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# Life cycle assessment and carbon reduction potential prediction of electric vehicles batteries

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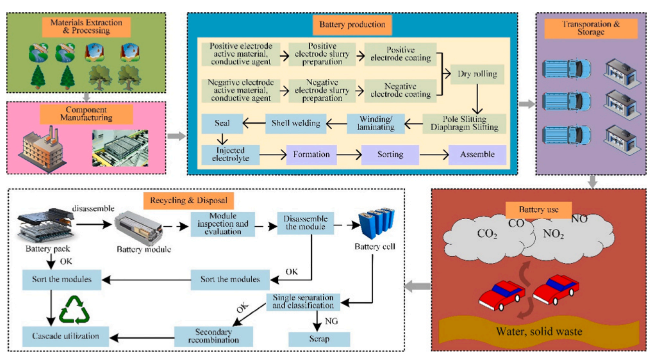
## HIGHLIGHTS

- Establish a life cycle assessment framework for EVs batteries.
- Calculate the energy consumption and emissions of EVs batteries in each life cycle phase.
- Analyze the results of energy consumption and environmental impact of EVs batteries.
- Discuss the carbon reduction potential of different recycling methods.
- Give a prediction of the carbon emission of EVs batteries in the future electricity mix.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Electric vehicles (EVs) battery is a crucial component of energy storage components for electric vehicles. However, the environmental impact of EVs battery is still not clear. Therefore, this paper establishes a cradle-to-cradle life cycle assessment (LCA) frame and clarifies the environmental impacts on the entire lifespan of EVs battery in China. Specifically, the environmental impact of battery production, battery use, and recycling & disposal stages are analyzed and measured. In addition, the carbon reduction potential of recycling and secondary use under a future electricity mix is estimated. Results show that: (1) The production stage of EVs battery with the carbon emission of 105 kgCO2-eq/kWh, which has the most significant impact on the environment. (2) In the recycling process, cascade utilization can reduce 1.536 kgCO2-eq/kWh carbon emission. In terms of recycling methods, hydrometallurgy can reduce the most carbon emission (13.3 kgCO2-eq/kWh), followed by the combined hydro-pyrometallurgical process (8.11 kgCO2-eq/kWh) and pyrometallurgy (0.57 kgCO2-eq/kWh). (3) Under the estimated electricity mix in 2030, 2040, and 2050, the carbon emission in battery production can be approximately reduced by 31.9 %, 45 %, and 48.1 %, respectively.

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## 1. Introduction

The goal of "carbon peaking and carbon neutrality" accelerates the transformation of the global energy structure (Guo and Fang, 2023; Wei et al., 2021). The layout of the EVs is one of the most important links (Wang et al., 2023). Electric vehicles (EVs) batteries are one of the most critical components of EVs. It is generally believed that EVs battery is more environmentally friendly than traditional petrochemical energy (Koroma et al., 2022; Kim et al., 2016). Although the pollution of EVs battery themselves is not severe, the metallic materials they contain will cause a certain degree of environmental damage during the mining and extraction smelting process (Zha et al., 2023). Take lithium metal as an example, its industrial production method mainly includes molten salt electrolysis and vacuum thermal reduction method (Lin et al., 2023). The molten salt electrolysis method uses lithium chloride as raw material, and the production process will precipitate chlorine gas at the anode, which will cause severe pollution to the environment (Naveenkumar et al., 2023). Transitioning to electrification will influence energy use, emissions, and resource consumption (Ouedraogo, 2023; Wu et al., 2021a; Wu et al., 2021b). The sustainable development of EVs battery should be assessed throughout their whole life cycle. Consequently, a large number of studies have evaluated the environment-economics-resource character of EVs battery (Cao et al., 2023; Luo et al., 2023; Wu and Zhang, 2023).

To evaluate the environmental impact of the EVs battery, resource acquisition should be considered at first (Wu et al., 2020a, 2020b; Zhang et al., 2022). To the best of our knowledge, critical metal resources, such as lithium, cobalt, and nickel distributed unevenly (Zhang et al., 2023a). Approximately 70 % of cobalt extraction takes place in the Democratic Republic of Congo, while Argentina, Bolivia, and Chile collectively account for 67 % of lithium distribution (Mohr et al., 2020). On the one hand, EVs battery is at risk of resource shortages and supply chain disruptions (Sun et al., 2020). On the other hand, massive resources and energy will be consumed in the extraction and processing of lithium (Cao et al., 2023). Moreover, production and transportation also produce a huge impact on the environment (Wu et al., 2022a). Finally, the disposal of retired power batteries also dramatically influences the environmental impact of EVs battery. Waste EVs battery contain a large amount of harmful substances such as electrolytes and heavy metals. If not handled properly, such as burying them in the soil, it will bring a potentially great threat to the natural environment and human health (Wu et al., 2020a, 2020b). In addition, some scarce metals can be recycled, which provides sustainable raw materials for battery production (Luo et al., 2023; Rana et al., 2023). If nickel-containing batteries can be fully recycled, they can meet one-third of the demand for new energy vehicle power batteries (Du et al., 2022).

Due to increasing resource demand and decreasing stock, recycling and reuse of EVs batteries have become a constant subject (Zhang et al., 2023b). It is predicted that the production of EVs battery will reach 1211 GWh by the year 2025 (Cao et al., 2022). Generally, the lifespan of EVs battery is 5–8 years, they will be retired when the capacity decays to 70 %–80 % (Ciez and Whitacre, 2019). It is predicted that the retired EVs battery battery will reach 7.05 million tons by 2030. If retired EVs battery cannot be disposed of properly, it will be a waste of resources and a heavy environmental burden (Lai et al., 2022; Jiang et al., 2021). The growing demand for power batteries has resulted in environmental impacts that run through the entire life cycle, from raw material mining and smelting to production, transportation, use, and disposal (Mohamed et al., 2023). At the same time, the environmental impact is complex and multifaceted, including the consumption of fossil energy, the consumption of mineral resources, greenhouse gas emissions, acid rain, and eutrophication substances (Gao et al., 2023). Therefore, considering the development of EVs battery from an overall and long-term perspective, efforts must be made to improve production efficiency, save energy and resources, reduce pollutant emissions, and improve their environmental performance throughout their life cycle. Therefore, this paper establishes an LCA frame to explore the potential carbon footprint of EVs batteries from raw material acquisition to final recycling and disposal. Based on the results, the carbon reduction potential of different recycling scenarios is estimated.

The remainder of the paper is organized as follows: Section 2 reviews and compares the previous literature; Section 3 clarifies the research goals and establishes the research frame. Section 4 obtains and analyzes the results. Section 5 summarizes the conclusions and puts forward policy suggestions.

## 2. Literature review

Already studies examined the environmental impacts of EVs batteries from different perspectives. As shown in Fig. 1, increasing studies pay attention to the EVs batteries. A majority of the research has concentrated on the evaluation of the life cycle of EVs batteries.

The life cycle assessment mainly concentrates on the energy, resource, and environmental impacts. Focus on the production processes, Troy et al. (2016) explored the environmental impacts of the manufacturing processes of a new all-solid-state battery concept in a pouch bag housing and pointed out that the research and development stage consumes more energy than the technology maturity stage. Under the European Union's new battery regulation, only power batteries with a declared carbon footprint will be allowed on the European market from July 1, 2024. More research has started to pay attention to the carbon footprint of EV batteries. Chen et al. (2022) studied the carbon footprint of lithium-ion batteries using a cradle-to-cradle life-cycle assessment approach. They argued that the carbon emission of battery remanufacturing through recycled materials is 51.8 % lower than that of battery production with raw materials. In addition, Liang et al. (2017) compared the carbon emission of nickel metal hydride batteries, solar cells, and lithium-ion secondary batteries. The results show that lithium-ion battery is the most environmentally friendliness.

Due to the increasing categories of EV batteries, environmental impacts comparison of different types of EV batteries is also popular. Zackrisson et al. (2016) explored the environmental impacts of lithium-air batteries and suggested recycling the battery environmentally benignly. Arvidsson et al. (2018) aim to identify the energy use and climate change of a lithium/sulfur (Li/S) battery. According to the results, they proposed suggestions to reduce energy use and climate change impact. In terms of flow batteries, Dieterle et al. (2022) conducted a life cycle assessment and explored their environmental footprint. Due to constant innovation, new types of EVs batteries are emerging. Focusing on a novel Li-ion battery type, Raugei and Winfield (2019) conduct a life cycle assessment of lithium cobalt phosphate batteries. Jiang et al. (2022) assessed the environmental impacts of lithium-ion traction batteries, which are recycled by hydrometallurgical method.

Ellingsen et al. (2014) found that complete traction battery inventories in most studies are based on secondary data and do not converge to a consistent conclusion regarding the impacts on traction batteries. Therefore, they compile data based mainly on the primary. To ensure the reliability of the datasets, Erakca et al. (2023) examined the environmental impact of lithium-ion battery cell production using lab-scale data. Jiang et al. (2020) emphasized the importance of upstream process raw data in life cycle assessment. The results of these studies also vary. Liang et al. (2017) argued that the lithium-ion batteries' carbon dioxide equivalence of the assembly process for raw materials is 12.7 kg CO2eq. Chordia et al. (2021) indicated that the carbon emission of Li-ion batteries is closely related to the energy structure. Although plenty of studies have been conducted to evaluate the environmental impacts of EVs batteries from different perspectives. However, the recycling phase gets little concern. With the continuous improvement of secondary-use technology, the environmental impact of this process needs to be further upgraded.

Based on the existing literature, the contributions of this paper are:

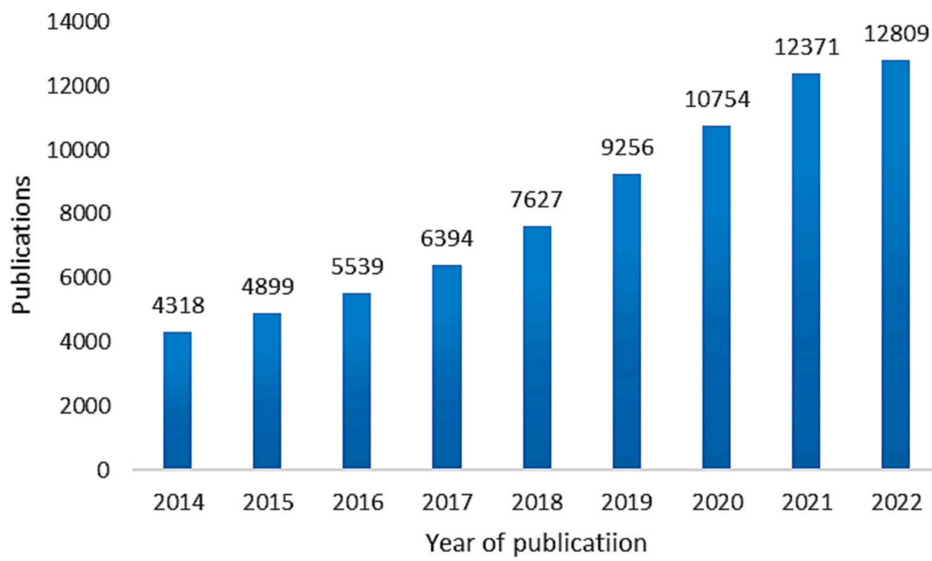


**Fig. 1.** Number of studies in recent years.

(1) Establish a life cycle assessment framework for EVs batteries. (2) Calculate the energy consumption and emissions of EVs batteries in each life cycle phase. (3) Analyze and evaluate the results of energy consumption and environmental impact of EVs batteries, and make corresponding interpretations. (4) Discuss the carbon reduction potential of different recycling methods. (5) Give a prediction of the carbon emission of EVs batteries in the future electricity mix.

## 3. Method and materials

The purpose of LCA can be traced back to the 1970s. The Society of Environmental Toxicology and Chemistry first defined LCA as a method of assessing the environmental impact of a product potential environmental impacts through material use, energy consumption, and waste emissions (Arshad et al., 2022). As shown in Fig. 2, International Standard Organization (ISO) formulated ISO 14000 standard and defines LCA as the resource utilization, human health, and ecological impacts of a product's whole life, including raw material acquisition, production, use, and disposal, which provides principles and framework (Li et al., 2023). Based on ISO 14000, ISO 14044 further supplements the "requirements and guidelines" outline (Rinne et al., 2021). Generally speaking, ISO 14000 provides a reference for administrators, while ISO 14044 is for the practitioner (Shi et al., 2023). In practice, LCA is widely used to evaluate the potential environmental impacts of a product's whole life by compiling and assessing its inputs and output (Feng et al., 2022).

The whole lifecycle of an EVs batteries consists of raw material acquisition, production and processing, transportation and use recycling, and final disposal (as shown in Fig. 3). Without loss of generality, the LCA methodological framework of this study is divided into four phases according to ISO 14,040 and ISO 14,044: goal and scope definition, life cycle inventory generation, life cycle impact assessment; and interpretation.

### 3.1. Goal and scope definition

This paper aims to establish a comprehensive whole life frame and clarify the environmental impacts of EVs batteries. The recycling and secondary use phase is studied as a critical research object. The findings of this research can provide a valuable reference for the recycling and disposal of retired batteries. In this paper, the environmental impacts of the NCM811 battery from cradle to cradle are constructed using the SimaPro, and the carbon emission and its distribution at each stage are estimated and discussed. As shown in Table 1, the components of EVs batteries mainly include cathode active materials, anode active materials, separators, electrolytes, aluminum foil, copper foil, and aluminum shell. Data on these components come from laboratory disassembly tests referring to Chen et al. (2022) and Gu et al. (2021). Each 1 kWh battery contains 0.599 kg of cathode active materials, which accounts for 34.43 % of the total ingredients. Similarly, anode-active materials weight 0.385 kg account for 22.13 %. Separator weights of 0.030 kg (2.87 %), aluminum foil weights of 0.058 kg (3.33 %), copper foil weights of 0.129 kg (7.41 %), and aluminum shell weights of 0.127 kg (7.30 %). In particular, electrolyte contains three kinds of materials, which are lithium hexafluorophosphate ($LiPF_6$), ethylene carbonate (EC), and ethyl methyl carbonate (EMC). $LiPF_6$ weights 0.057 kg (3.28 %), and EC and EMC weights 0.267 kg (15.34 %).

The whole process from cradle to cradle includes the raw materials extraction and processing, the component manufacture of the battery, battery production, the battery use phase, and the recycling and disposal of the battery. The core of the LCA is to count the material and energy input of each phase and calculate the direct and indirect emissions of each stage. Generally, direct emissions refer to the emissions caused by material and energy consumption in each phase, and indirect emissions

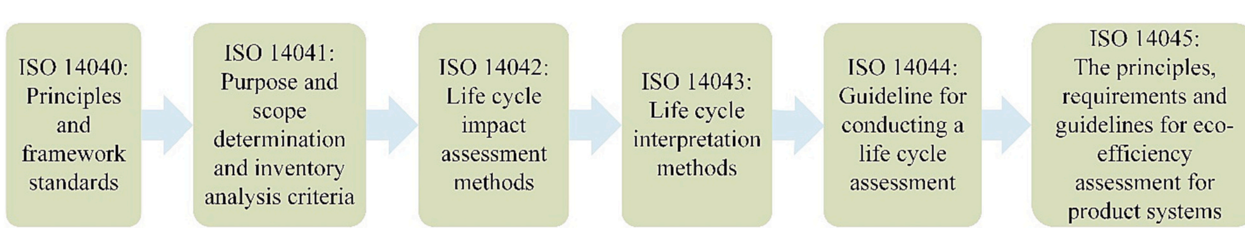


**Fig. 2.** ISO series of LCA standards.

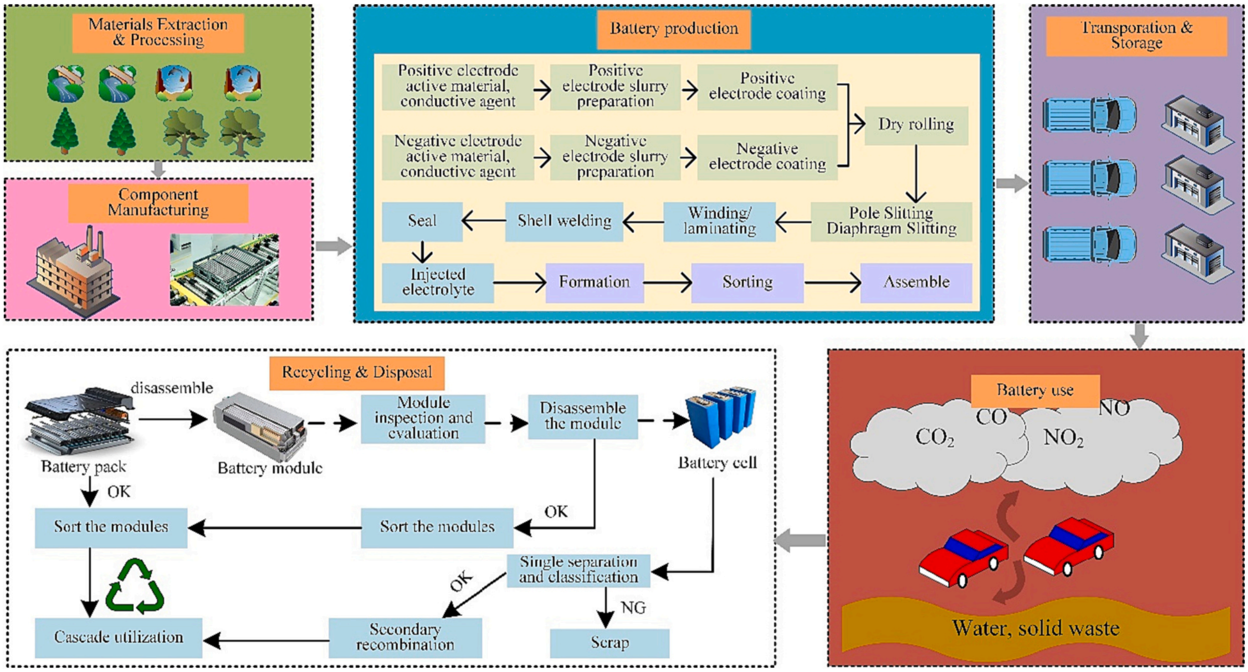


**Fig. 3.** LCA roadmap for the entire life cycle of EVs batteries.

**Table 1**
Input parameters of the NCM811 battery configuration.

| | Weight (KG) | Proportion | | Weight | Proportion |
|---|---|---|---|---|---|
| Cathode active materials | 0.599 | 34.43 % | Aluminum foil | 0.058 | 3.33 % |
| Anode active materials | 0.385 | 22.13 % | Copper foil | 0.129 | 7.41 % |
| Separator | 0.030 | 2.87 % | Aluminum shell | 0.127 | 7.30 % |
| Electrolyte: LiPF6 | 0.057 | 3.28 % | Others | 0.068 | 3.91 % |
| Electrolyte: EC (30 %), EMC (70 %) | 0.267 | 15.34 % | | | |

refer to emissions caused by traceable energy and raw materials (Wu et al., 2022b).

Before conducting the research, the research object and phases need to be defined. There are various battery categories in the market which have a difference in the environmental impact analysis. The cathode materials in the power battery market mainly include lithium iron phosphate, lithium manganese acid, and ternary cathode materials (nickel cobalt lithium manganate NCM or nickel cobalt lithium aluminate NCA). The ternary cathode material is the primary cathode material of lithium-ion batteries, which accounts for nearly 38 % of the total market. Brands such as Tesla and Chery Automobile have chosen to use ternary lithium batteries in the power batteries of new energy vehicles. Therefore, we selected NCM 811 battery as the study object because of its wide application in EVs. NCM 811 battery refers to a lithium-ion battery that uses Ni—Co manganate as anode material. In this study, a battery pack with a capacity of 74 kWh in an EV with a service life of 8 years and an overall driving range of 120,000 km is taken as the research object during the battery use phase. The system boundary studied is shown in Fig. 4. From the acquisition of raw materials for NCM battery production, the production of battery cells, the production of battery systems to the use of new energy vehicles, and the disposal of batteries using different recycling technologies, it includes the entire closed-loop process of the life cycle from production to use to recycling. Each stage will be introduced and analyzed in detail below.

## 3.2. Inventory analysis

Life cycle inventory (LCI) analysis is crucial for generating input and output flow lists for a product system. These flows encompass water, energy, and raw material inputs, as well as product outputs and emissions to the air, land, and water. LCI serves as the data collection component of Life Cycle Assessment (LCA), where data can be gathered through experiments, industry research, literature, and other methods. Additionally, LCI databases can be used to supplement and refine background data on upstream materials.

### 3.2.1. Raw material extraction and processing

The raw material of NCM battery includes lithium, cobalt, nickel, graphite, manganese, etc. Firstly, obtaining these materials requires experience in exploration, extraction, mineral processing, and other steps. Lithium mainly comes from lithium ore or extracted from lithium resources such as seawater and salt lakes. And high-purity lithium materials suitable for manufacturing NCM batteries can only be obtained through multiple refining and purification processes. Nickel mainly comes from nickel ore. After the raw materials are received, smelting, purification, or refining steps are carried out. The intermediate material of lithium is mainly lithium hydroxide or lithium carbonate, and the primary, intermediate material of nickel is nickel sulfide. In the above process, mineral mining, transportation, raw material smelting, and purification are complex and energy-consuming processes and the main contributors to production-related carbon emissions. Previous literature has estimated the carbon emission of NCM batteries in the battery material extraction process, and the results are listed in Fig. 5. As shown in Fig. 5, a significant difference exists. Therefore, collecting reliable battery raw material extraction and processing data directly determines the accuracy of calculation results.

### 3.2.2. Inventory of battery production phase

The cathode material of NCM811 battery is nickel cobalt lithium manganese oxide, which is a mixture of nickel, cobalt, and manganese in a ratio of 8:1:1. The main component of NCM811 battery consists of ternary cathode material production, anode material production,

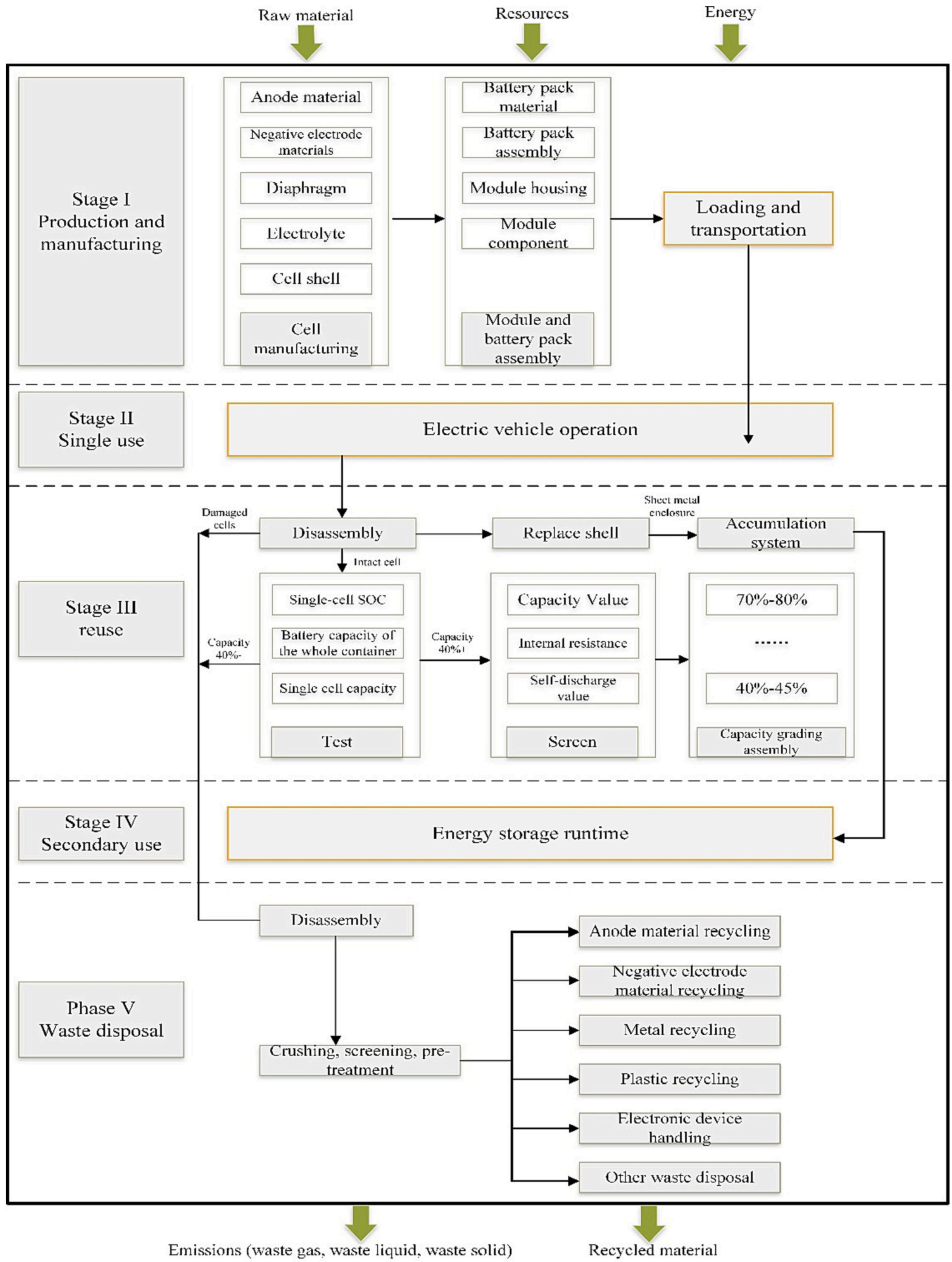


**Fig. 4.** The system boundary of the battery in the entire life cycle.

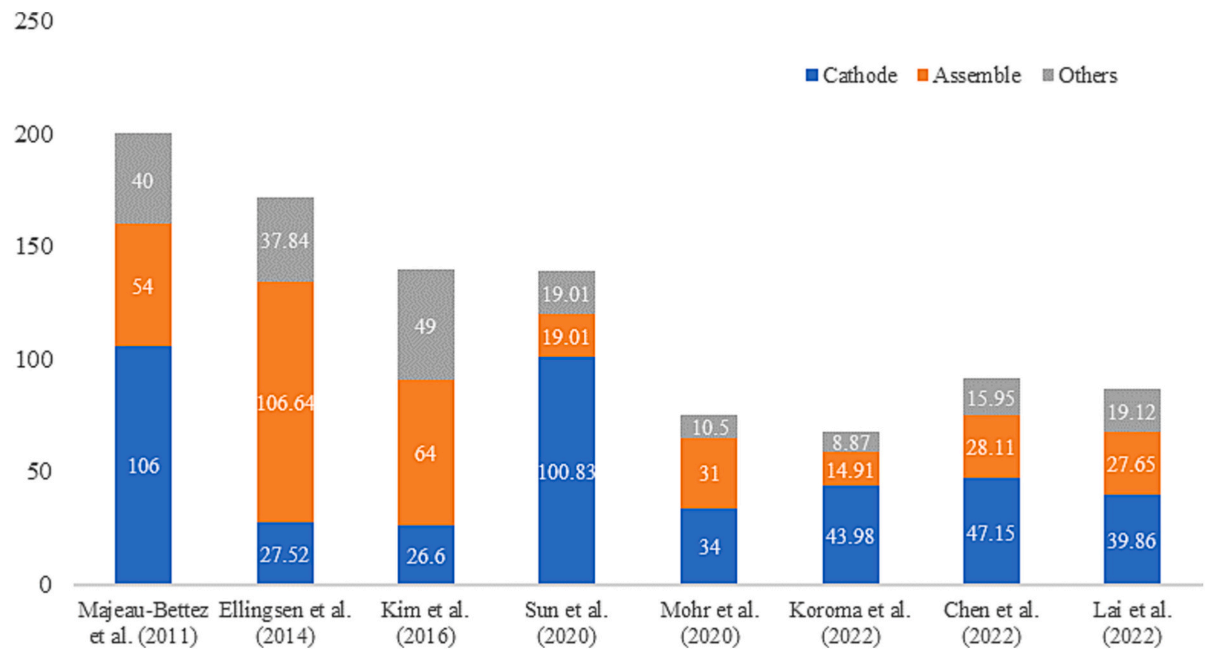


**Fig. 5.** Comparison of carbon emission in raw material extraction and processing phase (kg$CO_2$-eq/ kWh).

electrolyte production, diaphragm production, copper foil production, aluminum foil production, shell production, and cell production. The cathode material is lithium nickel-cobalt manganate, which is obtained from nickel-cobalt-manganese (NCM) ternary precursor and lithium carbonate through procedures such as sintering, crushing, spray coating, drying, screening, and demagnetization. The ternary precursor is obtained by mixing manganese sulfate solution, nickel sulfate solution, and cobalt sulfate solution in a certain proportion to obtain a mixed solution, adding liquid caustic soda and ammonia water for aging reaction, and then obtaining it after filtering, washing, drying, screening, and iron removal. Manganese sulfate is produced from manganese dioxide, nickel sulfate is produced from laterite nickel ore, and cobalt sulfate is produced from cobalt ore. Lithium carbonate is produced from lithium pyroxene concentrate by roasting transformation, acid roasting, slurry leaching, purification, evaporation and concentration, lithium precipitation, slurry conditioning, churning, drying, and micro-powder.

Graphite is used as the cath electrode material. The raw materials for production are mainly natural graphite and pitch. After the two are mixed, the surface is modified by heating, fused, stirred, screened twice, demagnetized twice, and finally packaged as a finished harmful electrode material. The electrolyte is made from a variety of carbonate esters and lithium hexafluorophosphate blending, specifically using vinyl carbonate, methyl carbonate, dimethyl carbonate, diethyl carbonate, etc., for mixing and dehydration, and then adding lithium hexafluorophosphate, etc. blending, and filtering to produce. Ethylene carbonate is produced by the synthesis of ethylene oxide and carbon dioxide. Methyl carbonate is produced by the ester exchange method, in which dimethyl carbonate is exchanged with ethanol for an ester group. In contrast, products such as diethyl carbonate can be co-produced. Lithium hexafluorophosphate is synthesized by reacting phosphorus pentachloride and hydrogen fluoride to generate phosphorus pentafluoride and then reacting with lithium fluoride to generate lithium hexafluorophosphate, which is synthesized by low-temperature crystallization and drying. The shell of the lithium battery includes the shell of the battery unit and the shell of the battery system. Generally, the aluminum shell is used, which is formed by one-time stretching and then cleaned and dried.

The diaphragm uses polyethylene and polypropylene as the base film and uses water-based acrylic emulsion as the carrier to disperse aluminum oxide particles to make a ceramic slurry. The base film is coated after gluing, premixing, dispersion, defoaming, mixing, Filtration, coating, drying, and other processes in the system. The copper foil used to produce negative electrodes is made of copper through electrolyte preparation, raw foil manufacturing, surface treatment, cutting, and packaging. The aluminum foil used in the production of the positive electrode is made of electrolytic aluminum, etc., through batching, melting, refining, casting, rolling, coiling, etc., and is first made into a cast-rolled coil and then made into an aluminum foil billet through cold rolling, intermediate annealing, etc., and finally rough-rolled, intermediate-rolled, coiling, finishing rolling, slitting, and annealing of the finished product to obtain the finished aluminum foil. The production of battery cells includes the steps of positive electrode sheet production, harmful electrode sheet production, crimping, welding, electrolyte injection, pre-charging, and sealing.

### 3.2.3. Battery use

Because of the difference in battery run scenarios and the complexity of technical indicators such as performance and life, the battery use phase is not considered in most studies. However, the battery use phase occupies most of the battery's life cycle, which is a crucial carbon emission source and should not be ignored. Therefore, carbon emission in the battery use phase is considered. Referring to Ellingsen et al. (2017), the energy consumption of lithium batteries in the use stage mainly includes two parts. One is the additional energy required to carry the weight of the battery during EVs driving $E_c$. The second is the power loss caused by the power battery itself being unable to achieve 100 % conversion during the charging and discharging process $E_l$. The calculation of $E_c$ and $E_l$ can be expressed as Eqs. (1) and (2) (Feng et al., 2022; Cong et al., 2023).

$$E_c = 30\% \times \frac{M_b}{M_v} \times D_b \times \frac{E_b}{\varphi} \tag{1}$$

$$E_l = D_b \times E_b \times (1 - \varphi) \tag{2}$$

Where 30 % represents the 30 % of EV's energy consumption related to its weight. $M_b$ indicates the weight of the battery system (Kg). $M_v$ denotes the total weight of EVs (Kg). $D_b$ expresses the total EVs mileage during the battery life cycle (Km). $E_b$ refers to power consumption per unit distance traveled of EVs (kWh/km). $\varphi$ signify the charge and discharge efficiency of the battery (%).

In this phase, the carbon emission results have a degree of uncertainty. Firstly, carbon emission is related to power consumption, which is indirectly related to energy structure. With the continuous development of renewable, the carbon emission in the battery use stage will also change. In addition, energy structure also varies among countries. Therefore, the results are also different. Secondly, emerging technology can also affect the electric power consumption per unit distance traveled by EVs by influencing the carbon in power electric power production and EVs running.

### 3.2.4. Impact assessment of battery recycling phase

As shown in Fig. 6, the recycling phases include the whole process of recycling decommissioned batteries to reuse and final disposal. The specific links include collection, transportation, disassembly, testing, pretreatment, crushing and sorting, electrode powder separation, plastic granulation, metal recycling, safe disposal of electrolytes, battery reorganization, and cascade utilization process. In this section, the paper will discuss carbon emission and carbon reduction potential in detail.

Firstly, EVs battery manufacturers entrust EVs manufacturers and professional third-party recyclers to collect retired batteries from the consumer. All the retired EVs batteries will be collective transfer to comprehensive utilization enterprises. In the dismantling stage, residual energy detection, charging and discharging, preliminary dismantling, re-dismantling of battery modules, detection and sorting, and battery cell sorting and performance evaluation are performed on retired lithium batteries. The power battery cells that meet the reorganization conditions are cascade utilized in the energy storage field through battery online, battery assembly and bundling, assembly and welding, module testing, battery pack assembly, battery pack testing, and battery pack case sealing. EVs battery that does not meet the recombination requirements are reused.

Secondly, EVs battery whose capacity is reduced to less than 80 % and cannot be applied to new energy vehicles will be used in cascade utilization. These retired EVs batteries can be used in energy storage, communication base stations, solar energy, and low-speed electric vehicles. When the usable capacity decays to 20 %–60 %, professional manufacturers will recycle and dismantle them into single cells and reassemble them in series and parallel combinations. The reassembled battery is mainly used on the user side/microgrid. If the usable capacity decays below 20 %, the battery can already be scrapped, and only some internal parts and rare chemical components of the battery need to be refined and recovered to recover metal elements. In the cascade utilization process, battery carbon emissions are closely related to factors such as cascade utilization scenarios, battery status, and secondary utilization life.

Thirdly, the retired EVs battery will be dismantled after cascade utilization. And this process mainly has three steps. (1) As the waste batteries still have some residual power and lithium batteries are easy to heat up and explode after extrusion, it is necessary to discharge the waste batteries deep, followed by crushing and physical sorting. There are two main ways to discharge, one is discharged through resistance, and the second is salt water immersion. (2) Secondary processing by physical separation. (3) Advanced treatment can be divided into hydrometallurgy, pyrometallurgy, and combined hydro-pyrometallurgical processes.

These treatment measures have different recovery processes, recovery products, and energy consumption (Table 2). The hydrometallurgy uses the solution as the medium to perform solvent extraction, chemical deposition, and electrolytic deposition on the target components in the crushed retired battery electrode materials so that they can be recovered in the form of compounds or metals. From the perspective of technology, the hydrometallurgy process is long and complicated, but the recovery efficiency of valuable metals such as lithium, cobalt, and nickel is high. And the investment cost of processing equipment is low, so it is used on a large scale. However, this method has the disadvantages of long process

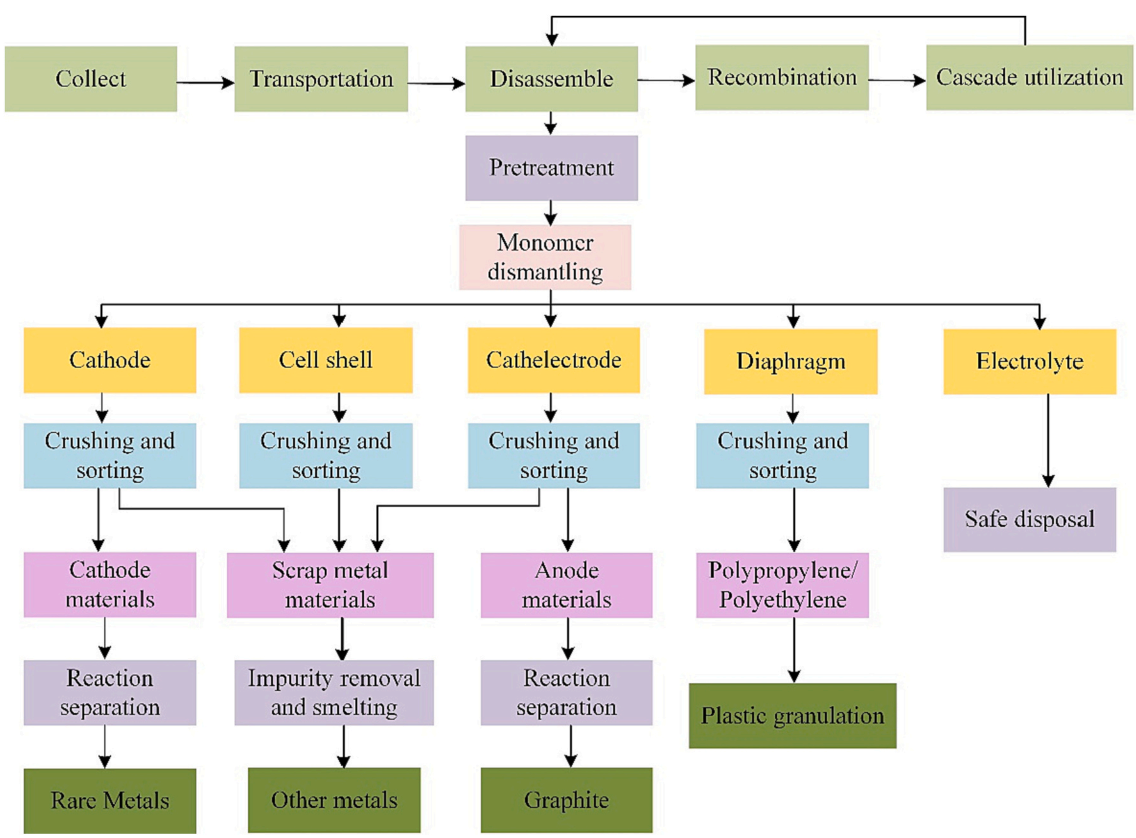


**Fig. 6.** Schematic diagram of the recycling phase.

**Table 2**
Main recycling methods for retired batteries.

| Method | Description | Advantages | Disadvantages |
|---|---|---|---|
| Pyrometallurgy | High-temperature pyrolysis | Simple process | Low recycling rate<br>High energy consumption |
| Hydrometallurgy | Chemical precipitation and solvent extraction | High recycling rate<br>No waste gasses | Complex process<br>High cost |
| Combined hydro-pyrometallurgical process | High-temperature roasting pretreatment and then wet recovery | Low cost | Complicated technology |

flow, high cost, and pollution caused by the extensive use of chemical reagents. Pyrometallurgy only requires simple disassembly and discharge of the used power battery system and pyrolytic smelting directly. In this process, adding slag former and reducing agent, metal alloys such as cobalt, nickel, and copper are obtained by controlling the reaction conditions. In contrast, metal elements such as aluminum and lithium enter the slag. This method has no high requirements on the battery type and is easy to operate. However, the requirements for the reaction conditions are relatively high, and more metal elements are wasted due to entering the slag. In addition, the high-temperature reaction consumes a lot of energy and is prone to produce toxic gases. The combined hydro-pyrometallurgical process prepares the cathode material of a retired power battery by simple pretreatment, disassembly, discharge, high-temperature melting, leaching, oxidation, and sintering. The characteristic of this process is that the product of fire recovery technology is further purified by the wet method, which not only requires fewer reaction objects but also reduces the waste of metal elements.

The carbon emission in the battery recycling phase also exists uncertainty. Firstly, optimizing the recovery network can reduce carbon emissions at the transport stage. Secondly, process improvements can reduce carbon emissions in the recycling phase. Finally, different end disposal methods also have additional carbon emissions.

### 3.3. Data sources

This paper uses SimaPro v9.5 to conduct a life cycle assessment of EVs battery, and the data comes from Ecoinvent3, China Products Carbon Footprint Factors Database (2022), and data published in the literature.

## 4. Results and discussion

### 4.1. Life cycle impact assessment results during battery production

#### 4.1.1. Life cycle impact assessment results

The environmental impacts of EVs battery production process are examined using the SimaPro v9.5. As shown in Table 3, three different LCIA methods are applied to confirm the robustness of the results, which are EDIP 2003 method, CML IA-baseline, and ReCiPe (2016) Midpoint (E) methods. The EDIP 2003, CML IA-baseline, and ReCiPe 2016 methods consider 19, 11, and 18 midpoint impact categories, respectively.

This study is not aiming to be a comparative study of different LCIA methods. It has been recognized that different LCIA methodologies vary considerably and interfere with the final results (Han et al., 2019; Burchart-Korol et al., 2016). Table 3 demonstrates the reliability of the inventory list and models developed in this study. Furthermore, it is important to recognize that the sensitivity of the LCIA method is complex, primarily due to uncertainties in the characterization process and

**Table 3**
Comparison of key impact categories under nominal load based on different LCIA methods.

| Items | Unit | LCA method | | |
|---|---|---|---|---|
| | | EDIP 2003 | CML IA-baseline | ReCiPe 2016 |
| Global warming | kg CO2 eq | 47.5 | 48 | 43.4 |
| Ozone depletion | kg CFC11 eq | 8.08E-7 | 8.08E-7 | |
| Ozone formation (Vegetation) | M2.ppm.h | 281 | – | |
| Ozone formation (Human) | Person. ppm. h | 0.0199 | – | |
| Acidification | $m^2$ | 5.29 | – | |
| Terrestrial eutrophication | $m^2$ | 3.17 | – | |
| Aquatic eutrophication EP(N) | kg N | 0.0149 | – | |
| Aquatic eutrophication EP(P) | kg P | 0.00888 | – | |
| Human toxicity air | person | 3.62 E6 | | |
| Human toxicity water | $m^3$ | 4.91 E3 | | |
| Human toxicity soil | $m^3$ | 7.38 | | |
| Ecotoxicity water chronic | $m^3$ | 1.21 E5 | | |
| Ecotoxicity water acute | $m^3$ | 2.42E4 | | |
| Ecotoxicity soil chronic | $m^3$ | 727 | | |
| Hazardous waste | kg | 0.00162 | | |
| Slags/ashes | kg | 0.0138 | | |
| Bulk waste | kg | 12.7 | | |
| Radioactive waste | kg | 0.000963 | | |
| Resources (all) | PR2004 | 0.0732 | | |
| Abiotic depletion | kg Sb eq | | 0.00277 | |
| Abiotic depletion (fossil fuels) | MJ | | 547 | |
| Human toxicity | kg 1,4-DB eq | | 40.8 | |
| Freshwater equatic ecotox | kg 1,4-DB eq | | 29 | |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | | 6.85E4 | |
| Terrestrial ecotoxicity | kg 1,4-DB eq | | 5.35 | |
| Acidification | kg SO2 eq | | 0.312 | |
| Photochemical oxidatin | kg C2H4 eq | | 0.0135 | |
| Eutrophication | kg PO4 eq | | 0.0555 | |
| Stratospheric ozone depletion | kg CFC11 eq | | | 2.73E-5 |
| Lonizing radiation | kBq Co-60 eq | | | 4.1718 |
| Ozone formation, Human health | kg NOx eq | | | 0.128 |
| Fine particulate matter formation | kg PM2.5 eq | | | 0.0945 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | | | 0.131 |
| Terrestrial acidification | kg SO2 eq | | | 0.256 |
| Freshwater eutrophication | kg P eq | | | 0.0116 |
| Marine eutrophication | kg N eq | | | 0.00238 |
| Freshwater ecotoxicity | kg 1,4-DCB eq | | | 2.24 |
| Marine ecotoxicity | kg 1,4-DCB eq | | | 1.16E-4 |
| Terrestrial ecotoxicity | kg 1,4-DCB eq | | | 401 |
| Human carcinogenic toxicity | kg 1,4-DCB eq | | | 134 |
| Human non-carcinogenic toxicity | kg 1,4-DCB eq | | | 1.04E4 |
| Land use | m2a crop eq | | | 0.872 |
| Mineral resource scarcity | kg Cu eq | | | 3.41 |
| Fossil resource scarcity | kg oil eq | | | 11.9 |
| Water consumption | m3 | | | 3.14 |

inventory list. The EDIP 2003 method utilized in this paper offers a single score indicator that assigns weights to all impact categories following normalization. In contrast, the ReCiPe method analyzes the final potential environmental damages to human health, ecosystems, and resources concurrently. For the sake of simplicity, the LCA analysis in this study opted for the EDIP 2003 method.

The contribution of plant construction, coal mining, transportation, and electricity generation to each impact category after normalization and weighting are presented in Fig. 7. The influence of impact categories on the environment is depicted in descending order. It can be found that the human toxicity water, resources (all), and ecotoxicity water acute account for a significant part of the total influence on the environment. The rest of the categories, including ozone depletion, Slags/ashes, and hazardous waste, are negligible according to the EDIP 2003 method. The present work focuses on evaluating the central environmental impact potentials for EVs battery. The human toxicity potential (HTP), a calculated index that reflects the potential harm of a unit of chemical released into the environment, is based on both the inherent toxicity of a compound and its possible dose, which includes $SO_X$, $NO_X$, CO, and so on. It is the predominant impact which contributes 10.4 % to the total. Cathode production contributes most to the total HIP (89.5 %), followed by aluminum foil production (5.61 %) and anode production (4.05 %). In terms of carbon emission, all these three methods have presented their amount, which is 47.5, 48, and 43.4 kg, respectively. Similarly, the carbon emission was mainly attributed to cathode production, which contributed 61.5 % to the total carbon emission, followed by copper foil production (23.6) and anode production (12.9 %). This is undoubtedly a significant concern in EVs battery's environmental impact assessment. On the one hand, it can be blocked by CO2 capture and storage. Besides, technologies such as green technology innovation can also bring about carbon emission reductions. However, these are not the core issue to be discussed in this paper. Due to the discharge of CO2 mainly depending on the consumption of electricity, the electric power structure influences carbon emission significantly. Therefore, this paper will further explore the carbon reduction potential from the perspective of electric power structures.

The single score of the carbon emission is obtained in the EDIP 2003 method, as shown in Fig. 8. As illustrated in the network of process contributions to the production per 1 kWh EVs battery. It can be seen that the output of the cathode contributes most to the carbon emission. The production of copper foil, anode, and aluminum foil also have significant influences.

### 4.1.2. Comparison with the existing results

To verify the accuracy of calculation results, the carbon emissions of EVs batteries production in this study are compared with those in existing studies, and the results are shown in Fig. 9. It can be observed that the carbon emissions of the production of NCM 811 EVs batteries have significant differences, ranging from 67.76 to 200 $kgCO_2$-eq/kWh. In this study, the carbon emission of the NCM 811 EVs battery during production is 105 $kgCO_2$-eq/kWh. This is because the calculation software, research method, and data source differ. The difference in carbon emissions during battery assembly is mainly due to the difference in power grid structure. The carbon emissions method in the assembly phase in this study comes with the SimaPro v9.5 software. The calculation results of this paper are within a reasonable range, showing high reliability.

## 4.2. Carbon emission results during the battery use phase

To the best of our knowledge, electricity is the only energy used in the usage phase of EVs, which means that the carbon emissions in the usage phase of batteries are mainly connected with the carbon intensity in electricity in China. The carbon emissions in the battery usage stage under different electricity mixes in China are calculated based on eqs. (1) and (2). Before figuring out the carbon emissions, several parameters need to be confirmed. Based on the practical research, the weight of the battery system is 520 kg, the total weight of EVs is 2190 kg, the unlimited EVs mileage during the battery life is 200,000 km, the power consumption per hundred kilometers is 16.7 kWh/100 km, and the charge and discharge efficiency of the battery is 95 %. It can be calculated that the carbon emission during the battery usage phase is 64.2 $kgCO_2$-eq/kWh.

## 4.3. Carbon emission results during the battery recycling process

The LCA of waste batteries recycling and remanufacturing is conducted in this study. Precisely, the carbon emissions of pyrometallurgy, hydrometallurgy, and combined hydro-pyrometallurgical process methods are calculated and compared. As shown in Fig. 10, the carbon

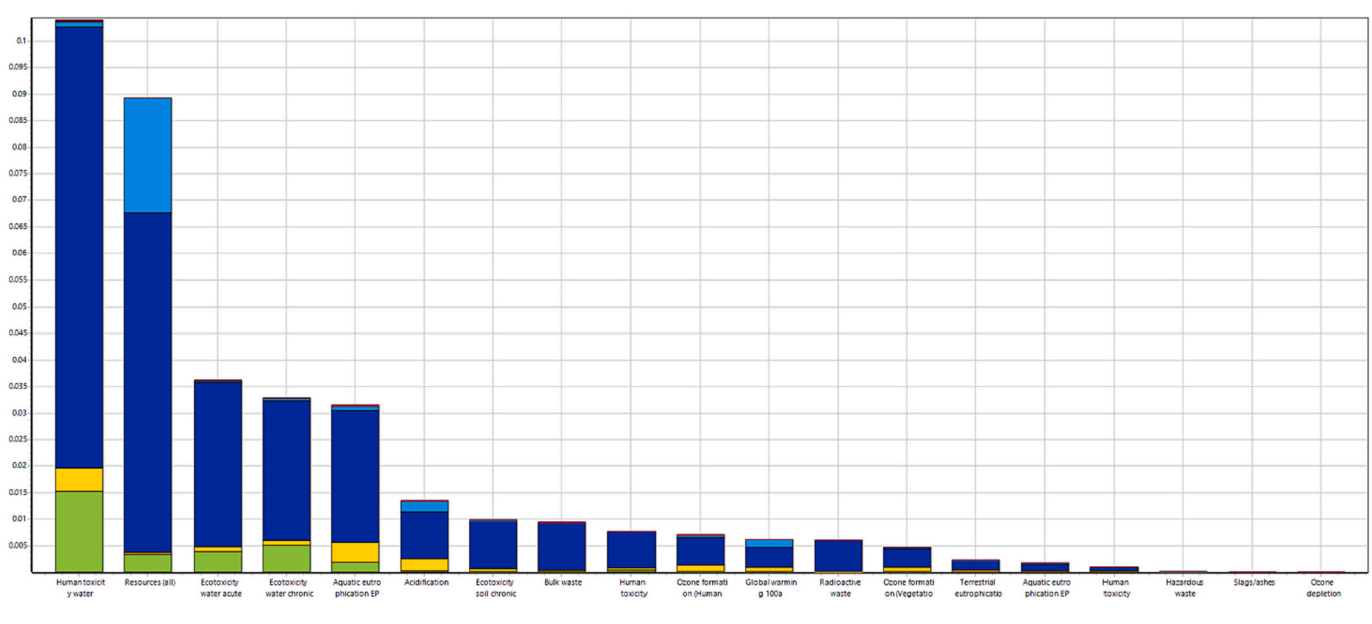


**Fig. 7.** Contributions of different stages to individual weighted EIPs.

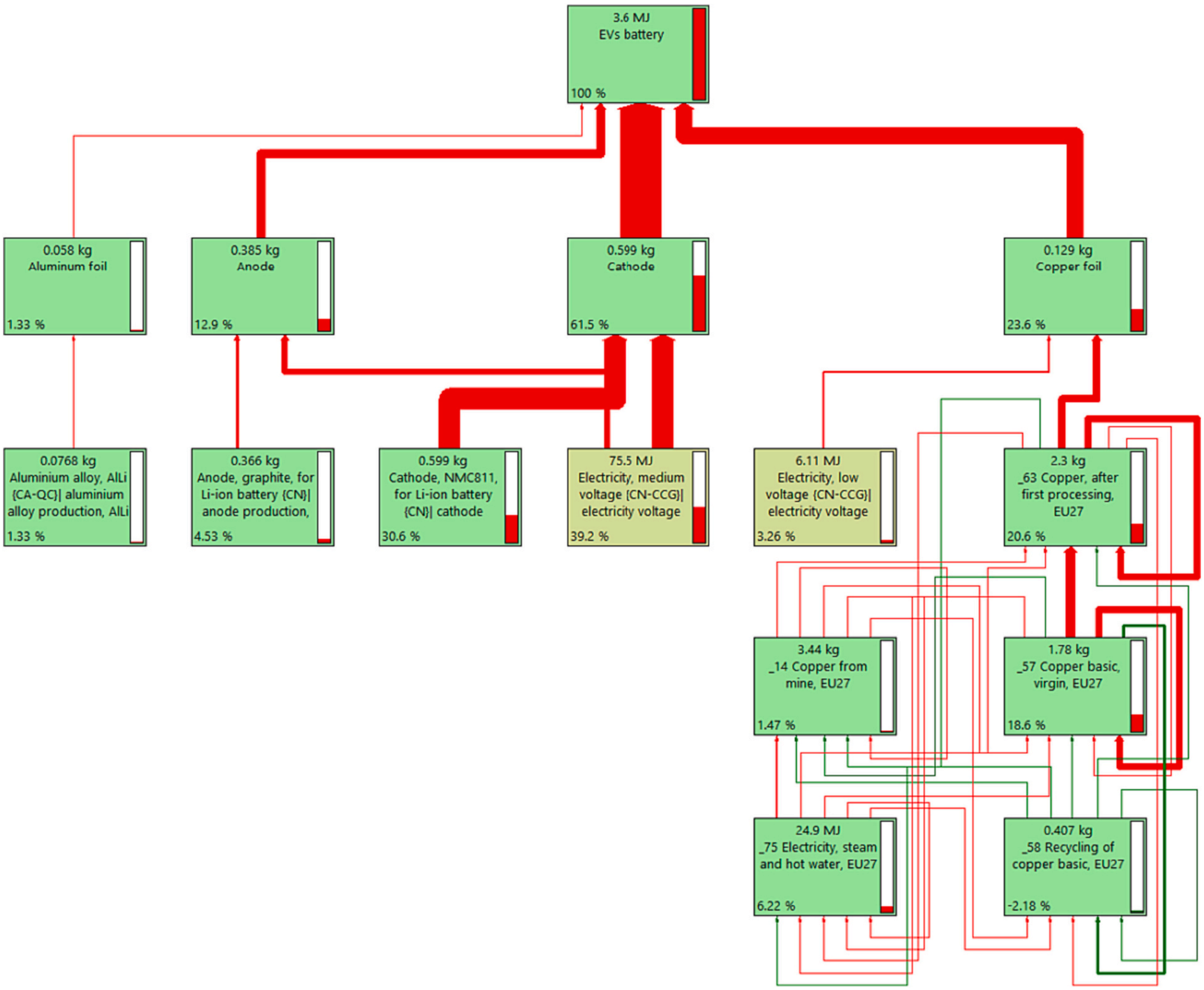


**Fig. 8.** Network of main process contributions to carbon emissions per 1 kWh EVs battery.

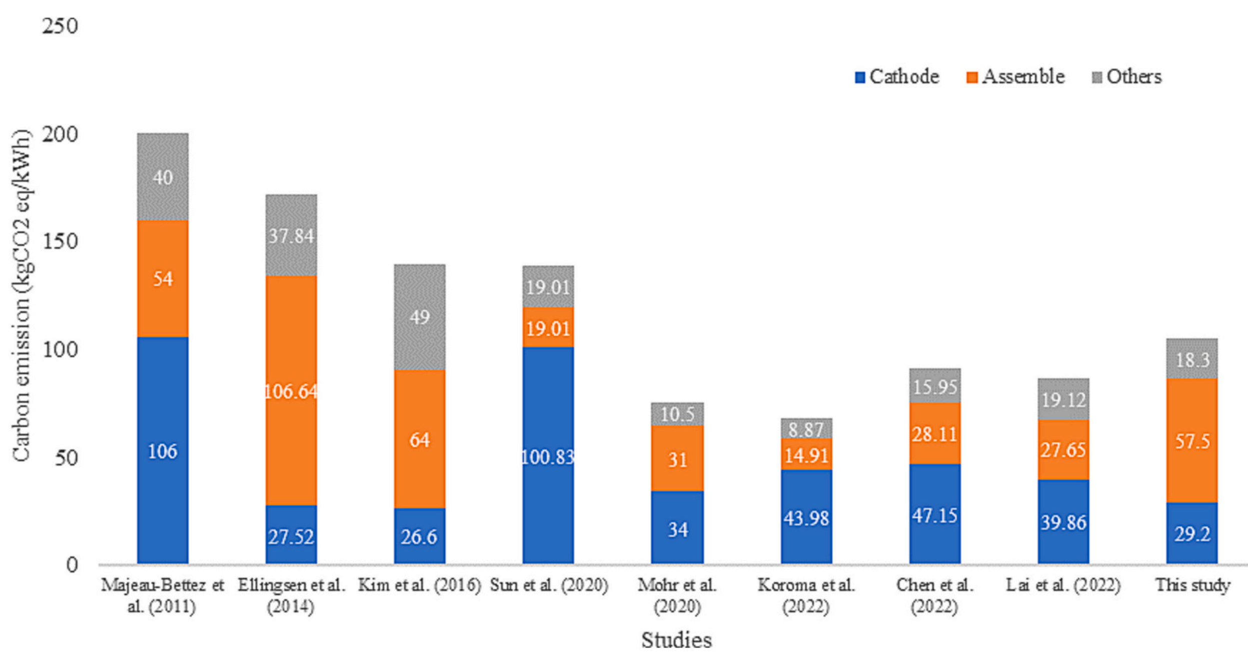


**Fig. 9.** Comparison of the results of this paper with the existing studies (kg$CO_2$-eq/kWh).

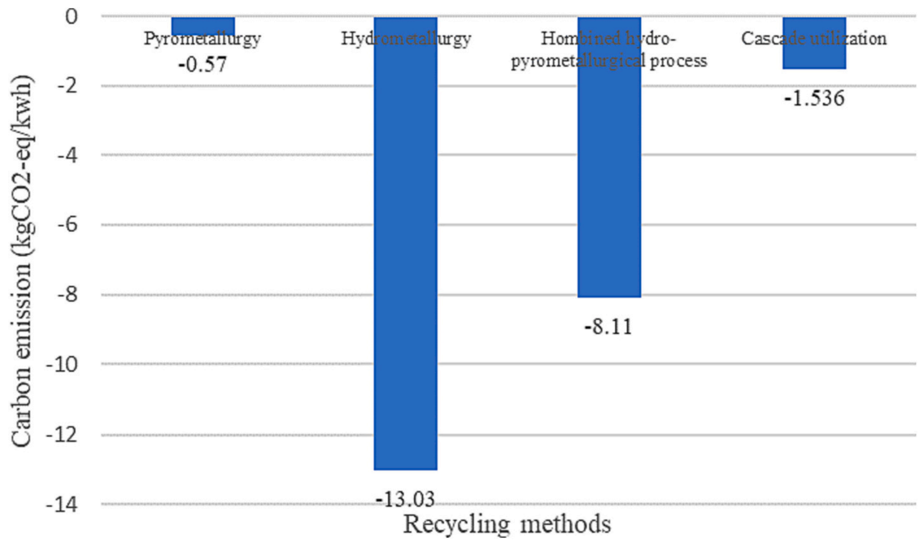


**Fig. 10.** Carbon emissions of batteries recycling and remanufacturing.

reduction of hydrometallurgy is −13.3 $kgCO_2$-eq/kWh, which is the highest carbon reduction among the three recycling methods. Compared with pyrometallurgy, hydrometallurgy carries out multi-step chemical treatment under low-temperature conditions, with high energy consumption and high carbon emission processes, such as high-temperature treatment, and the graphite in anode will not be converted into carbon emission. The final product of hydrometallurgy is cathode materials, which will reduce a great deal of carbon emissions from manufacturing it. Although hydrometallurgy can achieve environmentally friendly recycling, it usually needs to experience 10 major steps, which will generate a considerable number of toxic gases and waste solutions. In contrast, pyrometallurgy has the lowest carbon emission, which is 0.57 $kgCO_2$-eq/kWh. In the process of pyrometallurgical, high-temperature smelting batteries with a temperature of more than 1000°Care usually used. The carbon emission comes from the fossil energy consumed in the metallurgical process, which can produce many direct and indirect carbon emissions. In addition, the cathode cannot be recycled by pyrometallurgy, and the production of the cathode consumes the most carbon emissions. In addition, pyrometallurgy can bring economic value, but the weight is not ideal because only nickel-cobalt powder will be obtained. The carbon emission reduction of the combined hydro-pyrometallurgical process method is 8.11 $kgCO_2$-eq/kWh, which is between pyrometallurgy and hydrometallurgy. In terms of cascade utilization, it can be found that the carbon reduction potential is 1.536 $kgCO_2$-eq/kWh.

### 4.4. Uncertainty analysis

The EVs battery production technology differs worldwide, and battery use and recycling vary. Data quality, such as inaccuracy, missing data, lack of technical and process representation, and lack of geographical indication, will greatly affect the data certainty. To ensure the robustness of the results, this paper performs 10,000 times uncertainty analysis using Monte Carlo simulation in SimaPro v8.5. Regarding the carbon emission factor of products, several factors impact it, including the carbon content of raw materials, technological progress, reaction conditions, and the system boundary. It is generally believed that as cleaner production technology advances and the use of renewable energy increases, the carbon emission factor of products tends to decrease. The authors of the CPCD database have considered these factors, and the carbon emission factors in the database are based on the production and consumption levels in 2020. This paper primarily focuses on analyzing the uncertainty resulting from changes in input parameters, which are derived from the weight of the power battery composition. The weight of the power battery composition follows a normal distribution with a variance of 3 %. By assuming this distribution, the mean and standard deviation of the inputs can be determined for each process.

### 4.5. Sustainability metrics for EVs battery

Firstly, the carbon emission from battery production is affected by various factors, and the electricity consumed is the crucial source of carbon emission, which is greatly affected by the electricity mix. As shown in Table 4, the carbon emission of different types of power varies, and the carbon emission of the battery production phase depends on the electricity mix. Therefore, we will analyze and discuss the potential carbon reduction potential from the perspective of the electricity mix.

As shown in Table 5, the carbon emissions in the battery production stage are examined under different electricity mixes in this section. It

**Table 4**
Electricity carbon emission and electricity mix (Chen et al., 2022).

| Item | | Carbon emission ($kgCO_2$-eq/kWh) | 2021 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|
| Thermal power | | 0.93 | 67 % | 45 % | 32 % | 14 % |
| Hydropower | Large-scale<br>Middle-scale | 0.01357<br>0.0068 | 12.6 % | 10 % | 9 % | 8 % |
| Nuclear power | | 0.0122 | 5 % | 7 % | 8 % | 13 % |
| Photovoltaic power | | | 3.5 % | 8.4 % | 10.5 % | 15.5 % |
| Renewable power | Wind power | 0.02748 | 6 % | 20 % | 23.8 % | 31 % |
| | Biomass power | 0.1255 | 0.2 % | 2.5 % | 3 % | 4 % |
| | Solar energy generation | 0.09 | 4.3 % | 5 % | 7 % | 9 % |
| | Geothermal power | 0.08049 | 0.3 % | 1.5 % | 3.5 % | 4.5 % |
| Garbage power | | 0.92 | 0.2 % | 0.1 % | 0.2 % | 0.25 % |
| Others | | 0.53 | 0.9 % | 0.5 % | 3 % | 0.75 % |
| Average carbon emission | | | 0.636 | 0.433 | 0.330 | 0.155 |

**Table 5**
Carbon reduction potential ($kgCO_2$-eq/kWh).

| Items | | Current | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Battery production | Total | 105 | 71.5 | 54.48 | 25.59 |
| | Cathode | 29.2 | 19.880 | 15.151 | 7.116 |
| | Assembly | 57.5 | 39.147 | 29.835 | 14.013 |
| | Others | 18.3 | 12.459 | 9.495 | 4.460 |
| Battery use | | 64.2 | 43.71 | 33.31 | 15.65 |
| Battery recycling | Cascade utilization | −1.536 | −1.0457 | −0.7970 | −0.3743 |
| | Pyrometallurgy | −0.57 | −0.388 | −0.2957 | −0.1389 |
| | Hydrometallurgy | −13.03 | −8.871 | −6.76 | −3.176 |
| | Combined hydro-pyrometallurgical process | −1.536 | −1.046 | −0.797 | −0.374 |

can be observed that the carbon emission of battery manufacturing under electricity in 2030 will be 71.5 kgCO2-eq/kWh, which is 31.9 % lower than in 2021. The reason for the reduction is that thermal power will decrease to 45 % in 2030, which is the largest carbon emission source. And the proportion of renewable energy will increase, leading to carbon emission reduction. In 2040, the carbon emission of battery manufacturing will be 54.48 kgCO2-eq/kWh, 48.1 % lower than that in 2020. In the same calculation process, the carbon emissions from battery manufacturing will be 25.59 kgCO2-eq/kWh in 2050, which is 75.6 % lower than in 2020.

## 5. Conclusions

In this study, the cradle-to-cradle LCA of the EVs batteries in China is conducted, and some valuable carbon reduction measures are given. Moreover, the carbon emission of EVs batteries production under different electricity mixes will be examined in the next 30 years for China's carbon-neutral strategy. The main conclusions of this study can be summarized as follows:

(1) The battery production phase has the most carbon emission, of which the production of cathode accounts for the largest proportion. Then, the carbon emission in the battery use stage is 64.2 kgCO2-eq/kWh.
(2) The carbon reduction of the cascade utilization process is 1.536 kgCO2-eq/kWh. Among the three recycling methods studied in this paper, the hydrometallurgy method has the highest carbon reduction, followed by pyrometallurgy and the combined hydro-pyrometallurgical process.
(3) Compared with the electricity mix in 2021, under the predicted electricity mix in 2030, 2040, and 2050, the carbon emission will reduce by 31.9 %, 45 %, and 48.1 %, respectively.

Based on the above findings, EVs battery recycling can reduce carbon emissions significantly. Therefore, several battery recycling policy recommendations are suggested as follows.

1) Complete EVs battery recycling and secondary use. Formulate a standardized closed-loop industrial chain covering the entire life cycle of power batteries. Promote the linkage of upstream and downstream enterprises in the cascade utilization link, enrich the business model of cascade utilization, connect supply and demand enterprises, and improve the cascade utilization rate.
2) Since different recycling technologies have a greater impact on carbon emissions, technological innovation is particularly important. Encourage enterprises to increase investment in research and development, and overcome key technologies such as rapid sorting and testing for cascade utilization, flexible automatic disassembly of battery packs, and efficient recycling.
3) Since the increase in the proportion of renewable energy power generation is conducive to the reduction of carbon emissions in the life cycle of power batteries, the development of renewable energy should be promoted.

## CRediT authorship contribution statement

**Wenqi Wu:** Methodology, Software, Formal analysis, Writing – original draft. **Nan Cong:** Data curation. **Xueli Zhang:** Writing – review & editing. **Qian Yue:** Writing – review & editing. **Ming Zhang:** Funding acquisition, Supervision.

## Declaration of competing interest

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

## Data availability

Data will be made available on request.

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