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Bus fleet replacement optimization considering life-cycle carbon emissions and total cost of ownership

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Abstract: To explore the benefits and potential of electricity and hydrogen as alternative fuels for regular buses, a mixed-integer planning model was constructed to determine the schedule optimization scheme for bus fleet replacement. The model was based on the comprehensive analysis of carbon emissions and the total cost of ownership from a life cycle perspective. Using actual operational data of buses powered by diesel, natural gas, hybrid, plug-in electric, and hydrogen fuel cells, the effects of uncertainty in the power mix, acquisition cost, hydrogen production, and hydrogen usage cost on the fleet replacement schedule were explored. The results reveal that plug-in electric buses are currently the optimal choice for bus fleet replacement. Given the current level of vehicle technology and hydrogen production, hydrogen fuel cell buses (HFCEBs) are advisable during bus fleet replacement. Until the production of blue or green hydrogen becomes commercially viable, promoting HFCEBs on a large scale by extending financial subsidies is not recommended. The proposed method can help authorities identify optimized bus fleet replacement options under specific constraints and desired objectives to promote green and sustainable development.

Key words: bus fleet replacement; life-cycle carbon emissions; total cost of ownership; mixed-integer programming; alternative fuel; electric bus; hydrogen fuel cell bus

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Buses are a vital travel mode that helps alleviate transportation emissions and promote sustainable development in modern cities[1]. However, fossil fuels continue to be the dominant energy resource for bus operation. According to a statistics released in 2022, approximately 79% of buses in the UK was powered by diesel[2]. Sui et al.[3] claimed that when the ridership is less than 40%, the per-kilometer human emissions of buses increase significantly, making them less environmentally friendly than passenger vehicles. Thus, the challenge for authorities is to upgrade bus fleets while satisfying stringent ecological and environmental protection requirements[4].

Because electric buses and hydrogen fuel cell buses (HFCEBs) do not directly generate carbon or other pollutant emissions during operation, they are becoming viable options for the future bus fleet replacement. The prevailing charging technique for buses is stationary charging, often known as plug-in electric buses (PEBs). Meinrenken et al.[5] determined that under the combined effect of grid carbon intensity, vehicle range, and battery characteristics, the carbon emission reduction effect of an electrified fleet may not be as optimistic as expected. Ayetor et al.[6] revealed that diesel buses (DBs) have a higher life-cycle cost than PEBs and hybrid electric buses (HEBs), if the installation costs of charging stations are ignored. Du et al.[7] evaluated the advantages of replacing DBs with PEBs and HEBs and indicated that PEBs currently have lower carbon emissions; however, DBs have higher environmental costs because of pollutant emissions.

Furthermore, Islam et al.[8] developed a mixed-integer planning model to optimize the replacement schemes of DBs with PEBs and HEBs. However, the model considered only two types of alternative fuel vehicles and thus cannot provide comprehensive assessment information to transit operators. Similarly, Pelletier et al.[9] constructed an integer linear programing model to quantitatively understand the effects of replacing diesel buses with electrified ones under multiple scenarios. To analyze the uncertainty in bus fleet replacement, Harris et al.[10] proposed a probabilistic analysis model to assess the effects of factors on the life-cycle cost and carbon emissions. Nevertheless, the model only considered cost factors, i. e., the adoption percentage and cost decline of PEBs and social cost of carbon. Environmental factors, particularly the effects of changes in the power mix on carbon emissions, were not considered.

Thus, the existing studies provide insights that enable the analysis of the carbon emissions or costs of bus fleets, thereby allowing transit operators to identify replacement proposals through simple comparisons. However, only a few studies on fleet replacement have simultaneously considered the life-cycle carbon emissions (LCEs) and total

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cost of ownership (TCO). Moreover, the effects of future uncertainties have not been adequately considered in existing studies. To overcome this gap, a mixed-integer optimization model considering the effects of LCE and TCO was developed for bus fleet replacement. Furthermore, future fluctuations in emission reduction and cost-effectiveness were examined using uncertainty and sensitivity analyses.

1 Methodology

1.1 LCE assessment

Life-cycle assessment is widely employed as a quantitative approach to evaluate the environmental consequences of a product, process, or activity over its entire life cycle[11]. Studies have shown that the greenhouse gases, regulated emissions, and energy use in transportation (GREET) model developed by the Argonne National Laboratory is one of the most common tools for analyzing LCE[7]. Thus, the latest version of the GREET model, i.e., GREET© 2022, was used to analyze the LCE of various alternative fuels.

1.2 TCO analysis

The concept of the TCO includes vehicle purchase, deployment, operation and maintenance (O&M), and salvage. The current battery pack life of an electric bus is approximately 4 000 charge-discharge cycles with a life warranty of 12 a. Furthermore, to facilitate comparison with previous study[12], the vehicle life-cycle target was set as 12 a for each type of bus in this study.

1.3 Bus fleet replacement optimization model

1.3.1 Objective function

The objective of fleet replacement is to minimize the TCO and LCE. To facilitate the analysis while maintaining consistency with previous study[13], the carbon emissions were transformed into the emission cost. The objective function was constructed as follows:

$$\min \sum_{t=0}^{T} \Big[\sum_{k=1}^{K} (X_{t,k}e_{t,k} - X_{t,k}u_{t,k}) + \sum_{k=1}^{K} \sum_{i=0}^{I} (Y_{t,i,k}b_{i,k} + Y_{t,i,k}f_k)m_t + U_t l + V_t c + \sum_{i=1}^{I} Y_{t,i,5}m_t\varepsilon\eta - \sum_{k=1}^{K} \sum_{i=0}^{I} Z_{t,i,k}s_k \Big] \frac{(1+\alpha)^t}{(1+\beta)^t} + \sum_{k=1}^{K} \sum_{t=0}^{T} \sum_{i=0}^{I} Y_{t,i,k}\theta_k e_t m_t \tag{1}$$

where k is the type of bus powered by various fuels, with the numbers 1 to 5 representing DBs, HEBs, PEBs, CNGBs, and HFCEBs, respectively. $X_{t,k}$, U_t, and $Z_{t,i,k}$ are three basic decision variables; $X_{t,k}$ is the number of k-type buses purchased in year t; U_t is the number of charging stations purchased and installed in year t; and $Z_{t,i,k}$ is the number of i-year-old k-type buses salvaged in year t. $e_{t,k}$ is the acquisition cost of k-type buses in year t and $u_{t,k}$ is the financial subsidy obtained for k-type buses in year t; these two variables were used to measure the acquisition costs of buses. $Y_{t,i,k}$ is the number of available i-year-old k-type buses; $b_{i,k,t}$ is the maintenance cost per bus; f_k is the fuel cost of k-type buses; and m_t is the annual operation mileage of bus fleet; these four variables were used to measure the cost of maintenance. Further, l is the acquisition cost of charging stations; V_t is the number of available charging stations in year t; and c is the annual O&M cost of charging stations; these three variables were used to measure the costs of acquisition and maintenance of charging stations. ε is the average fuel consumption of HFCEBs and η is the average hydrogen refueling cost; these two variables were used to calculate the fuel costs of HFCEBs. Furthermore, considering the number of vehicles recovered, s_k is the salvage value of k-type buses; α is the price discount rate; β is the growth rate; $\theta_{t,k}$ is the carbon emission factor of k-type buses in year t; and e_t is the social cost of carbon emissions in year t.

1.3.2 Constraints

Based on the objective of the model, the following constraints were considered.

To ensure that the total number of buses operating in any given year satisfies the passenger demand, the following equation is used:

$$\sum_{k=1}^{K} \sum_{i=0}^{I} Y_{t,i,k} \geqslant d_t \qquad \forall\, t \tag{2}$$

where d_t is the bus fleet demand in year t.

The initial bus fleet mix is determined using the following equation:

$$Z_{0,i,k} + Y_{0,i,k} + X_{0,k} = h_{i,k} \qquad \forall\, i, k \tag{3}$$

where $h_{i,k}$ is the number of i-year-old k-type buses at the start of the planning horizon.

Because all buses purchased within a given year are new purchases, the number of k-type buses purchased in year t is the same as the number of available zero-year-old k-type buses, i.e.,

$$X_{t,k} = Y_{t,0,k} \qquad \forall\, t, k \tag{4}$$

Considering the regulations regarding salvaged buses, the current vehicle count is determined by the number of vehicles from the previous year andthat of salvaged buses, i.e.,

$$Y_{t,i,k} = Y_{t-1,i-1,k} - Z_{t,i,k} \qquad \forall\, t, i, k \tag{5}$$

Vehicles are prohibited from being salvaged if their useful life is less than ρ years, i.e.,

$$Z_{t,i,k} = 0 \qquad \forall\, t, i \in \{0, 1, \ldots, \rho\} \tag{6}$$

However, vehicles are salvaged if their useful life is not less than φ years, i.e.,

$$Y_{t,i,k} = 0 \qquad \forall\, t, i \in \{\varphi, \varphi+1, \ldots, I\} \tag{7}$$

To analyze the environmental and cost benefits of alternative fuel, no new DBs are acquired during the bus fleet renewal process, i. e.,

$$X_{t,1} = 0 \qquad \forall t, k \tag{8}$$

The number of charging stations required for PEBs and HEBs in any given year is determined using the following equation:

$$V_t \geqslant w \sum_{i=0}^{I} Y_{t,i,3} + v \sum_{i=0}^{I} Y_{t,i,4} \qquad \forall t \tag{9}$$

where w is the quantity ratio of charging stations and HEBs; v is the quantity ratio of charging stations and PEBs.

The initial conditions for a charging station can be specified as follows:

$$V_0 = U_0 \qquad \forall t \tag{10}$$

To ensure that charging stations are continuously used in the subsequent years after installation until they reach their designed lifetimes,

$$V_t = V_{t-1} + U_t \qquad \forall t \tag{11}$$

In addition, new charging stations are assumed to be ready for operation immediately after construction.

To ensure that the carbon emissions of an existing bus fleet in any given year are lower than the emission target, the following equation is used:

$$\sum_{k=1}^{K} \sum_{i=1}^{I} (m_t Y_{t,i,k} \theta_k) \leqslant \gamma_t \qquad \forall t \tag{12}$$

where γ_t is the expected carbon level in year t. The emission target is set at the end of an analysis period.

To ensure that the decision variables are nonnegative integers, the following equation is used:

$$X_{t,k} \in \mathbf{N}, \quad Z_{t,i,k} \in \mathbf{N}, \quad U_t \in \mathbf{N} \tag{13}$$

2 Case Study

To validate the proposed model and analyze the effects of the uncertainties of the primary parameters in the model, the bus fleet in Weifang, China, was chosen for the case study. All numerical analyses related to the case study were solved using CPLEX.

2.1 Base case scenario

Weifang city is located in the western part of Shandong Province, with a total land area of 1.62×10^5 ha and a total registered population of 9.19 million. In 2021, the city had a total of 1 610 buses, with a total route length of 2 783.8 km and an average daily passenger flow of 190 000 people. Since 2008, bus operators have been replacing DBs that have reached the end of their designed lifetimes with alternative fuel buses. The bus fleet compositions between 2009 and 2021 are shown in Table 1.

Based on the data provided by the Weifang Transportation Bureau, the average costs of each bus type at different stages are shown in Table 2.

The scope of the case study was from 2022 to 2030. The end year was set as 2030 because it is an essential time point for China to achieve its carbon neutrality objective.

Table 1 Bus fleet composition (2009—2021)

Age	9	10	11	12	13	14	15	16	17	18	19	20	21	Total
DBs	0	0	0	4	30	30	20	61	19	123	40	0	0	327
CNGBs	0	0	0	0	0	0	67	50	14	0	0	0	0	131
HEBs	0	0	0	2	400	194	135	0	0	0	0	0	0	731
PEBs	16	137	14	0	76	48	0	0	0	0	0	0	0	291
HFCEBs	100	30	0	0	0	0	0	0	0	0	0	0	0	130
Total	116	167	14	6	506	272	222	111	33	123	40	0	0	1 610

Table 2 Vehicle and model assumed parameters

Input data	DBs	CNGBs	HEBs	PEBs	HFCEBs
Average acquisition cost/10^6 yuan	0.60	0.63	0.77	0.85	2.30
Fuel cost/(yuan · km^{-1})	1.80	1.03	1.66	1.08	3.04
Bus O&M cost/(yuan · km^{-1})	0.45	0.5	0.32	0.16	0.21
Charging station installation cost/10^6 yuan			0.065	0.065	
Charger O&M cost /10^6 yuan			0.020	0.020	
Costs of hydrogen refueling facilities/(yuan · kg^{-1})					67
Financial subsidy/10^6 yuan	0	0	0	0	0.2
Maximum life cycle			12		
Minimum life cycle			8		
Annual purchase budget/10^6 yuan			500		
Annual mileage of a bus/km			7×10^4		
Annual discount rate/%			3		
Annual rate of price increase/%			3		

2.2 Results and discussion

Based on the China Energy Statistical Yearbook (2021), the local database of GREET© 2022 was updated, and the emission factors of LCE for buses powered by different fuel types were calculated. The results are shown in Table 3.

Table 3 Carbon emission factors for buses powered by different fuel types

Bus fuel type	DBs	CNGBs	HEBs	PEBs	HFCEBs
Emission factor/ $(\mathrm{kg \cdot km^{-1}})$	1.23	1.07	1.06	0.86	1.38

Although DBs and CNGBs have the lowest acquisition costs, Table 3 shows that PEBs have a significant environmental advantage. By contrast, HFCEBs have higher acquisition costs than PEBs but do not present substantial ecological benefits. The primary cause is that most hydrogen used in China is gray hydrogen, which generates a large amount of carbon emissions in its production process[14]. Based on four alternative fuels as fleet replacement targets, the optimization results of the bus fleet replacement schedule are summarized in Table 4.

The TCO and LCE under different replacement vehicle targets were determined. The results are shown in Fig. 1.

Table 4 Bus fleet replacement schedule for the base case

Target	Composition	2022	2023	2024	2025	2026	2027	2028	2029	2030
CNGBs	DBs	213	164	145	84	46	34	4	4	0
	CNGBs	245	294	357	418	633	726	858	1 169	1 610
	HEBs	731	731	687	687	583	502	400	266	0
	PEBs	291	291	291	291	218	218	218	71	0
	HFCEBs	130	130	130	130	130	130	130	100	0
HEBs	DBs	303	189	150	99	49	23	23	0	0
	CNGBs	131	131	96	58	58	43	10	10	0
	HEBs	755	869	943	1 032	1 152	1 216	1 289	1 484	1 610
	PEBs	291	291	291	291	221	198	158	16	0
	HFCEBs	130	130	130	130	130	130	130	100	0
PEBs	DBs	295	165	146	87	40	31	31	1	0
	CNGBs	163	160	46	35	35	35	35	35	0
	HEBs	731	731	731	676	644	571	150	66	0
	PEBs	291	424	557	682	761	843	1 264	1 408	1 610
	HFCEBs	130	130	130	130	130	130	130	100	0
HFCEBs	DBs	174	87	84	64	4	4	4	0	0
	CNGBs	149	94	27	27	27	27	27	27	0
	HEBs	742	742	683	597	532	372	186	51	0
	PEBs	305	305	305	263	219	186	172	106	0
	HFCBs	240	382	511	659	828	1 021	1 221	1 426	1 610

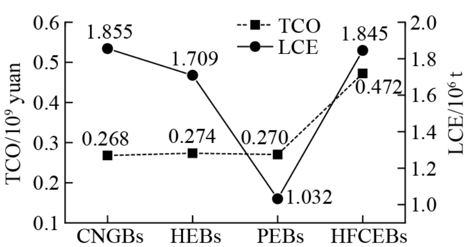

Fig. 1 Total cost of ownership and life-cycle of carbon emissions for various bus fleets

PEBs are replacement vehicles that exhibit the best overall performance, i.e., the lowest environmental impact and ownership cost. Moreover, CNGBs display the lowest total cost (2.68×10^8 yuan) but the highest carbon emissions (1.855×10^6 t) because of the low acquisition cost. The TCO of PEBs is only 0.74% higher than that of CNGBs, while the LCE of PEBs is 44.37% lower than that of CNGBs. Referring to a study by Cohan et al. [15], the social cost of carbon emissions was assumed to be approximately 310 yuan/t for the base case.

Therefore, if socioeconomic growth is considered, then economic losses due to carbon emissions will be higher in the future, which will further reduce the advantages of CNGBs. Although PEBs have similar total costs to HEBs, their carbon emissions are off target by 65.6%. In the base case, HFCEBs perform poorly despite substantial subsidies for their acquisition and operation. The TCO and LCE of HFCEBs are 78.78% and 74.81% higher than those of PEBs, respectively. Therefore, choosing HFCEBs is inadvisable until their acquisition cost and the LCE of hydrogen fuels are not significantly reduced.

3 Uncertainty Scenarios for Electricity Mix

The objectives of the 14th Five-Year Plan of China for a modern energy system were released by the National Development and Reform Commission. Based on those objectives, scholars have forecasted that by 2030, 40%, 20%, 12%, 20%, and 7% of electricity in China will originate from coal combustion, wind, solar, hydropower, and nuclear sources, respectively. To assess the risk and uncertainty of this forecast, various possible scenarios and outcomes using Monte Carlo simulations with repeated random sampling were performed. Consistent with previous studies, 5 000 Monte Carlo iterations were executed for each target, assuming that the future development follows a normal distribution. In Fig. 2, the simulation results are presented as cumulative distribution functions, with 20% and 80% probabilities representing the high-risk and low-risk levels of target achievement, respectively. Accordingly, the emission factors of LCE for PEBs and HEBs were calculated. The results are shown in Table 5.

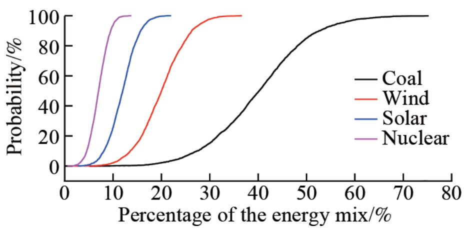

Fig. 2 Cumulative distribution function plots for various percentages of energy mix

Table 5 Carbon emission factors for different risk levels

kg/km

Risk levels	HEBs	PEBs
Base case	1.06	0.86
Low-risk	0.90	0.75
High-risk	0.88	0.54

Table 5 shows that a shift in the electricity mix significantly affects the carbon emission factors of HEBs and PEBs. Remarkably, the carbon emission factor of PEBs can be reduced to zero when electricity is entirely generated using renewable energy sources. Because HEBs use diesel fuel for operations, their carbon emission factor cannot reach zero in any scenario. Based on the carbon emission factors at different risk levels, the optimal fleet replacement schedules for HEBs and PEBs were recalculated. The results are summarized in Fig. 3.

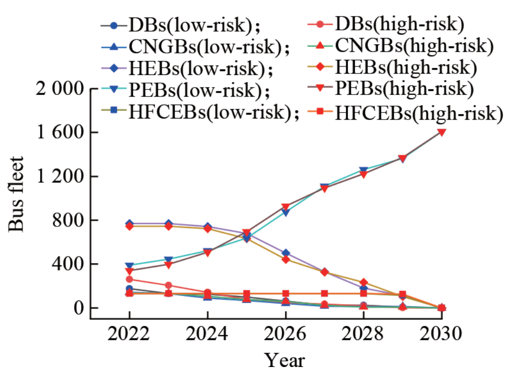

Fig. 3 Bus fleet replacement schedules for various risk levels

In Fig. 3, bus fleet replacement schedules vary with the carbon emission factors of the alternative fuel vehicles. In general, a low emission factor of the target bus fleet indicates a highly aggressive replacement of highly polluting buses at an early stage. The early replacement of highly polluting vehicles indicates significant and fast accruement of the possible environmental benefits, which aligns with the replacement target of this study.

4 Sensitivity Analysis

4.1 Sensitivity analysis of hydrogen production

Generally, hydrogen can be classified into three main types, namely, gray, blue, and green hydrogen, depending on the carbon emissions during its production process[16]. The emission factors of the three types of hydrogen were calculated. The results are shown in Table 6.

Table 6 Carbon emission factors for three hydrogen types

Hydrogen type	Gray hydrogen	Blue hydrogen	Green hydrogen
Emissions factor/ (kg · km^{-1})	1.38	0.72	0.35

As shown in Table 6, altering the production procedure significantly impacts the environmental benefits of hydrogen energy, which is consistent with the findings of previous studies[17].

Carbon emissions from the production of green hydrogen are only 25.36% of those from the production of gray hydrogen. Furthermore, the environmental benefits of blue hydrogen are already higher than those of other alternative fuels for the base case. In Fig. 4, the results for the three types of hydrogen bus fleets (i.e., gray, blue, and green hydrogen) indicate that the hydrogen production procedure significantly affects LCE, whereas it only has a minor impact on the TCO.

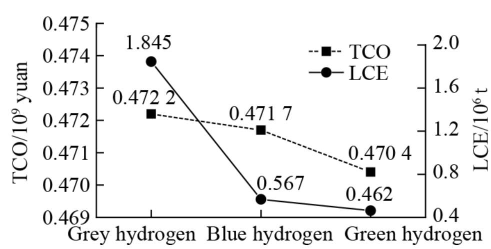

Fig. 4 Total cost of ownership and life-cycle of carbon emission of three types of HFCEBs

Currently, in addition to the high acquisition cost, the lack of a matured supply chain and refueling stations for hydrogen fuel has resulted in high usage cost, becoming a massive barrier for transit operators to choose HFCEBs[18]. Therefore, as shown in Fig. 5, the influence of hydrogen fuel usage cost on the TCO and LCE was analyzed for three hydrogen fuel usage costs of 80% (Case 1), 50% (Case 2), and 20% (Case 3) of the base case.

Fig. 5 shows that reducing the hydrogen usage cost does not significantly affect the TCO and LCE of the HFCEB fleet. In Case 3, when the hydrogen usage cost is reduced by 80% compared with the base case, the TCO and LCE of HFCEBs are reduced by only 2.33% and 2.49%, respectively. This trend is slightly distinct from the results reported by Cullen et al. [18], which can be attributed to the fact that the hydrogen usage cost is only a minor fraction of the TCO at the fleet level. Therefore, encouraging refueling station construction to reduce the hydrogen usage cost may not be the most urgent requirement for promoting the use of HFCEBs.

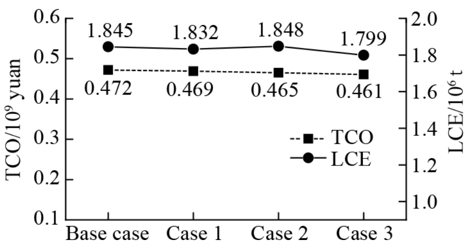

Fig. 5 Effects of hydrogen fuel usage cost on total cost of ownership and life-cycle of carbon emission

4.2 Sensitivity analysis of bus acquisition costs

The high acquisition cost of HFCEBs is one of the primary constraints for their large-scale adoption. Authorities must frequently provide considerable subsidies to transit companies to make them cost-competitive[19]. To analyze the impact of the acquisition cost on the TCO and LCE, three case scenarios were analyzed: HFCEBs with the acquisition costs of 1.70×10^6 yuan (Case 4), 1.275×10^6 yuan (Case 5), and 0.85×10^6 yuan (Case 6).

Fig. 6 shows that reducing the acquisition cost can significantly improve the cost-effectiveness of HFCEBs, which is consistent with the results of a study by Pamucar et al[19]. The TCO of HFCEBs in Case 6 is approximately 59.53% and 29.26% lower than those of the base case and PEBs, respectively. Moreover, the acquisition cost of HFCEBs is approximately 1.5 times that of PEBs (Case 5), and the TCO of the HFCEB fleet is approximately the same as that of the PEB fleet. However, reducing the acquisition cost does not significantly affect LCE, i. e., it does not improve the environmental benefits of HFCEBs.

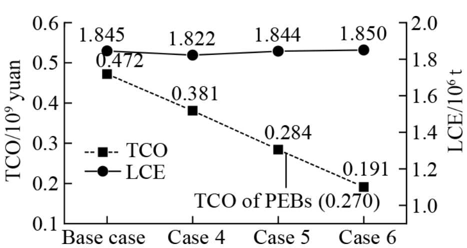

Fig. 6 Effects of acquisition cost on total cost of ownership and life-cycle of carbon emission

4.3 Combined effect of acquisition cost and fuel production

Based on the results of the sensitivity analysis, six scenarios were chosen to explore the acquisition cost and alternative fuel production effects on the TCO and LCE of HFCEBs and PEBs in the bus fleet replacement process. The six scenarios correspond to the six cases in the abscissa of Fig. 7. Specifically, two cases were analyzed for the PEB fleet: the base case (Case 7, which corresponds to the low-risk scenario discussed in Section 3) and the desired case (Case 8, which corresponds to the high-risk scenario discussed in Section 3). For the HFCEB fleet, four cases were analyzed: the use of blue (Case 9) and green (Case 10) hydrogen when the acquisition cost is 1.5 times that of PEBs and the use of blue (Case 11) and green (Case 12) hydrogen when the acquisition cost is the same as that of PEBs.

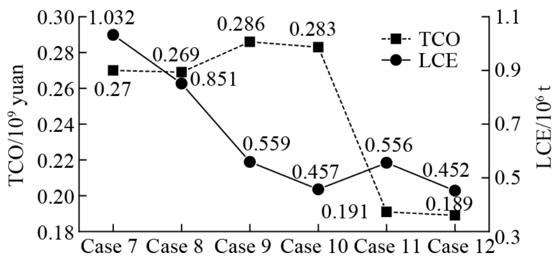

Fig. 7 Effects of acquisition cost and fuel production on total cost of ownership and life-cycle of carbon emission

Fig. 7 reveals that PEBs are the optimal alternate vehicles at this stage, considering the effects of the TCO and LCE. By 2030, the LCE of PEBs will be further reduced with changes in the energy mix. In the desired case scenario (Case 8), LCE is reduced by 17.54% compared with the base case. However, currently, HFCEBs not only have a significant cost disadvantage but also have higher carbon emissions than PEBs. The TCO of HFCEBs for Cases 9 and 10 are approximately 1.06 and 1.05 times that of PEBs in the desired case scenario (Case 8). Moreover, the corresponding carbon emissions are approximately 65.69% (Case 9) and 53.7% (Case 10) higher than those of PEBs when, instead of the current gray hydrogen fuel, blue or green hydrogen is used as the alternative fuel. With the transformation in the hydrogen production procedure, HFCEBs are expected to be more cost-effective by up to 29.74% and have approximately 53.11% lower carbon emissions than PEBs. Additionally, this will occur only when the acquisition cost of HFCEBs is the same as that of PEBs and green hydrogen is used.

Therefore, to further promote the use of HFCEBs, the most urgent requirements are to focus on developing vehicle technology and changing the hydrogen production process. Similarly, Gunawan et al. [20] claimed that producing hydrogen using renewable energy sources (e. g., wind or solar) will significantly enhance the environmental benefits of HFCEBs.

5 Conclusions

1) The TCO of PEBs is higher than that of CNGBs by

only 0. 74%, while the LCE of PEBs is 44. 37% lower than that of CNGBs. In particular, the uncertainty analysis of the electricity mix indicates that PEBs can also reduce carbon emissions by up to 17. 54% by 2030. Therefore, considering the cost and environmental benefits, PEBs are currently the best choice for bus fleet replacement. Although HEBs have a similar TCO to PEBs, they consume a certain amount of diesel fuel during operation, resulting in higher LCE than PEBs.

2) Choosing HFCEBs in the current bus fleet replacement process is inadvisable in terms of cost and environmental benefits. A series of sensitivity analyses suggested that to improve the competitiveness of HFCEBs, the immediate priority should be to reduce the acquisition cost and alter the hydrogen production procedure instead of focusing on lowering the hydrogen usage cost. Specifically, a large subsidy may instead significantly increase carbon emissions if hydrogen use cannot be simultaneously shifted from gray hydrogen to blue or green hydrogen.

3) Given the challenge of optimizing the energy mix and reducing the battery acquisition cost, the probability of further reductions in the TCO and LCE of PEBs in the near future is low. Correspondingly, for HFCEBs, with an increase in their production capacity, the acquisition cost can be reduced, and with the maturing of the production process of blue or green hydrogen, HFCEBs will have a broad development prospect.

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基于生命周期碳排放和总拥有成本的公交车队更新优化

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摘要:为探索电能和氢能源作为常规公交替代燃料的优势和潜力,确定公交车队更新时序的优化方案,从生命周期的角度综合考虑碳排放和总拥有成本的影响,提出了一种混合整数规划模型.基于柴油、天然气、油电混合、纯电动和氢燃料电池5种动力类型公交的运营数据,分析了电力结构、制氢方式、车辆购置成本和氢能源使用成本的不确定性对车队更新方案的影响.结果表明:电动公交车是当前公交车队更新的最佳选择;在现有的车辆技术水平和制氢方式情景下,不宜选择氢燃料电池公交;在蓝氢或绿氢得到大规模商业化之前,不建议通过财政补贴的方式全面推广氢燃料电池公交;采用该方法可以在不同情景和预期目标下确定公交车队的更新优化方案,促进绿色可持续发展.

关键词:公交车队更新;生命周期碳排放;总拥有成本;混合整数规划;替代燃料;电动公交;氢燃料电池公交
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