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RESEARCH ARTICLE

Are electric vehicles cost competitive? A case study for China based on a lifecycle assessment

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Abstract

Promoting the development of electric vehicles (EVs) is regarded as an important measure to ensure energy security, mitigate climate change, and solve the transport sector's air pollution problems. Nowadays, compared to gasoline vehicles, whether the EVs are more competitive in terms of cost is still a question. There is no consensus achieved since the total cost depends on the development stage of the automobile industry and power generation structure as well as the cost accounting boundary. Many of existing studies did not include the costs occurred in all the stages. In response to this concern, this study estimates the lifecycle cost covering the whole process of production, use, disposal, and infrastructure construction as well as externalities for passenger battery electric vehicle (BEV), fuel cell vehicle (FCV), and gasoline vehicle (GV) by applying the comprehensive lifecycle cost model to China. The results indicate that in 2018, BEV and FCV were more expensive than GV (1.2–5.3 times), but that BEV will become cheaper after 2025, and its cost advantage will be enlarged to $419 (5%) compared to GV by 2030. The lifecycle cost of FCV will be $527 (or 5%) lower than that of GV by 2030. These results clarify that the costs of vehicle production account for the largest proportion in the total lifecycle cost.

Keywords Battery electric vehicle (BEV) · Fuel cell vehicle (FCV) · Cost competitive · Lifecycle cost model · China

Abbreviations

BEV	battery electric vehicle
CO_2	carbon dioxide
CRC	coal reforming with CCS
EV	electric vehicle
FC	fast charging
FCV	fuel cell vehicle
IBP	industrial byproduct purification
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
GV	gasoline vehicle
HOP	high oil price
LOP	low oil price
NOx	nitrogen oxides
$PM_{2.5}$	particular matter with a diameter of less than 2.5 μm
REE	renewable energy electrolysis water
SC	slow charging
SO_2	sulfur dioxide
VOCs	volatile organic compounds

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Introduction

Increasing travel demands and petroleum's dominance of the fuel structure (92%) are rapidly increasing the energy demand and carbon emissions of the global transport sector (Li and Yu 2019; Yu et al. 2017). In 2019, China's crude oil dependence reached 71%, exceeding the international warning line (50%)

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(EV100 2020). Additionally, carbon emissions from petroleum consumption reached 1.5 Gt, accounting for 16% of China's energy-related carbon emissions in 2018 (CarbonBrief 2019; IEA 2019b). Vehicles accounted for 42% of the total consumption of crude oil and more than 80% of refined oil (iCET 2019). Emissions from fossil fuel vehicles are also the major source of air pollution in China. For example, $PM_{2.5}$ emissions from the vehicles in cities like Beijing and Shanghai have contributed 20–50% of the cities' total $PM_{2.5}$ (MEE 2018). Automobile stocks are projected to reach 530–623 million units by 2050 (Shen et al. 2014). With this increase, energy security and environmental pollution issues may become increasingly prominent (Wang et al. 2017; Zhao et al. 2019). It is thus necessary to reduce the prevalence of fossil fuel vehicles and shift towards clean-fuel vehicles.

Promoting the development of electric vehicles (EVs) is regarded as an important measure to ensure energy security, mitigate climate change, and solve the transport sector's air pollution problems (Liu et al. 2020; Peng et al. 2018; Zhao et al. 2020). Vehicle electrification has rapidly increased in recent years (IEA 2020). Some countries, including the USA, Japan, Germany, Norway, and China, have set aggressive EV targets (Crabtree 2019), and several countries and regions have announced plans to phase out internal combustion engine vehicles (ICEVs) (iCET 2019). China has set ambitious targets for developing electric vehicles.

Although the purchase costs of EVs are higher than that of the equivalent ICEVs (Hagman et al. 2016), EVs' advantages regarding energy saving, environmental friendliness, and low operation cost should not be neglected, especially in countries that lack petroleum and need to solve environmental issues (Zhao et al. 2015). Until now, the cost competitiveness of EVs compared to ICEVs has been widely disputed, but no consensus has been achieved since the total cost is related to the development stage of the vehicle industry, the power generation structure, and the cost-accounting boundary. However, most of previous studies, for example, Ahmadi and Kjeang (2017), Hao et al. (2017), and Zhao et al. (2015), that have been conducted thus far have only considered partial costs rather than costs covering all life stages of the vehicles. This makes comparisons of the costs of different types of vehicles less informative. Thus, it is essential to construct a comprehensive and systemic lifecycle cost model to evaluate and compare the costs of different types of EVs and ICEVs. This study attempts to develop a comprehensive lifecycle cost model for comparing the costs of different types of passenger vehicles in China and find the development roadmap for the vehicle industry. This study selected EVs and ICEVs as the research object and used China as the empirical context. The remainder of this paper is organized as follows: the "Literature review" section provides a literature review, the "Methods and data" section presents the methods and data used in the study, the "Results and discussions" section contains the results and discussions of the analysis, and the "Conclusions and policy implications" section presents conclusions and policy implications.

Literature review

Many studies, such as Ruffini and Wei (2018), Sun et al. (2010), Hao et al. (2017) and so on, have examined and discussed the costs associated with passenger vehicles. Several studies have considered the costs that occur during vehicle production and vehicle use as well as external costs such as the emission costs of carbon dioxide and air pollutants. Some of them have stated that EVs were more expensive than gasoline-based ICEV (GVs), but such conclusion would change with the changes in battery lifetimes, annual driving kilometers, battery learning rate, and power grid structures. Ruffini and Wei (2018) found that the cost of battery electric vehicles (BEVs) and fuel cell vehicles (FCVs) was higher than that of ICEVs. With an 18% increase in fuel cell learning rates, FCV was estimated to become cost competitive compared with ICEV by 2025, but this turning point would be postponed by almost 25 years with an 8% fuel cell learning rate. Sun et al. (2010) proposed that the externalities could reduce the buydown cost (the cumulative investment needed to bring FCVs to lifetime cost parity with GVs) by $10 billion relative to the reference case. Ahmadi and Kjeang (2017) presented similar conclusions, asserting that the cost of Canada's FCV was approximately $2,100 more costly than that of the equivalent GV in 2015. However, the study argued that the prospective enhancements in fuel cell durability could potentially reduce the cost of FCV, making FCV cheaper than GV. Zhang and Han (2017) and Hao et al. (2017) found that the cost of EVs was impacted by China's electricity mix. The former concluded that the cost competitiveness of EV was weaker than that of hybrid electric vehicle in the current electricity mix; and the latter found that the cost of BEV would be lower than that of ICEV by 2020 with the improvement of the electricity mix. A similar study from Zhao et al. (2015) indicated that the cost of BEVs was 1.4 times of that of ICEVs in 2014 and predicted that the cost of BEVs would be lower than that of ICEVs after 2030. Few scholars found the social lifecycle cost (including carbon dioxide and air pollutant emissions) of EVs to be lower than that of ICEVs (Rusich and Danielis 2015).

Thus far, few studies have considered the infrastructure costs in their evaluations of the costs of vehicles (Bekel and Pauliuk 2019; Lipman 2000), though the inclusion of such costs is reasonable. Bekel and Pauliuk (2019) indicated that the cost of BEVs is lower than that of FCVs ($81,392 VS. $153,687) considering the three stages of vehicle production, vehicle use, and infrastructure. Lipman (2000) found that the cost of FCVs will be less than that of low-emission GVs by

2026 when infrastructure- and emissions-related costs as well as production and use costs are considered.

So far, most studies conducted on this topic have not considered the cost of all stages in the lifecycle of vehicles. All stages include vehicle production, vehicle use, vehicle disposal, infrastructure construction, and externalities, such as the emissions of carbon dioxide and air pollutants. This omission makes the comparison of the costs of different types of vehicles less informative. Thus, it is essential to estimate the lifecycle cost of different types of vehicles. Besides, we find that there is limited study investigating the cost of FCV in China. Further, the existing analysis have not reflected the real situation of China's FCV industry enough (Cai et al. 2012; E4tech 2019). Thus, this study attempt to improve upon the basis of previous studies by (a) building a comprehensive lifecycle cost model to estimate the lifecycle cost of different types of EVs and ICEVs and (b) using industry information to replace the parameters of certain individual vehicle models, which make the results more reasonable and representative. In addition, another possible contribution is our sensitivity analysis for five of the most important factors to ensure the results are more reliable.

Methods and data

Goal and scope definition

This study aims to compare the costs of different types of passenger vehicles in China by using a lifecycle cost model, and the findings are expected to provide suggestions for countries in their construction of a roadmap for the development of passenger vehicles. Lifecycle cost model is an important method for evaluating the total cost of a product or a system over its given lifetime (Bekel and Pauliuk 2019). EVs include BEVs and FCVs, while ICEVs only refer to GVs. In Table 1, the vehicle categories adopted for LCA are Toyota Corolla luxury (ICEV), Nissan Leaf (BEV), and Toyota Mirai (FCV). We selected these reference vehicles because they are among the best-selling models in their subindustries and have similar parameters as well as driving experience. However, in order to conform with China's reality, we made several revisions for these parameters of three types of vehicles in accordance with the industrial average level in China (Table 10). The revised parameters include vehicle efficiency, fuel price, battery capacity/power, battery unit cost, the unit cost of vehicle maintenance, emission factor of battery manufacturing and fuel consumption, and the price of carbon dioxide and air pollutants (see detailed parameters in Tables 10, 11, 12, 13, and 14, Tables 2 and 3, Fig. 1). The function unit in this study is 150,000 km.

The assessment boundary of the lifecycle cost model used in this study includes the stages of infrastructure construction, vehicle production, vehicle use, vehicle disposal, and the external environmental costs (Fig. 2). Infrastructure includes gasoline stations, charging stations, and hydrogen refueling stations; vehicle production includes material production, parts manufacturing, vehicle assemble, and vehicle distribution; vehicle use includes the extraction, processing, transmission, and consumption of the fuel and vehicle maintenance (Wang et al. 2013); vehicle disposal includes basic vehicle disposal and battery disposal; and external costs include the emission costs of battery manufacturing and fuel consumption.

Considering the uncertainty of battery capacity and power, we further categorized BEVs and FCVs into two types. In this regard, our study includes five vehicle models: (1) GV; (2) BEV with a 48-kWh lithium-ion battery which refers to the top-selling EVs in China in 2018 (BEV48); (3) BEV with a 75-kWh lithium-ion battery which refers to the prediction of IEA (2018b) for 2030 (BEV75); (4) FCV with a 60-kW fuel cell which refers to the sample vehicle and future predictions

Table 1 Vehicle and battery parameter.

	ICEV	BEV	FCV	
Vehicle				
Curb weight (kg)	1350	1545	1850	Bekel and Pauliuk (2019), Nissan (2019), Toyota (2019)
Lifetime mileage (km)	150,000	150,000	150,000	Hao et al. (2017), Yang et al. (2020)
Lifetime (year)	10	10	10	Wang et al. (2020)
Fuel consumption	Detailed parameter in Table 10			
Battery				
Type		NMC*	Fuel cell	IEA (2018a), SAE-China (2017)
Storage capacity (kWh or kg H_2)		40	5	Bekel and Pauliuk (2019), Dongfang Securities (2019a)
Charging efficiency		90%		Miotti et al. (2017)
Replacement per lifetime		0	0	Nealer et al. (2015)

*NMC is the abbreviation of nickel-cobalt-manganese battery.

Table 2 Unit cost prediction of lithium-ion battery.

2018	2020	2025	2030	Unit	Source
	147	132	118	$/kWh	SAE-China (2017)
	145	131	116	$/kWh	Hao et al. (2017)
	110	87	62	$/kWh	BNEF (2019)
186	110	87	62	$/kWh	This paper

in China (SAE-China 2017) (FCV60); and (5) FCV with a 120-kW fuel cell which refers to the prediction of SAE-China (2017) for 2030 (FCV120).

Lifecycle inventory analysis

Infrastructure

China's gasoline station stocks were composed of 100,000 units in 2018, and this was only increased by 4,500 units between 2010 and 2018 less than 5% of the total stocks (QZIRI 2019). Further, the equipment cost of gasoline stations is much lower than that of charging station and hydrogen refueling station. Thus, we assume that the marginal cost of gasoline stations is 0 (Wanlian Securities 2019). The cost of charging stations and hydrogen refueling stations includes investment and maintenance cost. The investment cost here only considers the purchase cost of equipment, while the maintenance cost is equal to 5% of the investment cost (Bekel and Pauliuk 2019). The lifetime of charging stations is considered to be 10 years (Bekel and Pauliuk 2019).

Charging station includes several charging piles. Charging piles are divided into ACCP and DCCP (see detailed feature in Table 4). This study assumes that one charging station has five direct current charging piles (DCCP) and ten alternating current charging piles (ACCP) (EV100, NRDC 2019). Electric vehicles can be charged through slow or fast charging. There are three types of slow charging, which use a single-phase AC outlet. They include (1) the connection of EV to the AC line using standard stream sockets, (2) a special cable via electronic device function driver control and protection, and (3) connecting to the AC power network using a computer (Martínez-Lao et al. 2017). In China, the first type of slow charging is the most prevalent (EV100, NRDC 2019). Considering the difficulty of data acquisition, we consider

Table 3 Unit cost prediction of fuel cell stack.

2018	2020	2025	2030	Unit	Source
	221	118	29	$/kW	SAE-China (2016)
	40		30	$/kW	Plotkin et al. (2009)
662	221	118	29	$/kW	This paper

only one slow recharging mode. Fast charging uses a single-phase or three-phase AC outlet. The stock, price, and investment costs of charging stations (piles) and hydrogen refueling stations from 2018 to 2030 (Table 5 and Table 6) were obtained from the report of National Development and Reform Commission of China (NRDC) and Dongfang Securities. Hydrogen refueling stations are divided into on-site production and central production, and global hydrogen production is now mainly from central hydrogen refueling stations. Hydrogen refueling stations have a lifespan of 20 years (Ruffini and Wei 2018).

Vehicle production

Vehicle production includes the production of basic vehicle and traction batteries. The basic vehicle includes the glider

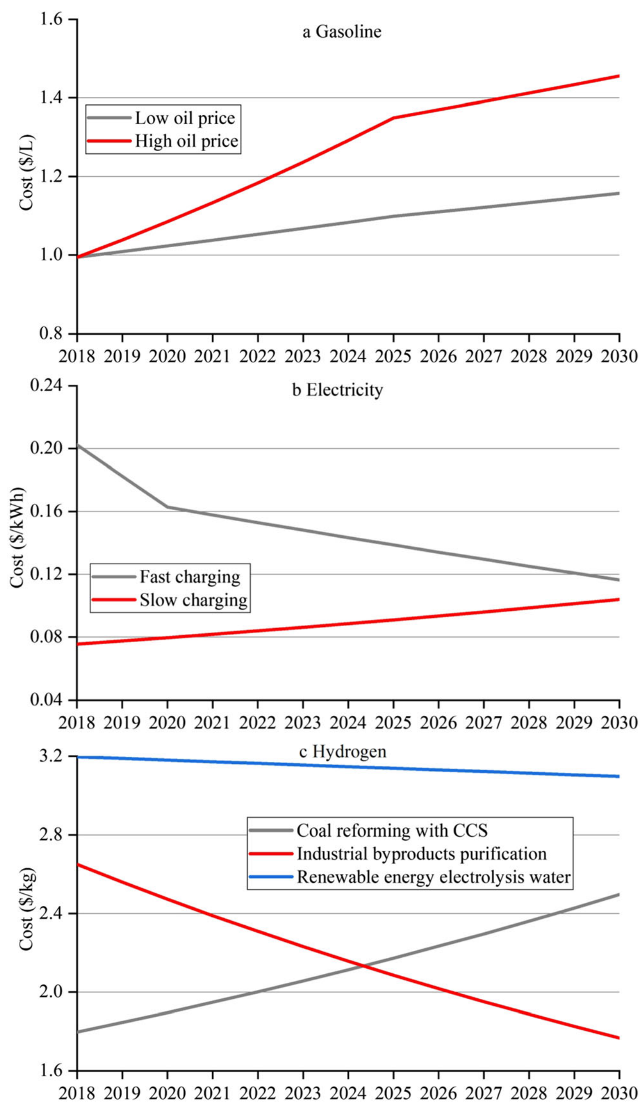

Fig. 1 Change tendency of fuel price in different scenarios (**a** gasoline; **b** electricity; **c** hydrogen) (CHA 2019; CPKB 2018; EIA 2014; Hao et al. 2017; IEA 2019a; Xiao 2018).

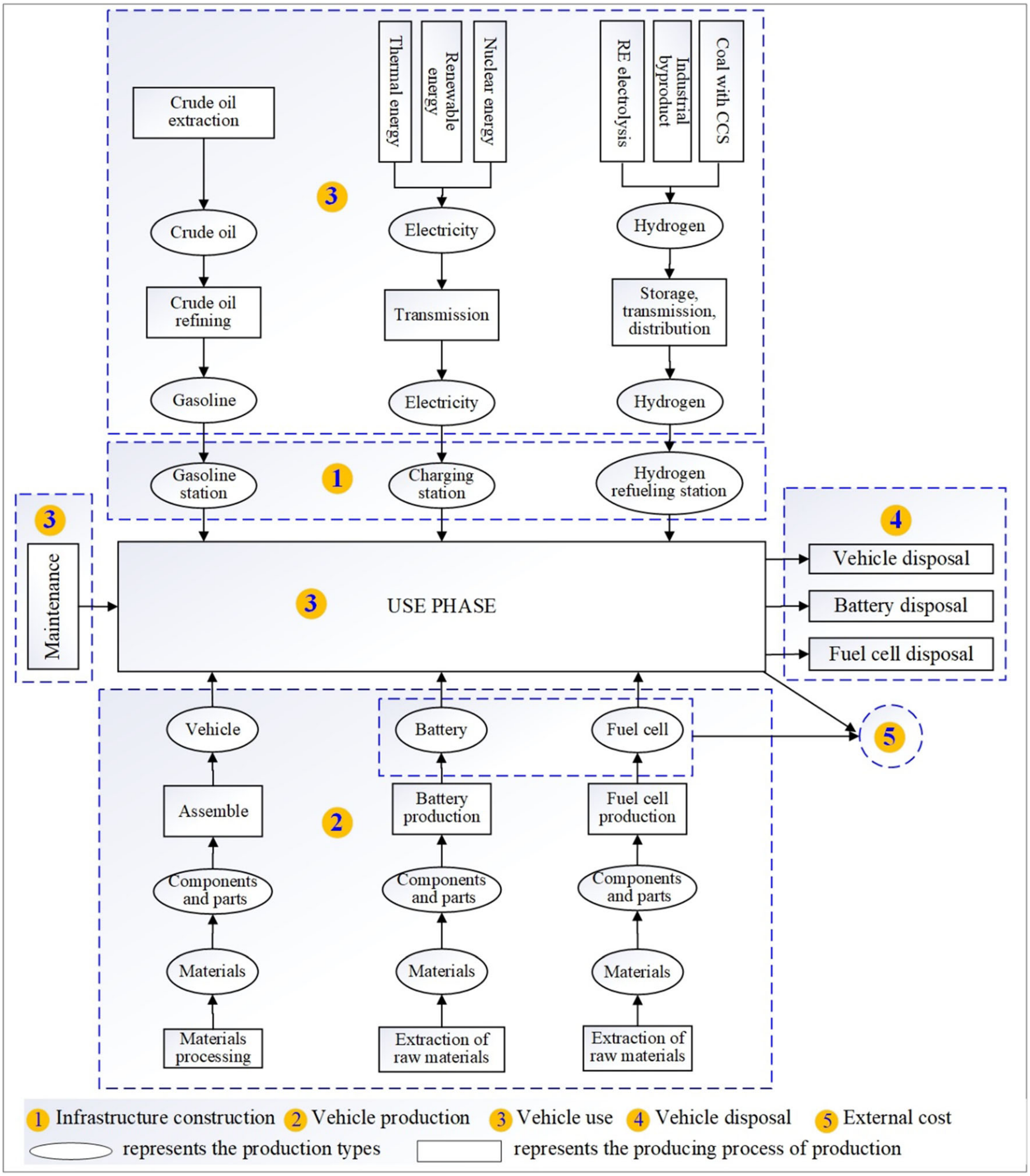

Fig. 2 Lifecycle cost assessment boundary.

containing all components that are common for three vehicle types, the internal combustion engine (ICE), and the powertrain system. The largest difference among the three types of vehicles is the traction batteries which are chosen as the major research object in this section (Qiao et al. 2019).

(1) Basic vehicle production

We obtained the cost of different parts of the three types of basic vehicles (excluding traction batteries) between 2018 and 2030 from Bekel and Pauliuk (2019) and Miotti et al. (2017). This study assumes that the glider cost of GV, BEV, and FCV is the same and the powertrain system cost of BEV and FCV is the same in different years (Table 7).

(2) Traction battery production

Since the lead-acid battery in GVs is only used to start the engine and power accessories and its capacity is very small, our study did not consider the cost of lead-acid batteries (Nealer et al. 2015). BEV usually relies on much larger lithium-ion batteries to power the vehicle itself. With the development of lithium-ion battery technology, NMC batteries

Table 4 Feature comparison of direct current and alternating current of charging pile (Dongfang Securities 2019b; EV100, NRDC 2019).

	ACCP	DCCP
Charging mode	Transmit alternating current by connecting the car charger	Direct to charge for storage battery by direct current
Input voltage	220 V	380 V
Output voltage	220 V	200–700 V
Charging power	<10 kW	30–120 kW
Charging time	8–15 h	20–150 min
Feature	Small volume, small power, slow charging, low effect for battery degradation	Large volume, large power, fast charging, high effect for battery degradation
Application scenarios	Public parking, private parking	Public parking

are gradually dominating the battery market. Moreover, lithium-ion batteries are expected to continue to be the best choice for EVs in the next decade, while other cutting-edge battery technologies may not be available for commercial use until 2030 (IEA 2018a). In this regard, our study only considered NMC battery costs (Table 2). Fuel cell stack is the main power of FCVs, and its cost is very high (Table 3). Currently, FCVs have adopted a hybrid powertrain system (i.e., hydrogen fuel cell and battery) to ensure the durability of fuel cells and reduce vehicle costs (SAE-China 2016). The data from the fuel cell passenger vehicles across the globe shows that the battery capacity of FCV is 1.6–24 kWh and most batteries are lithium-ion batteries (CATRC 2017). This study assumes that the battery type used in FCVs is NCM and its capacity is 5 kWh.

Vehicle use

The costs of vehicle use include fuel consumption costs and maintenance costs. Fuel costs include the cost of mining, refining, and transport; and maintenance costs include the fees related to insurance, license, registration, tax, and repair.

(1) Fuel costs

We used the market price to represent the cost of gasoline and electricity. China's gasoline prices are adjusted by the government, which imposes higher taxes than other countries. The gasoline prices in China are assumed to be 40% higher than the EIA estimation based on historical data (Hao et al. 2017). In reference to the prediction of presented by EIA (2014), we obtained the change tendency of gasoline costs under high oil price (HOP) and low oil price (LOP) scenarios (Fig. 1a). The charging modes are divided into slow charging (SC) and fast charging (FC), which use residential electricity price and industrial electricity price plus charging service fees (under the level of 10 kV), respectively (NDRC 2014). In 2018, the average electricity price of the residential and industrial markets are \$0.076/kWh and \$0.085/kWh, respectively, in China (CPKB 2018). Following the examples from Hao et al. (2017) and Xiao (2018), we assume that the electricity price will continue to increase at an annual rate of 2.7% from 2018 to 2030 and the charging service fee will be 0 in 2030, declining from \$0.12/kWh in 2018. The change tendency of electricity price is shown in Fig. 1b.

Hydrogen costs include three components: production, storage, and transport costs. There are currently three ways to produce hydrogen in China: (1) coal reforming with CCS (carbon capture and storage) (CRC), in which coal is converted into syngas by gasification technology and then treated by water gas shift separation to improve the purity of hydrogen. In order to control the carbon emissions, CCS technology is used for hydrogen production (IEA 2019a). (2) industrial byproducts purification (using coke oven gas) (IBP). This technology is mainly distributed in the iron and steel and chemical industries. China is the largest coke producer in the world. Part of coke oven gas can be used for pressure swing adsorption purification technology to produce high-purity hydrogen (CHA 2019). (3) renewable energy electrolysis water

Table 5 Investment cost of charging station (CEEP-BIT 2021; Dongfang Securities 2019b; EV100, NRDC 2019; SAE-China 2017; SAE-China 2018).

	EV stock (million units)	Stock of charging pile (million units)	Price of ACCP/DCCP (\$/kW; \$/unit)	Total investment cost (billion \$)
2018	2.61	0.81	61.8; 441.2	1.0
2020	4.92	1.57	54.4; 294.1	2.2
2025	26.09	14.36	30.9; 117.6	9.8
2030	80.00	80.00	30.9; 117.6	24.4

Table 6 Investment cost of hydrogen refueling station (CHA 2019; FUA 2019; SAE-China 2017; SAE-China 2018; Wanlian Securities 2019).

	FCV stock (thousand units)	Stock of hydrogen refueling station (unit)	Investment cost (million $/unit)	Total investment cost (million $)
2018	3.4	23	2.2	51.5
2020	8.0	100	2.1	205.9
2025	100	300	1.6	494.1
2030*	1000	1000	0.9	1102.9

*The investment cost of hydrogen refueling station in 2030 refers to the Germany's level in 2025.

(REE), which is an electrochemical process that splits water into hydrogen and oxygen. The production cost is greatly affected by electricity price, which accounts for more than 70% of the total cost. With declining costs for renewable electricity, the development potential of hydrogen production from REE will be huge in the future (CHA 2019). According to IEA (2019a), CHA (2019), and IRENA (2019), the costs of hydrogen production under the CRC, IBP, and REE scenarios in 2018 were $1.5/kg, $2.4/kg, and $2.9/kg, respectively. However, it was expected that these cost will change to $2.2/kg, $1.5/kg, and $2.8/kg in 2030, respectively. The cost of transport and storage is important for the competitiveness of hydrogen. Hydrogen is commonly stored in its gas, liquid, or solid forms. This study only considers high-pressure gas storage because it is currently the most mature technology. The transport modes of high-pressure hydrogen include tube trailer and pipeline. Tube trailer transport is an important method of short-distance (<200 km) transmission. This technology is mature, and the cost is $0.3/kg (CHA 2019). Pipeline transport is more suitable for large-scale and long-distance (>500 km) transmission. Its advantage is large-scale transport with low-energy consumption and low costs ($0.04/kg) (CHA 2019). Hydrogen transport is now dominated by tube trailer, and the pipeline method will become mainstream with the increasing demand of long-distance transmission from 2025. The cost of different hydrogen production modes is shown in Fig. 1c.

(2) Maintenance costs

Maintenance costs are defined as non-fuel costs during vehicle operation, including fees related to insurance, license, registration, taxes, and repair (Hao et al. 2015). However, the insurance, license fee, registration fee, and taxes are influenced by vehicle owners and regions in which the vehicles are driven (Miotti et al. 2017); hence, these fees were excluded in this study. The maintenance cost of BEV and FCV is lower than that of ICEV because these types of vehicles do not require the replacement of engine oil, spark plugs, mufflers, and brake pads (Hagman et al. 2016; Ruffini and Wei 2018). The maintenance cost is determined by the maintenance cost per km, annual driving kilometers, and vehicle lifetime. Our study assumes that the maintenance cost per km is constant. According to Hao et al. (2017), the maintenance cost for GV, BEV, and FCV is $0.011/km, $0.003/km, and $0.009/km, respectively.

Vehicle disposal

Vehicles have three disposal channels when they reach the end of their service lives : reuse, recycle, or landfill (Nealer et al. 2015). Most vehicles still have residual value when they have been used for 10 years. For instance, most parts of GVs can be used in other fields, while the batteries of BEVs and FCVs can be used in other applications—for example, storage for intermittent renewable energy sources such as solar and wind. Therefore, our study assumes that vehicles still have residual value at the end of their lifetime. Nowadays, GV's residual value can be evaluated, but EV's residual value is difficult to evaluate because the majority of EVs are still on the road—i.e., they have not yet been retired (Nealer et al. 2015). Li (2019) indicated that the residual values of BEV and GV are 9% and 16% of the vehicle production cost, respectively. Thus, it is assumed that the residual value ratio of GV, BEV, and FCV were 16%, 9% and 9%, respectively. There is much potentials to reduce the costs of emerging fuel cell technologies. In order to make the evaluation of residual value more

Table 7 Parts cost of three types of basic vehicles in China (Bekel and Pauliuk 2019; Miotti et al. 2017).

Vehicle types	GV				BEV				FCV			
Year	2018	2020	2025	2030	2018	2020	2025	2030	2018	2020	2025	2030
Glider ($)	7500	6765	5000	3824	7500	6765	5000	3824	7500	6765	5000	3824
ICE ($)	3529	3088	2353	1765								
Powertrain ($)					5441	4706	3235	2206	5441	4706	3235	2206
Total ($)	11029	9853	7353	5589	12941	11471	8235	6030	12941	11471	8235	6030

reasonable, we used the unit cost of fuel cells after 10 years to replace the current costs before 2025.

External cost

External cost is the economic loss from the emissions of vehicle production and use. These include the cost of accidents, air pollution, climate change, noise, and congestion (Jochem et al. 2016). This study mainly focuses on the emissions of CO_2, VOCs, NO_X, $PM_{2.5}$, and SO_2 from battery manufacturing and fuel consumption in China. The detailed parameters are shown in Tables 11, 12, 13, 14, 15, and 16.

Lifecycle cost assessment

Lifecycle cost assessment is defined as an economic method that adopts a structured approach to address all the different costs of the "project" over the given period with all the potential cost during its lifetime (Zhao et al. 2019). By considering all the costs incurred during the stages of production, use, and disposal of vehicle, this analytical process helps economic decision-makers to select the most cost-effective alternative investments or projects (Yang et al. 2021). Typically, lifecycle cost consists of only vehicle production, vehicle use (include maintenance expenditures and fuel cost), and vehicle disposal. However, considering the increasing demand for a type of vehicles, additional infrastructure are required, and meanwhile during the lifecycle of vehicles, many externalities may occur (e.g., emissions that are not good for the environment). Consequently, for a more comprehensive comparison on the cost between ICEVs and EVs, our study added the cost of infrastructure and external cost into the accounting boundary. The detailed information of the model is shown in Fig. 2.

As mentioned above, the lifecycle cost of vehicles can be divided into five categories: infrastructure construction costs, vehicle production costs, vehicle use costs, vehicle disposal costs, and external costs. The net present value of overall lifecycle cost for each vehicle was estimated using the following formulas. All the parameters are listed in Table 8. As Eq. (1) shows, cost is discounted to the base year (2018) and annualized by assuming that cash flows occurred at the beginning of each year. All monetary figures are given in real values in 2018, unless otherwise specified. The exchange rate used for US Dollars is $1USD_{2018} = 6.8\ CNY_{2018}$ (Zhao et al. 2015). The real discount rate is assumed to be 5% in this study (Newbery and Strbac 2016).

$$LCC_j = \frac{I_j + P_j + U_j - D_j + E_j}{(1+r)^{j-k}} \tag{1}$$

The infrastructure cost includes equipment costs and maintains costs. The infrastructure cost per vehicle is calculated as follows:

$$I_j = \frac{N_j \times (C_{e,j} + C_{m,j})}{S_j} \tag{2}$$

The vehicle production cost includes basic vehicle production (including the glider, ICE, and powertrain) cost and battery production cost. The production cost of ICEV includes the cost of glider and ICE. The production cost of BEV and FCV includes the cost of the glider, powertrain, and battery. The vehicle production cost is calculated as follows:

$$\mathrm{P_j} = \mathrm{C_{basic,j}} + \mathrm{C_{battery,j}} \tag{3}$$

$$\mathrm{C_{basic,j}} = \mathrm{C_{glider,j}} + \mathrm{C}_{ICE,\mathrm{j}} + \mathrm{C_{power,j}} \tag{4}$$

$$C_{battery,j} = C_{bat,j} \times Q_j \tag{5}$$

The vehicle use costs include fuel consumption costs and maintenance costs. The vehicle use cost is calculated as follows:

$$\mathrm{U_j} = \sum_{\mathrm{t=j}}^{\mathrm{j+n}} \frac{(D \times C_{f,j} \times P_{f,t} + D \times C_m)}{(1+r)^{t-j}} \tag{6}$$

The vehicle disposal cost is determined by the vehicle production cost (basic vehicle and battery cost) and disposal value ratio.

$$D_j = \frac{(C_{basic,j} + C_{battery,j}) \times R}{(1+r)^n} \tag{7}$$

The external cost of the vehicle is the emission cost from fuel consumption and battery manufacturing. The formula is shown as follows:

$$E_j = E_{f,j} + E_{b,j} \tag{8}$$

$$\mathrm{E_{f,j}} = \sum_{i=1}^{5} \sum_{\mathrm{t=j}}^{\mathrm{j+n}} \frac{\mathrm{D \times C_{f,j} \times FF_{f,i} \times P_{j,i}}}{(1+\mathrm{r})^{\mathrm{t-j}}} \tag{9}$$

$$E_{b,j} = \sum_{i=1}^{5} Q_j \times FB_{j,i} \times P_{j,i} \tag{10}$$

Lifecycle costs are influenced by different factors. In order to reveal the uncertain impact of different factors on the result, we conduct sensitivity analysis, which indicates that the sensitivity of the result was in relation to various key factors. In this study, we only considered five of the most important factors: annual driving kilometers, battery unit cost, vehicle efficiency, carbon price, unit maintenance cost, and residual value ratio. In each simulation of the lifecycle cost impact, one of the factors increases by 20%, while the other factors are fixed. We choose 2030 as the reference scenario.

Table 8 Summary of key terms in the model.

Parameter		Unit
LCC_j	Lifecycle cost of vehicle in the j^{th} year	$
r	Real discount rate	%
j	The goal year, which includes 2018, 2020, 2025, and 2030	Year
k	The base year, which is 2018 in this study	Year
t	Time	Year
n	The vehicle lifetime	Year
D	Annual driving kilometers of vehicle	km
R	Disposal value ratio of vehicle	%
I_j	Infrastructure cost in the j^{th} year	$
P_j	Vehicle production cost in the j^{th} year	$
U_j	Vehicle use cost in the j^{th} year	$
D_j	Vehicle disposal cost in the j^{th} year	$
E_j	Vehicle external cost in the j^{th} year	$
N_j	The number of infrastructure in the j^{th} year	
$C_{e,j}$	Net present value of equipment cost in the j^{th} year	$/unit
$C_{m,j}$	Net present value of maintenance cost in the j^{th} year	$/unit
S_j	Stock of BEVs or FCVs in the j^{th} year	
$C_{basic,j}$	Cost of basic vehicle production in the j^{th} year	$
$C_{battery,j}$	Cost of battery production in the j^{th} year	$
$C_{glider,j}$	Production cost of glider in the j^{th} year	$
$C_{ICE,j}$	Production cost of ICE in the j^{th} year	$
$C_{power,j}$	Production cost of powertrain in the j^{th} year	$
$C_{bat,j}$	Unit cost of battery production in the j^{th} year	$/kWh; $/kW
Q_j	Battery capacity or fuel cell power in the j^{th} year	kWh; kW
$C_{f,j}$	Fuel consumption per km in the j^{th} year	L/km; kWh/km; kg/km
$P_{f,t}$	Fuel price in the t^{th} year	$/L; $/kWh; $/kg
C_m	Maintenance cost per km	$/km
i	Different types of emissions	
$E_{f,j}$	Emission cost from fuel consumption in the j^{th} year	$
$E_{b,j}$	Emission cost from battery manufacturing in the j^{th} year	$
$FF_{j,i}$	Emission factor of different types of fuels in the j^{th} year	g/L; g/kWh; g/kg
$FB_{j,i}$	Emission factor of emissions from battery manufacturing in the j^{th} year	g/kWh; g/kg
$P_{j,i}$	Price of emission i in the j^{th} year	$/t; $/kg

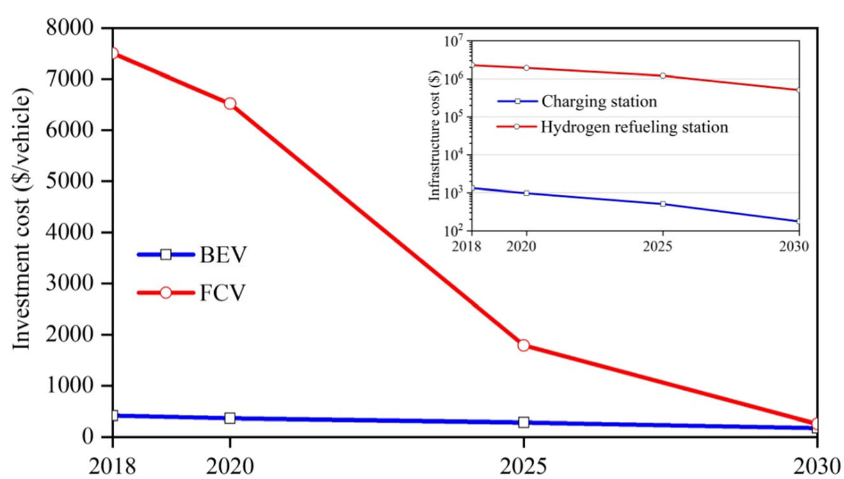

Fig. 3 Change tendency of infrastructure construction cost.

Results and discussions

This section discusses the results of the model in terms of the cost of various vehicle parts, including infrastructure costs, vehicle production costs, vehicle use, vehicle disposal costs, and external costs. Through this process, the lifecycle cost of vehicles was finally obtained, and sensitivity analyses were conducted for the main vehicle parameters.

Cost analysis of various parts of vehicles

In this section, we analyze and compare the cost differences of various parts of GVs, BEVs, and FCVs from 2018 to 2030.

Infrastructure cost

Fig. 3 shows the change tendency of the infrastructure cost per vehicle and the unit cost of infrastructure. From 2018 to 2030, the charging station cost per BEV is likely to decline to $176 from $411, while the hydrogen refueling station cost per FCV may decline to $254 from $7,600. The charging station cost per BEV will be lower than the hydrogen refueling station cost per FCV, but the decline rate of the charging station cost will be slower than that of hydrogen refueling stations because charging station technology is predicted to be more mature than hydrogen refueling station technology. At the same time, the unit cost of charging stations will decrease by 87%, which is higher than that of hydrogen refueling stations (78%).

Vehicle production costs

Fig. 4 compares the production costs of five vehicle models. From 2018 to 2030, the production cost of FCV120 is much higher than that of the other vehicle models because the fuel cell technology is immature, which results in a high cost for FCV. As fuel cell technology improves, the ratio that fuel cell accounts for in the cost of vehicle production gradually declines, while the cost difference between FCV and the other vehicle models gradually narrows. For example, in 2018 and 2030, the production cost of FCV120 is 88% and 45% higher than that of GV, respectively, meaning that the rate of the decline of FCV is faster than that of GV. In all types of vehicles, the production costs of GV and FCV are the lowest and highest before 2030, respectively, while the production cost of BEV75 is $441 (or 4%) higher than that of FCV60 in 2030. This difference is caused by the cost of the traction battery of BEV75, which is 6% higher than that of the fuel cells of FCV60.

Vehicle use costs

Fig. 5 shows the use cost of different types of vehicle models under different scenarios. This study assumes that the unit maintenance cost for the different BEV and FCV models is same. The

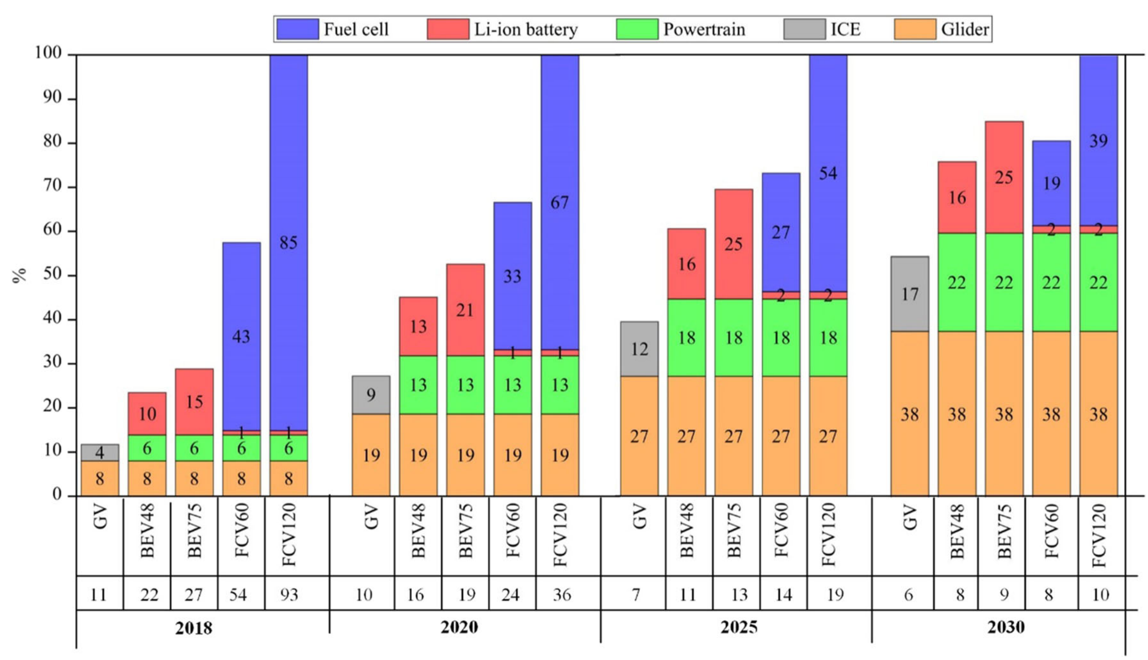

Fig. 4 Contribution of different parts for production cost of five vehicle models. Note: Different parts cost is normalized to the cost of FCV120 in the corresponding year. The x-axis represents the production cost of different vehicle types from 2018 to 2030. The y-axis represents the percentage of different parts of vehicles accounting in the FCV cost in same year. The unit of the second line in the x-axis is thousand $.

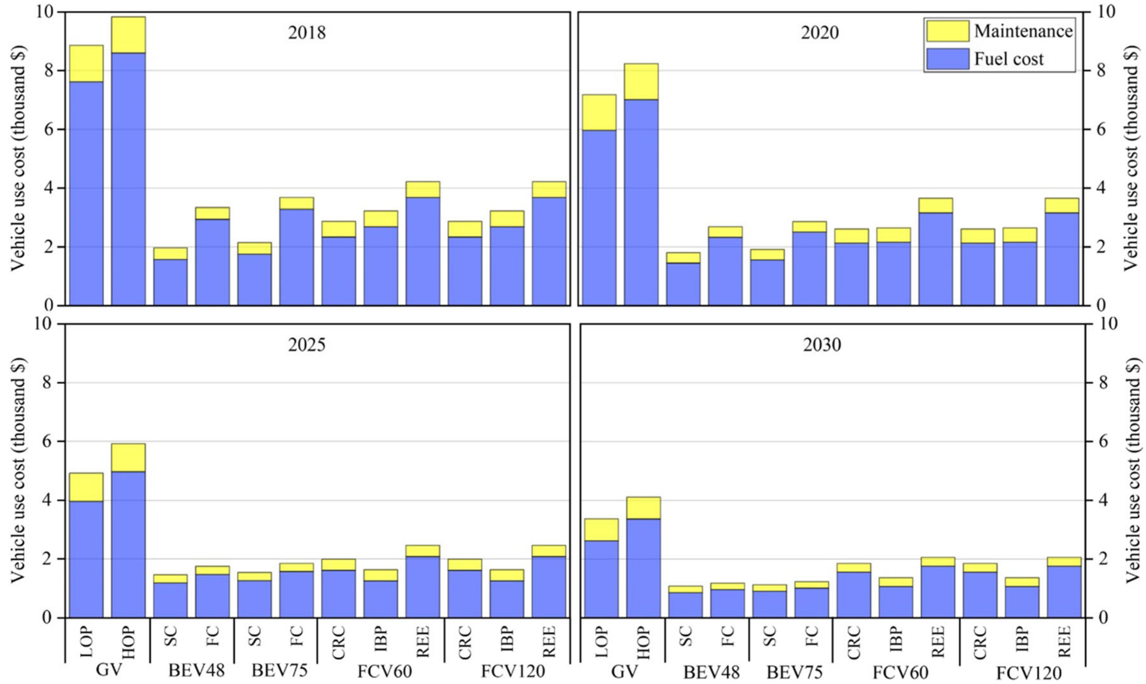

Fig. 5 Vehicle use cost of different types of vehicle models in different scenarios. Note: LOP, low oil price; HOP, high oil price; SC, slow charging; FC, fast charging; CRC, coal reforming with carbon capture and storage; IBP, industrial byproduct purification; REE, renewable energy electrolysis water.

use cost of GV is much higher than that of BEV and FCV. In 2018, the use cost of GV under the HOP scenario and FCV120 under the REE scenario was $9,836 and $4,219, respectively. The former's cost is 2.3 times that of the latter. By 2030, the use costs of the two vehicle models will decline to $4,115 and $1,582, respectively, while the difference in use costs will expand to 2.6 times because the rate at which hydrogen cost decline is faster than that of gasoline. The use costs of BEV under the SC scenario are lower than that of FCV from 2018 to 2030. The use cost of BEV under the FC scenario is higher than that of FCV under the CRC and IBP scenarios from 2018 to 2020 and is only higher than that of FCV under the IBP scenario after 2020 because the high charging service cost leads to the high electricity use cost under the FC scenario before 2025 (Fig. 1b).

Vehicle disposal costs

Fig. 6 compares the residual value of vehicles from 2018 to 2030. In 2018 and 2020, the residual value of BEV75 was highest among all vehicle models because the retired large-capacity battery has higher residual value. However, in the same year, the residual value of FCV60 is the lowest among all vehicle models due to the immaturity of fuel cell technologies. In 2025 and 2030, the residual value of FCV is higher than that of BEV75 because retired fuel cells can be used in household microgeneration. We also find that the residual value of GV declines slightly. From 2018 to 2030, the residual value of BEV75 declines by 68% while GV's residual value declines by 49%.

External costs

Table 9 compares the external costs of three types of vehicles. The external cost of BEV and FCV includes the emission cost of CO_2 and air pollution from fuel consumption and the battery manufacturing process, while the external cost of GV only includes the emission cost of fuel consumption. The external cost of BEV is much higher than that of GV due to the higher emission cost of battery manufacturing. However, if only fuel consumption is considered, the emission cost of BEV is lower than that of GV. From 2018 to 2030, the external cost of FCV is the lowest in three types of vehicles excluding the IBP scenario. The external cost of BEV is higher than that of FCV in 2018 and 2020, while the external cost of BEV48 is lower than that of FCV under the IBP scenario in 2025 and 2030. Further, we find that the emission cost of battery manufacturing from FCV is lower than that of BEV.

Lifecycle cost analysis

Fig. 7 compares the lifecycle costs of different types of vehicle models in different scenarios. In 2018 and 2020, the lifecycle cost of GV and FCV are the lowest ($15,726–$ 19,409) and highest ($31,933–$103,193) in all vehicle models, respectively. In 2025 and 2030, the lifecycle cost of GV is the lowest ($8,220–$11,371) under the LOP scenario, while the lifecycle cost of FCV120 is the highest ($11,191–$21,372) in all vehicle models. Regarding the ratio of production costs accounting

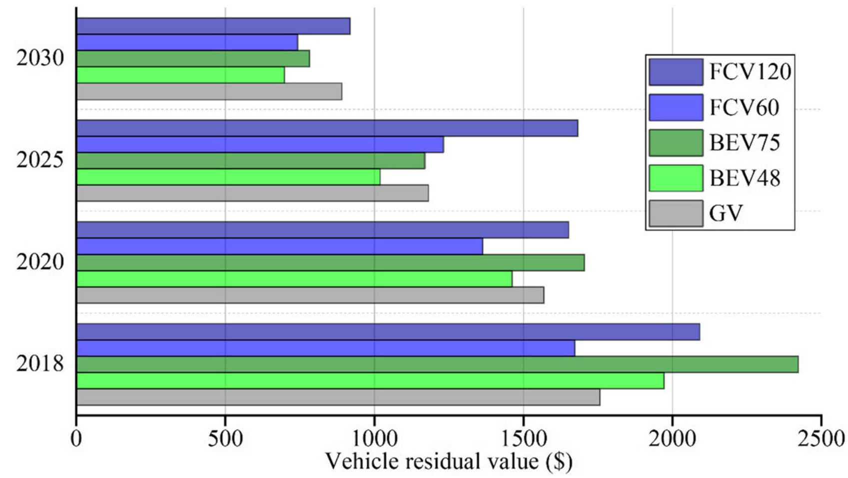

Fig. 6 Comparison of vehicles' residual value from 2018 to 2030.

for the lifecycle costs, BEV (84–89%) and FCV (82–90%) are much higher than that of GV (52–54%) because EV has lower operation costs and higher production costs. By 2030, the ratio of GV's production cost accounting for the lifecycle cost will be increased to 56–61%, while BEV and FCV will remain almost unchanged. This is because the production costs of EV have been sharply reduced with the development of battery technologies, while the total cost is also obviously reduced.

In 2018 and 2020, the lifecycle costs of BEV and FCV were much higher than that of GV. The lifecycle cost of BEV48 under the SC scenario is the lowest, while the lifecycle cost of FCV120 under the REE scenario is the highest in all vehicle models. In 2018, the lifecycle cost of BEV48 under the SC scenario is $4,429 (or 24%) higher than that of GV under the LOP scenario and is $3,456 (or 18%) higher than that of GV under the HOP scenario; the lifecycle cost of FCV120 under the REE scenario is $84,757 (or 4.6 times) higher than that of GV under the LOP scenario and is $83,784 (or 4.3 times) higher than that of GV under the HOP scenario. In 2020, the lifecycle cost of BEV48 under the SC scenario is $1,642 (or 10%) and $591 (or 3%) higher than that of GV under the LOP and HOP scenarios, respectively; the lifecycle cost of FCV120 under the REE scenario is $28,947 (or 1.8 times) and $27,896 (or 1.7 times) higher than that of GV under the LOP and HOP scenarios, respectively. In 2025, the lifecycle cost of BEV will be lower than that of GV for the first time. The lifecycle cost of BEV48 under the SC scenario will be $14 (or 0.1%) lower than that of GV under the HOP scenario and be $989 (or 9%) higher than that of GV under the LOP scenario, respectively. In 2030, the lifecycle cost of BEV48 under the SC scenario will be $419 (or 5%) lower than that of GV under the HOP scenario and be $323 (or 4%) higher than that of GV under the LOP scenario, respectively. Meanwhile, the lifecycle cost of BEV48 under the FC scenario will be $316 (or 4%) lower than that of GV under the HOP scenario. In 2025 and 2030, the difference between FCV and GV will be gradually narrowing; the lifecycle cost of FCV will be at least $120 (or 1%) higher than that of GV.

It is estimated that the lifecycle cost of all types of BEV will be lower than that of FCV before 2025. In 2018, the lifecycle cost of FCV60 under the CRC scenario was $33,232 (or 113%), which was the lowest in all scenarios but higher than that of BEV75 under the FC scenario. In 2025, the difference between FCV and BEV will be gradually narrowing; the lifecycle cost of FCV60 under the IBP scenario will be $2,011 (or 13%) higher than that of BEV75 under the FC scenario. In 2030, the lifecycle cost of FCV60 is lower than that of BEV75; the lifecycle cost of FCV60 under the IBP scenario will be $419 (or 4%) and $527 (or 5%) which will be lower than that of BEV75 under the SC and FC scenarios, respectively.

Sensitivity analysis

We further conduct a sensitivity analysis by evaluating the effect of a 20% increase in the key parameters (see Fig. 8). The annual driving kilometers, battery unit cost, carbon price, and unit maintenance cost have a positive impact on lifecycle costs. The vehicle efficiency and residual value ratio have a negative impact on the lifecycle costs. GV is found highly sensitive to annual driving kilometers, while BEV and FCV are found highly sensitive to battery unit cost. Three types of vehicles are found to have low sensitivity to carbon price. Thus, we conclude that the cost competitiveness of BEV and FCV will be improved as the annual driving kilometers increase and battery unit cost decreases. The price of carbon has slight influence on the lifecycle cost because the ratio of external cost in lifecycle cost is less than 3%.

Table 9 External cost comparison of three types of vehicles.

Vehicle types	Scenarios	2018		2020		2025		2030	
		Bat ($)	Fuel ($)	Bat ($)	Fuel ($)	Bat ($)	Fuel ($)	Bat ($)	Fuel ($)
GV			351		307		248		175
BEV48		313	242	193	226	144	177	99	131
BEV75		489	270	301	242	224	188	155	138
FCV60	CRC	52	91	36	88	27	74	20	56
	IBP	52	328	36	331	27	300	20	235
	REE	52	62	36	60	27	52	20	40
FCV120	CRC	71	91	52	88	39	74	31	56
	IBP	71	328	52	331	39	300	31	235
	REE	71	62	52	60	39	52	31	40

Note: Bat represents the emission cost of battery manufacturing; Fuel represents the emission cost of fuel consumption in the process of vehicle operation.

Conclusions and policy implications

To clarify whether EVs are cheaper than GVs, this study adopts the lifecycle cost method to investigate the cost of different types of passenger vehicles in China, extending the existing research to cover all the life stages of vehicles, including vehicle production, use, disposal, infrastructure construction, and external costs.

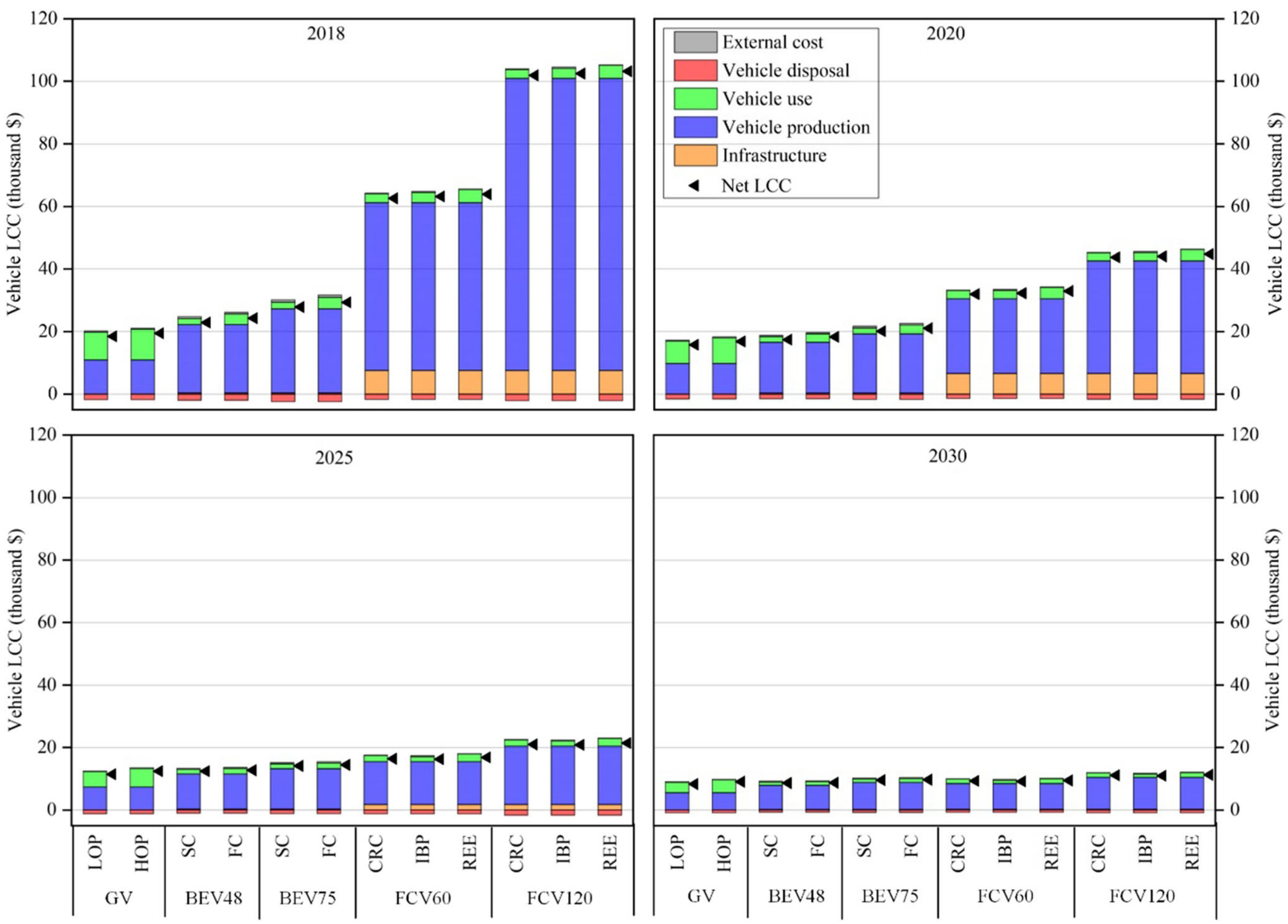

Fig. 7 Lifecycle cost comparison of different types of vehicle models in different scenarios. Note: x-axis represents the five vehicle models in different scenarios; Net LCC=infrastructure construction cost + vehicle production cost + vehicle use cost − vehicle disposal cost + external cost.

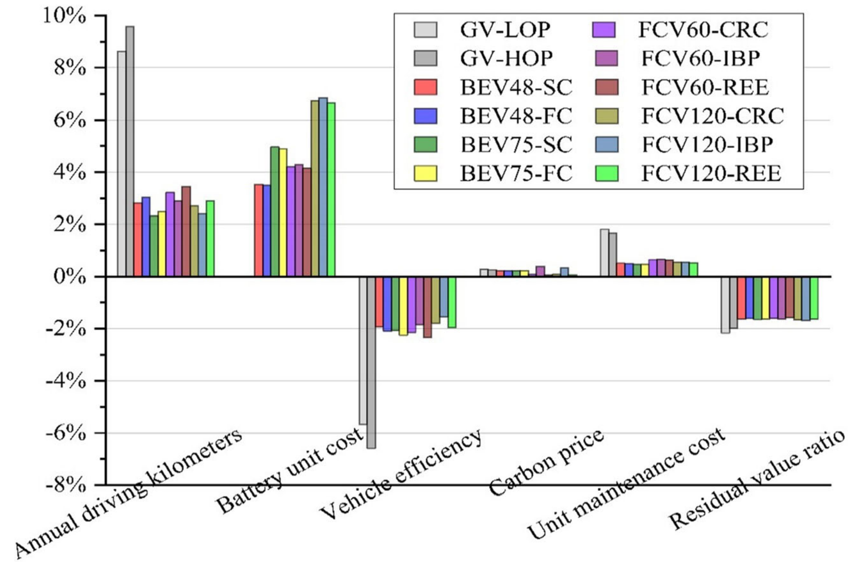

Fig. 8 Sensitivity analysis results for main parameters to lifecycle cost. Note: y-axis represents the increasing ratio of lifecycle cost due to a 20% increase in the key parameters.

We can draw the following conclusions from the results of this study: (1) currently (in 2018), our study indicates that FCVs have the highest lifecycle cost, followed by BEVs and then GVs; (2) in the future (from 2020 to 2030), the lifecycle cost of small-battery BEVs will be cheaper than that of GVs under part scenarios after 2025; the lifecycle cost of FCVs will be higher than that of GVs; and the lifecycle cost of low-power FCVs will be higher than that of large-battery BEVs before 2030.

The cost of vehicle production accounts for the largest proportion in the total lifecycle cost. For GVs, the ratio of production costs account for 57–68% of the total lifecycle costs, while the glide cost accounts for 68% of the total production cost from 2018 to 2030. For BEVs and FCVs, the ratio of production costs accounts for 89–97% of the total lifecycle cost and 73–92% from 2018 to 2030, respectively. The battery cost accounts for 21–52% and 26–76% of the total production cost of BEVs and FCVs, respectively.

This study also provides implications regarding the improvement of the cost competitiveness of EVs. First, keeping the technology updated will reduce costs. For example, the battery costs of EVs should be lowered by improving battery energy density and decreasing the battery capacity/power used in passenger vehicles. Second, for the market, the government should encourage the development of small-sized BEVs from 2025 to 2030 and low-power FCVs after 2030. Lastly, in order to realize the green development of the vehicle industry, the government should consider offering proper subsidy or incentive polices to enhance the competitiveness of EVs.

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Availability of data and materials The data that support the plots presented in this paper and other findings of this study are available from the corresponding author upon reasonable request.

Author contribution Lai Yang, Biying Yu, and Yi-Ming Wei designed the study. Lai Yang conducted data collection, modeling, and analysis and wrote the original draft of the paper. All authors revised and edited the manuscript. All authors have read and approved the final manuscript.

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Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

Appendix

Table 10 Relevant parameter of different vehicle types in China (Bekel and Pauliuk 2019; CATRC 2018; iCET 2019; IEA 2018a; Miotti et al. 2017; SAE-China 2017).

Year	Vehicle models	Engine power (kW)	Motor power (kW)	Energy/power density (kWh/kg; kW/kg)	Vehicle efficiency (L/km; kWh/km; kg/km)	Battery capacity/fuel cell power (kWh/kW)	Weight (battery/fuel cell) (kg)
2018	GV	81			0.058		
	BEV48		80	0.16	0.138	48	300
	BEV75		80	0.16	0.154	75	469
	FCV60		113	1.5	0.01	60	40
	FCV120		113	1.5	0.01	120	80
2020	GV	81			0.05		
	BEV48		80	0.25	0.133	48	192
	BEV75		80	0.25	0.143	75	300
	FCV60		113	2	0.009	60	30
	FCV120		113	2	0.009	120	60
2025	GV	81			0.04		
	BEV48		80	0.28	0.121	48	171
	BEV75		80	0.28	0.129	75	268
	FCV60		113	2.5	0.008	75	30
	FCV120		113	2.5	0.008	60	24
2030	GV	81			0.032	120	
	BEV48		80	0.35	0.11	48	137
	BEV75		80	0.35	0.116	75	214
	FCV60		113	3	0.007	60	20
	FCV120		113	3	0.007	120	40

Note: The efficiency of BEV48 and FCV60 use average data from the industry. BEV75 is given more weight than BEV60 due to the differences in battery capacity; the efficiency of BEV75 is lower than that of BEV60. According to Wang et al. (2019), vehicle efficiency will improve by 6–8% (this study assumes that the value is 7%) when vehicle weight is reduced by 10%. Thus, we obtained BEV75 efficiency in different years. Because the increasing weight of FCV120 is fewer than that of FCV60, we assume that the efficiency of FCV120 and FCV60 is the same.

Table 11 Emission factor of lithium battery manufacturing in China (CATRC 2018; Kim et al. 2016; SAE-China 2017).

	CO_2 (kg/kWh)	VOCs (g/kWh)	NO_X (g/kWh)	$PM_{2.5}$ (g/kWh)	SO_2 (g/kWh)
2018	88	54	253	113	801
2020	56	35	162	72	513
2025	50	31	144	65	458
2030	40	25	115	52	366

Table 12 Emission factor of gasoline and fuel cell manufacturing in China (ANL 2019).

	CO_2	VOCs	NO_X	$PM_{2.5}$	SO_2
Gasoline (g/L)	2747	1.82	2.23	0.13	0.9
Fuel cell manufacturing (g/kg)	23860	3.81	26.19	1.99	45.27

Table 13 Carbon price prediction in China (BHP 2017; CCF 2018).

	2018	2020	2025	2030
Carbon price ($/t)	3.1	6.3	11.0	17.1

Table 14 Air pollutant price from 2018 to 2030 in China (Tong et al. 2017).

	VOCs	NO_X	$PM_{2.5}$	SO_2
Pollutant price ($/kg)	4.6	7.2	8.8	4.0

Table 15 Emission factor of China's average electricity (ANL 2019; Greenpeace 2017; NDRC 2017).

	CO_2 (g/kwh)	VOCs (mg/kWh)	NOx (mg/kWh)	$PM_{2.5}$ (mg/kWh)	SO_2 (mg/kWh)
2018	614	60	404	50	1688
2020	586	58	358	46	1594
2025	527	57	353	51	1421
2030	444	56	350	67	1210

Table 16 Hydrogen emission factor in different production modes in China (ANL 2019; CHA 2019).

Production mode	CO_2 (kg/kg)	VOCs (g/kg)	NOx (g/kg)	$PM_{2.5}$ (g/kg)	SO_2 (g/kg)
Coal reforming with CCS	2.97	1.93	3.05	0.33	4.27
Industrial byproduct purification	15.92	5.23	5.14	3.14	11.72
Renewable energy electrolysis water	2.31	0.32	2.09	0.13	3.56

References

Ahmadi P, Kjeang E (2017) Realistic simulation of fuel economy and life cycle metrics for hydrogen fuel cell vehicles. Int J Energy Res 41: 714–727

ANL (2019) The greenhouse gases, regulated emissions, and energy use in transportation model. Argonne National Laboratory.

Bekel K, Pauliuk S (2019) Prospective cost and environmental impact assessment of battery and fuel cell electric vehicles in Germany. Int J Life Cycle Assess:1–18

BHP (2017) Carbon prices will rise to around $25 by 2030. Broken Hill Proprietary. https://finance.sina.com.cn/chanjing/ gsnews/2017-12-15/doc-ifyptkyk4744011.shtml. Accessed 25 Dec 2017

BNEF (2019) Global EV Outlook 2019. Bloomberg New Energy Finance

Cai Z, Ou X, Zhang Q, Zhang X (2012) Full lifetime cost analysis of battery, plug-in hybrid and FCEVs in China in the near future. Frontiers in Energy 6:107–111

CarbonBrief (2019) China's CO2 emissions grew slower than expected in 2018

CATRC (2017) The development roadmap of China's fuel cell vehicle. China Automotive Technology & Research Center

CATRC (2018) Annual report on energy-saving and new energy vehicle in China 2018. China Automotive Technology and Research Center. Posts & Telecom Press, Beijing

CCF (2018) China carbon price survey in 2018. China Carbon Forum. http://www.tanjiaoyi.com/article-24482-1.html. Accessed 11 Jul 2018

CEEP-BIT (2021) Review and future prospect of new energy vehicle industry in 2020. Center for Energy & Environmental Policy Research of Beijing Institute of Technology. https://ceep.bit.edu.cn/zxcg/ndycbg/45479ca7334542e5a164053dd4a62ec3.htm. Accessed 11 Jan 2021

CHA (2019) China hydrogen energy and fuel cell industry white paper. China Hydrogen Alliance

CPKB (2018) Summary of the latest electricity price nationwide. China Power Knowledge Base. http://www.sohu.com/a/271827080_146940. Accessed 28 Oct 2018

Crabtree G (2019) Battery technology: the coming electric vehicle transformation. Science 366:422–425

Dongfang Securities (2019a) Summary of new energy passenger vehicle sales in 2018. http://vip.stock.finance.sina.com.cn/q/go.php/vReport_Show/kind/industry/rptid/4482176/index.phtml. Accessed 16 Jan 2019

Dongfang Securities (2019b) Charging pile prosperity continued to rise, the industry chain to improve the quality and efficiency. http://www.doc88.com/p-1901752078174.html. Accessed 23 Apr 2019

E4tech (2019) The Fuel Cell Industry Review 2019. http://www.fuelcellindustryreview.com/. Accessed 25 Dec 2019

EIA (2014) Annual Energy Outlook 2014. U.S. Energy Information Administration. http://www.eia.gov/forecasts/archive/aeo14/. Accessed 7 Mar 2014

EV100 (2020) Comprehensive evaluation and promotion recommendations for the timetable for full electrification of vehicles in China

EV100, NRDC (2019) How to develop the charging service market in China. China EV100, Natural Resources Defense Council. http://nrdc.cn/information/informationinfo?id=204&cook=2. Accessed 1 Apr 2019

FUA (2019) The amount of China's fuel cell vehicle will reach 14,600 units by 2020. Finance Union Agency. http://finance.sina.com.cn/china/2019-06-21/doc-ihytcerk8351931.shtml. Accessed 21 Jun 2019

Greenpeace (2017) Co-benefits of wind and solar power in China. https://www.sohu.com/a/133583745_617284.Accessed 12 Apr 2017

Hagman J, Ritzen S, Stier JJ, Susilo Y (2016) Total cost of ownership and its potential implications for battery electric vehicle diffusion. Res Transp Bus Manag 18:11–17
Hao H, Wang M, Zhou Y, Wang HW, Ouyang MG (2015) Levelized costs of conventional and battery electric vehicles in china: Beijing experiences. Mitig Adapt Strateg Glob Chang 20:1229–1246
Hao H, Cheng X, Liu ZW, Zhao FQ (2017) Electric vehicles for greenhouse gas reduction in China: a cost-effectiveness analysis. Transport Res D-Tr E 56:68–84
iCET (2019) A study on China's timetable for phasing-out traditional ICE-Vehicles. Innovation Center for Energy and Transportation
IEA (2018a) Global EV Outlook 2018: towards cross-modal electrification. International Energy Agency. https://webstore.iea.org/global-ev-outlook-2018. Accessed 21 Jun 2018
IEA (2018b) Emission factors 2018 database documentation. International Energy Agency
IEA (2019a) The future of hydrogen. International Energy Agency. https://www.iea.org/hydrogen2019/. Accessed Jun 2019
IEA (2019b) Global energy and CO2 status report 2018. International Energy Agency
IEA (2020) Global EV Outlook 2020: entering the decade of electric drive. International Energy Agency
IRENA (2019) Hydrogen: a renewable energy perspective. International Renewable Energy Agency. https://www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective. Accessed Sept 2019
Jochem P, Doll C, Fichtner W (2016) External costs of electric vehicles. Transport Res D-Tr E 42:60–76
Kim HC, Wallington TJ, Arsenault R, Bae C, Ahn S, Lee J (2016) Cradle-to-gate emissions from a commercial electric vehicle li-ion battery: a comparative analysis. Environ Sci Technol 50:7715–7722
Li HW (2019) Residual value evaluation of battery electric vehicle based on replacement cost method. Automobile & Parts 3:61–63
Li X, Yu B (2019) Peaking CO2 emissions for China's urban passenger transport sector. Energ Policy 133:110913
Lipman TE (2000) Manufacturing and lifecycle costs of battery electric vehicles, direct-hydrogen fuel cell vehicles, and direct-methanol fuel cell vehicles. In: 35th Intersociety Energy Conversion Engineering Conference & Exhibit, pp 1352–1358
Liu R, Ding Z, Jiang X, Sun J, Jiang Y, Qiang W (2020) How does experience impact the adoption willingness of battery electric vehicles? The role of psychological factors. Environ Sci Pollut R 27: 25230–25247
Martínez-Lao J, Montoya FG, Montoya MG, Manzano-Agugliaro F (2017) Electric vehicles in Spain: an overview of charging systems. Renew Sust Energ Rev 77:970–983
MEE (2018) China vehicle environmental management annual report. Ministry of Ecology and Environment of China. http://www.mee.gov.cn/xxgk2018/xxgk/xxgk15/201806/t20180601_630215.html. Accessed 1 Jun 2018
Miotti M, Hofer J, Bauer C (2017) Integrated environmental and economic assessment of current and future fuel cell vehicles. Int J Life Cycle Assess 22:94–110
NDRC (2014) Notice on electricity pricing policy for electric vehicles. National Development and Refrom Commission. http://jgs.ndrc.gov.cn/zcfg/201408/t20140801_621052.html. Accessed 1 Aug 2014
NDRC (2017) The 13th five-year plan for power industry development (2016-2020). National Development and Reform Commission. http://www.ndrc.gov.cn/fzgggz/fzgh/ghwb/gjjgh/201706/t20170605_849994.html. Accessed 5 Jun 2017
Nealer R, Reichmuth D, Anair D (2015) Cleaner cars from cradle to grave: how electric cars beat gasoline cars on lifetime global warming emissions. Union of Concerned Scientists
Newbery D, Strbac G (2016) What is needed for battery electric vehicles to become socially cost competitive? Econ Transp 5:1–11
Nissan (2019) 2019 Nissan Leaf Specifications. http://www.nissanusa.com/electric-cars/leaf/versions-specs/. Accessed 8 Aug 2019
Peng T, Ou X, Yuan Z, Yan X, Zhang X (2018) Development and application of China provincial road transport energy demand and GHG emissions analysis model. Appl Energy 222:313–328
Plotkin SE, Singh MK, Ornl (2009) Multi-path transportation futures study: vehicle characterization and scenario analyses. Argonne National Laboratory
Qiao QY, Zhao FQ, Liu ZW, Hao H (2019) Electric vehicle recycling in China: economic and environmental benefits. Resour Conserv Recycl 140:45–53
QZIRI (2019): Analysis on the development and trend of China's gas station industry in 2018. Qianzhan industry research institute
Ruffini E, Wei M (2018) Future costs of fuel cell electric vehicles in California using a learning rate approach. Energy 150:329–341
Rusich A, Danielis R (2015) Total cost of ownership, social lifecycle cost and energy consumption of various automotive technologies in Italy. Res Transp Econ 50:3–16
SAE-China (2016) Hydrogen fuel cell vehicle technology roadmap. Society of Automotive Engineers of China
SAE-China (2017) Technology roadmap for energy saving and new energy vehicles. China Machine Press, Beijing
SAE-China (2018) Implementation plan of eight key projects of mid-and-long term development plan of automobile industry. Society of Automotive Engineers of China. https://max.book118.com/html/2018/1121/8125037011001134.shtm. Accessed 21 Nov 2018
Shen W, Han WJ, Wallington TJ (2014) Current and future greenhouse gas emissions associated with electricity generation in China: implications for electric vehicles. Environ Sci Technol 48:7069–7075
Sun YL, Ogden J, Delucchi M (2010) Societal lifetime cost of hydrogen fuel cell vehicles. Int J Hydrogen Energ 35:11932–11946
Tong F, Hendrickson C, Biehler A, Jaramillo P, Seki S (2017) Life cycle ownership cost and environmental externality of alternative fuel options for transit buses. Transport Res D-Tr E 57:287–302
Toyota (2019) 2019 Toyota Corolla specifications. https://www.ftms.com.cn/carSellHelp/carBrandModels. Accessed 18 Nov 2019
Wang DW, Zamel N, Jiao K, Zhou YB, Yu SH, Du Q, Yin Y (2013) Life cycle analysis of internal combustion engine, electric and fuel cell vehicles for China. Energy 59:402–412
Wang ZH, Zhao CY, Yin JH, Zhang B (2017) Purchasing intentions of Chinese citizens on new energy vehicles: how should one respond to current preferential policy? J Clean Prod 161:1000–1010
Wang M, Xia S, Pan H (2019) Status and prospect of automobile lightweight technology. The second thesis contest of automobile technologist in 2019
Wang L, Shen W, Kim HC, Wallington TJ, Zhang Q, Han W (2020) Life cycle water use of gasoline and electric light-duty vehicles in China. Resour Conserv Recycl 154:104628
Wanlian Securities (2019) In the early stage of fuel cell vehicle industry, infrastructure should be priority to develop. http://www.doc88.com/p-1015069523986.html. Accessed 5 May 2019
Xiao Q (2018) Market scale of electric vehicle charging service fee and charging standard of each province. http://www.istis.sh.cn/list/list.aspx?id=11621. Accessed 30 Oct 2018
Yang L, Yu B, Yang B, Chen H, Malima G, Wei Y-M (2020) Life cycle environmental assessment of electric and internal combustion engine vehicles in China. J Clean Prod 124899
Yang B, Wei Y-M, Liu L-C, Hou Y-B, Zhang K, Yang L, Feng Y (2021) Life cycle cost assessment of biomass co-firing power plants with CO2 capture and storage considering multiple incentives. Energy Econ 96:105173
Yu B, Ma Y, Xue M, Tang B, Wang B, Yan J, Wei Y-M (2017) Environmental benefits from ridesharing: a case of Beijing. Appl Energy 191:141–152

Zhang YP, Han QL (2017) Development of electric vehicles for China's power generation portfolio: a regional economic and environmental analysis. J Clean Prod 162:71–85

Zhao X, Doering OC, Tyner WE (2015) The economic competitiveness and emissions of battery electric vehicles in China. Appl Energy 156:666–675

Zhao X, Ma J, Wang S, Ye Y, Wu Y, Yu M (2019) Developing an electric vehicle urban driving cycle to study differences in energy consumption. Environ Sci Pollut Res Int 26:13839–13853

Zhao X, Ye Y, Ma J, Shi P, Chen H (2020) Construction of electric vehicle driving cycle for studying electric vehicle energy consumption and equivalent emissions. Environ Sci Pollut Res Int 27:37395–37409