–94] In **Figure 12**, the gasoline PVs demonstrate relatively concentrated performances on the aspects of energy consumption and GHG emissions as the vehicle models, driving patterns, and GHG emission densities are less differentiating among different studies. The scattered results of diesel ICEV and BEV are mainly caused by different vehicle models. The life cycle energy consumption and GHG emissions of FCV are influenced by many factors such as vehicle models, driving patterns, and hydrogen sources, leading to the great scattered results in different studies.

The most important factor affecting the results is the source of hydrogen energy, the GHG emission density which varies a lot considering different production methods. and different energy-system structures in different regions and time frames. Normally, the cleaner the energy source of hydrogen and the

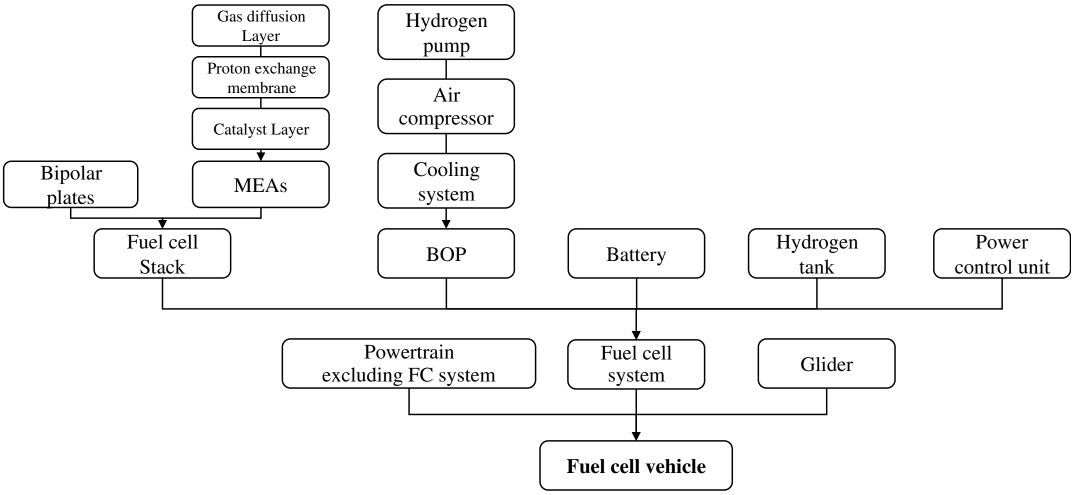


Figure 11. PEMFC vehicle components and hierarchy, revised from a previous study. Reproduced with permission.[82] Copyright 2016, Elsevier Ltd.

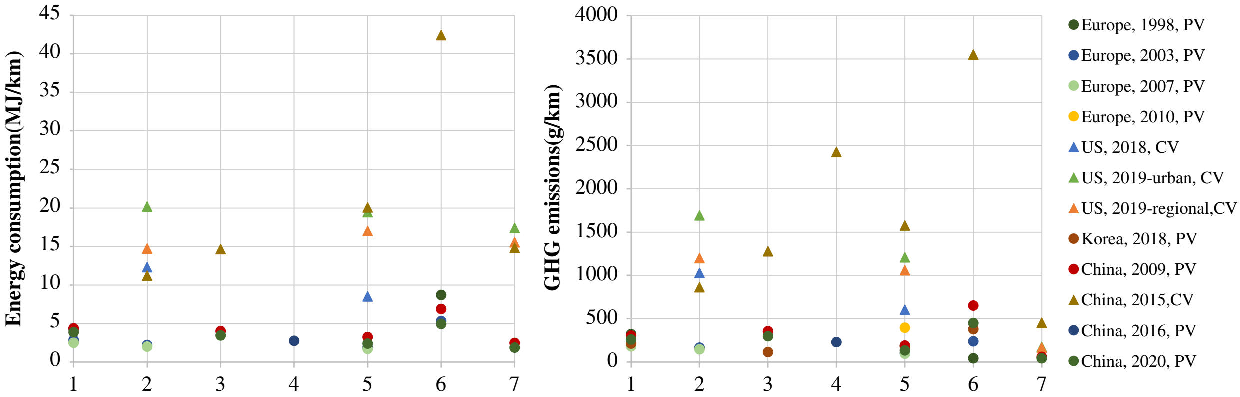


Figure 12. Life cycle energy consumption and GHG emissions comparison between different vehicles. Dots represent PVs and triangles represent CVs. 1) ICEV (gasoline), 2) ICEV (diesel), 3) BEV (grid elec.), 4) FCV (coal), 5) FCV (NG), 6) FCV (grid elec.), 7) FCV (RES elec.).[83–94]

shorter the production chain, the lower the GHG emission density of hydrogen. Hao et al.[94] evaluated the energy consumption and GHG emissions of China's fuel cell buses in 2015 (China, 2015, CV in Figure 11). Under the energy structure of fuel cell technology at that time, FCVs using hydrogen produced by traditional production methods, that is coal gasification, steam methane reformation, and water electrolysis by grid mix, show a higher energy consumption and GHG emissions than diesel ICEV and BEV, whereas FCV using hydrogen produced from renewable energy shows better energy and environmental performances than those of diesel ICEV and BEV.

The vehicle segmentation obviously has a great impact on the absolute values of energy consumption and GHG emissions. The vehicle models and driving patterns are not explored in detail in the article as the assumptions in different studies vary greatly. In summary, with the optimization of hydrogen technology and the energy-system structure, the potential of FCV to reduce energy consumption and GHG emissions will rise in a period of time. Thus, it is important to ensure clean sources of hydrogen. The energy consumption and GHG emission intensity of hydrogen are strongly related to the production pathway and the regional energy structure. Usually, electrolysis with electricity from fossil fuels exhibits the worst life cycle GHG emissions. Many studies have been conducted in different energy contexts and the results varied depending on the share of renewable energy in the energy mix. Only when fueled with hydrogen produced from renewable sources such as biomass, wind, and solar can FCVs provide great potential to reduce energy consumption and GHG emissions.[95,96]

Table 3. Global sales and vehicle price of three FCV models in 2019.[100–103]

	Hyundai NEXO	Toyota Mirai	Honda Clarity Fuel Cell
Sales (vehicles)	4818	2407	349
Price ($)	58 735	$389/month, 36 months $2,499 Due	$379/month, 36 months $2,878 Due

4.2. Economic Analysis of FCVs

Having been developed for decades, the cost of FCV is still too high, prohibiting the large-scale commercialization of FCVs. Although FCVs are far more expensive than other types of vehicles such as ICEVs and BEVs at the current stage, they hold great potential to be competitive in the future.[92,97–99] From a life cycle perspective, the cost of FCVs consists of the purchase cost, the fuel cost, and the maintenance cost, all of which significantly affect the market acceptance of FCVs.

4.2.1. Purchase Cost

Table 3 shows the global sales[100] and vehicle price[101–103] of three FCV models in 2019, from which we can see that, at present, the price of FCV is higher than that of ICEV and BEV with the same level. The high purchase cost of FCV is mainly due to the high cost of the fuel cell system. Therefore, one of the solutions to the cost problem is to reduce the cost of the fuel cell system through technology improvement such as decreasing the Pt loading and increasing the active reaction areas.[104]

Small-scale production is another reason leading to the high purchase cost.[105] As Table 3 shows, in 2019, the global sales of FCVs only reached 7574, nowhere close to practical commercialization, resulting in the high purchase cost of FCV.

Thus, with different scale assumptions and technology selections, the cost evaluation can be quite different. With low-production-scale (1000 systems/year) and relatively immature technologies (technology level in 2013), the system cost could be as high as $280 kW^{-1}.[106] Over the past two decades, the US Department of Energy (DOE) has conducted many researches in the cost evaluation of fuel cell systems. As shown in **Figure 13**, it is predicted by the US DOE that, with the improvement of technology and the increase in production volume, the fuel cell system cost could be reduced to $30 kW^{-1} in 2025 at the annual production rate of 500 000 systems/year,[61] thereby achieving cost parity between FCVs and ICEVs. In the past few years, different technologies have been applied to fuel cell systems due to the change in performance requirements

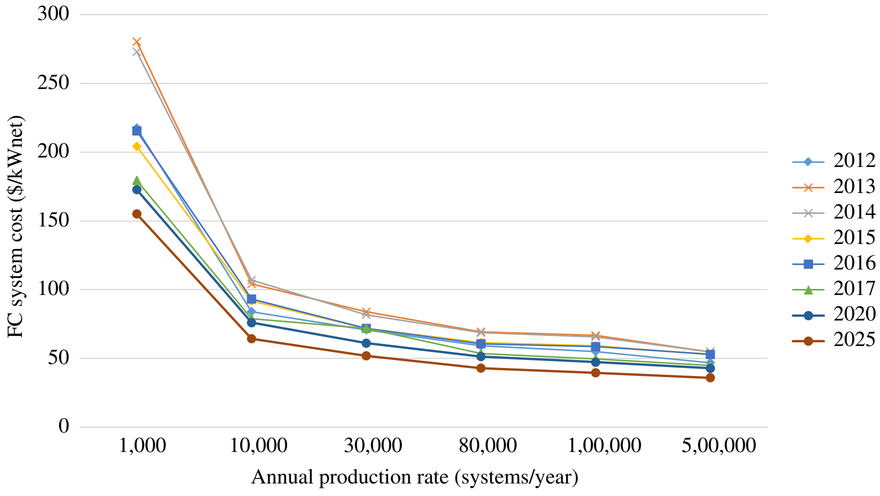


Figure 13. Fuel cell system cost estimation.[61,106]

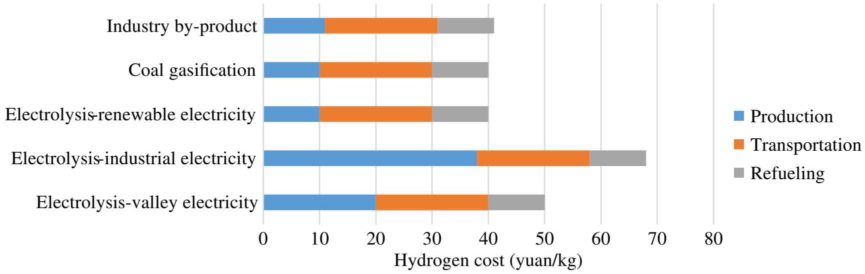


Figure 14. Hydrogen cost in China.[101]

of policies, so the costs didn't present a trend of decreasing steadily over time. In the future, namely 2020 and 2025 in the Figure 10, the technical level has been assumed to gain improvement to different extents, so the costs will be lower. In contrast, the cost reduction caused by scale effect is more significant. However, there are significant uncertainties in the projection of the FCV market, as some experts believe that reaching a production volume of 500 000 units per year is very challenging in the short term. The FC cost target of the US DOE could fall short in 2020, whereas the ultimate targets could be met in the future.[107]

4.2.2. Fuel Cost

Both the production methods and applications have significant influences on the cost of hydrogen. Currently, hydrogen generated from fossil fuels (coal gasification) dominates the market due to its low production cost. As shown in **Figure 14**,[108] the hydrogen cost consists of production cost, transportation cost, and refueling cost. The production costs are quite different in terms of different production technologies. Industry byproduct hydrogen has a high cost advantage. The cost of byproduct hydrogen together with purification is only about 8–14 yuan kg^{-1}. Currently in China, hydrogen from fossil fuels such as coal costs lower than other traditional methods at the cost of 10–15 yuan kg^{-1}. Hydrogen from water electrolysis is more costly than other methods. The electricity consumption used in water electrolysis is about 5–5.5 kWh Nm^{-3} hydrogen. Therefore, the cost of hydrogen from renewable electricity, industrial electricity, and valley electricity is about 10, 38, and 20–22 yuan kg^{-1}, respectively. Transportation, assumed to be delivered 100 km by the tube trailer, costs about 10 yuan kg^{-1} and refueling costs 10 yuan kg^{-1} because of the high price of the equipment at the refueling station. Transportation and refueling account for a larger proportion of the total cost compared with hydrogen production, leading to a high end-use cost of 35–50 yuan kg^{-1}.

From the application perspective, using hydrogen as a transportation fuel is still uneconomical at the current stage.[109] With cost reductions in hydrogen production, transportation, and refueling, and the advancements in FCV technology, hydrogen can be competitive for road transportation in the future.[110,111]

4.2.3. Maintenance Cost

Due to the unexpected defects of fuel cell systems, the current maintenance and repair (M&R) costs of FCVs are relatively high, resulting in a substantially higher total cost of ownership.[112] In addition, the drivetrains of FCVs have similar levels of complexities to those of ICEVs, so the M&R costs are also comparable between the two.[113] Improving the reliability of FCVs could lead to a significant reduction in the M&R cost.

In addition to the technology readiness level, the cost of FCV varies significantly with the production volume. Generally, the cost will decrease when the production scale increases. Scaling up fuel cell manufacturing can effectively reduce the life cycle cost of clean energy, as has been proven by solar photovoltaics in China.[114]

5. Conclusions

Hydrogen presents the possibility for the establishment of a low-carbon society in the future energy landscape with its attribute of zero carbon content. Energy can be stored in the form of hydrogen at a large scale for a long time, overcoming the limitations of current renewable energy storage. Hydrogen can be produced from fossil fuels and RESs and can be used widely in the areas of energy storage, transportation, and chemical industry. Rich in hydrogen supply, China has great potential to form a regional hydrogen society. FCVs are one of the most important applications of hydrogen energy in the transportation sector. Therefore, the development of hydrogen FCVs plays an important role in the development of the hydrogen society.

At present, from a global perspective, many countries have policies to promote the development of hydrogen and FCVs at different supportive levels. Aiming at promoting the commercial application of hydrogen and FCVs, the policies of the Chinese central government are more focused on the supply side rather than the demand side. Guided by the central government, local governments actively respond to national policies with local industry plans, subsidy policies, and FCV demonstration operation projects, which are conducive to the formation of regional hydrogen FCV industry chains. Hydrogen and FCV industrial clusters have taken shape in the Yangtze River Delta, the Pearl River Delta, and the Beijing–Tianjin–Hebei regions in China.

However, it has been difficult to lay a solid foundation for the hydrogen and FCV industries because their industry chains involve many complicated procedures. With the involvement of relevant traditional energy enterprises, China's hydrogen FCV industry chain has taken shape. In terms of fuel cell technologies, China is still far behind foreign rivals and should make greater efforts to tackle technical problems. The commercialization of FCVs in China still faces significant challenges.

Due to their high energy and power densities, fuel cells have superior advantages over battery for medium- and heavy-duty vehicles travelling long distances, and China has established a strategy to form an early-stage FCV market for CVs and then expand to the PV market. The FCV market has developed rapidly in the past two years. With the leading role of the central and local governments, various regional FCV demonstration projects have been initiated in Beijing, Shanghai, Jiangsu, and other cities. It can be seen that the fuel cell CVs have entered the market, starting from transit buses and logistic vehicles, and will gradually extend to applications in heavy-duty CVs.

The deployment of hydrogen and FCVs serves the goal of reducing the dependence on fossil fuels and reducing GHG emissions but whether FCVs can completely solve the energy and environmental issues remains unclear. FCVs can only achieve zero emissions in the usage phase, whereas the life cycle emissions still depend on each country's energy mix. In China, the GHG emission intensity of hydrogen is generally higher than that of fossil fuels such as diesel. Therefore, to ensure the ability of FCVs to save energy and reduce GHG emissions, it is essential to establish a hydrogen energy industry chain based on a clean energy system. From the economic perspective, currently, FCVs cost a lot more than other vehicle technologies. Therefore, reducing the cost of ownership and improving system reliability through technology improvement are prerequisites for the large-scale commercialization of FCVs.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

fuel cell vehicles, hydrogen fuel cells, industry chains

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