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The impact of fuel cell vehicle deployment on road transport greenhouse gas emissions: The China case

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ABSTRACT

Considerable attention has been paid to energy security and climate problems caused by road vehicle fleets. Fuel cell vehicles provide a new solution for reducing energy consumption and greenhouse gas emissions, especially those from heavy-duty trucks. Although cost may become the key issue in fuel cell vehicle development, with technological improvements and cleaner pathways for hydrogen production, fuel cell vehicles will exhibit great potential of cost reduction. In accordance with the industrial plan in China, this study introduces five scenarios to evaluate the impact of fuel cell vehicles on the road vehicle fleet greenhouse gas emissions in China. Under the most optimistic scenario, greenhouse gas emissions generated by the whole fleet will decrease by 13.9% compared with the emissions in a scenario with no fuel cell vehicles, and heavy-duty truck greenhouse gas emissions will decrease by nearly one-fifth. Greenhouse gas emissions intensity of hydrogen production will play an essential role when fuel cell vehicles' fuel cycle greenhouse gas emissions are calculated; therefore, hydrogen production pathways will be critical in the future.

Introduction

Background

The problems of energy security and climate change have drawn increasing attention worldwide. According to the International Energy Agency (IEA), though global energy demand growth is projected to slow until 2040, the total energy need will increase by 30% and will be equivalent to adding another China and India to today's energy demand [1]. Growing electrification will shift the energy mix to cleaner energy, and renewable energy and nuclear energy will play important roles in the future energy structure. Both developed and developing countries have made strides towards improving energy efficiency and promoting the development of alternative energy resources.

The transportation sector, as a main energy consumer and source of greenhouse gas (GHG) emissions, is a concern for sustainable development. In 2015, the transport sector accounted for approximately 24% of worldwide CO_2 emissions from fuel combustion [2]. Rapid technological development of

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List of acronyms

BEV	Battery electric vehicle
CATARC	China Automotive Technology & Research Center
CCS	Carbon capture and storage
CNG	Compressed natural gas
DOE	the Department of Energy
EV	Electric vehicle
FCV	Fuel cell vehicle
FTA	Federal Transit Administration
GHG	Greenhouse gas
HDB	Heavy-duty bus
HDT	Heavy-duty truck
ICE	Internal combustion engine
iCET	Innovation Center for Energy and Transportation
IEA	International Energy Agency
LDB	Light-duty bus
LDT	Light-duty truck
LNG	Liquefied natural gas
MDB	Medium-duty bus
MDT	Medium-duty truck
MT	Mini truck
NREL	National Renewable Energy Laboratory
PHEV	Plug-in hybrid electric vehicle
PV	Passenger vehicle
SMR	Steam methane reforming

alternative powertrains has generated great interest, and many countries have begun to introduce regulations or subsidy mechanisms to advocate for alternative fuel vehicles [3–6]. The electrification of automotive powertrains provides an effective pathway to reduce road transport sector CO_2 emissions through clean power systems [7–9].

In China, transport CO_2 emissions in 2015 were 612 kg/capita, which is much lower than the world average, 1055 kg/capita [2]. Because the road transport subsector accounts for most CO_2 emissions in the transport sector, the results indicate that there is great potential for China's automotive market. During the ‘2015 United Nations Climate Change Conference’, the Chinese government pledged that CO_2 emissions in China would peak before 2030 [10]. Correspondingly, a series of policies have been issued in the past few years to accelerate the development of alternative fuel vehicles in China, including both credit regulations and financial subsidies [3,11,12]. While most recent studies have focused on the deployment of electric vehicles (battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs)), these studies ignore the impact of fuel cell vehicles (FCVs) on greenhouse gas emissions reduction.

Advantages and disadvantages of FCVs

Compared with other powertrain vehicles, FCVs have unique strengths and weaknesses, as shown in Table 1. Importantly, unlike electricity production, the production of hydrogen can provide a solution to the waste of renewable energy power.

Table 1 – The strengths and weaknesses of FCV/hydrogen development [13–18].

Strengths	Weaknesses
• Abundant resource reserves and sustainable supply • Production using any energy sources, including renewable energy • Localization of fuel production • High energy content on a mass basis • Great development potential • Reduction of harmful emissions– emits only water • Convenient and fast refueling • Non-toxic emissions • Safe	• Low energy content by volume • High cost • Lacking key technologies: hydrogen storage, distribution, etc. • Incomplete hydrogen infrastructure

Vehicle models and demonstrations

Due to the advantages of using hydrogen and FCVs, many automakers have begun introducing fuel cell passenger vehicles, and some countries have launched pilot projects using fuel cell city buses. Fig. 1 summarizes the development of fuel cell passenger vehicles by different automakers from different countries, including Germany, the U.S., Japan, Korea, the U.K. and China. Especially since 2010, fuel cell passenger vehicle models have been increasingly released. The Mirai, the FCV manufactured by Toyota, has already been mass-produced in Japan and the U.S [19].

Some governments worldwide are actively promoting the development of FCVs, mainly by introducing fuel cell bus pilots, as shown in Fig. 2. In the U.S., the Department of Energy (DOE) and Federal Transit Administration (FTA) have provided funding to the National Renewable Energy Laboratory (NREL) to evaluate the performance of fuel cell transit buses since 2006 [20,21]. The scale of the test fleet is expanding gradually, and demonstrations are located in increasingly more cities in the U.S. Fuel cell transit bus services are operated by various bus operators, such as Zero Emission Bay Area, Connecticut Transit, etc. The collected data are used to inform next-generation vehicle research to improve the reliability and durability of FCVs. Several demonstration projects were also adopted in the EU, including NextHyLights, CHIC, HyTransit, High V.LO-City, etc. Future plans have been made for the next generation based on the collected data [22–29]. Additional demonstrations have occurred in China. In 2008, during the Beijing Olympics Games, 20 fuel cell passenger vehicles provided by Shanghai-Volkswagen served as public cars and 3 fuel cell buses provided by Beiqi Foton Motor Co., Ltd. and Tsinghua University served as city buses [30]. More FCVs, including 196 fuel cell passenger vehicles, 100 fuel cell sightseeing buses and 6 fuel cell city buses, were used for the Shanghai World Expo [31]. In addition, the Guangzhou Asian Games and Shenzhen Universiade both introduced fuel cell sightseeing buses or transit buses during the events.

Policies and plans of FCVs in China

In addition to demonstrations, to promote the FCV development, both the state government and local governments in

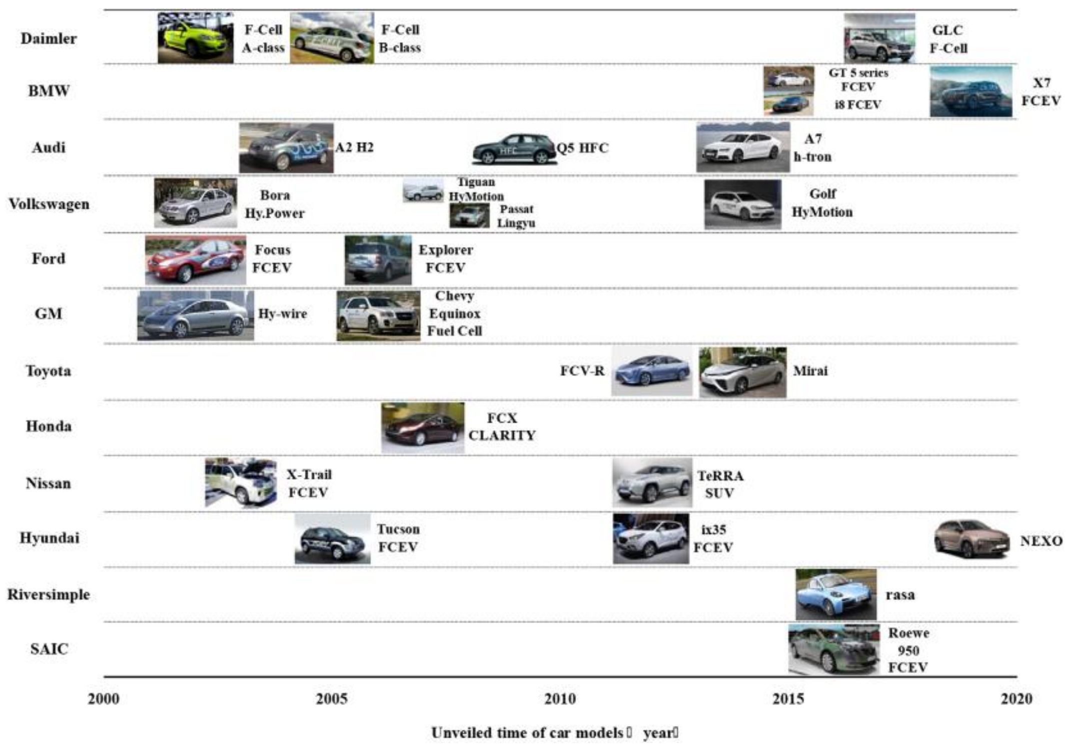


Fig. 1 — Fuel cell passenger vehicle models released by different automakers. Source: online.

Fig. 2 — The distribution of fuel cell bus demonstrations throughout the world. Some FCVs from demonstrations are still in active service, while other projects have already concluded.

Table 2 – Incentives and plans in China for FCVs [32–40].

Incentive policies	Plans
Interim Measures for the Management of Financial Support Funds for Energy-saving and New Energy Vehicle Demonstration and Promotion (2009.02) ✓ Subsidy: 250,000 RMB (≈36387 USD) for each passenger vehicle and 600,000 RMB (≈87330 USD) for each bus in the demonstrations	**Made in China 2025 (2015.05)** ✓ 1000 FCVs in operation in 2020 ✓ The supporting infrastructure, such as hydrogen production and refueling station will be basically complete in 2025 ✓ Small-scale operation in specific regions
Notice on New Energy Vehicles Charging Infrastructure Award (2014.11) ✓ Subsidy: 4 million RMB (≈582199 USD) for each new hydrogen refueling station	**Blue Book on the Development of Infrastructure in China's Hydrogen Industry (2016) (2016.10)** ✓ 100 hydrogen refueling stations and 10,000 FCVs in use in 2020 ✓ 1000 hydrogen refueling stations and 2 million FCVs in use in 2030 ✓ 10 million FCVs in use in 2050
Notice on the Financial Support Policy for the Promotion and Application of New Energy Vehicles in 2016–2020 (2015.04) ✓ Subsidy: 200,000 RMB (≈29106 USD) for each passenger vehicle, 300,000 RMB (≈43659 USD) for each light-duty bus or truck, 500,000 RMB (≈72765 USD) for each middle/heavy-duty bus or truck ✓ From 2017 to 2020, the subsidy standards for other types of new energy vehicles would gradually decline, and for FCVs would not change	**Energy-saving and New Energy Vehicles Technology Roadmap (2016.10)** ✓ 5,000, 50,000 and over 1 million FCVs in use in 2020, 2025 and 2030 ✓ Over 100, 300 and 1000 hydrogen refueling stations in 2020, 2025 and 2030 **Rugao in Jiangsu Province** ✓ United Nations Demonstration City of Hydrogen Economy
Shenzhen in Guangzhou Province (2017) ✓ Financial support policy for new energy vehicles in Shenzhen 2016 • Subsidy: 200,000 RMB (≈29106 USD) for each passenger vehicle, 300,000 RMB (≈43659 USD) for each light-duty bus or truck, 500,000 RMB (≈72765 USD) for each middle/heavy-duty bus or truck	**Shanghai** ✓ 2017–2020: 3000 FCVs in use; 5 to 10 hydrogen refueling stations; actively promoting fuel cell buses, logistics and other vehicle pilot projects ✓ 2021–2025: over 20,000 fuel cell passenger vehicles; over 10,000 other vehicles; 50 hydrogen refueling stations ✓ 2026-2030: **Wuhan in Hubei Province** ✓ 2018-2020: 2000 to 3000 fuel cell buses, commuter and logistics vehicles in use; 5 to 20 hydrogen refueling stations ✓ 2021-2025: 10,000 to 30,000 FCVs in use; 30 to 100 hydrogen refueling stations

Supplementary notes:
[1]Exchange rate: 1 USD = 6.8705 RMB.

China have issued a series of policies in succession. The incentive policies and plans will provide powerful inspiration and clearer targets for related industries in the future. Table 2 exhibits the incentives and plans in China for FCVs in recent years.

Literature review

Many studies have been conducted on the rapid development of FCVs. The production of hydrogen is essential for FCV development. Yazdanie et al. compared the energy demand and GHG emissions for operating conventional and alternative vehicles, which included FCVs, in Switzerland. 9 hydrogen production processes were analyzed in there research [41]. However, the energy structure in Switzerland is better than China. Hydrogen can be produced in cleaner pathways. Chinese study should be analyzed. Guo et al. analyzed solar hydrogen production methods and their development in China [42]. Lv et al. researched the feasibility of hydrogen production by using biomass residues and conducted a cost sensitivity analysis based on the situation in China [43]. Wang et al. conducted a study on the energy, environmental and economic impacts of FCVs from a well-to-wheel perspective [44]. According to the final results, methanol is the most suitable hydrogen source for FCVs. Yao et al. noted the cost of hydrogen from a life cycle point of view [45]. Based on the research, natural gas reforming was shown to be a minimum cost process. Ren et al. analyzed hydrogen production technologies more comprehensively by using DPSIR framework, fuzzy AHP and fuzzy TOPSIS methods [46]. The results indicate that coal gasification with CO_2 capture and storage as well as hydropower-based water electrolysis were the two most significant ways to promote the development of a hydrogen economy in China. These studies focused only on part of the FCV life cycle. They did not show the impact of FCVs from a more comprehensive perspective and did not compare FCVs with other fuel type vehicles across the whole life cycle.

In addition, many studies have compared FCV energy consumption or GHG emissions with those of other types of vehicles. Elgowainy et al. did the research of light-duty vehicle cradle-to-grave lifecycle, which included both fuel and vehicle cycles, GHG emissions and cost assessment in the U.S., including FCVs [47]. Besides, they also provided a prediction of reduction for potential. However, the research is based on the U.S. case. Yoo et al. calculated the GHG emissions of the FCV in Korea from well-to-wheel perspective and reached a wide range results, from 50.7 to 388.0 g-CO_2/km [48].

As for China, Ou et al. concluded that a fuel cell bus fueled by hydrogen derived from natural gas would result in 33% and 16% higher fossil energy use and GHG emissions, respectively, than a diesel bus [49]. The research of Huang et al. suggested that if inefficient hydrogen pathways were used, FCVs might not realize GHG benefits [50]. Wang et al. compared FCVs with electric vehicle (EVs) and internal combustion engine (ICE) vehicles in 2009 and 2020 based on a life cycle analysis [51]. Although carbon emissions would improve for all hydrogen pathways, hydrogen from the electrolysis of water powered by the Chinese electricity grid, powered by coal-fired energy and from natural gas reforming in central power plants would still cause higher carbon emissions than ICE vehicles in 2020. Hao et al. also compared 19 FCVs utilization pathways in China and recommended that vehicle technology and hydrogen production issue would be the key part to ensure FCVs' life-cycle low-carbon performance [52]. However, all studies treated FCVs as individuals only and did not consider their influence on the whole road vehicle fleet.

There are also some researches to predict the energy consumption or GHG emissions of the road vehicle fleet. Laberteaux et al. analyzed more than 65 thousand real-world trips from California household travel survey to quantify the benefit in reduction of GHG emissions in light-duty vehicle fleet [53]. While, in their research, only BEVs and PHEVs are taken into consideration to make comparison with ICEs. When the result in the U.S. was estimated by Bandivadekar et al., this same problem exist [54]. Previous studies that calculated the energy consumption or GHG emissions of the road vehicle fleet in China also did not take FCVs into consideration or did not consider the most up-to-date planning. Zhou et al. analyzed the development of EV use in China from the life cycle perspective and mentioned that FCVs would ultimately become part of the road vehicle fleet, but the authors failed to consider FCV integration into the fleet [55]. Hao et al. estimated the market penetration rates of different vehicle powertrains for passenger vehicles [56]. However, the authors did not consider hydrogen as an alternative fuel for future vehicles, and the research was based on an assumption of no FCVs. In addition, the paper focused on passenger vehicles and not the whole road vehicle fleet.

In conclusion, previous studies only focus on part of FCVs life cycle, individual vehicle comparison, or do not use latest plan to estimate the impact of FCVs on GHG emissions of the whole road vehicle fleet in China. Therefore, a gap exists between FCV development and road vehicle fleet GHG emissions. Thus, in this study, the influence of introducing FCVs to the road vehicle fleet on the GHG emissions of the entire fleet is analyzed based on the latest technical information and government plans in China under five different scenarios. The objective of this research is to evaluate the impacts of FCV deployment on GHG emissions and provide references for policy makers to make further decision about FCVs. The next part introduces the method used in this research. The following section shows the data. The fourth section provides results and offers some discussion. The final part summarizes the study and offers some recommendations.

Method

System boundary

GHG emissions of a road vehicle fleet are usually evaluated from a fuel cycle perspective, which includes the stages of resource exploitation/extraction, resource transportation, refining/power generation, product transportation/transmission, delivery/distribution and usage [57,58]. In this study, the fuel cycle is considered to provide a comprehensive comparison among different scenarios. Vehicle types in this study include passenger vehicles (PVs), heavy-duty buses (HDBs), medium-duty buses (MDBs), light-duty buses (LDBs), heavy-duty trucks (HDTs), medium-duty trucks (MDTs), light-duty trucks (LDTs) and mini trucks (MTs). The energy sources used directly for vehicles in this paper includes gasoline, diesel, compressed natural gas (CNG), liquefied natural gas (LNG), electricity and hydrogen.

Method

The bottom-up method is widely used to calculate the energy consumption and GHG emissions of a road vehicle fleet based on vehicles sales, survival rate, annual travel distance, fuel economy and GHG emissions intensities [59–62]. Eqn. (1) is the calculation of road vehicle fleet GHG emissions.

$$GHG_i = \sum_t \sum_f \left[\sum_{j=i-l_t}^{i} Sales_{t,f,j} \times SR_{t,i-j} \times VKT_t \times \left[FCR_{t,f,j} \times (1-\alpha) \times GI_f \times LHV_f \times \rho_f + PC_{t,f,j} \times \alpha \times GI_{electricity} \right] \right] \quad (1)$$

where

GHG_i is the GHG emissions of the road vehicle fleet in target year i (mt CO_2 eq.);
$Sales_{t,f,j}$ is the number of sales of vehicle type t with fuel type f in year j (unit);
$SR_{t,i-j}$ is the survival rate of vehicle type t in the $(i-j)_{th}$ year (%);
$VKT_{t,i-j}$ is the mileage of vehicle type t in the $(i-j)_{th}$ year (100 km/year);
$FCR_{t,f,j}$ is the fuel consumption rate of vehicle type t with fuel type f in year j (L/100 km);
α is the fraction of travel distance that is powered by electricity, so $(1-\alpha)$ represents the fraction of the travel distance powered by the liquid or gaseous fuel;
GI_f is the GHG emissions intensity of fuel type f used for the vehicle (g-CO2/MJ);
LHV_f is the lower heating value of fuel type f used for the vehicle (MJ/kg);

ρ_f is the density of the fuel type f used for the vehicle (kg/L);
$PC_{t,f,j}$ is the power consumption of vehicle type t with fuel type f in year i (kWh/100 km);
l_t is the life span of vehicle type t (year); and.
$GI_{electricity}$ is the GHG emissions intensity of electricity (g-CO_2/kWh).

Data

General data

Scenario introduction

There are five scenarios in this study, as Table 3 shows. Sales and GHG emission factor assumptions are introduced in the previous sections. Under the 'no FCV' scenario, there will be no FCVs in the road vehicle fleet. For light-duty vehicles, BEVs will replace FCVs and for HDTs, there will be few EVs if no FCVs are deployed.

Fig. 3 shows the number of sales of different vehicle types from 2005 to 2050 under different scenarios. Vehicle types include ICEs, BEVs, PHEVs and FCVs. ICE vehicles include vehicles fueled by gasoline, diesel and natural gas in this study.

Fuel consumption rate

Historical data of fuel consumption rates are obtained from the Innovation Center for Energy and Transportation (iCET) and the China Automotive Technology & Research Center (CATARC), and the future plan is based on the target set by SAE-China and trends in regulation development [63–67]. As for the fraction of travel distance that is powered by electricity for PHEVs, the research result of Samaras et al. is applied in this paper [68].

Survival rate

Survival rates of different vehicle types in this study are based on the research of Yan [62]. The sales data in this research are from 1995 to 2017. To check the reliability of the survival rates, the real vehicle stock and calculated vehicle stock are compared from 2015 to 2017. The results indicate that the real and theoretical values are very close. The differences are all below 1%.

Vehicle travel distance

Many factors have an impact on vehicle travel distance, which varies significantly from individual to individual. The data used in this paper is from the CATARC and several Chinese case studies [63,64,69–71]. The variation from year to year is not considered in this study. The final data used in this study is shown as Table 4.

Table 3 – The introduction of different scenarios analyzed in this research.

	FCVs sales	GHG emissions intensity of hydrogen
1	Optimistic	Optimistic
2		Conservative
3	Conservative	Optimistic
4		Conservative
5	No FCVs	–

GHG emissions intensity

For conventional fuels, there is little room left for GHG emissions intensity improvement. Thus, in this study, the GHG emissions intensities of gasoline, diesel, CNG and LNG are assumed to be constant [46,68,72–75]. The GHG emissions intensity improvement of electricity will have a great impact on the evaluation and assessment of BEVs and PHEVs. The assumption of IEA is used in this paper, based on the current policy scenario in the report [1].

FCV and hydrogen production data

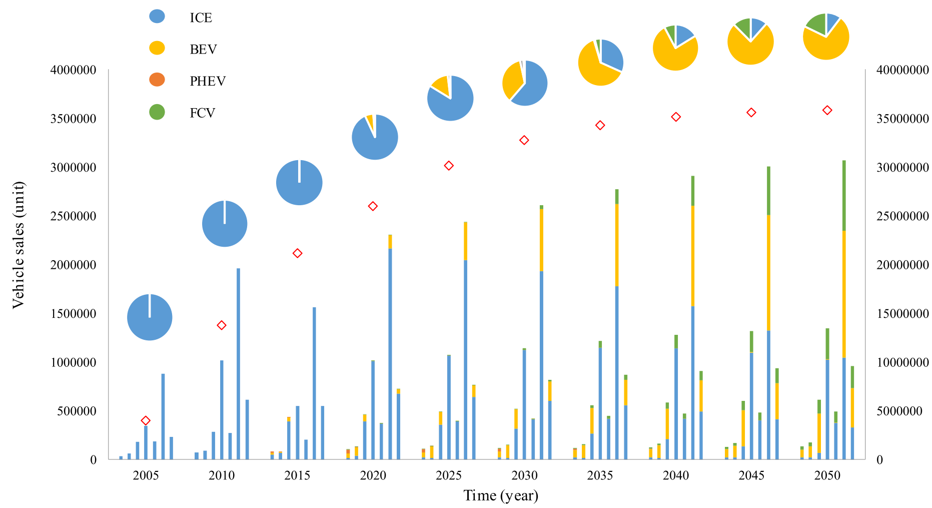
FCV sales

As mentioned before, the state government has paid considerable attention to the development of FCVs and has established a series of plans. According to the latest plan, the Energy-saving and New Energy Vehicles Technology Roadmap, the FCV stock is expected to reach 5,000, 50,000 and 1 million respectively by 2020, 2025 and 2030 in China [38]. The sales data used in this study is achieved by fitting a curve to data points of the stock and doing subtraction. Because the time period is not very long, scrappage is not considered in the calculation of FCV sales from 2020 to 2030. Fig. 3 illustrates a comparison of the assumptions of previous studies and the results of this research [61,76,77]. FCV sales will be approximately 2.25, 18.45 and 450.72 thousand in 2020, 2025 and 2030, and the proportion of FCV sales to total vehicle sales will respectively reach 0.01%, 0.05% and 1.19%. Compared with other studies, the most up-to-date planning shows a relatively conservative prediction from 2020 to 2025, and fast growth is expected after 2025. Therefore, the period from 2015 to 2020 is regard as the demonstration period, 2021 to 2025 will be the popularization period and application, and after 2025, the FCVs will enter the stage of large-scale promotion.

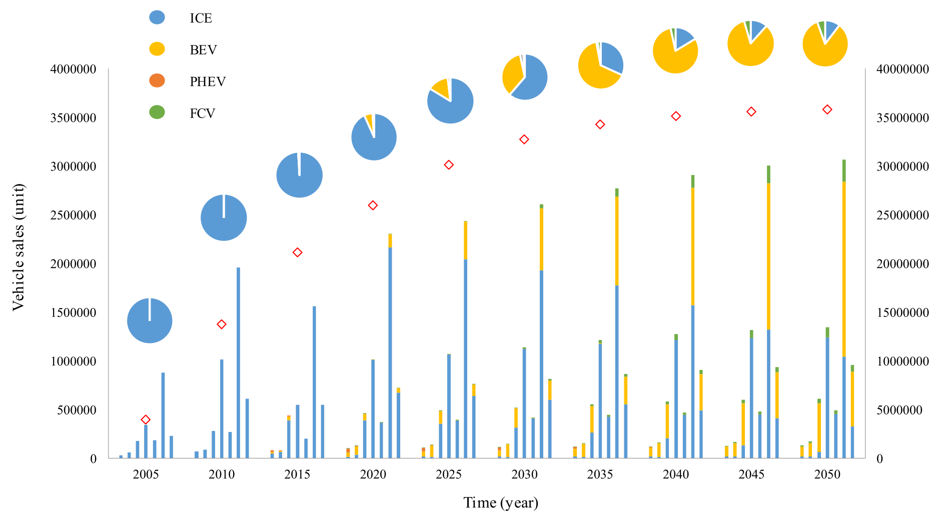
Based on sales data before 2030, two scenarios are assumed in this paper, as shown in Fig. 4. Unlike BEVs, FCVs are more easily applied in commercial road vehicle fleets, especially as trucks; therefore, the deployment of FCVs can increase more rapidly. Under the optimistic scenario, FCVs will reach 3.4 million and 8 million in 2040 and 2050, respectively. Under the conservative scenario, FCV sales increase more slowly, with linear growth from 2030, and the penetration of FCVs in the total road vehicle fleet will reach 3.5% and 5.8% in 2040 and 2050, respectively, under the conservative scenario.

Hydrogen consumption rate of FCVs

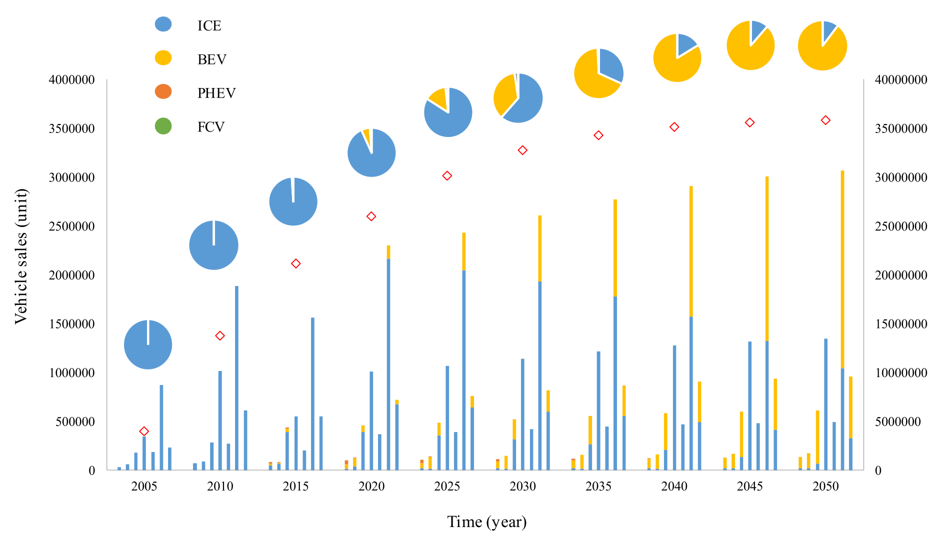
Existing data of the fuel economy of FCVs are primarily available for PVs and buses. Fig. 5 summarizes the collected data from demonstrations and the future targets for fuel cell buses. The historical data is derived from literature reviews and reports released from the demonstration projects. Few academic studies provide data about fuel cell buses, and most data come from reports provided by the demonstrations [20–29,49,78]. Due to the different driving and road conditions, differences between fuel consumption rates exist in reality, even in the same project, but the minimum values remain relatively stable at the level of approximately 9–10 kg-H_2/100 km. The government in each country has also made predictions. The U.S. DOE set performance, cost and durability



(a) Vehicle sales under the optimistic FCV sales scenario



(b) Vehicle sales under the conservative FCV sales scenario



(c) Vehicle sales under the no FCV scenario

Fig. 3 — Vehicles sales under different scenarios. (Order of bars: HDBs, MDBs, LDBs, HDTs, MDTs, LDTs, MTs).

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Table 4 – Annual travel distance of different types of vehicles.

	PVs	HDBs	MDBs	LDBs	HDTs	MDTs	LDTs	MTs
Annual travel distance/km	19000	54000	52000	37000	55000	35000	28000	19500

targets for fuel cell transit buses in the Fuel Cell Technologies Program in 2012. The fuel economy targets were 7 mpge (miles per gallon diesel equivalent) in 2012 and 8 mpge in 2016. The ultimate target remains at 8 mpge, while cost would be a key point later [20]. The work plan and roll-out plan for hydrogen buses were also released by the EU. The fuel economy target set for the next generation would be 7 to 12 kg-H_2/100 km [26]. The most up-to-date plan in China also included an outlook for the future fuel cell bus fuel economy [38]. Compared with the existing collected data, planning of hydrogen consumption of fuel cell buses in China is at a relatively low level. The average levels of the fuel economy are predicted to be 7, 6.5 and 6 kg-H_2/100 km in 2020, 2025 and 2030, respectively, based on historical data of 8.5 kg-H_2/100 km in 2015.

Medium-duty and HDTs account for a large part of road vehicle fleet GHG emissions [65]. However, the policies of introducing alternative fuel vehicles into this fleet remains unclear, in part because of the high diversity in vehicle size and use. Only recently, policy makers have begun to focus on fuel cell trucks. Fuel cell trucks can solve the problem of a short driving range, which imposes restrictions on battery electric trucks. In addition, a fuel cell truck does not need to carry a heavy battery to achieve the driving range, which will contribute to higher energy consumption. The research of Kast et al. proved the feasibility of the introduction of FCVs in a truck fleet and demonstrated that with an increase in gross vehicle weight, the decline in fuel economy decreased approximately linearly, shown as Equation (2) and Fig. 6 (a) [79,80].

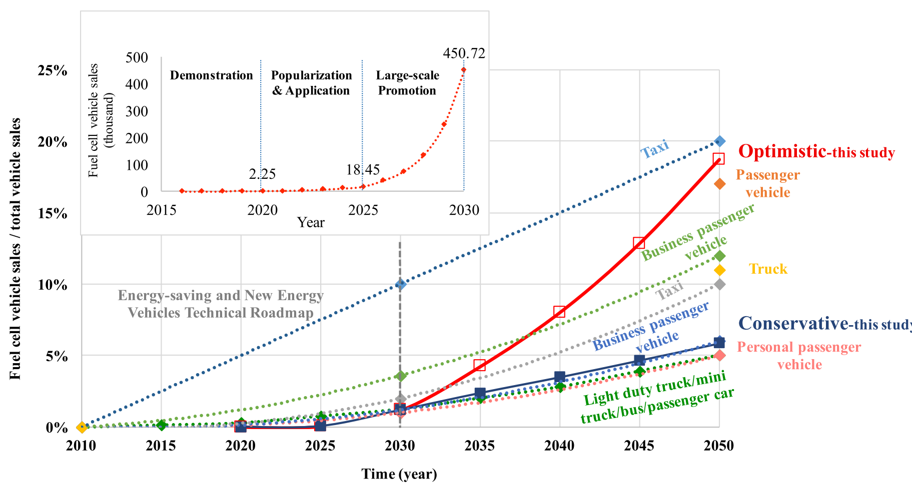


Fig. 4 – FCV sales and their proportion with respect to the total vehicles sales.

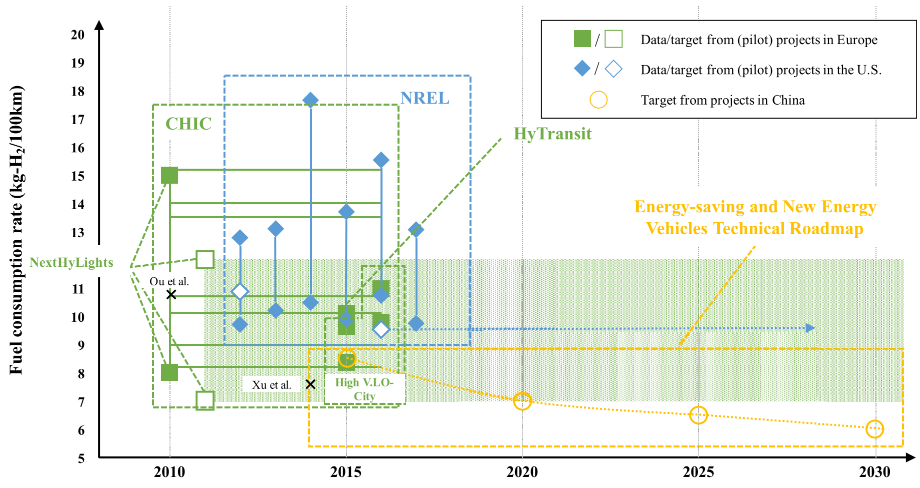
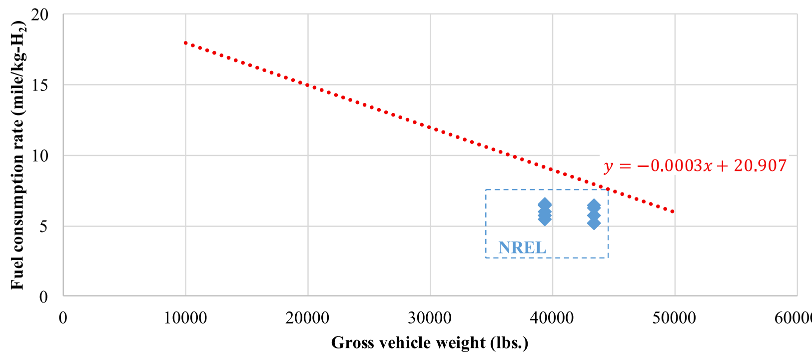
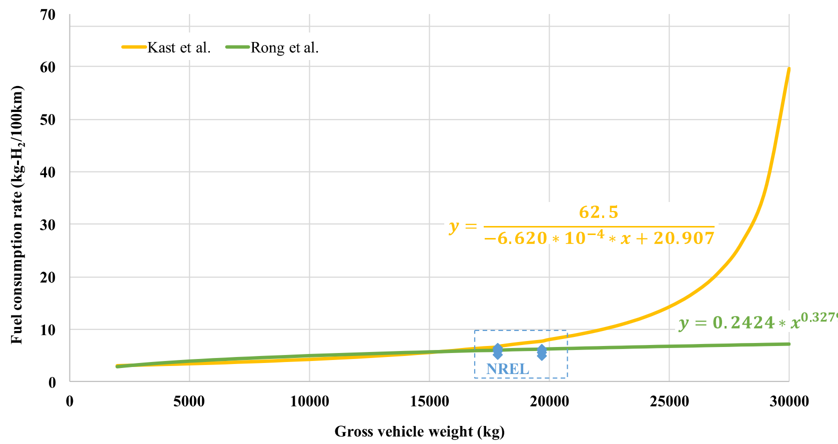


Fig. 5 – Historical data and future planning for a fuel economy of fuel cell buses.



(a) Fuel cell commercial vehicle fuel economy in reality and the research of Kast et



(b) ICE and fuel cell commercial vehicle fuel economy re-fitted curve as a function of gross vehicle weight

Fig. 6 – Fuel cell commercial vehicle fuel economies as a function of gross vehicle weight.

$$y = -0.0003x + 20.907 \quad (2)$$

where

x is the gross vehicle weight rating in lbs.;
y is the fuel economy of fuel cell trucks in miles/kg-H_2.

The research of Kast et al. showed that the fuel economy of FCVs (miles per kg-H_2) was linearly related to weight (lbs.). When the formula is changed to the relationship between kg-H_2/100 km and kg, with increasing mass, the fuel economy increases dramatically, which is opposite of the trend of ICE vehicles. Based on the difference between ICE and the fuel cell efficiency, the fuel economy of fuel cell trucks is re-fitted in this study, as shown in Fig. 6(b) [81]. Two fitting curves almost coincide when the gross vehicle weight is less than 15,000 kg. In addition, the real data from NREL also fit better with the new curve in this study. Thus, a new fuel economy and gross vehicle weight function is determined and validated.

Studies related to the fuel consumption rates of fuel cell PVs are summarized in Fig. 7. The orange rhombuses represent the fuel economy of existing vehicle modes, and the data are provided by automakers. The green squares show the fuel economy targets set by the EU during a certain period. The yellow circles represent the plans in place in China. In 2020, the fuel economy of fuel cell PVs will decline to 1.0 kg-H_2/100 km, and this value might be the ultimate target. The series of crosses indicates the assumptions of the fuel economy of fuel cell PVs in previous studies. Some points show forecasted data [59,63,82–91]. From 2015 to 2020, most factual data or predictions are within the range of 0.9–1.1 kg-H_2/100 km. In this research, because an explicit plan is in place, the fuel consumption rates from 2015 to 2020 are based on the plan. Compared with the data of existing vehicles, the prediction of Gambhir et al., as shown by the red dotted line, is the most consistent with reality and is at an approximate average level seen for all data. Thus, after 2020, the data in Gambhir's research are used in this paper.

Though it is more appropriate to use FCV data in China, it is really difficult to get a comprehensive overview and predictions. Most FCVs are still in test phase, so a summary of the real data and literature review is necessary. Therefore, the data in other countries are used as references and the main trend is still based on Chinese' case.

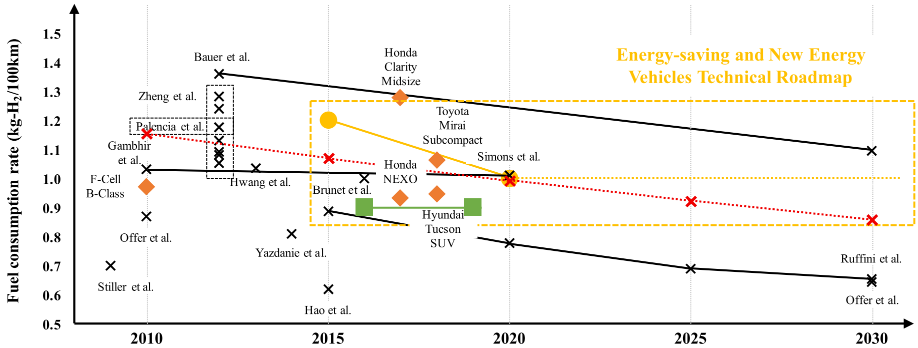


Fig. 7 – Summary of fuel consumption rates of fuel cell PVs. Supplementary notes: 1 Green marks represent targets set by EU pilot projects. 2 Orange marks represent data from existing fuel cell passenger vehicle models provided by automakers. 3 Yellow marks represent status quo and targets set by the Chinese government. 4 Cross are data from literature review.

GHG emissions intensity of hydrogen used for FCVs

The GHG intensity of hydrogen is always a debatable topic. Based on various production, distribution and storage methods, the GHG emissions intensity of hydrogen used for FCVs vary greatly. As shown in Fig. 8, several mainstream pathways are listed, including coal gasification, steam methane reforming (SMR), water electrolysis based on different power sources, coke over gas-H_2 and chlor-alkali-H_2.

As reported in the study of Parthasarathy et al., the current share of hydrogen produced from natural gas is 49%, from liquid hydrocarbons is 29% and from coal is 18%. Only 4% of hydrogen is produced from renewable sources [92]. In addition, most studies conclude that SMR is the most cost-effective current hydrogen production method or the most promising pathway in the near term, and SMR has recently become a widely commercialized hydrogen production method [44,45,93–95]. Many studies have also calculated the GHG emissions of FCVs with the assumption that hydrogen was produced from an SMR pathway [91,96–98]. However, without carbon capture and storage (CCS), the GHG intensity of hydrogen produced by SMR is still relatively high. In addition, according to the plan in China, hydrogen as a by-product of the chlor-alkali industry will be the main source of FCV fuel in the short term. In the long term, electrolysis of water powered by renewable or nuclear energy will be another popular pathway for hydrogen production in China. Thus, more attention should be paid to sustainable pathways to reduce reliance on fossil fuel and related GHG emissions.

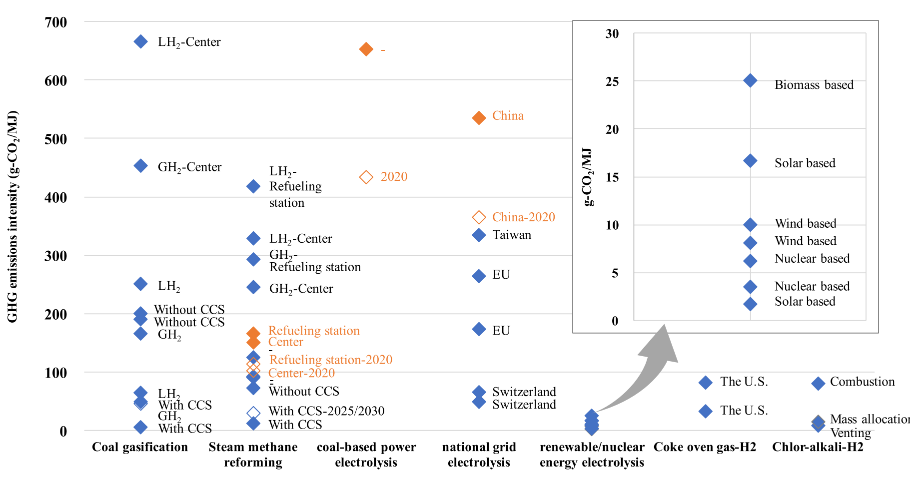


Fig. 8 – Well-to-wheel GHG emissions intensity of various hydrogen pathways. Supplementary notes: 1 LH_2: Liquid hydrogen. 2 GH_2: Gaseous hydrogen. 3 Center: Hydrogen is produced in the central plant. 4 Refueling station: Hydrogen is produced in the refueling station. 5 CCS: Carbon capture and storage. 6 Combustion: As a by-product, hydrogen is used in a boiler to process heat. If it is replaced, more natural gas will be needed and GHG emissions will increase. 7 Mass allocation: GHG emissions allocation factors are estimated based on the mass of the three products in chlor-alkali processes, Cl_2, NaOH and H_2. 8 Venting: Hydrogen is vented/wasted directly to the air. 9 Biomass/solar/wind/nuclear-based: Energy sources of the power grids comes from biomass, solar, wind or nuclear energy. 10 Country name: Hydrogen electrolysis by different national grids, including China. 11 The orange marks represent the data from China. 12 Dark color marks represent the status quo, and light ones are based on future prediction.

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Fig. 9 — The distribution of hydrogen refueling stations in China.

In China, by the end of 2017, there were 12 hydrogen refueling stations in use and over 20 stations under construction, as shown in Fig. 9. Most of the refueling stations are located in the eastern region in China. Xu et al. calculated the cost of introducing FCVs and hydrogen stations in Shenzhen, China in the short term (from 2015 to 2025) [99]. In their research, the on-site SMR station was considered as the solution to hydrogen refueling because natural gas, which has rich reserves, can be easily accessed, thanks to the West-East program in China. Due to the high cost performance, technological feasibility and real data, in this study, SMR is currently regarded as the main pathway to hydrogen production in China to determine the GHG emissions intensity from a life cycle perspective. With the expansion of the hydrogen industry and the increasing deployment of FCVs, more clean pathways will be applied to future fuel production.

Thus, combined with the current situation and the plan for the future, two scenarios are assumed in this study, as shown

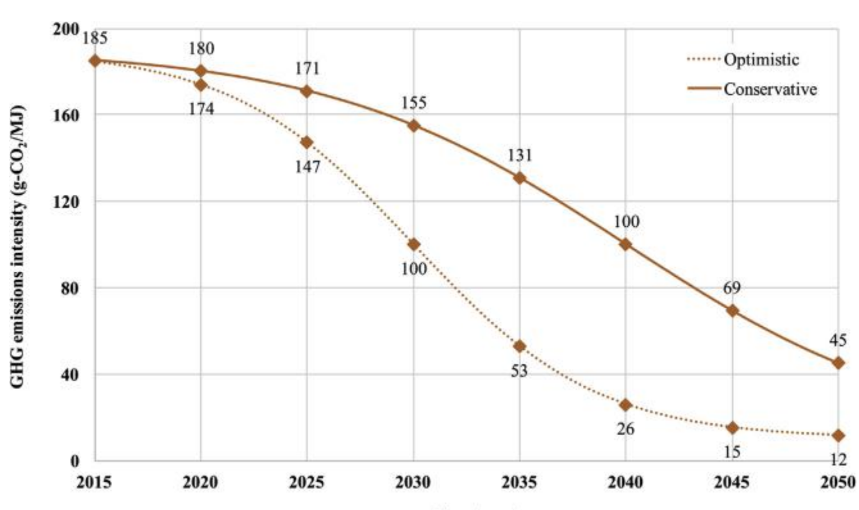

Fig. 10 — GHG emissions intensity of hydrogen used for FCVs.

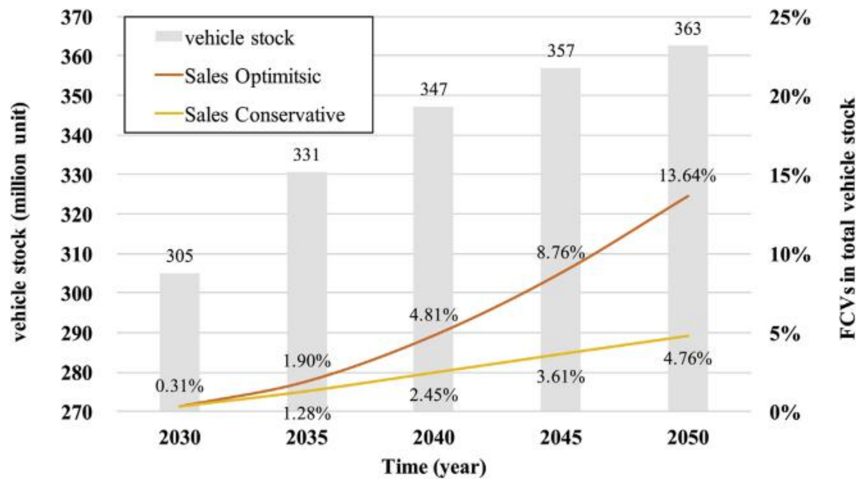

Fig. 11 – Vehicle stock and the proportion of FCVs in the whole vehicle stock.

in Fig. 10. The GHG emissions intensity of hydrogen from a life cycle perspective will drop to 100 g-CO_2/MJ in 2030 and 2040 under the optimistic and conservative scenarios. In 2050, the GHG emissions intensity will drop to 12 g-CO_2/MJ under the optimistic and 45 g-CO_2/MJ under the conservative scenarios. Under the optimistic scenario, from 2050, hydrogen used for FCVs will almost totally depend on water electrolysis from renewable energy.

Results and discussion

As planned, in 2030, the FCV sales in China will reach 1 million. However, compared with the total sales and vehicle stock, FCVs will still account for only a small proportion. Thus, before 2030, the differences among various scenarios are not distinct, and the effect of FCVs on vehicle GHG emissions is not clear. Thus, the results from 2030 to 2050 are considered as a main part in this study.

Vehicle stock

The vehicle stock in China will increase from around 305 million in 2030 to around 363 million in 2050, as shown in Fig. 11. Under the 'Sales Optimistic' scenario, FCVs stock will reach around 49 million in 2050, and the proportion of FCVs in the whole vehicle stock will reach 4.18% in 2040 and 13.64% in 2050. While, under the conservative scenario, FCVs stock will only be around 17 million in 2050, 35% of that under optimistic scenario.

Energy consumption

As more ICE vehicles are replaced by FCVs, hydrogen consumption will gradually increase, as shown in Fig. 12. After 2030, hydrogen consumption will first exceed 1 million tons. To 2050, FCVs will consume over 62 million tons of hydrogen under the 'Sales Optimistic' scenario, and around 22 million tons under the 'Sales Conservative' scenario. Enough

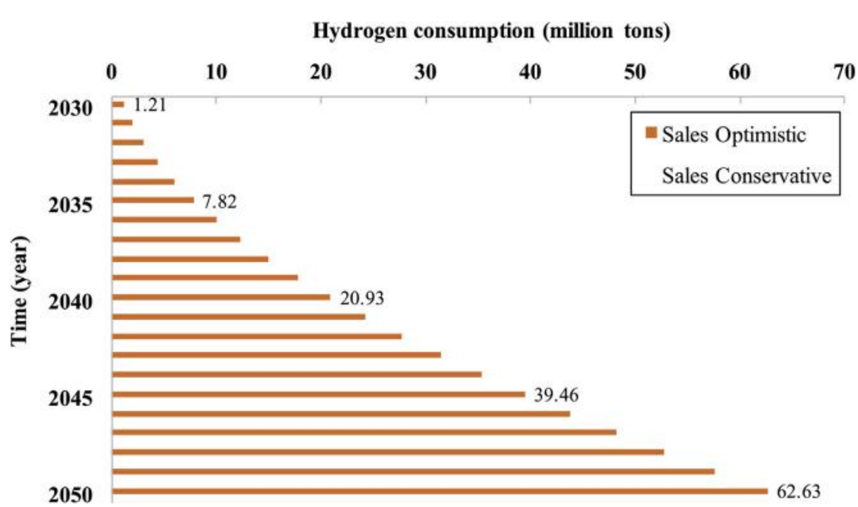

Fig. 12 – Hydrogen consumption of the whole FCV fleet from 2030 to 2050.

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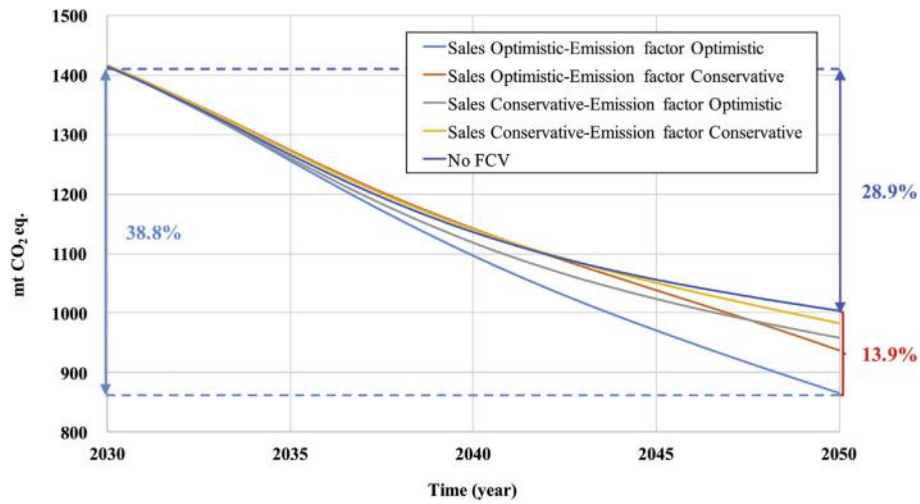

Fig. 13 – GHG emissions of the whole road vehicle fleet in China from 2030 to 2050 under different scenarios.

hydrogen supply for vehicles will become another key topic in the long term.

GHG emissions

Whole road vehicle fleet

Under the 'no FCV' scenario, the GHG emissions generated by the whole road vehicle fleet in 2050 will be 1004.5 mt CO_2 eq., 28.9% lower than that in 2030. Most of the reduction comes from the electrification of PVs and the improved fuel economy of light-duty vehicles. Under the 'Sales Optimistic-Emission factor Optimistic' scenario, the GHG emissions of the fleet will decrease by 38.8%, as shown in Fig. 13. The deployment of FCVs and the improvement in hydrogen generation will abundantly demonstrate the benefit of FCVs. There will be a 13.9% reduction compared to the level in the 'no FCV' scenario. 139.5 mt CO_2 eq. GHG emissions will be reduced.

If the pathways of hydrogen generation are not clean enough, the introduction of FCVs will lead to higher GHG emissions, as shown in Fig. 13. As more hydrogen is generated by renewable energy, with more FCV sales, the GHG emissions reduction effect of FCVs gradually appears. When the sales are under the optimistic scenario, optimistic emission factors can reduce the whole fleet GHG emissions 0.14%, 4.01% and 7.68% in 2030, 2040 and 2050, compared with conservative factors. While, when the sales are under the conservative scenario, the difference between 'Emission factor Optimistic' and 'Emission factor Conservative' scenarios will reach 25.45 mt CO_2 eq. in 2050.

In conclusion, emission factors of FCVs have a considerable impact on GHG emissions of the whole road vehicle fleet. In the short term, if the emission factors cannot be low enough, the total GHG emissions will be even higher. The hydrogen production pathways should be improved continuously. In the long term, a good sales volume can compensate for a relatively higher emission factor. With the improvement of hydrogen production in both the optimistic and conservative scenarios, sales will play a more important role in the final result. All in all, the deployment of FCVs combined with clean hydrogen production pathways will lead to a significant reduction in the whole road vehicle fleet GHG emissions.

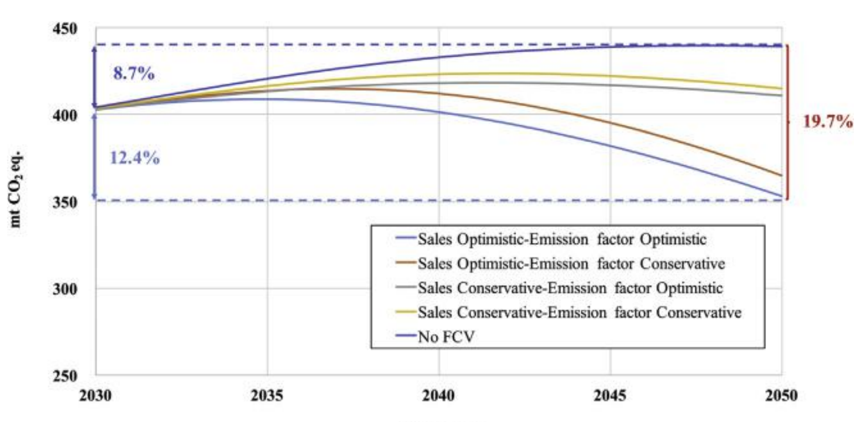

Fig. 14 – GHG emissions of the heavy-duty truck fleet in China from 2030 to 2050 under different scenarios.

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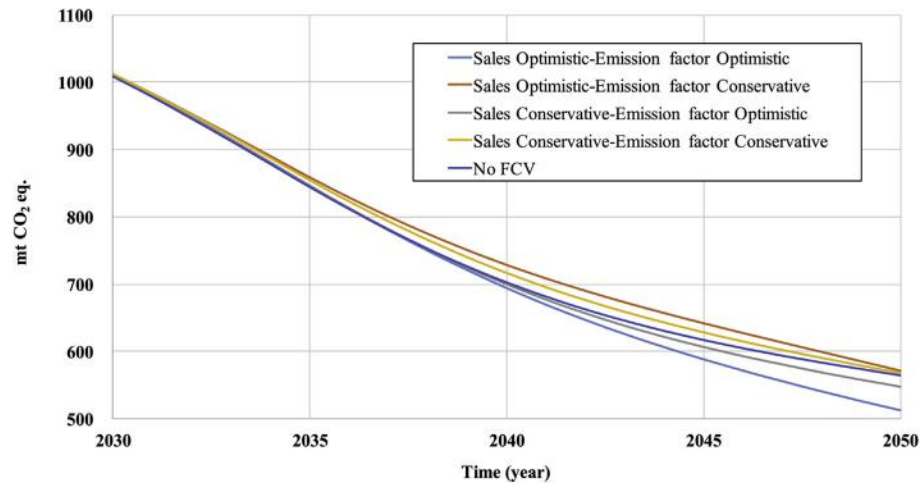
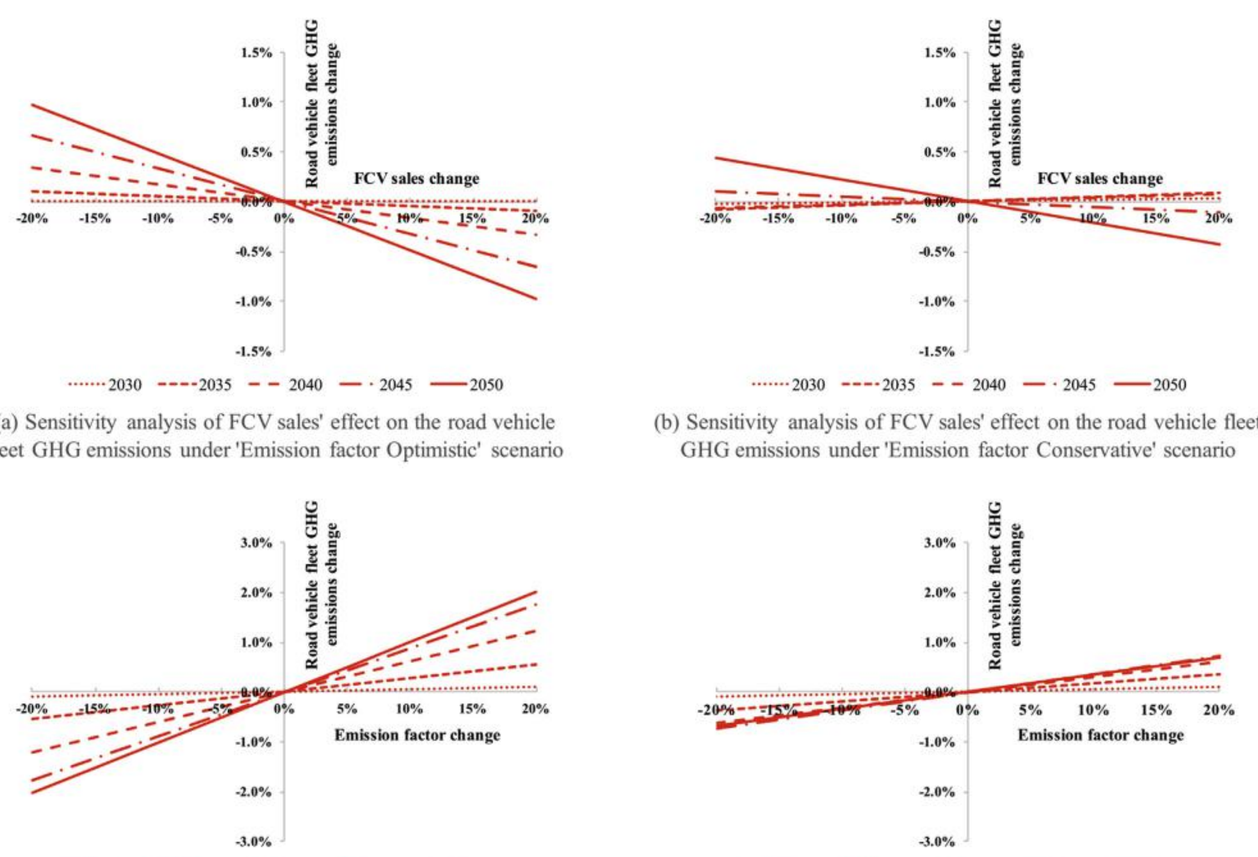


Fig. 15 – GHG emissions of other types of vehicles (excluded heavy-duty trucks) in China from 2030 to 2050 under different scenarios.

Heavy-duty trucks

Unlike BEVs and PHEVs, the greatest advantage of FCVs is when they are applied as HDTs. Using batteries as powertrains in heavy-duty vehicles is difficult, and due to their usage purpose, limiting, monitoring and reducing the fuel economy of HDTs is also difficult. Thus, the introduction of FCVs in the heavy-duty truck fleet will have a considerable influence on GHG emissions. As shown in Fig. 14, if no FCVs are deployed in the heavy-duty truck fleet, the GHG emissions generated by this fleet will almost continue to increase until 2050 because the



(a) Sensitivity analysis of FCV sales' effect on the road vehicle fleet GHG emissions under 'Emission factor Optimistic' scenario

(b) Sensitivity analysis of FCV sales' effect on the road vehicle fleet GHG emissions under 'Emission factor Conservative' scenario

(c) Sensitivity analysis of GHG emission factor' effect on the road vehicle fleet GHG emissions under 'Sales Optimistic' scenario

(d) Sensitivity analysis of GHG emission factor' effect on the road vehicle fleet GHG emissions under 'Sales Conservative' scenario

Fig. 16 – Sensitivity analysis of FCV sales and GHG emission factors.

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improvement in the fuel economy cannot compensate for the increase in sales, and GHG emissions generated by heavy-duty trucks can reach around 440 mt CO_2 eq. However, if FCVs are introduced to the HDT fleet, under the 'Sales Optimistic-Emission factor Optimistic' scenario, GHG emissions will decrease by almost one-fifth, be around 353 mt CO_2 eq in 2050. The deployment of fuel cell trucks will significantly decrease the emissions. Even with FCV sales under the conservative scenario, GHG emissions from HDTs will still stop increasing by 2050.

Other types of vehicles

For HDTs, FCVs are considered more as a substitute for ICE vehicles; while for other types of vehicles, FCVs are regarded as a contender for BEVs, as mentioned in the scenario description part. Thus, the influence of FCV on GHG emissions for other types of vehicles is summarized as shown in Fig. 15.

As shown in Fig. 15, only when emissions factor is under the optimistic scenario, FCVs exhibit the effects of GHG emission reduction. This result indicates that, only when the GHG emission factor of FCVs reach a relatively low value, they can compete with BEVs in the aspect of GHG emission reduction. While, with the improvement of emission factor, the results of the conservative scenarios gradually trend to draw close to the 'no FCV' scenario, and the differences are not significant.

Sensitivity analysis

As presented by Fig. 16 (a) and (b), road vehicle fleet GHG emissions in later years are more sensitive to FCV sales. While, under the 'Emissions factor Conservative' scenario, the decline in FCV sales may lead to a lower result of the road vehicle fleet GHG emissions. FCV sales change will lead to a greater change under the 'Emission factor Optimistic' scenario than under the conservative one. Fig. 16 (c) and (d) exhibit the sensitivity analysis for emission factors. With more FCVs in the 'Sales Optimistic' scenario, the change of emission factors will have greater impact on the emissions.

Summary

Because using renewable energy to produce hydrogen will be the future trend, GHG emission factors of hydrogen will likely decrease. As cleaner pathways are applied to hydrogen production, FCVs will effectively show advantages in GHG emissions reduction. In addition, with more FCVs, fleet emissions will also drop significantly. FCVs also provide an effective solution to reduce the reliance of HDTs on diesel and decrease GHG emissions from HDTs. If fuel cell trucks are applied, there will be fewer technical requirements for fuel economy improvements. While, compared with BEVs, FCVs do not show advantages in the aspect of GHG emission reduction, under the conservative emission factor scenarios. As a whole, the deployment of FCVs on HDTs can compensate for part of emission increase. Thus, introducing FCVs to HDTs will be a breakthrough point. Besides, taken together FCV's advantages over BEV, like easy and fast refueling/charging, longer driving range, etc., FCVs may be a better choice for future.

Policy recommendation

FCVs show great potential in reducing China's road vehicle fleet's GHG emissions. Especially for HDTs, it is hard to introduce BEVs or PHEVs into the fleet and improve the fuel consumption rates. FCVs provide a good solution to solve these problems. Thus, policy makers in China should take FCVs seriously as one of the options for future vehicle technical route. Followings are some suggestions for policymaking in China as reference.

1. Though some national and local incentive policies have already been introduced, there are only a few pilot projects for FCVs in China as mentioned before. The promotion of FCVs is still at the beginning stage. Government should encourage more research institutes and carmakers to join the research and development of FCVs to realize the technology progress. More pilots and incentive policies should be launched.
2. One of the key issues of FCVs is the cost. Policy makers should provide proper subsidies for FCVs to go through this threshold. Once the production volume of FCVs reaches a certain number, the cost problem will correspondingly and gradually be solved.
3. Nowadays, the government in China pays a lot of attention on passenger vehicles, in terms of not only fuel economy regulations, but also EVs promotion. While, another key emission source, commercial road vehicle fleet, is not taken so seriously. More moves should be introduced to highlight this part.
4. As for EVs, almost all of the sales come from BEVs and PHEVs, especially for passenger vehicles. Policy makers can take commercial vehicles as a breakthrough point for FCVs, due to their outstanding performance in GHG emissions reduction.
5. In addition to vehicle itself, hydrogen production pathways also play an important role. More measures should be taken to ensure that hydrogen used for FCVs is produced in low GHG emissions pathways, and enough hydrogen supply. Using renewable energy to produce hydrogen and using by-product hydrogen should become the main trend to ensure the cleanness of FCVs.
6. Infrastructure is also an essential part. Refueling stations should be planned and set up with the promotion of FCVs correspondingly. Overall layout planning from national and local governments will be necessary.
7. Policy makers are also supposed to focus on the development of energy storage. Hydrogen offers a solution to solve the problems of waste renewable energy. It also provides a feasible solution for hydrogen production.

Conclusion

By analyzing the plan for FCVs and the development trend of hydrogen production, this study calculates the impact of FCVs on road vehicle fleet GHG emissions in China under five different scenarios.

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- Increasingly more countries and automakers are showing interest in the research and development of FCVs worldwide.
- If FCV sales in China reach the target of 8 million in 2050, compared with emissions in the 'no FCVs' scenario, the GHG emissions of the whole road vehicle fleet would be reduced by approximately 13.9%. HDTs have the potential to decrease GHG emissions by one-fifth.
- Unlike BEVs and PHEVs, FCVs do not need to carry heavy batteries. FCVs provide a solution for heavy-duty vehicles to solve the problem of high GHG emissions, especially for HDTs, instead of improving fuel economy.
- Pathways for hydrogen production will have a great influence on the effect of GHG emissions reduction. Only clean ones can lead to a reduction of GHG emissions. The deployment of FCVs can compensate for a relatively higher GHG emission factor in the long term.
- BEVs and PHEVs are not the only vehicles available to reduce the GHG emissions of a road vehicle fleet. More attention should be paid and more measures should be taken from the government side to promote the development of FCVs and ensure clean hydrogen production pathways.

According to this research, FCVs exhibit remarkable GHG emissions mitigation effect. Controlling GHG emissions is always considered as a hard task. From a broader perspective, not only for China, but also for the whole world, FCVs give an effective solution to solve the problem of heavy reliance on fossil fuel consumption and great GHG emissions. More researches can be done in this field to evaluate the importance of FCVs on the road vehicle fleet in term of the whole world in the future.

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REFERENCES

[1] IEA. World energy outlook 2017. International Energy Agency; 2017.
[2] IEA. CO2 emissions from fuel combustion 2017. International Energy Agency; 2017.
[3] Liu Z, Hao H, Cheng X, Zhao F. Critical issues of energy efficient and new energy vehicles development in China. Energy Pol 2018;115:92–7.
[4] Zhang X, Liang Y, Yu E, Rao R, Xie J. Review of electric vehicle policies in China: content summary and effect analysis. Renew Sustain Energy Rev 2017;70:698–714.
[5] Zhang H, Song X, Xia T, Yuan M, Fan Z, Shibasaki R, et al. Battery electric vehicles in Japan: human mobile behavior based adoption potential analysis and policy target response. Appl Energy 2018;220:527–35.
[6] Hao H, Liu F, Liu Z, Zhao F. Compression ignition of low-octane gasoline: life cycle energy consumption and greenhouse gas emissions. Appl Energy 2016;181:391–8.
[7] Hao H, Cheng X, Liu Z, Zhao F. Electric vehicles for greenhouse gas reduction in China: a cost-effectiveness analysis. Transport Res Transport Environ 2017;56:68–84.
[8] Ke W, Zhang S, He X, Wu Y, Hao J. Well-to-wheels energy consumption and emissions of electric vehicles: mid-term implications from real-world features and air pollution control progress. Appl Energy 2017;188:367–77.
[9] Woo JR, Choi H, Ahn J. Well-to-wheel analysis of greenhouse gas emissions for electric vehicles based on electricity generation mix: a global perspective. Transport Res Part D 2017;51:340–50.
[10] 2015 United Nations climate change Conference, Paris, France. 2015.
[11] Li Y, Zhang Q, Liu B, McLellan B, Gao Y, Tang Y. Substitution effect of New-energy vehicle credit program and corporate average fuel consumption regulation for green-car subsidy. Energy 2018;152:223–36.
[12] Zhao S, Zhao F, Liu Z. The current status, barriers and development strategy of new energy vehicle industry in China[C]//International Conference on industrial technology and Management. IEEE; 2017. p. 96–100.
[13] Sharma S, Ghoshal SK. Hydrogen the future transportation fuel: from production to applications. Renew Sustain Energy Rev 2015;43:1151–8.
[14] Ren J, Gao S, Tan S, Dong L. Hydrogen economy in China: strengths–weaknesses–opportunities–threats analysis and strategies prioritization. Renew Sustain Energy Rev 2015;41(1):1230–43.
[15] Mazloomi K, Gomes C. Hydrogen as an energy carrier: prospects and challenges. Renew Sustain Energy Rev 2012;16(5):3024–33.
[16] Shafiei E, Davidsdottir B, Leaver J, Stefansson H, Asgeirsson E. Energy, economic and mitigation cost implications of transition toward a carbon-neutral transport sector: a simulation-based comparison between hydrogen and electricity. J Clean Prod 2017;141:237–47.
[17] Das V, Padmanaban S, Venkitusamy K, Selvamuthukumaran R, Blaabjerg F, Siano P. Recent advances and challenges of fuel cell based power system architectures and control – a review. Renew Sustain Energy Rev 2017;73:10–8.
[18] Alaswad A, Baroutaji A, Achour H, Carton J, Makky A, Olabi A. Developments in fuel cell technologies in the transport sector. Int J Hydrogen Energy 2016;41(37):16499–508.
[19] Moritsugu K. Toyota to start sales of fuel cell car next month. https://www.yahoo.com/tech/toyota-launch-fuel-cell-car-022146611.html.
[20] NREL. Fuel cell buses in U.S. transit fleets: current status 2016. National Renewable Energy Laboratory; 2017.
[21] Satyapal S. Hydrogen and fuel cells overview. DLA Worldwide Energy Conference; 2017.
[22] HyFleet:CUTE. Hydrogen transports: bus technology & fuel for today and for a sustainable future. http://gofuelcellbus.com/uploads/HyFLEETCUTE_Brochure_Web.pdf.
[23] Element energy limited. Post-2014 London hydrogen activity: options assessment. 2012. http://www.hydrogenlondon.org/wp-content/uploads/2013/10/HydrogenBuses-Post-2014-221012.pdf.
[24] Carnevali C, High V. LO-city project monitoring, integration and evaluation of impacts. 2017. http://hyer.eu/wp-content/uploads/2017/04/170316_4_DITEN_FCB-_AberdeenHydrogenTransportSummit.pdf.
[25] HyTransit. http://hyer.eu/eu-projects/hytransit/.
[26] Nexthylights. https://setis.ec.europa.eu/energy-research/sites/default/files/project/docs/FinalPublishableSummaryReport_V03_NextHyLights.pdf.
[27] CHIIC. reportClean hydrogen in European cities: final report. https://www.fuelcellbuses.eu/sites/default/files/documents/Final%20Report_CHIC_28022017_Final_Public.pdf.

[28] CertifHy. Roadmap for the establishment of a well-functioning EU hydrogen GO system. http://www.fch.europa.eu/sites/default/files/project_results_and_deliverables/D5.1.%20Implementation%20Roadmap-v15-final.pdf.
[29] JRC. reportWell-to-tank report version 4.0: JEC well-to-wheel analysis. https://iet.jrc.ec.europa.eu/about-jec/sites/about-jec/files/documents/report_2013/wtt_report_v4_july_2013_final.pdf.
[30] Dixon R, Wang X, Wang M, Wang J, Zhang Z. Development and demonstration of fuel cell vehicles and supporting infrastructure in China. Mitig Adapt Strategies Glob Change 2011;16(7):775−89.
[31] Han W, Zhang G, Xiao J, Benard P, Chahine R. Demonstrations and marketing strategies of hydrogen fuel cell vehicles in China[J]. Int J Hydrogen Energy 2014;39(25):13859−72.
[32] MOF, MOST. Interim measures for the management of financial support funds for energy-saving and new energy vehicle demonstration and promotion. Ministry of Finance of the People's Republic of China. Ministry of Science and Technology of the People's Republic of China; 2009. http://www.mof.gov.cn/zhengwuxinxi/caizhengwengao/2009niancaizhengbuwengao/caizhengwengao2009dierqi/200904/t20090413_132178.html.
[33] MOF, MOST, MIIT, NDRC. Notice on new energy vehicles charging infrastructure award. Ministry of finance of the People's Republic of China, Ministry of Science and Technology of the People's Republic of China, Ministry of industry and information technology of the People's Republic of China. National Development and Reform Commission; 2014. http://jjs.mof.gov.cn/zhengwuxinxi/tongzhigonggao/201411/t20141125_1160262.html.
[34] MOF, MOST, MIIT, NDRC. Notice on the financial support policy for the promotion and application of new energy vehicles in 2016-2020. Ministry of finance of the People's Republic of China, Ministry of Science and technology of the People's Republic of China, Ministry of industry and information technology of the People's Republic of China. National Development and Reform Commission; 2015. http://jjs.mof.gov.cn/zhengwuxinxi/zhengcefagui/201504/t20150429_1224515.html.
[35] Development and Reform Commission of Shenzhen Municipality. Financial support policies for new energy vehicle promotion and application in Shenzhen. 2017. http://www.sz.gov.cn/cn/xxgk/zfxxgj/tzgg/201707/t20170725_7949268.htm.
[36] The State Council of the People's Republic of China. Made in China 2025. http://www.gov.cn/zhuanti/2016/MadeinChina2025-plan/index.htm.
[37] China national institute of standardization, SAC/TC 309. Blue Book on the development of infrastructure in China's hydrogen industry. Beijing: China zhijian public house; 2016.
[38] SAE-China. Technology roadmap for energy saving and new energy vehicles. Beijing: China Machine Press; 2016.
[39] Science and Technology Commission Shanghai Municipality, Shanghai municipal commission of economy and informatization, Shanghai municipal development & reform commission. Roadmap for Shanghai fuel cell vehicle development.
[40] Proposal of Wuhan hydrogen industry development. http://www.gov.cn/xinwen/2018-01/21/content_5259104.htm.
[41] Yazdanie M, Noembrini F, Dossetto L, Boulouchos K. A comparative analysis of well-to-wheel primary energy demand and greenhouse gas emissions for the operation of alternative and conventional vehicles in Switzerland, considering various energy Carrier production pathways. J Power Sources 2014;249(2):333−48.
[42] Guo L, Zhao L, Jing D, Lu Y, Yang H, Bai B, et al. Reprint of: solar hydrogen production and its development in China. Energy 2009;34(9):1073−90.
[43] Lv P, Wu C, Ma L, Yuan Z. A study on the economic efficiency of hydrogen production from biomass residues in China. Renew Energy 2008;33(8):1874−9.
[44] Wang C, Zhou S, Hong X, Qiu T, Wang S. A comprehensive comparison of fuel options for fuel cell vehicles in China. Fuel Process Technol 2005;86(7):831−45.
[45] Yao F, Yuan J, Mao Z. The cost analysis of hydrogen life cycle in China. Int J Hydrogen Energy 2010;35(7):2727−31.
[46] Ren J, Gao S, Tan S, Dong L, Scipioni A, Mazzi A. Role prioritization of hydrogen production technologies for promoting hydrogen economy in the current state of China. Renew Sustain Energy Rev 2015;41(1):1217−29.
[47] Elgowainy A, Han J, Ward J, Joseck F, Gohlke D, Lindauer A, et al. Current and future United States light-duty vehicle pathways: cradle-to-grave lifecycle greenhouse gas emissions and economic assessment. Environmental Science & Technology 2018;52(4):2392.
[48] Yoo E, Kim M, Song H. Well-to-wheel analysis of hydrogen fuel-cell electric vehicle in Korea. Int J Hydrogen Energy 2018;43(41):19267−78.
[49] Ou X, Zhang X, Chang S. Alternative fuel buses currently in use in China: life-cycle fossil energy use, GHG emissions and policy recommendations. Energy Pol 2010;38(1):406−18.
[50] Huang Z, Zhang X. Well-to-wheels analysis of hydrogen based fuel-cell vehicle pathways in Shanghai. Energy 2006;31(4):471−89.
[51] Wang D, Zamel N, Jiao K, Zhou Y, Yu S, Du Q, et al. Life cycle analysis of internal combustion engine, electric and fuel cell vehicles for China. Energy 2013;59:402−12.
[52] Hao H, Mu Z, Liu Z, Zhao F. Abating transport GHG emissions by hydrogen fuel cell vehicles: chances for the developing world. Front Energy 2018:1−15.
[53] Laberteaux K, Hamza K. A study on opportune reduction in greenhouse gas emissions via adoption of electric drive vehicles in light duty vehicle fleets. Transport Res Transport Environ 2018;63:839−54.
[54] Bandivadekar A, Cheah L, Evans C. Reducing the fuel use and greenhouse gas emissions of the US vehicle fleet. Energy Pol 2008;36(7):2754−60.
[55] Zhou G, Ou X, Zhang X. Development of electric vehicles use in China: a study from the perspective of life-cycle energy consumption and greenhouse gas emissions. Energy Pol 2013;59(3):875−84.
[56] Hao H, Wang H, Ouyang M. Fuel conservation and GHG (Greenhouse gas) emissions mitigation scenarios for China's passenger vehicle fleet. Energy 2011;36(11):6520−8.
[57] Wang M. The greenhouse gases regulated emissions and energy use in trans portation (GREET) model. Argonne National Laboratory; 2015.
[58] Ou X, Yan X, Zhang X. Life-cycle energy consumption and greenhouse gas emissions for electricity generation and supply in China. Appl Energy 2011;88(1):289−97.
[59] Hao H, Liu Z, Zhao F, Li W, Hang W. Scenario analysis of energy consumption and greenhouse gas emissions from China's passenger vehicles. Energy 2015;91:151−9.
[60] Hao H, Geng Y, Li W, Guo B. Energy consumption and GHG emissions from China's freight transport sector: scenarios through 2050. Energy Pol 2015;85:94−101.
[61] Ou X, Zhang X, Chang S. Scenario analysis on alternative fuel/vehicle for China's future road transport: life-cycle energy demand and GHG emissions. Energy Pol 2010;38(8):3943−56.
[62] Yan X, Crookes RJ. Reduction potentials of energy demand and GHG emissions in China's road transport sector. Energy Pol 2009;37(2):658−68.
[63] CATARC. Report on the development of China energy-saving and new energy vehicle 2017. China Automotive Technology & Research Center; 2017.

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[64] iCET. China passenger vehicle fuel consumption development annual report 2016. Innovation Center for Energy and Transportation; 2017.
[65] Hao H, Wang H, Ouyang M. Fuel consumption and life cycle GHG emissions by China's on-road trucks: future trends through 2050 and evaluation of mitigation measures. Energy Pol 2012;43(C):244–51.
[66] Ou X, Yan X, Zhang X, Liu Z. Life-cycle analysis on energy consumption and GHG emission intensities of alternative vehicle fuels in China. Appl Energy 2012;90(1):218–24.
[67] He K, Huo H, Zhang Q, He D, An F, Wang M, et al. Oil consumption and CO2 emissions in China's road transport: current status, future trends, and policy implications. Energy Pol 2005;33(12):1499–507.
[68] Samaras C, Meisterling K. Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: implications for policy. Environmental Science & Technology 2008;42(9):3170–6.
[69] IEA. The future of trucks, implications for energy and the environment. International Energy Agency; 2017. http://www.iea.org/publications/freepublications/publication/the-future-of-trucks—implications-for-energy-and-the-environment.html [accessed January 2018].
[70] Hou C, Wang H, Ouyang M. Survey of daily vehicle travel distance and impact factors in Beijing. IFAC Proceedings Volumes 2013;46(21):35–40.
[71] Lin X, Tang D, Ding Y, Yin H, Ji Z. Study on the distribution of vehicle traveled in China. Research of Environmental Sciences 2009;22(3):377–80.
[72] Ou X, Yan X, Zhang X. Using coal for transportation in China: life cycle GHG of coal-based fuel and electric vehicle, and policy implications. International Journal of Greenhouse Gas Control 2010;4(5):878–87.
[73] Hekkert MP, Hendriks FHJF, Faaij APC, Neelis ML. Natural gas as an alternative to crude oil in automotive fuel chains well-to-wheel analysis and transition strategy development. Energy Pol 2005;33(5):579–94.
[74] Tong F, Jaramillo P, Azevedo IM. Comparison of life cycle greenhouse gases from natural gas pathways for medium and heavy-duty vehicles. Environmental Science & Technology 2015;49(12):7123–33.
[75] Song H, Ou X, Yuan J, Yu M, Wang C. Energy consumption and greenhouse gas emissions of diesel/LNG heavy-duty vehicle fleets in China based on a bottom-up model analysis. Energy 2017;140:966–78.
[76] Gambhir A, Lawrence KC, Tong D, Martinez-Botas R. Reducing China's road transport sector CO 2, emissions to 2050: technologies, costs and decomposition analysis ☆. Appl Energy 2015;157:905–17.
[77] IEA. Energy technology perspective 2012. International Energy Agency; 2012.
[78] Xu L, Li J, Ouyang M, Hua J, Yang G. Multi-mode control strategy for fuel cell electric vehicles regarding fuel economy and durability. Int J Hydrogen Energy 2014;39(5):2374–89.
[79] Kast J, Morrison G, Gangloff J, Vijayagopal R, Marcinkoski J. Designing hydrogen fuel cell electric trucks in a diverse medium and heavy duty market. Res Transport Econ 2017. in press.
[80] Kast J, Morrison G, Gangloff J, Vijayagopal R, Marcinkoski J. Clean commercial transportation: medium and heavy duty fuel cell electric trucks. World Hydrogen Energy Conference; 2016.
[81] Rong J. Research of energy and environmental impact of heavy trucks. Tsinghua University; 2018.
[82] Yazdanie M, Noembrini F, Heinen S, Espinel A, Boulouchos K. Well-to-wheel costs, primary energy demand, and greenhouse gas emissions for the production and operation of conventional and alternative vehicles. Transport Res Transport Environ 2016;48:63–84.
[83] Hwang JJ. Sustainability study of hydrogen pathways for fuel cell vehicle applications. Renew Sustain Energy Rev 2013;19(1):220–9.
[84] Ruffini E, Wei M. Future costs of fuel cell electric vehicles in California using a learning rate approach. Energy 2018;150:329–41.
[85] Stiller C, Svensson AM, Rosenberg E, Moller-Holst S, Bunger U. Building a hydrogen infrastructure in Norway. World Electric Vehicle Journal 2009;3:104–13.
[86] Palencia JCG, Sakamaki T, Araki M, Shiga S. Impact of powertrain electrification, vehicle size reduction and lightweight materials substitution on energy use, CO2 emissions and cost of a passenger light-duty vehicle fleet. Energy 2015;93:1489–504.
[87] Zheng CH, Oh CE, Park YI, Cha SW. Fuel economy evaluation of fuel cell hybrid vehicles based on equivalent fuel consumption. Int J Hydrogen Energy 2012;37(2):1790–6.
[88] Simons A, Bauer C. A life-cycle perspective on automotive fuel cells ☆. Appl Energy 2015;157(10):884–96.
[89] Offer GJ, Howey D, Contestabile M, Clague R, Brandon NP. Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. Energy Pol 2010;38(1):24–9.
[90] Offer GJ, Contestabile M, Howey D, Clague R, Brandon NP. Techno-economic and behavioural analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system in the UK. Energy Pol 2011;39(4):1939–50.
[91] Bauer C, Hofer J, Althaus HJ, Del Duce A, Simons A. The environmental performance of current and future passenger vehicles: life cycle assessment based on a novel scenario analysis framework ☆. Appl Energy 2015;157(3):871–83.
[92] Parthasarathy P, Narayanan KS. Hydrogen production from steam gasification of biomass: influence of process parameters on hydrogen yield - a review. Renewable Energy 2014;66(3):570–9.
[93] Nikolaidis P, Poullikkas A. A comparative overview of hydrogen production processes. Renew Sustain Energy Rev 2017;67:597–611.
[94] Balat M. Potential importance of hydrogen as a future solution to environmental and transportation problems. Int J Hydrogen Energy 2008;33:4013–29.
[95] Alazemi J, Andrews J. Automotive hydrogen fuelling stations: an international review. Renew Sustain Energy Rev 2015;48:483–99.
[96] Lajunen A, Lipman T. Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses. Energy 2016;106:329–42.
[97] Hwang J, Kuo J, Wu W, Chang W, Lin C, Wang S. Lifecycle performance assessment of fuel cell/battery electric vehicles. Int J Hydrogen Energy 2013;38(8):3433–46.
[98] Ahmadi P, Kjeang E. Comparative life cycle assessment of hydrogen fuel cell passenger vehicles in different Canadian provinces. Int J Hydrogen Energy 2015;40(38):12905–17.
[99] Xu X, Xu B, Dong J, Liu X. Near-term analysis of a roll-out strategy to introduce fuel cell vehicles and hydrogen stations in Shenzhen China. Appl Energy 2016;196:229–37.

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