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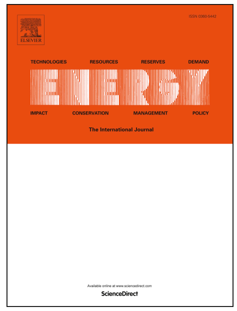

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Fuel-cycle based environmental and economic assessment of hydrogen fuel cell vehicles in China

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Abstract: Hydrogen fuel cell vehicle (HFCV) is regarded as one of the most promising technical paths towards transportation sector's carbon neutrality in China, to assess the environmental and economic performances of HFCV is of great significance for emission reduction policies construction. This study carries out a fuel-cycle analysis of HFCV in 2020 and 2030 using the GREET model. 19 fuel paths are generated by combining mainstream patterns of HFCV's hydrogen production, storage and transportation, and filling processes. The results show a contradiction at present that, hydrogen production from electrolytic water with renewable energy has the lowest air pollutants and carbon emissions, while the traditional hydrogen production from natural gas, coke oven gas and coal, etc., have better economic performances. However, the decreasing trends of both pollution emissions and costs of HFCVs are expected towards 2030. Specifically, the CO_2, VOC, NO_x, $PM_{2.5}$ and SO_2 emissions would decrease by 21.58%, 16.55%, 22.35%, 22.49%, and 18.76%, respectively. The total cost of fuel path with the participation of renewable energy decreases rapidly, which is mainly benefit from its lower environmental externality costs. This study put forward policy suggestion of improving the hydrogenation infrastructure construction, accelerating the large-scale and low-cost renewable energy hydrogen production.

Keywords: Hydrogen fuel cell vehicle (HFCV); fuel-cycle analysis; carbon emission reduction; environmental externality cost; hydrogen production from electrolytic water

1. Introduction

Global warming and greenhouse effect are threatening the sustainable development of society (Diffenbaugh et al., 2017). Over the past decade, carbon emissions related to fossil energy have continued to grow, accounting for 65% of total greenhouse gases in 2019 (IEA, 2021). To explore a more resilient, inclusive and sustainable way of energy production and consumption is increasingly

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urgent, and the establishment of a clean, low-carbon, safe and efficient energy system with greater proportion of renewable energy is a critical solution (Marques, et al., 2018; Sharma et al., 2020; Zeng et al., 2021). China has taken the initiative to achieve "carbon peak" in 2030 and "carbon neutrality" in 2060, and has actively promoted the transformation of towards the clean and high-quality energy development (Liu, et al., 2019). At present, transportation sector becomes one of the main industries of energy consumption in China. The continuous growth of car ownership has brought severe environmental challenges, accounting for about 10% of total carbon emissions (Li and Yu, 2019; MEE, 2021). As a clean and efficient secondary energy, hydrogen has gradually been applied and developed into an important alternative for the third energy revolution. One of the most widely used and promising applications of hydrogen energy is hydrogen fuel cell vehicle (HFCV), aiming at reducing greenhouse gas and air pollutants emissions from the transportation industry (Ehrenberger, 2019; Mohammed, et al., 2019; Wang, et al., 2020; Ren, et al., 2020). Cernat et al. (2020, 2021) have shown that hydrogen can be a viable alternative fuel for modern diesel engines, offering benefits on efficiency and performance improvement. Therefore, to assess and simulate the environmental performances of HFCV is of great significance for energy conservation and emission reduction policies construction for low-carbon transportation.

In the previous studies, automobile life cycle environmental assessments are mostly carried out in two dimensions: the fuel-cycle analysis and the vehicle-cycle analysis. DeLuchi (1991) has firstly evaluated the life cycle energy consumption and greenhouse gas emission of automobile from the aspects of fuel types and body materials, concluding that energy conservation and emission reduction of new energy vehicles are better than those of the traditional fossil-fuel vehicles. US DOE Argonne National Laboratory (ANL) developed the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model in 1995, which is specially used to evaluate the life cycle energy consumption and pollutant emission of different fuels and types of vehicles (Wang, 2002). Based on this, researches have been carried out on the environmental benefit of HFCV under different hydrogen production paths (Zamel and Li ,2006; Joseck, et al., 2008; Huo, 2009; Simons and Bauer, 2015).

The hydrogen fuel cell vehicle (HFCV) industry mainly includes hydrogen production, storage and transportation, and filling processes (Lin, 2018; Alvarez-Meaza, et al., 2020). The traditional hydrogen production technologies are mature with good economics, but their environmental benefits are still unsatisfactory (Yoo et al., 2018; Zheng et al., 2019; Zhang, et al., 2021). Therefore, attentions are paid to exploring the energy consumption and pollutant emission reduction of cleaner hydrogen

fuel paths. In the hydrogen production process, efforts have been putting in CO_2 capture technologies attached to traditional hydrogen production, hydrogen production from biomass, "green hydrogen" production from electrolytic water technology using renewable energy, etc. (Nazir, et al., 2019; Nematollahi, et al., 2019; Mazzeo, et al., 2022). In addition, to explore an economic and efficient hydrogen storage, transportation and filling mode is also very critical in the HFCV industry chain (Ajanovic, et al., 2020; Lu et al., 2022). At present, hydrogen storage methods are mainly divided into three types: low-temperature liquid hydrogen storage, high-pressure gaseous hydrogen storage and hydrogen storage materials, and mainly gaseous hydrogen storage (Lahnaoui, et al., 2021). Last but not least, finding more suitable hydrogenation station planning scheme also have to be settled urgently and rationally (Cesar, et al., 2019). However, most of the previous studies are focusing on traditional fossil raw materials hydrogen production paths, lacking concerns of the renewable energy and the carbon capture use and storage (CCUS) technologies.

In terms of economic benefits of HFCVs, studies related to hydrogen production cost show that the hydrogen production from coal is the most economical form at present, and hydrogen productions from natural gas and industrial by-production have also great development potential (Huang, 2019). As the hydrogen production from electrolytic water with renewable energy are getting promoted, the cost is expected to drop rapidly with the technological breakthroughs and commercial operation in the near future (Wang et al., 2022; Xu et al., 2022; Liu et al., 2022). The costs of storage, transportation and hydrogenation are also key factors affecting HFCV's economic performance (Shan, 2020). In addition, more attention should be paid to environmental or social cost of HFCV (Zhang, 2021). Al-Qahtani (2021) considers that by adding costs of human health, ecosystem quality, and resources, the actual total costs of HFCV have been revealed. While most of the existing studies in China have compared direct economic costs of fuel paths, and the externality costs of HFCVs, in other words, the cost of pollution and carbon emissions need to be further evaluated.

In recent years, China's government has intensively support HFCV industry. Thus far China has built more than 270 hydrogen refueling stations, accounting for about 40% of the global total stations (NEA, 2022). However, the researches on fuel-cycle analysis of HFCV in China are still rare and lack of corresponding data support. It is necessary to establish a localized database and evaluate the environmental and economic benefits of the various HFCVs fuel paths considering the technological innovation in the long run, so as to make a more systematic fuel-cycle evaluation framework suitable for China. Meanwhile, although the hydrogen is regarded as clean energy, the CO_2 and pollutant

emissions also exist during the processes such as hydrogen production, storage and transportation, which may vary significantly under different HFCV's fuel paths. This study reveals the actual energy-saving and emission-reduction benefits of HFCV under different fuel paths, and takes the environmental economic benefits into consideration as well. The results can be served as a benchmark situation for reference, and provides theoretical basis and suggestions for the green development path planning of HFCV industry and transportation sector in China.

2. Methodology and data

2.1. Fuel cycle analysis for HFCV based on GREET_2021

Generally, the life cycle of automobile can be divided into the fuel cycle and material cycle. The fuel cycle describes the process from the fuel generation to final combustion, mainly includes two phases: well-to-pump (WTP) and pump-to-wheels (PTW). The WTP stage represents the upstream production of fuel, includes raw material recovery and processing, transportation and storage, fuel filling, etc. The PTW stage covers downstream vehicle operation activities, mainly refers to the fuel consumption process during driving. The material cycle includes the acquisition of automotive raw materials, material processing and manufacturing, production of automotive parts, vehicle assembly, vehicle scrapping and recycling. A series of studies have shown that energy consumption and greenhouse gas emissions in the whole life cycle are mainly concentrated in the fuel cycle (70%-90%) (Nansai et al., 2002; Zamel et al., 2006; Lin, 2018), while the material cycle takes a relatively small proportion. This study focuses on the analysis of the fuel cycle, or the so-called well-to-wheels (WTW) stage analysis (shown in Fig.1), the fuel cycle evaluation of HFCV is carried out based on GREET_2021 software developed by Argonne National Laboratory.

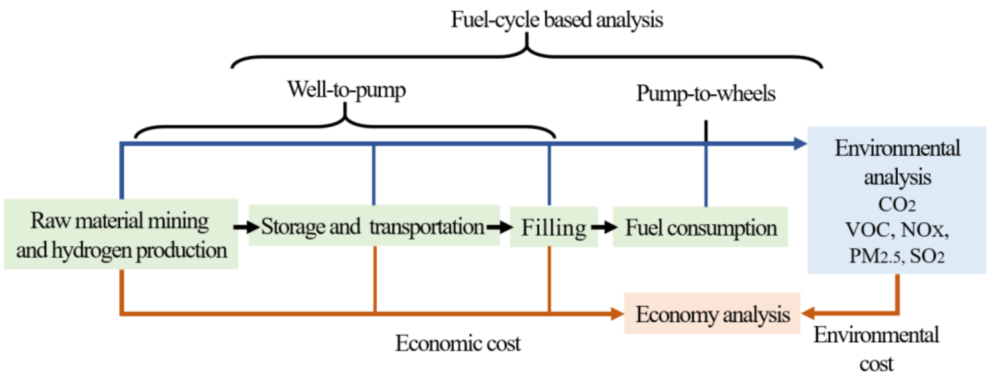


Fig. 1 Boundary of environmental and economy asssenment of HFCV based on fuel-cycle analysis

(1) Research boundary and objective

Hydrogen fuel cell passenger vehicles are selected as research objects to study the energy-saving and emission reduction benefits. Mirai, the Toyota second-generation HFCV, is taken as reference, which is currently the most representative HFCV in China in terms of comprehensive technology and actual market stock situation. Mirai is equipped with a 60L and a 62.4L hydrogen storage tanks (withstand 700 MPa pressure), which can load 5kg hydrogen and range 502 km (Toyota, 2022). Accordingly, the hydrogen consumption of HFCV in this study is approximately set as 1kg/100 km (hereinafter referred to as hkm) (Yahashi et al., 2021). The research time-points of this study are 2020 (current status year) and 2030 (forecast year). The fuel-cycle energy impact of HFCV is measured by the consumption of fossil energy, including coal, oil and natural gas; and the environmental impact is represented by CO_2 and atmospheric pollutants (VOC, NO_X, $PM_{2.5}$ and SO_2) emissions.

(2) Selection of fuel path for HFCVs

The HFCV fuel cycle includes the hydrogen production, storage and transportation, refueling process. Each process can be realized by different technical routes and combined to obtain different fuel paths. Firstly, the energy of hydrogen production can be from: coal (with CCS technology, Coal+CCS), natural gas (NG), Coke oven gas (COG), biomass (BIO), electrolytic water with hybrid electric power (EWHEP), and electrolytic water with renewable energy (EWRE). The traditional energy (coal, natural gas and coke oven gas) hydrogen production technologies have been generally mature with sufficient reserve of raw materials, which may dominate in the near term. The technologies of renewable hydrogen (electrolytic water, hydrogen produced from biomass) are still in the research and development stage, which is considered as a long-term energy storage strategy. Secondly, storage methods include gaseous and liquid hydrogen, and the corresponding transportation modes are pipeline, trailer, and tank wagon, respectively. Considering the actual situations, gaseous hydrogen is mainly transported by pipeline or long tube trailer and liquid hydrogen by tank wagon (Xu and Yu, 2022), which bring together three storage and transportation methods: gas+pipeline (G+P), gas+trailer (G+T), liquid+tank wagon (L+T). In addition, hydrogen generated from natural gas can also be produced in the stations to avoid long-distance storage and transportation costs. By permutation and combination in each part, 19 representative HFCV fuel paths are selected as shown in Tab.1.

Tab.1 WTW Fuel paths of HFCV in China

Hydrogen production	Storage and transportation			Station
	Gas+Pipeline (G+P)	Gas+Trailer (G+T)	Liquid+Tank wagon (L+T)	

Coal + CCS	P-A1	P-A2	P-A3	-
Natural Gas (NG)	P-B1	P-B2	P-B3	P-B4
Coke Oven Gas (COG)	P-C1	P-C2	P-C3	-
Biomass (Bio)	P-D1	P-D2	P-D3	-
Electrolytic water with hybrid electric power (EWHEP)	P-E1	P-E2	P-E3	-
Electrolytic water with renewable energy (EWRE)	P-F1	P-F2	P-F3	

(3) Energy consumption assessment methods

The fuel-cycle energy consumption is the base of air pollution and carbon emission calculations (Wu et al., 2012), which can be divided into two stages as follows:

$$E_{WTW,j} = E_{WTP,j} + E_{PTW,j} \tag{1}$$

Where, j represents the type of fuel. $E_{WTW,j}$ represents the WTW energy consumption of fuel j, $E_{WTP,j}$, $E_{PTW,j}$ refer to the energy consumption of fuel j in WTP and PTW stages respectively, the units are MJ/hkm.

The energy consumption in PTW stage is closely related to the fuel economy of the vehicle and can be calculated by:

$$E_{PTW,j} = LHV_j \times \rho_j \times FE_j \tag{2}$$

Where, LHV_j (MJ/kg) is the low calorific value of fuel j. ρ_j (kg/L) is the density of fuel j. FE_j (L/hkm) is the fuel economy.

The energy consumption of WTP stage can be calculated by energy efficiency and its consumption intensity as follows:

$$E_{WTP,j} = E_{PTW,j} / \eta_j \tag{3}$$

η_j is the comprehensive energy efficiency of WTP stage.

(4) Environmental impact analysis of WTW stage

In this study, the decrease of air pollutant emissions and CO_2 emissions due to the growth of HFCVs and the different technical level of different fuel paths were considered as environmental benefits. Therefore, the environmental impact analysis includes two dimensions. By horizontally comparing different fuel paths in the same time period, the reductions of air pollutant emissions and CO_2 emission bring environmental benefits. Meanwhile, for each fuel path, the improvements of technological level and energy efficiency can also help to reduce pollutant emissions.

Four primary air pollutants are examined: volatile organic compound (VOC), nitrogen oxide (NO_x), particulate matter with diameters of 2.5 mm or less ($PM_{2.5}$), and sulfur dioxide (SO_2). For VOC,

NO_x and $PM_{2.5}$ emissions during WTP stage, the calculation formula are as follows:

$$FC_{j,k} = FC \times fuel_j \times tech_{j,k} \tag{4}$$

$$EF_{WTP,i} = \sum_j \sum_k EF_{i,j,k} \times FC_{j,k} \times 1000 \tag{5}$$

Where $FC_{j,k}$ is the consumption of fuel *j* under control technology *k*, and the unit is kJ/hkm. *FC* refers to the total energy consumption of fuel combustion process, and the unit is kJ/hkm. $fuel_j$ is the proportion of fuel *j* in the total fuel consumption ($\sum fuel_j$=1). $tech_{j,k}$ refers to the proportion of technology *k* in the total technology composition ($\sum tech_{j,k}$=1). $EF_{WTP,i}$ refers to the combustion emission of class *i* pollutant in WTP stage, in g/hkm. $EF_{i,j,k}$ refers to the emission factor of class *i* pollutant under the fuel *j* use control technology *k*, and the unit is g/kJ.

Specially, SO_2 emission during WTP stage is calculated according to sulfur balance method, using formula (6):

$$SO_{2,\ WTP,j} = \frac{E_{WTP,j} \times S\_ratio_j}{LHV_j} \times \frac{64}{32} \times 1000 \tag{6}$$

Where, $SO_{2,\ WTP,j}$ is the SO_2 emission of fuel *j* during combustion, in g/hkm. S_ratio_j refers to the sulfur content of fuel *j*.

Pollutant emission in PTW stage refers to the amount of pollutants discharged during vehicle driving. The emissions of VOC, CO, NO_x, $PM_{2.5}$ during PTW stage are acquired based on GICEV database from GREET 2022, while the emission of SO_2 during PTW stage is shown in formula (7).

$$SO_{2,\ PTW,j} = \frac{E_{PTW,j} \times S\_ratio_j}{LHV_j} \times \frac{64}{32} \times 1000 \tag{7}$$

Therefore, the WTW VOC, NOx, $PM_{2.5}$ and SO_2 emissions can be obtained by adding the emissions from WTP stage and PTW stage.

The carbon balance method is used to calculate the CO_2 emission. The basic idea is the conservation of mass, namely the carbon content in the emitted CO_2 is equal to the carbon content in the fuel minus the carbon content in the emissions VOC, CO and CH_4. In addition, this study also considers the amount of VOC and CO converted into CO_2 through a series of reactions such as oxidation in the atmosphere. Therefore, the calculations of CO_2 emission in WTP stage and PTW stage in this study are shown in formula (8) and (9).

$$CO_{2,\ WTP,j,k} = [\frac{E_{WTP,j} \times C\_ratio_j}{LHV_j} - (VOC_{j,k} \times 0.85 + CO_{j,k} \times 0.43 + CH_{4,j,k} \times 0.75) + (VOC_{j,k} \times 0.85 + CO_{j,k} \times 0.43)] \times \frac{44}{12} \times 1000 \tag{8}$$

$$CO_{2,\ PTW,j,k} = [\frac{E_{PTW,j} \times C\_ratio_j}{LHV_j} - (VOC_j \times 0.85 + CO_j \times 0.43 + CH_{4,j} \times 0.75) \tag{9}$$

$$+ \left(VOC_j \times 0.85 + CO_j \times 0.43 \right)] \times \frac{44}{12} \times 1000$$

Where, $CO_{2,WTP,j,k}$ and $CO_{2,PTW,j,k}$ (kg/hkm) refer to the CO_2 emission intensity of fuel j in WTP and PTW stages respectively, using class k combustion technology. C_ratio_j is the carbon content of fuel j; $VOC_{j,k}$, $CO_{j,k}$, and $CH_{4,j,k}$ respectively represent the emission factors of VOC, CO and CH_4 of fuel j using class k combustion technology in WTP stage, and the unit are kg/hkm. VOC_j, CO_j, and $CH_{4,j}$ are the emission factors of VOC, CO and CH_4 of fuel j in PTW stage, and the unit are kg/hkm. Constant values of 0.85 is the average carbon mass ratio of VOC, 0.43 and 0.75 represent the carbon mass ratio of CO and CH_4. The total CO_2 emission of WTW is expressed as the sum of the emissions of WTP stage and PTW stage.

In order to compare the energy-saving and emission reduction effects of different paths, index normalization method is used to process the results calculated above, so as to rank the environmental benefit of each path. The emissions of CO_2 and other pollutants are be normalized according to Acar and Dincer (2015). As the energy consumption and pollutant emission trends of the three storage and transportation modes are similar, taking the gas hydrogen pipeline as an example, the WTW energy consumption and CO_2, VOC, NOx and $PM_{2.5}$ of HFCV light vehicles under each fuel path are normalized using formula (10).

$$Rank_j \left(Method\ i \right) = \frac{Maximum_j\text{-}Method\ i_j}{Maximum_j} \times 10 \tag{10}$$

$Maximum_j$ represents the maximum of the result values of index j for six different fuel paths, $Method\ i_j$ represents the result of index j of class i fuel path, and then expand the result ten times so that all values are between 0-10.

2.2. Localized database construction of the HFCV fuel-cycle analysis

(1) Hydrogen feedstock production stage

A database of energy consumption and pollutant emissions of hydrogen feedstock production stage has been established. Firstly, power composition and generation efficiency are the key parameters that affect the energy consumption and emission of HFCV in the paths of hydrogen production by electrolytic water. China's power sources compositions in 2020 and 2030 are drawn from according to the report of *China's energy and electric power Development Plan in 2030 and 2060* (GEIDCO, 2021), shown in Tab.2. The total installed capacity of China's power supply will reach 3.8 billion kw in 2030, including 2.57 billion kw of clean energy (67.5%).

Tab. 2 Energy structure for power generation in China

Energy source	Generation efficiency(%)		Power proportion (%)	
	2020	2030	2020	2030
Coal	36	42	49.0	27.6
Gas	40	45	4.5	4.9
Hydropower	-	-	16.8	14.6
Nuclear	-	-	2.3	2.8
Wind	-	-	12.7	21.0
Solar	-	-	11.3	27.0
Other	-	-	3.4	2.1

Secondly, for different hydrogen production technologies, fossil fuel raw material extraction efficiency, the proportion and distance of the transport efficiency are also necessary parameters. Settings of raw material mining efficiency and transport-related parameters for coal, natural gas and biomass hydrogen production are shown in Tab.3 (Lin, 2018; Geng et al., 2020). Other basic parameter setting are based on GREET_2021 model.

Tab. 3 Efficiency and transportation mode for different fuel in GREET model

Fuel	Power generation efficiency	Transportation mode	Transportation distance (km)	References
Coal	Extraction efficiency 97% Washing efficiency 95%	Railway (75%) Waterway (17%) Road (8%)	650 1500 180	Song and Wang, 2008; Shen et al., 2014
Natural gas	Extraction efficiency 96% Processing efficiency 97% Compression efficiency 93%	Pipeline (100%)	1000	Wang et al., 2016; Li et al., 2016; ANL, 2021
Biomass	Rate of logging residue 25%	Road (100%)	180	Ou et al., 2010; Huo et al., 2016

(2) Hydrogen production, storage and transportation stages

Hydrogen production efficiency is one of the key parameters in the WTP stage. Tab. 4 lists the energy efficiency of different hydrogen production methods. For hydrogen production from Coal + CCS, Natural Gas (NG), Coke Oven Gas (COG), and Biomass (Bio), the data in 2020 is based on literature research, and the 2030 data mainly refer to the default value of the GREET_2021 model. As the efficiency of hydrogen production from electrolytic water may vary a lot due to the different regional power structures, so for electrolytic water with hybrid electric power (EWHEP) and electrolytic water with renewable energy (EWRE), hydrogen production efficiencies in 2020 are acquired by a Data Envelopment Analysis (DEA) cross-efficiency model, are set at 76.0% and 74.5%, respectively, and those in 2030 are calculated with a 5% increase (HC and CHA, 2020).

Tab. 4 Efficiency of different hydrogen production patterns

Hydrogen production	Hydrogen production efficiency(%)		References
	2020	2030	
Coal + CCS	55.8	60	Li, 2018
Natural Gas (NG)	66	71	Li et al., 2016
Coke Oven Gas (COG)	91.9	91.9	Joseck et al., 2008
Biomass (Bio)	46.1	51	ANL, 2021

Electrolytic water with hybrid electric power (EWHEP)	76.0	81	HC and CHA, 2020
Electrolytic water with renewable energy (EWRE)	74.5	79.5	HC and CHA, 2020

2.3. Environmental Economic analysis of WTW stage

For the economy of WTW, we consider the material and the environmental externality cost of fuel usage.

(1) Economic cost

Since the fuel cycle analysis mainly includes hydrogen production, storage, transportation and filling, the cost of the material is obtained by summing up the costs of the three stages.

Tab. 5 Economic cost of HFCV (hydrogen production, storage and transportation, and filling process)

	Unit cost(yuan/hkm)		Reference
Hydrogen production	2020	2030	
Coal + CCS	16.81	14.29	Wang (2016), HC and CHA (2020), Zhang et al. (2021), Wang et al. (2021)
Natural Gas (NG)	12.8	12.16	
Coke Oven Gas (COG)	12	11.4	
Biomass (Bio)	33	31.35	
Electrolytic water with hybrid electric power (EWHEP)	31.36	14.11	
Electrolytic water with renewable energy (EWRE)	33.6	11.76	
Storage and transportation			
Gas+Pipeline (G+P)	13.4	8.71	Zhang et al. (2021)
Gas+Trailer (G+T)	12.06	7.37	
Liquid+Tank wagon (L+T)	12.73	4.02	
Hydrogen Filling			
Annual fixed cost depreciation	4.93	3.94	Shan et al. (2020)
Annual operation and maintenance cost	10.96	8.77	

(2) Environmental cost

By multiplying the unit external cost of pollutants and the total amount of emissions of various pollutants calculated above, the environmental externalities are internalized (Meng, 2007; Jin, 2019).

$$C_{i,\ PTW}=\sum e_i d_i \tag{11}$$

Where, C_i is the environmental cost of pollutant i; e_i is the emission of the pollutant i. d_i is the unit external costs of pollutants i in China. The unit external costs of pollutants are drawn from External Cost Values for EE SUT Framework (IER, 2010) in European Union, and are adjusted by consumer price index (CPI).

$$d_i=d_i^{'}\times \frac{CPI}{CPI_0} \times R \tag{12}$$

Where, $d_i^{'}$ refers to the unit external cost of the pollutant i in Europe in 2000. CPI represents the average values of China's consumer price index in 2020 or 2030, with 1978 as the constant price, and

CPI_0 represents the average values of China's consumer price index in 2000. R refers to the annual average exchange rate of euro against RMB in 2000. The unit emission costs of several pollutants calculated according to the formula are shown in Tab.6. Due to the high attention paid to particulate matter treatment in the past five years, the emission cost of $PM_{2.5}$ is significantly higher than others.

Tab. 6 Unit emission costs of CO_2 and major air pollutants

Emissions	Unit cost (yuan/kg)	
	2020	2030
CO_2	0.25	0.24
VOC	10.53	10.00
NO_X	81.08	77.03
$PM_{2.5}$	762.44	724.32
SO_2	78.66	74.73

3. Results and Discussion

3.1. HFCV fuel-cycle environmental assessment

(1) Energy consumption

As shown in Fig.2, the energy consumption in WTW stage of HFCV under different paths in 2020 and 2030 are obtained. The energy consumptions under all paths have decreased significantly in 2030, with an average decline rate of 10.88%, mainly contributed by the WTP stage.

From the perspective of hydrogen production ways, it can be found that the energy consumptions of EWHEP and BIO are the highest on the average, while those of EWRE are the lowest. The energy consumption of EWHEP has the highest decline rate from 2020 to 2030, reaching 23.22%, 23.24% and 23.98% under the three storage and transportation patterns respectively, followed by BIO with the energy consumption reduced by 10.47%, 18.92% and 10.08%, respectively. For each hydrogen production mode, we can observe that the energy consumption of gas hydrogen storage and transportation way is lower than that of the liquid formation. Taking the G+P storage and transportation mode as an example, the energy consumption of EWRE is only 72.11 MJ/hkm. In terms of storage and transportation patterns, the energy consumption of G+T reduces the most, with the decrease rate of 12.19%. The energy consumption of G+P and L+T is reduced by 10.67% and 10.45%, respectively.

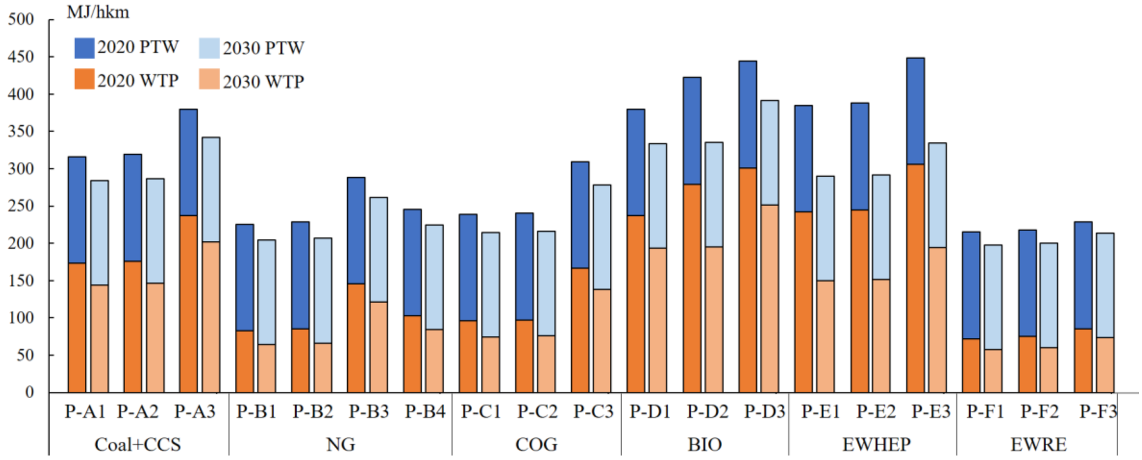


Fig.2 WTW energy consumption of HFCV under different fuel paths in 2020 and 2030

(2) Air pollutants and CO_2 emissions

The results of air pollution emissions in WTW stage of HFCV under different paths in 2020 and 2030 are shown in Fig.3. It can be seen that the VOC, NO_X, $PM_{2.5}$, SO_2 emissions under all fuel paths have decreased significantly in 2030, with an average decline rate of 16.55%, 22.35%, 22.49%, and 18.76%, respectively. This is mainly due to the improvements of technical level, energy conversion efficiency and the proportion of clean energy.

Considering the hydrogen production ways, the VOC emissions of COG are the highest and those of EWRE are the lowest. Taking the G+P storage and transportation mode as an example, the VOC emissions of COG and EWRE are 6.10 g/hkm and 0.38 g/hkm, respectively. The decline proportions of VOC emissions from 2020 to 2030 under the mode of EWHEP are the highest, which can reach 41.67%, 40.00%, and 42.86%, respectively for the three storage patterns, followed by the BIO with the reduction rates of 21.21%, 37.94% and 16.67%, respectively for the three storage patterns. For the same hydrogen production mode except EWRE, we can observe that the VOC emissions of L+T, G+T, and G+P increase in turn. For instance, the VOC emissions of L+T, G+T, and G+P after NG hydrogen production are 1.6 g/hkm, 1.7 g/hkm, and 2.1 g/hkm, respectively. From 2020 to 2030, the VOC emissions of G+T decrease the most by 19.75%, and those of G+P and L+T decrease by 15.35% and 15.12%, respectively.

During the WTW stage, NO_x emissions of EWHEP are the highest and those of EWRE are the lowest. For instance, the NOx emission of EWHEP is ten times more than those of EWRE (20.10 g/hkm and 2.10 g/hkm) under the G+P storage and transportation mode. While the decline rate of the NO_x emissions from 2020 to 2030 of EWHEP is the highest, reaching 42.79%, 42.16% and 43.98% under the three storage paths respectively, followed by BIO, which can decrease by 30.51%, 44.30%

and 25.58%, respectively. From the perspective of storage and transportation, the NO_x emissions of L+T are obviously higher than the other two modes except under EWRE mode. Taking NG generation pattern, the NOx emissions of G+P, G+T, L+T are 4.4 g/hkm, 4.8 g/hkm, 7.1 g/hkm, respectively. The NO_x emission reduction rate of G+T is the highest, which is 25.22%, and those of G+T and L+T are 22.45% and 21.10%, respectively.

The reduction proportion of $PM_{2.5}$ emissions from 2020 to 2030 under the mode of EWHEP is the highest, which can reach 47.37%, 42.11%, and 45.45% respectively under the three paths, followed by the mode of BIO, which can reduce 34.23%, 51.51%, and 27.98% respectively. Comparing the $PM_{2.5}$ emissions of WTW stage under different hydrogen production modes, it can be found that the $PM_{2.5}$ emissions of COG are the highest and the $PM_{2.5}$ emissions of EWRE are the lowest. For the same hydrogen production mode, we can observe that the $PM_{2.5}$ emissions of L+T are higher than the other two modes. On the average, the proportions of $PM_{2.5}$ emission reduction of G+T is the highest, which is 22.93%, and those of G+P and L+T are 20.98% and 19.09% respectively.

The SO_2 emission under the hydrogen production mode of EWHEP is the highest and that of EWRE is the lowest. Taking the G+P storage and transportation mode as an example, the SO_2 emission under these two hydrogen production modes are 25.1 g/hkm and 1.5 g/hkm respectively. From 2020 to 2030, the declining proportion of SO_2 emissions of EWHEP is the highest, which can reach 45.02%, 45.02%, and 45.60% under the three paths respectively, followed by EWRE, which can reduce 20.00%, 20.00%, and 20.19%, respectively. It is speculated that the improvement of sulfur-containing catalyst or conductive solution used in hydrogen production from electrolytic water may greatly reduce SO_2 emission. For the same hydrogen production mode, the SO_2 emission of L+T is higher than the other two modes. The SO_2 emission reduction rate of the gas hydrogen+trailer is the highest, which is 21.04%, while that of the other two modes are 17.72% and 18.64%, respectively.

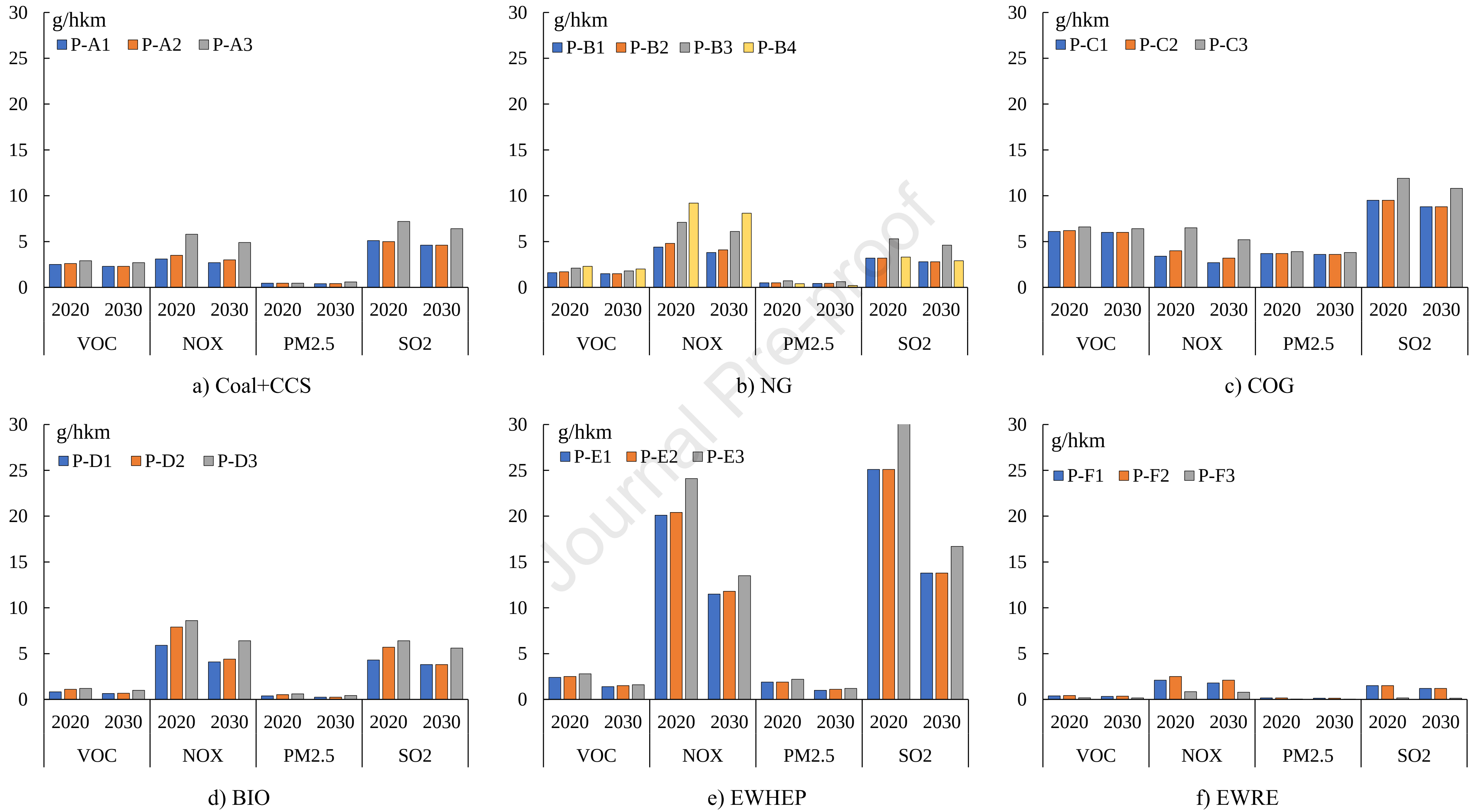


Fig. 3 WTW air pollutants emissions of HFCV under different fuel paths in 2020 and 2030

As shown in Fig.4, the CO_2 emission of HFCV under all paths decreased significantly in 2030 comparing to 2020, with an average decline rate of 21.58%. It can be found that the CO_2 emissions of EWHEP and NG are the highest, and those of EWRE are the lowest. Taking the G+P storage and transportation mode as an example, the CO_2 emissions of EWHEP and NG are 26.64 and 12.74 kg/hkm, respectively, while that of EWRE is 2.49 kg/hkm. The decline proportions of CO_2 emissions from 2020 to 2030 under EWHEP are the highest, reaching 41.96%, 41.79% and 43.54% respectively under the three paths, followed by COG, which can reduce 25.51%, 25.14% and 21.95% respectively. For the same hydrogen production mode, the CO_2 emissions of L+T storage and transportation mode are higher than that of the other two modes except for EWRE. The CO_2 emission reduction rate of G+T is the highest, which is 25.73%. The CO_2 emission reduction rates of G+P and L+T in the other two modes are 20.87% and 20.42%, respectively.

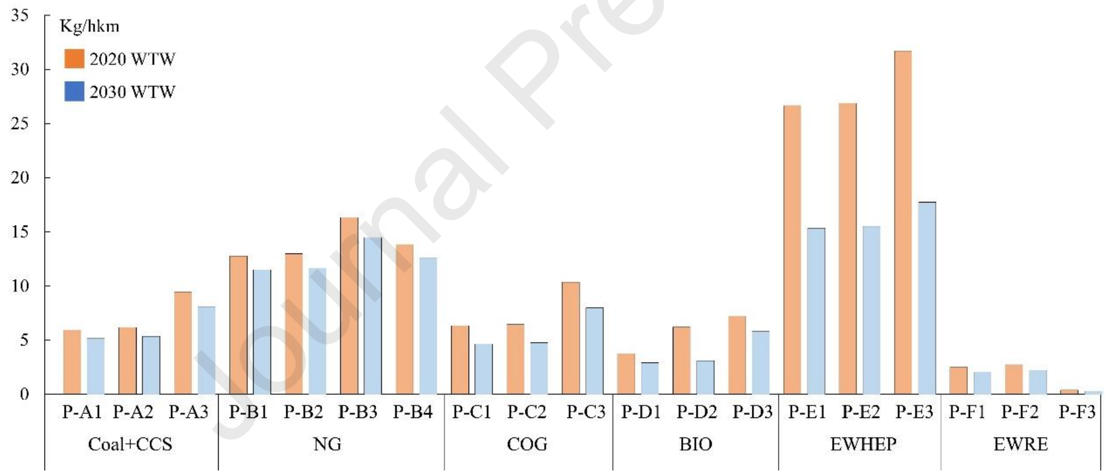


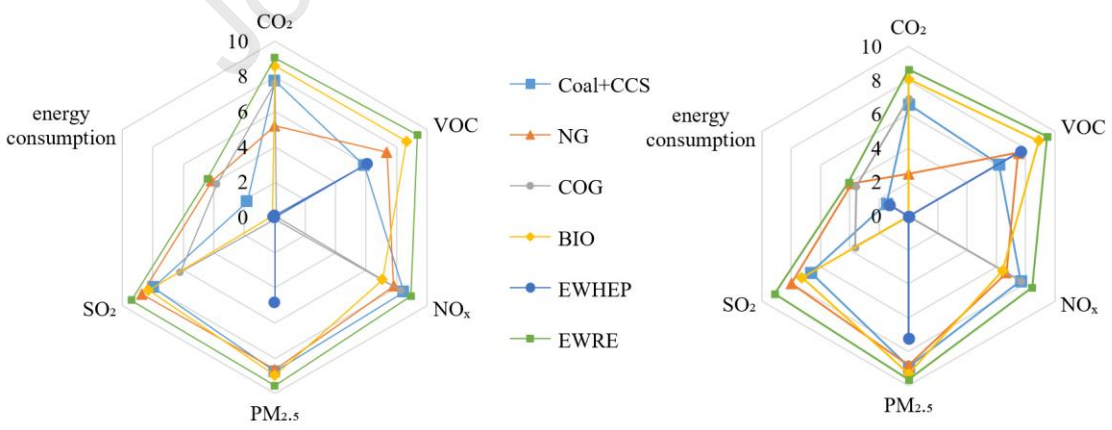
Fig.4 WTW CO_2 emissions of HFCV under different fuel paths in 2020 and 2030

(3) WTW environmental benefits comparison

In general, as to hydrogen production mode, the EWRE shows great advantages in environmental performance, with the lowest emissions of all of the five types of air pollutants and CO_2. While when it comes to the storage and transportation process, the situations are more complex. The gas hydrogen form modes work better than liquid ones under Coal+CCS, NG, COG, BIO and EWHEP paths. However, under EWRE, the emissions of VOC, NO_x, $PM_{2.5}$, SO_2 and CO_2 of L+T are the lowest, which reduced by 54.77%, 59.52%, 81.25%, 89.33%, and 84.34% respectively comparing with those of G+P. To display the difference of 19 fuel paths more intuitively, the

normalization results of the air pollutants and CO_2 emissions are shown in Fig.5. In specific, the six endpoints of the radar chart represent six evaluation environmental indexes respectively, and the hexagonal frame line represents 0-10 points respectively. The closer to the outer edge of the radar chart or the higher the score of this index, the better the benefits of energy saving and emission reduction.

As shown in Fig.5-a), overall, hydrogen production from EWRE is distributed on the outermost side of the radar chart. That indicated, the HFCV under this path has the best environmental benefit, followed by the BIO, which has the second-best emission reduction effects of CO_2, $PM_{2.5}$ and SO_2. On single term, the emission reduction effect of NG is relatively worse in terms of CO_2 emission and other pollutants. Coal+CCS technology is particularly outstanding in reducing CO_2 and NO_x emissions, but the energy consumption is higher than other paths. COG hydrogen production path has a certain effect in CO_2 and NO_x emission reduction, while its $PM_{2.5}$ and VOC emission reduction benefits are in the rear position. The overall performances of hydrogen production from EWHEP are relatively the worst. As shown in Fig.5-b), the radar map distribution of different fuel paths in 2030 is similar to that in 2020. HFCV under the hydrogen production path of EWRE has the best environmental benefit, followed by BIO, NG and Coal+CCS. The overall performance of COG and EWHEP are relatively the worst.



a) environmental benefit in 2020 b) environmental benefit in 2030

Fig.5 Comparison of environmental benefit of HFCV under different hydrogen production ways in 2020 and 2030

3.2. HFCV fuel-cycle environmental economic assessment

(1) Economic cost

As shown in Fig.6, in the HFCV production stage, from the perspective of hydrogen production mode, the costs of hydrogen production from new technologies, such as BIO, EWHEP, and EWRE are still relatively high at this stage, and the costs of traditional hydrogen production from NG and COG are relatively low. In terms of storage and transportation mode, the costs of the storage and transportation mode of G+P are relatively high, followed by G+T and L+T. From the cost comparison of HFCV production stage in 2020 and 2030, the cost of each path has decreased significantly, among which the cost of hydrogen production from EWRE has the most obvious downward trend, and the decline proportion under the three storage and transportation modes can reach 47.24%, 48.27% and 54.21% respectively.

(2) Environmental cost

The environmental externality costs when driving 100km in 2020 and 2030 are calculated, as shown in Fig.6. From 2020 and 2030, the environmental externality cost of each fuel path has decreased significantly, among which EWHEP has the most obvious downward trend. The decline proportion under the three storage and transportation modes can reach 47.24%, 48.27% and 54.21% respectively, which is mainly due to the improvement of power structure, that is, the increase of the proportion of renewable energy power generation. From the perspective of hydrogen production mode, the environmental externality costs of EWHEP are the highest, and those of EWRE are relatively the lowest. From the perspective of storage and transportation mode, the environmental externality costs of L+T mode are relatively high, except for EWRE.

(3) Total Cost

According to the cost of HFCV production stage and environmental externality cost, the comprehensive cost of HFCV can be obtained. From the comparison of the comprehensive cost of HFCV in 2020 and 2030, the comprehensive cost of each path has decreased significantly. Among them, the comprehensive cost of hybrid electric electrolytic water hydrogen production and renewable energy electrolytic water hydrogen production has the most obvious downward trend. The decline proportion of the three storage and transportation modes can reach 46.81%, 47.78% and 54.09% respectively. From the perspective of hydrogen production mode, the comprehensive cost of BIO, EWHEP and EWRE are higher, mainly because the cost of production stage is higher. The total costs of NG hydrogen production are relatively lowest. From the perspective of storage and

transportation mode, the comprehensive costs of HFCV are relatively high under the mode of L+T.

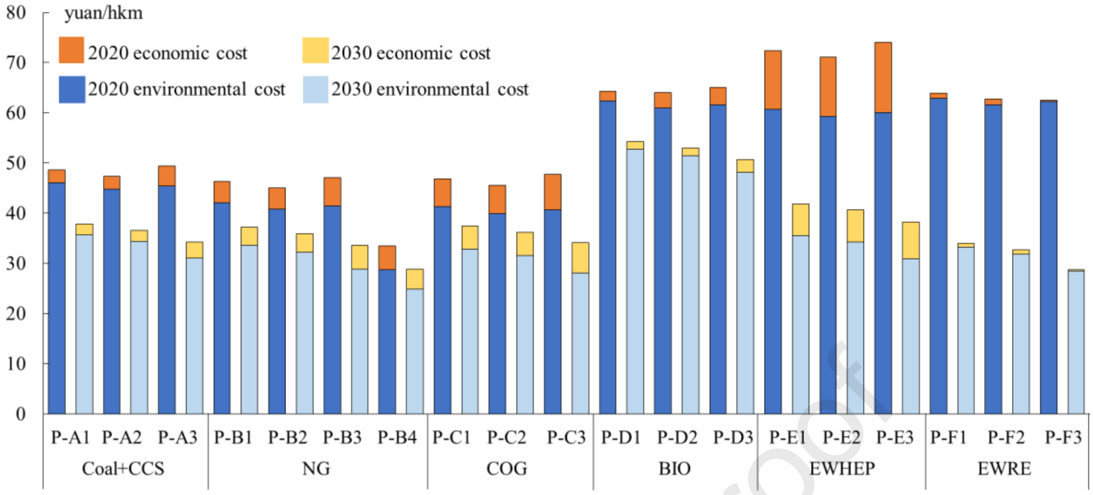


Fig.6 Production and environmental externality costs of HFCV under different fuel paths in 2020 and 2030

3.3. Discussion and policy implication

To achieve the effect of energy saving and emission reduction while meeting the transportation demand in the context of carbon neutrality target in China. this study combines the major hydrogen production and storage and transportation methods, bringing up together 19 fuel paths of HFCV. The environment benefits analysis show that, as to hydrogen production mode, the EWRE shows great advantages in environmental performance, with the lowest emissions of all of the five types of air pollutants and CO_2, followed by the BIO hydrogen generation. As to the storage and transportation ways, hydrogen stored in gas form and the corresponding pipeline or trailer transportation are most environmental friendly. While the economic feasibility of these fuel paths is slightly different, the costs of traditional paths of NG, COG and Coal+CCS are much cheaper in 2020. In the long run, due to the development of hydrogen production and emission treatment technology, the unit costs of production stage and pollutant emissions drop rapidly of EWRE and BIO, etc., which shows a promising application prospect.

From the perspective of hydrogen production, most of the current hydrogen is still produced from fossil fuels. Thus, the environmental concerns of hydrogen production from fossil fuel is still prominent. To overcome this issue, the hydrogen production from renewable energy will become the key development direction in the future. In addition, considering that all kinds of storage and

transportation modes have their applicable scenarios, the storage and transportation mode of gas hydrogen+pipeline or gas hydrogen+trailer shall be mainly used in short-distance and small-scale transportation, and the storage and transportation mode of liquid+tank wagon can be considered in long-distance and large-scale transportation. At the same time, the pace of infrastructure construction is also accelerated, and the high-quality development of the hydrogen energy industry should not be restricted by infrastructure construction. From the perspective of filling link, hydrogen filling stations can be built independently, together with gas stations, or jointly with hydrogen production plants, etc. The filling method is mainly cascade high-pressure hydrogen injection design.

For the economy evolution of HFCVs, Jin et al. (2019) has taken 9 pollutants emissions into consideration (CO_2, CH_4, N_2O, NO_x, SO_x, $PM_{2.5}$, PM_{10}, CO, and VOC) and made environmental cost evaluation of battery electric vehicle, electric vehicle and hydrogen fuel cell vehicle, and the results are 18 yuan/hkm, 20 yuan/hkm, and 33 yuan/hkm, respectively. Chen et al. (2021) calculated the environmental cost as approximate 53.3 yuan/hkm and the pollutants includes CO_2, CH_4, NO_x, SO_x, PM, CO, and VOC. Liang (2020) has defined the implicit cost of new energy vehicles as the cost of environmantal and fuel vehicle quota policies, and the results in Beijing, Hangzhou, and other four cities range between 20-300 yuan/hkm. It can be seen that the results are basically comparable in the same order of magnitude.

4. Conclusion

This study explores the life-cycle environmental and economic benefits of HFCV in China. In 2030, the energy consumption and pollutant emissions of HFCV under all paths have decreased significantly, which mainly due to the improvement of technical level, energy conversion efficiency and the proportion of clean energy. Among them, HFCV under the path of EWRE-L+T has the best environmental benefits. In addition, comparing the economic benefits under the several fuel paths, from the perspective of hydrogen production methods, the total costs of hydrogen production from biomass, electrolytic water with hybrid electronic energy and renewable energy, combining the liquid tank storage and transportation paths are higher than the traditional ways in 2020. In the long run, the total costs of HFCV paths have all decreased significantly comparing the results in 2020 and 2030. Among them, the costs of hydrogen production from EWHEP and EWRE drop the most obviously, which mainly due to the increase of the proportion of renewable energy power generation

during the power structure improvement process in China.

Considering the technical level, environmental impacts and economic benefits, the FCV under the hydrogen production path of EWRE has the best performance in 2030. Therefore, the corresponding green hydrogen production capacity is an important factor to promote the high-quality development of China's FCV industry. At present, the reserves of coal, oil, natural gas, electricity and other hydrogen production resources in various regions of China are abundant. In the next step, efforts should be made to promote the transformation of FCV to a cleaner and more efficient mode, and gradually transition from fossil fuel-based hydrogen production to a renewable energy-based one, so as to achieve the effects of energy saving and emission reduction. Therefore, in terms of technological development, it is necessary to: 1) Accelerate technological innovation and improve the construction of hydrogenation infrastructure; 2) steadily build a storage and transportation system and improve its economic efficiency; 3) comprehensively plan the hydrogenation network; 4) and accelerate the transformation of a safer, more stable and efficient renewable energy supply network.

Last but not the least, there are mainly two limitations in this study. Firstly, the variation of main parameters in HFCV's fuel-cycle analysis such as power structure, hydrogen production efficiency, unit costs of pollutants and CO_2, etc., could be taken into consideration to carry out sensitivity analysis and generate flexible results. Secondly, as this study has accomplished the fuel-cycle analysis of HFCV, the environmental and economic valuation could be extended to the material-cycle stage as well, which will further complete the life cycle analysis of HFCV in China.

Credit author statement

Yuanying Chi: Writing - original draft; Conceptualization; Supervision; Funding acquisition; Weiyue Xu: Data curation; Formal analysis; Meng Xiao: Methodology; Software; Validation; Writing - original draft; Zhengzao Wang: Methodology; Software; Writing - review & editing； Investigation; Xufeng Zhang: Methodology; Writing - review; Yahui Chen: Writing - review.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal

relationships that could have appeared to influence the work reported in this paper.

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Abbreviations

BIO	Biomass
CCUS	carbon capture use and storage
COG	Coke Oven Gas
EWHEP	Electrolytic water with hybrid electric power
EWRE	Electrolytic water with renewable energy
G+P	Gas+Pipeline
G+T	Gas+Trailer
HFCV	Hydrogen fuel cell vehicle
hkm	100 km
L+T	Liquid+Tank wagon
NG	Natural Gas
PTW	pump-to-wheels
WTP	well-to-pump
WTW	Well-to-Wheels

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Life cycle-based environmental and economic assessment of hydrogen fuel cell vehicles in China

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Highlights

Fuel-cycle analysis of hydrogen fuel cell vehicle using localized GREET model

Environmental and economic assessment of 19 fuel paths in 2020 and 2030

Electrolytic water with renewable energy paths show great pollution reduction effect

Material and environmental cost of hydrogen fuel cell vehicle drop significantly in 2030

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: