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RESEARCH ARTICLE

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Abating transport GHG emissions by hydrogen fuel cell vehicles: Chances for the developing world

Abstract Fuel cell vehicles, as the most promising clean vehicle technology for the future, represent the major chances for the developing world to avoid high-carbon lock-in in the transportation sector. In this paper, by taking China as an example, the unique advantages for China to deploy fuel cell vehicles are reviewed. Subsequently, this paper analyzes the greenhouse gas (GHG) emissions from 19 fuel cell vehicle utilization pathways by using the life cycle assessment approach. The results show that with the current grid mix in China, hydrogen from water electrolysis has the highest GHG emissions, at 3.10 $kgCO_2$/km, while by-product hydrogen from the chlor-alkali industry has the lowest level, at 0.08 $kgCO_2$/km. Regarding hydrogen storage and transportation, a combination of gas-hydrogen road transportation and single compression in the refueling station has the lowest GHG emissions. Regarding vehicle operation, GHG emissions from indirect methanol fuel cell are proved to be lower than those from direct hydrogen fuel cells. It is recommended that although fuel cell vehicles are promising for the developing world in reducing GHG emissions, the vehicle technology and hydrogen production issues should be well addressed to ensure the life-cycle low-carbon performance.

Keywords hydrogen, fuel cell vehicle, life cycle assessment, energy consumption, greenhouse gas (GHG) emissions, China

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1 Introduction

Hydrogen plays an important role in the field of new energies due to its abundant reserves, high heating value, and zero emissions during the usage phase. Fuel cell vehicles (FCVs) are an effective way of reducing greenhouse gas (GHG) emissions, and are one of the most significant applications of hydrogen. It is for these reasons that the technology has received a lot of attention in recent years. Compared to battery electric vehicles (BEVs), FCVs offer definite advantages in terms of driving range and dynamics [1]. Moreover, with their high efficiency, and zero or near zero emissions, FCVs have attracted significant R&D investment from automobile manufacturers. FCVs have developed rapidly since the beginning of their commercialization in 2015. According to China-hydrogen.org[1)], the number of global FCVs (passenger cars only) registered in 2016 rose by 225% year-on-year and accounted for 0.3% of 2016 global sales of new energy passenger cars (774384). Toyota, Hyundai, and Honda are the three main producers of FCVs, which are now experiencing the same development as BEVs in 2009. If FCVs follow the same growth curve as BEVs, more than 100000 a year will be sold by 2019.

However, as a secondary energy, hydrogen has to be made from coal gasification, natural gas reforming, water electrolysis or other methods, the processes of which usually consume energy and electricity. Therefore, even if the FCV has no emissions at the usage phase, from the perspective of the whole life-cycle, GHG emissions from FCVs cannot be overlooked. Only from the perspective of the whole life-cycle can the impact of FCVs on energy and environment be reasonably assessed.

Many studies have been conducted based on the comparison between FCVs and other alternative fuel vehicles, BEVs, and internal combustion engine vehicles (ICEVs). Campanari et al. have studied energy and environmental balances of BEVs and FCVs by using the

1) Global FCV sales increased by 225% in 2016. 2017–4–30, http://www.china-hydrogen.org/fuelcell/mix/2017-02-17/5913.html (in Chinese)

well-to-wheel (WTW) methodology, applied to ECE-EUDC driving cycle simulations. They have concluded that a BEV only achieves its best results for a very limited driving range, while FCVs are better for extended driving ranges where the battery becomes too heavy [2]. Schafer and other researchers have projected energy use and GHG emissions from different FCV configurations and compared these values to the projected characteristics of similarly sized and performing gasoline and diesel fueled automobiles throughout life cycle, suggesting that for the next 20 or more years, new internal combustion engine (ICE) hybrid drive train vehicles can achieve similar levels of reduction in energy use and GHG emissions compared to hydrogen FC vehicles, assuming that the hydrogen is derived from natural gas [3]. Ekdunge and Raberg have analyzed the energy consumption and emissions of FCVs running on different primary fuels, and compared fuel cells with ICEs, finding that in global terms, the ICE consumes less energy whereas the FCV has a lower emissions level [4].

A number of academics have conducted some very helpful research into FCVs. Wang from ANL has evaluated the WTW energy and emissions effects of FCVs using the GREET model. The results show that different fuel-cell fuels can have significantly different energy and greenhouse gas emissions [5]. Some studies focus on a certain part of the life cycle of a FCV. Paster et al. have examined five different hydrogen vehicle storage technologies on a WTW basis by evaluating cost, energy efficiency, greenhouse gas (GHG) emissions, and performance, finding that only the CcH2 (cryo-compresses liquid hydrogen) system can meet the critical 2015 volumetric efficiency target of the Department of Energy (DOE) and achieve an ideal driving range [6].

At present, mass applications of fuel cell technology have not yet started, so many studies conducted to predict the impact of FCV on the energy and environment are based on future scenarios. Felgenhauer et al. have conducted an integrated analysis of a community energy system in various electric vehicle penetration scenarios in the US and Germany, and their findings show that while both BEVs and FCVs can modestly reduce the overall carbon dioxide emissions of the community, the FCV carries higher overall costs, primarily due to the hydrogen generation infrastructure [7,8]. Offer et al. have qualitatively compared BEVs to hydrogen FCVs and hydrogen fuel cell plug-in hybrid vehicles (FCHEV) based on technologies and infrastructural requirements, and conducted a quantitative comparison based on a 2030 scenario of lifecycle costs of the powertrain. The analysis shows that, by 2030, FCVs could achieve lifecycle cost parity with conventional gasoline vehicles. However, both the BEV and FCHEV have significantly lower lifecycle costs, so BEVs are a more cost-efficient choice for reducing CO_2 emissions [9].

Most FCV application scenarios are based on the foreign technology background. Wagner and Eckl [10], Ahmadi and Kjeang [11], and Winter and Weidner [12] have respectively analyzed the life cycle of FCVs in Germany, Canada, North America, and other countries in Europe. However, FCVs have begun to receive increasing attention in China in recent years. Han et al. have predicted that it will be around 2030 when FCVs really become a household name and the total cost of the FCV reaches the same level of the combustion engine based on the popularity and tendency of such cars with international standards of technology [13]. Zhang et al. have proposed a group of factors that may affect customer preferences for FCVs by using a fishbone diagram, field survey, and workshop discussions, and prioritizing them through fuzzy AHP and Pareto analysis. The results indicate that fuel availability, vehicle performance, and economic costs are the most important factors in affecting customer attitudes toward FCVs [14]. Xu et al., from Harbin Institute of Technology, have analyzed a near-term strategy to introduce FCVs and hydrogen stations in Shenzhen, China [15]. Furthermore, some researchers have assessed FCVs in China from the life cycle perspective. Wang et al., from the State Key Laboratory of Engines at Tianjin University, have assessed ICEVs, EVs, and FCVs through a life cycle analysis in terms of energy consumption, carbon emissions, $PM_{2.5}$ and well-to-wheel (WTW) efficiency based on the current (2009) and predicted (2020) situations in China, suggesting that FCVs using hydrogen from NG reforming are suitable for short-term energy conservation and emissions reduction in China, because they are less dependent on the Chinese electricity mix, which is currently dominated by coal-fired energy [16].

China and many other developing countries have great advantages in developing new energy vehicles. Besides, hydrogen fuel cell vehicle is a promising breakthrough. However, it can be seen from the above description that most FCV analyses in the existing studies are based on foreign applications and foreign data. No systematic and specialized life cycle analysis of energy consumption and GHG emissions for hydrogen FCV has yet been conducted in China. The local scenario and data used in this paper to analyze FCV development in China will provide a typical example.

2 Unique advantages for China to deploy FCVs

2.1 Favorable policies

Hydrogen FCVs are the development trend of new energy vehicles. A number of key governmental sectors have introduced policies to support the development of the FCV industry and proposed the corresponding goals. It was as early as 2001 that Chinese government launched the FCV strategic planning. In “863” Special Project for Electric Vehicles, the “Three Verticals and Three Horizontals” strategy was established, of which the three verticals are to develop BEVs, hybrid electric vehicles (HEVs) and FCVs[1)]. The “Made in China 2025” and “Energy Technology Revolutionary Innovation Action Plan (2016 – 2030)” have been compiled these years, proposing the problems that fuel cell technology is to overcome[2)3)]. To achieve the planning goal and overcome the technology problems, fiscal subsidies and tax breaks have been continuously granted to FCVs by the Government of the People’s Republic of China since 2009. Especially in recent years the financial subsidies play an active role in promoting the introduction of FCV into the market with the subsidies for BEVs and HEVs gradually declining and FCVs remaining as high as $32000 for the passenger car. China’s new energy vehicle policy lays a solid foundation for the rapid development of FCV.

2.2 Broad market

China is the largest new energy vehicle market in the world. More than 1 million new energy vehicles had been sold by the end of 2016 in China, making it rank 1st worldwide in terms of the ownership of new energy vehicle. According to EV-sales statistics, in September 2017, a total of 122860 new energy vehicles were sold globally. Divided by region, China sold 58986, accounting for 48.01% of the total, and Europe and the US are 33716 (27.44%) and 21282 (17.32%), from which it can be seen that China’s new energy vehicle market still has a broader development. When commercialization of FCV is ready, China is undoubtedly the most promising market.

Fuel cell passenger car has stricter requirements for fuel cell system integration, hydrogen refueling, and other issues, meanwhile the technical threshold for fuel cell commercial vehicle is comparatively lower and its fixed operation pathway facilitates the infrastructure construction. Therefore, it is widely believed that the fuel cell commercial vehicle is a breakthrough in commercialization of FCV. China takes the lead in world fuel cell bus development. For example, Foton AUV gained 100-unit contract of hydrogen fuel electric buses, becoming the first mass-produced fuel cell commercial vehicle[4)]. As urban population increases, the market for commercial vehicles such as inner-city buses and intercity buses in China is massive. China promises to be the largest fuel cell commercial vehicle market in the future.

2.3 Promising industry chain

Insufficient infrastructure construction is one of the major bottlenecks that limit the development of FCVs. It has been a “chicken-and-egg issue” for at least a couple of decades whether FCV should be developed first or hydrogen refueling station be developed first. FCVs have just entered the commercialization demonstration phase in China; therefore the construction of hydrogen station is still in its infancy. There had been only 6 hydrogen refueling stations in operation by the end of September, 2017 in China, which were located in Beijing, Shanghai, Zhengzhou, Shenzhen, Dalian, and Foshan respectively. It is estimated that by 2020, 2025, and 2030, the number of hydrogen refueling stations in China will reach 100, 350 and 1000 [17]. Since the hydrogen infrastructure has not yet been fully established in China, there is larger space for optimizing its operation mode, business mode and so on. The FCV will, therefore, be more promising if there exists no infrastructure technology lock-in.

Another reason for the failure in large-scale commercialization of the FCV is that the using cost (mainly fuel cost) for customers is too high. Currently, hydrogen is supplied at a price of $9.99/kg in hydrogen refueling stations in California, which is a lot cheaper than before. However, the resulting fuel cost is still 3 to 4 times as much as that of ICEV per 100 km. At present, hydrogen is mainly produced from coal gasification, natural gas reformation, and water electrolysis, whose process is complicated and usually consumes much energy, leading to a high production cost. Exceptionally, industrial by-product hydrogen is the ideal source of hydrogen for vehicle because of its simple purification and low cost. The cost of hydrogen with a purity of 99.99% annually is only $0.2/ Nm^3 (~$1.74/Nm^3) with 25000 Nm^3/h of coke oven gas as raw material [18]. In addition to lower cost, by-product hydrogen requires less energy consumption and GHG emissions during the producing process, showing a great potential for energy and environment, and China has a great advantage in the by-product hydrogen industry with nearly 10 million tons of by-product hydrogen per year, mainly from coke oven gas, ammonia, methanol, and chlor-alkali industries.

1) National Key Research and Development Program of New Energy Vehicle. 2018–02–13, http://www.most.gov.cn/tztg/201502/t20150216_118251.htm
2) Made in China 2025. 2018–02–13, http://www.gov.cn/zhengce/content/2015-05/19/content_9784.htm
3) http://www.nea.gov.cn/2016-06/01/c_135404377.htm
4) Beiqi Foton Motor Co. Ltd. The announcement about the order of 100 Foton AUV Fuel Cell buses. 2018–02–13, http://quotes.money.163.com/f10/ggmx_600166_2489946.html

3 Estimating life cycle GHG emissions from FCVs

3.1 Research framework and definitions

This paper involves the transportation of various fuels. To clearly describe the various subsystems, the fuel is first defined from the perspective of the subsystems.

1) Vehicle fuel: fuel from a refueling station to fill the FCV;

2) Product fuel: fuel transported to the refueling station after factory processing;

3) Feedstock: primary energy processed by a factory.

According to the definitions above, the study framework is shown in Fig. 1.

In the definition of the fuel life cycle, this paper uses the GREET model developed by Argonne National Laboratory, which defines the fuel life cycle as a WTW system. This paper is based on a modified version of the GREET model, which makes use of the local data. In this way, the results will be more in line with the actual situation in China.

As shown in Fig. 1, this paper divides the hydrogen FCV life-cycle system into four subsystems: feedstock processing subsystem, product fuel transporting subsystem, product fuel storing subsystem (refueling station) and vehicle fuel use subsystem (fuel cell vehicle). Focusing on greenhouse gas emissions, the emission gases for this paper include CO_2, CH_4, and N_2O. According to IPCC (Intergovernmental Panel on Climate Change), if the GWP (global warming potential) of CO_2 is 1, the GWP of CH_4 and N_2O are 23 and 296[1)].

Based on the definitions in Fig. 1, for the subsystems used in this paper, the feedstock processing subsystem consists of hydrogen via coal gasification, hydrogen via NG (natural gas) reforming, hydrogen from water electrolysis (The electricity used is relatively from state grid and water), by-product hydrogen from the chlor-alkali industry, methanol via coal and NG production. The product fuel transporting subsystem consists of GH2 (gas hydrogen) transported by tube trailers, LH2 (liquid hydrogen) transported by tank, GH2 transported by pipeline, CNG (compressed natural gas) transported by tank, LNG (liquefied natural gas) transported by tank and methanol transported by tank. The product fuel storing subsystem consists of off-site HRS (hydrogen refueling station), on-site HRS via NG gasification, on-site HRS via water electrolysis, and MRS (methanol refueling station).The vehicle fuel use subsystem consists of DHFCV (direct hydrogen FCV) and IMFCV (indirect methanol FCV). After certain permutations, a total of 19 pathways of hydrogen technology are used in this paper, as listed in Table 1.

The Foton fuel cell city bus BJ6123FCEVCH, running in Yongfeng, Beijing, is selected as the FCV model. Meanwhile, the same sized models of BEV and ICEV are used to compare their energy consumption and GHG emissions with the FCV. To compare the results in a unified form, the fuel life cycle of the two is also divided into four subsystems, in which the feedstock processing subsystem is defined as diesel refining and electricity generation, the product fuel transporting subsystem is defined as diesel transportation and electricity transmission, the product fuel storing subsystem is defined as diesel refueling station and

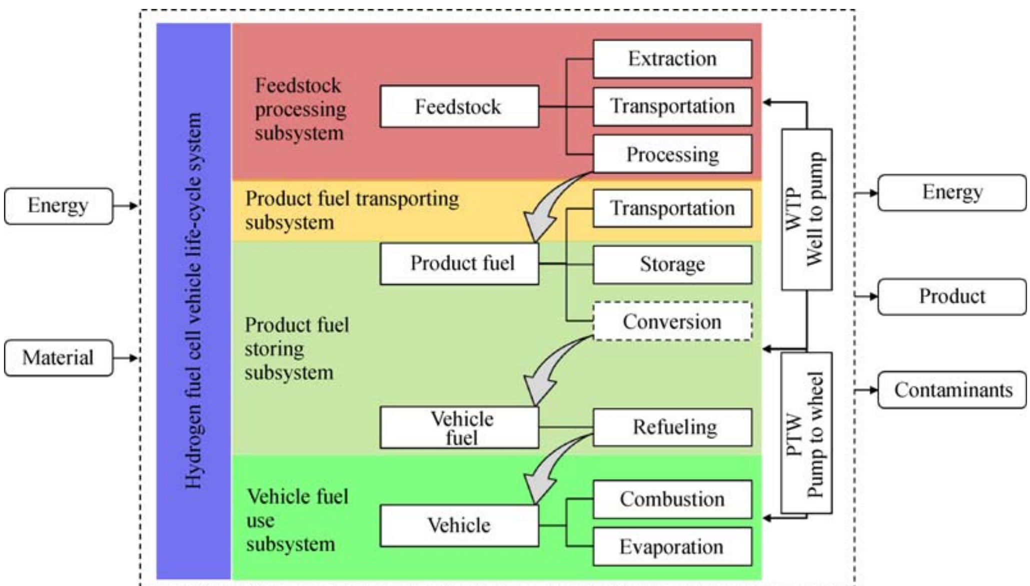

Fig. 1 Study framework

1) Fourth Assessment Report IPCC. Climate Change 2007 (AR4). 2017–04–30, http://www.ipcc.ch/report/ar4/wg1/

Table 1 Technology pathways in this paper

Pathway No.	Feedstock processing	Product fuel transporting	Product fuel storing	Vehicle fuel use
1	Coal gasification	GH2 by tube trailer	Off-site HRS1	DHFCV
2	Coal gasification	LH2 by tank	Off-site HRS2	DHFCV
3	Coal gasification	GH2 by pipeline	Off-site HRS2	DHFCV
4	NG reforming	GH2 by tube trailer	Off-site HRS1	DHFCV
5	NG reforming	LH2 by tank	Off-site HRS2	DHFCV
6	NG reforming	GH2 by pipeline	Off-site HRS2	DHFCV
7	Water electrolysis (State grid electricity)	GH2 by tube trailer	Off-site HRS1	DHFCV
8	Water electrolysis (State grid electricity)	LH2 by tank	Off-site HRS2	DHFCV
9	Water electrolysis (State grid electricity)	GH2 by pipeline	Off-site HRS2	DHFCV
10	Water electrolysis (Water electricity)	GH2 by tube trailer	Off-site HRS1	DHFCV
11	Water electrolysis (Water electricity)	LH2 by tank	Off-site HRS2	DHFCV
12	Water electrolysis (Water electricity)	GH2 by pipeline	Off-site HRS2	DHFCV
13	By-product H2 of chlor-alkali industry	GH2 by tube trailer	Off-site HRS1	DHFCV
14	By-product H2 of chlor-alkali industry	LH2 by tank	Off-site HRS2	DHFCV
15	By-product H2 of chlor-alkali industry	GH2 by pipeline	Off-site HRS2	DHFCV
16	NG production	CNG by tank	On-site HRS via GN gasification	DHFCV
17	NG production	LNG by tank	On-site HRS via GN gasification	DHFCV
18	/	/	On-site HRS via water electrolysis	DHFCV
19	Methanol via coal	Methanol by tank	MRS	IMFCV

charging station, and the vehicle fuel use subsystem is defined as diesel ICE bus and battery electric bus respectively. Since there have been many studies on the diesel ICEV and BEV, and this study is focused on the hydrogen technology pathway, and the data for ICEV and BEV used to calculate the energy consumption and GHG emissions are referred to directly from Ref. [19].

To quantify the impact of fuel on energy and environment, the functional units of "per km of travel" and "per kg of fuel" are used. When "per kg of fuel" is used, it often focuses on the manufacturing process of the fuel, taking into no account of the actual use phase. However, in order to intuitively embody the usage features of the fuel, and facilitate the comparison with other energy-driven vehicles in terms of impact on energy and environment, it is more intuitive and accurate to select "per km of travel." Therefore, the final WTW functional unit of energy consumption and GHG emissions in this study is MJ/km and kg CO_2-eq /km. For computational convenience, in the WTP phase, "per kg of fuel" is used as a functional unit.

3.2 Calculation method

There are two parts in the calculation of GHG emissions: direct emission and indirect emission, as expressed in Eq. (1). Direct emissions are generated by the combustion of primary energy, which can be calculated using the emission factor, as shown in Eq. (2). Indirect carbon emissions are generated from escaping and evaporation from the transportation and storage process in the WTP phase, which can be calculated using the GHG equivalent of the transported fuel, as demonstrated in Eq. (3).

$$Em_{\mathrm{WTP}} = Em_{\mathrm{dir}} + Em_{\mathrm{indir}}, \tag{1}$$

$$Em_{\mathrm{dir}} = \sum\nolimits_p \sum\nolimits_j \sum\nolimits_i EN_{i,p,j} EmF_{i,j}, \tag{2}$$

$$Em_{\mathrm{indir}} = \sum\nolimits_p \sum\nolimits_j \sum\nolimits_i EN_{i,p,j} R_j C_{Q,j}, \tag{3}$$

where i refers to the type of energy, p refers to the process in each sub-system, j refers to the type of fuel produced in the process, $EN_{i,p,j}$ refers to the amount of consumed energy i in the process p to produce fuel j, $EmF_{i,j}$ refers to the emission factor of energy i,R_j refers to the evaporation rate of fuel j, and $C_{Q,j}$ refers to the CO_2 equivalent of fuel j.

3.3 Data localization

Based on Eqs. (2) and (3), the data to be collected for the life cycle energy consumption and GHG emissions of the FCV include the values of electricity, material, energy, GHG emissions factor, evaporation rate input in each step of the fuel production, transportation and storage processes, and the CO_2 equivalent of fuel that will escape during transport and storage. To create the life cycle inventory, a literature review and a factory investigation are used in this study. The commonly seen GHG emissions factors of process energy are tabulated in Table 2, and have all been localized with the data source listed in Table 2.

Since GHG emissions factor of fossil fuels and electricity varies from regions to regions in China, the data from Ref. [20] have been processed to represent the average GHG emissions intensity of fossil fuels in China. As for electricity whose GHG emissions factor is influenced by production and mixture pathways, the uncertainty analysis will be given in Sub-section 4.3.

Because no systematic study has been conducted on the hydrogen life cycle system of FCVs in China, most of the data for fuel production, transportation and storage in this paper are based on the scientific literature of the domestic energy industry, with others obtained through interviews with a fuel cell manufacturer, as listed in Table 3.

4 Results

4.1 Result of hydrogen life cycle system

To compare the life cycle energy consumption and GHG emissions horizontally, the same-sized models of BEV and diesel ICEV are used, as described in Sub-section 2.1. The

Table 2 Commonly seen GHG emissions factors in China

Process energy	Average lower heating value	GHG emissions factor	Data source
Coal	20908 kJ/kg	94.75 g-CO_2/MJ	[20]
Natural gas	38931 kJ/m^3	63.48 g-CO_2/MJ	[20]
Gasoline	43070 kJ/kg	81.98 g-CO_2/MJ	[20]
Diesel	42552 kJ/kg	79.91 g-CO_2/MJ	[20]
Electricity (grid)	—	834.5 g-CO_2/kWh	*

Note: *Chinese Regional Power System GHG emission factors in 2016 (consultation edition). 2017–04–30, http://qhs.ndrc.gov.cn/gzdt/201704/t20170414_844347.html

Table 3 Source of energy consumption/GHG emissions data of the battery manufacturing process

Subsystem		Data source
Feedstock processing subsystem	Hydrogen via coal gasification	[21,22]
	Hydrogen via natural gas reforming	[21,23]
	Hydrogen from water electrolysis	Factory data
	By-product hydrogen of chlor-alkali industry	[22,24]
	Methanol via coal	[25]
	Natural gas production	[21]
Product fuel transporting subsystem	Gas hydrogen transported by tube trailer	①,②
	Liquid hydrogen transported by tank	[26,27]
	Gas hydrogen transported by pipeline	①
	CNG transported by tank	②,③, [28]
	LNG transported by tank	②,④, [29]
	Liquid methanol transported by tank	②,⑤
Product fuel storing subsystem	Off-site hydrogen refueling station	Factory data
	On-site hydrogen refueling station via NG gasification	[23]
	On-site hydrogen refueling station via water electrolysis	Factory data
	Methanol refueling station	⑥
Vehicle fuel use subsystem	Direct hydrogen FCV	Factory data
	Indirect methanol fuel cell station	Factory data

***Notes**: The electricity is supplied by the state grid power (GP) and hydropower (HP).
① CCEN.NET. Hydrogen diaphragm compressor parameters. 2017–06–01, http://www.ccen.net/product/detail-430650.html
② 360CHE.COM. FAW Jiefang tractor JP6 parameters. 2017–06–01, https://product.360che.com/s0/64_66_param.html
③ VW-075/10–250 Natural gas compressor parameters. 2017–06–01, https://detail.1688.com/offer/687576674.html
④ LNG transportation vehicle. 2017–06–01, https://detail.1688.com/offer/522050460833.html?spm = a261b.2187593.1998088710.28.lJcKdH
⑤ Methanol transportation vehicle. 2017–06–01, https://detail.1688.com/offer/522217382826.html?spm = a261b.8768596.0.0.okXIDA&tracelog = p4p
⑥ Ministry of Industry and Information Technology of the People's Republic of China. MIIT Notice on Code for construction of methanol refueling station and Code for safety operation of methanol. 2017–06–01, http://www.miit.gov.cn/n1146295/n1652858/n1652930/n3757016/c4376749/content.html

diesel production/transportation process and the electricity production/transportation directly refer to the data in Ref. [19]; the energy consumption of the diesel filling process is approximately 0; and the charging efficiency is 90% (referring to data in Ref. [30]), with a loss of 10%. Therefore, the production, transmission, and charging process for electricity are classified as the feedstock processing subsystem, product fuel transporting subsystem and product fuel storing subsystem. The total energy consumption and GHG emissions of each technical pathway are displayed in Figs. 2 and 3 and listed in Tables 4 and 5.

4.2 Results of subsystem

4.2.1 Results of vehicle fuel use subsystem

Figure 4 shows the energy consumption and GHG emissions per 100 km of two types of FCVs, indirect methanol FCVs (IMFCV) and direct hydrogen FCVs (DHFCV), during the usage phase. As a result of hydrogen production from methanol, the GHG emissions and energy consumption of IMFCV are higher than those of DHFCV.

4.2.2 Results of product fuel storing subsystem

Figure 5 exhibits the energy consumption and GHG emissions for the five product fuel storing subsystems, where the off-site hydrogen refueling station (HRS)-1 refers to the station mode for gas hydrogen by trailer transportation (only requiring the second stage of compression), while the off-site HRS-2 refers to the station mode for gas hydrogen by pipeline (requiring two stages of compression). The two kinds of on-site stations energy consumption and GHG emissions are higher due to the hydrogen production process, of which the water electrolysis results in a higher energy consumption and GHG emissions due to electricity consumption. As for the methanol refueling station (MRS), the energy consumption only takes place at the time of filling, which is so low that the energy consumption and GHG emissions can be ignored.

4.2.3 Results of product fuel transportation subsystem

The energy consumption and GHG emissions for the product fuel transporting subsystem are depicted in Fig. 6. The results of the pipeline transportation are the lowest of the three modes of hydrogen transportation, but this result is based on large-scale hydrogen transportation, of which the energy and materials are consumed during the construction stage. Besides, regardless of the high construction costs and regional restrictions on the hydrogen pipeline network, this study only focuses on the transportation process. Therefore, the energy consumption and GHG emissions have the lowest values. For the two transportation types of natural gas (NG), compressed natural gas (CNG) by tank, due to the large capacity and less compression work of the tank, has a far lower energy consumption and GHG emissions rate than liquid natural

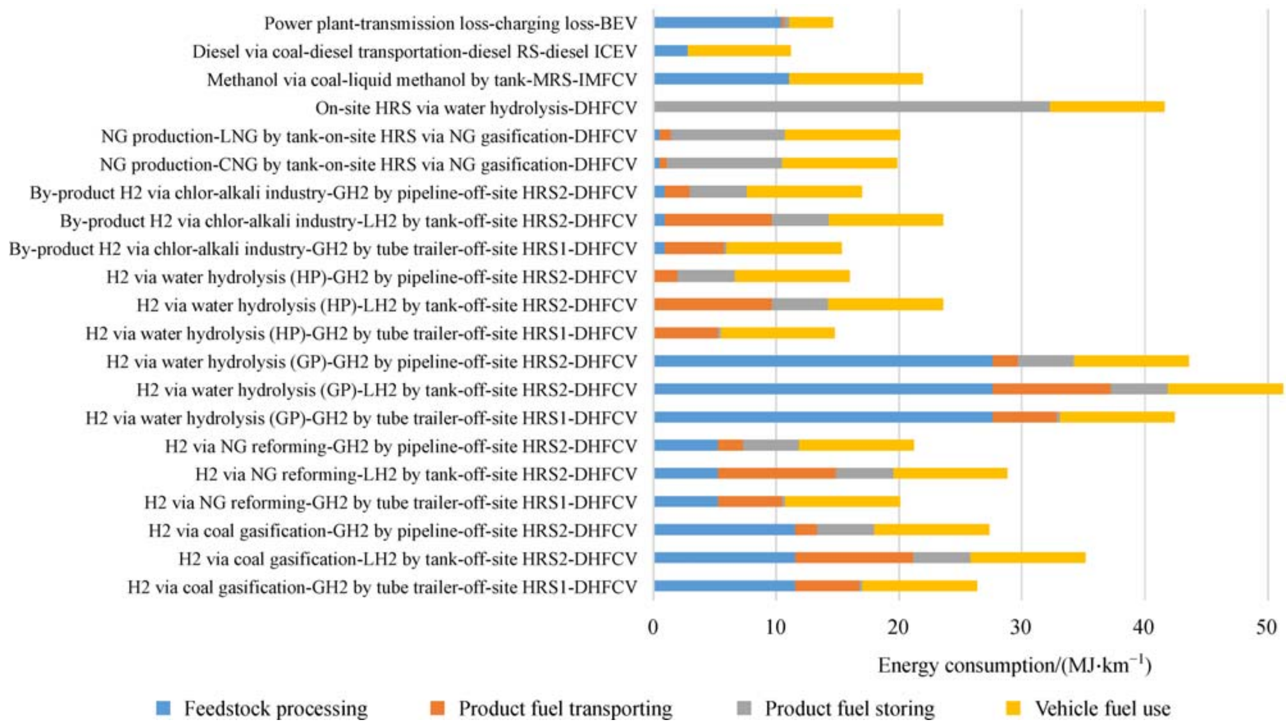

Fig. 2 Energy consumption of each technology pathway

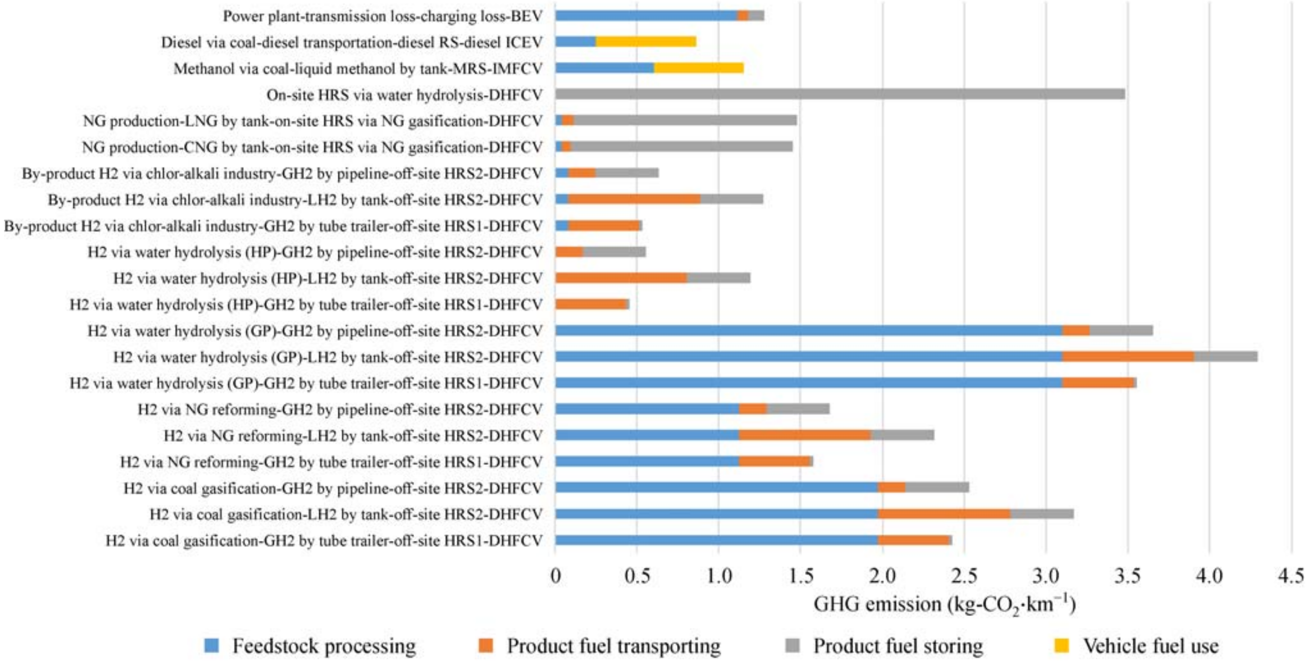

Fig. 3 GHG emissions of each technology pathway

gas (LNG) for the same gas demands. As a kind of liquid fuel, no compression process is required during transportation. Therefore, due to its large transporting capacity and zero compression energy consumption, the results for methanol are the lowest.

4.2.4 Results of feedstock processing subsystem

The energy consumption and GHG emissions of the feedstock processing subsystem are plotted in Fig. 7. Because no hydrogen is generated when natural gas and methanol are produced by coal, these two methods are not discussed here. In the four methods of direct acquisition of hydrogen, the methods of energy consumption and GHG emissions from the highest to the lowest are water electrolysis (GP), natural gas reforming, coal gasification, by-product hydrogen from the chlor-alkali industry, and water electrolysis (HP). It is worth noting that the energy consumption and GHG emissions of natural gas reforming are lower than those of coal gasification.

4.3 Uncertainty analysis

As can be concluded from the above analysis, the greatest factor in the final energy consumption and GHG emissions is electricity. In the analysis above, when the electricity is taken from the national grid, which has low power generation efficiency and high carbon content, the final energy consumption and GHG emissions of water electrolysis subsystem are relatively high; however, when water electricity is used, the water electrolysis subsystem has the least energy consumption and GHG emissions. Therefore, where electricity is involved, the energy consumption and GHG emissions of the subsystem can vary considerably.

According to the electricity generation structure in China from 1990 to 2014 [31], it can be seen that in recent years, thermal electricity and water electricity has played a big part, with thermal electricity accounting for 80% and water electricity for 20% or so. Thermal electricity mainly comes from coal-fired power plants; therefore, in the following analysis it is assumed that the electricity is a mixture of water electricity and coal-electricity, to be able to compare energy consumption and GHG emissions between BEV, ICEV, and FCV using several different pathways, with an increase in the proportion of water electricity. The selected FCV technology pathways are pathway 1 (coal gasification → GH2 by tube trailer → off-site HRS1 → DHFCV), pathway 4 (NG reforming → GH2 by tube trailer → off-site HRS1 → DHFCV), pathway 7 (water electrolysis → GH2 by tube trailer → off-site HRS1 → DHFCV) and pathway 15 (on-site HRS via water electrolysis → DHFCV) from Table 3.

According to the "Situation of China's electricity industry in 2014," the comprehensive average coal-electricity generation efficiency is 38.6%, and net coal consumption rate is 318 g/kWh[1]. According to Ref. [20],

1) China Electricity Council. Annual Statistics of China Power Industry 2014. 2017–06–09, http://www.cec.org.cn/guihuayutongji/gongxufenxi/dianliyunxingjiankuang/2015-02-02/133565.html

Table 4 Energy consumption of each technology pathway (Unit: MJ/km)

Technical routes	Subsystems			
	Feedstock processing	Product fuel transporting	Product fuel storing	Vehicle fuel use
H2 via coal gasification-GH2 by tube trailer-off-site HRS1-DHFCV	11.5265	5.2212	0.2321	9.3746
H2 via coal gasification-LH2 by Tank-off-site HRS2-DHFCV	11.5265	9.6198	4.6295	9.3746
H2 via coal gasification-GH2 by pipeline-off-site HRS2-DHFCV	11.5265	1.8168	4.6295	9.3746
H2 via NG reforming-GH2 by tube trailer-off-site HRS1-DHFCV	5.2366	5.2212	0.2321	9.3746
H2 via NG reforming-LH2 by tank-off-site HRS2-DHFCV	5.2366	9.6198	4.6295	9.3746
H2 via NG reforming-GH2 by pipeline-off-site HRS2-DHFCV	5.2366	2.0106	4.6295	9.3746
H2 via water electrolysis (G-Ele)-GH2 by tube Trailer-off-site HRS1-DHFCV	27.6008	5.2212	0.2321	9.3746
H2 via water electrolysis (G-Ele)-LH2 by tank-off-site HRS2-DHFCV	27.6008	9.6198	4.6295	9.3746
H2 via water electrolysis (G-Ele)-GH2 by pipeline-off-site HRS2-DHFCV	27.6008	2.0106	4.6295	9.3746
H2 via water electrolysis (W-Ele)-GH2 by tube trailer-off-site HRS1-DHFCV	0	5.2212	0.2321	9.3746
H2 via water electrolysis (W-Ele)-LH2 by tank-off-site HRS2-DHFCV	0	9.6198	4.6295	9.3746
H2 via water electrolysis (W-Ele)-GH2 by pipeline-off-site HRS2-DHFCV	0	2.0106	4.6295	9.3746
By-product H2 via chlor-alkali industry-GH2 by tube trailer-off-site HRS1-DHFCV	0.9411	4.8074	0.2321	9.3746
By-product H2 via chlor-alkali industry-LH2 by tank-off-site HRS2-DHFCV	0.9411	8.6937	4.6295	9.3746
By-product H2 via chlor-alkali industry-GH2 by pipeline-off-site HRS2-DHFCV	0.9411	2.0106	4.6295	9.3746
NG production-CNG by Tank-on-site HRS via NG gasification-DHFCV	0.5058	0.6164	9.36	9.3746
NG production-LNG by tank-on-site HRS via NG gasification-DHFCV	0.5058	0.874	9.36	9.3746
On-site HRS via water electrolysis-DHFCV	0	0	32.23	9.3746
Methanol via coal-liquid methanol by tank-MRS-IMFCV	11.0493	0.002	0	10.8942
Diesel via coal-diesel transportation-diesel RS-diesel ICEV	2.771922384	0.02688588	0	8.3997648
Power plant-transmission loss-charging loss-BEV	10.34652406	0.278074866	0.427807487	3.6

the average lower heating value of coal in China is 20908 kJ/kg, and the GHG emission factor is 94.75 g CO_2-eq. The emission factor of coal-electricity is, therefore, 883.68 g CO_2-eq. There are still a number of disputes and questions on whether water electricity is a clean energy source, since the energy consumption and GHG emissions of water electricity come mainly from the associated infrastructure construction. However, in this study, infrastructure construction and investment are excluded from the system; therefore, the energy consumption and GHG emissions of water electricity can be taken as approximately zero.

The change in energy consumption and GHG emissions at different coal-electricity proportions are presented in Figs. 8 and 9. Diesel ICEV is almost immune to electricity; therefore, it is used as a reference value.

Compared with diesel ICEVs, FCVs with the hydrogen produced from fossil fuels require higher energy consumption and GHG emissions no matter what the proportion of coal-electricity is. Therefore, if the technology for hydrogen production from fossil fuels does not make significant advances in terms energy saving, this kind of FCV will have a significant negative impact on the energy required and on the environment. The energy consumption and GHG emissions of FCVs using the hydrogen produced from water is comparable to those of

Table 5 GHG emissions of each technology pathway (Unit: kg-CO_2/km)

Technical routes	Subsystems			
	Feedstock processing	Product fuel transporting	Product fuel storing	Vehicle fuel use
H2 via coal gasification-GH2 by tube trailer-off-site HRS1-DHFCV	1.9734	0.4343	0.0194	0
H2 via coal gasification-LH2 by tank-off-site HRS2-DHFCV	1.9734	0.806	0.3879	0
H2 via coal gasification-GH2 by pipeline-off-site HRS2-DHFCV	1.9734	0.1685	0.3879	0
H2 via NG reforming-GH2 by tube trailer-off-site HRS1-DHFCV	1.1234	0.4343	0.0194	0
H2 via NG reforming-LH2 by tank-off-site HRS2-DHFCV	1.1234	0.806	0.3879	0
H2 via NG reforming-GH2 by pipeline-off-site HRS2-DHFCV	1.1234	0.1685	0.3879	0
H2 via water electrolysis (G-Ele)-GH2 by tube trailer-off-site HRS1-DHFCV	3.098	0.4343	0.0194	0
H2 via water electrolysis (G-Ele)-LH2 by tank-off-site HRS2-DHFCV	3.098	0.806	0.3879	0
H2 via water electrolysis (G-Ele)-GH2 by pipeline-off-site HRS2-DHFCV	3.098	0.1685	0.3879	0
H2 via water electrolysis (W-Ele)-GH2 by tube trailer-off-site HRS1-DHFCV	0	0.4343	0.0194	0
H2 via water electrolysis(W-Ele)-LH2 by tank-off-site HRS2-DHFCV	0	0.806	0.3879	0
H2 via water electrolysis(W-Ele)-GH2 by pipeline-off-site HRS2-DHFCV	0	0.1685	0.3879	0
By-product H2 via chlor-alkali industry-GH2 by tube trailer-off-site HRS1-DHFCV	0.0789	0.4351	0.0194	0
By-product H2 via chlor-alkali industry-LH2 by tank-off-site HRS2-DHFCV	0.0789	0.806	0.3879	0
By-product H2 via chlor-alkali industry-GH2 by pipeline-off-site HRS2-DHFCV	0.0789	0.1685	0.3879	0
NG production-CNG by tank-on-site HRS via NG gasification-DHFCV	0.0427	0.0517	1.3609	0
NG production-LNG by tank-on-site HRS via NG gasification-DHFCV	0.0427	0.0731	1.3609	0
On-site HRS via water electrolysis-DHFCV	0	0	3.4859	0
Methanol via coal-liquid methanol by tank-MRS-IMFCV	0.6067	0.00015	0	0.546
Diesel via coal-diesel transportation-diesel RS-diesel ICEV	0.2507	0.0022	0	0.6106
Power plant-transmission loss-charging loss-BEV	1.1151	0.0645	0.0992	0

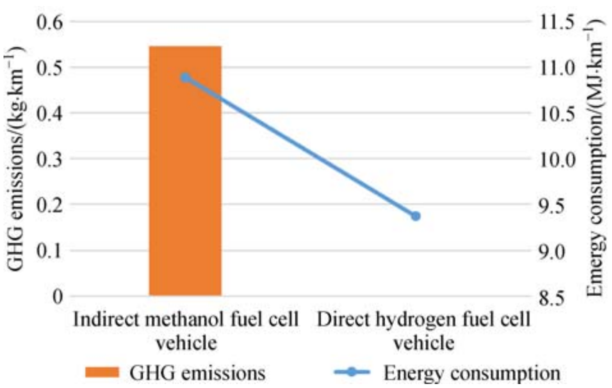

Fig. 4 Energy consumption and GHG emissions of vehicle fuel use subsystem

diesel ICEVs when the proportion of coal-electricity is about 20%.

Compared with BEVs, the energy consumption and GHG emissions of FCVs are always higher. For the hydrogen produced from fossil fuels, a lot of the fossil energy is consumed during the production process, in addition to electricity. For the hydrogen produced from water, the electrolysis process consumes much more energy. In addition to this, the hydrogen consumption of FCVs is high when using the currently available technology. Therefore, unless there are any major breakthroughs in water electrolysis technology, the development of FCVs will have no positive impact on the energy required or on the environment.

5 Discussion

As can be seen from the results in Figs. 2 and 3, most hydrogen FCVs do not have any advantages in terms of energy consumption and carbon emissions when compared to conventional diesel and BEVs. This is especially true for hydrogen produced by water electrolysis, for which the energy consumed and GHG emissions produced are much higher than those using other technology pathways. Below is the subsystem technology pathway analysis.

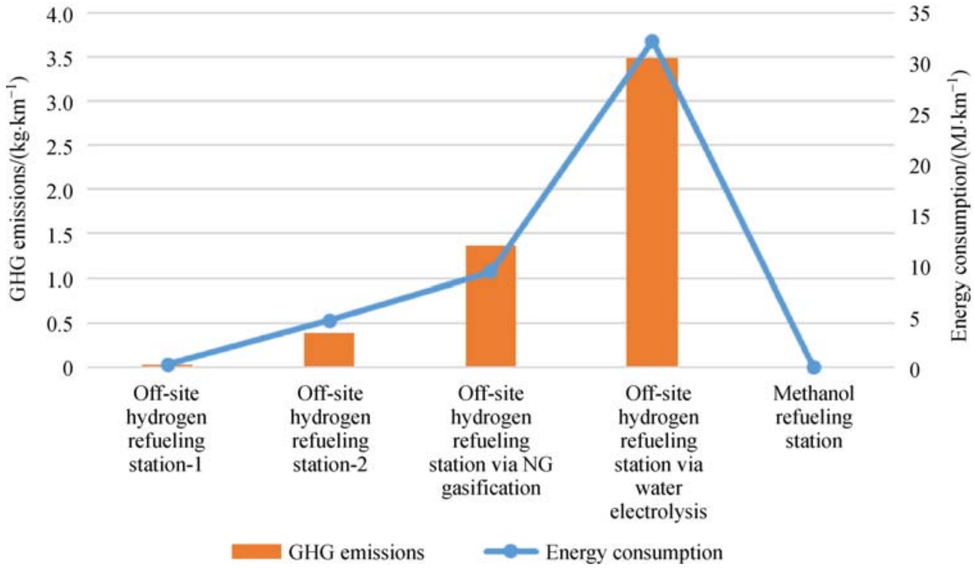

Fig. 5 Energy consumption and GHG emissions of product fuel storing subsystem

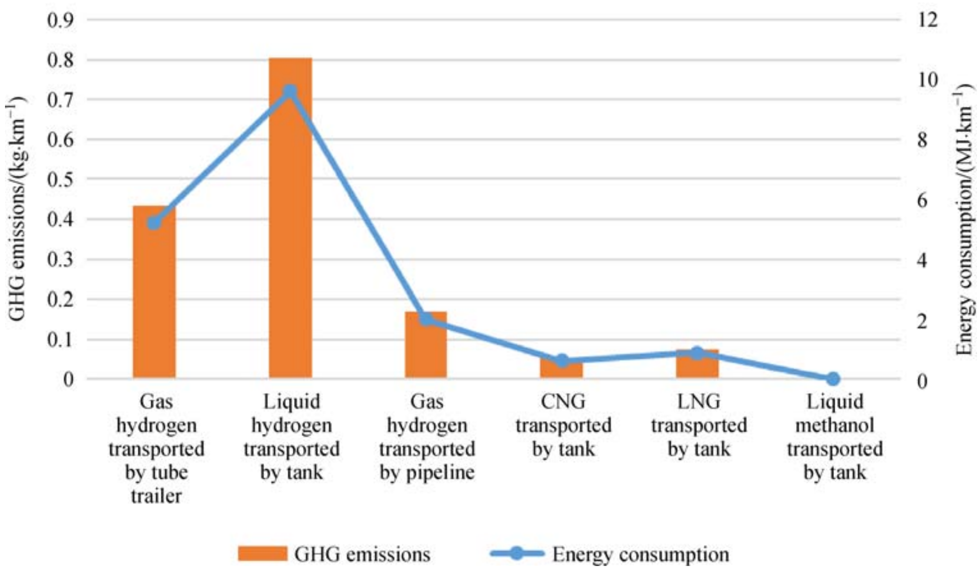

Fig. 6 Energy consumption and GHG emissions of the product fuel transporting subsystem

5.1 Comparative studies

Different fuel economy data are used in each existing study; therefore, the fuel economy data in existing studies whose hydrogen consumption differ considerably are replaced by the data used in this study (6.57 kg/100 km). A comparison is made in Figs. 10 and 11.

Figure 10 shows the comparison of NG-based hydrogen technology pathways, that is, the hydrogen is produced from natural gas reforming. The results of Ou et al. [32] and of Dong et al. [33] are the results for China, while that of Ballard[1)] is for Europe and that of Argonne[2)] is for the US. It can be concluded that the GHG emission intensity of NG-based hydrogen is higher in China than that in Europe and the US. The GHG emissions can be decreased by the improvement of hydrogen production efficiency and vehicle efficiency.

1) Ballard Power Systems Incorporated. Fuel cell electric buses: an attractive value proposition for zero-emission buses in the United Kingdom. 2016, https://www.fuelcellbuses.eu/public-transport-hydrogen/fcebs-attractive-value-proposition-zero-emission-buses-united-kingdom

2) Amgad E. GREET life-cycle analysis model. Department of Energy, US. 2016, https://www.hydrogen.energy.gov/pdfs/review16/sa057_elgowainy_2016_o.pdf

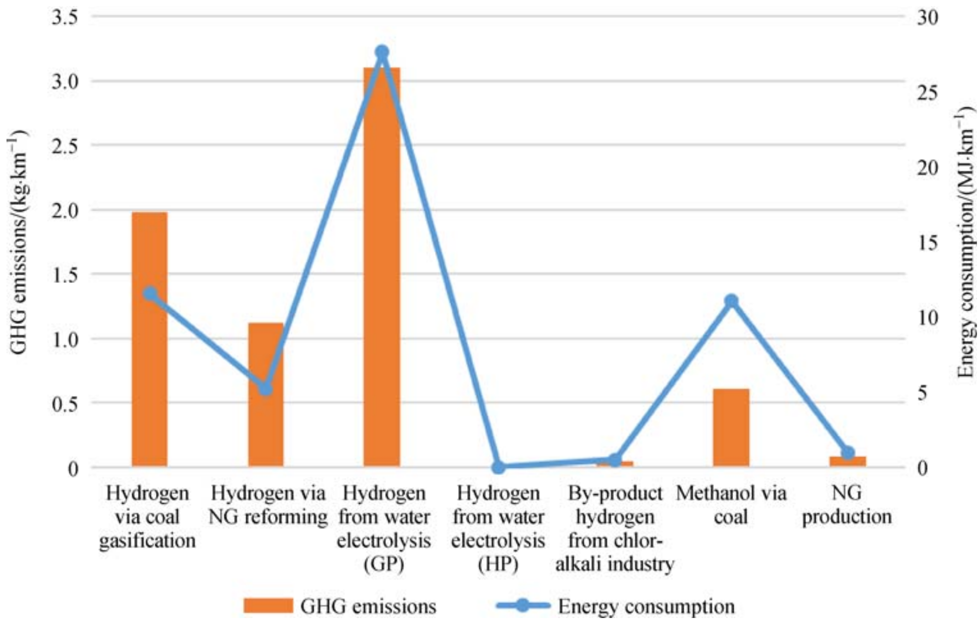

Fig. 7 Energy consumption and GHG emissions of the feedstock processing subsystem

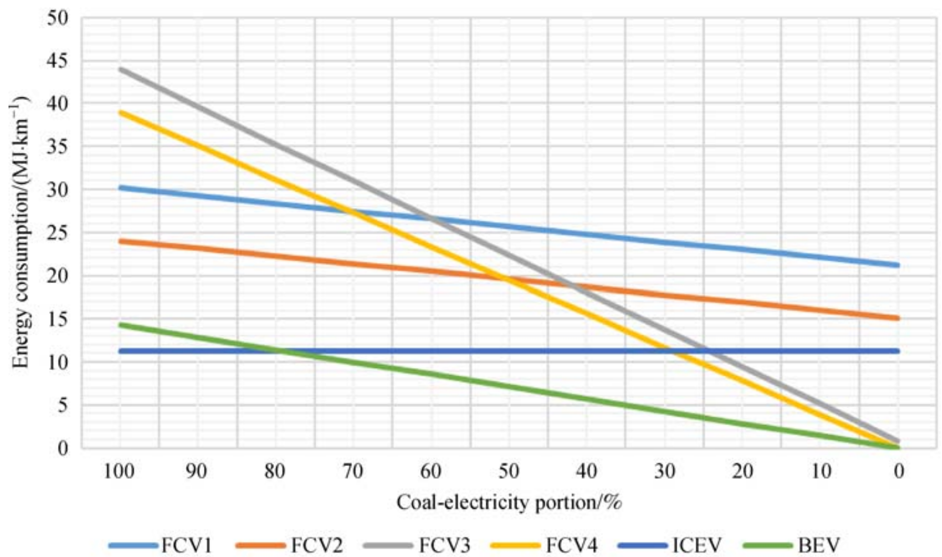

Fig. 8 Change of energy consumption in China at different coal-electricity proportions

Figure 10 is a comparison of water based hydrogen technology pathways, that is, the hydrogen is produced from water electrolysis. The existing study is from Ballard[1)] in Europe. Figure 10 indicates that the result of GHG emission for China is among the worst in the world.

5.2 Life cycle analysis

The results suggest that during the hydrogen production process, water electrolysis requires the highest energy consumption and GHG emissions, while the by-product hydrogen from chlor-alkali industry requires the lowest. The GHG emissions of the former are about 17 times that of the latter, which is largely due to the high GHG emissions factor for electricity generated in China. During the hydrogen transportation process, the hydrogen transported by pipeline has the lowest energy consumption and GHG emissions, while liquid hydrogen transported by tank

1) Ballard Power Systems Incorporated. Fuel cell electric buses: an attractive value proposition for zero-emission buses in the United Kingdom. 2016, https://www.fuelcellbuses.eu/public-transport-hydrogen/fcebs-attractive-value-proposition-zero-emission-buses-united-kingdom

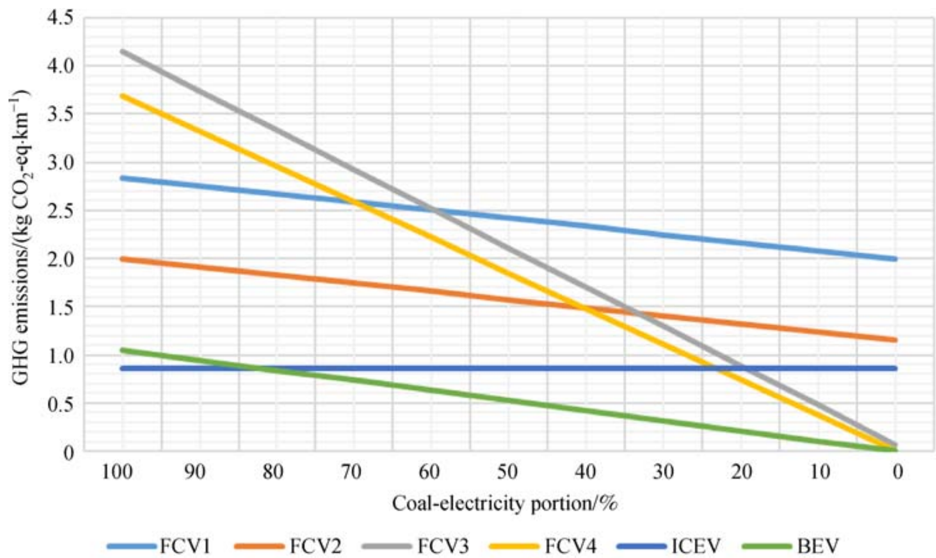

Fig. 9 Change of GHG emissions in China at different coal-electricity proportions

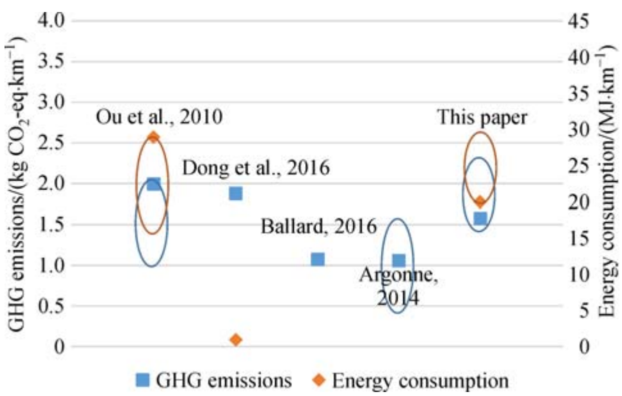

Fig. 10 Comparison of existing NG-based studies

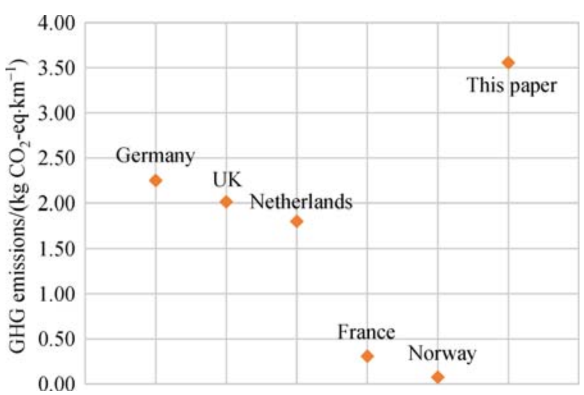

Fig. 11 Comparison of existing water-based studies

has the highest. However, since the laying of these pipelines also requires consideration of cost, safety, technique, and other issues, the development of hydrogen pipelines still needs to be further discussed. When taking hydrogen transportation and storage as a whole, the combination of gas hydrogen transported by tube trailer and off-site hydrogen refueling station is found to be the best. For the vehicle fuel use subsystem, although the production of hydrogen from methanol onboard has energy consumption and GHG emissions at this stage, from the perspective of the entire life cycle, its value is the lowest.

In terms of energy consumption and GHG emissions, most of the technology pathways for FCV (except by-product hydrogen from chlor-alkali industry) have no advantages when compared to the traditional diesel ICEV and BEV.

5.3 Vehicle fuel use technology pathways

The comparison of energy consumption and GHG emissions above indicates that the impact of indirect methanol FCV on energy consumption and on the environment is not as negative as that of direct hydrogen FCVs.

In the feedstock processing subsystem, the methanol made from coal consumes less energy than the other two methods of hydrogen production via fossil fuel; therefore, its GHG emissions are also lower. In the product fuel transporting and storing subsystem, methanol consumes significantly less than hydrogen. In the vehicle fuel use subsystem, though indirect methanol FCVs require hydrogen production process, with the optimized method of hydrogen production, its energy consumption and GHG emissions are much lower than the accumulated results of the other three.

5.4 Product fuel transportation and storage technology pathways

In this study, the technology selected for the product fuel storing subsystem is strongly related to the feedstock processing subsystem and the product fuel transporting subsystem. As such, the product fuel transporting subsystem will be discussed in combination with the product fuel storing subsystem.

For an off-site hydrogen refueling station: in terms of the comparison of energy consumption and GHG emissions between different technologies, when hydrogen is transported in its liquid or gas state by pipeline, the corresponding refueling station needs to compress it in two stages, and this compression process consumes a large amount of electricity. It is true that the process of hydrogen transportation by pipeline consumes less energy and emits less GHG compared with the other two transportation methods, but when the transportation and storage are seen as a whole, the combination of GH2 transported by pipeline and HRS with two-stage compression has the highest energy consumption and GHG emissions. So, in the end, the combination of GH2 transported by tube trailer and off-site HRS with one-stage compression gives the lowest result.

For off-site HRS and on-site HRS: the hydrogen from off-site HRS is made centrally at a plant and transported to the refueling station, whereas the hydrogen from on-site HRS is made at a refueling station and stored locally without transportation. On-site HRS is better than off-site HRS if only the energy and environmental impacts are considered, because under the assumptions made in this study, the two types of hydrogen production consume the same energy and emit equal amounts of GHG.

5.5 Feedstock processing technology pathways

For the hydrogen produced centrally at a plant, it can be observed that the water electrolysis has the highest energy consumption requirements and GHG emissions. The reason for this is that most of the power in China is generated by thermal electricity stations, which have a high energy consumption and low efficiency. The hydrogen made from water has more energy consumption and GHG emissions than that made from fossil fuels. The energy consumption and GHG emissions of by-product hydrogen from the chlor-alkali industry are the lowest, since the hydrogen is a by-product of the alkali and chlorine, whose energy consumption and GHG emissions are only one part of the entire process.

6 Conclusions and policy implications

This paper focuses on the energy consumption and GHG emissions of FCVs and analyzes 19 hydrogen technology pathways, showing that based on the current state of the technology, there is no compelling reason for China to develop FCVs, since in actual fact it will bring higher energy consumption and GHG emissions.

In a certain period of time, hydrogen will still be produced mainly from fossil fuels, during the production process of which the acquisition of by-products (such as tar, naphtha, etc.) will share energy consumption and carbon emissions. Therefore, in addition to improving the technical level to decrease the overall energy consumption, it is also advisable to develop such technology to acquire by-product. Water electrolysis is relatively mature since it has been applied in some of hydrogen refueling stations in China. Still, its energy consumption and GHG emissions depend on the grid mix; therefore, it is imperative that the grid mix of China be improved. Besides, transporting hydrogen by pipeline is the best way in the fuel transport subsystem; therefore, it is advised for the government to plan ahead to promote the laying of hydrogen transportation pipelines considering the future development of FCVs. In summary, if FCVs are to be developed in China, the issues of hydrogen production, hydrogen storage, and hydrogen consumption for FCVs must first be overcome. The development of FCVs in China still has a long way to go.

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