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Article

Comprehensive Evaluation of the Sustainable Development of Battery Electric Vehicles in China

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Abstract: Due to the rapid growth in the total number of vehicles in China, energy consumption and environmental pollution are serious problems. The development of electric vehicles (EVs) has become one of the important measures for solving these problems. As EVs are in a period of rapid development, sustainability research on them is conducive to the timely discovery of—and solution to—problems in the development process, but current research on the sustainability of EVs is still scarce. Based on the strategic development direction of EVs in China, battery electric vehicles (BEVs) were chosen as the research object of this study. The theory and method of the life cycle sustainability assessment (LCSA) were used to study the sustainability of BEVs. Specifically, the indicators of the life cycle assessment (LCA) were constructed, and the GaBi software was used to assess the environmental dimensions. The framework of life cycle costing (LCC) was used to assess the economic dimensions from the perspective of consumers. The indicators of the social life cycle assessment (SLCA) of stakeholders were constructed to assess the social dimension. Then, the method of the technique for order preference by similarity to ideal solution (TOPSIS) was selected for multicriteria decision-making in order to integrate the three dimensions. A specific conclusion was drawn from a comparison of BEVs and internal combustion engine vehicles (ICEVs). The study found that the life cycle sustainability of ICEVs in China was better than that of BEVs. This result might be unexpected, but there were reasons for it. Through sensitivity analysis, it was concluded that the current power structure and energy consumption in the operation phase of BEVs had a higher environmental impact, and the high cost of batteries and the government subsidy policy had a higher impact on the cost of BEVs. Corresponding suggestions are put forward at the end of the article.

Keywords: BEVs; sustainable development; LCSA; LCA; LCC; SLCA; MCDM

1. Introduction

In response to global climate change, energy consumption, and environmental pollution, many countries are setting targets for energy conservation and emission reduction and actively carrying out innovative actions to achieve sustainable development. As one of the main sources of energy consumption and environmental pollution, internal combustion engine vehicles (ICEVs) have become a main reform objective for transportation innovation, while electric vehicles (EVs), having energy conservation and environmental protection benefits, have become a development trend in motor vehicles. In recent years, EVs have developed rapidly all over the world. In 2018, global EV sales reached 2.1 million units, which was an increase of 64% compared with the sales in 2017. In the same year, EV sales in the United States and Europe increased by 79% and 34%, respectively, and sales outside China, Europe, and the United States increased by 39%. It is worth mentioning that China is still the largest contributor to the growth of EV sales. In 2018, EV sales in China increased by 78% to 520,000 units [1]. With regard to the development of EVs in the future, according to the new policy scenario, IEA projects that the global electric vehicle stock will exceed 55 million units in 2025 and reach about 135 million units in 2030, with an average year-on-year compound annual growth rate of 30% over the projection period. Global EV sales will reach 12 million in 2025 and nearly 23 million in 2030, increasing by an average of 21% per year [2]. In addition, China proposes that by 2020, the production and sales of EVs will reach 2 million units, and the cumulative production and sales will exceed 5 million units [3]. Countries are promoting the development of EVs through measures such as technology development, infrastructure construction, and the formulation of policies and regulations. It can be seen that EVs are in a period of rapid development, but there will inevitably be various problems. In order to identify whether EVs are sustainable at present, and to discover and solve the problems in their development in a timely fashion, it is necessary to conduct sustainability research on them.

Recently, the concepts and assessment tools of sustainability have been introduced into the strategic decision-making system of products, which can be used to evaluate the sustainability of products [4]. Therefore, it is necessary to carry out sustainability assessments of various alternative products at an early stage, which enables relevant decision makers to make decisions based on the assessment results. The life cycle sustainability assessment (LCSA) is one of the most promising methods of sustainability assessment [5]. It uses the Brundtland definition of sustainability as the starting point of analysis [6]. The most common explanation for this definition is that sustainability emphasizes the simultaneous optimization of environmental performance, economic issues, and social issues [7]. Therefore, the environment, economy, and society are regarded as the three pillars of sustainability, and the LCSA method is widely used to assess their performance [8]. The LCSA method is primarily conceptualized as a combination of three methods of the life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (SLCA). The described LCSA framework can be expressed as LCSA = LCA + LCC + SLCA [9]. Among these methods, LCA is a method to study the potential impact of products on the environment during their whole life cycle, from beginning to end [10]. LCC is a method for incorporating relevant costs from different perspectives into an assessment practice [11]. SLCA is a method for assessing the potential impacts of products on society throughout their life cycle, with an emphasis on measuring the impacts on workers, local communities, consumers, value chain participants, and society, which are affected by the production and consumption of products [12]. The method framework of LCA has been widely accepted and standardized [13,14]. With the development of informatization, many types of database software for product life cycle assessment have been developed, such as GaBi, GREET, SimaPro, and other software from abroad, in addition to Ebalance, eFootprint, DHU-LCA, and other software from China. The LCC method has not been standardized, but there are some suggested methodological guidelines [15]. The SLCA method is still in the evolution stage due to its high subjectivity, but it has also been provided with some suggested guidelines [16–18]. In general, the LCSA method is generally accepted conceptually [19], but it is still a new field of research. At present, current research on LCSA can be divided into two categories: the first is focused on developing LCSA methods, and the second involves the study of case studies using the LCSA method [10,20–22].

Around 45% of the world's EVs are located in China. The EVs of China mainly include three types: battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs). This study selected BEVs instead of PHEVs or FCEVs as the research object. The reasons that motivated this selection are as follows. In 2018, there were 11,200 fuel cell passenger cars worldwide. This is much lower than the number of BEVs and PHEVs circulating in 2018, which is why FCEVs were not chosen as research objects. In addition, the majority of global EV sales tend to be BEVs (about 70% in 2018), mainly because China is the world's largest EV market, and its BEV adoption rate is very high [2]. The Chinese government has also clearly pointed out that BEVs are the strategic direction for the development of EVs. Therefore, BEVs were choose as the research objects. So far, there has been almost no research on the application of LCSA in BEVs, but there are many related studies that apply on LCA and LCC. Most of the LCA studies on BEVs used the comparative method to draw conclusions from the perspective of emissions. In the research on the whole vehicle, some conclusions showed that the impacts of EVs on the environment was generally better than other vehicles [23], and other conclusions were the opposite. The difference in the conclusions was due to factors such as the local power structure [24–26]. In addition, in the research on the core components of vehicles, the research on the battery was mainly based on a comparison of the EVs with batteries of different materials to assess the different environmental impacts [27–29]. The research on the dynamic system compared the impacts of the dynamic systems of BEVs and ICEVs on the environment, and a general conclusion was obtained that the impacts of BEVs were relatively large [30]. It can be seen from the above that in the existing research on the whole vehicle, the conclusion that BEVs had advantages with respect to the environment was still controversial, and their advantages were conditional. The LCC research on BEVs was mainly concerned with energy costs and subsidy policies. In these studies, some focused on the establishment of cost analysis frameworks [31], some took the partial cost of an electric vehicle as the research object [32,33], and some concluded that the cost of EVs was generally higher than that of other vehicles [34–37]. Others mainly considered the factors affecting the cost of EVs [38]. It can be seen that the studies generally concluded that the life cycle cost of BEVs is very high. At present, there is almost no SLCA research on BEVs. The reason may be that SLCA is an emerging tool that is under development, but increasingly more institutions and scholars are conducting SLCA research, including methodological and case studies. Among them, the research on methods has been mainly based on the overall assessment framework for constructing stakeholder classifications, as defined by the UNEP/SETAC guidelines. Since the data collected by SLCA studies usually contain qualitative and quantitative data, how to quantify qualitative data and integrate all data is the main content of the current research [39–42].

In summary, the development of EVs is one of the important measures for energy conservation and emission reduction. However, EVs are in a period of rapid development. At this stage, their sustainability assessment helps to identify current development problems and solve them in a timely manner. Therefore, sustainability research on EVs is necessary. This study took China as the research context and used BEVs as the research object to carry out a life cycle sustainability assessment. The purpose was to comprehensively analyze the development advantages and problems related to BEVs and provide suggestions as to their development planning. The specific research contents were as follows. Firstly, LCA, LCC, and SLCA studies were performed on a selected BEV and ICEV, and their scores in three dimensions were obtained. In addition, the scores in these three dimensions were integrated through a multicriteria decision-making method, and the integration results of the BEV and the ICEV were compared. It was concluded that the life cycle sustainability of the ICEV was better than that of the BEV. Finally, the main influencing factors affecting the sustainable development of the BEV were obtained through sensitivity analysis.

The innovation of this study lies in the following aspects. Because LCSA is still a new research field, application case studies are very limited [43]. In particular, related research on EVs in China is almost non-existent, and this study enriches the application cases of LCSA. In addition, research on EVs using SLCA did not exist, and this study is the first to carry out an SLCA application to BEVs.

2. Methods

2.1. Goal and Scope Definition

2.1.1. Goal of the Study

The goal of this study is to assess the life cycle sustainability of BEVs in China, and the results obtained by comparison with ICEVs will be used to analyze the developmental advantages and problems of BEVs. It is hoped that the problems discovered in this study can give direction to the sustainable development of EVs in China.

2.1.2. Scope of the Study

The system boundary of this study comprises three phases, namely manufacturing, operation, and recycling, which are the basic phases of the life cycle sustainability assessment of vehicles. Because of the complexity of the situation and the difficulty of obtaining data, the transportation, sales, and maintenance phases of vehicles are not considered in this study. The system boundary for the study is shown in Figure 1.

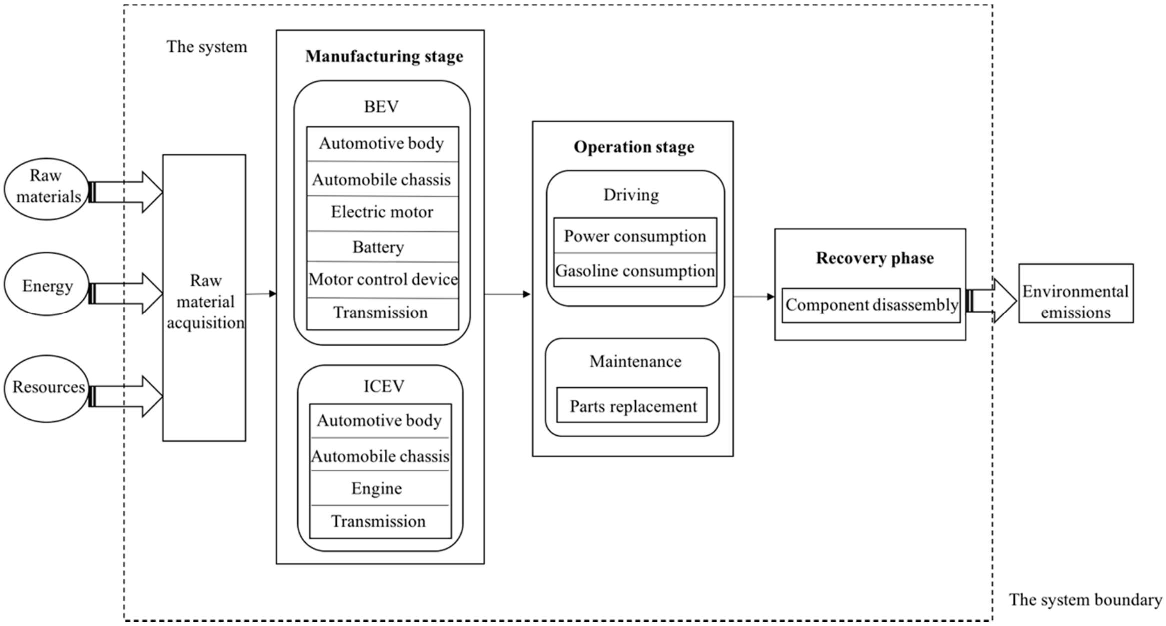


Figure 1. The system boundary of the study. Note: BEV = battery electric vehicle; ICEV = internal combustion engine vehicle.

A functional unit is considered to be a quantitative representation of a product system and is intended as a reference unit to provide a unified measurement basis for the input and output of the system boundary. This study used a travel distance of 1 km as a functional unit.

The specific analysis objects of this study are BEVs and ICEVs of the light passenger vehicle type. A BEV and an ICEV are selected based on similarities in many respects, such as the length, width, and height of the vehicle body, the maximum torque and maximum power of the engine or motor, and vehicle sales [31]. The main performance parameters of the vehicles are shown in Table 1.

Table 1. The main performance parameters of the vehicles.

Parameter Type	ICEV (BYD-M6) [44–46]	BEV (BYD-E6) [45,46]
Curb weight/kg	1720	2295
Overall dimension/mm	4820 × 1810 × 1765	4560 × 1822 × 1630
Maximum torque/N·m	234	450
Power source	gasoline	lithium iron phosphate battery
Energy consumption	9.6 L/100 km	33.54 kWh/100 km
Engine/motor characteristics	2.4 L	permanent magnet synchronous motors
Engine maximum power/kW	123	–
Motor maximum power/kW	–	120
Pure electric mileage/km	–	400
Battery capacity/kW·h	–	82

2.2. Sustainability Assessment Framework and Indicators

2.2.1. Environmental Dimensions

Assessment indicators of the environmental life cycle were constructed based on three types of impacts: resource depletion, climate change, and pollutant emissions. When the LCA method is used to assess environmental sustainability, the environmental impact issues are usually classified into 11 categories, based on the CML2001 impact assessment method. This study selected 7 of them as assessment indicators. The specific indicators are shown in Table 2.

Table 2. The assessment indicators of the environmental life cycle.

Impact Types	**Indicators**	**Units**	**Impact Areas**		
			Natural Resources	**Natural Environment**	**Human Health**
Resource depletion	Abiotic resource depletion potential (elements) (ADP(e))	kg Sb-eq	√		
	Abiotic resource depletion potential (fossil fuels) (ADP(f))	MJ	√		
Climate change	Global warming potential (GWP)	kg -eq		√	(√)
Emissions	Acidification potential (AP)	kg -eq		√	(√)
	Eutrophication potential (EP)	kg Phosphate-eq		√	(√)
	Ozone layer depletion potential (ODP)	kg CFC-eq		√	(√)
	Photochemical oxidant creation potential (POCP)	kg Ethene-eq		√	√

Note: "√" represents the direct impact and "(√)" represents the indirect impact.

2.2.2. Economic Dimension

In this study, the life cycle cost of the vehicles was considered from the perspective of consumers, including the initial purchase cost, operating cost, and recycling cost. The framework of the life cycle cost of the vehicles is shown in Figure 2.

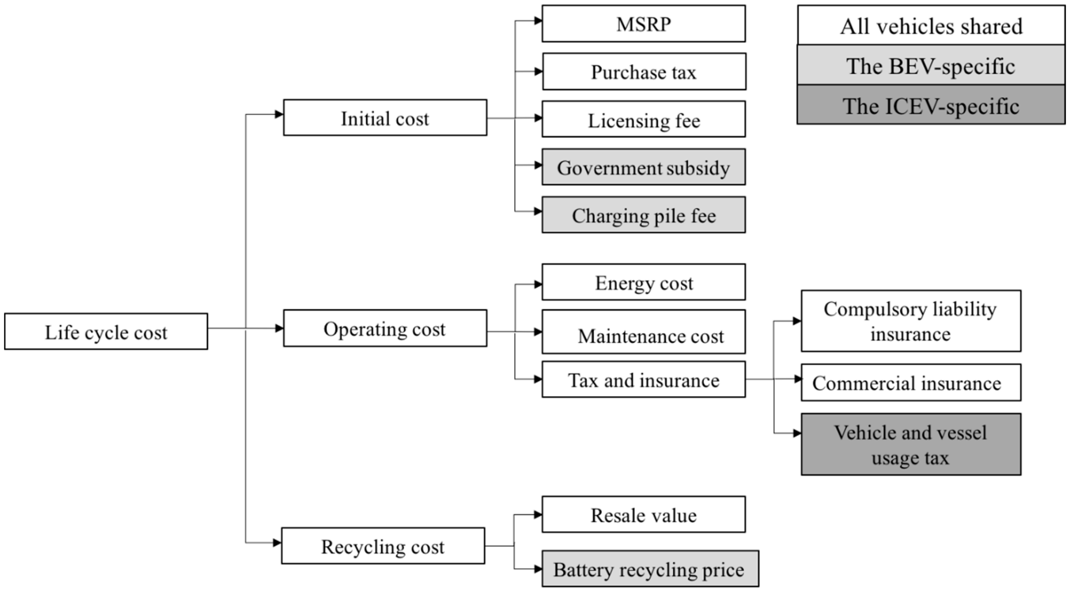


Figure 2. The framework of the life cycle cost of the vehicles.

The life cycle cost of the vehicles is calculated, as shown in Equations (1)–(4):

$$LCC = IC + OC_n - SV \tag{1}$$

where LCC is the discounted value of the life cycle cost of vehicles; IC is the initial cost, which is the one-time cost for consumers to buy a vehicle; OC_n is the operating cost, which is the discounted value of the sum of the cost incurred by the consumer in the process of using the vehicle for n years; and SV is the resale value, which is the discounted value of the residual value generated by consumers in a recycling process of vehicles.

$$IC = MSRP - GS + PT + LP + CP \tag{2}$$

where $MSRP$ is the manufacturer's suggested retail price; GS is the government subsidies, including national and local financial subsidies; PT is the purchase tax of a vehicle; $PT = MSRP/(1 + \text{VAT rate}) \times \text{purchase tax rate}$; LP is the licensing fee for a vehicle; and CP is the cost for BEV consumers to install a charging pile themselves.

$$OC_n = \sum_{i=1}^{n} \frac{EC_i + TIC}{(1+k)^{i-1}} + \sum_{i=1}^{n} \frac{MC}{(1+k)^{i}} \tag{3}$$

where EC_i is the energy cost of the i-th year; EC = energy consumption per 100 kilometers × energy price per unit × annual vehicle mileage/charging efficiency of EVs; TIC is the vehicle and vessel usage tax and insurance premium; the insurance premium = compulsory liability insurance premium + commercial insurance premium. MC is the maintenance cost and k is the discount rate, which is set at 8% in this study [47].

$$SV = \frac{(1-r)^n \times MSRP + BRP}{(1+k)^n} \tag{4}$$

where BRP is the recycling price of batteries and r is the annual depreciation rate, which is set at 20% in this study [48]. The specific values of the calculation parameters of the life cycle cost of the vehicles are shown in Table 3.

2.2.3. Social Dimension

In this study, the construction of assessment indicators of the social life cycle of the vehicles followed the SLCA guidelines and the "Methodological Sheets of Subcategories of Impact for a Social LCA" [49,50]. The subcategories and indicators most relevant to this study were selected. Generally, subcategories refer to stakeholders, including workers, consumers, local communities, society, and value chain participants. However, this study did not consider value chain participants but considered the government as a stakeholder affected by the vehicle life cycle. The reason for not considering value chain participants is that they involve investors, suppliers, dealers, competitors, etc., and these participants cannot be fully identified and assessed. The reason for considering the government is that BEVs can be sold at a lower price than the market price, which is due to a series of preferential policies adopted by the government. The assessment indicators of the social life cycle of the vehicles are shown in Table 4.

Table 3. The calculation parameters of the life cycle cost of the vehicles.

Cost Type	Parameter Name	ICEV	BEV	Remarks
Initial cost	MSRP (yuan)	135,900	330,000	
	GS (yuan):			
	national financial subsidy	0	44000	In accordance with national financial subsidies: local financial subsidies = 1:1 [1].
	local financial subsidy	0	44000	
	PT:			
	VAT rate (%)	17	-	The state will waive the vehicle purchase tax for EVs before December 31, 2020.
	purchase tax rate (%)	10	-	
	LP (yuan)	500	500	Calculated according to the merchants' unified service price of 500 yuan.
	CP (yuan)	0	8000	
Operating cost	EC:			
	energy consumption per 100 kilometers (kWh/100 km, L/100 km)[2]	9.6 L/100 km	33.54 kWh/100 km	
	energy price per unit (yuan/kWh, yuan/L)			Electricity and gasoline prices change every year.
	annual vehicle mileage (km/year)	13,000	13,000	
	charging efficiency of EVs (%) [44]	-	90	
	TIC:			
	vehicle and vessel usage tax (yuan)	900	0	
	insurance premium (yuan/year):			The state exempts EVs from vehicle and vessel usage tax.
	compulsory liability insurance premium	950	950	
	commercial insurance premium	2668.5	5580	
	MC (yuan/year): [36]	4774	3565	
Resale value	SV: battery recycling price (yuan) [48]	0	8000	

Notes: [1] Local subsidies vary from provinces to cities. This study, referring to the practices of Beijing and other provinces and cities in 2017, provided subsidies according to the 1:1 ratio between local financial subsidies and national financial subsidies. [2] Because the national electricity and gasoline prices change every year, the average prices of electricity and 92# gasoline over the past 18 years (2000–2018) were collected, and linear regression was used to predict electricity and gasoline prices for the next 13 years (2019–2031).

Table 4. The assessment indicators of the social life cycle.

Stakeholders	Subcategories	Indicators
Worker	Freedom of association and collective bargaining	Respect for freedom of association and freedom of collective bargaining
	Child labor	No child labor
	Fair salary	Fair salary structure design
	Forced labor	Workers are not forced to exceed normal working hours
	Equal opportunities/discrimination	Fair opportunities between groups of different genders, ages, and races
	Health and safety	No work accidents
Consumer	Health and safety	The product is safe to use
	Feedback mechanism	There are channels for feedback of product problems Feedback problems can be effectively solved
Local community	Access to material resources	Raw materials can be obtained quickly in the local area
	Local employment	Career opportunities are created Local labor is used
Society	Contribution to economic development	Products contribute to economic progress
	Technology development	The production of products promotes the development of related technologies
Government	Policy	There are sound policies, laws, and regulations in this field
	Subsidy	There are government subsidies in this field

2.3. Basic Assumptions

2.3.1. Environmental Assumptions

- This study only considered the main components of the vehicles, neglecting the parts with a relatively small mass. According to the relevant literature [24,26], the life cycle mileage of automobiles is generally set at 150,000–300,000 km. At present, the batteries of BEVs are mainly lithium-ion batteries, which can meet the requirements for EVs of running for 15 years and about 250,000 km [51]. This study set the life cycle mileage of the vehicles to 200,000 km and the service life to 15 years. It also considered the BEV as free of battery replacement during its life cycle.
- This study only considered the vehicle life cycle, without considering the fuel life cycle.
- When calculating the comprehensive impact values of the resource environment, it was assumed that all environmental impact types were equally important, and the weights of the indicators for each environmental impact type were the same.
- This study did not consider air conditioning being used when the vehicles were in use.

2.3.2. Economic Assumptions

- Financial loans were not considered when purchasing a vehicle, so the cost of the loans was not included in the purchase cost.
- This study considered a consumer purchasing a vehicle in 2017 and calculated the discounted value of the cost of the 15-year vehicle life cycle, with 2017 as the base year.
- This study only considered that owners of BEVs installed their own charging piles to charge their vehicles, at the same price as residential electricity.
- This study did not consider air conditioning being used when the vehicles were in use.

2.3.3. Social Assumptions

- In this study, the subcategories and indicators of the social life cycle assessment had the same weight.

2.4. Data Sources

2.4.1. Environmental Data

- The data were obtained from the built-in database of the GaBi software. Since this study is based on the Chinese background, the principle of data selection required that the corresponding inventory data for China be selected first, followed by data for other regions (Germany, etc.).
- The data were obtained from public data presented in journals or on the Internet, at home and abroad. Such data need to be compared and checked for consistency before they can be used.

2.4.2. Economic Data

The data were from the official BYD website, automobile and financial websites, relevant literature, notices from the Ministry of Industry and Information of the People's Republic of China (MIIT), and the Ministry of Finance of the People's Republic of China (MOF).

2.4.3. Social Data

The data were drawn from questionnaires and on-site interviews with stakeholders in the three phases of manufacturing, operation, and recycling of the vehicles. However, these data were usually qualitative. In order to aggregate the data into the corresponding subcategories, the qualitative data needed to be quantified first. Therefore, all questions in the questionnaire were set to questions of a "yes" or "no" type [52], and then the number of respondents who answered "yes" in each questionnaire was converted into percentage data. Secondly, the quantized data were aggregated according to the method of Vinyes et al. [42]. The specific operation process involved converting the collected indicator data into contribution percentages, then converting each percentage datum into a score ranging from 1 to 5, and finally assigning the scores to the corresponding subcategories. Since the social impact indicator is a benefit indicator, the scores corresponding to the percentage data are set as follows: a percentage contribution of 1–20% is 1 point, 21–40% is 2 points, 41–60% is 3 points, 61–80% is 4 points, and 81–100% is 5 points.

2.5. Multicriteria Decision-Making

Multicriteria decision-making (MCDM)—also known as multi-attribute decision analysis—usually proposes a limited set of scenarios, designed to consider multiple criteria and prioritize a limited set of alternatives [53]. Since this study deals with alternatives and multiple standards, MCDM is applicable. There are many specific methods for MCDM, including VIKOR, PROMETHEE, TOPSIS, gray analysis, promotion theory, DEA, etc. Since the method of the technique for order preference by similarity to ideal solution (TOPSIS) is an analysis method to compare and choose multiple schemes according to multiple indicators, this study chooses the TOPSIS method as the decision analysis method. The specific steps of the TOPSIS method are outlined below. The original data form, supposing that there are n evaluation objects and m evaluation indicators, is shown in Table 5.

Table 5. The original data form.

Evaluation Object	Indicator 1	Indicator 2	...	Indicator m
1	x_{11}	x_{12}	...	x_{1m}
2	x_{21}	x_{22}	...	x_{2m}
...	...	...	...	
n	x_{n1}	x_{n2}	...	x_{nm}

Step 1: The assimilation of indicator attributes can transform low-priority indicators and neutral indicators into high-priority indicators. Data can be appropriately expanded or reduced by a certain percentage to convert the data.

$$x'_{ij} = \begin{cases} x_{ij} & high-priority\ indicators \\ 1/x_{ij} & low-priority\ indicators \\ M/\left[M+\left|x_{ij}-M\right|\right] & neutral\ indicators \end{cases}$$

Step 2: Normalization of the assimilation data.

$$Z_{ij} = \begin{cases} \dfrac{x_{ij}}{\sqrt{\sum_{i=1}^{n}\left(x_{ij}\right)^2}} & Original\ high-priority\ indicators \\ \dfrac{x'_{ij}}{\sqrt{\sum_{i=1}^{n}\left(x'_{ij}\right)^2}} & Original\ low-priority\ indicators\ or\ neutral\ indicators \end{cases}$$

Thus, the normalized matrix can be obtained:

$$Z = \left(Z_{ij}\right)_{m\times n}$$

The normalization of the data, calculated according to the above formulas, is more complicated, and it is not easy to find the positive and negative ideal solutions. Therefore, the improved normalization method is used to normalize the various indicators of the evaluation object [54].

For benefit indicators: $Z_{ij} = \begin{cases} \frac{x_{ij}-x_{jmin}}{x_{jmax}-x_{jmin}} & x_{jmax} \neq x_{jmin} \\ 1 & x_{jmax} = x_{jmin} \end{cases}$

For cost indicators: $Z_{ij} = \begin{cases} \frac{x_{jmax}-x_{ij}}{x_{jmax}-x_{jmin}} & x_{jmax} \neq x_{jmin} \\ 1 & x_{jmax} = x_{jmin} \end{cases}$

Step 3: Identification of the best and worst schemes.

The best scheme Z^+ consists of the maximum values in each column of Z: $Z^+ = (\max z_{i1}, \max z_{i2}, \ldots, \max z_{im})$, and the worst scheme Z^- consists of the minimum value in each column of Z: $Z^- = (\min z_{i1}, \min z_{i2}, \ldots, \min z_{im})$.

Step 4: Calculation of the distance D_i^+ and D_i^- between each evaluation object and Z^+ and Z^-.

$D_i^+ = \sqrt{\sum_{i=1}^{m}\left(maxZ_{ij} - Z_{ij}\right)^2}$ $D_i^- = \sqrt{\sum_{i=1}^{m}\left(minZ_{ij} - Z_{ij}\right)^2}$

Step 5: Calculation of how close each evaluation object is to the best scheme.

$C_i = \frac{D_i^-}{D_i^+ + D_i^-}$ when $0 \leq C_i \leq 1$, $C_i \rightarrow 1$, which indicates that the evaluation object is superior.

Step 6: Sorting by size, giving the result of the evaluation.

3. Results and Discussion

3.1. Sustainability Assessment

3.1.1. Environmental Life Cycle Assessment

Based on the environmental impact inventories of the vehicle life cycle, this study was combined with the GaBi software to obtain the impact results on the resource environment. The specific results are shown in Table 6.

(1) Comparison of the assessment results of the comprehensive impact of the resource environment.

Figure 3 and Table 6 show the comprehensive impact values of the resource environment of the life cycles of the BEV and ICEV. It can be seen that the comprehensive impact value of the BEV was greater than that of the ICEV. Specifically, except for the fossil energy depletion, the impacts of mineral resource depletion, climate change, and emissions of the BEV were greater than those of ICEV. Figure 4 shows the comprehensive impacts of the resource environment at each phase of the life cycle of the BEV and ICEV. It can be concluded that the main phase of the comprehensive impact of the BEV was the raw material acquisition and manufacturing phase, while for the ICEV, it was the operation phase. In the following, a detailed analysis of the resource depletion, climate change, and emissions at each phase of the life cycle of the BEV and ICEV is provided.

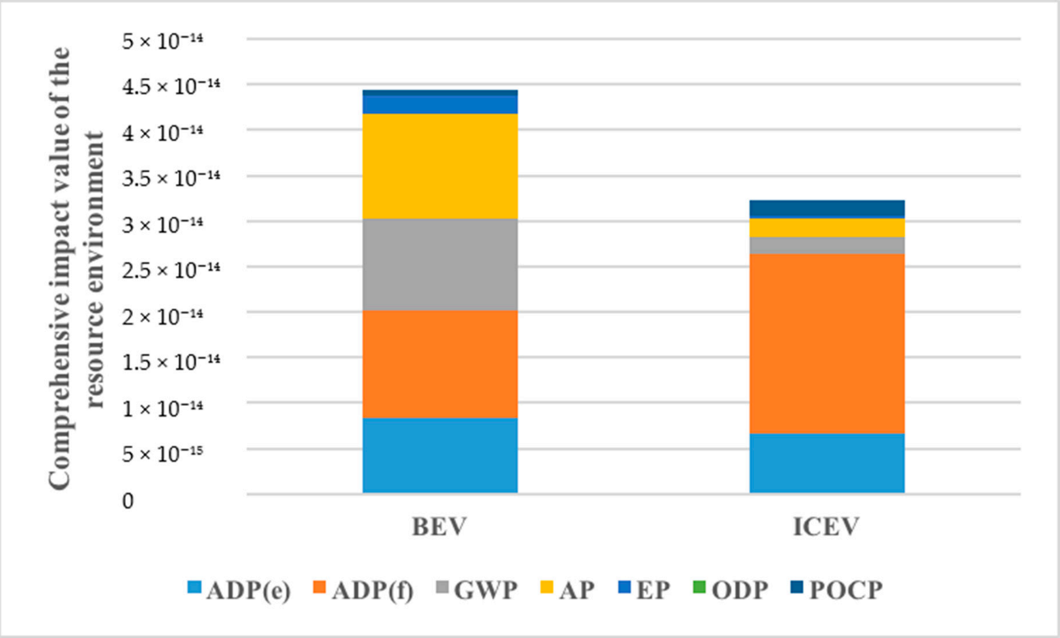


Figure 3. The comprehensive impacts of the resource environment of the life cycle of the BEV and ICEV.

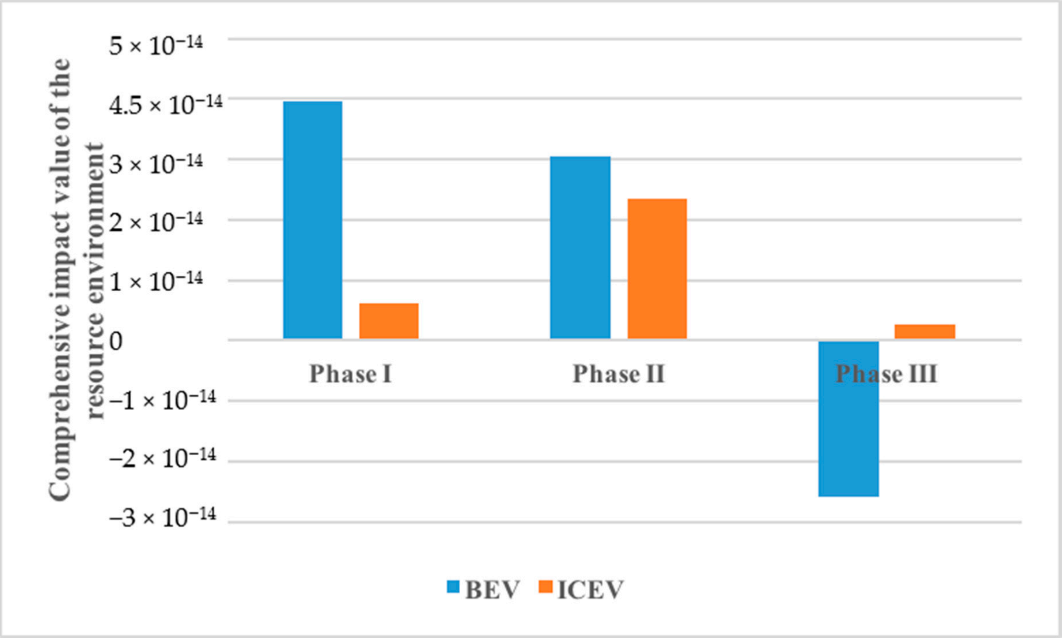


Figure 4. The comprehensive impacts of the resource environment at each phase of the life cycle of the BEV and ICEV.

(2) Comparison of the assessment results of the resource depletion.

Figure 5 and Table 6 show that the mineral resource depletion at each phase of the life cycle of the BEV and ICEV. It can be seen that the mineral resource depletion for the BEV and ICEV mainly occurred in the raw material acquisition and manufacturing phase, but at this phase, the depletion of mineral resources of the BEV was about 27% higher than that of the ICEV. The main reason for this may be that the curb quality of BEVs is larger than that of ICEVs, and the structure of BEVs is more complicated. As for the production of the main components of the vehicles, BEVs require more raw materials than ICEVs, such as steel, copper, and aluminum. In addition, the acquisition process of raw materials for the lithium iron phosphate batteries of BEVs also consumes a large amount of mineral resources, such as lithium ores and geotechnical resources. Therefore, under the premise of ensuring the performance and cruising range of BEVs, reducing the curb quality, especially reducing the battery quality to reduce the mineral resource depletion, has become a key issue for development.

From Figure 6 and Table 6, the fossil energy depletion at each phase of the life cycle of the BEV and ICEV can be seen. It can be concluded that the fossil energy depletion of the BEV and ICEV mainly occurred in the operation phase, and the fossil energy depletion of the ICEV was greater than that of the BEV. The reason why BEVs consume fossil energy is that although BEVs consume a large amount of electric energy during the operation phase, more than 70% of electric energy in China comes from coal-fired power generation, so a large amount of coal is consumed. However, although the fossil energy depletion of one BEV is less than that of one ICEV, with the increasing number of BEVs, a large amount of fossil energy will be consumed. Therefore, efforts should be made to change the coal-fired power structure of China to reduce the fossil energy depletion of BEVs.

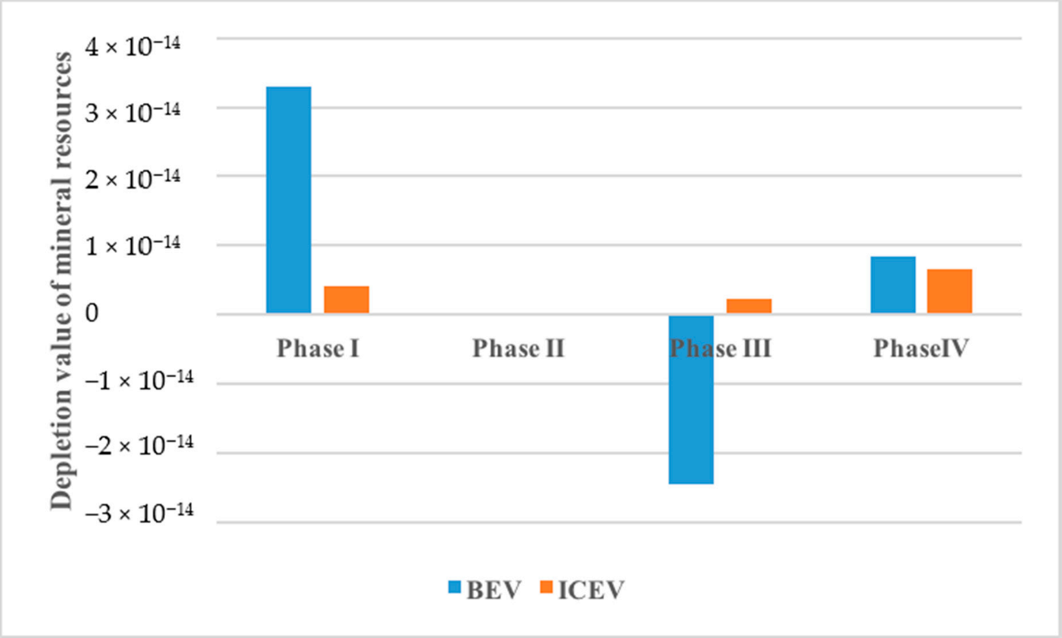


Figure 5. Mineral resource depletion at each phase of the life cycle of the BEV and ICEV.

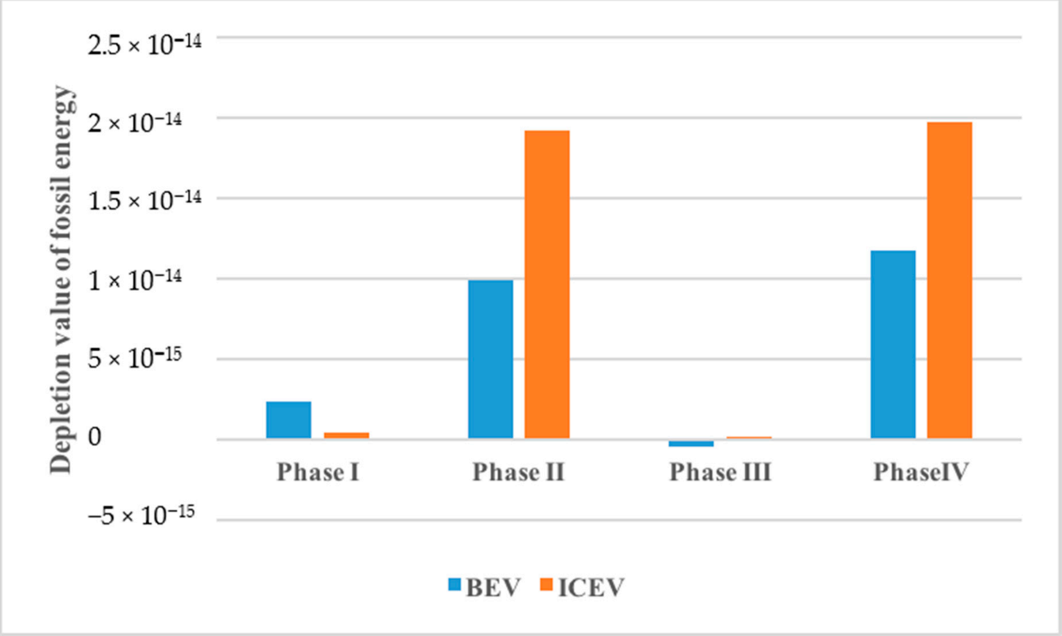


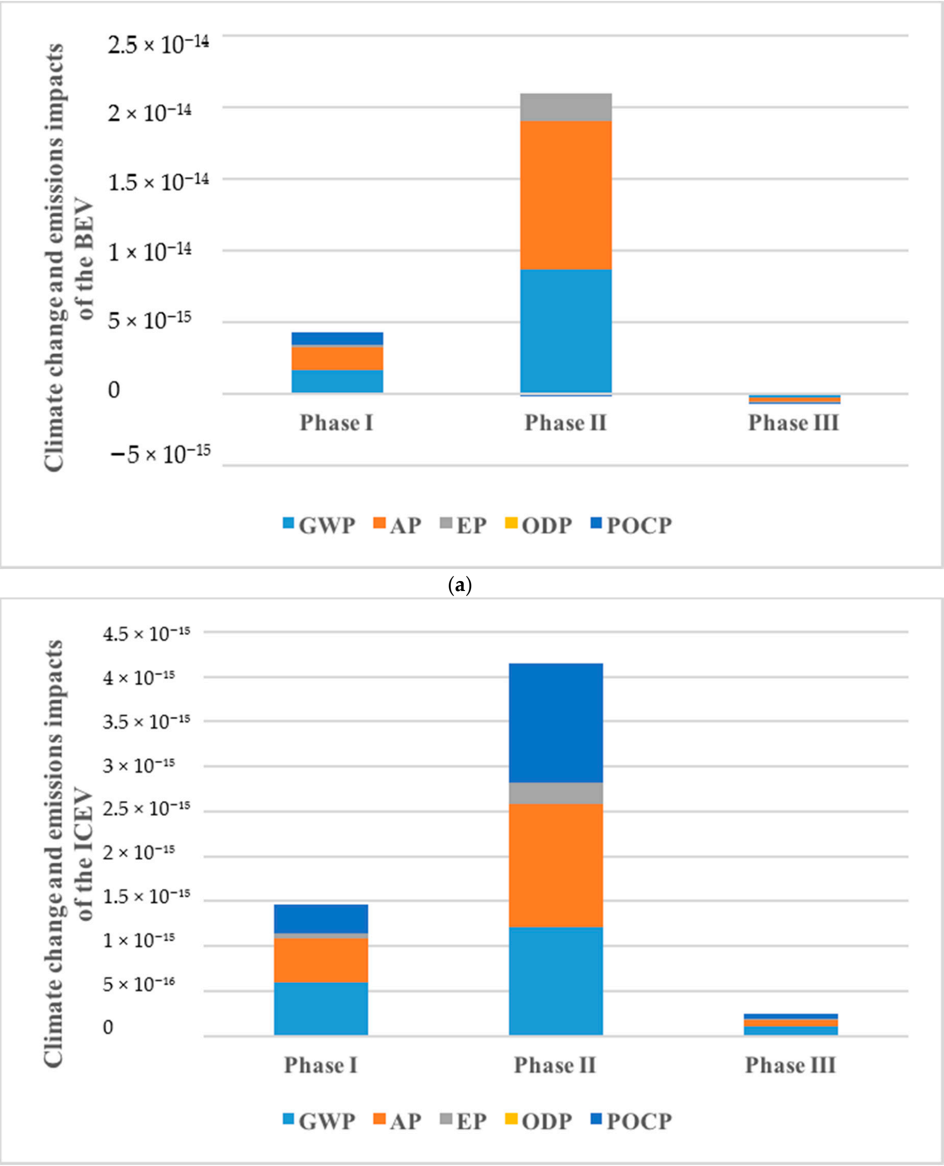
Figure 6. Fossil energy depletion at each phase of the life cycle of the BEV and ICEV.

(3) Comparison of the assessment results concerning climate change and emissions.

Figure 7a and Table 6 show the impacts of climate change and emissions at each phase of the life cycle of the BEV. It can be seen that the impacts, from most significant to least significant, were caused by GWP > AP > EP > POCP > ODP, and the environmental impacts mainly occurred in the operation phase. The contribution rates of this phase to the environmental impacts were 85.3%. The main reason is that BEVs consume a large amount of electric energy during operation. According to the power structure of China, BEVs emit a large amount of greenhouse gases (CO_2) and acidified gases, such as SO_2 and NO_x. Therefore, it is of great significance to reduce the power consumption during the operation phase and change the coal-fired power generation structure in China. In addition, energy-saving and emission reduction can also be achieved under different operation modes based on BEVs. Because of the energy storage characteristics of BEVs, they can operate in two modes—grid to vehicle (G2V) and vehicle to grid (V2G)—to realize a two-way energy flow with the grid. In the G2V mode, BEVs are used as electrical loads. A large number of vehicles randomly connected to the grid will cause the peak load to be very high, while the use of traditional coal-fired power generation will cause a large amount of emissions from BEVs. Adopting a coordinated charging strategy and maximizing the use of sustainable energy can reduce the environmental impacts of BEVs. In the V2G mode, BEVs can be used as controllable loads and distributed power supplies in smart grids. By optimizing the charging and discharging energy of BEVs, improving the utilization rate of renewable energy and energy conversion efficiency, power grid losses can be minimized. As a piece of energy storage equipment, a BEV can also reduce the emissions of atmospheric pollutants during the power generation by replacing some high-emission generators in the power system during peak load periods.

Figure 7b and Table 6 show the impacts of climate change and emissions at each phase of the life cycle of the ICEV. It can be concluded that the impacts of climate change and emissions, from most significant to least significant, were caused by AP > GWP > POCP > EP > ODP, and the contribution rates of the operation phase to the environmental impacts were 70.9%. The main reasons for the great burden on the environment in this phase is that ICEVs consume a large amount of gasoline during the operation phase, and gasoline produces a large amount of greenhouse gases (CO_2), acidified gases (SO_2), and other toxic and harmful gases, such as NO_x, during the combustion process. Photochemical smog is mainly the result of excessive hydrocarbon (HC) and nitrogen oxide (NO_x) emissions from the process. Therefore, to reduce the environmental impacts of ICEVs, we should improve the utilization efficiency of gasoline and other fuels, and increase the development and use of clean energy.

Table 6 shows the results concerning the environmental life cycle assessment of the vehicles. From the perspective of the life cycle of the vehicles, the impact value of climate change and the emissions of the BEV were much larger than those of the ICEV. Based on the above analysis, the main reason is that although the exhaust emissions of BEVs during the operation phase are zero, the environmental impacts of BEVs during the operation phase are transferred to the power generation process, because of the large amount of electrical energy consumed. Therefore, BEVs do not really achieve zero pollution. Moreover, since China mainly uses coal-fired power generation, the energy consumption and emissions in the life cycle of BEVs are not low in China, and the environmental benefits of BEVs are not ideal.



(**a**)

(**b**)

Figure 7. The impacts of climate change and the emissions at each phase of the life cycle of the (**a**) BEV and (**b**) ICEV.

3.1.2. Life Cycle Costing

According to the framework of the life cycle cost of the vehicles proposed in this study, the specific results of life cycle cost calculation of the BEV and ICEV are shown in Table 7 and Figure 8. They were 1.87 yuan/km and 1.73 yuan/km, respectively, and the life cycle cost of the BEV was about 1.08 times that of the ICEV. From this point of view, based on the selected vehicles, the BEV did not have an economic advantage over the ICEV. This was because the initial cost of the BEV was about 1.69 times that of the ICEV, despite its low operating cost and high resale value relative to the ICEV. The higher initial cost of the BEVs is mainly due to the high MSRP, which leads to a higher purchase tax and insurance costs for BEVs. The reasons for the high initial cost of BEVs are as follows: first, BEVs have higher development cost associated with the battery technology; and second, the government policy support for BEVs has been weakened, including the reduction of the government price subsidies and the expiration of the preferential tax policies for BEVs. Therefore, BEVs do not have economic advantages over ICEVs at the present stage.

Table 6. Normalized results of the environmental life cycle assessment of the vehicles.

Vehicle Type	**Phase**	**Resource Depletion**		**Climate Change**	**Emissions**				**Comprehensive Impact Value**
		ADP(e)	ADP(f)	GWP	AP	EP	ODP	POCP	
BEV	I	3.30×10^{-14}	2.30×10^{-15}	1.68×10^{-15}	1.51×10^{-15}	2.28×10^{-16}	3.68×10^{-20}	8.35×10^{-16}	3.96×10^{-14}
	II	4.67×10^{-17}	9.88×10^{-15}	8.65×10^{-15}	1.04×10^{-14}	1.85×10^{-15}	4.79×10^{-22}	-1.96×10^{-16}	3.06×10^{-14}
	III	-2.46×10^{-14}	-4.66×10^{-16}	-2.75×10^{-16}	-3.01×10^{-16}	-2.23×10^{-17}	-1.48×10^{-20}	-1.14×10^{-16}	-2.58×10^{-14}
	IV	8.42×10^{-15}	1.17×10^{-14}	1.01×10^{-14}	1.16×10^{-14}	2.05×10^{-15}	2.25×10^{-20}	5.25×10^{-16}	4.44×10^{-14}
ICEV	I	4.20×10^{-15}	4.22E $\times 10^{-16}$	5.95×10^{-16}	4.83×10^{-16}	6.65×10^{-17}	3.69×10^{-21}	3.18×10^{-16}	6.09×10^{-15}
	II	4.59×10^{-17}	1.02×10^{-14}	1.21×10^{-15}	1.38×10^{-15}	2.34×10^{-16}	7.07×10^{-21}	1.33×10^{-15}	1.44×10^{-14}
	III	2.38×10^{-15}	1.20×10^{-16}	1.09×10^{-16}	7.20×10^{-17}	9.05×10^{-18}	7.00×10^{-22}	6.14×10^{-17}	2.75×10^{-15}
	IV	6.63×10^{-15}	1.98×10^{-14}	1.91×10^{-15}	1.93×10^{-15}	3.09×10^{-16}	1.15×10^{-20}	1.71×10^{-15}	2.32×10^{-14}

Notes: I—Raw material acquisition and manufacturing phase, II—Operation phase, III—Recycling phase, IV—Life cycle process. Part of the BEV data was derived from [44], and the rest of the data were calculated by the GaBi software.

Table 7. Life cycle cost of the vehicles (unit: yuan/km).

Cost Type	ICEV	BEV
Initial cost	0.74	1.25
Operating cost	0.98	0.58
Resale value	0.0075	0.031
Total cost	1.73	1.86

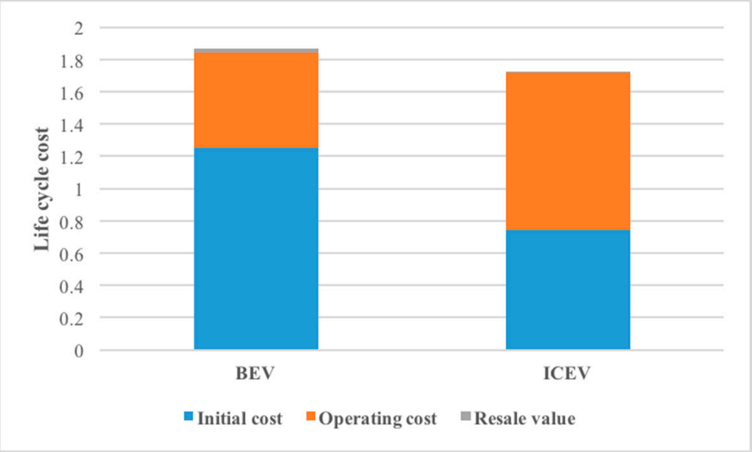


Figure 8. Life cycle cost of the vehicles.

3.1.3. Social Life Cycle Assessment

The social impact results for the selected vehicles are shown in Table 8. In general, the BEV had a higher positive social impact than the ICEV. Specifically, from the indicator scores of the five stakeholders, the indicator scores for society and government for the BEV were higher than those for the ICEV, and the BEVs had no obvious advantage in terms of the indicator scores of other stakeholders. The specific reason may be that from the perspective of workers, since the ICEV and BEV selected in this study are all BYD brand vehicles, the workers belong to a company. Even if the workers work in different production lines, the rules and regulations of the company are nearly consistent. Therefore, there is no difference between ICEVs and BEVs in the indicator scores of workers. From the perspective of consumers, consumers believe that ICEVs are more mature and safer than BEVs, which is due to their long-term use of—and familiarity with—ICEVs. Consumers generally find the problems related to short driving mileage and slow charging speed of BEVs to be significant from their experiences. These problems are mainly affected by the low level of battery technology, but the problem of backward technology cannot be solved in a short time. In addition, imperfect after-sales service is also a concern for consumers, mainly because the number of ICEVs in the city is much larger, vehicle maintenance and repair shops mainly serve ICEVs, and most technicians lack knowledge and experience in BEV maintenance. There are also problems related to the insufficient supply and high price of automobile parts. There was no difference between the BEV and ICEV in terms of the indicator score for the local community. As for the indicator score for society, China has given priority to the development of BEVs in recent years. Therefore, BEVs, for which new ideas are constantly brought forth, are bound to make a great contribution to the innovation of vehicle production technology. As for the indicator score for the government, although ICEVs have been developed for much longer, and the relevant laws and regulations associated with them are basically mature, the government has supported and encouraged the development of BEVs in recent years for the purpose of sustainable development. The state has enacted some laws and regulations for EVs, but most of them are based on policies related to subsidies and fostering growth.

3.1.4. Multicriteria Decision-Making

Based on the specific calculation of the environmental, economic, and social impacts of the selected vehicles, the specific results are shown in Table 9, where the environment and cost are cost indicators, and society is a benefit indicator. According to the TOPSIS method, the data for the three dimensions in Table 9 were integrated. The calculation results are shown in Table 10. At present, the life cycle sustainability of the ICEV is better than that of the BEV, while the sales of BEVs are increasing every year. Such a result may be unexpected, but it is not difficult to understand, given the above analyses. As for the environmental dimension, the comprehensive impact value of the resource environment of the life cycle of the BEV was higher than that of the ICEV. Specifically, except for the fossil energy depletion, the impacts of mineral resources depletion, climate change, and emissions for BEV were greater than those for ICEV. Moreover, the main phase of the comprehensive impacts of the resource environment of the life cycle of the BEV was the raw material acquisition and manufacturing phase. In the phase of raw material acquisition, the BEV consumes more mineral resources than the ICEV, because of the former's larger curb quality and more complex structure. Since a large amount of electrical energy is used in the process of mining and the production of various raw materials, the BEV will generate more greenhouse gas emissions and cause greater climate change at this stage. In the manufacturing phase, in addition to the production of vehicle bodies similar to ICEVs, the production of batteries and motors are also included for BEVs. There are many processes involved in the production of batteries and motors. Complex processes consume a lot of electrical energy, which in turn generates a large amount of greenhouse gas emissions and causes climate change. It can be seen that a large amount of electrical energy is consumed in the phase of raw material acquisition and manufacturing, so the environmental impacts of BEVs are transferred to the power generation process. Therefore, the main reason for the poor sustainability of the life cycle of BEVs is the power structure of China, of which coal-fired power accounts for more than 70% [55]. Although the pollution emission of BEVs is almost zero in the operation phase, the electric energy used is generated by coal-fired power generation, so a large number of pollutants will be emitted during the whole power generation process. In 2017 and 2018, China accounted for 91 percent and 80 percent, respectively, of the world's electricity demand for EVs [2,56]. Such a large electricity demand and carbon-intensive power production structure have led to a concentration of carbon dioxide emissions related to EVs, mainly in China. It can be concluded that the BEVs of China are at a disadvantage in terms of the environment. The economic dimension was based on the consumer perspective. Since the initial cost of BEVs is significantly higher than that of ICEVs, the total cost of BEVs is higher than that of ICEVs. The main reason for this result is that the battery cost accounts for a high proportion of the price of EVs [56]. From the indicator scores of the five stakeholders in the social dimension, the total score of the BEV was higher than that of the ICEV, and the scores of the stakeholders of society and the government were dominant. So far, public policy has been the most important factor affecting the Chinese EV market [57], and the growing sales of BEVs are less likely to be related to their current sustainability results than to policy-driven results. A number of policies introduced by the Chinese government include credit management policies, fuel consumption regulations, and carbon quota policies to promote the development of EVs and solve the problems of energy consumption and environmental pollution [58]. Therefore, once the policy incentives for EVs are reduced, their sales will be affected.

Table 8. Raw data for the life cycle sustainability assessment of vehicles.

	Environment (1/km)	**Cost (yuan/km)**	**Society**
ICEV	2.32×10^{-14}	1.73	62.5
BEV	4.44×10^{-14}	1.86	64

Table 9. The results of the social life cycle assessment of the vehicles.

Stakeholders	**Subcategories**	**Indicators**	**Results/Contributions (%)**		**Scores**	
			ICEV	BEV	ICEV	BEV
Worker	Freedom of association and collective bargaining	Respect for freedom of association and freedom of collective bargaining	100	100	5	5
	Child labor	No child labor	100	100	5	5
	Fair salary	Fair salary structure design	70	70	4	4
	Forced labor	Workers are not forced to exceed normal working hours	78	78	4	4
	Equal opportunities/discrimination	Fair opportunities between groups of different genders, ages, and races	90	90	5	5
	Health and safety	No work accidents	89	89	5	5
Consumer	Health and safety	The product is safe to use	88	76	5	4
	Feedback mechanism	There are channels for feedback of product problems	89	89	5	4.5
		Feedback problems can be effectively solved	93	75		
Local community	Access to material resources	Raw materials can be obtained quickly in the local area	55	43	3	3
	Local employment	Career opportunities are created	85	85	4.5	4.5
		Local labor is used	80	80		
Society	Contribution to economic development	Products contribute to economic progress	100	100	5	5
	Technology development	The production of products promotes the development of related technologies	75	88	4	5
Government	Policy	There are sound policies, laws, and regulations in this field	100	90	5	5
	Subsidy	There are government subsidies in this field	60	100	3	5
			Total score		62.5	64

Table 10. The results of the life cycle sustainability assessment of vehicles using the technique for order preference by similarity to ideal solution (TOPSIS) method.

	D^+	D^-	C_i	Sorted Result
ICEV	0.02	0.48	0.96	1
BEV	0.48	0.02	0.04	2

While the life cycle sustainability of the ICEV is better than that of the BEV at present, this study does not deny the sustainable development prospect of BEVs in the future. This study is helpful for identifying the development problems of BEVs, and the solution to these problems is conducive to the sustainable development of BEVs. In terms of the environment, EVs provide fuel efficiencies that are two to four times higher than ICEV powertrains. If the proportion of clean energy generation can be improved in the future, the combination of high-efficiency electric motors and a low-carbon power structure will greatly reduce the carbon dioxide emissions of EVs. For example, under the European electricity production structure, BEVs can reduce greenhouse gas emissions by about 30% compared with ICEVs, which is higher than that of the United States and Japan, because the carbon intensity of power generation in these two countries is higher than that in Europe [56]. With the increasing popularity of EVs, in the future, the increasing demand for electricity will affect the transmission and distribution network. As a means of enhancing power generation and distribution, a smart grid is more flexible, efficient, and secure. As an important part of the smart grid technology, the application of the V2G technology can realize bidirectional interaction and exchange between the energy of EVs and the electric grid under controlled conditions. The V2G technology can use EVs as dynamic loads and potential dispatchable distributed energy sources, avoiding peak loads, improving the operation efficiency of the electric grid, and reducing atmospheric pollutant emissions [59]. The V2G technology also uses EVs to integrate renewable energy sources (such as wind and photovoltaic solar) into power systems, thus increasing the use of clean energy [60]. Moreover, the smart grid can access devices, such as small-scale home wind power generation and rooftop photovoltaic power generation, which is conducive to the large-scale application of EVs. In terms of cost, four key cost and performance drivers have been identified for Li-ion batteries: capacity, chemistry, manufacturing capacity, and charging speeds. With the development of this technology, battery chemistries will evolve into options with a higher energy density and lower reliance on cobalt; battery capacities will increase to serve all-electric driving ranges; and the emergence of battery enterprises with a large-scale production capacity will produce economies of scale [56]. The drop in battery prices has led to lower initial costs of EVs. With the increasing number of EVs, considering the role of the smart grid, future EVs using the V2G technology could be charged when electricity prices are lower. At higher electricity prices, the storage energy of EVs will be sold to power companies for cash subsidies to reduce the operating costs of EVs. Therefore, taking certain measures to reduce costs is conducive to the large-scale promotion of EVs. In terms of society, the classification and evaluation of existing policies shows that macropolicies are considered to be of high importance and to cause great satisfaction, while industry management policies are considered to be of low importance and to cause little satisfaction. Preferential tax policies and demonstration policies are paid less attention, but they cause greater satisfaction. There is a high awareness of the importance of subsidies, technical support, and infrastructure policies, but a low awareness of the resulting satisfaction [57]. It can be seen that although policy plays an important role in the promotion of EVs at present, there is still room for improvement, and we should also be alert to the dependence of sales on policy.

3.2. Sensitivity Analysis

The above analyses considered the impacts of the three dimensions of the life cycle sustainability of the BEV, in which the social impact was the result of the subjective assessment. Therefore, based on the objectivity of the results, the main factors affecting the environment and cost of the BEV were further clarified by sensitivity analysis.

3.2.1. Power Structure Analysis and Sensitivity Analysis of Environmental Impact Factors

(1) Power structure analysis

Because of the power structure, which is dominated by coal-fired power in China, in order to obtain the different impacts of power structure changes on the environment, this study mainly analyzed the changes of the environmental impact indicators of the BEV under different proportions of coal-fired power, in scenarios where other renewable energy power replaced coal-fired power. The current power structure in China is as follows: coal-fired power accounts for 70.92%; hydropower accounts for 18.61%; wind power accounts for 4.76%; nuclear power accounts for 3.87%; and solar power accounts for 1.84% [55]. This study assumed that the proportion of coal-fired power was reduced to 50%, and the proportion of other renewable energy generation was 50%. The environmental impact values of the vehicles, under different proportions of coal-fired power, are shown in Table 11. According to the analysis, with the decrease of the proportion of coal-fired power, the environmental impact values of most indicators of the BEV showed a downward trend, and the comprehensive impact value also dropped by about 31%. The environmental impact values of most indicators of the ICEV showed a downward trend, but the downward trend was not obvious. It can be concluded that changing the power structure mainly based on coal-fired power generation in China plays an important role in reducing the environmental impacts of BEVs. Therefore, we should make extensive use of other renewable energy to generate electricity, and actively develop clean and efficient coal and fuel technology to improve the efficiency of energy conversion in the process of combustion, so that the environmental impacts of BEVs can be greatly reduced.

Table 11. The different impacts of the changes in the proportion of coal-fired power on the environment.

Environmental Impact Indicator	**Proportion of Coal-Fired Power**			
	BEV		**ICEV**	
	70.92%	50%	70.92%	50%
GWP	1.01×10^{-14}	6.87×10^{-15}	1.91×10^{-15}	1.89×10^{-15}
AP	1.16×10^{-14}	8.12×10^{-15}	1.93×10^{-15}	1.91×10^{-15}
EP	2.05×10^{-15}	1.46×10^{-15}	3.09×10^{-16}	3.09×10^{-16}
ODP	2.25×10^{-20}	5.65×10^{-20}	1.15×10^{-20}	1.14×10^{-20}
POCP	5.25×10^{-16}	3.73×10^{-16}	1.71×10^{-15}	1.72×10^{-15}
Comprehensive impact value	2.43×10^{-14}	1.67×10^{-14}	5.86×10^{-15}	5.82×10^{-15}

(2) Sensitivity analysis of energy consumption in the raw material acquisition and manufacturing phase, and the operation phase

According to the above analysis, the environmental impacts of climate change and emissions of the BEV mainly occurred in the operation phase, followed by the raw material acquisition and manufacturing phase. The sensitivity analysis was helpful for analyzing the degree of environmental impacts of the BEV on climate change and emissions in these phases. Assuming that the energy consumption of these two phases varied by ±10% as sensitivity factors, the environmental impacts of these two sensitive factors on climate change and emissions are shown in Figure 9. The result showed that when the energy consumption in the raw material acquisition and manufacturing phase and in the operation phase was reduced by 10%, the sensitivity coefficients of the energy consumption of the two phases of the BEV to the environmental impacts of climate change and emissions were 0.12 and 1.07, respectively. The sensitivity of energy consumption in the operation phase was much greater. It can be seen that under the premise of ensuring the various performance and cruising ranges of BEVs, it is particularly important to reduce the power consumption per 100 kilometers and improve the charging efficiency of the battery.

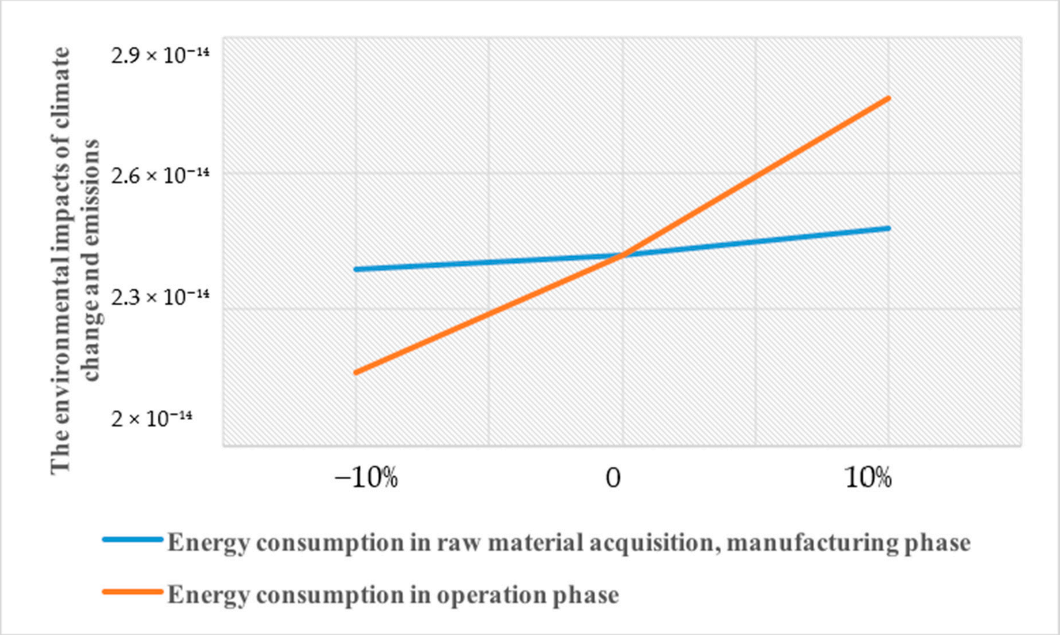


Figure 9. Sensitivity of energy consumption in the raw material acquisition and manufacturing phase and the operation phase to the environmental impacts of climate change and emissions.

3.2.2. Sensitivity Analysis of the Cost Impact Factors

(1) Development level of the battery technology for BEVs

The high cost of batteries due to the immature battery technology is the main reason for the higher cost of BEVs. As an important part of the dynamic system of BEVs, the battery technology directly affects the power consumption of BEVs. The combination of high power consumption and high battery cost will inevitably lead to an increase in the life cycle cost of BEVs. Therefore, the development level of the battery technology has a great impact on the life cycle cost of BEVs. In view of the development of the battery technology for BEVs in China in the future, the ministry of science and technology of the People's Republic of China (MOST) proposed that the power consumption of BEVs should be less than 10 kWh/100 km, and the battery cost should be reduced to 1 yuan/Wh by 2020 [61]. Therefore, this study considered the development level of the battery technology for BEVs from the two aspects of power consumption and battery cost, and then conducted a sensitivity analysis on these two aspects.

In this study, the power consumption per 100 kilometers was selected as a sensitivity factor for sensitivity analysis of the life cycle cost of the BEV. Based on the BEV selected in this study, the power consumption was 33.54 kWh/100km. The life cycle cost of the BEV was analyzed when the power consumption per 100 kilometers was reduced to 30 kWh, 20 kWh, and 10 kWh per 100 km. The battery cost was selected as a sensitivity factor for sensitivity analysis of the life cycle cost of the BEV. The cost of the current mainstream lithium iron phosphate battery on the market is about 1100 yuan/kWh, while the battery capacity of the selected BEV is 82 kWh. When the battery cost dropped, in order to make the power consumption per 100 kilometers and the battery cost have approximately the same rate of change to facilitate the comparison between the two, this study analyzed the life cycle cost of the BEV, with the battery cost reduced to 1,000 yuan, 660 yuan, and 330 yuan per kWh. The sensitivity analysis results for the power consumption per 100 kilometers and the battery cost are shown in Figure 10.

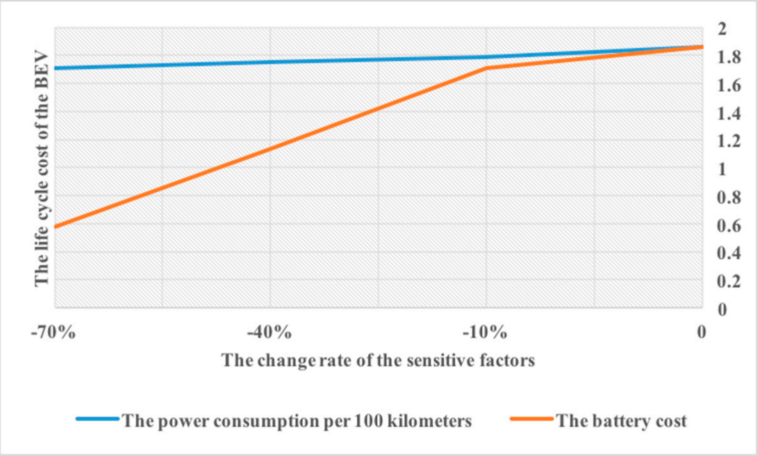


Figure 10. Sensitivity of the power consumption per 100 kilometers and battery cost to the life cycle cost of the BEV.

When the power consumption of the BEV was reduced from 33.54 kWh/100 km to 30 kWh, 20 kWh, and 10 kWh per 100 km, its sensitivity coefficient to the life cycle cost of the BEV was 0.36, 0.15, and 0.11, respectively. When the battery cost of the BEV was reduced from 1100 yuan/kWh to 1000 yuan, 660 yuan, and 330 yuan per kWh, its sensitivity coefficient to the life cycle cost of the BEV was 0.89, 0.98, and 0.98, respectively. Accordingly, when the change rate of the power consumption per 100 kilometers was approximately the same as that of the battery cost, the battery cost had a greater impact on the life cycle cost of the BEV, as shown through a comparison with the sensitivity coefficient. Based on the above conclusions, under the premise of maintaining the various performances and cruising range of BEVs, lowering the battery cost has a priority effect on the reduction of the life cycle cost of BEVs.

(2) Government Subsidies and Preferential Tax Policies

In recent years, government subsidies for EVs have been gradually reduced, and there may not even be any subsidies in the future. The state stipulates that EVs will be exempted from the vehicle purchase tax by 2021, and the tax exemption policy will probably be abolished after 2021. Both the government subsidies and preferential tax policies directly affect the life cycle cost of EVs. Therefore, both of these were selected as sensitivity factors for sensitivity analysis of the life cycle cost of the BEV. The sensitivity analysis of the government subsidies as a sensitivity factor in this study was based on the current government subsidy of 88,000 yuan for the BEV, considering the changes of the life cycle cost of the BEV, when the government subsidy was reduced by 0%, 25%, 50%, 75%, and 100%. The sensitivity analysis of the preferential tax policies as a sensitivity factor was based on the current exemption of the vehicle purchase tax for EVs by the government. We suppose that the government will start to levy a vehicle purchase tax on BEVs and levy it at a certain proportion of preferential treatment. We considered the change of the life cycle cost of the BEV when the preferential rate of vehicle purchase tax was 0%, 25%, 50%, 75%. and 100%. The sensitivity analysis results of the government subsidies and preferential tax policies are shown in Figure 11.

When the government subsidies were reduced by 0%, 25%, 50%, 75%, and 100%, their sensitivity coefficients to the life cycle cost of the BEV were 1.8, 1.91, 2.02, 2.13, and 2.24, respectively. When the preferential rate of the vehicle purchase tax was 0%, 25%, 50%, 75%, and 100%, its sensitivity coefficient to the life cycle cost of BEV was 1.94, 1.91, 1.87, 1.84, and 1.8, respectively. When the change rate of the sensitive factors ranged from 0% to 25%, the life cycle cost of the BEV was more sensitive to the preferential tax policies, but in general, the government subsidies had a greater impact on the life cycle cost of the BEV. At present, the state has made a double subsidy to EVs by the central and local governments to promote the development of EVs. As such, the purchase of EVs has increased every year in recent years. The price of subsidized EVs is generally higher than that of ICEVs. When the subsidies for EVs are gradually reduced, or there are no subsidies, EVs may face serious market shocks due to price disadvantages. However, subsidies for EVs can also easily make enterprises dependent. In the long run, enterprises may lack the motivation for technology development and product upgrading, and the industry could be prone to low-level blind expansion. Therefore, in order to compensate for the impacts of government subsidies on the life cycle cost of BEVs, enterprises should get rid of policy dependence and win the market competition by developing emerging technologies, improving the quality of automobiles, improving cost performance, and improving after-sales services.

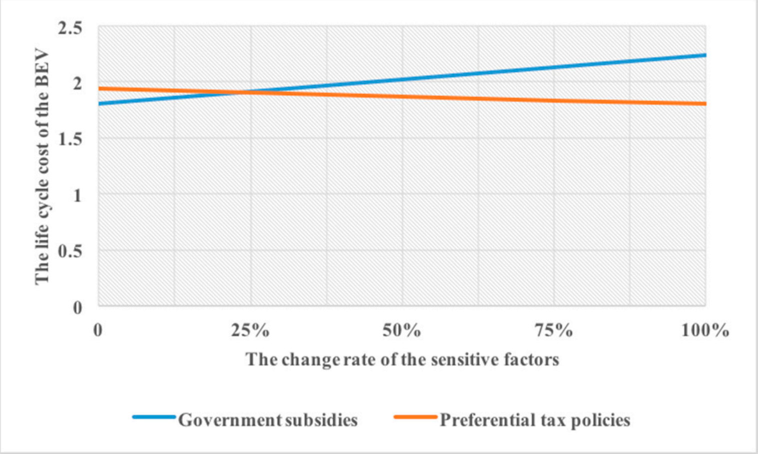


Figure 11. Sensitivity of government subsidies and preferential tax policies to the life cycle cost of the BEV.

4. Conclusions

With the rapid growth in the total number of automobiles in China, issues such as energy security and environmental pollution are imminent. Therefore, the Chinese government has proposed a development strategy for EVs. In order to discover the advantages and problems associated with the sustainable development of EVs in China, this study took BEVs as the research object, established an LCSA framework based on the life cycle sustainability assessment theory, and drew conclusions through a comparison of EVs and ICEVs. The main research conclusions include the following.

Based on the LCA theory, because the comprehensive impact value of the resource environment of the life cycle of the BEV was higher than that of the ICEV, the BEVs of China were at a disadvantage in terms of the environment. Moreover, the main phase of the comprehensive impact of the BEV was the raw material acquisition and manufacturing phase. Based on the LCC theory, it was concluded that the life cycle cost of the BEV was about 1.08 times that of the ICEV. Thus, the BEV had no economic advantage over the ICEV. Based on the SLCA theory and questionnaire surveys of stakeholders, it was concluded that the BEV had a higher positive social impact than the ICEV. Based on the theory of multicriteria decision-making and the method of TOPSIS, this study integrated the data from the three dimensions of the environment, cost, and society for the BEV and ICEV, and obtained the conclusion that the life cycle sustainability of the ICEV was better than that of the BEV.

The conclusion based on the analysis may be unexpected, but this study does not deny the development advantages of BEVs in the future. It is hoped that the problems discovered in this study can provide direction for the sustainable development of EVs in China and provide development ideas for EVs in countries similar to China, in terms of vehicle development strategies and energy structures. Based on the results of the sensitivity analysis of the factors affecting the BEV environment and cost dimension, this study proposes some suggestions to solve the problems existing in the development of BEVs in China. This study recommends efforts to improve the proportion of clean energy generation in the power structure; reduce the power consumption per 100 kilometers; improve the charging efficiency of power batteries; further develop smart grid technology that integrates EVs and the electric grid; and remove policy dependence by developing emerging technologies, improving the quality of automobiles, improving cost performance, and improving after-sales services.

It should be pointed out that there are still some shortcomings of this study. Firstly, the research object of this study is a BEV and an ICEV based on the choice of light passenger vehicle type, so the research object was limited, and the conclusion had certain limitations. Secondly, due to the lack of basic data on the environmental life cycle of China, the inventory data in this study used relevant foreign data, which might cause inaccuracies in the analysis results. Thirdly, based on the complexity of the research object, this study made some assumptions to limit the uncertainty in the research process, but these assumptions might be different from the actual situation. Therefore, in the follow-up study, we should expand the scope of the study to draw more general conclusions, strengthen the accumulation of the basic data of the environmental life cycle and the construction of the regional inventory database, and even if all the situations cannot be included in the discussion of the research content, statistical methods can be used to conduct statistical research on various situations, in order to try to predict the actual situation.

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