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Life Cycle Energy, Environmental, and Economic Impact Assessment of Hydrogen Fuel Cell Electric Vehicles: A Case Study in China

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ABSTRACT

Although hydrogen fuel cell electric vehicles (HFCEVs) are more environment-friendly compared to the conventional vehicles, their energy consumption, emissions, and the economic impacts involved remain unclear from a life cycle perspective. Therefore, these aspects of HFCEVs were investigated herein using the GREET model under operating conditions for China. The results showed that HFCEVs can reduce the life cycle cost by 13.2%, energy consumption by 9.7%, and greenhouse gas emissions by 13.1% in comparison with gasoline internal combustion engine vehicles (GICEVs). However, the life cycle results showed that HFCEVs can increase the acidification potential by 111.7%, aerosol pollution by 273.9%, and human toxicity potential by 87.7%. Therefore, compared with GICEVs, the impacts of energy consumption and environmental emissions of HFCEVs are transferred from the use phase to the production phase of the fuel, and the purchase cost of HFCEVs is shifted from end users to the government.

Keywords: life cycle assessment, hydrogen fuel cell electric vehicle (HFCEV), battery electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV), GREET model

1. INTRODUCTION

Conventional vehicles or gasoline internal combustion engine vehicles (GICEVs) are a primary source of air pollutants and greenhouse gas (GHG) emissions. Hydrogen fuel cell electric vehicles (HFCEVs) do not emit such pollutants during the use phase, and their fueling time and total mileage are similar to GICEVs; hence, HFCEVs are regarded as one of the best alternatives to GICEVs. Driven by a series of policies formulated by the Chinese government, the production and sale of HFCEVs in China reached to 2,833 and 2,737 units in 2019, respectively. These values represent increases of 85.5% for production and 79.2% for sale over the previous year [1]. Despite the surge in HFCEV use, it is still unclear whether HFCEVs reduce energy consumption, environmental emissions, and total costs from a life cycle perspective under Chinese market conditions in comparison with other conventional vehicles. This research gap is not conducive to the promotion of HFCEVs in China.

Various researchers have studied the life cycle environmental impacts and costs of HFCEVs in different countries. Although the majority of existing studies concluded that HFCEVs reduce greenhouse gas emissions more than other types of new energy vehicles, such research also found that HFCEVs may increase or decrease environmental impacts depending on the hydrogen production pathways, technical conditions, and presence of other factors [2,3]. In terms of cost, current research argues that HFCEVs have no competitive advantage over GICEVs because of their high production cost [4,5]. In general, the existing literature has mainly focused on the fuel cycle of HFCEVs in China, and there is presently a lack of evaluation data on the vehicle cycle.

To fill this research gap, we built a life cycle assessment model with Chinese parameters to investigate the life cycle energy consumption, environmental impacts, and comprehensive cost of HFCEVs in China. This study’s novelty is two-fold, namely, (1) the energy, environmental, and cost

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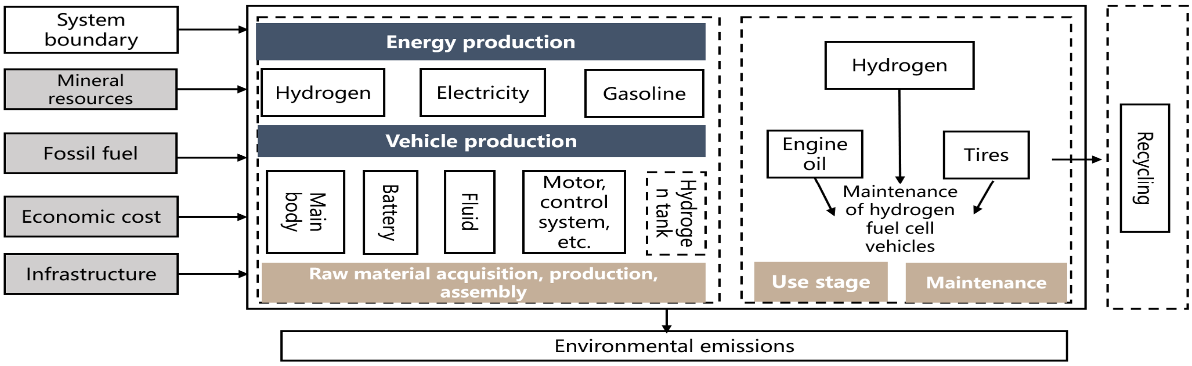

Fig 1 System boundary of the life-cycle assessment

impacts of HFCEVs were assessed under the same analytical framework; and (2) the latest application status of China's hydrogen production technology was reflected in the analysis.

2. METHODS AND DATA

2.1 Life cycle assessment model

2.1.1 Scope definition, functional unit, and system boundary

We used "1 km of distance traveled" as the functional unit. The life cycle assessment of an HFCEV consisted of the following three phases: (1) the phase of raw material production, which was divided into fuel production and vehicle production; (2) the use phase, which included vehicle operation and energy consumption; and (3) the maintenance phase, which included the maintenance and repair of the vehicle. The system boundary of the study is shown in Figure 1.

For the analysis, we selected Toyota's HFCEV, battery electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV), and GICEV models, which have relatively high market shares (Table 1). The indicators we used were energy consumption (hydrogen, gasoline, and electricity), air pollutant emissions ($PM_{2.5}$, PM_{10}, NO_x, CO, SO_2, and volatile organic compounds (VOC)), and GHG emissions (CO_2, CH_4, and N_2O). We assumed that the total mileage of a vehicle during its life cycle was 200,000 km.

Table 1 Information for specific car models

Vehicle Type	GICEV	PHEV	BEV	HFCEV
Toyota model	Corolla	Prius	iA5	Mirai
Energy source	gasoline	gasoline, Ni-MH battery	ternary lithium battery	hydrogen
Endurance mileage (km)	-	60	510	520
Fuel economy (fuel/100 km)	7.5 L	4.3 L or 15 kW·h	13.1 kW·h	1.04 kg

In this study, we chose the most widely used technology pathway for hydrogen production and consumption in China, which involves (1) the production of hydrogen from coal gasification, (2) transportation of the hydrogen to refueling stations via long tube trailers; and (3) filling of the hydrogen fuel in an HFCEV.

2.1.2 Energy and environmental impact assessment

The life cycle assessment for energy consumption and environmental impacts consisted of the following two parts: the fuel cycle (well-to-wheel, WTW) and the vehicle cycle. The fuel cycle was further divided into the following two parts: (1) the upstream stage (well-to-tank, WTT), including all activities before the final use of a fuel, such as raw material extraction and treatment; and (2) the downstream stage (tank-to-wheel, TTW), including the vehicle operation, which consumes energy directly. The vehicle cycle mainly included the extraction and processing of raw materials, manufacturing and assembly of vehicle parts, maintenance, and vehicle recycling. The GREET 2019 model was used to calculate the life cycle impacts of HFCEVs in China.

Based on the CML 2001 guidelines, we further categorized the environmental impacts into the following four groups: energy usage (EU), global warming potential (GWP), acidification potential (AP), and human toxicity potential (HTP). In addition, this study also used the aerosol formation potential (AFP) to evaluate the impact of haze. The characterization factors were obtained from the ISO 14041 standard.

2.1.3 Cost analysis

The life cycle cost assessment included the following two parts: the total cost of ownership (TCO) and the environmental cost. The TCO was composed of the vehicle purchase cost, the use cost during the operation of the vehicle, and the vehicle recycling cost. This study assumed that vehicles were purchased in 2019 and the lifespan of a vehicle was 10 years.

Environmental cost was estimated through the environmental treatment cost.

2.2 Life cycle inventory data

Most of the data in this study came from various sources in China, including statistical yearbooks, government reports, and peer-reviewed articles. However, when Chinese data were unavailable, foreign data were used in a few cases, such as for the combustion emission factors of fossil fuels for $PM_{2.5}$, PM_{10}, CO, CH_4, N_2O, NO_x, and VOC; these data were obtained from the United States Environmental Protection Agency (US EPA).

3. RESULTS AND DISCUSSION

3.1 Life cycle energy consumption assessment

The results indicated that the life cycle energy consumption of an HFCEV is 3.64 MJ/km, which is 9.7% (0.39 MJ/km) lower than that of a GICEV, but 29.5% (0.83 MJ/km) and 59.0% (1.35 MJ/km) higher than that of a PHEV and BEV, respectively (Figure 2). Most of the energy is consumed in the fuel cycle of these vehicles, and the computed values accounted for 85.6%, 79.3%, 77.4%, and 69.4% of the total energy for GICEVs, HFCEVs, PHEVs, and BEVs, respectively. Furthermore, more than 60% of the life cycle energy of a GICEV is consumed in the TTW stage, while over 40% of the total energy of other new energy vehicles is utilized in the WTT stage, according to the assessment results. Therefore, in the context of China's current energy structure and technology, a viable way to reduce the life cycle energy consumption of HFCEVs is to improve the energy efficiency of the production, transportation, and storage of hydrogen.

3.2 Life cycle environmental impact assessment

The results indicated that the life cycle GHG emissions of an HFCEV are 297.6-CO_2/km, a value lower than that of GICEVs but higher than that of PHEVs and BEVs (Figure 3). The emissions of a GICEV and PHEV are mainly from the TTW stage, which accounted for 57.9% and 40.2% of the total emissions, respectively. In comparison, 80.5% of HFCEV emissions and 73.2% of BEV emissions were from the WTT stage.

According to the assessment, an HFCEV will emit 66.5%, 31.0%, and 11.5% more SO_2 throughout its life cycle compared to a GICEV, PHEV, and BEV, respectively (Figure 4). Moreover, 67.6% of the SO_2 emissions from HFCEVs are from the WTT stage. The PM_{10} emissions of an HFCEV showed a similar pattern to SO_2 emissions. In addition, the CO and VOC emissions of an HFCEV are mainly from the vehicle cycle, which accounted for 90.6% and 94.1% of its life cycle emissions, respectively.

The results indicated that compared with a GICEV, an HFCEV has 273.9%, 111.7%, and 87.7% more AFP, AP, and HTP, respectively (Table 2). This is because a large amount of particulate matter is emitted during the extraction and treatment of raw materials that are used in hydrogen production from coal gasification. In addition, the GWP of an HFCEV was found to be only 13.1% smaller than that of a GICEV. Therefore, with hydrogen mainly produced from coal gasification and coal dominating the energy structure in China, the overall environmental benefits of HFCEVs are not as good as those of BEVs and PHEVs.

In summary, although an HFCEV does not produce

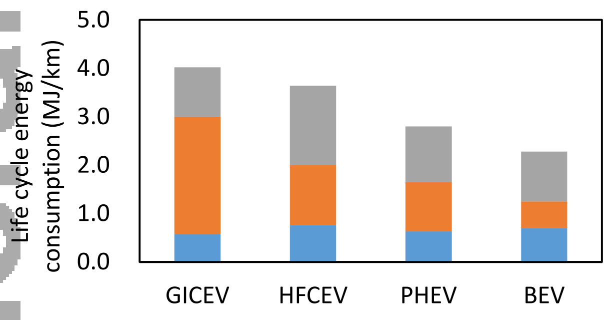

Fig 2 Life cycle energy consumption of vehicles

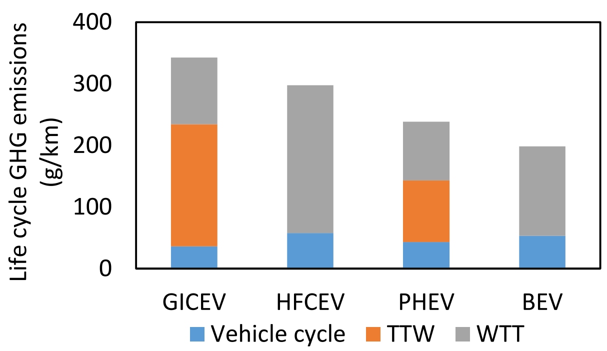

Fig 3 Life cycle GHG emissions of vehicles

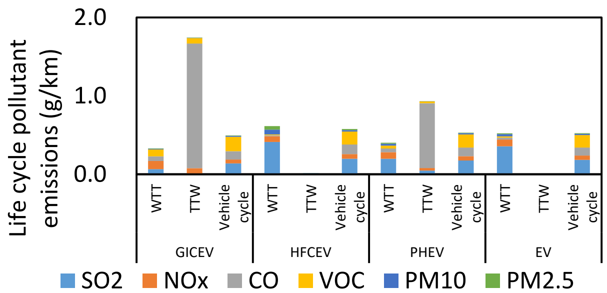

Fig 4 Life cycle air pollutant emissions of vehicles

environmental emissions in the TTW stage, large amounts of GHGs, SO_2, and particulate matter are emitted in the WTT stage. Therefore, the most viable way to improve the life cycle environmental benefits of HFCEVs in China is to reduce the environmental emissions from hydrogen production.

Table 2 Potential environmental impacts of vehicles

Impact Category	GICEV	HFCEV	PHEV	BEV
GWP (g CO_2-eq/km)	342.5	297.6	238.3	198.5
AP (mg SO_2-eq/km)	319.9	677.1	506.4	610.6
AFP (mg PM_{10}-eq/km)	41.8	156.3	66.0	66.8
HTP (mg 1,4 DB-eq)	446.3	837.9	649.9	759.5

3.3 Life cycle cost assessment

Despite high government subsidies, the life cycle cost of HFCEVs is still higher than that of PHEVs and BEVs. The total cost of an HFCEV is 547.5 thousand yuan, 13.2% (83.5 thousand yuan) lower than a GICEV's cost, 10.6% (52.4 thousand yuan) higher than a PHEV's cost, and 43.1% (164.8 thousand yuan) higher than a BEV's cost (Figure 5). The reason for this result is that the technology and supply chains for electric vehicles are relatively mature, while those for the HFCEV industry are in a stage of infancy, and the production cost is higher because of the small production scale. In the future, with further improvements in hydrogen technology and the expansion of market capacity, HFCEVs are expected to achieve rapid cost reductions through large-scale production efficiencies.

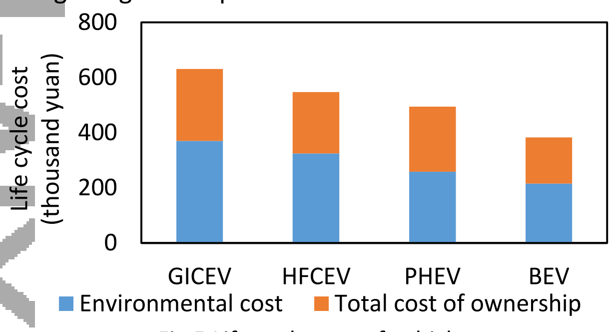

Fig 5 Life cycle cost of vehicles

3.4 Uncertainty of the results

The uncertainty of the results presented in this study mainly came from the input data used in the LCA model. Although most input data were obtained from China, some emission factors were sourced from other countries, such as the US EPA's air pollutant emission factors for fossil fuels, which could have increased the uncertainty. In addition, the study's base year was 2019, but because of the lack of contemporary data, we had to use old parameters from various years for certain analyses. This could have contributed to the uncertainty. Lastly, truncation errors related to the ignorance of some process flows, such as the construction of automobile factories, could also have contributed to the uncertainty.

4. CONCLUSIONS

With hydrogen mainly produced from coal gasification and coal dominating the energy structure in China, the energy, environmental, and economic benefits of HFCEVs are not significant from a life cycle perspective. Compared with GICEVs, the energy consumption and environmental emissions of HFCEVs are transferred from the use phase to the production phase of the fuel, and the purchase cost of HFCEVs is shifted from end users to the government. Therefore, under the current technological and market conditions in China, HFCEVs lack a comparative advantage over electric vehicles. In the future, as China's hydrogen production technology continues to mature and the large-scale production of HFCEVs is accelerated, the comparative advantage of HFCEVs is expected to emerge.

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