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Comparative evaluation of energy consumption and emissions in the life cycle of extended-range and battery electric vehicles

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Abstract

In order to explore the difference between EREV (extended range electric vehicles) and BEV (battery electric vehicles) in terms of energy consumption and pollution emissions, two representative models in the Chinese market are taken as research object. Meanwhile, mineral resources, fossil energy consumption, and pollution emissions are selected as comparative evaluation indexes, and corresponding mathematical evaluation difference models are established. Then, an analysis model for vehicles and components is constructed by using GaBi software based on the evaluation indexes and mathematical evaluation difference models. In addition, energy consumption and pollution emission of two vehicles under different operation modes are compared based on the structural differences of two power systems. From the respective of life cycle assessment (LCA), mineral resources consumption of BEV is 0.184 kg Sb eq, fossil energy consumption is $1.85\,E+05$ MJ, and carbon emission is $1.69\,E+04$ kg, which is approximately 1.29 times, 0.52 times, and 1.23 times of EREV. In the three electric system, mineral resources consumption of battery, motor, and electronic control of BEV is approximately 2.7 times, 1.29 times, and 1.22 times of that of EREV, respectively. Fossil energy consumption in raw material acquisition stage is approximately 1.92 times, 1.29 times, and 1.22 times, respectively, and that in manufacturing and assembly stage is approximately 2.03 times, 1.29 times, and 1.22 times, respectively. Carbon emissions are approximately 1.92 times, 1.29 times, and 1.22 times, respectively. In the pure electric mode, crude oil consumption of the EREV is 283.43 kg, which is approximately 4.06 times of that of the BEV; raw coal consumption of the BEV is 5231.7 kg, which is approximately 4.71 times that of the EREV; and natural gas consumption is approximately 7.4 times that of the EREV. In the extended range mode, natural gas consumption of the EREV is 515.45 kg, which is approximately 3.16 times that of the BEV in pure electric mode. Finally, from the aspects of manufacturing process optimization, body lightweight, and low-carbon energy structure, some suggestions are given to provide reference for policy formulation and filed research on energy saving and pollution emission reduction, so that the technology route of new energy vehicles in China is promoted and application of LCA in the field of new energy vehicles is improved.

Keywords Extended range electric vehicles · Battery electric vehicles · Life cycle assessment · Energy consumption · Pollution emissions · Operation mode · Comparative analysis

Introduction

China is experiencing rapid economic growth, followed by rapid growth in car ownership. The rapid growth in car ownership and use has exacerbated global warming, pollution emissions, and other environmental problems (Chen et al. 2020). In addition, in recent years, China's resource and energy situation has become increasingly tense, and its dependence on fossil resource is much higher than that of other countries (Xu and Xu 2021) . As one of the important industries of national energy sustainable development strategy and green ecological environmental protection, new energy vehicles can effectively alleviate energy and environmental problems, which are developing

rapidly around the world. According to the plan of the Chinese government, the cumulative output of electric vehicles will reach 5 million vehicles (Qiao et al. 2017). In 2020, in order to promote the high-quality development of the new energy automobile industry and accelerate the establishment of a powerful automobile country, the General Office of the State Council issued the "New Energy Automobile Industry Development Plan (2021–2035)," clearly pointing out that the development of new energy vehicles is the focus of energy conservation and emission reduction. At present, China's new energy vehicles have formed a trend of parallel development of multiple technical routes, and extended-range electric vehicles (EREV) and battery electric vehicles (BEV) have become two important technical routes for the electrification of China's automobile industry. Therefore, comprehensive research on the benefits of energy-saving and emission reduction of EREV and BEV will help to further explore solutions to alleviate the problems of resource depletion energy consumption and environmental pollution, and explore to accelerate the realization of new energy vehicle industry and energy green development path in China.

Literature review

Life cycle assessment (LCA) is a tool to evaluate the energy consumption and environmental impact of products, processes, or services in the whole life cycle (from cradle to grave) from raw material collection to product production, transportation, use, and final disposal (Wang et al. 2015). It has been widely used in various fields such as energy, environment, economic evaluation, and social policy for many years. For example, Mu et al. (2021) uses the life cycle assessment method to establish the life cycle inventory of nuclear power generation system; conduct environmental impact assessment; compare with the life cycle assessment results of thermal power generation, wind power, hydropower, and other renewable energy power; and predict the improvement potential of power grid in the future. Song et al. (2021) used the LCA method to evaluate the environmental impact of the cement manufacturing process with carbide slag and other industrial solid wastes as all raw materials, and evaluated the environmental impact of the process in 17 sub categories such as global warming, fossil resource consumption, and land occupation, and three major categories such as human health impact, ecosystem impact, and resource consumption.

The theory and method system of LCA has been also widely used in the research of new energy vehicles in recent years. For example, Hawkins et al. (2012b, a) developed the life cycle inventory of conventional diesel/gasoline vehicles and electric vehicles and applied this inventory to assess a series of environmental impacts of conventional diesel/gasoline vehicles and electric vehicles. The results showed that hybrid electric vehicles can reduce global warming potential by 10–24%, and

electric vehicles have a substantial increase in potential in terms of reducing environmental impact. Bickert et al. (2015) analyzed the impact of the carbon emissions of small gasoline vehicles and BEVs on the environment and economy. The results showed that the emissions of BEVs are higher than that of gasoline vehicles in the production stage, but the emissions are less in the operation process. Hooftman et al. (2018) compared and analyzed the power systems of plug-in hybrid electric vehicles, BEVs, and EREVs by using the LCA method. The results showed that the electric power system may improve urban air quality, but battery manufacturing is an important factor in the rise of the overall impact of electric vehicles. Evangelisti et al. (2017) conducted a life cycle comparative analysis on hydrogen fuel cell vehicles, BEVs, and gasoline vehicles and conducted a sensitivity analysis on the fuel cell stack and key components of fuel cell systems. The results showed that the production process of fuel cell vehicles has a great impact on the environment. Correa et al. (2017) proposed a multiphysical index model from well to wheel and compared the energy and environment of five kinds of urban bus powertrains. The results showed that short- and medium-term hybrid electric buses have the optimal effect, battery electric buses are suitable for short driving distances, and fuel cell buses are suitable for long driving distances. Lewis et al. (2014) evaluated the energy saving and emission reduction potential of BEVs and the impact of light weight on energy and greenhouse gas emissions. The results showed that when steel is replaced by aluminum, energy consumption and greenhouse gas emissions are significantly reduced in the entire cycle. Onat et al. (2015) compared BEVs, plug-in hybrid electric vehicles, hybrid electric vehicles, and gasoline vehicles in 50 states by comprehensively considering regional driving mode, power generation structure differences, vehicles, and battery manufacturing process. The results showed that electric vehicles are mostly concentrated in states with low carbon density, and hybrid electric vehicles are considered the most energy-saving choice in other situations. Noori et al. (2015) predicted the environmental emissions and life cycle costs of gasoline vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, EREVs, and BEVs in different regions of the USA in 2030 in accordance with the research model. The research results could help in identifying the ideal combination of different models in different regions of the USA in 2030 and prepare the transportation system of the USA to cope with the influx of electric vehicles.

Compared with research on the LCA of new energy vehicles in foreign countries, that in China started relatively late. At present, research is mainly focused on universities and has achieved corresponding results and practical application. For example, Shi et al. (2019) conducted LCA on the whole vehicle and fuel of gasoline vehicles and BEVs and analyzed their emission reduction potential under different policies. The results showed that BEVs can effectively reduce energy consumption by 25–50%, but the emission in the upstream process is higher. Xiong et al. (2019) studied the life cycle

energy consumption and greenhouse gas emissions of BEVs and plug-in hybrid electric vehicles. In Qinghua University, Qiao et al. (2017) analyzed the greenhouse gas emissions of BEVs and gasoline vehicles in the production stage, and the results showed that the CO_2 emission of BEVs is nearly 60% higher than that of gasoline vehicles. Peng et al. (2018) proposed an extensible EV-LCA model and evaluated the energy consumption and emissions of BEVs and gasoline vehicles by considering the grid structure and vehicle energy efficiency performance. The results showed that the BEVs can reduce greenhouse gas emissions by 30–80% compared with gasoline vehicles. Hao et al. (2017a, b) studied the life cycle costs and greenhouse gas emissions of gasoline vehicles, hybrid electric vehicles, and BEVs. The results showed that the cost-effectiveness of BEVs cannot be compared with hybrid electric vehicles but can reduce greenhouse gas emissions. Driven by the optimization of power grid structures and battery cost, the cost effectiveness of BEVs is expected to be significant in the next 10 years, thus improving and surpassing hybrid vehicles. In Shanghai Jiaotong University, Hu et al. (2004) used LCA technology to evaluate China's bioethanol hybrid fuel vehicles from the aspects of economy, environment, and energy consumption. The results showed that the consumption of fossil fuel and oil and the emission of CO_2, Co, HC, and other pollutants are low, but the total energy consumption and NOx emission are high. Yu et al. (2018) assessed the life cycle of gasoline vehicles and BEVs equipped with lithium iron phosphate and nickel cobalt manganese lithium batteries, respectively. The results showed that the nonbiological exhaustion potential (ADP) and environmental impact comprehensive value of BEVs are greater than those of gasoline vehicles. Zhang et al. (2019) of the Research Center for Ecological and Environmental Sciences, Chinese Academy of Sciences, comprehensively evaluated the energy consumption and greenhouse gas emissions of four major types of electric vehicle chargers in China during the manufacturing, service, and end-of-life stages and analyzed the changes of the global warming potential of chargers from 2020 to 2040.

Contribution of this work

The application of LCA in the field of new energy vehicles is mainly focused on BEVs and gasoline vehicles, followed by hybrid electric vehicles and hydrogen fuel cell vehicles; research on EREVs is less. Nevertheless, EREVs are an important development technology route in China's electric vehicle development planning. In the literature, a detailed comparative study on the entire life cycle stages of EREVs and BEVs have yet to be conducted. Therefore, this study takes the typical EREVs and BEVs in the Chinese market as specific research objects; selects mineral resources, fossil energy, and carbon emissions as evaluation indicators; adopts the life cycle assessment method (ISO 14040 2006); establishes corresponding mathematical evaluation

models around the three evaluation indexes; uses GaBi software to build vehicle models; and analyzes the specific parts of the two models from the perspective of the entire life cycle. On the one hand, the research results can provide data support for the formulation of China's electric vehicle technology route; on the other hand, it can improve research on LCA in the field of new energy vehicles and provide reference for new energy vehicle enterprises in terms of formulating strategic planning.

Methods

Assessment objects and functional units

This study considers the proportion of vehicle sales, technology maturity, market application, and data completeness and selects same-level vehicles (i.e., Chevrolet Volt and BYD EV5) as the empirical research objects. The main performance parameters of the two models are shown in Table 1. A functional unit refers to the process of unified conversion of all data units to make the research results comparable. Based on the existing research (Hawkins et al. 2012b, a) and considering the average mileage in the actual use of vehicles (Hawkins et al. 2013), this study selects 150,000 km of both vehicles on Chinese roads as the functional unit.

System boundaries and data sources

In this study, the entire life cycle is divided into four stages: raw material acquisition, parts manufacturing and assembly, vehicle operation, and recycling. In accordance with the differences between the two models, the EREV is mainly divided into nine important components, such as range extender group (engine and generator), and the BEV is divided into seven important components, such as power battery. The division of each component is shown in Fig. 1.

In the process of inventory data collection, the vehicle model data involved in various stages are mainly from domestic and foreign research literature (Li 2015, 2014; Liu 2013; Gu 2011; Zhang 2011), vehicle disassembly reports (Burnham et al. 2012), enterprise research, and the company's official website. In addition, upstream energy consumption data, such as electric energy and thermal energy, mainly come from the database in GaBi 9.1.

Assumption

The main differences between EREV and BEV are the range extender and the power battery. The engine of the range extender has a displacement of 1.4 L, and the power battery has a battery capacity of 43 kWh (see Table 1). According to the actual investigation, the mass of the engine is assumed to be 122.4 kg, the power battery of EREV is assumed to be 171.7 kg, and the mass of the power battery of BEV is assumed to be 482 kg. It is difficult to obtain the latest disassembly data for the specific material

Table 1 Main performance parameters of EREVs and BEVs

Vehicle type	Chevrolet volt	BYD EV5	Data sources
Body size/mm	4498×1798×1430	4680×1765×1500	Wu (2012) ; Ma (2019)
Curb weight/kg	1715	1845	Wu (2012); Ma (2019)
Battery energy/kW•h	16	43	Wu (2012); Ma (2019)
Maximum motor power/kW	111	160	Wu (2012); Ma (2019)
Engine displacement/L	1.4	/	Wu (2012)
Electric range/km	56	305	Wu (2012); Ma (2019)
Total mileage/km	570	305	Wu (2012); Ma (2019)
Fuel consumption (pure oil)/[L•(100 km)$^{-1}$]	6.36	/	Wu (2012)
Comprehensive energy consumption/[kW • h•(100 km)$^{-1}$]	22.5	11.8	Wu (2012); Ma (2019)
Maximum speed of BEV/km • h^{-1}	161	130	Wu (2012); Ma (2019)
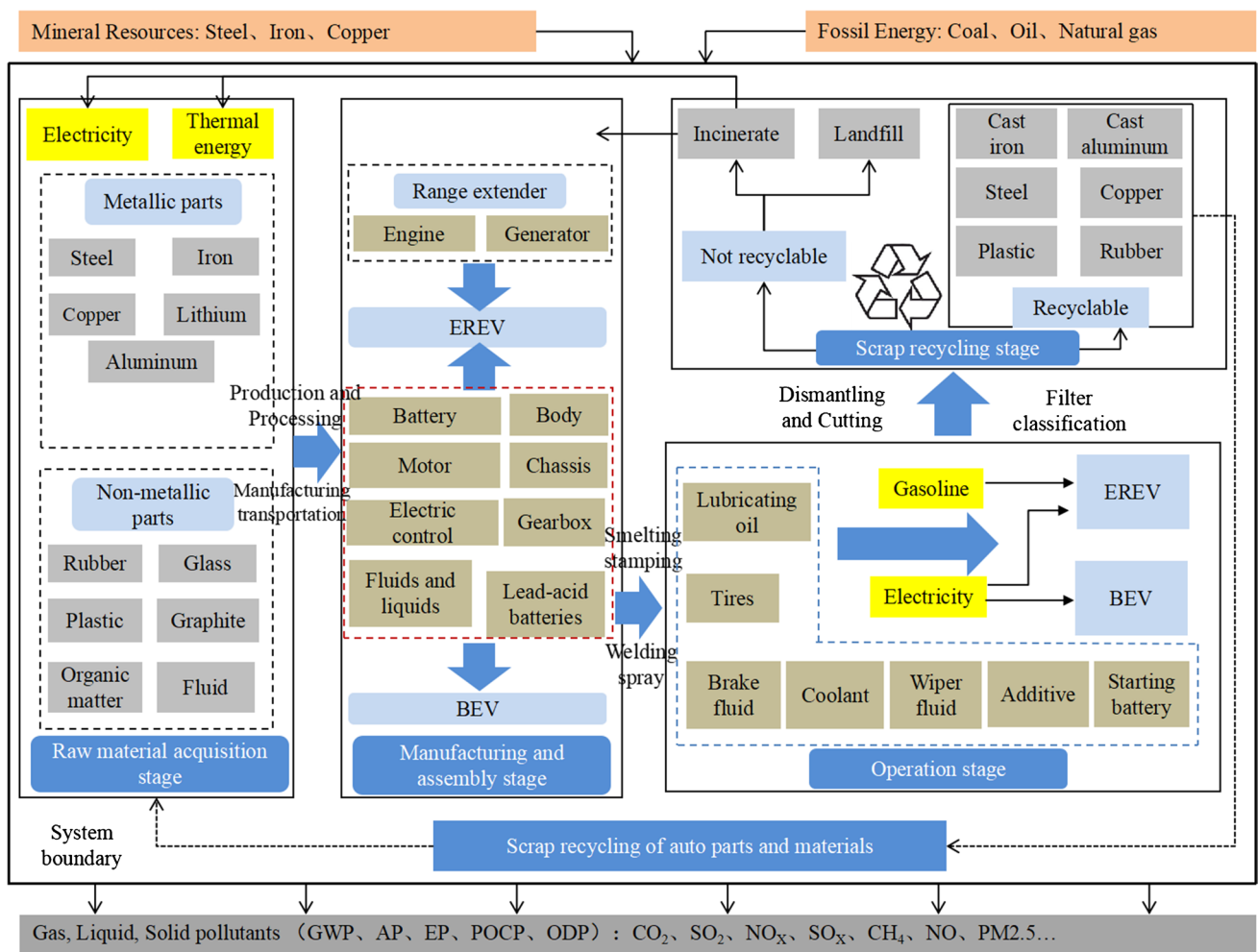
Fig. 1 Diagram of the system boundary

composition of the engine and power battery; therefore, previous vehicle disassembly report (Burnham et al. 2012) is referred to as data of this study; the specific material inventory of the engine and power battery is seen in the Appendix Tables 2 and 3. The

carbon emission factors of unit steel, iron, aluminum, and copper are assumed to be 2.41 kg CO_2, 2.38 kg CO_2, 20.7 kg CO_2, and 4.76 kg CO_2 (GaBi 2019). A total of 11.7 kWh of electricity and 8.8 kWh of natural gas are consumed to manufacture 1 kg power

battery (Zhang 2011); meanwhile, 2.67 kWh of electricity is consumed to assembly 1 kg power battery (Li 2014). In the operation stage, the comprehensive power consumption of EREV is 22.5 kWh, and the pure oil mode and pure electric mode are considered and compared, which will be elaborated in detail below. The carbon emission factor of electric energy is assumed to be 0.8 kg CO_2/kWh (GaBi 2019). Due to the energy loss in the process of energy exploitation and power generation, the fossil energy consumed is assumed to be 8.06 MJ/kWh (GaBi 2019). Because the specific process of scrap recovery stage is relatively complex, it is assumed that the recovery and utilization of steel, iron, aluminum, and copper are mainly considered, and the recovery of precious metals in power batteries is also mainly considered.

Impact assessment indicators and calculation method

In this paper, mineral resource depletion, fossil energy consumption, and carbon emission (CO_2) are selected as the evaluation indexes of energy consumption and emission respectively, and the inventory analysis is carried out by constructing resource consumption difference model, energy consumption difference model, and carbon emission difference model, so as to calculate and compare the resource consumption of aluminum, iron, copper and other resources, energy consumption of coal, oil, natural gas, and other equivalent emissions produced by two vehicles of the same class in the whole life cycle. However, only calculating the consumption of various resources, energy and gas emissions are not enough to directly reflect the performance difference of energy saving and emission reduction. Therefore, in order to make the results more comparable, when analyzing and measuring the calculation results of the model, the CML2001 (Dordrecht 2001) characteristic calculation method in the database of GaBi software developed by Stuttgart University in Germany is selected to integrate each kind of environmental impact indicators. The steel, iron, copper, aluminum, and other metal mineral resources consumed in the whole life cycle are uniformly converted into mineral resource depletion (ADP (element)), which is calculated by antimony equivalent in units of (kg, Sb-Eq). The non-renewable energy sources such as crude oil, raw coal, and natural gas are uniformly classified into fossil energy consumption (ADP (fossil)), and the unit is uniformly converted into MJ. The carbon emission mainly focuses on the emission of greenhouse gas CO_2.

Assessment model

Differential model of mineral energy consumption

According to the actual structural differences between the two models and considering the number of vehicle parts, main material composition, material preparation process, and part processing process, this study establishes the resource consumption model.

$$R_{EREV} = \sum_{i=1}^{s} M_{ij} \times U_k \times Q_k \quad (1)$$

$$R_{BEV} = \sum_{i=1}^{s} M_{ij} \times U_k \times Q_k \quad (2)$$

In the formula, R_{EREV} and R_{BEV} represent the resource consumption of the EREV and BEV, respectively; M_{ij} represents the amount of mineral resource i required for type j components; U_k and Q_k represent the material utilization rate of mineral resource k during processing and preparation; and s indicates the number of parts.

Differential model of fossil energy consumption

According to the system boundary determined in this study, the scope of research on the entire life cycle mainly includes four stages: raw material acquisition, manufacturing and assembly, operation and use, and scrap recycling. Given that the energy consumption of the two models at different stages varies, the energy consumption models for each stage are established as follows:

$$E_{EREV} = \sum_{i=1}^{s} Q_{ij} \cdot E_{jr} + \sum_{i=1}^{t} Q_{in} \cdot E_{nr} + \sum_{e} Q_u \cdot E_u + L \cdot (\eta_1 \cdot E_f + \eta_2 \cdot E_e) + \sum_{f} [Q_{RC} \cdot (E_{s1} - E_{s2})] \quad (3)$$

$$E_{BEV} = \sum_{i=1}^{s} Q_{ij} \cdot E_{jr} + \sum_{i=1}^{t} Q_{in} \cdot E_{nr} + \sum_{e} Q_u \cdot E_u + L \cdot E_e \cdot \eta_2 + \sum_{f} [Q_{RC} \cdot (E_{s1} - E_{s2})] \quad (4)$$

In the formula, E_{EREV} and E_{BEV}, respectively, indicate fossil energy consumption of EREVs and BEVs; Q_{ij} indicates the quantity of type j raw materials required for type i vehicle materials; E_{jr} indicates the amount of type r fossil energy consumption in producing type j per unit raw material; s indicates the number of vehicle material; Q_{in} represents the quality of type n vehicle material required for type i vehicle component; E_{nr} indicates the amount of type r fossil energy consumption in producing type n per unit vehicle material; t indicates the number of vehicle component; Q_u indicates the quality of vehicle components that need to be replaced during operation and use; E_u indicates fossil energy consumption required to replace vehicle components during operation and use; e indicates the number of vehicle component that need to be replaced; E_f, E_e, respectively, indicate fuel consumption and electricity power consumption during driving; L is the total mileage; η_1 and η_2 represent fuel and electric energy utilization efficiency, respectively; Q_{RC} indicates the quality of the corresponding recycled vehicle components; E_{s1} indicates fossil energy consumption during recycling vehicle components; E_{s2} represents fossil energy recovered from recycled components; and f indicates the number of vehicle component that needed to be recycled.

Model of carbon emission difference

The carbon emission model mainly calculates the carbon dioxide emissions of auto parts in the various processes of raw material production, parts processing, product manufacturing, operation and use, and scrap recycling. The modeling process is mainly divided into two parts: direct and indirect emissions. The details are as follows:

$$P_T = P_Z + P_J = \left(P_{Z_{ij}} \right)_{m \times n} + \left(P_{J_{ij}} \right)_{m \times n} \qquad (5)$$

In the formula, P_T, P_Z, and P_J, respectively, represent total carbon emissions, direct carbon emissions, and indirect carbon emissions, respectively; $P_{Z_{ij}}$ represents the direct carbon emissions per unit of the jth gas emissions generated when the ith energy is burned; $P_{J_{ij}}$ represents the indirect carbon emissions of the second gas emissions produced when the unit of energy is produced; m represents the number of primary energy types; and n represents the number of types of gas emissions.

The material composition and energy consumption data of the main components of EREV and BEV are shown in the Appendix Tables 2 and 3. In accordance with the data listed in the table, two vehicle models are established in GaBi and then analyzed and calculated.

Results and discussion

Comparison of differences in mineral resource consumption

Through calculation and analysis, the characteristic results of the mineral resource consumption of the two vehicles in the entire life cycle are shown in Fig. 2. In various stages, the ADP (element) consumption of the EREV in the raw material acquisition stage is 0.286 kg Sb eq, which is 13.94% higher than that of the BEV, mainly due to the increase in the parts of the EREV power system. The range extender group (engine and generator) must consume additional mineral resources. Minimal difference is found between the manufacturing stage and assembly and operation. In the phase of scrapping and recycling, the positive benefit of the EREV is 0.248 kg Sb eq, which is 41.71% more than that of BEVs, mainly because of the current needs of BEVs. The power battery has no complete recovery process, and its recovery efficiency is lower than that of the engine. During the entire life cycle, the mineral resource consumption of BEVs is 0.184 kg Sb eq, which is 28.67% higher than that of EREVs, mainly because BEVs must be equipped with higher energy density power batteries to meet the endurance requirements. Therefore, additional mineral resources must be consumed.

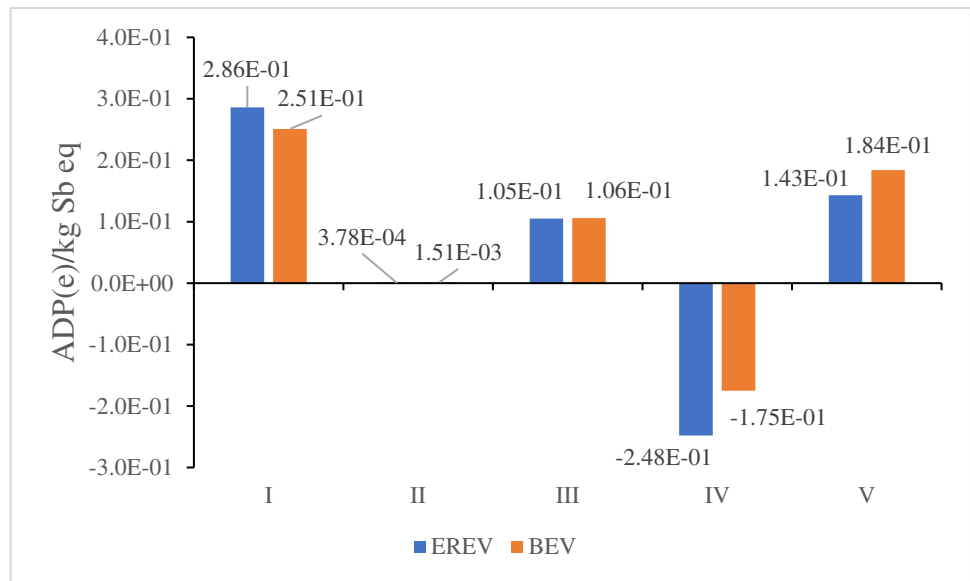The mineral resource consumption of each component of the two vehicles is shown in Fig. 3. In the raw material acquisition stage, the EREV consumes more mineral resources of the engine and generator due to the difference in the power system structure of the two vehicles, and the mineral resource consumption of the BEV power battery is the EREV. The motor and electronic control are respectively 29.23% and 22.27% higher than the extended range of the car mainly because the battery electric car is equipped with high-energy–density batteries (43 kWh) and high power motor (160 kW), to meet the needs of power and cruising range. The mineral resource consumption of the body and chassis of the two is not much different, but the body and chassis of the two account for approximately 41.2–45.8% of the mineral resource consumption of each vehicle. In the manufacturing and assembly stage, the difference in performance is more evident. The mineral resource consumption of BEVs accounts for 83.60% of the entire vehicle, whereas that of the EREV accounts for 37.10%. The main reason is that the manufacturing and assembly process of power batteries requires substantial mineral resources consumption.

## Comparison of differences in fossil energy consumption

Figure 4 shows the characteristic results of the fossil energy consumption of the two vehicles during the entire life cycle. The fossil energy consumption of BEVs in the raw material acquisition phase is 6.19E + 04 MJ, which is 14.42% higher than that of EREVs, mainly due to the high quality of the entire vehicle and the need to obtain raw materials. Consume more energy, and in the other three stages, the benefits of BEVs are better than EREVs, especially the fossil energy consumption in the operation stage. The consumption of EREVs is 2.73E + 05 MJ, which is approximately 2.65 times that of electric vehicles. In the phase of scrapping and recycling, BEVs have a positive benefit of 4.24E + 04 MJ, which is 10.42% higher than that of EREVs. In the entire life cycle, the total fossil energy consumption of EREVs is 3.57E + 05, which is approximately 1.93 times that of BEVs. The results show that BEVs can effectively reduce the consumption of fossil energy due to the difference in the power system structure of the two vehicles. BEVs use the power source as the power source during operation, whereas EREVs use gasoline and electric energy as the power source, resulting in the direct consumption of fossil energy. In addition, EREVs convert two energy sources, thus increasing fossil energy consumption.

Figure 5 shows the fossil energy consumption of each component of the two vehicles during the raw material acquisition and manufacturing and assembly stages. The components of the two vehicles have differences in the two stages. Given the difference in the structure of the power systems of the two vehicles, the range extender group (engine and generator) consumes more energy in the range extender electric vehicle. They are 8.81E + 03 MJ and 2.46E + 03 MJ. In terms of power batteries, the consumption of BEVs is

Fig. 2 Mineral resource consumption of EREV and BEV at different stages. (Note: I—raw material acquisition phase, II—manufacturing assembly stage, III—operational use phase, IV—scrap recovery stage, V—total)

Fig. 3 Consumption of mineral resources for the main parts and components of the two vehicles. (Note: I—raw material acquisition stage, II—manufacturing assembly stage)
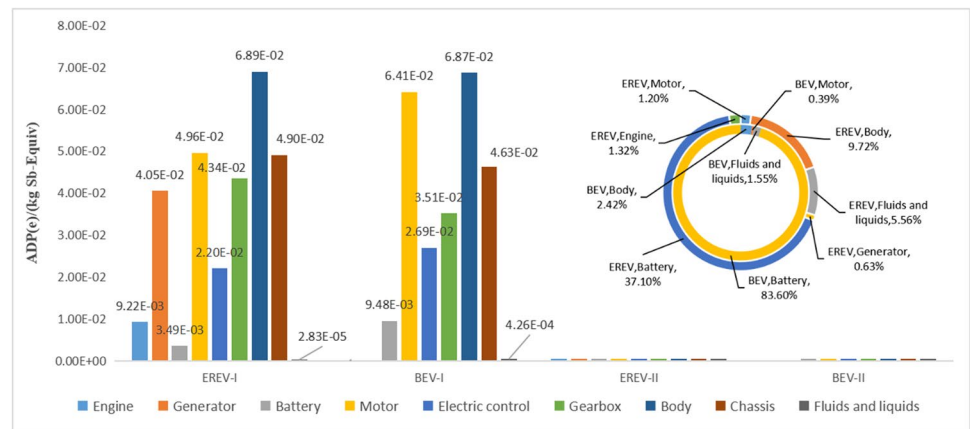

3.36E + 04 MJ and 4.88E + 04 MJ, which are 1.92 and 2.03 times that of EREVs, mainly because BEVs are equipped with high-energy–density batteries. In terms of motors, BEVs are 29.10% and 29.56% higher than EREVs in the two phases mainly because they are equipped with more powerful motors. In terms of electronic control, BEVs are better than EREVs in the two stages. The car is 22.46% and 22.43% higher. The two cars are not much different in the body, chassis, and final drive. In terms of fluid and liquid, the range of EREVs is approximately 2.79 times that of BEVs in the raw material acquisition stage because EREVs consume more lubricating oil and coolant for components, such as engines and generators.

Comparison of carbon emission differences

The CO_2 emission results of the two vehicles during the entire life cycle are shown in Fig. 6. The carbon emission of EREVs is higher than that of BEVs in the raw material

acquisition stage mainly because the number of parts (engine + generator) of EREVs is large and is used in the manufacturing and assembly stage and operation. At this stage, the carbon emissions of BEVs are 6.24E + 03 kg and 9.29E + 03 kg, which are 6.84% and 58.3% higher than those of EREVs. On the one hand, it is mainly because BEVs are equipped with high quality, energy-dense power batteries increase the quality of the vehicle, and battery manufacturing and assembly require additional natural gas and electricity. On the other hand, it consumes substantial electricity during operation and use, and the proportion of thermal power in China's electricity sources is close to 70%. The proportion of carbon in the power structure makes BEVs emit more CO_2 during operation and use. When scrapped and recycled, BEVs generate a positive benefit of 2.49E + 03 kg, which is 23.9% higher than that of EREVs. However, during the entire life cycle, the carbon emission of BEVs is 1.69E + 04 kg, which is approximately 22.5% more than that of EREVs. Therefore, the quality of

Fig. 4 Fossil energy consumption of EREV and BEV at different stages
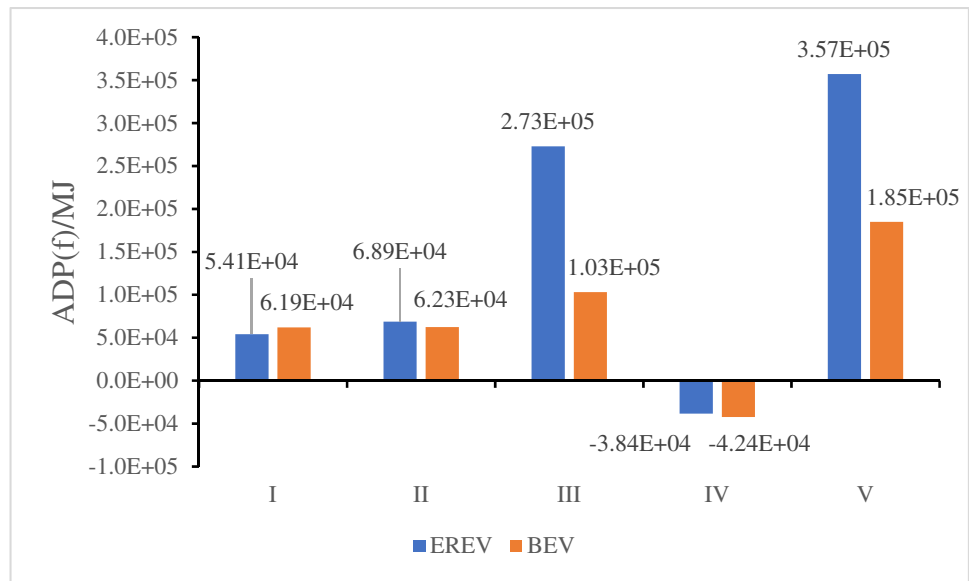
BEVs, especially the quality of power batteries, as well as the carbon content in China's power structure, must be effectively reduced.

Figure 7 shows the CO_2 emissions and proportions of the components of the two vehicles during the raw material acquisition and manufacturing and assembly stages. The difference between BEVs and EREVs is evident. In the raw material acquisition stage, EREVs have more emissions from the range extender group (617.59 and 162.36 kg). In terms of power batteries, the emission of electric vehicles is 1769.53 kg, which is 1.92 times that of EREVs. The main reason is that power batteries consume more raw materials during production, thus increasing carbon emissions. In terms of motors and electronic control, BEVs emit 395.78 and 404.17 kg, respectively, which are 29.1% and 22.2% higher than EREVs. The body and the chassis do not differ greatly. However, in terms of fluid and liquid, the emission of the EREV is 450.35 kg, which is 5.69 times that of

BEVs, because EREVs must consume more materials, such as engine lubricating oil and coolant. In the manufacturing and assembly stage, the difference between the two in terms of power batteries is the most evident. Among them, the emission of BEVs is 3697.84 kg, which is 2.16 times that of EREVs. According to the literature, the unit mass of power batteries must consume 11.7 kWh during manufacturing. Electricity and 8.8 kWh natural gas (Zhang 2011) consume 2.67 kWh/kg (Li 2014) during the assembly process. Therefore, larger-mass power batteries need to consume more electricity and generate more carbon emissions.

## Analysis on the difference of energy consumption and emission under operation mode

Given the difference in the structure of the power systems of the two vehicles, their operation modes vary. During the operation of the EREV, the engine does not directly

Fig. 5 Fossil energy consumption of the main components of EREV and BEV. (Note: I—raw material acquisition stage, II—manufacturing assembly stage)
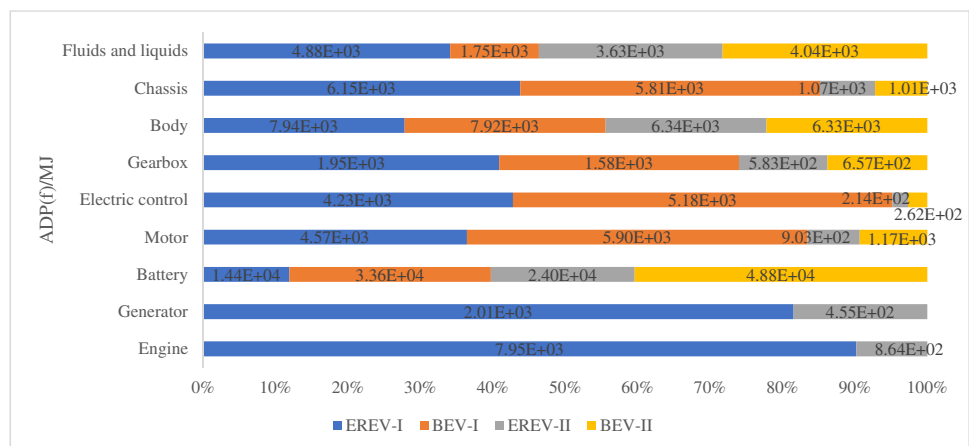
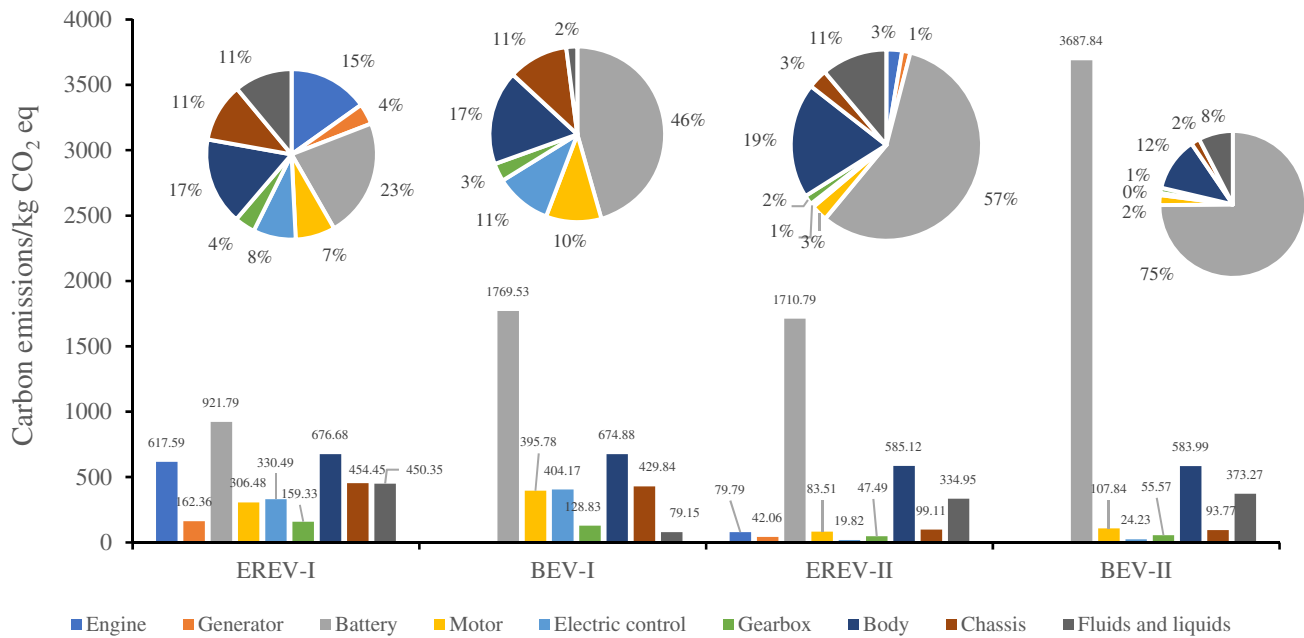**Fig. 6** Carbon emissions of EREVs and BEVs at different stages
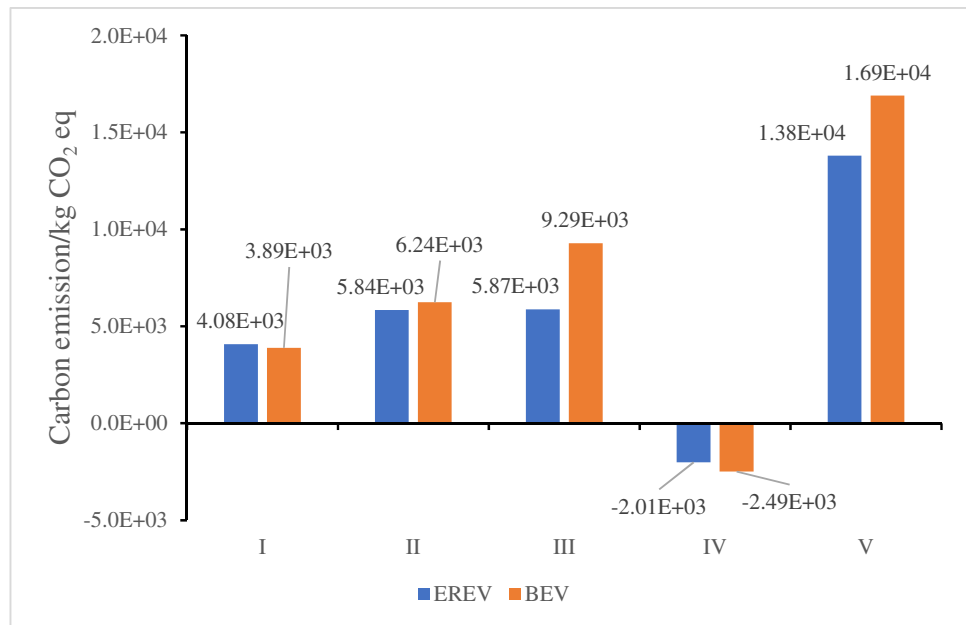
participate in the drive but forms a range extender group with the generator to supply power to the battery. The operating mode is mainly divided into pure electric mode and extended range mode. When the state of charge (SOC) is above the minimum threshold, it is in the pure electric mode (that is, the power consumption stage), and the power battery provides energy to drive the motor and provide driving power. When the SOC is lower than the minimum threshold, it is in the extended range mode, that is, the power maintenance stage. The range extender group provides energy to drive the motor while charging the battery. However, BEV is only driven by the motor driven by the power battery in the whole operation process, and only consumes electric energy. The energy consumption and emissions caused by fuel consumption and electric energy consumption are very different. Therefore, in the calculation process of energy consumption and emissions in operation and use stage, according to the system boundary constructed above, the total fuel consumption and total power consumption of two vehicles in operation and use stage are calculated, and then, the energy consumption and emissions of two vehicles in operation and use stage are calculated and analyzed by using the mathematical model constructed. See the Appendix Tables 2 and 3 for the fuel economy and energy consumption of the two vehicles in different operating modes.

The energy consumption and carbon emission analysis results of the two vehicles in different operating modes are shown in Fig. 8. EREVs consume a large amount of crude oil in the extended-range mode mainly because the production of gasoline needs to be based on a large amount of crude oil, and the pure electric mode can effectively reduce the consumption of crude oil. In the pure electric mode, the

crude oil consumption of EREVs is 283.43 kg, which is 4.06 times that of BEVs, mainly because the power source of EREVs is the engine. The raw coal consumption of BEVs during operation is 5231.7 kg mainly because it consumes substantial electric energy, whereas my country's electric energy structure is mainly based on thermal power generation. At the same time, the combustion of coal also indirectly leads to relatively large carbon emissions, which is approximately 4.71 times that of electric vehicles. In terms of natural gas consumption, the consumption of EREVs in extended-range mode is 515.45 kg, which is approximately 3.16 times that of BEVs in pure electric mode. In pure electric mode, the consumption of BEVs is approximately 7.4 times that of a programmed electric car. Overall, compared with BEVs, EREVs can effectively reduce the consumption of fossil energy, such as crude oil and natural gas, but consume more raw coal.

Comparison with other literature results

The results of this study were compared to findings coming from similar studies. This is shown in Fig. 9 where it is observable that the order of magnitude of the carbon emissions produced for the life cycle BEV per km is similar for all the studies considered. Tagliaferri et al. (2016) considered two different manufacturing inventories for the BEV; the carbon emission results of life cycle BEV are 120 g CO_2 • km^{-1} and 110 g CO_2 • km^{-1}, respectively. This is similar to the values calculated for the BEV in this study. Although they studied the carbon emission of the life cycle of the extended range electric vehicle (considering hybridization factors as 90%), there is no inventory and carbon emission

Fig. 7 Carbon emissions of the main components of EREVs and BEVs. (I—raw material acquisition stage, II—manufacturing and assembly stage)

calculation of the motor, generator, main reducer, body, chassis and fluid of the extended range electric vehicles, and no comparison of energy consumption and carbon emission under different operation mode. These two studies reported that the manufacturing phase was a significant burden of the total carbon emissions of a BEV and it was comparable to the use phase; meanwhile, the manufacturing of power battery is the main reason for the high carbon emission in the manufacturing process of BEV (Tagliaferri et al. 2016; Evangelisti et al. 2017). Similar conclusions are obtained in this study. Carbon emission during the manufacturing and use stage of BEV is 6240 kg and 9290 kg CO_2 (see Fig. 6), and carbon emission of the manufacturing battery accounts for 59.1% of the manufacturing of BEV. The comparative analysis shows the same trend between EREV and BEV, supporting the results obtained by this study.

Conclusions

In order to explore the difference between EREV and BEV, life cycle assessment methods are used and corresponding mathematical evaluation difference models are established. Meanwhile, mineral resources consumption, fossil energy consumption, and pollution emissions are selected as comparative evaluation indexes. In addition, energy consumption and pollution emission of two vehicles under different

operation modes are compared based on the structural differences of two power systems. The main conclusions are as follows:

(1) In terms of mineral resources consumption, the number of EREV and BEV are 0.143 kg Sb and 0.184 kg Sb, respectively, from life cycle perspective. EREVs consume more mineral resources than BEV during raw material acquisition stage due to the increase in the component of the EREV power system. In detail, body and chassis account for approximately 41.2–45.8% of the mineral resource consumption of each vehicle. Therefore, the lightweight body and the application of new materials in automobiles can help reduce mineral resources consumption.

(2) In terms of fossil energy consumption, the number of EREVs is about 1.93 times that of BEVs from life cycle perspective. From the perspective of each main component, BEVs are 1.92 and 2.03 times that of EREVs in the raw materials acquisition and manufacturing and assembly stages for power batteries. Therefore, battery manufacturing and processing technologies must be improved to reduce energy consumption in the manufacturing and assembly stage in order to further increase the energy-saving effect of BEVs.

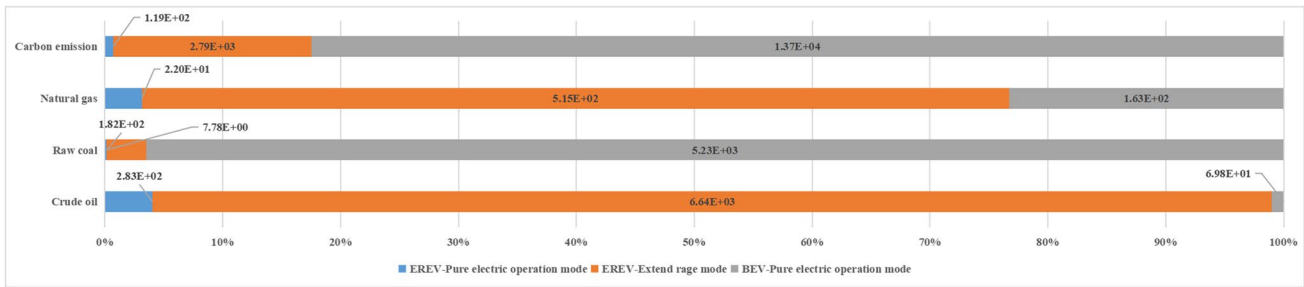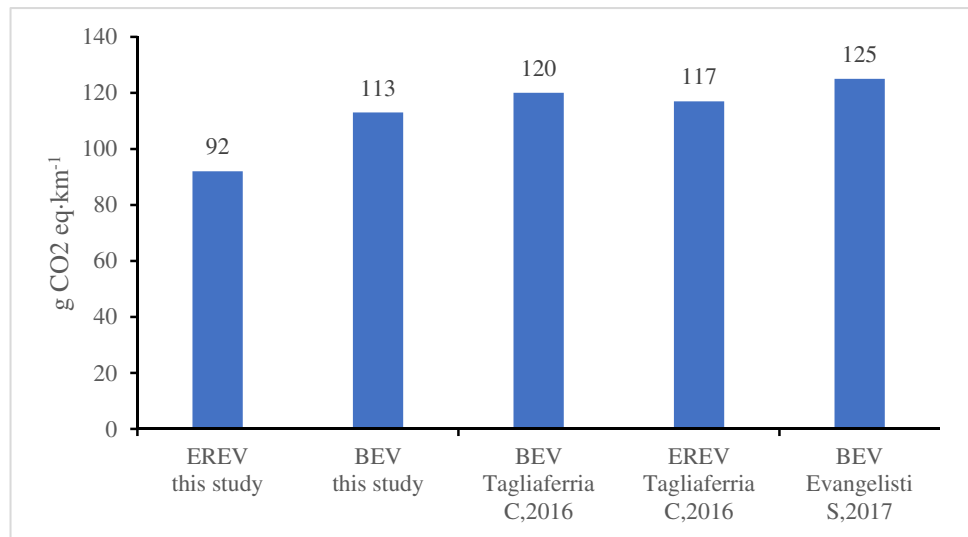(3) In terms of carbon emissions, the number of BEVs is approximately 22.5% higher than that of EREVs due

Fig. 8 Energy consumption and carbon emissions under different working conditions

Fig. 9 Comparison with other literature results of carbon emission

to the high quality of BEVs and the high proportion of carbon content in China's power sources. From the perspective of each main component, the emissions of BEVs are 1.92 times and 2.16 times that of EREVs in the raw material acquisition and manufacturing and assembly stages for power batteries. Therefore, promoting clean energy power generation and researching high-specific energy and low-quality power batteries are critical to the emission reduction effect of BEVs.

(4) In different operating modes, compared with BEVs, crude oil and natural gas consumption of EREV is 4.06 times and 3.16 times of that of BEV respectively. However, raw coal consumption is significantly higher than that of BEVs. Therefore, the promotion of BEVs can effectively reduce crude oil and natural gas consumption. EREVs have great advantages in reducing raw coal consumption and carbon emissions.

A comparative analysis of energy saving and emission reduction of BEVs and EREVs in the entire life cycle is conducted to future improve the application of LCA in China in the field of new energy vehicles in this study. An in-depth research on the main components is conducted to clarify the energy consumption and carbon emissions of each component and eventually determine the key influencing factors. Thus, a reference is provided for the formulation and research on the energy saving and emission reduction of China's new energy vehicles and technical route promotion in this study. However, it is not considered that the impact of the dynamic change process of China's energy structure on the energy-saving in detail and emission-reduction effects of the two vehicles in the future. Further research can be conducted to clarify the energy-saving and emission-reduction effects of electric vehicles.

Appendix

Table 2 Material composition and energy consumption of the main parts of EREVs and BEVs

Part name	Vehicle type	Weight/kg	Material composition	Electricity/kw·h	Thermal energy/MJ	Other energy types	Data sources
Engine	EREV	122.4	42% cast aluminum, 27.3% steel, 12.6% cast iron, 8.4% stainless steel, 4.2% rubber, 4.2% plastic, 1.3% copper	371.96	/	/	Li (2015); Liu (2013); Li (2015); Gu (2011); Burnham et al. (2012)
Generator	EREV	35.7	36.1% cast aluminum, 36.1% steel, 27.3% copper, 0.5% others	48.53	46.73	/	Zhang (2011); Liu and Xu (2016)
Battery	EREV	171.7	28.2% anode active material, 18.3% graphite, 2.4% adhesive, 11.4% copper, 19.7% forged aluminum, 1.9% lithium hexafluorophosphate, 5.4% ethylene carbonate, 5.4% dimethyl carbonate, 1.7% polypropylene, 0.3% polyethylene, 1.2% polyethylene terephthalate, 1.5% steel, 0.3% glass fiber, 1.0% ethylene glycol, 1.0% battery management system	2136.23	/	108.79 kg natural gas	Zhang (2011); Li (2014); Lu (2014)
	BEV	482	24.4% anode active material, 15.2% graphite, 2.1% adhesive, 12.4% copper, 20.3% forged aluminum, 2.7% lithium hexafluorophosphate, 7.8% ethylene carbonate, 7.8% dimethyl carbonate, 1.9% polypropylene, 0.3% polyethylene, 1.3% polyethylene terephthalate, 1.5% steel, 0.3% glass fiber, 1.0% ethylene glycol, 1.0% battery management system	5996.88	/	305.39 kg natural gas	
Motor	EREV	69.7	36.1% steel, 36.1% cast aluminum, 27.8% copper	92.02	126.67	/	Zhang (2011); Liu and Xu (2016)
	BEV	90		118.84	163.57	/	
Electric control	EREV	64.6	47% cast aluminum, 5.0% steel, 3.7% rubber, 23.8% plastic, 8.2% copper, 12.3% organics	25.66	/	/	Li (2015); Burnham et al. (2012)
	BEV	79		31.38	/	/	
Gearbox	EREV	54.4	60.5% steel, 20.0% forged aluminum, 19.0% copper, 0.2% plastic, 0.3% organics	111.79	234.19	1.53 kg diesel oil	Li (2015); Zhang (2011)
	BEV	44		58.47	101.78	1.21 kg Diesel oil	
Body	EREV	717	68.7% steel, 0.77% forged aluminum, 1.93% copper, 0.04% magnesium, 17.4% plastic, 6.62% glass, 0.51% rubber, 4.03% others	757	/	82 kg processed water	Zhang (2011); Liu and Xu (2016)
	BEV	716		/	/		
Chassis	EREV	434	82.2% steel, 6.32% iron, 0.94% aluminum, 2.27% copper, 3.33% plastic, 4.15% rubber, 0.79% others	108.32	157.38	/	Burnham et al. (2012); Liu and Xu (2016)
	BEV	410		102.45	148.85	/	
Lead-acid batteries	EREV	10	69.0% lead, 7.9% sulfuric acid, 6.1% polypropylene, 2.1% glass fiber, 14.1% water, 0.8% other	124.42	/	6.34 kg natural gas	Burnham et al. (2012)
	BEV	10		/	/		

Table 2 (continued)

Part name	Vehicle type	Weight/kg	Material composition	Electricity/kw•h	Thermal energy/MJ	Other energy types	Data sources
Fluids and liquids	EREV	32.2	11.9% engine oil, 2.54% transmission lubricant, 2.87% brake fluid, 32.2% coolant, 8.39% wiper fluid, 42.1% adhesive	588.61	/	/	Li (2014); Burnham et al. (2012)
	BEV	24	3.17% lubricating oil, 3.58% brake fluid, 28.58% coolant, 10.71% wiper fluid, 53.96% adhesive	483	/	/	

Table 3 Operating modes and main parameters of EREVs and BEVs

Vehicle type	Fuel economy in pure electric mode/(L, kW•h)•(100 km)$^{-1}$	Fuel economy in extended range mode/ L•(100 km)$^{-1}$	Pure electric mileage/km	Pure oil mileage/ km	Total mileage/km	Power consumption/L or kW • h	Fuel consumption/L
EREV	2.50	6.36	14,700	135,300	150,000	367.5	8605.08
BEV	11.8	/	150,000	/	150,000	17,700	/

Data availability The data used to support the findings of this study are available and included within the article.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

Bickert S, Kampker A, Greger D (2015) Developments of CO_2 emissions and costs for small electric and combustion engine vehicles in Germany. J Transp Res D 36:138–151. https://doi.org/10.1016/j.trd.2015.02.004

Burnham A, Wang M, Wu Y (2012) Development and applications of GREET2.7—the transportation vehicle-cycle model. U.S.: Energy Systems Division, Argonne National Laboratory. https://doi.org/10.2172/898530

Chen Y, Lin Lawell CYC, Wang Y (2020) The Chinese automobile industry and government policy. J Res Transp Econ 84:100849. https://doi.org/10.1016/j.retrec.2020.100849

Correa G, Muñoz P, Falaguerra T, Rodriguez CR (2017) Performance comparison of conventional, hybrid, hydrogen and electric urban buses using well to wheel analysis. J Energy 141:537–549. https://doi.org/10.1016/j.energy.2017.09.066

Dordrecht (2001) Assessment—operational Guide to the ISO Standards. Kluwer Academic Publishers, The Netherlands

Evangelisti S, Tagliaferri C, Brett DJL, Lettieri P (2017) Life cycle assessment of a polymer electrolyte membrane fuel cell system for passenger vehicles. J J Clean Prod 142:4339–4355. https://doi.org/10.1016/j.jclepro.2016.11.159

GaBi (2019) GaBi sustainability software. Official website. http://www.gabisoftware.com/index/

Gu GG (2011) Comparative study on life cycle assessment of power system of electric vehicle and internal combustion engine vehicle. Dissertation, University of Hefei Technology

Hao H, Cheng X, Liu Z, Zhao FQ (2017a) Electric vehicles for greenhouse gas reduction in China: a cost-effectiveness analysis. J Transp Res D Transp Environ 56:68–84. https://doi.org/10.1016/j.trd.2017.07.025

Hao H, Mu ZX, Jiang SH, Liu ZW, Zhao FQ (2017b) GHG emissions from the production of lithium-ion batteries for electric vehicles in China. Sustainability 9(4):504. https://doi.org/10.3390/su9040504

Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH (2012a) Comparative environmental life cycle assessment of conventional and electric vehicles. J J Ind Ecol 17(1):53–64. https://doi.org/10.1111/j.1530-9290.2012.00532.x

Hawkins TR, Gausen OM, Strømman AH (2012b) Environmental impacts of hybrid and electric vehicles—a review. Int J Life Cycle Assess 17(8):997–1014. https://doi.org/10.1007/s11367-012-0440-9

Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH (2013) Comparative environmental life cycle assessment of conventional and electric vehicles. J J Ind Ecol 17(1): 53–64. https://doi.org/10.1111/j.1530-9290.2012.00532.x

Hooftman N, Maarten M, Joint F, Segard JB, Thierry C (2018) In-life range modularity for electric vehicles: the environmental impact of a range-extender trailer system. Appl Sci 8(7):1016. https://doi.org/10.3390/app8071016

Hu ZY, Pu GQ, Fang F, Wang CT (2004) Economics, environment, and energy life cycle assessment of automobiles fueled by bio-ethanol blends in China. J Renewable Energy 29:2183–2192. https://doi.org/10.1016/j.renene.2004.03.014

ISO, 2006. ISO14040. ISO/TC 207/SC 5 Life cycle assessment; 13.020.10 Environmental management 13.020.60 Product life-cycles

Lewis AM, Kelly JC, Keoleian GA (2014) Vehicle light weighting vs. electrification: life cycle energy and GHG emissions results for diverse powertrain vehicles. J Appl Energy 126:13–20. https://doi.org/10.1016/j.apenergy.2014.03.023

Li SH (2014) Life cycle analysis and environmental benefit evaluation of electric vehicles. Dissertation, University of Jilin

Li J (2015) Life cycle assessment and analysis of battery electric vehicle and fuel vehicle power system. Dissertation, University of Hunan

Liu ZC (2013) Life cycle assessment method of engine original manufacturing and remanufacturing. Dissertation, University of Dalian Technology

Liu KH, Xu JQ (2016) Life cycle assessment of battery electric vehicle drive motor. J Journal of environmental science 36 (09):3456–3463. https://doi.org/10.13671/j.hjkxxb.2016.0022

Lu Q (2014) Life cycle analysis and evaluation of electric vehicle power battery. Dissertation, University of Jilin

Ma JQ (2019) Life cycle assessment of battery electric vehicles with different power batteries. Dissertation, University of Chang'an University

Mu XZ, Xu GQ, Hu GW (2021) Environmental impact analysis of nuclear power based on lif-e cycle assessment. J/OL J Saf Environ 1–8. http://doi-org-s.vpn.chd.edu.cn:8080/10.13637/j.issn.1009-6094.2021.1289

Noori M, Gardner S, Tatari O (2015) Electric vehicle cost, emissions, and water footprint in t-he United States: development of a regional optimization model. J Energy 89:610–625. https://doi.org/10.1016/j.energy.2015.05.152

Onat NC, Kucukvar M, Tatari O (2015) Conventional, hybrid, plug-in hybrid or electric vehicles? State-based comparative carbon and energy footprint analysis in the United States. J Appl Energy 150:36–49. https://doi.org/10.1016/j.apenergy.2015.04.001

Peng TD, Ou XM, Yan XY (2018) Development and application of an electric vehicle's life cycle energy consumption and greenhouse gas emissions analysis model. J Chem Eng Res Des 131:699–708. https://doi.org/10.1016/j.cherd.2017.12.018

Qiao QY, Zhao FQ, Liu ZW, Jiang SH, Hao H (2017) Comparative study on life cycle CO_2 emissions from the production of electric and conventional vehicles in China. J Energy Procedia 105:3584–3595. https://doi.org/10.1016/j.egypro.2017.03.827

Shi SN, Zhang HR, Yang W, Zhang QR, Wang XJ (2019) A life-cycle assessment of battery electric and internal combustion engine vehicles: a case inHebei Province, China. J J Clean Prod 228:606–618. https://doi.org/10.1016/j.jclepro.2019.04.301

Song XL, Liang ZL, Luo W, Huang D, Yang Z, Xu PP, Hu JP, Liu BC, Yang JK (2021) Study on life cycle assessment of cement preparation process from industrial solid waste raw materials. J J Environ Sci 1–10. http://doi-org-s.vpn.chd.edu.cn:8080/10.13671/j.hjkxxb.2021.0276

Tagliaferri C, Evangelisti S, Acconcia F, Domenech T,Ekins P, Barletta D, Lettieri P (2016) Life cycle assessment of future electric and hybrid vehicles: a cradle-to-grave systems engineering approach. J Chem Eng Res Des (112): 298–309. https://doi.org/10.1016/j.cherd.2016.07.003

Wang CB, Zhang LX, Pang MY (2015) A review of life cycle assessment methods—also on the development and application of hybrid life cycle assessment. J J Nat Resour 30(07):1232-1242. https://doi.org/10.11849/zrzyxb.2015.07.015

Wu XT (2012) Performance comparison of Qin, Wolanda and Prius plug-in hybrid electric vehicles. J Automob Accessories 41:30–31

Xiong SQ, Ji JP, Ma XM (2019) Comparative life cycle energy and GHG emission analysis for Bevs and Phevs: a case study in China. Energies 12:834. https://doi.org/10.3390/en12050834

Xu X, Xu X (2021) Can resource policy adjustments effectively curb regional "resource curse" ? New evidences from the "energy golden triangle area" of China. J Resour Policy 73:102146. https://doi.org/10.1016/j.resourpol.2021.102146

Yu A, Wei YQ, Chen WW, Peng NJ, Peng LH (2018) Life cycle environmental impacts and carbon emissions: a case study of electric and gasoline vehicles in China. J Transp Res D Transp Environ 65:409–420. https://doi.org/10.1016/j.trd.2018.09.009

Zhang L (2011) Research on life cycle assessment of electric vehicles based on GaBi4. Dissertation, University of Hefei Technology

Zhang Z, Sun X, Ding N, Yang JX (2019) Life cycle environmental assessment of charging infrastructure for electric vehicles in China. J J Clean Prod 227:932–941. https://doi.org/10.1016/j.jclepro.2019.04.167