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Research papers

Comparative life cycle assessment of sodium-ion and lithium iron phosphate batteries in the context of carbon neutrality

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ABSTRACT

The promotion of electric vehicles (EVs) is of great significance to reduce the use of fossil fuels, decrease vehicle emissions and promote the transformation of the automotive industry to a green and low-carbon direction within the context of the global "carbon neutrality" goal. However, with the rapid development of EV industry, the environmental problems of power batteries represented by lithium batteries are increasingly prominent, and there is an urgent need to develop new high-efficiency and environmentally friendly power batteries to promote the further development of the automotive industry. New sodium-ion battery (NIB) energy storage performance has been close to lithium iron phosphate (LFP) batteries, and is the desirable LFP alternative. In this study, the environmental impact of NIB and LFP batteries in the whole life cycle is studied based on life cycle assessment (LCA), aiming to provide an environmental reference for the sustainable development of electric vehicle industry and the improvement of new power batteries. During the study, four research scenarios were set up combining battery gradient utilization technology and various battery end-of-life recycling technologies, focusing on the carbon footprint of NIB and LFP and the corresponding environmental impacts. The results show that LFP batteries have better environmental performance in the production stage, but NIB seems to be better in the long-term development perspective. In the battery recycling stage, hydrometallurgical recycling has better environmental performance, while battery gradient utilization further exploits the residual value of the battery and is more suitable for real-life disposal of retired batteries. In the future, NIB is expected to further develop and replace LFP for sustainable battery development.

1. Introduction

Various countries around the world have launched "carbon-neutral" green development strategies in response to the environmental and climate problems caused by global warming [1,2]. As Australia is expected to be carbon neutral by 2040, the US, Europe, Japan, and South Korea are expected to complete their carbon neutrality targets by 2050 [3–5]. China has proposed a 2060 carbon neutrality plan [6,7]. In light of governments' macro policies, the global electric vehicle (EV) industry is booming [8–10], with global EV sales reaching 6.7 million units by 2021, up 108 % from 2020. The rapid rise of the EV industry has contributed significantly to the development of the energy storage battery industry but simultaneously accelerated the intensification of the conflict between resources and the environment in the battery industry [11,12].

Currently, electric vehicle power battery systems built with various types of lithium batteries have dominated the EV market, with lithium nickel cobalt manganese oxide (NCM) and lithium iron phosphate (LFP) batteries being the most prominent [13]. In recent years, with the continuous introduction of automotive environmental regulations, the environmental impact of lithium batteries has become a crucial indicator to assess the environmental performance of EVs. Feng [14] conducted a life cycle assessment on common vehicle types in China with NCM and LFP batteries, revealing that the cathode material in the

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battery production process is the main cause of environmental impact. Furthermore, the recycling of power batteries, which are discarded alongside EVs when they are retired, has become an important area of research and an urgent issue to address globally [15]. Utilizing power batteries in a graded manner and implementing efficient and green recycling methods are effective means to mitigate environmental impacts [16]. As the global carbon neutrality plans advance, the future development of the EV industry is expected to accelerate significantly. However, global lithium resources are limited, with a crustal abundance of only 20 ppm [17]. With the rapid development of the EV industry, the demand for lithium batteries has surged, leading to the gradual emergence of resource constraints and a rapid increase in the production cost of lithium batteries, which hampers their further development. In contrast to the scarcity of lithium resources, sodium resources are abundant, with a crustal abundance of about 2.46 % and reserves far exceeding those of lithium. In addition, sodium resources are widely distributed, easy to extract, and have lower costs. Research on the development and use of sodium-ion batteries (NIB) as alternatives to lithium-ion batteries has gained increasing attention in the field of energy storage [18].

In 2021, China's leading energy storage battery industry leader, CATL (Contemporary Amperex Technology Co. Limited), introduced the first-generation NIB, with a single-cell energy density reaching 160 Wh/kg, exhibiting performance comparable to LFP batteries [20]. Additionally, the outstanding cost control and abundant resource reserves make NIB the most promising lithium battery alternative product. Chao [21] focusing on NIB with ultra-thin layered tin sulfide nanostructures, demonstrates the potential for low-cost manufacturing and high safety. Chen [22] proposed a Bi (Bismuth) nanoparticle-embedded graphite layer as the anode material for NIB, enhancing its cycling lifespan and providing exceptionally high safety performance. It can easily withstand safety tests involving rapid charge and discharge, short circuits, punctures, and compression, while maintaining excellent performance in extreme temperatures ranging from −40 °C to 80 °C. Furthermore, by combining efficient electrode materials with battery structure design, the charging rate of NIB can be effectively improved [23,24]. Compared to traditional lithium-ion batteries, NIB's outstanding energy supplementation advantages and significant cost benefits have propelled it to a new level, showing enormous potential for future EV development [25–28]. However, current research on NIB mainly focuses on battery material development, energy storage performance improvement, and battery structure design, with limited studies addressing the environmental impact assessment of NIB. Moreover, due to the nascent state of the NIB industry, there is an urgent need to assess the gap in resource and environmental impacts between sodium-ion batteries and lithium-ion batteries. Such an evaluation holds crucial significance for the green development of the global energy storage battery industry under the backdrop of carbon neutrality [29–31].

As the performance of NIB is similar to that of LFP, this paper selected LFP as a representative of lithium batteries and established an assessment model based on Life Cycle Assessment (LCA) to investigate the differences in resource and environmental impacts between the batteries, including the production, use, and recycling phases. Based on the above scenario setting and the background of carbon neutral research, this study focuses on analyzing the carbon footprint of the NIB and LFP during their use phase and comparing the resource and environmental impacts of the batteries over the entire cycle of the two types of batteries. Furthermore, this study provides inventory data for both power cells to facilitate the corresponding LCA studies. The final LCA study results will show the difference in resource and environmental impacts between NIB and LFP under the current process, providing data support and technical reference for future NIB industry layout and further optimized development and promoting the sustainable development of the battery industry.

2. Method

2.1. Goal and scope definition

The objectives of this study are to establish a life cycle assessment model for NIB and LFP batteries based on LCA, compare and investigate the resource and environmental impacts of the two types of batteries, explore the differences and current problems, provide improvement and optimization ideas for the future layout and development of the NIB industry, which will promote the sustainable development of the battery industry. The lifecycle system boundary for NIB and LFP is defined in Fig. 1. To further explore the potential of battery gradient applications, this study divides the battery use phase into two parts: the first use in service for EVs and the second use in service for communication base stations (CBS). Meanwhile, we set up three technical solutions based on the EV power battery decommissioning and recycling market: hydrometallurgical recycling, pyrometallurgical recycling, and physical recycling. In addition, the functional unit of the battery system is defined as 1 kWh, and the total mileage of the electric vehicle in the use phase is 200,000 km.

In this study, to further highlight the primary differences between the two batteries, a simplified treatment was applied to some minor factors within the battery life cycle. The first use phase, in which the battery is in service with the EV, involves mainly the consumption of electrical energy during the use of the EV, without the need to consider the assessment of fuel and material consumption. In the second use phase, the battery is in service in the CBS, a process that involves the loss of both the battery after it has been re-processed from EV retirement and the use of the battery in the CBS. At last, the recycling phase of the battery is set up with various recycling options for comparative studies.

2.2. Life cycle inventory analysis

The real-life data used in the lifecycle inventory for this study is sourced from local enterprises, previous research findings, industry statistical yearbooks, as well as publicly available data from government regulations and standards. Background data, on the other hand, is based on the SimaPro 9.0 software and the built-in Ecoinvent 3.5 database. It should be noted that the usage phase can be divided into two parts. The first usage involves the battery serving in EVs, while the second usage involves the battery being retired and utilized in a cascading manner for service in communication base stations. With respect to the aforementioned data, we conducted meticulous and rigorous organization and analysis, extracting relevant and representative data to construct the LCA model for both NIB and LFP batteries across all stages and aspects of their lifecycles.

2.2.1. Battery production phase

The lifecycle inventory analysis of the battery production phase includes all material, energy, and emissions inventory data from the extraction of raw materials, the manufacture of components, and the assembly and molding of the battery. Their detailed inventory data can be found in Tables S1-S23.

2.2.2. Battery first use in EV

Since the NIB is not yet commercially available on a large scale, a use-phase LCA model of the NIB was constructed in this study based on data from a model of an electric vehicle currently fitted with an LFP. The background parameters associated with this vehicle model and the corresponding power cell during the modeling process can be found in Table S24. The vehicle-related parameters were taken from a BYD model, the NIB battery parameters were taken from the latest NIB parameters released by CATL, and the LFP battery was chosen from the current average parameters for short-range EV performance. The data analysis process was simplified to highlight the differences in battery performance by considering the first use phase of battery service in

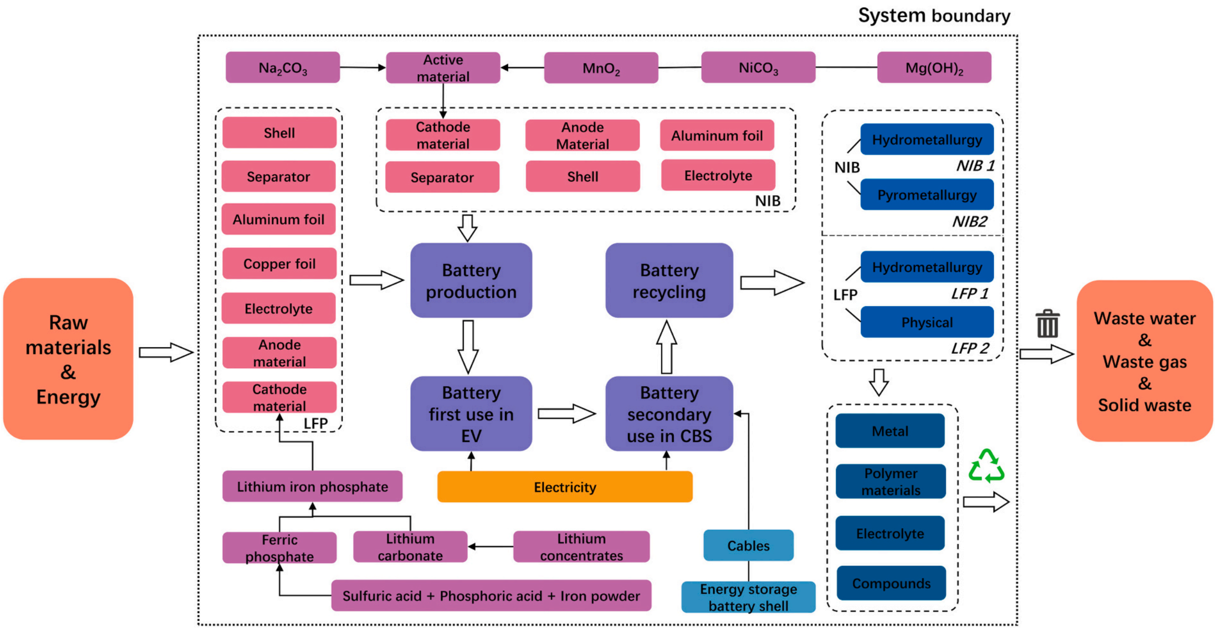

Fig. 1. LCA system boundary of NIB and LFP batteries.

electric vehicles. Only electricity loss was considered in this phase, and other processes, such as battery maintenance, were not considered in this study.

The actual capacity of the battery will drop during repeated charging and discharging, which is combined with the retirement standard for EV power batteries in China, providing that the actual capacity of the battery will be replaced after it drops to 80 % [32]. The power loss in the first use phase of the battery is mainly used to drive the car and to offset the energy loss of the battery due to energy conversion efficiency. Among them, the electric energy loss in the process of driving the car and carrying mass forward by the battery is inevitable consumption, which is not discussed in this study, and the focus is on exploring the electric energy consumption caused by the excessive mass of the battery itself. Therefore, in the theoretical analysis of the electrical energy loss caused by the battery overcoming its mass, the expression for the energy loss E_m (kWh) of the process battery can be defined as Eq. (1).

$$E_m = f \cdot E_p \cdot L \cdot \left(\frac{m}{M}\right) \tag{1}$$

In the calculation of the energy loss caused by the battery overcoming its mass, f is the energy distribution coefficient of the battery control system during EV driving and represents the ratio of the battery's electrical energy consumption to the mass of the vehicle [33]. E_p is the electric energy consumption per 100 km of EV driving (kWh/100 km), and L is the total mileage within the EV use phase (km). Furthermore, m and M in the above equation denote the mass of the battery system and the mass of the EV (kg), and the vehicle's overall mass marked on the vehicle's factory nameplate is chosen. According to previous studies [34], the energy distribution coefficient f takes a value of 0.49, while the EV electrical energy consumption per 100 km is determined to be 12.2 kWh/100 km based on public data from manufacturers and national standards. In addition, the detailed parameters of the electric vehicle in the above equation involving the mass of the battery system m and the mass of the car M can be found in Table S24.

The energy loss caused by the conversion efficiency between electrical energy and chemical energy inside the battery is inevitable during the charging and discharging process. Here the energy loss (E_c, kWh) due to battery charging and discharging efficiency during the first use of the battery is defined as Eq. (2).

$$E_c = E_p \cdot L \cdot (1 - \eta_1) \tag{2}$$

The η_1 is the charge and discharge efficiency of the battery serving in the EV. In this study, to simplify the calculation, it is stipulated that the charge and discharge efficiency of the battery does not decrease with the increase of the number of battery cycles, and concerning the previous research results [35,36], it is stipulated that the value is 90 %.

2.2.3. *Battery second use in CBS*

In the course of EV usage, when the battery capacity diminishes to 80 %, it undergoes retirement procedures. Nevertheless, the power battery systems retrieved from retired electric vehicles still possess substantial battery capacity and retain considerable value for utilization. Herein, we establish a battery gradient recycling scenario based on the current electric vehicle power battery retirement methods, transforming retired batteries into CBS energy storage batteries, The principle of the battery application process is shown in Fig. 2. But retired power batteries can not be used directly for energy storage batteries, which still need to be further modified and processed, so this phase can be divided into modified processing of retired batteries and work as energy storage batteries.

In the second use phase of the battery as a CBS energy storage battery, its work process still requires repeated charging and discharging to maintain the CBS work, so the process of battery capacity continues to decrease with the increase in the number of cycles of use. Concerning the current CBS energy storage battery application standards and battery retirement treatment, this article defines that batteries will be disposed of when their capacity is reduced to 60 % [37], at which time the battery will enter the recycling phase.

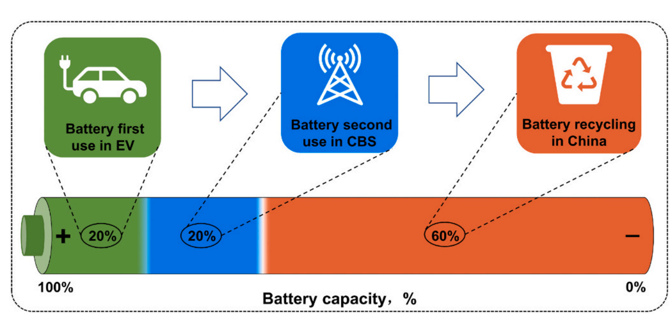

Fig. 2. Schematic diagram of battery life cycle usage.

Since the battery capacity will be reduced to 80 % from the EV retirement application to CBS, it is easier to lose the battery capacity at this phase, and to ensure that the battery capacity decays to 60 % for timely retirement and recycling, the battery capacity decay process and energy loss relationship need to be further investigated [38]. Previous studies have shown that the battery capacity decay is closely related to the number of charge and discharge cycles [39–41], and the expression of the relationship can be defined as Eq. (3).

$$\varphi = \lambda \cdot e^{-(E_a/Rt)} \cdot n^z \tag{3}$$

In the equation, φ is the capacity loss of the battery, λ is the calculation constant, E_a is the activation energy ($J \cdot mol^{-1}$), R is the value of the gas constant ($J \cdot mol^{-1} \cdot K^{-1}$), t is the thermodynamic temperature (K), n is the number of charges and discharge cycles in the secondary use phase of the battery, and z is the power-law coefficient. For the above expressions of capacity loss and the number of charges and discharge cycles of the battery, this paper applies them to the capacity loss calculation of NIB and LFP batteries [39].

The calculated relationship between the battery capacity loss and the number of charges and discharge cycles was obtained to further explore the energy loss during each charges and discharge cycle [42,43], and the energy loss E_{loss} of the battery in the secondary use of CBS was defined as Eq. (4).

$$E_{loss} = \sum_{n=1}^{i} E_f \cdot DoD \cdot (1-\varphi) \cdot \frac{1-\eta_T \cdot \eta_2}{\eta_T \cdot \eta_2} \tag{4}$$

where i indicates the number of charges and discharge cycles required to dissipate the battery capacity to 60 %, and E_f is the initial capacity (kWh) when the battery is applied to CBS for secondary use. The *DOD* is the depth of discharge during battery use, η_T is the battery transfer efficiency, and η_2 is the charges and discharge efficiency during the secondary use phase of the battery. From the current situation of EV power battery retirement research in China and the requirements of using energy storage batteries in CBS, combined with the results of previous studies [44], the DOD was specified as 80 %, η_T as 90 %, and η_2 as 85 %.

2.2.4. Battery recycling phase

This study uses the recycling process of Jiangxi Ganfeng Lithium Corporation [45] for EV power batteries and CBS lithium batteries as a reference representative based on the technological development of the Chinese battery recycling market. Among them, hydrometallurgical recycling and pyrometallurgical recycling scenarios are set up for NIB, while hydrometallurgical recycling and physical recycling scenarios are set up for LFP batteries. The specific recycling process of the battery is shown in Fig. 3, and the relevant details of the process can be found in Tables S27-S30.

2.3. Life cycle impact assessment

In the life cycle assessment phase, this study has conducted a life cycle assessment study of batteries by ISO 14040 and focused on a comparative analysis of the carbon footprint of batteries in the production phase [46]. Product modeling was completed based on Simapro 9.0 software, while carbon footprint and environmental impact assessments were conducted based on the ReCiPe 2016 methodology [47,48]. In addition, the 18 environmental indicators in the ReCiPe 2016 assessment methodology are divided into four categories: atmospheric impact, water impact, terrestrial impact, and resource impact, based on the categories of resource and environmental impacts caused during the life cycle of the battery.

2.4. Sensitivity analysis

Sensitivity analysis is used to investigate the impact of fluctuations in data parameters on the final assessment results during the battery life cycle assessment process, which can be used for later targeted optimization and improvement. Considering the battery production phase is the main phase of pollutant generation in the full cycle and taking into account regional differences and resource use factors, this paper analyses the fluctuation of the assessment results by applying a ±10 % transformation to the LCA model parameter data for electrical energy and primary resource consumption in the battery production phase.

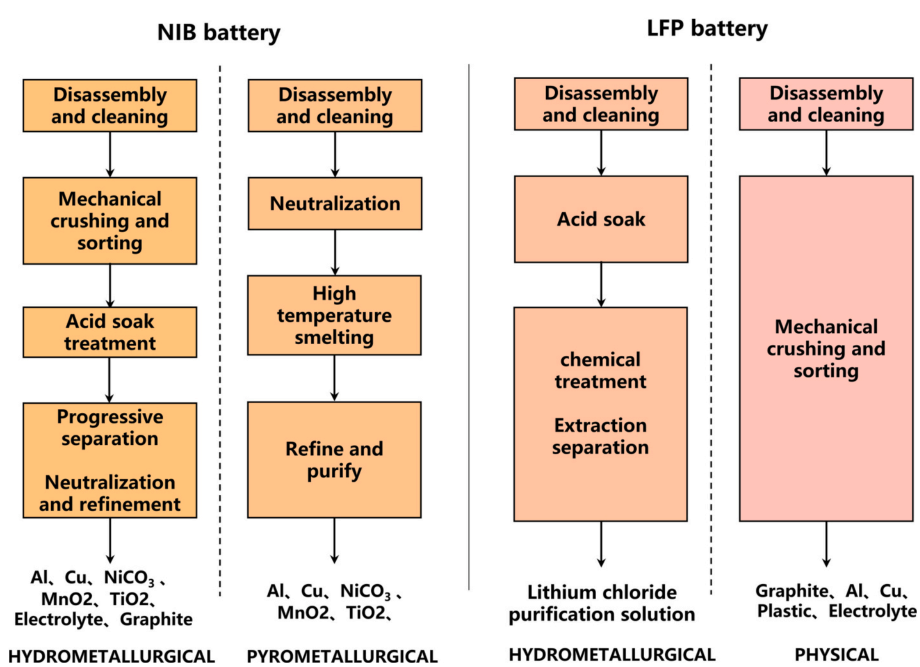

Fig. 3. Comparison of NIB and LFP battery recycling process.

3. Results and discussion

3.1. The results of carbon footprint

The full-cycle carbon emissions of batteries are concentrated in the production phase. Complicated production processes and significant energy consumption in the production phase make the full-cycle carbon footprint of the battery ambiguous. This study investigated the carbon footprint of the battery production phase based on the IPCC 100a methodology. The study explored the flow direction of the battery carbon footprint based on the module division of the battery structure and main component types. A graph comparing the carbon emission intensity and carbon footprint trend of NIB and LFP batteries was established, as shown in Fig. 4.

The NIB and LFP have similar carbon emission trends overall from a macro perspective, with the primary sources of emissions being concentrated in the battery cathode material. However, NIB is significantly higher than LFP batteries in terms of carbon emissions from the battery cathode, the battery management system (BMS), and the electrical energy of the battery manufacturing process, especially in terms of the electricity factor, which is ten times higher than LFP. As the NIB battery is still in the laboratory stage, it is not yet commercially available, and the production process has not yet been optimized to take into account factors such as production costs and environmental emissions. In contrast, LFP has a mature industrial production system and technological routes that have been fully optimized in terms of energy consumption. Correspondingly, due to the structure of the LFP, copper and aluminum foil are used for the positive and negative electrodes, whereas aluminum foil can be used for both the positive and negative electrodes of the NIB instead. In addition, a large amount of NMP is used, resulting in higher carbon emissions in the production of metal foil, electrolyte and NMP than in NIB. Following a carbon footprint analysis perspective, the NIB and LFP carbon footprint paths are similar, forming a carbon footprint network with a predominantly positive battery carbon footprint and multiple factor carbon footprint branches co-existing, as shown in Fig. 5. The NIB's carbon footprint is more clearly defined, with its carbon footprint being mainly in the carbon emissions generated by the electricity consumed during the production of the battery's positive electrode and individual components. While LFP appears to be multi-polar, with multiple materials such as the battery cathode, the metal foil, and the NMP in the electrolyte all possessing outstanding carbon emission values, as determined by the battery construction.

The above carbon footprint analysis shows that the problem of carbon emissions from NIB batteries arises from the use of rare metal resources used in the battery's cathode and that improved processing and manufacturing techniques and the selection of new low-carbon materials are the keys to future energy-saving and emission reduction. In addition, electricity and energy (heat and natural gas) use continue to account for a large share of the NIB's carbon footprint, accounting for around 20 % of the total. The electricity data for North China was chosen as the background for this study, representing to some extent the electricity energy mix in China and indicating the problem of high carbon emissions from electrical energy in the region. And this is because coal-fired power generation accounts for about 80 % of China's electricity in northern China, and coal burning leads to significant carbon emissions. Therefore, from a long-term perspective, restructuring the electricity mix and developing new energy sources are essential measures for the future low-carbon development of the battery industry and industry. Due to its design, few rare metal resources are involved in the cathode material of LFP batteries. Therefore, the carbon footprint of LFP batteries is mainly focused on the consumption of electricity and energy during the processing and manufacturing of the batteries. In addition, the metal resources and chemicals used in processing copper and aluminum foils and electrolyte production for LFP batteries are other sources of carbon emissions. The LFP battery does not form a significant carbon footprint stream compared to the NIB, and its carbon footprint flow is more dispersed, making future energy-saving and emission-reduction efforts for the LFP battery more complex.

3.2. The results of environmental influence

This study sets up the following four research scenarios for different recycling options of NIB and LFP batteries in order to facilitate the analysis and calculation during the resource and environmental impact assessment.

NIB 1: NIB battery production, the first use in EV, second use in CBS, hydrometallurgical recycling.

NIB 2: NIB battery production, the first use in EV, second use in CBS, pyrometallurgical recycling.

LFP 1: LFP battery production, the first use in EV, second use in CBS, hydrometallurgical recycling.

LFP 2: LFP battery production, the first use in EV, second use in CBS, physical recycling.

The above study scenario is set up based on the LCA analysis process and battery recycling scheme, which stipulates that the calculated result value will have the resource and environmental impacts when it is greater than zero, while when the calculated result is less than zero, it will be identified as environmental benefits generated, which can offset the corresponding resource and environmental impacts. Further, this study used the global-scale characterization factors provided by the ReCiPe 2016 midpoint method in the resource and environmental assessment process, and the results of the study were categorized as follows.

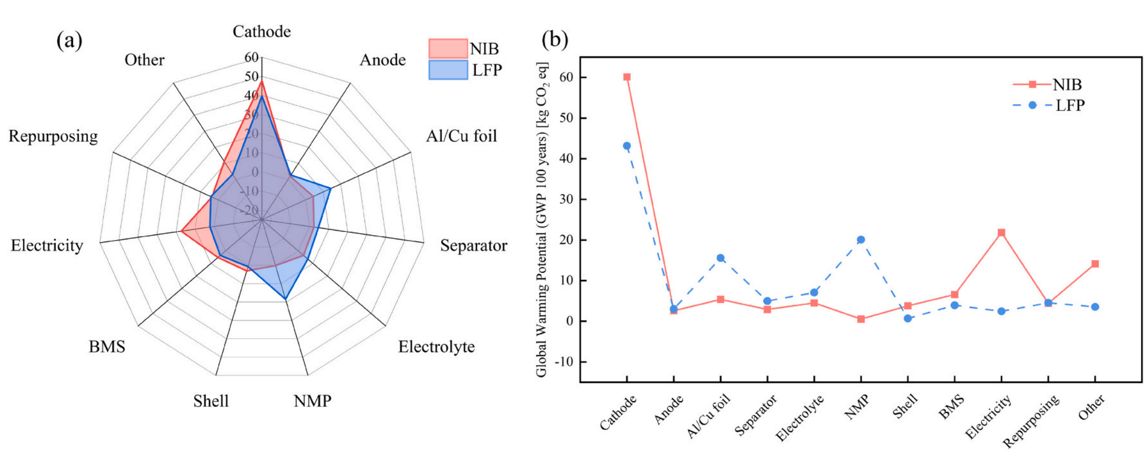

Fig. 4. Comparison of carbon emissions of key components of NIB and LFP batteries.

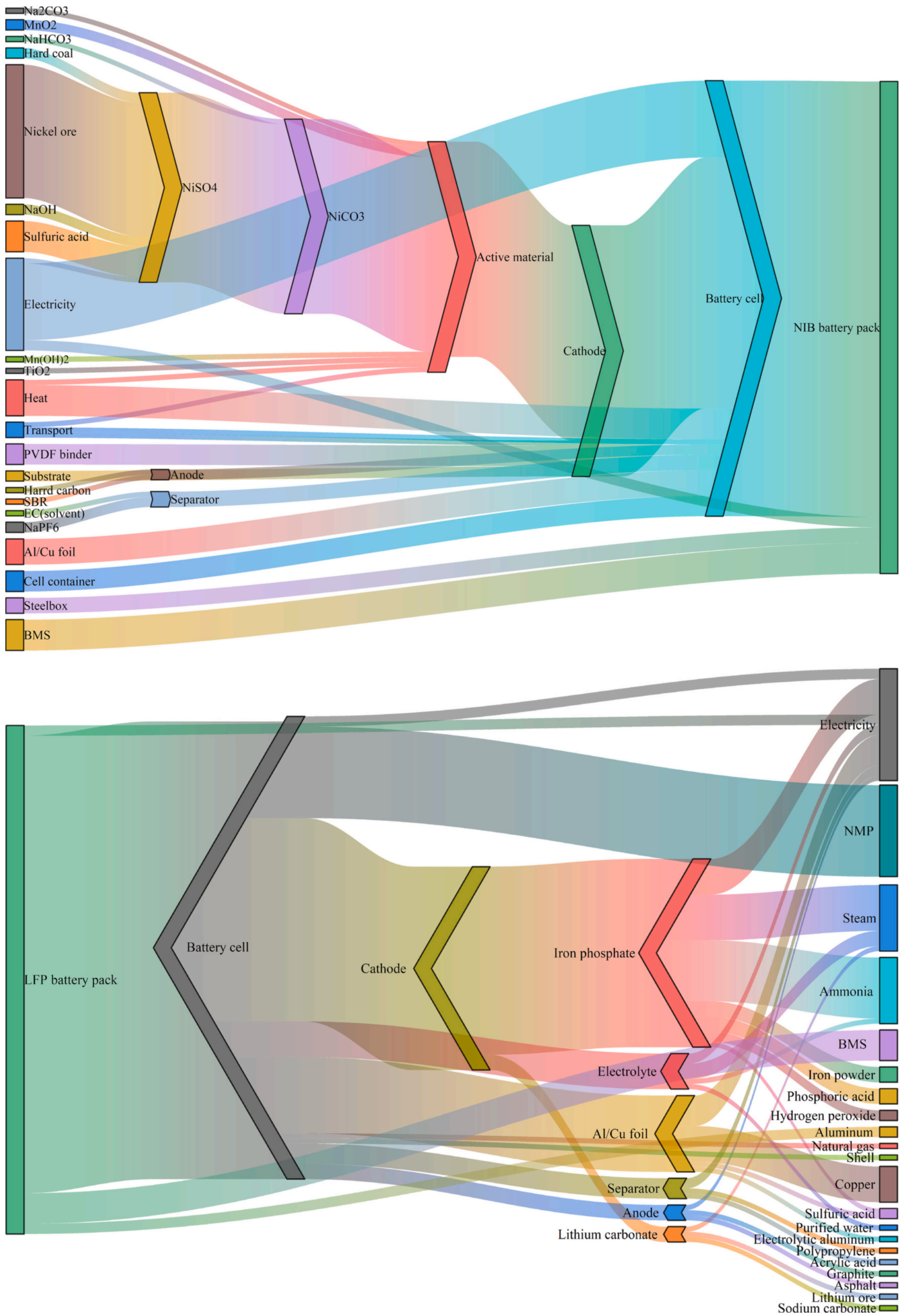

Fig. 5. Comparison of the carbon footprint of NIB and LFP batteries at the production phase.

3.2.1. Ozone depletion

The absorption of solar ultraviolet radiation by the ozone layer is of great importance in reducing human skin diseases. There is already widespread concern about problems such as the hole in the ozone layer as a direct result of pollutants in the development of human society. In this study, the impacts of two battery life-cycle activities on the ozone layer were investigated based on the Ozone depleting potential (ODP), Human health ozone formation potential (HOFP), and Terrestrial ecosystems ozone formation potential (EOFP) indicators in the ReCiPe assessment method as shown in Fig. 6.

In general, the ozone impact over the life cycle of the NIB is higher than LFP batteries, and the environmental performance of the NIB 1 option in the NIB is better than NIB 2, which indicates that the more significant environmental benefits of the hydrometallurgical recycling process partially offset the ecological impact. However, there is no significant difference between the environmental impact values of the two options in the LFP battery, indicating that the recycling phase of the LFP battery cannot effectively mitigate the environmental impact under the ozone impact index. In contrast, the ecological benefit values of hydrometallurgical recycling and physical recycling in LFP batteries are similar, but the effect of hydrometallurgical recycling is slightly better than physical recycling. Further, it was found that 70 to 90 % of the ozone impact originates from the battery production phase when analyzing the environmental impact of the various stages of the battery life cycle. Next is the second use phase, which also shows that the battery's energy consumption will gradually increase as the number of charge and discharge cycles increases during use. In addition, there is a significant difference between the two batteries at the ODP index, with the NIB causing approximately 2–4 times the ozone impact of the LFP battery. However, at the HOFP and EOFP indexes, the overall impact of NIB treated in the recycling phase can be mainly at the level of LFP batteries, which shows the potential for the future development of NIB.

3.2.2. Eutrophication depletion

Eutrophication is the dominant pollution mode for water bodies. In this study, eutrophication studies based on Freshwater eutrophication potentials (FEP) and Marine eutrophication potential (MEP) were conducted to investigate NIB and LFP batteries' impacts on water bodies. As shown in Fig. 7, the magnitude of the eutrophication impact caused by NIB and LFP batteries is approximately the same during the production and use phases, with the environmental benefits of the recycling process determining the magnitude of the overall environmental impact of the batteries. In further analysis, it was found that LFP2 had better environmental performance, which means that physical recovery was better, but there is no significant difference between the two recovery methods in the NIB. In further analysis, LFP2 was found to have better environmental performance, which means that physical recycling is better, but the superiority of the recycling method in the NIB needs to be further analyzed under the evaluation index. Of these, NIB 1 showed significant differences at the FEP and MEP indexes, demonstrating the limitations of hydrometallurgical recovery at different environmental indexes. Equally, it is worth noting that in the NIB 1 scheme under the MEP indicator, the hydrometallurgical recovery does not generate environmental benefits but even exacerbates the ecological impact. This indicates that the hydrometallurgical recovery does not recover elemental N for the MEP index but rather that the hydrometallurgical recovery increases the emission of elemental N. Therefore, it is necessary to choose a reasonable recycling method for different environmental needs in the future battery decommissioning recycling process.

3.2.3. Ecotoxicity depletion

Ecotoxicity is another crucial index for environmental impact assessment. There are three categories of ecotoxicity: water ecotoxicity, human ecotoxicity, and terrestrial ecotoxicity, which are shown in Fig. 8. In this study, the water ecotoxicity potential is divided into Freshwater ecotoxicity potential (FETP) and Marine ecotoxicity potential (METP), where the toxicity problem is higher in the production and use phases of NIB than in LFP due to the processing of nickel-containing materials in the NIB production process. Whereas in the battery recycling process, hydrometallurgical recycling shows excellent performance in NIB but does not work well in LFP. Human ecotoxicity is divided into Human carcinogenic toxicity potential (HTPc) and Human no-carcinogenic toxicity potential (HTPnc), with more significant differences in the assessment results. In HTPc, NIB is similar to LFP production and uses phases in terms of the extent of the problem. In contrast, it is apparent in HTPnc, highlighting the problematic nature of NIB in Human no-carcinogenic toxicity potential. Correspondingly, it is worth noting that the recovery of NIB 1 by hydrometallurgical processes is outstanding and that the choice of hydrometallurgical recycling of decommissioned NIBs is effective in reducing human ecotoxicity. Contrary to other ecotoxicity effects, the LFP battery has a significantly higher impact than the NIB under the Terrestrial ecotoxicity potential (TETP) index, indicating the advantage of the sodium ion battery.

3.2.4. Resource depletion

In this study, the resource impacts of NIB and LFP battery lifetime are investigated, which include land resources assessed by the Agricultural land occupation potential (LOP) indicator, mineral resources assessed by the Surplus Ore Potential (SOP) indicator, fossil resources assessed by the Fossil Fuel Potential (FFP) indicator, and Water consumption potential (WCP) indicator, and the results are shown in Fig. 9.

Within the resource impact, different batteries show a clear tendency to select resources where the resource impact of NIB is more inclined to land resources and mineral resources, while LFP battery is inclined to

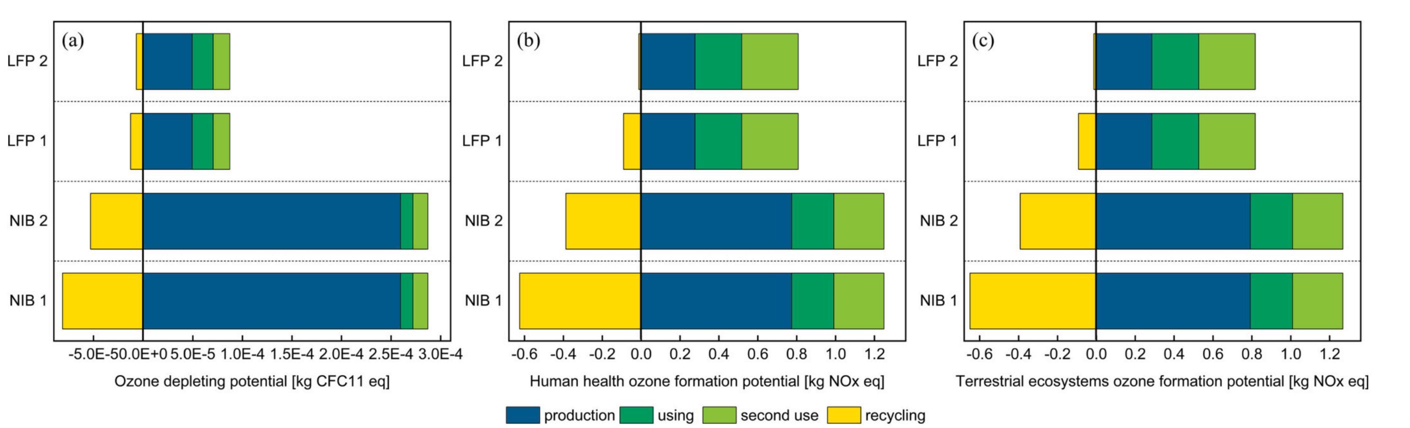

Fig. 6. Comparison of ozone layer impact, (a) ozone depleting potential, (b) human health ozone formation potential, (c) terrestrial ecosystems ozone formation potential.

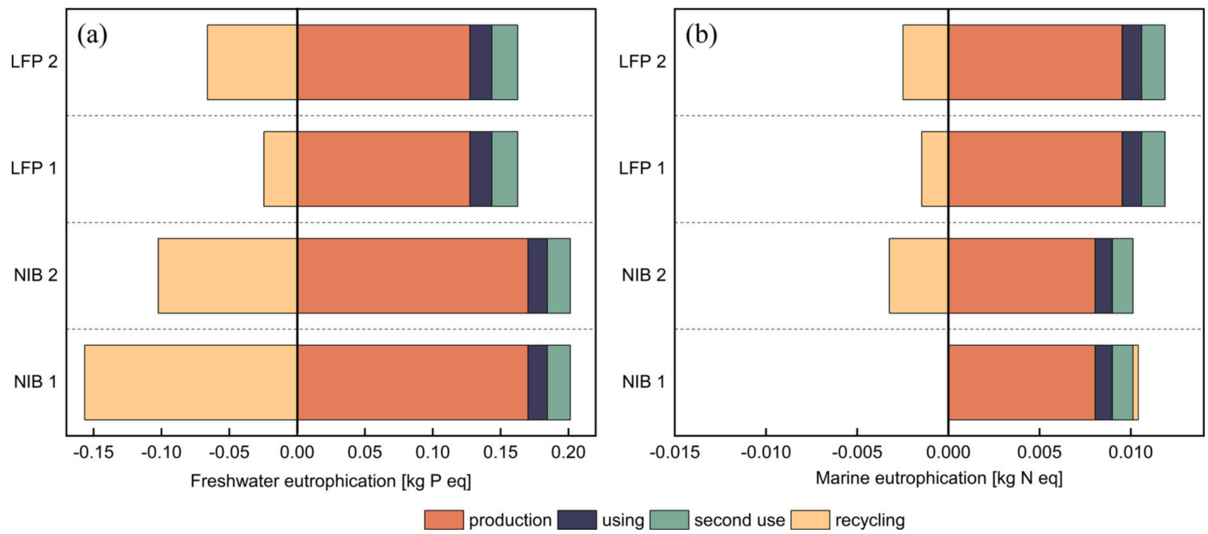

Fig. 7. Comparison of eutrophication effects in water bodies, (a) freshwater eutrophication potentials, (b) marine eutrophication potential.

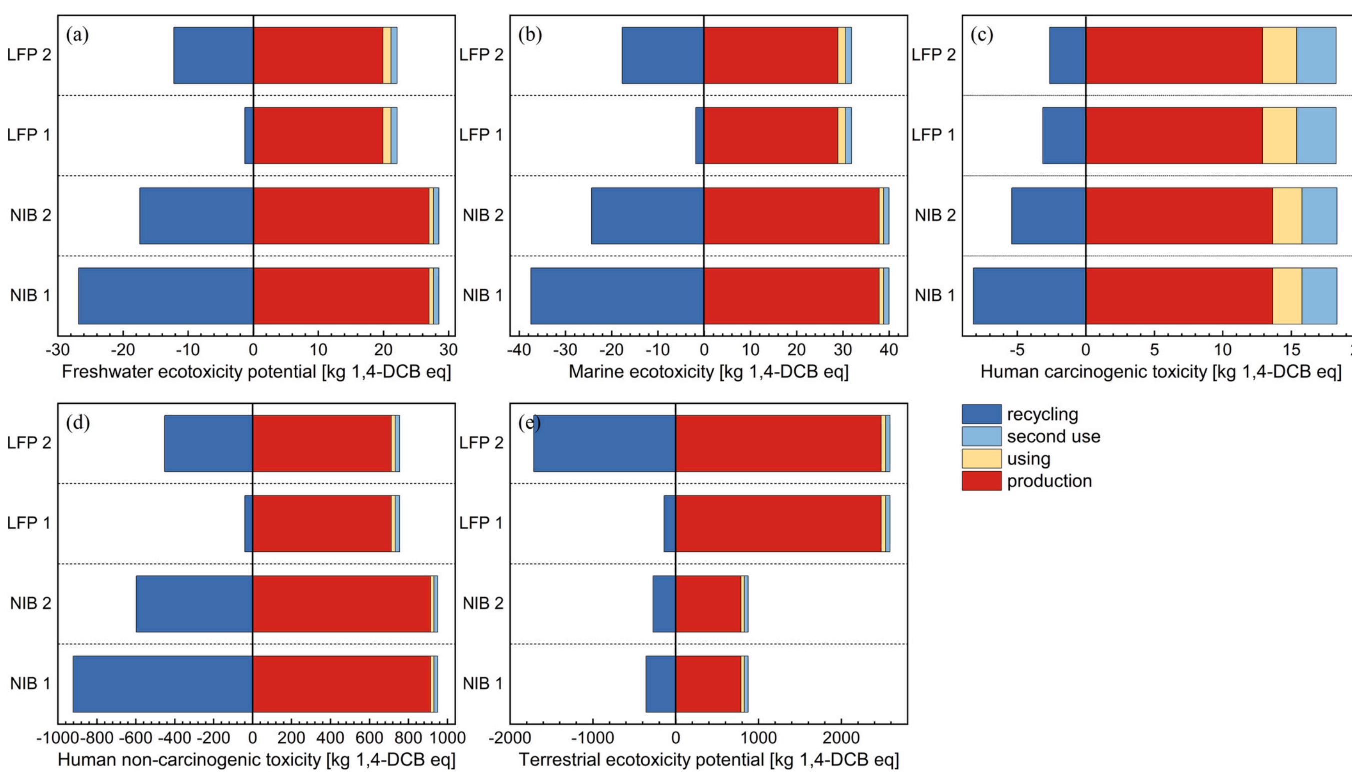

Fig. 8. Comparison of ecotoxic impact, (a) freshwater ecotoxicity potential, (b) marine ecotoxicity potential, (c) human toxicity potential, (d) human toxicity potential, (e) terrestrial ecotoxicity potential.

fossil resources and water resources. As for the performance of recycling technologies in terms of resource impact indicators, especially physical recycling in the LFP 2 scenario does not have a beneficial impact in terms of land, fossil, and water resources but more or less increases the consumption of resources. But in general, recycling technology still has a good environmental benefit impact, especially on mineral resources, and it is worthwhile to vigorously develop battery recycling technology.

3.2.5. The results of other influence

Beyond the ozone, eutrophication, ecotoxicity, and resource impacts discussed above, we also explored the environmental impacts under the indicators of Ionising radiation potential (IRP), Particulate matter formation potential (PMFP), and Acidification potentials (AP) during the whole lifetime of the battery. The results are presented in Fig. 10. The environmental impact of the NIB is generally lower than that of the LFP battery, which is due to the advanced recycling technology. Ultimately, there is a better result for hydrometallurgical recycling in PMFP and AP impact. However, the NIB 2 scenario and LFP 1 have a better environmental impact under the IRP indicator.

3.3. Sensitivity analysis

This paper conducted a sensitivity analysis for the electrical energy consumption at the battery production site and the main contributors to

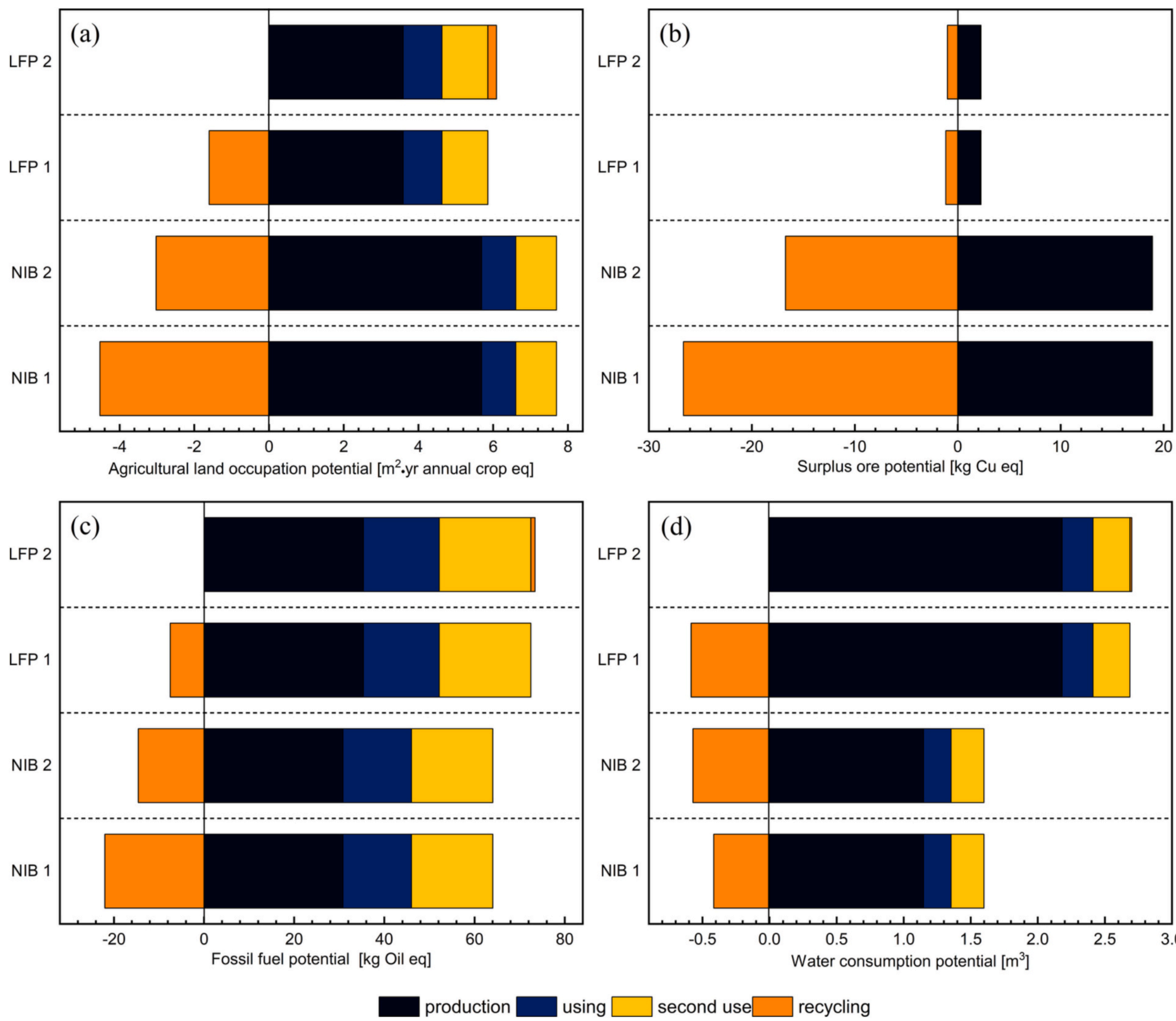

Fig. 9. Comparison of resource impact, (a) agricultural land occupation potential, (b) surplus ore potential, (c) fossil fuel potential, (d) water consumption potential.

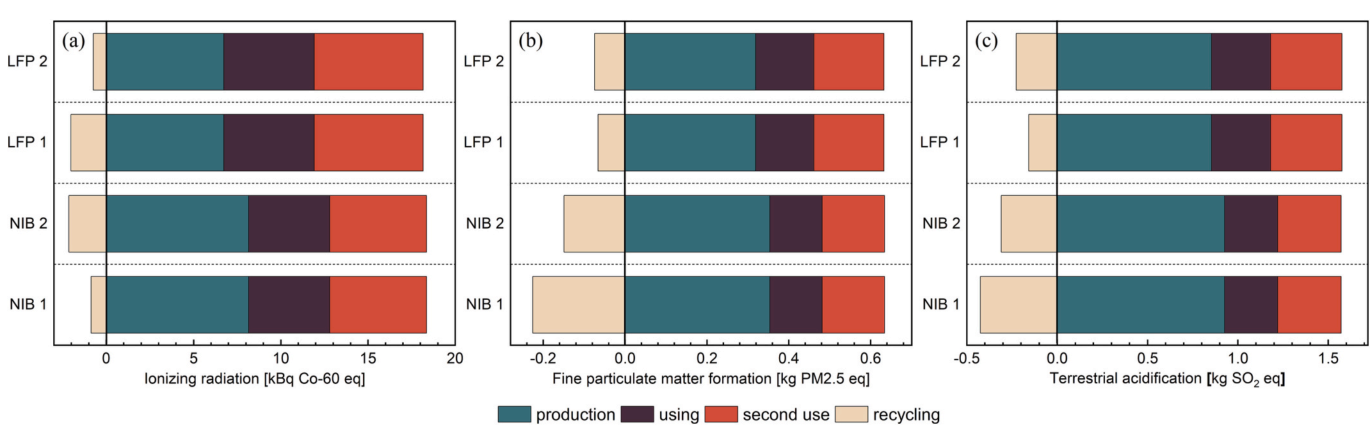

Fig. 10. Comparison of resource impact, (a) ionising radiation potential, (b) particulate matter formation potential, (c) acidification potential.

environmental issues in the production process, including nickel sulfate for NIB and copper consumption parameters for LFP. The results are shown in Table S31.

The results highlighted the significant role of electricity as a key factor influencing the environmental impact during battery production. To further investigate the carbon emissions impact of electricity, the study integrated China's regional power distribution and energy structure into the analysis, the results are shown in Fig. 11. The findings revealed that the carbon emissions impact varied across different regions. Specifically, the southwestern and central regions of China exhibited lower carbon emissions compared to the national average due to their abundant hydroelectric resources, which effectively mitigated

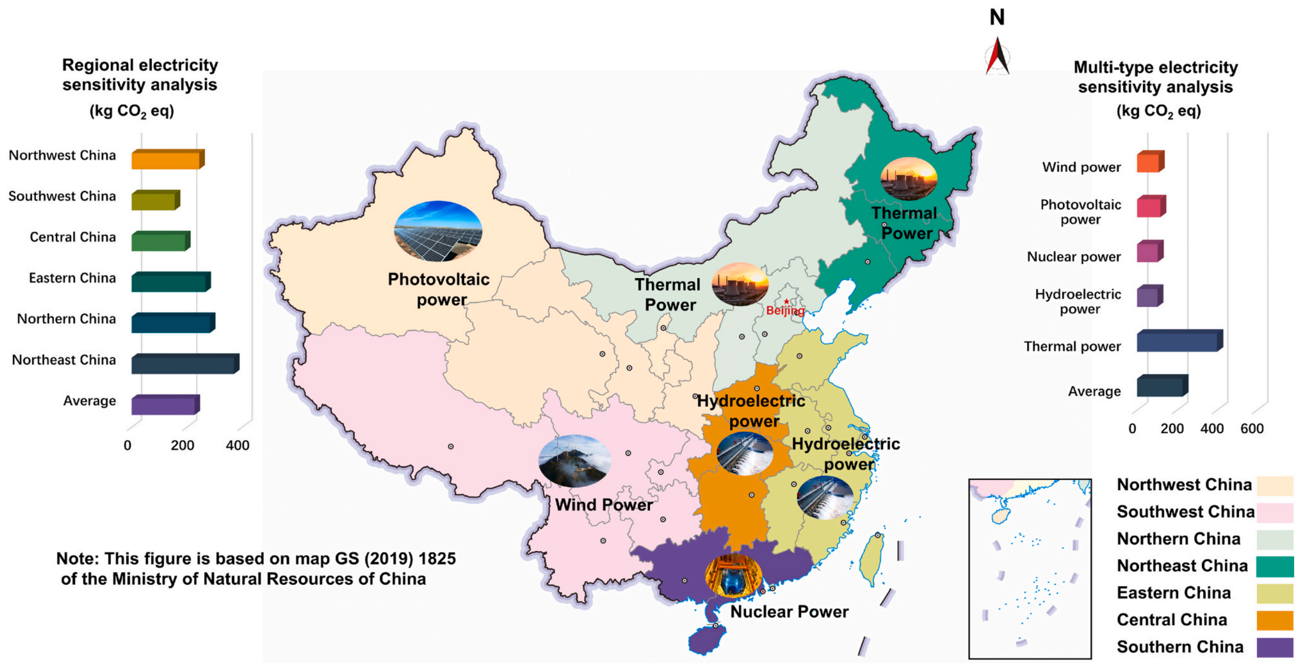

Fig. 11. Analysis of electricity and energy in China.

carbon emissions resulting from electricity losses during battery production. In contrast, the northeastern and northern regions demonstrated significantly higher carbon emissions impact, indicating a predominant reliance on thermal power generation in these areas. These findings emphasize the importance of considering regional power distribution and promoting clean energy sources in the southwestern and central regions for future battery production, while also optimizing the existing power grid to improve carbon emissions, thus addressing the environmental challenges associated with battery production in China.

4. Conclusion

This study applies the life cycle assessment methodology to investigate the environmental impacts of 1kWh NIB and LFP batteries. A comparative analysis of their recycling effects is conducted based on the current end-of-life battery recovery practices in China's automotive industry.

The results reveal that the production phase is the primary driver of environmental impacts for both battery types. Notably, LFP exhibits superior environmental performance during the production phase. However, when considering the entire life cycle, NIB demonstrates greater development potential, making it a promising candidate to replace LFP as a new-generation power battery. Nonetheless, further optimization of production technologies is essential to mitigate the environmental impacts associated with battery manufacturing.

During the usage phase, NIB demonstrates higher energy conversion efficiency, resulting in lower energy losses compared to LFP. Nevertheless, both battery types experience significant power losses during their second use, highlighting the importance of investigating end-of-life battery capacity thresholds to achieve optimal battery performance. Moreover, secondary use through battery cascading unlocks untapped battery value, effectively mitigating the environmental impacts of battery retirement. Hence, focusing on advancing battery recycling technologies is crucial to facilitate the circular utilization of batteries in future developments.

Regarding the recycling phase, wet metallurgical recycling proves to be more suitable for handling both battery types at the end of their life cycles, as it offers higher recycling efficiency and lower environmental impacts. Nevertheless, given the diverse variety of retired batteries encountered during actual recycling processes, further efforts are necessary to develop battery classification and select appropriate recycling methods based on practical considerations.

CRediT authorship contribution statement

Wei Guo is the first author who built the assessment model and wrote the original manuscript; Tao Feng is also a co-first author, and his contributions to the manuscript are equivalent to those of the primary first author; Wei Li is the corresponding author who guided the ideas and revised the manuscript; Lin Hua is the corresponding author who provided the data and the opportunity to visit the plant; Zhenghua Meng is involved in the revision of the article; Ke Li and Weicheng Liang are associated with the model building and data analysis.

Declaration of competing interest

The authors declare 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.est.2023.108589.

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