Life Cycle Prediction Assessment of Battery Electrical Vehicles with Special Focus on Different Lithium-Ion Power Batteries in China

Yang Yang, Libo Lan, Zhuo Hao, Jianyou Zhao, Geng Luo, Pei Fu, and Yisong Chen

Abstract: The incentive policies of new energy vehicles substantially promoted the development of the electrical vehicles technology and industry in China. However, the environmental impact of the key technology parameters progress on the battery electrical vehicles (BEV) is uncertain, and the BEV matching different lithium-ion power batteries shows different environmental burdens. This study conducts a life cycle assessment (LCA) of a BEV matching four different power batteries of lithium-ion phosphate (LFP), lithium-ion nickel-cobalt-manganese (NCM), lithium manganese oxide (LMO), and lithium titanate oxide (LTO) batteries. In addition, the 2025 and 2030 prediction analyses of the batteries production and life cycle BEV are conducted with the specially considered change and progress of the power battery energy density, battery manufacturing energy consumption, electricity structure, battery charge efficiency, and vehicle lightweight level. In addition, sensitivity analyses of power battery energy density, battery manufacturing energy consumption, electricity structure, and battery charge efficiency are conducted. The results show that the LFP battery is more environmentally friendly in the global warming potential (GWP) and acidification potential (AP), and the NCM battery is more environmentally friendly in abiotic depletion (fossil) (ADP(f)) and human toxicity potential (HTP). However, the LTO battery shows the highest environmental impact among the four environmental impact categories due to the lower energy density. For life cycle BEV, GWP and ADP(f) of BEV based on LFP, NCM, and LMO are lower than those of internal combustion engine vehicles (ICEV), while AP and HTP of BEV based on the four batteries are higher than those of ICEV. The grave-to-cradle (GTC) phase of vehicle has substantial environmental benefit to reduce the human toxicity emission. With the improvement of the battery density, battery charge efficiency, electricity structure, and glider lightweight level, life cycle BEVs based on the four different batteries show substantial environmental benefits for four environmental impact categories.

Keywords: battery electrical vehicle (BEV); lithium-ion power battery; life cycle assessment; prediction analysis; global warming potential (GWP); sensitivity analysis

1. Introduction

The latest data show that China’s dependence on foreign oil consumption reached 72% in 2021, and energy security has become an important issue to be solved urgently. Meanwhile, to address global warming problems, the Chinese government committed to reaching a carbon peak by 2030 and achieving carbon neutrality by 2060. Facing a carbon-neutral future prospect, the China State Council issued “the Notice on The Action Plan for Carbon Peak by 2030” on 24 October 2021, which took green and low-carbon transport action as one of the important tasks. It showed that the proportion of new and clean energy-powered transport vehicles would reach about 40% and the carbon emission intensity per unit of converted turnover of operating vehicles would be reduced by about 9.5% by 2030 compared with 2020. Meanwhile, the State Council issued “Made in China
2025” in 2015, which made energy-saving and new energy vehicles as one of the ten essential development areas. Moreover, the “New Energy Vehicle Industry Development Plan (2021–2035)” proposed that new energy vehicle sales volume of new car sales would achieve about 20% by 2025. The incentive policies substantially promoted the development of new energy vehicles market.

China has become the largest market of electric vehicles (EVs) globally in recent years. In 2021, there have been over 3545 thousand units of EVs (including plug-in hybrid ones) sold in China [1]. In 2021, China’s total power battery capacity produced and assembled in those EVs is 154.5 GWh, increasing by 142.8% when compared with 2020. Due to the fast-growing number of EVs and the soaring capacity of lithium-ion power batteries, the potential environmental impacts have drawn much attention. Electric vehicles have obvious environmental benefits during operation. However, it is uncertain whether the electrical vehicles have environmental benefits compared with internal combustion engine vehicles (ICEV) when considering the source of electricity energy and the environmental burden of the vehicle manufacturing process. Therefore, domestic and foreign scholars have systematically quantified the environmental impact of electric vehicles by using the life cycle assessment method.

1.1. Literature Review

Life cycle assessment (LCA) is a method of objectively evaluating the environmental impacts of a product, process, or activity through quantitative analysis on the process of energy transfer and conversion, material consumption, and the discharge of environmental pollutants [2]. To date, there have been several LCA studies of battery electrical vehicles (BEV) and other power fuel vehicles [3–10]. In detail, Notter et al. compiled a rough LCA of BEV and provided a detailed life cycle inventory of a Li-ion battery [11]. Wu et al. calculated and compared the life cycle greenhouse gas emissions of BEV and ICEV in 2010, 2014, and 2020. It was found that with the optimization of electricity structure, the progress of electricity generation technology, and combined heat and power scales, the life cycle greenhouse gas emissions of BEV will be reduced by 13.4% in 2020 when compared to ICEV [12]. Shafique et al. presented a comparative cradle-to-grave life cycle environmental footprint analysis of BEV in 10 selected countries using the current and future electricity mix scenarios [13]. Qiao et al. analyzed the greenhouse gas emissions of the cradle-to-gate phase, well-to-wheel phase, and grave-to-cradle phase for BEV and ICEV in different times. It was found that the greenhouse gas emissions of producing a BEV are 15.0–15.2 t CO$_2$-eq, which are 50% higher than the 10.0 t CO$_2$-eq of ICEV. However, the life cycle greenhouse gas emissions of a BEV are about 41.0 t CO$_2$-eq, which are 18% lower than those of an ICEV [14,15]. Tagliaferri et al. presented and compared the LCA of BEV and ICEV for Europe. Two manufacturing inventories were analyzed, and different vehicle disposal pathways were considered for BEV [16]. Burchart et al. presented a LCA of BEV in Poland and the Czech Republic, considering the production of electricity structure. It was found that greenhouse gas emissions and fossil energy consumption of BEV would be lower than those of ICEVs both current and future scenarios, while the acidification, eutrophication, human toxicity, and particulate formation caused by BEVs are higher than ICEV [17].

Some scholars evaluated and compared the life cycle assessment of different power batteries applied for BEV [18–20]. In detail, Ellingsen et al. provided a transparent inventory for a lithium-ion nickel-cobalt-manganese (NCM) battery and quantitatively assessed its cradle-to-gate environmental impacts [21]. Marques et al. presented and compared a life cycle primary fossil energy, global warming potential, acidification potential, and eutrophication potential of lithium manganese oxide (LMO) and lithium-ion phosphate (LFP) battery, addressing real-life operational conditions and battery capacity fade [22]. Shu et al. conducted the life cycle environmental impact of LFP and NCM battery and found that LFP battery is more environmentally friendly in the phase of production, while NCM battery is more environmentally friendly in the phase of the application and transportation [23]. Sun et al. collected primary inventory data from two Chinese
leading lithium-ion battery suppliers, two leading cathode material producers, and two battery recycling corporations from 2017 to 2019 to quantitively evaluate the environmental impact of NCM battery. It was found that the material preparation stage is the largest contributor to life cycle environmental impact of the lithium-ion battery, with the cathode active material, wrought aluminum and electrolytes as the predominant contributors [24]. Hao et al. estimated the greenhouse gas emissions from the production of LFP, NCM, and LMO batteries by establishing a life cycle assessment framework. It was found that the greenhouse gas emission from the production of a 28 kWh LFP, NCM, and LMO battery are 3061 kg CO$_2$-eq, 2912 kg CO$_2$-eq, and 2705 kg CO$_2$-eq, respectively [25]. Yin et al. studied and constructed a life cycle assessment of lithium titanate oxide (LTO) batteries for battery electrical buses, including the resetting and reusing phase, and calculated that the life cycle greenhouse gas emission of each kWh LTO battery is 1860 kg CO$_2$-eq [26].

When the capacity of lithium-ion battery is reduced by 20–30%, it can no longer satisfy the demands of BEV. The disposal methods of retired battery mainly include remanufacturing, cascade utilization, recycling, and direct scrapping [27]. Considering the cascade utilization application scenarios, the retired batteries have been reused on the residential energy storage with rooftop photovoltaic [28,29], utility-level photovoltaic firming [30], and utility-level peak-shaving [31,32]. Considering the recycling methods of retired battery, different scholars researched pyrometallurgical, hydrometallurgical, bio-hydrometallurgical, and direct recycling technologies [33,34].

In summary, life cycle assessment of different type vehicles and power batteries were compared, and cascade utilization and recovery of batteries were researched and conducted by different scholars. Meanwhile, the vehicle inventories, calculation model, important influence factors were established and analyzed by scholars. However, few studies quantitatively evaluate life cycle environment impact of battery electrical vehicles when matching different power batteries, especially considering the LTO batteries used for battery electrical passenger vehicles. Meanwhile, the green technology of vehicle, battery, and fuel will rapidly develop and advance with the motivation of the Chinese government incentive policy and the carbon reduction pressure of transportation industry. The impact of the key technology parameters progress on the life cycle BEV becomes uncertain. Moreover, limited studies have conducted a sensitivity analysis of power battery energy density, battery manufacturing energy consumption, electricity structure, and battery charge efficiency according to different assumption scenarios.

1.2. Contribution of This Work

To bridge the research gap, this study conducts a life cycle assessment of a battery electrical passenger vehicles matching four different power batteries of LFP, NCM, LMO, and LTO batteries. The 2025 and 2030 prediction analyses of the batteries production and life cycle BEV are conducted especially considering the change and progress of the power battery energy density, battery manufacturing energy consumption, electricity structure, battery charge efficiency, and vehicle lightweight level. The entire life cycle BEV includes cradle-to-gate (CTG), well-to-wheel (WTW), and grave-to-crane (GTC) in this study. The inventories of four different power batteries are summarized and the life cycle assessment calculation models are established. Potential environmental impacts are further explored based on the CML 2001 method.

In addition, sensitivity analyses of power battery energy density, battery manufacturing energy consumption, electricity structure, and battery charge efficiency are conducted according to different assumption scenarios. Quantitative research on production, use, and disposal of battery electrical vehicles and sensitivity analysis of key components can provide reference for sustainable development of battery electrical vehicle industry and policy-making.

The remainder of this study is organized as follows. Section 2 illustrates the methodology for the life cycle assessment of the BEV. In particular, the assessment objects and function unit are presented in Section 2.1. The system boundary is shown in Section 2.2.
The calculation models including CTG, WTW, and GTC calculation model are introduced in Section 2.3. Life cycle inventories including power battery, glider, ICEV, vehicle assembly, and prediction scenarios are summarized in Section 2.4. Section 3 presents research results including the environmental impact of CTG phase of different power battery in Section 3.1 and the environmental impact of life cycle BEV based on different batteries in Section 3.2. Section 4 presents the sensitivity analysis results including the power battery energy density in Section 4.1, battery manufacturing energy consumption in Section 4.2, electricity structure in Section 4.3, and battery charge efficiency in Section 4.4. Section 5 provides the concluding remarks.

2. Methodology

The LCA method is now widely applied in many industry sectors and playing a more and more important role in the eco-design, green manufacturing, and other sustainability-related fields.

2.1. Assessment Object and Functional Unit

Vehicle model specification and assessment object was the basic assumption for quantitative analysis and substantially influences the assessment results. The vehicle model matched the popular BEV market, because the goal of this study is to reveal the real situation in China. The BYD qin BEV and Chang an CS55 ICEV were chosen as the research object, whose vehicle model specification is presented as Table 1. The LFP battery was used in the baseline scenario, whose capacity is 57 kWh. This study assumes that both BEV and ICEV can drive 150,000 km in China road conditions.

Table 1. Vehicle model specification [15,35,36].

| Vehicle Type | BEV | ICEV |
|--------------|-----|------|
| Body size/mm | $4765 \times 1837 \times 1515$ | $4500 \times 1855 \times 1690$ |
| Life time mileage/km | 150,000 | 150,000 |
| Battery capacity/kWh | 57 | / |
| Fuel economy/kWh or L-(100 km)$^{-1}$ | 12.3 | 8.5 |
| Battery type | LiFePO$_4$ | Lead-acid |
| Curb weight/kg | 1650 | 1490 |
| Lithium-ion power battery (mass fraction) | 20.3% | / |
| Lead-acid battery | / | 1.3% |
| Engine | / | 10.1% |
| Transmission | / | 8.4% |
| Motor | 2.1% | / |
| Electronic controller | 0.6% | / |
| Final drive | 2.1% | / |
| Body | 41.8% | 42.0% |
| Chassis | 31.3% | 36.3% |
| Fluid | 1.8% | 1.9% |

Function unit can quantify and compare selected product performance characteristics. To compare different lithium-ion power batteries production, 1 kWh was chosen as the function unit. To compare life cycle BEV based on different batteries, 1 km was chosen as the function unit.

2.2. System Boundary

The goal of this study is to quantitatively assess and predict the environmental impacts of BEV based on different lithium-ion power batteries and to quantitatively identity the effect of different influence factors on environment benefits for BEV. As Figure 1 shows, the entire life cycle BEV includes CTG, WTW, and GTC. The CTG phase is the BEV production phase, including power battery production, glider production, and vehicle assembly. The process includes material extraction, material transformation, component manufacturing,
and vehicle assembly. Component manufacturing includes different batteries manufacturing and glider manufacturing. Different power batteries include LFP battery, NCM battery, LMO battery, and LTO battery.

2.2. System Boundary

The goal of this study is to quantitatively assess and predict the environmental impacts of BEV based on different lithium-ion power batteries and to quantitatively identify the effect of different influence factors on environment benefits for BEV. As Figure 1 shows, the entire life cycle BEV includes CTG, WTW, and GTC. The CTG phase is the BEV production phase, including power battery production, glider production, and vehicle assembly. Component manufacturing includes different batteries manufacturing and glider manufacturing. Different power batteries include LFP battery, NCM battery, LMO battery, and LTO battery.

Figure 1. System boundary of BEV.

The WTW phase is the BEV use phase. The fuel economy of BEV based on LFP battery is 12.3 kWh/(100 km)$^{-1}$, which comes from official enterprise data. BEV will generate different electricity consumption when matching different power batteries. Therefore, some parameters such as fuel economy are calculated linearly based on the curb weight of BEV matching four different batteries. When the curb weight of BEV increases 1 kg, the electricity consumption will increase 0.0051 kWh [37]. Meanwhile, battery charge efficiency can significantly influence life cycle electricity consumption, which is assumed as 90% for the baseline scenario.

The GTC phase is the BEV recycling phase. The beginning of BEV recycling is vehicle dismantling, which is divided into recyclable parts and unrecyclable parts [38]. Unrecyclable parts are incinerated and landfilled. The vehicle recycling technology has noth-
ing special and is commonly adopted by both BEVs and ICEVs [14]. Pyrometallurgical and hydrometallurgical technologies are two major vehicle recycling technologies worldwide [33,34]. This study assumes that the hydrometallurgical technology will be widely used in future China, and only steel, aluminum, copper, and iron recycling are considered.

The key parameters prediction includes electricity structure, battery energy density, battery manufacturing energy consumption, glider lightweight level, and battery charge efficiency. The key parameters change according to the literature, development tendency, and industry policy.

2.3. Calculation Model

Life cycle assessment calculation model for BEV is established based on the previous work of the authors’ research team [36,39,40]. The calculation model includes CTG calculation model, WTW calculation model, and GTC calculation model.

2.3.1. CTG Calculation Model

The CTG calculation model includes an energy consumption model and a pollution emission model.

(1) Calculation model of energy consumption

Energy consumption matrix of CTG phase for BEV is

$$E_{CTG} = \sum_k [(m_{ij})_{k \times n} \cdot (e_{1ij})_{n \times u} \cdot (e_{0ij})_{n \times r} \cdot (e_{2ij})_{r \times x}] + (e_{3ij})_{x \times r} \cdot (e_{0ij})_{r \times u} \quad (1)$$

where $m_{ij}$ denotes the mass of $j$ vehicle material contained in $i$ vehicle component/kg, $k$ denotes the quantity of vehicle component, $n$ denotes the quantity of vehicle material; where $e_{0ij}$ denotes the quantity of $j$ primary energy consumption (crude coal, crude oil, natural gas, etc.) in producing $i$ per unit secondary energy (electricity, thermal energy, etc.)/MJ·MJ$^{-1}$, $r$ denotes the quantity of secondary energy, $u$ denotes the quantity of primary energy; where $e_{1ij}$ denotes the quantity of $j$ primary energy consumption in producing $i$ per unit vehicle material/MJ·kg$^{-1}$; where $e_{2ij}$ denotes the quantity of $j$ secondary energy consumption in manufacturing $i$ vehicle component/MJ·kg$^{-1}$; and where $e_{3ij}$ denotes the quantity of $j$ secondary energy consumption in vehicle assembly/MJ.

(2) Calculation model of pollution emission

The pollution emission matrix of CTG phase for BEV is

$$P_{CTG} = \sum_k [(m_{ij})_{k \times n} \cdot (p_{0ij})_{n \times s} \cdot (p_{1ij})_{k \times r} \cdot (e_{2ij})_{r \times x}] + (e_{3ij})_{x \times r} \cdot (p_{1ij})_{r \times s} \quad (2)$$

where $p_{0ij}$ denotes the pollution emission intensity of $j$ pollutant in producing $i$ per unit vehicle material/kg·kg$^{-1}$, $s$ denotes the quantity of pollutant; $p_{1ij}$ denotes the pollution emission intensity of $j$ pollutant in producing $i$ per unit secondary energy/kg·MJ$^{-1}$.

2.3.2. WTW Calculation Model

The WTW calculation model includes energy consumption model and pollution emission model.

(1) Calculation model of energy consumption

Energy consumption matrix of WTW phase for BEV is

$$E_{WTW} = Q_1 \times l/100 \times 3.6/\eta \cdot (e_{0})_{1 \times u} \quad (3)$$

where $Q_1$ denotes fuel economy of vehicle/kWh·(100 km)$^{-1}$, $l$ denotes the life time mileage/km, $\eta$ denotes battery charge efficiency, $e_{0}$ denotes the quantity of $j$ primary energy consumption in producing per unit electricity energy/MJ·MJ$^{-1}$. 
The pollution emission matrix of WTW phase for BEV is

\[ P_{WTW} = Q_1 \times 100 \times 3.6/\eta \cdot (p_{ij})_{1 \times s} \]  

(4)

where \( p_{ij} \) denotes the pollution emission intensity of \( j \) pollutant in producing per unit electricity energy/kg·MJ\(^{-1}\).

2.3.3. GTC Calculation Model

The GTC calculation model includes energy consumption model and pollution emission model. This study mainly considers the recovery of steel, cast iron, aluminum, and copper in metal material. The cobalt, nickel, and lithium are considered for battery recycling. It is assumed that the recovery rates of steel, cast iron, aluminum, copper, cobalt, nickel, and lithium are \( \xi_1, \xi_2, \xi_3, \xi_4, \xi_5, \xi_6, \) and \( \xi_7 \) respectively.

(1) Calculation model of energy consumption

The energy consumption matrix of GTC phase for BEV is

\[ E_{GTC} = \sum_k (m_{ij} \cdot \xi_j)_{k \times 7} \cdot \left( (e_{3ij})_{7 \times r} \cdot (e_{0ij})_{r \times u} - (e_{1ij})_{7 \times u} \right) \]  

(5)

where \( e_{3ij} \) denotes the quantity of \( j \) secondary energy consumption in recycling \( i \) per unit vehicle metal material/MJ·kg\(^{-1}\).

(2) Calculation model of pollution emission

The pollution emission matrix of GTC phase for BEV is

\[ P_{GTC} = \sum_k (m_{ij} \cdot \xi_j)_{k \times 7} \cdot \left( (e_{3ij})_{7 \times r} \cdot (p_{ij})_{r \times s} - (p_{0ij})_{7 \times s} \right) \]  

(6)

The CML2001 assessment method developed by the Institute of Environmental Sciences of Leiden University was selected as the based method \([5,36]\). Four impact categories, including abiotic depletion (fossil) (ADP(f)), global warming potential (GWP), acidification potential (AP), and human toxicity potential (HTP) were chosen to assess the impact characterization results.

Global warming potential (GWP) represents potential impacts on global warming due to the emissions of CO\(_2\), CH\(_4\), and N\(_2\)O, with the potentials of 1, 25, and 298 units CO\(_2\)-eq, respectively.

Abiotic depletion (fossil) (ADP(f)) indicates the fossil energy consumption as a result of the consumption of hard coal, crude oil, and natural gas.

Acidification potential (AP) indicates potential impacts on the environment as a result of NO\(_x\) and SO\(_2\) emissions.

Human toxicity potential (HTP) represents potential impacts on human health due to emissions of toxic substances such as heavy metals and hydrocarbons.

2.4. Life Cycle Inventory

2.4.1. Power Battery

In 2020, the output of lithium iron phosphate power batteries for new energy vehicles in China was 34.6 GWh, accounting for 32.4% of the total output of power batteries. According to the enterprise investigation, LFP battery of capacity density is assumed as 170 W·h·kg\(^{-1}\) and NCM battery of capacity density is assumed as 175 W·h·kg\(^{-1}\). According to literature investigation \([25,26]\), LMO battery of capacity density is 133 W·h·kg\(^{-1}\) and LTO battery of capacity density is assumed as 60 W·h·kg\(^{-1}\). This study assumes that battery capacity of LFP, NCM, LMO, and LTO battery is 57 kWh. Different power battery inventories are shown in Table 2. Power batteries include cathode, anode, electrolyte, diaphragm, shell, cooling liquid, and battery management system (BMS).

The battery manufacturing energy consumption shows differences when the battery manufacturing process, electricity structure, and battery type are different. Battery
manufacturing inventories are presented in detail in the literature [11,21]. Two different battery manufacturing inventories were analyzed by the literature [16], whose battery manufacturing electricity energy consumptions are 27 and 100.8 MJ·kg⁻¹, respectively. According to the Argonne National Laboratory in the United States and literature [41], energy consumption in battery assembly is proportional to mass, which is about 2.67 MJ·kg⁻¹. Based on enterprise research and literature data [11,16,21,41], this paper assumes that the electricity energy and natural gas consumption are 18 MJ·kg⁻¹ and 8.8 MJ·kg⁻¹ for battery manufacturing based on enterprise research and literature data for the baseline scenario.

**Table 2.** Different power batteries inventories.

|                | LFP Battery/kg | NCM Battery/kg | LMO Battery/kg | LTO Battery/kg |
|----------------|----------------|----------------|----------------|----------------|
| **Total**      | 335            | 326            | 429            | 950            |
| **Cathode**    |                |                |                |                |
| LFP (1)        | 82             | 92             | LMO (3)        | 144            |
| Aluminum       | 68             | 64             | Aluminum       | 79             |
| Polyvinylidene fluoride (PVDF) | 4             | PVDF           | PVDF           | 5              |
| **Anode**      |                |                |                |                |
| Graphite (4)   | 51             | 60             | Graphite       | 63             |
| Copper         | 41             | 37             | Copper         | 47             |
| PVDF           | 4              | PVDF           | PVDF           | 5              |
| **Electrolyte**|                |                |                |                |
| LiPF₆ (5)      | 9              | 6              | LiPF₆ (8)      | 8              |
| Ethylene carbonate (6) | 26          | 18             | Ethylene carbonate | 23            |
| Dimethyl carbonate (7) | 26          | 18             | Dimethyl carbonate | 23            |
| **Diaphragm**  | Polypropylene (PE) Polyethylene (PP) | PE | PE | PE |
|                | 6              | 6              | 8              | 8              |
| **Shell**      |                |                |                |                |
| PP             | 4              | PP             | PP             | 6              |
| Steel          | 5              | Steel          | Steel          | 6              |
| Glass fiber    | 1              | Glass fiber    | Glass fiber    | 1              |
| **Cooling**    | Ethylene glycol | Ethylene glycol | Ethylene glycol | Ethylene glycol |
|                | 3              | 3              | 4              | 35             |
| **BMS**        | Transistor     | Transistor     | Transistor     | Transistor     |
|                | 2              | 2              | 2              | 2              |
| **References** | [25,41–43]     | [25,41,42]     | [25,41,42]     | [18,26]        |

Note: (1) Processing 1 kg LFP can produce 26 kg CO₂-eq and 0.06 kg SO₂-eq [25,42]; (2) Processing 1 kg NCM can produce 36.8 kg CO₂-eq and 0.08 kg SO₂-eq [25,42]; (3) Processing 1 kg LMO can produce 19.6 kg CO₂-eq and 0.045 kg SO₂-eq [25,42]; (4) Processing 1 kg graphite can produce 1.12 kg CO₂-eq and 0.0026 kg SO₂-eq [41]; (5) Processing 1 kg LTO can produce 18.3 kg CO₂-eq [18]; (6) Ethylene as a proxy for ethylene carbonate; (7) Dimethyl ketone as a proxy for dimethyl carbonate.

2.4.2. Glider

The glider of BEV mainly includes motor, electronic controller, final drive, body, chassis, and fluid [35]. Permanent magnet synchronous motor is installed on battery electric vehicles in this study, whose total power and torque are 100 kW and 180 N·m, respectively. The motor inventories refer to literature [44]. The production process of body mainly consists of stamping, welding, painting, final assembly [36]. Material inventories and energy consumption for BEV glider are shown in Table 3.

2.4.3. ICEV

The Chang’an CS55 internal combustion engine vehicle was chosen as representative vehicle type based on the comprehensive consideration of the curb quality, market sales, and fuel economy. The fuel consumption of ICEV is 8.5 L·(100 km)⁻¹, the curb weight of ICEV is 1490 kg. The material inventories and energy consumption of ICEV are shown in Table 3 [8,15,36].
Table 3. Material inventories and energy consumption for ICEV and BEV (exclude battery) [8,15,36].

| Component         | Vehicle Type | Material Proportion                                                                 | Mass/kg | Electricity Energy Consumption/MJ | Thermal Energy Consumption/MJ |
|-------------------|--------------|---------------------------------------------------------------------------------------|---------|----------------------------------|------------------------------|
| Engine            | ICEV         | 35.7% steel, 42% aluminum, 12.3% iron, 1% copper, 4.5% rubber and 4.5% plastic        | 150     | 1653                             | /                            |
| Transmission      | ICEV         | 30% steel, 30% aluminum, 30% iron, 5% rubber and 5% plastic                           | 125     | 2246.25                          | 1337.5                       |
| Lead-acid battery | ICEV         | 69% lead, 7.9% sulfuric acid, 6.1% polypropylene, 2.1% glass fiber, 14.1% water and 0.8% others | 19      | 51.68                            | /                            |
| Motor             | BEV          | 31.5% steel, 39.5% aluminum, 15.8% copper, 12.3% neodymium iron boron                | 35      | 184.8                            | 66.5                         |
| Electronic controller | BEV      | 5% steel, 47.5% aluminum, 8.3% copper, 23% plastic, 3.8% rubber and 12.4% organics | 10      | 13.8                             | /                            |
| Final drive       | BEV          | 60.6% steel, 20% aluminum, 19% copper, 0.2% plastic and 0.2% organics                | 35      | 630                              | 352.45                       |
| Body              | ICEV         | 68.7% steel, 0.8% aluminum, 0.1% magnesium, 6.6% glass fiber, 17.4% plastic, 1.9% copper and 4.5% others | 626     | 2147.18                          | /                            |
| Chassis           | BEV          | 82.3% steel, 6.3% iron, 1.0% aluminum, 2.3% copper, 3.3% plastic, 4.2% rubber and 0.6% others | 541     | 751.99                           | 232.63                       |
| Fluid             | BEV          | 3.2% lubricating oil, 3.6% braking liquid, 28.6% cooling liquid, 10.7% wiper liquid and 53.9% additive | 29      | 2102.5                           | /                            |

2.4.4. Vehicle Assembly

The main energy consumption in an automobile assembly plant comes from processes or equipment, including painting, air conditioning and lighting, heating, material handling, welding, and workshop compressed air utilization [45]. The energy consumption data of the vehicle assembly stage are shown in Table 4.

Table 4. Energy consumption data of vehicle assembly stage [45,46].

| Painting                  | Air Conditioning and Lighting | Heating | Material Handling | Welding | Workshop Compressed Air Utilization |
|---------------------------|-------------------------------|---------|------------------|---------|------------------------------------|
| Electricity/MJ kg⁻¹       | 2.72                          | 2.18    | 0.45             | 0.61    | 0.9                                |
| Thermal energy/MJ kg⁻¹    | /                             | /       | 2.03             | /       | /                                  |

2.4.5. Prediction Scenarios

The Chinese government incentive policy including “New Energy Vehicle Industry Development Plan (2021–2035)” and “Technology Roadmap for Energy Saving and New Energy Vehicles 2.0” will promote the technology development of battery electrical vehicles and battery. The future development tendency includes the improvement of battery energy density, the reduction of battery manufacturing energy consumption, the reduction of cathode and anode carbon emission factors, the cleanliness of electricity structure, the reduction of glider mass, and the improvement of battery charge efficiency. Therefore, the prediction scenarios of key parameters for BEV are shown in Table 5.

Table 5. Prediction scenarios of key parameters for BEV.

| Key Parameters                        | Object | 2020 | 2025 | 2030 | References |
|---------------------------------------|--------|------|------|------|------------|
| Battery energy density/W·h·kg⁻¹       | LFP    | 170  | 200  | 225  |            |
|                                       | NCM    | 175  | 205  | 230  |            |
|                                       | LMO    | 133  | 150  | 175  |            |
|                                       | LTO    | 60   | 90   | 100  | [25,26,47] |
3. Results

The following LCA results were generated from life cycle inventories of BEV using calculation model and CML2001 method. The first results were evaluated on the CTG phase of different power battery to identify the environmental impact difference of the different battery type and different component, and to predict the environmental impact of the key technology parameters change on different power batteries. The second results were evaluated on the life cycle BEV to identify the environmental impact difference when matching different power batteries, and to predict the environmental impact of the development of vehicle lightweight, electricity structure, and fuel economy on BEV.

3.1. CTG Phase of Different Power Battery

Characterization results of the CTG environment impact of different power batteries are shown in Table 6. The function unit for the CTG phase of different power battery is per kWh. GWP, ADP(f), AP, and HTP of CTG phase of different batteries are shown in Figure 2. It can be found that the LTO has the highest GWP, ADP(f), AP, and HTP among the four batteries because of the lowest battery energy density and the highest battery quality. As shown in Figure 2a, the GWP of LFP, NCM, LMO, and LTO in the CTG phase is 93.7, 113.0, 118.4, and 383.6 kg·kWh⁻¹, respectively. LFP battery shows the lowest carbon emission among four different batteries, and the cathode accounts for 66.3% among different component parts in 2020 scenario. With the progress and development of battery energy density, battery manufacturing energy, and electricity structure, the GWP of the CTG phase of LFP, NMC, LMO, and LTO will decrease by 26.7%, 26.1%, 24.1%, and 41.5%, respectively, in the 2025 scenario, and the GWP of the CTG phase of LFP, NMC, LMO, and LTO will decrease by 43.8%, 42.9%, 44.0%, and 53.8%, respectively, in the 2030 scenario.

As shown in Figure 2b, the ADP(f) of NCM battery shows the lowest fossil energy consumption among four different batteries, and the battery manufacturing accounts for 46.8% among different component parts in 2020 scenario. In terms of component contribution, the cathode has the highest contribution among the four different batteries and the battery manufacturing has the second contribution. With the progress and development of battery energy density, battery manufacturing energy, and electricity structure, the GWP of the CTG phase of LFP, NMC, LMO, and LTO will decrease by 26.7%, 26.1%, 24.1%, and 41.5%, respectively, in the 2025 scenario, and the GWP of the CTG phase of LFP, NMC, LMO, and LTO will decrease by 43.8%, 42.9%, 44.0%, and 53.8%, respectively, in the 2030 scenario.

As shown in Figure 2b, the ADP(f) of NCM battery shows the lowest fossil energy consumption among four different batteries, and the battery manufacturing accounts for 46.8% among different component parts in 2020 scenario. With the progress and development of battery energy density, battery manufacturing energy, and electricity structure, the ADP(f) of the CTG phase of LFP, NMC, LMO, and LTO will decrease by 29.2%, 29.3%, 26.9%, and 43.7%, respectively, in the 2025 scenario, and the ADP(f) of the CTG phase of LFP, NMC, LMO, and LTO will decrease by 46.1%, 46.2%, 46.9%, and 56.0%, respectively, in the 2030 scenario.
| Year | Component       | LFP | NMC | LMO | LTO | LFP | NMC | LMO | LTO | LFP | NMC | LMO | LTO |
|------|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 2020 | Cathode         | 3540.0 | 4710.0 | 4496.0 | 10,730.0 | 13,200.0 | 12,300.0 | 15,570.0 | 21,874.0 | 12.7 | 15.3 | 13.1 | 33.1 |
|      | Anode           | 262.0 | 252.0 | 304.0 | 2850.0 | 3190.0 | 4050.0 | 4720.0 | 1980.0 | 3.0  | 2.7  | 3.4  | 0.1  |
|      | Electrolyte     | 86.3 | 66.5 | 87.5 | 194.0 | 2850.0 | 2200.0 | 2890.0 | 6400.0 | 0.3  | 0.2  | 0.3  | 0.7  |
|      | Diaphragm       | 19.1 | 15.6 | 20.5 | 78.5 | 631.0 | 513.0 | 675.0 | 2690.0 | 0.03 | 0.02 | 0.03 | 0.1  |
|      | Shell            | 28.2 | 25.1 | 34.2 | 3655.0 | 551.0 | 491.0 | 669.0 | 33,700.0 | 0.1  | 0.1  | 0.2  | 17.7 |
|      | Cooling liquid  | 2.9  | 2.8  | 3.7  | 30.0 | 120.0 | 117.0 | 153.0 | 1256.0 | 0.01 | 0.01 | 0.01 | 0.1  |
|      | BMS             | 0.9  | 0.9  | 1.2  | 8.3  | 10.0 | 10.0 | 13.0 | 86.6  | 0.001 | 0.001 | 0.001 | 0.2  |
|      | Manufacturing   | 1400.0 | 1370.0 | 1800.0 | 3980.0 | 17,800.0 | 17,300.0 | 22,800.0 | 50,400.0 | 3.0  | 3.0  | 3.9  | 8.6  |
|      | All             | 5340.0 | 6440.0 | 6740.0 | 21,900.0 | 39,130.0 | 36,980.0 | 47,400.0 | 118,000 | 19.1 | 21.3 | 20.9 | 60.5  |
| 2025 | Cathode         | 2830.0 | 3728.0 | 3730.0 | 6587.0 | 11,200.0 | 11,140.0 | 14,500.0 | 18,600.0 | 10.8 | 13.01 | 11.6 | 22.1 |
|      | Anode           | 218.0 | 209.0 | 263.0 | 1920.0 | 3380.0 | 3450.0 | 4180.0 | 1320.0 | 2.54 | 2.32 | 3.0  | 0.1  |
|      | Electrolyte     | 73.5 | 56.7 | 77.5 | 129.0 | 2430.0 | 1870.0 | 2560.0 | 4270.0 | 0.257 | 0.198 | 0.271 | 0.451 |
|      | Diaphragm       | 16.2 | 13.3 | 18.1 | 52.3 | 537.0 | 437.0 | 598.0 | 1790.0 | 0.025 | 0.0206 | 0.0282 | 0.08  |
|      | Shell            | 24.0 | 21.4 | 30.3 | 2436.0 | 469.0 | 419.0 | 593.0 | 22,500.0 | 0.108 | 0.096 | 0.135 | 11.8  |
|      | Cooling liquid  | 2.43 | 2.4  | 3.24 | 20.0 | 102.0 | 99.0 | 136.0 | 837.0 | 0.005 | 0.0048 | 0.0066 | 0.04  |
|      | BMS             | 0.67 | 0.65 | 0.89 | 4.6  | 7.0 | 7.0 | 9.0 | 48.3  | 0.001 | 0.001 | 0.002 | 0.01  |
|      | Manufacturing   | 750.0 | 731.0 | 999.0 | 1660.0 | 9400.0 | 12,900.0 | 21,400.0 | 35,200.0 | 3.6  | 3.5  | 3.9  | 8.6  |
|      | All             | 3914.0 | 4760.0 | 5120.0 | 12,800.0 | 39,130.0 | 36,980.0 | 47,400.0 | 118,000 | 19.1 | 21.3 | 20.9 | 60.5  |

**Table 6.** Characterization results of the CTG environment impact of different power batteries.
As shown in Figure 2c, the AP of LFP, NCM, LMO, and LTO in the CTG phase is 0.336, 0.374, 0.367, and 1.060 kg·kWh⁻¹ respectively. LFP battery shows the lowest acidification gas emission among four different batteries, and the cathode accounts for 66.4% among different component parts in the 2020 scenario. With the progress and development of battery energy density, battery manufacturing energy, and electricity structure, the AP of the CTG phase of LFP, NCM, LMO, and LTO will decrease by 19.5%, 19.4%, 17.9%, and 36.8%, respectively, in the 2025 scenario, and the AP of the CTG phase of LFP, NCM, LMO, and LTO will decrease by 32.1%, 31.1%, 33.6%, and 45.7%, respectively, in the 2030 scenario.

As shown in Figure 2d, the HTP of NCM battery shows the lowest human toxicity emission among four different batteries, and the cathode accounts for 52.3% among different component parts in 2020 scenario. With the progress and development of battery energy density, battery manufacturing energy, and electricity structure, the HTP of the CTG phase of LFP, NCM, LMO, and LTO will decrease by 15.9%, 15.7%, 12.5%, and 34.3%, respectively, in the 2025 scenario, and the ADP(f) of the CTG phase of LFP, NCM, LMO, and LTO will decrease by 26.0%, 25.7%, 25.7%, and 41.5%, respectively, in the 2030 scenario.

For the production of four different power batteries, the LFP battery is more environmentally friendly in the GWP and AP, and the NCM battery is more environmentally
friendly in ADP(f) and HTP. However, the LTO battery shows the highest environmental impact for four environmental impact categories due to the lower energy density.

### 3.2. Life Cycle BEV Based on Different Batteries

Characterization results of the life cycle environment impact of BEV based on different power batteries are shown in Table 7. The function unit for life cycle BEV based on different batteries is g·km\(^{-1}\). The GWP, ADP(f), AP, and HTP of life cycle BEV based on different batteries are shown in Figure 3. It was found that the GWP and ADP(f) of life cycle BEVs based on LFP, NCM, LMO, and LTO are lower than those of ICEV, while the AP of life cycle BEVs is higher than that of ICEV.

As shown in Figure 3a, the GWP of life cycle BEVs based on LFP, NCM, LMO, and LTO are 162.0, 169.1, 175.1, and 281.1 g CO\(_2\)·km\(^{-1}\) in the 2020 scenario. Compared with ICEV, BEVs based on LFP, NCM, and LMO have substantial carbon emission reduction benefits. BEV based on LTO battery has similar carbon emission with ICEV. In terms of different phases, the WTW phase of BEV has the highest carbon emissions due to the high coal electricity proportion in China electricity structure, and the WTW phase of ICEV has the highest carbon emissions due to the high carbon emission of gasoline combustion. Meanwhile, the CTG power batteries have higher carbon emission compared with CTG engine. With the development of vehicle lightweight, battery charge efficiency, and electricity structure, the GWP of life cycle BEV based on LFP, NCM, LMO, and LTO batteries will decrease by 28.7%, 28.5%, 28.2%, and 37.8%, respectively, in the 2025 scenario. The GWP of life cycle BEV based on LFP, NCM, LMO, and LTO batteries will decrease by 49.7%, 49.0%, 49.7%, and 55.1%, respectively, in the 2030 scenario. The GTC phase of ICEV and BEV contributes to the carbon emission reduction.

As shown in Figure 3b, the ADP(f) of the life cycle BEVs based on LFP, NCM, LMO, and LTO are 1627, 1616, 1721, and 2277 kJ·km\(^{-1}\) in the 2020 scenario. Compared to ICEV, the ADP(f) results of BEV based on different power batteries are similar to the results of GWP. With the development of vehicle lightweight, battery charge efficiency, and electricity structure, the ADP(f) of life cycle BEV based on LFP, NCM, LMO, and LTO batteries will decrease by 28.8%, 28.8%, 19.4%, and 36.7%, respectively, in the 2025 scenario. The ADP(f) of life cycle BEV based on LFP, NCM, LMO, and LTO batteries will decrease by 49.5%, 49.6%, 49.8%, and 55.3%, respectively, in the 2030 scenario. The GTC phase of ICEV and BEV contributes to the energy consumption reduction.

As shown in Figure 3c, the AP of the life cycle BEVs based on LFP, NCM, LMO, and LTO are 0.364, 0.382, 0.380, and 0.604 g SO\(_2\)·km\(^{-1}\) in the 2020 scenario. Compared with ICEV, BEVs based on LFP, NCM, LMO, and LTO have higher acidification gas emission. In terms of different phases, the WTW phase and CTG power battery are the main contributors for acidification gas emissions. With the development of vehicle lightweight, battery charge efficiency, and electricity structure, the AP of life cycle BEV based on LFP, NCM, LMO, and LTO batteries will decrease by 27.4%, 27.0%, 27.3%, and 36.1%, respectively, in the 2025 scenario. The GWP of life cycle BEV based on LFP, NCM, LMO, and LTO batteries will decrease by 47.3%, 46.5%, 48.3%, and 52.0%, respectively, in the 2030 scenario. The GTC phase of ICEV and BEV contributes to the acidification gas emission reduction.

As shown in Figure 3d, the HTP of the life cycle HTP of BEV based on LFP, NCM, LMO, and LTO are higher than ICEV when the GTC phase of vehicle is not considered. The GTC phase of vehicle has substantial environmental benefit to reduce the human toxicity emission. The CTG power battery phase accounts for the largest proportion in human toxicity emission. With the development of vehicle lightweight, battery charge efficiency, and electricity structure, the HTP of life cycle BEV based on LFP, NCM, LMO, and LTO batteries will decrease by 20.9%, 21.6%, 18.6%, and 34.1%, respectively, in the 2025 scenario. The HTP of life cycle BEV based on LFP, NCM, LMO, and LTO batteries will decrease by 35.4%, 36.3%, 34.7%, and 47.3%, respectively, in the 2030 scenario.
For life cycle BEV based on different batteries, the GWP and ADP(f) of BEV based on LFP, NCM, and LMO are lower than those of ICEV, while the AP and HTP of BEV based on the four batteries are higher than those of ICEV.

Figure 3. GWP, ADP(f), AP, and HTP of life cycle BEVs based on different batteries.
Table 7. Characterization results of the life cycle environment impact of BEVs based on different power batteries.

| Year   | Phase                      | GWP/kg CO₂-eq | ADP(f)/MJ | AP/kg SO₂-eq | HTP/kg DCB-eq |
|--------|-----------------------------|----------------|------------|--------------|---------------|
|        | LFP                        | NMC            | LMO        | LTO          | LFP            | NMC          | LMO          | LTO          | LFP            | NMC          | LMO          | LTO          |
| 2020   | CTG Power battery           | 5340           | 6440       | 6740         | 21,900         | 39,130        | 36,980       | 47,400       | 118,000        | 19.1          | 21.3         | 20.9         | 60.5         | 1725         | 1597.7       | 2045.7       | 4038.4       |
|        | CTG Glider                 | 4880           | 4880       | 4880         | 55,100         | 55,100        | 55,100       | 15.5         | 15.5          | 15.5          | 15.5         | 1170         | 1170         | 1170         | 1170         | 1170         |
|        | Vehicle assembly           | 2680           | 2670       | 2840         | 28,200         | 28,000        | 29,800       | 5.8          | 5.77          | 6.13          | 7.96         | 113          | 113          | 120          | 156          |
|        | WTW phase                  | 15,300         | 15,200     | 15,900       | 19,200         | 160,000       | 166,000      | 201,000      | 33.1          | 33            | 34.4         | 41.5         | 656          | 654          | 682          | 823          |
|        | GTC phase                  | −3900          | −3820      | −4090        | −7510          | −38,400       | −37,700      | −40,200      | −71,200       | −18.9         | −18.3        | −20          | −34.8        | −2260        | −2190        | −2410        | −4400        |
|        | Life cycle                 | 24,300         | 25,370     | 26,270       | 42,160         | 42,403        | 258,100      | 341,600      | 54.6          | 57.27         | 56.93        | 90.66        | 1404         | 1344.7       | 1607.7       | 1787.4       |
| 2025   | CTG Power battery           | 3914           | 4760       | 5120         | 12,800         | 27,700        | 34,700       | 66,700       | 15.4          | 17.2          | 17.2         | 38.2         | 1450.50      | 1346.03      | 1789.88      | 2654.01      |
|        | CTG Glider                 | 3980           | 3980       | 3980         | 45,100         | 45,100        | 45,100       | 45,100       | 12.8          | 12.8          | 12.8         | 12.8         | 988          | 988          | 988          | 988          |
|        | Vehicle assembly           | 1960           | 1950       | 2090         | 2440           | 20,600        | 24,700       | 25,700       | 4.22          | 4.19          | 4.5          | 5.26         | 88.1         | 87.7         | 94.1         | 110          |
|        | WTW phase                  | 10,900         | 10,800     | 11,300       | 12,600         | 114,000       | 119,000      | 132,000      | 23.5          | 23.4          | 24.5         | 27.2         | 504          | 503          | 527          | 585          |
|        | GTC phase                  | −3420          | −3360      | −3640        | −5590          | −33,700       | −35,800      | −53,400      | −16.3         | −15.8         | −17.6        | −25.5        | −1920        | −1870        | −2090        | −3160        |
|        | Life cycle                 | 17,334         | 18,130     | 18,850       | 26,230         | 173,700       | 208,100      | 216,100      | 39.6          | 41.79         | 41.4         | 57.96        | 1110.60      | 1054.73      | 1308.98      | 1177.01      |
| 2030   | CTG Power battery           | 3000           | 3680       | 3780         | 10,100         | 21,100        | 25,200       | 52,100       | 13            | 14.7          | 13.9         | 32.8         | 1275.64      | 1187.361     | 1519.307     | 2360.71      |
|        | CTG Glider                 | 3340           | 3340       | 3340         | 3340           | 38,000        | 38,000       | 38,000       | 10.9          | 10.9          | 10.9         | 10.9         | 867          | 867          | 867          | 867          |
|        | Vehicle assembly           | 1420           | 1410       | 1500         | 1780           | 14,900        | 15,800       | 18,700       | 3.05          | 3.03          | 3.23         | 3.82         | 69.7         | 69.4         | 73.8         | 87.5         |
|        | WTW phase                  | 7600           | 7580       | 7880         | 8810           | 80,000        | 82,900       | 92,600       | 16.4          | 16.3          | 17           | 19           | 394          | 393          | 409          | 457          |
|        | GTC phase                  | −3130          | −3070      | −3280        | −5090          | −30,900       | −32,300      | −48,700      | −14.6         | −14.3         | −15.6        | −23          | −1700        | −1660        | −1820        | −2830        |
|        | Life cycle                 | 12,230         | 12,940     | 13,220       | 18,940         | 123,100       | 122,200      | 129,600      | 28.75         | 30.63         | 29.43        | 43.52        | 906.34       | 856.761      | 1049.107     | 942.21       |
4. Sensitivity Analysis

4.1. Power Battery Energy Density

The above results indicate that the difference of battery energy density has an important impact on the environment burdens of the CTG phase of different power batteries. Meanwhile, the value of power battery energy density is uncertain due to the difference of enterprise development level and the development of battery technology. In order to quantitatively evaluate the impact of the power battery energy density on the environmental burdens of the CTG phase of BEVs based on different batteries, the power battery energy density was chosen as a sensitive factor in this study. Different power battery energy density scenarios are shown in Table 8. The results of sensitivity analysis of power battery energy are shown in Figure 4.

Table 8. Different power battery energy density scenarios/W·h/kg⁻¹.

| Scenarios                  | LFP | NCM | LMO | LTO |
|----------------------------|-----|-----|-----|-----|
| Baseline                   | 170 | 175 | 133 | 60  |
| Battery energy density + 10%| 187 | 192.5| 146.3| 66  |
| Battery energy density + 20%| 204 | 210 | 159.6| 72  |
| Battery energy density + 30%| 221 | 227.5| 172.9| 78  |

As Figure 4 shows, with the power battery energy density increases by 10%, the GWP of CTG phase of BEV based on LFP, NMC, LMO, and LTO decreases by 4.75%, 5.17%, 5.27%, and 7.43%, respectively; the ADP(f) decreases by 3.77%, 3.65%, 4.20%, and 6.20% respectively; the AP decreases by 5.02%, 5.26%, 5.27%, and 7.24%, respectively; the HTP decreases by 5.42%, 5.25%, 5.78%, and 7.05%, respectively. The improvement of power battery energy density has the highest environmental benefit on the CTG phase of BEV.
based on the LTO. The improvement of power battery energy density has substantial impact on GWP and AP.

4.2. Battery Manufacturing Energy Consumption

The battery manufacturing energy consumption shows differences when the battery manufacturing process, electricity structure, and battery type are different. Therefore, the value of battery manufacturing energy consumption is uncertain due to the difference of enterprise manufacturing process and battery technology development. The electricity energy and natural gas consumption are 18 MJ·kg\(^{-1}\) and 8.8 MJ·kg\(^{-1}\) for battery manufacturing based on enterprise research and literature data for baseline scenario in this study. The battery manufacturing energy consumption decreases by 10%, 20%, and 30%, respectively, for three different scenarios. The sensitivity analysis of battery manufacturing energy consumption is shown in Figure 5.

![Sensitivity analysis of battery manufacturing energy consumption](image)

**Figure 5.** Sensitivity analysis of battery manufacturing energy consumption.

As Figure 5 shows, with the battery manufacturing energy consumption decreases by 10%, the GWP of CTG phase of BEV based on LFP, NMC, LMO, and LTO decreases by 1.43%, 1.21%, 1.55%, and 1.49%, respectively, the ADP(f) decreases by 1.89%, 1.88%, 2.22%, and 2.91%, respectively, the AP decreased by 0.88%, 0.80%, 1.07%, and 1.13%, respectively, the HTP decreases by 0.21%, 0.21%, 0.24%, and 0.33%, respectively. The reduction of the battery manufacturing energy consumption has the highest impact on ADP(f) while it has the lowest impact on HTP.
4.3. Electricity Structure

The above results indicate that electricity structure has an important impact on the environment burdens of the life cycle BEV. In order to quantitatively evaluate the impact of the electricity structure on the environmental burdens of the life cycle BEVs based on different batteries, three electricity structure scenarios were constructed, as shown in Table 9. The baseline electricity structure scenario is based on Chinese realistic development state, and scenario 1 and scenario 2 are the hypothetical scenarios. The results of sensitivity analysis of electricity structure are shown in Figure 6.

Table 9. Different electricity structure scenarios.

| Electricity Structure       | Baseline | Scenario 1 | Scenario 2 |
|----------------------------|----------|------------|------------|
| Coal electricity           | 71%      | 60%        | 48%        |
| Wind electricity           | 4%       | 10%        | 14%        |
| Nuclear electricity        | 3%       | 4%         | 8%         |
| Hydroelectric electricity  | 15%      | 17%        | 18%        |
| Photovoltaic electricity   | 2%       | 6%         | 11%        |
| Other electricity          | 5%       | 3%         | 1%         |

Figure 6. Sensitivity analysis of electricity structure.
As Figure 6 shows, the optimization of electricity structure has some environmental benefit on the life cycle BEV. Compared to the baseline scenario, the GWP of the life cycle BEV based on LFP, NMC, LMO, and LTO will decrease by 14.0%, 13.5%, 13.8%, and 11.3% in scenario 1; the ADP(f) of those will decrease by 14.6%, 14.6%, 14.4%, and 13.7% in scenario 1; the AP of those will decrease by 13.8%, 13.3%, 14.0%, and 11.3% in scenario 1; and the HTP of those will decrease by 6.2%, 6.7%, 5.7%, and 6.8% in scenario 1. Compared to the baseline scenario, the GWP of the life cycle BEV based on LFP, NMC, LMO, and LTO will decrease by 22.9–29.4% in scenario 2; the ADP(f) of those will decrease by 29.1–30.4% in scenario 2; the AP of those will decrease by 23.4–29.0% in scenario 2; and the HTP of those will decrease by 12.2–13.7% in scenario 2. The optimization of electricity structure has an obvious impact on GWP, ADP(f), and AP while it has a lower impact on HTP.

4.4. Battery Charge Efficiency

The battery charge efficiency is assumed as 90% in the baseline scenario, which has an impact on the electricity energy consumption. Three different battery charge efficiency sensitivity analysis scenarios were established. The battery charge efficiencies were 90%, 94%, and 98%. The results of sensitivity analysis of battery charge efficiency are shown in Figure 7.

Figure 7. Sensitivity analysis of battery charge efficiency.

As Figure 7 shows, when the battery charge efficiency increases from 90% to 98%, the GWP of the life cycle BEV based on LFP, NMC, LMO, and LTO decreases by 5.1%, 4.9%, 4.9%, and 3.7%; the ADP(f) of the life cycle BEV based on LFP, NMC, LMO, and LTO decreases by 5.4%, 5.4%, 5.3%, and 4.8%; the AP of the life cycle BEV based on LFP, NMC, LMO, and LTO decreases by 4.9%, 4.7%, 4.9%, and 3.7%; the HTP of the life cycle
BEV based on LFP, NMC, LMO, and LTO decreases by 3.8%, 3.9%, 3.5%, and 3.8%. The improvement of battery charge efficiency has minor environmental benefit on the life cycle BEV based on the LTO.

5. Conclusions

In this study, the environmental impacts of battery electrical passenger vehicles matching four different power batteries (LFP, NCM, LMO, and LTO) in China are conducted throughout the life cycle assessment approach. The future prediction analysis of batteries production and life cycle BEV are conducted to evaluate the environmental benefits of the development of key technology parameters. Inventories of four different power batteries are collected from the literature investigation and enterprise investigation. The study results can be concluded as follows.

For the production of four different power batteries, the LFP battery is more environmentally friendly in the GWP and AP, and the NCM battery is more environmentally friendly in ADP(f) and HTP. However, the LTO battery shows the highest environmental impact for four environmental impact categories due to the lower energy density. In detail, the cathode is the largest contributor to GWP, AP, and HTP due to the production of cathode active material and aluminum. The battery manufacturing energy consumption is the largest contributor to ADP(f). Meanwhile, with the improvement of the battery density, the reduction of battery manufacturing energy consumption, the clean of electricity energy, four different batteries show substantial environmental benefits for four environmental impact categories, which are decreased by 26.0% to 56% in 2030 when compared with 2020.

For life cycle BEV based on different batteries, GWP and ADP(f) of BEV based on LFP, NCM, and LMO are lower than those of ICEV, while AP and HTP of BEV based on the four batteries are higher than those of ICEV. In terms of different phases, the WTW phase of BEV has the highest GWP and ADP(f); the CTG phase power battery has higher contributors to AP and HTP; the GTC phase of the vehicle has substantial environmental benefit to reduce the human toxicity emission. With the improvement of battery charge efficiency and glider lightweight level, the BEV based on the four different batteries shows substantial environmental benefits for four environmental impact categories, which are decreased by 35.4% to 55.3% when compared with 2020.

A sensitivity analysis of power battery energy density, battery manufacturing energy consumption, electricity structure, and battery charge efficiency was conducted according to different assumption scenarios. The improvement of power battery energy density has a substantial impact on GWP and AP. Reduction of battery manufacturing energy consumption has the highest impact on ADP(f) while it has the lowest impact on HTP. The optimization of electricity structure has an obvious impact on GWP, ADP(f), and AP while it has lower impact on HTP. The improvement of battery charge efficiency has minor environmental benefit on the life cycle BEV based on the LTO.

The inventories of power batteries and battery electrical vehicles remain uncertain. The sensitivity analysis of different important factors can improve the accuracy of research results. The assessment model used is static and ignores the underlying dynamics within the system [50]. The accuracy of battery inventories will be improved in the future [51].

Author Contributions: Conceptualization, Y.Y.; data curation, G.L.; formal analysis, Y.C.; investigation, L.L.; methodology, Z.H.; software, J.Z.; writing—original draft, L.L.; writing—review and editing, P.F. All authors have read and agreed to the published version of the manuscript.

Funding: This work is financially supported by the National Key Research and Development Program (Grant No. SQ2021YFE0192900), the Shaanxi Provincial Key Research and Development Program (Grant No. 2021LLRH-04-04-02), the Youth Science and technology star project of Shaanxi Province (Grant No. 2021KJXX-15), the Shaanxi Provincial Key Industry Innovation Chain Project (Grant No. 2020ZDLGY16-08), and the Fundamental Research Funds for the Central Universities of Ministry of Education of China (Grant No. 300102221106).

Institutional Review Board Statement: Not applicable.
Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

| Abbreviation | Definition                                      |
|--------------|------------------------------------------------|
| ADP(f)       | Abiotic depletion (fossil)                     |
| AP           | Acidification potential                        |
| BEV          | Battery electrical vehicle                     |
| BMS          | Battery management system                      |
| CTG          | Cradle-to-gate                                 |
| GTC          | Grave-to-crade                                 |
| GWP          | Global warming potential                       |
| HTP          | Human toxicity potential                       |
| ICEV         | Internal combustion engine vehicles            |
| LCA          | Life cycle assessment                          |
| LFP          | Lithium-ion phosphate                          |
| LMO          | Lithium manganese oxide                        |
| NCM          | Lithium-ion nickel-cobalt-manganese            |
| PE           | Polyethylene                                   |
| PP           | Polypropylene                                  |
| PVDF         | Polyvinylidene fluoride                        |
| LTO          | Lithium titanate oxide                         |
| WTW          | Well-to-wheel                                  |

References

1. China Association of Automobile Manufacturers. *An Overview of the Automobile Industry in 2021*; China Association of Automobile Manufacturers: Beijing, China, 2022. (In Chinese)
2. *ISO 14040; Environmental Management-Life Cycle Assessment Principles and Framework.* International Organization for Standardization: Geneva, Switzerland, 2006.
3. Xia, X.N.; Li, P.W. A review of the life cycle assessment of electric vehicles: Considering the influence of batteries. *Sci. Total Environ.* 2022, 814, 152870. [CrossRef] [PubMed]
4. Sisani, F.; Dimaria, F.; Cesari, D. Environmental and human health impact of different powertrain passenger cars in a life cycle perspective. A focus on health risk and oxidative potential of particulate matter components. *Sci. Total Environ.* 2022, 805, 150171. [CrossRef] [PubMed]
5. Yu, A.; Wei, Y.Q.; Chen, W.W.; Peng, N.J.; Peng, L.H. Life cycle environmental impacts and carbon emissions: A case study of electric and gasoline vehicles in China. *Transp. Res. Part D Transp. Environ.* 2018, 65, 409–420. [CrossRef]
6. Souza, L.; Lora, E.; Palacio, J.; Rocha, M.; Reno, M.; Venturini, O. Comparative environmental life cycle assessment of conventional vehicles with different fuel options, plug-in hybrid and electric vehicles for a sustainable transportation system in Brazil. *J. Clean. Prod.* 2018, 203, 444–468. [CrossRef]
7. Held, M.; Schücking, M. Utilization effects on battery electric vehicle life-cycle assessment: A case-driven analysis of two commercial mobility applications. *Transp. Res. Part D Transp. Environ.* 2019, 75, 87–105. [CrossRef]
8. Shafique, M.; Azam, A.; Rafiq, M.; Luo, X.W. Life cycle assessment of electric vehicles and internal combustion engine vehicles: A case study of Hong Kong. *Res. Transp. Econ.* 2021, 91, 101112. [CrossRef]
9. Bauer, C.; Hofer, J.; Althaus, H.; Del, D.; Simons, A. The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework. *Appl. Energy* 2015, 157, 871–883. [CrossRef]
10. Evangelisti, S.; Tagliaferri, C.; Brett, D.J.; Lettieri, P. Life cycle assessment of a polymer electrolyte membrane fuel cell system for passenger vehicles. *J. Clean. Prod.* 2017, 142, 4339–4355. [CrossRef]
11. Notter, D.; Gauch, M.; Widmer, R.; Wager, P.; Stamp, A.; Zah, R.; Althaus, H.J. Contribution of Li-ion batteries to the environmental impact of electric vehicles. *Environ. Sci. Technol.* 2010, 44, 6550–6556. [CrossRef]
12. Wu, Z.X.; Wang, M.; Zheng, J.H.; Sun, X.; Zhao, M.N.; Wang, X. Life cycle greenhouse gas emission reduction potential of battery electric vehicle. *J. Clean. Prod.* 2018, 190, 462–470. [CrossRef]
13. Shafique, M.; Luo, X. Environmental life cycle assessment of battery electric vehicles from the current and future energy mix perspective. *J. Environ. Manag.* 2022, 303, 114050. [CrossRef] [PubMed]
14. Qiao, Q.Y.; Zhao, F.Q.; Liu, Z.W.; He, X.; Hao, H. Life cycle greenhouse gas emissions of electric vehicles in China: Combining the vehicle cycle and fuel cycle. *Energy* 2019, 177, 222–233. [CrossRef]
15. Qiao, Q.Y.; Zhao, F.Q.; Liu, Z.W.; Jiang, S.H.; Hao, H. Cradle-to-gate greenhouse gas emissions of battery electric and internal combustion engine vehicles in China. *Appl. Energy* 2017, 204, 1399–1411. [CrossRef]
16. Tagliaferri, C.; Evangelisti, S.; Acconcia, F.; Domenech, T.; Ekins, P.; Barlettab, D.; Lettieri, P. Life cycle assessment of future electric and hybrid vehicles: A cradle-to-grave systems engineering approach. *Chem. Eng. Res. Des.* 2016, 112, 298–309. [CrossRef]

17. Burchart, K.D.; Jursova, S.; Folępą, P.; Korol, J.; Pustejovska, P.; Blaut, A. Environmental life cycle assessment of electric vehicles in Poland and the Czech Republic. *J. Clean. Prod.* 2018, 202, 476–487. [CrossRef]

18. Yin, R.S.; Hu, S.H.; Yang, Y. Life cycle inventories of the commonly used materials for lithium-ion batteries in China. *J. Clean. Prod.* 2019, 227, 960–971. [CrossRef]

19. Cusenza, M.A.; Bobba, S.; Ardente, F.; Cellura, M.; Persio, D.F. Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles. *J. Clean. Prod.* 2019, 215, 634–649. [CrossRef]

20. Kim, H.C.; Wallington, T.J.; Arsenault, R.; Bae, C.; Ahn, S.; Lee, J. Cradle-to-Gate emissions from a commercial electric vehicle Li-ion battery: A comparative analysis. *Environ. Sci. Technol.* 2016, 50, 7715–7722. [CrossRef]

21. Ellingsen, L.A.W.; Majeau, G.; Singh, B.; Srivastava, A.K.; Valoen, L.O.; Stromman, A.H. Life cycle assessment of a lithium-ion battery vehicle pack. *J. Ind. Ecol.* 2014, 18, 113–124. [CrossRef]

22. Marques, P.; Garcia, R.; Kuly, L.; Freire, F. Comparative life cycle assessment of lithium-ion batteries for electric vehicles addressing capacity fade. *J. Clean. Prod.* 2019, 229, 787–794. [CrossRef]

23. Shu, X.; Guo, Y.F.; Yang, W.X.; Zhu, G.H. Life-cycle assessment of the environmental impact of the batteries used in pure electric passenger cars. *Energy Rep.* 2021, 7, 2302–2315. [CrossRef]

24. Sun, X.; Luo, X.L.; Zhang, Z.; Meng, F.R.; Yang, J.X. Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles. *J. Clean. Prod.* 2020, 273, 123006. [CrossRef]

25. Hao, H.; Mu, Z.X.; Jiang, S.H.; Liu, Z.W.; Zhao, F.Q. GHG Emissions from the Production of Lithium-ion Batteries for Electric Vehicles in China. *Sustainability* 2017, 9, 504. [CrossRef]

26. Yin, R.S.; Wang, Y.P.; Yang, Y.; Chen, Z.L. Life cycle assessment of the lithium titanate batteries used for electric vehicles. *China Environ. Sci.* 2018, 38, 2371–2381. (In Chinese)

27. Hua, Y.; Liu, X.H.; Zhou, S.; Huang, Y.; Ling, H.P.; Yang, S.C. Toward sustainable reuse of retired lithium-ion batteries from electric vehicles. *Resour. Conserv. Recycl.* 2021, 168, 105249. [CrossRef]

28. Bobba, S.; Mathieux, F.; Ardente, F.; Blengini, G.A.; Cusenza, M.A.; Podias, A.; Pfrairg, A. Life cycle assessment of repurposed electric vehicle batteries: An adapted method based on modelling energy flows. *J. Energy Storage* 2018, 19, 213–225. [CrossRef]

29. Cusenza, M.A.; Guarino, F.; Longo, S.; Mistretta, M.; Cellura, M. Reuse of electric vehicle batteries in buildings: An integrated load match analysis and life cycle assessment approach. *Energy Build.* 2019, 186, 339–354. [CrossRef]

30. Ahmadi, L.; Young, S.B.; Fowler, M.; Fraser, R.A.; Achachlouei, M.A. A cascaded life cycle: Reuse of electric vehicle lithium-ion battery packs in energy storage systems. *Int. J. Life Cycle Assess.* 2015, 22, 111–124. [CrossRef]

31. Sun, B.X.; Su, X.J.; Wang, D.; Zhang, L.; Liu, Y.; Yang, Y.; Liang, H.; Gong, M.; Zhang, W.; Jiang, J. Economic analysis of lithium-ion batteries recycled from electric vehicles for secondary use in power load peak shaving in China. *J. Clean. Prod.* 2020, 276, 123327. [CrossRef]

32. Kamath, D.; Shukla, S.; Arsenault, R.; Kim, H.C.; Anctil, A. Evaluating the cost and carbon footprint of second-life electric vehicle batteries in residential and utility-level applications. *Waste Manag.* 2020, 113, 497–507. [CrossRef]

33. Harper, G.; Sommerville, R.; Kendrick, E.; Driscoll, L.; Slater, P.; Stolkin, R.; Walton, A.; Christensen, P.; Heidrich, O.; Lambert, S.; et al. Recycling lithium-ion batteries from electric vehicles. *Nature* 2019, 575, 75–86. [CrossRef] [PubMed]

34. Fan, E.; Li, L.; Wang, Z.; Lin, J.; Huang, Y.; Yao, Y.; Chen, R.; Wu, F. Sustainable recycling technology for Li-ion batteries and beyond: Challenges and future prospects. *Chem. Rev.* 2020, 120, 7020–7063. [CrossRef] [PubMed]

35. Burnham, M.; Wang, Y. Development and Applications of GREET 2.7—The Transportation Vehicle-Cycle Model; USA Energy Systems Division, Argonne National Laboratory: Argonne, IL, USA, 2006.

36. Liu, Y.T.; Qiao, J.; Xu, H.B.; Liu, J.H.; Chen, Y.S. Optimal vehicle size and driving condition for extended-range electric vehicles in China: A life cycle perspective. *PLoS ONE* 2020, 15, e0241967. [CrossRef]

37. Li, Y.M.; Ha, N.N.; Li, T.T. Research on carbon emissions of electric vehicles throughout the life cycle assessment taking into vehicle weight and grid mix composition. *Energies* 2012, 5, 3612. [CrossRef]

38. Halabi, E.E.; Third, M.; Doolan, M. Machine-based dismantling of end of life vehicles: A life cycle perspective. *Procedia CIRP* 2015, 29, 651–655. [CrossRef]

39. Chen, Y.S.; Hu, X.; Liu, J.H. Life cycle assessment of fuel cell vehicles considering the detailed vehicle components: Comparison and scenario analysis in China based on different hydrogen production schemes. *Energies* 2019, 12, 3031. [CrossRef]

40. Chen, Y.S.; Ding, Z.S.; Wang, W.J.; Liu, J.H. Life-cycle assessment and scenario simulation of four hydrogen production schemes for hydrogen fuel cell vehicles. *China J. Highw. Transp.* 2019, 32, 172–180.

41. Li, S.H. Life Cycle Assessment and Environmental Benefits Analysis of Electric Vehicles. Ph.D. Thesis, Jilin University, Changchun, China, 2014. (In Chinese)

42. Wang, Q. Comparative Analysis of Cathode Materials Based on Life Cycle Assessment. Ph.D. Dissertation, South China University of Technology, Guangzhou, China, 2012. (In Chinese)

43. Ma, J.Q. Life cycle Assessment on a Specific BEV with Different Power-Batteries. Ph.D. Thesis, Chang’ an University, Xi’an, China, 2019. (In Chinese)

44. Xiong, X.Q. Key Technology Analysis and Production Evaluation of Intelligent Connected Vehicle from the Perspective of Patent. Ph.D. Thesis, Hunan University, Changsha, China, 2020. (In Chinese)
45. Sullivan, A.; Burnham, M. *Energy-Consumption and Carbon-Emission Analysis of Vehicle and Component Manufacturing*; USA Argonne National Laboratory: Argonne, IL, USA, 2010.

46. Safari, F.; Dincer, I. Assessment and optimization of an integrated wind power system for hydrogen and methane production. *Energy Convers. Manag.* **2018**, *177*, 693–703. [CrossRef]

47. Society of Automotive Engineers (SAE-China). *Technology Roadmap for Energy Saving and New Energy Vehicles 2.0*; China Machine Press: Beijing, China, 2020. (In Chinese)

48. Power Planning and Design Institute. *China Power Development Report 2020, China*; Power Planning and Design Institute: Beijing, China, 2021. (In Chinese)

49. Wang, Q.; Xue, M.; Lin, B.; Lei, Z.; Zhang, Z. Well-to-wheel analysis of energy consumption, greenhouse gas and air pollutants emissions of hydrogen fuel cell vehicle in China. *J. Clean. Prod.* **2020**, *275*, 123061. [CrossRef]

50. Mamkhezri, J.; Malczynski, L.A.; Chermak, J.M. Assessing the economic and environmental impacts of alternative renewable portfolio standards: Winners and losers. *Energies* **2021**, *14*, 3319. [CrossRef]

51. Shahzad, M.W.; Burhan, M.; Ang, L.; Ng, K.C. Energy-water-environment nexus underpinning future desalination sustainability. *Desalination* **2017**, *413*, 52–64. [CrossRef]