Comparison of three typical lithium-ion batteries for pure electric vehicles from the perspective of life cycle assessment

Tingting Jiang
Shanghai Institute of Technology
Huifang Wang
Shanghai Institute of Technology
Qiang Jin (jinqiang@sjtu.edu.cn)
Shanghai Jiao Tong University

Research Article

Keywords: Lithium-ion battery , Lithium iron phosphate battery , lithium nickel cobalt manganese oxide battery , Life cycle assessment , Pure electric vehicles

Posted Date: April 20th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2829799/v1

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Clean Technologies and Environmental Policy on November 13th, 2023. See the published version at https://doi.org/10.1007/s10098-023-02629-6.

Abstract

In the present study, environmental impacts of lithium-ion batteries (LIBs) has become a concern due the large-scale production and application. The present paper aims to quantify the potential environmental impacts of three LIBs in terms of life cycle assessment (LCA), as well as to identify hotpots and ways to reduce the environmental impacts. Three different batteries are compared in this study: lithium iron phosphate (LFP) batteries, lithium nickel cobalt manganese oxide (NCM) 811 batteries and NCM622 batteries. The results show that the environmental impacts caused by LIBs is mainly reflected in five aspects from eleven evaluation indexes. They are abiotic depletion (fossil fuels), global warming (GWP 100a), human toxicity, fresh water aquatic ecotox and marine aquatic ecotoxicity. Besides, the "Production phase" and "Assembly phase" of LIBs are the main sources of carbon emissions, the GHG emission of NCM622 battery is 1576 kg CO_2-eq/kWh, which accounts for 37.5% of the total GHG emissions. The study shows that the hydrometallurgical method in the "Recycle phase" may not always be environmentally friendly, it can increase the indicators of human toxicity, fresh water aquatic ecotox and marine aquatic ecotoxicity. The precursor materials in NCM batteries and the electricity consumption of LFP batteries are sensitive factors to environmental impacts, which can be effectively improved by improving the process and optimizing the power structure. The findings are likely to provide the LIBs manufacturing sector with data. Suggestions for process optimization of China's LIBs industry were proposed based on the adjustment projection of China's LIB industry.

Introduction

In recent years, China is a leading producer of lithium-ion batteries (LIBs), which rely on essential components such as lithium, cobalt and graphite. The number of battery electric vehicles (BEVs) on the road is predicted to reach over 130 million globally by 2030 (Kapustin and Grushevenko 2020). The requirement for LIBs is anticipated to increase significantly, with an estimated global demand of 9300 GWh by 2030 (Lai, Chen et al. 2022). This growth in the BEV market is expected to be driven largely by China, which in the near future will have a significant impacts on the production and the disposal of LIBs. Given that LIBs are the primary power source for BEVs, their production, assembly, usage and disposal will result in significant environmental impacts (Ghandi and Paltsev 2020). China faces greater energy pressure compared to developed countries in particularly (Chen, Lai et al. 2022). Thus, it is critical to accurately estimate the life cycle resource consumption of various LIBs in China to mitigate potential environmental pressures.

New energy vehicles, in particular pure electric vehicles, have lower energy usage and atmospheric pollution discharge than gasoline-powered vehicles (Kelly, Dai et al. 2020). Promoting pure electric vehicles will help to solve our nation's problem with energy security (Haustein and Jensen 2018). BEVs use a variety of chemistries and battery architectures, including Li-ion, nickel metal hydride and sodium-nickel chloride (Asef, Milan et al. 2021). LIBs are being utilized extensively in BEVs in China, including those built of lithium manganese oxide (LMO), lithium iron phosphate (LFP), and lithium nickel cobalt manganese oxide (NCM) (Lei Zhang 2020). At the same time, the advancement of battery technology and commercial potential suggest that LIBs are better option for the growth of the BEVs industry due to their technological maturity and lower manufacturing costs (Diaz-Ramirez, Ferreira et al. 2020). In both mobile and permanent energy storage systems, LIBs are regarded as a crucial component to assist in lowering harmful emissions from the transportation sector by enabling electric mobility (Tourlomousis and Chang 2017).

Currently, there are various types of LIBs available, with LFP batteries and NCM batteries being the most commonly used in BEVs (Shu, Guo et al. 2021). In the context of electric passenger vehicles, the predominant LIB chemistry used in China is NCM 622 battery, although there are other types such as NCM 111 and NCM 811 available (Yang, Mu et al. 2020). However, the production and application of these batteries have the potential to emit greenhouse gases (GHG) and environmental damage during their whole life cycle (Manh-Kien, Mevawala et al. 2020). The carbon footprint associated with the production of LIBs can vary significantly depending on their chemical composition, ranging from 40 to 350 kg of carbon dioxide emissions per kWh of battery capacity (Chen, Lai et al. 2022). It is important to examine environmental effects across entire life cycle, including long lifespan and multiple stages (Kelly, Dai et al. 2020). One promising strategy for reducing the environmental impacts of LIBs is secondary use, which can delay disposal and provide commercial and environmental benefits (Ahmadi, Young et al. 2015).

Additionally, the environmental impacts of LIBs varies depending on the use of various materials, industrial procedures, manufacturing strategies and recycling methods (Du, Ouyang et al. 2017). To meet the demands of the LIBs industry, new cathode materials with greater density of energy and capacity are constantly being created (Wang, Wu et al. 2019). Currently, lithium iron phosphate is used as the positive electrode in LFP batteries, while the positive electrodes of NCM batteries consist of nickel, cobalt, and aluminum (Yang, Liu et al. 2021). Nevertheless, there is a persistent effort to develop cathode materials with greater energy density and capacity to meet the requirements of LIBs (Chakraborty, Banerjee et al. 2018).

The life cycle assessment LCA employed in this studies to quantify possible environmental impacts. This methodology comprehensively evaluated the environmental hotpots, which describes a technique for systematic analysis used to quantify the collection of raw materials, manufacturing, use of resources, transportation, disposal and any potential environmental effects from release (Arshad, Lin et al. 2022). The LCA can be used to pinpoint critical elements in the environmental effects of different LIBs and put forward strategies to effectively reduce environmental impacts.

There has been considerable attention given to conducting LCA research on LIBs in recent years, particularly in terms of resource utilization and environmental impacts (Liu, Liu et al. 2021). However, many studies have mainly focused on the "Production phase" of the battery and have not taken into account the potential impacts of battery recycling phase (Nordelof, Messagie et al. 2016). Additionally, few studies have investigated the overall environmental impacts of LIBs throughout entire life cycle (Wang, Deng et al. 2020). Instead, most of the available research has concentrated on a single stage of the life cycle. For example, some studies have examined the environmental impacts of NCM batteries, indicating that the material development phase contributes the most to energy utilization, potential for global warming and acidification (Sun, Luo et al. 2020). The production of NCM111 batteries, which involves cathode materials and aluminum manufacturing has been identified as a primary source of contamination by researchers (Dai, Kelly et al. 2019). In other studies, researchers used midpoint indicators to evaluate the environmental impacts of recycling phase (Ioakimidis, Murillo-Marrodán et al. 2019).

Scholars have also studied the environmental effects of various LIBs. To mention a few, MajeauBettez et al. assessed the environmental impacts of NCM batteries, NiMH batteries and LFP batteries during the manufacturing process and found that NiMH batteries posed the greatest environmental load (Majeau-Bettez, Hawkins et al. 2011). Smith et al. proved that solid-state batteries exhibit lower carbon emissions than lithium iron phosphate batteries during the manufacturing stage (Smith, Ibn-Mohammed et al. 2021). Oliveira et al. used Simapro software to evaluate several environmental variables of LMO batteries and LFP batteries (Oliveira, Messagie et al. 2015). These comparisons do not take into account the LIBs' entire life cycle. Besides, several studies examining the environmental effects of LIBs from other angles. For instance, Zackrisson et al. assessed the effect of LFP batteries produced using various solvents on the environment, which revealing that water exhibits superior performance than N-methyl-2-pyrrolidone (NMP) (Zackrisson, Avellán et al. 2010). While numerous research have looked into the effects on the environment of LIBs, less focus has been placed on the long-term environmental impacts of different types of LIBs throughout their life cycles. Therefore, more research is required to thoroughly assess the environmental impacts of different types of LIBs through entire life cycles.

The purpose of this study is to contribute new viewpoints to the existing body of literature by investigating the environmental impacts of three different types of batteries, namely LFP batteries, NCM 811 batteries and NCM622 batteries, which are widely utilized as energy storage units in BEVs. Through this study, we aim to offer a thorough insight of the environmental implications connected to the utilization of LIBs. The LCA approach was applied in this study, which enables to use the ReCiPe and CML assessment method to quantify the environmental effects at the midpoint levels. The results of the study help the LIBs industries identify the major substances and factors affecting the environment.

Methodology

The LCA technique was employed to the extent of ISO 14040-14044 standards, to analyze the whole life cycle of a product, process, service, or activity and assess its environmental effects in a quantitative manner (Daniele Landi 2022). In this study, the evaluation will strictly adhere to the international standard ISO 14044 to ensure the accuracy of the findings (Hua, Zhou et al. 2020).

Goal and scope

The functional unit (FU) was established as the rated capacity of 28 kWh battery pack, which was commonly utilized unit in previous LCA studies. To make the environmental effects of various batteries comparable, all the gathered data must be converted to FU, the accuracy of the calculated results depends on this (Wu, Hu et al. 2021). The LIB is made up of a single cell, a shell, a wire and a battery management system. The cathode, anode, electrolyte and diaphragm are the four most crucial components of the LIB used in BEVs (Tian, Qin et al. 2020). The weight of the NCM622 battery is 140 kg, the overall mass of the LFP battery is 180.65 kg, and the total mass of the NCM811 battery is 121.74 kg. **Table 1** shows the material composition of three batteries.

Scope of "cradle-to-grave" was employed in this study to evaluate the environmental effects of three LIBs, LFP batteries, NCM811 and NCM622 batteries throughout their entire life cycle. The research scope is shown in **Fig. 1**. The system boundaries were focused on the industrial production phase of LIBs, including first use in BEVs, transportation and recycling stages. The hydrometallurgical recycling method commonly used in China was utilized to investigate the environmental effects of the recycling process for decommissioned LIBs. However, the production and recycling of other electric vehicle components not related to the power battery were not considered in this study. The system boundaries of this study are depicted in **Fig. 2**.

Life cycle inventory

Life cycle inventory (LCI) analysis is a crucial step in constructing an input and output list for a product system to analyze its environmental impacts (Qiao, Zhao et al. 2017). LCI data can be obtained directly through experimentation (Bobba, Mathieux et al. 2018) or cooperation with companies (Koroma, Costa et al. 2021), or indirectly throughsources of literature, LCA software and databases (Wernet, Bauer et al. 2016). To ensure data completeness and representation, we conducted a field survey of three leading LIB factories and two recycling enterprises in China to collect primary LCI data. The data used in this study were mainly from technical data sheets and literature readings (Sun, Zheng et al. 2017), leading battery providers contributed data for environmental impacts evaluations. Ecoinvent 3.0 supplemented the inventory data. Data sources for three types of LIBs are listed in **Table 2.**

Life cycle impact assessment

One the one hand, due to the fact that LIBs have become such a growing issue in recent years, different LIBs have not been compared during their whole life cycles. On the other hand, LIB production technology is very mature, the assessment of its environmental impacts on the whole life cycle is helpful to provide the LIBs industries with an appropriate reference value. The purpose and scope of the research, the LCI statistics used, the conclusions made, the impact analysis technique and the categories considered all have an impact on the life cycle impact assessment (LCIA) of products (Wang, An et al. 2021). The creation of LIBs is a complicated process that uses resources, produces waste and releases different exhaust gases. To fully assess the environmental effects of LIBs, a variety of indicators must be used. The CML-IA baseline v3.05 and version 1.03 of the ReCiPe 2016 model were used to determine the LCA findings.

Interpretation

By life cycle interpretation, the primary contributing factors and essential components of LIBs' environmental effects are discovered. The environmental indexes of three LIBs' various phases are discussed, with each of the following topics covered: GHG, acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP), human toxicity potential (HTP), marine eutrophication potential (MEP), marine ecotoxicity potential (METP), freshwater ecotoxicity potential (FETP) and fine particulate matter formation (FPMF). It is important to identify critical stages and significant environmental weakness by summarizing and analyzing all indicators. The sensitivity analysis was carried out to identify the most sensitive substances to environmental impacts. Besides, it was possible to achieve the LIBs manufacturing method with the least amount of environmental impacts by creating scenarios to improve the strategy. Certain recommendations are put forward for the development of the LIBs industry.

Results And Discussion

Life cycle assessment results

This work conducts a life cycle environmental effects evaluation of LFP batteries and NCM batteries, which are widely utilized in BEVs. The environmental impacts of LIBs are evaluated and analyzed using Simapro software's CML-IA baseline v3.05 and ReCiPe 2016 v1.03 midway evaluation technique.

The findings of the LCA are shown in **Table 3**, which highlights the major contributing processes. The batteries' effects on the environment will vary depending on how they are assessed. The 11 evaluation indicators assessment findings reveal that the batteries would mostly cause environmental degradation in five areas. These include "human toxicity", "freshwater aquatic ecotoxicity", "global warming (GWP100a)", "abiotic depletion (fossil fuels)", "human toxicity", "and marine aquatic ecotoxicity". In various stages of their lives, the three batteries each have a unique influence on the environment. The three LIBs have the most substantial environmental contamination during the "Production phase" of the five stages indicated in **Table 3**, which is followed by the "Use phase," "Assembly phase" and "Transport phase" . In addition, **Table 3** shows that the recycling of NCM622 batteries and NCM811 batteries results in greater "Human toxicity", "Fresh water aquatic ecotoxicity" and "Marine aquatic ecotoxicity". This proved that the "Recycling stage" is not always a stage of offsetting environmental pollution.

Different battery types have quite varied effects on the environment. While NCM622 and NCM811 batteries demonstrate lower levels of "Human Toxicity" than LFP batteries during the "Production phase", the utilization of particular metals in manufacturing processes can lead to increased environmental impacts compared to LFP batteries. On the other hand, LFP batteries exhibit higher levels of environmental impacts than NCM622 and NCM811 batteries in 11 categories during the "Use phase" and "Transport phase", primarily due to lower energy density and higher weight as compared to NCM622 and NCM811 batteries. The findings of our study suggest that the choice of battery technology for BEVs should consider both the "Production phase" and "Use phase", as different battery types exhibit varying environmental impacts across different stages of their life cycles.

The research findings reveal that NCM622 batteries have a higher GHG emission than NCM811 batteries, as demonstrated by **Fig. 3**. In contrast, LFP batteries exhibit significantly lower GHG emissions at 1913.98 kg CO_2-eq/kWh, indicating that Prioritizing LFP battery utilization can successfully cut carbon emissions. Moreover, the study examined the GHG emissions contribution of various components in the production of LIBs. The results indicate that the assembly of NCM811 batteries resulted in GHG emission of 658.2 kg CO_2-eq/kWh, accounting for 31.5% of the total GHG emissions. Notably, the "Production phase" and "Assembly phase" are the primary contributors to GHG emissions across all phases of LIBs. These findings suggest that reducing emissions during the "Production and Assembly phases" of batteries should be a priority area for minimizing the environmental effect of LIBs.

The evaluation of the Acidification Potential (AP) index is crucial in assessing the emissions of components contributing to acid rain, such as sulfur dioxide (SO_2), nitrogen oxides (NO_X), nitrogen dioxide (NO_2) and others (AlShafi and Bicer 2021). **Fig. 4** depicts the AP of three types of LIBs during their entire life cycle. The analysis reveals that the primary contributor to AP is the "Production phase" of battery manufacturing. This is due to the fact that the preparation of raw materials for ternary precursors, such as nickel sulfate and cobalt sulfate, involves the use of concentrated sulfuric acid. The reaction of concentrated sulfuric acid results in the production of SO_2, which is the main component affecting AP. In contrast, LFP batteries require less metal sulfate in the preparation of precursors, thereby generating significantly lower AP levels during the "Production phase" compared to NCM622 and NCM811 batteries. These findings suggest that minimizing the use of concentrated sulfuric acid during the "Production phase" of LIBs is a promising approach to reduce AP.

Excessive nitrogen and phosphorus enrichment in plants and wastewater contributes to Eutrophication Potential (EP), which measures the level of nutrient enrichment in soil or water (Nwankwegu, Li et al. 2019). As shown in **Fig. 5**, the EP of LFP batteries is higher than NCM622 and NCM811 batteries. This is mainly because the primary raw material for the positive electrode generates ammonium-containing waste liquid during the "Production phase", which is the main factor causing eutrophication. The electrolyte in LIBs also generates EP. Furthermore, the EP of NCM811 batteries is marginally higher than NCM622 batteries. The findings suggest that reducing ammonium-containing waste liquid generation during the "Production phase" of LIBs is crucial in mitigating EP and reducing environmental impacts.

POCP is an index used to evaluate the extent of photochemical oxidation of waste gas emissions (Jeong, Jeon et al. 2020). High concentrations of ozone can have toxic effects on human health, leading to respiratory paralysis, lung function impairment, decreased exercise ability and even ecosystem damage (Holm and Balmes 2022). **Fig. 6** illustrates the POCP of the three types of LIBs. The "Production stage", especially the production of cathode materials, is found to be the main contributor to the POCP of NCM622 and NCM811 batteries. Conversely, LFP batteries exhibit much lower POCP values compared to NCM622 and NCM811 batteries. The increase in nickel content in NCM batteries results in higher POCP, likely due to the higher photochemical oxidation pollution caused by nickel sulfate compared to cobalt sulfate and manganese sulfate.

HTP is an evaluation index that measures how hazardous substances affect the human body (Smith, Hill et al. 2020). **Fig. 7** shows the HTP values for the three types of LIBs. The "Production phase" is found to be the main source of HTP for NCM622 and NCM811 batteries, due to the heavy metal elements such as nickel, cobalt and manganese present in these batteries, which can cause significant harm to human health. On the other hand, the HTP of LFP batteries mainly comes from the "Assembly phase", as energy consumption during this phase leads to the production of hazardous compounds. LFP batteries can be recycled to mitigate the risk to human health, unlike NCM622 and NCM811 batteries. **Table 4** presents a comparison of the energy consumption during the assembly of the three types of batteries.

Marine Eutrophication Pollution (MEP) is a type of water pollution caused by an imbalance in species distribution in marine ecosystems, which results in excessive growth of certain species due to high nutrient levels such as nitrogen and phosphorus (Paerl 2018). The root cause of MEP is the disproportionate input and output of nutrients. The MEP impact of three types of LIBs is depicted in **Fig. 8**. It is evident that the MEP index of NCM622 and NCM811 batteries during the "Production stage" is higher than that of LFP batteries. This is primarily because the production process of cathode materials for NCM622 and NCM811 batteries involves heavy metals that can lead to environmental pollution in water. Furthermore, the findings indicate that the MEP index of LFP batteries during the "Use phase" is higher than that of NCM622 and NCM811 batteries. This finding is of great concern and demands heightened attention.

Marine Ecotoxicological Pollution (METP) refers to the adverse effects of toxic chemical emissions on marine ecosystems, including the accumulation and discharge of substances like mercury, copper, lead and radioactive elements (Jackson, Eadsforth et al. 2016). **Fig. 9** illustrates the METP impact of three types of LIBs. The results reveal that the highest METP impact is during the "Production and Assembly stages" of cathode materials. This is likely due to the presence of heavy metal pollutants in cathode production and toxic pollutants produced during the "Assembly stage". Consistent with the MEP analysis, NCM622 and NCM811 batteries have a higher environmental impacts than LFP batteries. However, during the "Recycling stage", the environmental benefit of LFP batteries is higher than that of ternary lithium batteries.

Freshwater Ecotoxicological Pollution (FETP) is a measure of the impact of pollutants on freshwater ecology. It refers to the interdependent relationship between all biological communities and their physical and chemical environment within a given water area, formed through the cycling of substances (Aurisano, Albizzati et al. 2019). **Fig. 10** presents the FETP impact of three types of LIBs throughout their lifec ycle. The causes of FETP during the battery "Production stage" are consistent with those of METP, which involve the presence of heavy metal pollutants and toxic substances. These causes will not be elaborated upon here.

The Toxicity and Ecotoxicity Potential (TETP) aims to assess the impact of various toxic and harmful factors on soil ecosystems (Sydow, Chrzanowski et al. 2020). **Fig. 11** illustrates that the TETP associated with NCM622 and NCM811 batteries primarily arises from the battery "Production phase" and "Assembly stage". However, for LFP batteries, the TETP mainly originates from the battery "Use phase" and "Production stage". During the production of LIBs, heavy metals may infiltrate the soil, leading to plant malnutrition and physiological disorders. Additionally, the use of coal-generated electricity in the "Use stage" may produce sulfides, which are toxic to soil. This poses a significant risk to the health and well-being of the soil ecosystem.

The term FPMF refers to the formation of solid or liquid particles that are uniformly dispersed in an aerosol system (Shafique and Luo 2022). Research has revealed that prolonged exposure to particulate matter in the atmosphere raises the risk of developing lung cancer (Ciabattini, Rizzello et al. 2021). **Fig. 12** illustrates the FPMF values for the entire life cycle of three types of LIB batteries. It is evident that NCM622 and NCM811 batteries have a higher FPMF compared to LFP batteries, with major contribution originating from the production of cathode materials. Conversely, LFP batteries have a relatively lower FPMF due to the use of fewer heavy metal salts in cathode material production. Moreover, the FPMF of NCM batteries increases as the nickel content in the cathode material rises.

Identification of significant environmental impacts

Currently, LIBs are commonly recycled using hydrometallurgy and pyrometallurgy. This study employed the hydrometallurgy method for LIB recycling. **Fig. 13** displays a comparison of 11 ecological indicators across the entire life cycle of three LIBs. The analysis reveals that the "Production phase" of all three LIBs has the most significant impact on ecological metrics, with battery assembly also contributing significantly to various ecological indicators. The "Assembly process" requires substantial power consumption due to constant temperature and humidity, the environmental burden is closely related to China's power structure, with the average power generation in China in 2020 being 67.9% thermal, 17.0% hydro, 6.0% wind, 3.5% PV and 5.6% others (CEC 2021). Furthermore, during the "Transportation phase", LFP batteries consume more energy than NCM batteries. In terms of the TETP, the "Use stage" of all three batteries contributes the most, with the GHG and HTP also playing significant roles.

The study found that the "Production stage" of NCM622 battery is the largest contributor to Abiotic depletion (fossil fuel) and GHG in the ternary lithium battery system. During the "Assembly and Transportation phases", the contribution of NCM811 battery is almost identical to that of NCM622 battery. However, NCM622 battery has a greater impact on fossil fuel consumption than NCM811 battery. As the development of LIBs moves towards high nickel content, it is important to consider ecological indexes such as AP, EP and POCP. In the case of LFP battery systems, almost all Abiotic depletion (fossil fuels), GHG and HTP occur during the "Use phase". The study also found that the highest contribution value to marine aquatic ecotoxicity occurs throughout the entire life cycle of LFP batteries.

Sensitivity analysis

The analysis highlights that the "Production stage" of LIBs materials has the most significant impact on environmental sustainability, particularly for positive active materials. To ensure the accuracy of the model, expert consultation was utilized to assume that the cathode active material's mass and battery energy density remain unchanged despite variations in the material's chemical properties. By analyzing the sensitivities of LFP batteries and NCM batteries over their life cycles, this study determined the key parameters that have a high sensitivity and impact the model output. The sensitivity of each parameter was carefully examined to identify the critical factors that have the most substantial impact on the battery's environment.

This study employed a floating interval of 10% for sensitivity analysis and presented the results in **Fig. 14** and **Fig. 15**. The findings reveal that electricity usage is the most sensitive factor throughout the entire life cycle of LFP batteries. In contrast, for NCM batteries, the precursor material in the cathode material was identified as the most sensitive factor. This is primarily because of the increased $NiSO_4$ content during the production of NCM 811 precursor, which leads to higher consumption of steam, LiOH and oxygen.

Scenario analysis

Increasing the proportion of clean energy sources in the production of LFP batteries can effectively mitigate environmental impacts throughout their life cycle, as demonstrated in **Fig. 16**. An analysis of various energy sources, such as natural gas, hydropower, biomass and wind power, revealed that hydropower has the greatest potential for reducing greenhouse gas emissions, followed by wind power. Moreover, the use of clean energy sources can decrease environmental indicators such as HTP, FATP, METP and EP, but may increase TETP. In the short term, carbon emissions from battery production can be reduced by remanufacturing batteries using recycled materials. In the long term, the LIBs industry's carbon emissions problem can be resolved through the adoption of green electricity structures and negative carbon technologies.

Currently, various methods are used to prepare cathode materials for ternary lithium batteries, such as coprecipitation, hydrothermal, sol-gel, solid phase and combustion methods. The coprecipitation method involves dissolving the metal salt solution with nickel, cobalt and manganese, precipitating each component according to the stoichiometric ratio, and obtaining the precursor through extraction and filtration treatment. The precursor is transformed into the ternary cathode material through high-temperature burning. In this study, the sol-gel method was employed to prepare the positive electrode material of ternary lithium battery, using lithium acetate, nickel acetate, manganese acetate and acetic acid as raw materials. The optimization diagrams of the two ternary lithium batteries are shown in **Fig. 17**. The positive electrode material was obtained by grinding and calcination. The environmental impacts of the NCM811 and NAM622 batteries prepared by the sol-gel method was analyzed and the optimization diagrams were presented, indicating a significant reduction in five environmental impacts indexes, including AD, POCP, AP, FAETP and HTP. Detailed data are available in **Table 5**.

Industrial recommendations

Research results underline how crucial it is to take into account a battery's whole life cycle in order to precisely calculate its environmental impacts and make defensible choices in a variety of applications. As LIBs technology continues to evolve, ongoing environmental LCA research is necessary to guide the design of power lithium batteries and provide effective strategies for the entire value chain, particularly to address the environmental burden during the "Production phase". Moreover, hydrometallurgical methods are recommended for the recycling of LIBs.

One of the key challenges in the development of environmentally-friendly batteries is how to achieve high energy density while using sustainable materials. NCM batteries rely on precious metals such as nickel, cobalt and manganese, have achieved high energy density but pose significant environmental risks. On the other hand, LFP batteries are more eco-friendly but have lower energy density compared to ternary lithium batteries. To optimize LIBs technology, future research must focus on finding ways to improve both the environmental sustainability and energy density of battery materials. It is essential to focus on optimizing the cathode active materials to improve the environmental impacts of LIB batteries, while prioritizing the impact of different life cycle stages.

Conclusions

The study found that NCM batteries have a greater environmental impacts during the "Production stage" compared to LFP batteries. The packaging process during battery assembly was identified as a significant contributor to the environmental impacts of LFP batteries, specifically in terms of POCP, GHG and FEP. Although BEVs equipped with LFP batteries consume more energy during "Transportation phase", the study concluded that using LFP batteries is more environmentally friendly than using NCM622 and NCM811 batteries throughout entire life cycle. The "Production stage" was identified as the main factor influencing the environmental impact of NCM811 batteries, with a high proportion of environmental burden in POCP and FPMF. In summary, the analysis indicates that LFP batteries are more environmentally sustainable than NCM622 and NCM811 batteries. However, the study found that overall, NCM811 batteries provide greater environmental benefits than NCM622 batteries.

The study suggests that enhancing electrochemical efficiency of NCM622 and NCM811 batteries, as well as expanding the usage of sustainable energy in LFP battery production are essential for reducing the influence on the environment of LIBs throughout their entire life cycle. According to the study, LIBs have a significant environmental impact, with a large proportion of impact attributed to GHG and AP. Furthermore, the electrolyte of LIBs contains lithium hexafluorophosphate, which is highly toxic, and its decomposition products can release hydrogen fluoride, which is extremely harmful to human health. Regarding the "Recycling stage", the study found that the hydrometallurgical recycle of LIBs provides significant environmental benefits for almost every type of environmental impacts. However, the hydrometallurgical process of NCM batteries involves a large amount of ammonia, which has a significant effect on EP. The precursor materials in NCM batteries and the electricity consumption of LFP batteries are sensitive factors to environmental hotpots, which can be effectively improved by optimizing the power structure and production process.

Abbreviations

LCIA	Life cycle impact assessment	LFP	Lithium iron phosphate
AP	Acidification potential	LIB	Lithium-ion battery
BEVs	Battery electric vehicles	LIBs	Lithium-ion batteries
EOL	End of life	LMO	lithium manganese oxide
EP	Eutrophication potential	NCM	Lithium nickel cobalt manganese oxide
FETP	Freshwater ecotoxicity potential	METP	Marine ecotoxicity potential
FEP	Freshwater eutrophication potential	MEP	Marine eutrophication potential
FPMF	Fine particulate matter formation	NMP	N-methyl-2-pyrrolidone
FU	Functional unit	NO2	Nitrogen dioxide
GHG	Greenhouse gas	NOX	Nitrogen oxides
GWP	Global warming potential	POCP	Photochemical oxidant creation potential
HTP	Human toxicity potential	PVDF	Polyvinylidene fluoride
LCA	Life cycle assessment	SO2	Sulfur dioxide
LCI	Life cycle inventory	TETP	Terrestrial ecotoxicity potential

Declarations

Acknowledgements This work was supported by Major Science and Technology Program for Development and Demonstration on Key Technologies for Urban Advanced Sewage Treatment (ZJWM-KJYF-2021-A-01) from CCCC Sinobioway Environmental Protection Co., Ltd., Jinan China.

Author contribution Tingting Jiang: investigation, data analysis, software, and writing-original draft preparation; Huifang Wang: resources, supervision, writing-review and editing, and visualization; Qiang Jin: conceptualization and methodology. All authors of this paper have directly participated in this study's writing, editing, planning, execution, and analysis.

Corresponding author Correspondence to: Qiang Jin, School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China. E-mail addresses: jiangtingting@ sit. edu. cn (T. Jiang), jinqiang@ sjtu. edu. cn (Q. Jin).

Funding We declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data availability The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate We affirm that all authors have participated in the investigation and writing work and are fully aware of ethical responsibilities.

Consent for publication We affirm that all authors have agreed on the submission of the paper to ESPR and are fully aware of ethical responsibilities.

Competing interests 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.

References

1. Ahmadi, L., S. B. Young, M. Fowler, R. A. Fraser and M. A. Achachlouei (2015). "A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems." The International Journal of Life Cycle Assessment **22**(1): 111-124. http://doi.org/10.1007/s11367-015-0959-7
2. AlShafi, M. and Y. Bicer (2021). "Life cycle assessment of compressed air, vanadium redox flow battery, and molten salt systems for renewable energy storage." Energy Reports **7**: 7090-7105. http://doi.org/10.1016/j.egyr.2021.09.161
3. Arshad, F., J. Lin, N. Manurkar, E. Fan, A. Ahmad, M.-u.-N. Tariq, F. Wu, R. Chen and L. Li (2022). "Life Cycle Assessment of Lithium-ion Batteries: A Critical Review." Resources Conservation and Recycling **180**. http://doi.org/10.1016/j.resconrec.2022.106164
4. Asef, P., M. Milan, A. Lapthorn and S. Padmanaban (2021). "Future Trends and Aging Analysis of Battery Energy Storage Systems for Electric Vehicles." Sustainability **13**(24). http://doi.org/10.3390/su132413779
5. Aurisano, N., P. F. Albizzati, M. Hauschild and P. Fantke (2019). "Extrapolation Factors for Characterizing Freshwater Ecotoxicity Effects." Environmental Toxicology and Chemistry **38**(11): 2568-2582. http://doi.org/10.1002/etc.4564
6. Bobba, S., F. Mathieux, F. Ardente, G. A. Blengini, M. A. Cusenza, A. Podias and A. Pfrang (2018). "Life Cycle Assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows." Journal of Energy Storage **19**: 213-225. http://doi.org/10.1016/j.est.2018.07.008
7. CEC. (2021). "Annual report on development of China power industry 2021." from cec. org. cn/menu/index. html?688. (Accessed January 2022).
8. Chakraborty, S., A. Banerjee, T. Watcharatharapong, R. B. Araujo and R. Ahuja (2018). "Current computational trends in polyanionic cathode materials for Li and Na batteries." Journal of Physics-Condensed Matter **30**(28). http://doi.org/10.1088/1361-648X/aac62d
9. Chen, Q., X. Lai, H. Gu, X. Tang, F. Gao, X. Han and Y. Zheng (2022). "Investigating carbon footprint and carbon reduction potential using a cradle-to-cradle LCA approach on lithium-ion batteries for electric vehicles in China." Journal of Cleaner Production **369**. http://doi.org/10.1016/j.jclepro.2022.133342
10. Ciabattini, M., E. Rizzello, F. Lucaroni, L. Palombi and P. Boffetta (2021). "Systematic review and meta-analysis of recent high-quality studies on exposure to particulate matter and risk of lung cancer." Environmental Research **196**. http://doi.org/10.1016/j.envres.2020.110440
11. Dai, Q., J. C. Kelly, L. Gaines and M. Wang (2019). "Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications." Batteries **5**(2). http://doi.org/10.3390/batteries5020048

12. Daniele Landi, M. M., Giorgia Pietronib (2022). "Comparative life cycle assessment of two different battery technologies:lithium iron phosphate and sodium-sulfur." http://doi.org/https://doi.org/10.1016/j.procir.2022.02.080
13. Diaz-Ramirez, M. C., V. J. Ferreira, T. Garcia-Armingol, A. M. Lopez-Sabiron and G. Ferreira (2020). "Battery Manufacturing Resource Assessment to Minimise Component Production Environmental Impacts." Sustainability **12**(17). http://doi.org/10.3390/su12176840
14. Du, J., M. Ouyang and J. Chen (2017). "Prospects for Chinese electric vehicle technologies in 2016–2020: Ambition and rationality." Energy **120**: 584-596. http://doi.org/10.1016/j.energy.2016.11.114
15. Ghandi, A. and S. Paltsev (2020). "Global CO2 impacts of light-duty electric vehicles." Transportation Research Part D: Transport and Environment **87**. http://doi.org/10.1016/j.trd.2020.102524
16. Haustein, S. and A. F. Jensen (2018). "Factors of electric vehicle adoption: A comparison of conventional and electric car users based on an extended theory of planned behavior." International Journal of Sustainable Transportation **12**(7): 484-496. http://doi.org/10.1080/15568318.2017.1398790
17. Holm, S. M. and J. R. Balmes (2022). "Systematic Review of Ozone Effects on Human Lung Function, 2013 Through 2020." Chest **161**(1): 190-201. http://doi.org/10.1016/j.chest.2021.07.2170
18. Hua, Y., S. Zhou, Y. Huang, X. Liu, H. Ling, X. Zhou, C. Zhang and S. Yang (2020). "Sustainable value chain of retired lithium-ion batteries for electric vehicles." Journal of Power Sources **478**. http://doi.org/10.1016/j.jpowsour.2020.228753
19. Ioakimidis, C., A. Murillo-Marrodán, A. Bagheri, D. Thomas and K. Genikomsakis (2019). "Life Cycle Assessment of a Lithium Iron Phosphate (LFP) Electric Vehicle Battery in Second Life Application Scenarios." Sustainability **11**(9). http://doi.org/10.3390/su11092527
20. Jackson, M., C. Eadsforth, D. Schowanek, T. Delfosse, A. Riddle and N. Budgen (2016). "COMPREHENSIVE REVIEW OF SEVERAL SURFACTANTS IN MARINE ENVIRONMENTS: FATE AND ECOTOXICITY." Environmental Toxicology and Chemistry **35**(5): 1077-1086. http://doi.org/10.1002/etc.3297
21. Jeong, B., H. Jeon, S. Kim, J. Kim and P. Zhou (2020). "Evaluation of the Lifecycle Environmental Benefits of Full Battery Powered Ships: Comparative Analysis of Marine Diesel and Electricity." Journal of Marine Science and Engineering **8**(8). http://doi.org/10.3390/jmse8080580
22. Kapustin, N. O. and D. A. Grushevenko (2020). "Long-term electric vehicles outlook and their potential impact on electric grid." Energy Policy **137**. http://doi.org/10.1016/j.enpol.2019.111103
23. Kelly, J. C., Q. Dai and M. Wang (2020). "Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries (vol 13, pg 514, 2020)." Mitigation and Adaptation Strategies for Global Change **25**(3): 495-495. http://doi.org/10.1007/s11027-020-09913-6
24. Koroma, M. S., D. Costa, G. Cardellini, M. Messagie and Ieee (2021). Life Cycle Assessment of Lithium-ion Battery Pack: Implications of Second-life and Changes in Charging Electricity. 18th IEEE Vehicle Power and Propulsion Conference (IEEE VPPC), Electr Network.
25. Lai, X., Q. Chen, X. Tang, Y. Zhou, F. Gao, Y. Guo, R. Bhagat and Y. Zheng (2022). "Critical review of life cycle assessment of lithium-ion batteries for electric vehicles: A lifespan perspective." eTransportation **12**. http://doi.org/10.1016/j.etran.2022.100169
26. Lai, X., H. Gu, Q. Chen, X. Tang, Y. Zhou, F. Gao, X. Han, Y. Guo, R. Bhagat and Y. Zheng (2022). "Investigating greenhouse gas emissions and environmental impacts from the production of lithium-ion batteries in China." Journal of Cleaner Production **372**. http://doi.org/10.1016/j.jclepro.2022.133756
27. Lei Zhang, Y. L. a. B. P. (2020). "China's Development on New Energy Vehicle Battery Industry: Based on Market and Bibliometrics." http://doi.org/10.1088/1755-1315/581/1/012003
28. Liu, W., H. Liu, W. Liu and Z. Cui (2021). "Life cycle assessment of power batteries used in electric bicycles in China." Renewable and Sustainable Energy Reviews **139**. http://doi.org/10.1016/j.rser.2020.110596
29. Majeau-Bettez, G., T. R. Hawkins and A. H. Stromman (2011). "Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles." Environ Sci Technol **45**(10): 4548-4554.

http://doi.org/10.1021/es103607c

30. Manh-Kien, T., A. Mevawala, S. Panchal, K. Raahemifar, M. Fowler and R. Fraser (2020). "Effect of integrating the hysteresis component to the equivalent circuit model of Lithium-ion battery for dynamic and non-dynamic applications." Journal of Energy Storage **32**. http://doi.org/10.1016/j.est.2020.101785
31. Nordelof, A., M. Messagie, A.-M. Tillman, M. L. Soderman and J. Van Mierlo (2016). "Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles-what can we learn from life cycle assessment? (vol 19, pg 1866, 2014)." International Journal of Life Cycle Assessment **21**(1): 134-135. http://doi.org/10.1007/s11367-015-1004-6
32. Nwankwegu, A. S., Y. Li, Y. Huang, J. Wei, E. Norgbey, L. Sarpong, Q. Lai and K. Wang (2019). "Harmful algal blooms under changing climate and constantly increasing anthropogenic actions: the review of management implications." 3 Biotech **9**(12). http://doi.org/10.1007/s13205-019-1976-1
33. Oliveira, L., M. Messagie, S. Rangaraju, J. Sanfelix, M. H. Rivas and J. Van Mierlo (2015). "Key issues of lithium-ion batteries - from resource depletion to environmental performance indicators." Journal of Cleaner Production **108**: 354-362. http://doi.org/10.1016/j.jclepro.2015.06.021
34. Paerl, H. W. (2018). "Mitigating Toxic Planktonic Cyanobacterial Blooms in Aquatic Ecosystems Facing Increasing Anthropogenic and Climatic Pressures." Toxins **10**(2). http://doi.org/10.3390/toxins10020076
35. Qiao, Q., F. Zhao, Z. Liu, S. Jiang and H. Hao (2017). "Cradle-to-gate greenhouse gas emissions of battery electric and internal combustion engine vehicles in China." Applied Energy **204**: 1399-1411. http://doi.org/10.1016/j.apenergy.2017.05.041
36. Raugei, M. and P. Winfield (2019). "Prospective LCA of the production and EoL recycling of a novel type of Li-ion battery for electric vehicles." Journal of Cleaner Production **213**: 926-932. http://doi.org/10.1016/j.jclepro.2018.12.237
37. Shafique, M. and X. Luo (2022). "Environmental life cycle assessment of battery electric vehicles from the current and future energy mix perspective." Journal of Environmental Management **303**. http://doi.org/10.1016/j.jenvman.2021.114050
38. Shu, X., Y. Guo, W. Yang, K. Wei and G. Zhu (2021). "Life-cycle assessment of the environmental impact of the batteries used in pure electric passenger cars." Energy Reports **7**: 2302-2315. http://doi.org/10.1016/j.egyr.2021.04.038
39. Silvestri, L., A. Forcina, G. Arcese and G. Bella (2020). "Recycling technologies of nickel-metal hydride batteries: An LCA based analysis." Journal of Cleaner Production **273**. http://doi.org/10.1016/j.jclepro.2020.123083
40. Silvestri, L., A. Forcina, G. Arcese and G. Bella (2020). "Recycling technologies of nickel–metal hydride batteries: An LCA based analysis." Journal of Cleaner Production **273**. http://doi.org/10.1016/j.jclepro.2020.123083
41. Smith, C., A. K. Hill and L. Torrente-Murciano (2020). "Current and future role of Haber-Bosch ammonia in a carbon-free energy landscape." Energy & Environmental Science **13**(2): 331-344. http://doi.org/10.1039/c9ee02873k
42. Smith, L., T. Ibn-Mohammed, D. Astudillo, S. Brown, I. M. Reaney and S. C. L. Koh (2021). "The Role of Cycle Life on the Environmental Impact of Li6.4La3Zr1.4Ta0.6O12 based Solid-State Batteries." Advanced Sustainable Systems **5**(2). http://doi.org/10.1002/adsu.202000241
43. Sun, X., X. Luo, Z. Zhang, F. Meng and J. Yang (2020). "Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles." Journal of Cleaner Production **273**. http://doi.org/10.1016/j.jclepro.2020.123006
44. Sun, X., J. H. Zheng, P. Zhang, M. N. Zhao, H. X. Wu and Y. T. Yan (2017). "Comparative Life Cycle Assessment of Chinese Radial Passenger Vehicle Tire." Materials Science Forum **898**: 2432-2445. http://doi.org/10.4028/www.scientific.net/MSF.898.2432
45. Sydow, M., L. Chrzanowski, M. Z. Hauschild and M. Owsianiak (2020). "Influence of metal speciation on soil ecotoxicity impacts in life cycle assessment." Journal of Environmental Management **266**. http://doi.org/10.1016/j.jenvman.2020.110611
46. Tian, H., P. Qin, K. Li and Z. Zhao (2020). "A review of the state of health for lithium -ion batteries: Research status and suggestions." Journal of Cleaner Production **261**. http://doi.org/10.1016/j.jclepro.2020.120813

47. Tourlomousis, F. and R. C. Chang (2017). "Dimensional Metrology of Cell-matrix Interactions in 3D Microscale Fibrous Substrates." Procedia CIRP **65**: 32-37. http://doi.org/10.1016/j.procir.2017.04.009
48. Wang, F., Y. Deng and C. Yuan (2020). "Life cycle assessment of lithium oxygen battery for electric vehicles." Journal of Cleaner Production **264**. http://doi.org/10.1016/j.jclepro.2020.121339
49. Wang, L., H. Wu, Y. Hu, Y. Yu and K. Huang (2019). "Environmental Sustainability Assessment of Typical Cathode Materials of Lithium-Ion Battery Based on Three LCA Approaches." Processes **7**(2). http://doi.org/10.3390/pr7020083
50. Wang, Y., N. An, L. Wen, L. Wang, X. Jiang, F. Hou, Y. Yin and J. Liang (2021). "Recent progress on the recycling technology of Li-ion batteries." Journal of Energy Chemistry **55**: 391-419. http://doi.org/10.1016/j.jechem.2020.05.008
51. Wernet, G., C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz and B. Weidema (2016). "The ecoinvent database version 3 (part I): overview and methodology." International Journal of Life Cycle Assessment **21**(9): 1218-1230. http://doi.org/10.1007/s11367-016-1087-8
52. Wu, H., Y. Hu, Y. Yu, K. Huang and L. Wang (2021). "The environmental footprint of electric vehicle battery packs during the production and use phases with different functional units." International Journal of Life Cycle Assessment **26**(1): 97-113. http://doi.org/10.1007/s11367-020-01836-3
53. Yang, Gu, Guo and Chen (2019). "Comparative Life Cycle Assessment of Mobile Power Banks with Lithium-Ion Battery and Lithium-Ion Polymer Battery." Sustainability **11**(19). http://doi.org/10.3390/su11195148
54. Yang, J., D. Mu, X. Li and I. O. P. Publishing (2020). A system dynamics analysis about the recycling and reuse of new energy vehicle power batteries: an insight of closed-loop supply chain. 6th International Conference on Energy Materials and Environment Engineering (ICEMEE), Electr Network.
55. Yang, X.-G., T. Liu and C.-Y. Wang (2021). "Thermally modulated lithium iron phosphate batteries for mass-market electric vehicles." Nature Energy **6**(2): 176-185. http://doi.org/10.1038/s41560-020-00757-7
56. Yao, Y., M. Zhu, Z. Zhao, B. Tong, Y. Fan and Z. Hua (2018). "Hydrometallurgical Processes for Recycling Spent Lithium-Ion Batteries: A Critical Review." Acs Sustainable Chemistry & Engineering **6**(11): 13611-13627. http://doi.org/10.1021/acssuschemeng.8b03545
57. Yuan, C., H. Cao, K. Shen, Y. Deng, D. Zeng, Y. Dong and M. Hauschild (2021). "Water-based manufacturing of lithium ion battery for life cycle impact mitigation." Cirp Annals-Manufacturing Technology **70**(1): 25-28. http://doi.org/10.1016/j.cirp.2021.04.038
58. Zackrisson, M., L. Avellán and J. Orlenius (2010). "Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles – Critical issues." Journal of Cleaner Production **18**(15): 1519-1529. http://doi.org/10.1016/j.jclepro.2010.06.004
59. Zhao, S. and F. You (2019). "Comparative Life-Cycle Assessment of Li-Ion Batteries through Process-Based and Integrated Hybrid Approaches." ACS Sustainable Chemistry & Engineering **7**(5): 5082-5094. http://doi.org/10.1021/acssuschemeng.8b05902

Tables

Table 1 The material composition for the three types of 1 kWh battery systems (Shu, Guo et al. 2021)

Item	LFP	NCM811	NCM622
Cathode	25.2	26.8	26.4
Anode	15.3	15.5	15.6
Polypropylene	4.6	4.2	4.2
Copper Foil	12.8	12.9	12.9
Aluminum	18.3	18.1	18.5
Electrolyte	13.9	11.8	11.6
Stell	2.2	2.4	2.6
PVDF	3.4	3.2	3.1
Electronic Parts	0.6	0.7	0.7
Thermal Insulation	1.3	1.2	1.2
Carbon Black	2.1	2.4	2.4
Polyethylene	0.3	0.8	0.8

Table 2 Data sources for three types of LIBs

Name	Data source
Material	
NCM Precursor	Factories
Active Material: NCM 811	(Chen, Lai et al. 2022)
Active Material: NCM 622	(Sun, Luo et al. 2020)
Active Material: LFP	(Zhao and You 2019)
Graphite	Ecoinvent
Binder: PVDF	(Yuan, Cao et al. 2021)
Copper	Ecoinvent
Separator	(Silvestri, Forcina et al. 2020)
Wrought Aluminum	Ecoinvent
Electrolyte: $LiPF_6$	(Zhao and You 2019)
Electrolyte: EC	(Yang, Gu et al. 2019)
Plastic: Polypropylene	Ecoinvent
Steel	Factories
Coolant: Glycol	Ecoinvent
Electronic Parts	Ecoinvent
Energy and resources	
Electricity	Factoriesy
Steam	(Yao, Zhu et al. 2018)
Natural gas	(Silvestri, Forcina et al. 2020)
Water	(Raugei and Winfield 2019)

Table 3 LCA results of 28 kWh LFP batteries NCM622 batteries and NCM811 batteries (CML-IA baseline v3.05)

No	Impact category	Unit	Type of battery	Total	Production phase	Assembly phase	Transport phase	Use phase	Recycle phase
1	Abiotic depletion	kg Sb eq	LFP	2.93E-02	8.34E-04	6.81E-05	5.05E-06	4.70E-05	-1.29E-03
			NCM622	2.32E-02	2.51E-02	1.12E-04	5.07E-06	3.08E-05	-2.05E-03
			NCM811	2.18E-02	2.23E-02	1.14E-04	5.07E-06	2.86E-05	-7.01E-04
2	Abiotic depletion (fossil fuels)	MJ	LFP	2.03E+04	6.77E+03	6.55E+03	8.13E+02	6.71E+03	-5.35E+02
			NCM622	1.91E+04	8.53E+03	6.02E+03	8.16E+02	3.31E+03	4.19E+02
			NCM811	1.85E+04	7.43E+03	6.12E+03	8.16E+02	4.15E+03	-4.84E+00
3	Global warming (GWP100a)	kg CO_2 eq	LFP	1.75E+03	6.24E+02	6.81E+02	1.36E+01	4.81E+02	-5.21E+01
			NCM622	1.89E+03	8.10E+02	6.30E+02	1.24E+01	3.95E+02	4.04E+01
			NCM811	1.89E+03	7.45E+02	6.39E+02	1.19E+01	4.90E+02	4.82E+00
4	Ozone layer depletion (ODP)	kg CFC-11 eq	LFP	1.15E-04	1.29E-05	1.12E-05	1.04E-05	8.57E-05	-4.96E-06
			NCM622	1.28E-04	7.13E-05	1.01E-05	1.05E-05	3.18E-06	3.29E-05
			NCM811	9.15E-05	7.25E-05	1.04E-05	1.05E-05	1.38E-06	-3.38E-06
5	Human toxicity	kg 1,4-DB eq	LFP	3.58E+02	2.22E+02	2.04E+02	2.44E+00	8.03E+01	-1.50E+02
			NCM622	2.08E+03	1.88E+03	1.92E+02	2.45E+00	1.19E+02	2.42E+01
			NCM811	1.98E+03	1.68E+03	1.94E+02	2.45E+00	1.49E+02	4.02E+01
6	Fresh water aquatic ecotox.	kg 1,4-DB eq	LFP	2.73E+02	1.56E+02	1.48E+02	1.13E+00	1.66E+01	-4.88E+01
			NCM622	1.97E+03	1.87E+03	1.51E+02	1.13E+00	8.40E+01	1.37E+01
			NCM811	1.93E+03	1.73E+03	1.52E+02	1.13E+00	1.07E+02	1.98E+01
7	Marine aquatic ecotoxicity	kg 1,4-DB eq	LFP	1.78E+06	9.14E+05	9.56E+05	3.90E+03	5.44E+04	-1.46E+05
			NCM622	4.94E+06	3.67E+06	8.90E+05	3.92E+03	5.42E+05	1.64E+05
			NCM811	4.92E+06	3.38E+06	9.00E+05	3.92E+03	7.00E+05	6.81E+04
8	Terrestrial ecotoxicity	kg 1,4-DB eq	LFP	7.82E-01	7.09E-01	9.83E-01	1.46E-02	3.04E-01	-8.50E-01
			NCM622	5.56E+00	4.35E+00	9.33E-01	1.46E-02	4.00E-01	-1.37E-01
			NCM811	5.30E+00	3.91E+00	9.44E-01	1.46E-02	5.11E-01	-7.16E-02
9	Photochemical oxidation	kg C2H4 eq	LFP	3.22E-01	1.22E-01	1.07E-01	5.51E-03	1.14E-01	-2.64E-02
			NCM622	3.07E+00	3.12E+00	9.92E-02	5.28E-03	1.42E-01	-2.88E-01
			NCM811	3.95E+00	3.79E+00	1.01E-01	5.40E-03	1.82E-01	-1.32E-01
10	Acidification	kg SO_2 eq	LFP	7.76E+00	7.73E+00	2.76E+00	9.17E-02	2.88E+00	-7.10E-01
			NCM622	7.73E+01	5.80E+01	2.56E+00	8.65E-02	3.82E+00	-5.19E+00
			NCM811	7.43E+01	7.99E+01	2.59E+00	8.98E-02	4.92E+00	-3.18E+00
11	Eutrophication	kg PO_4–- eq	LFP	5.40E+00	4.78E+00	6.02E-01	1.11E-02	2.63E-01	-2.56E-01
			NCM622	4.50E+00	3.59E+00	5.62E-01	1.10E-02	4.13E-01	-7.46E-02
			NCM811	4.61E+00	3.47E+00	5.69E-01	1.10E-02	5.20E-01	-3.80E-02

Table 4 Energy consumption of three batteries assembly in China (Lai, Gu et al. 2022)

Produce	Energy consumption(MJ/kWh)		
	LFP	NCM811	NCM622
Mixture	1.51	1.3	1.34
Coating	2.51	2.17	2.23
Drying	100	86.49	88.89
Rolling	5.03	4.35	4.47
Cutting	10.15	8.78	9.02
Lamination	12.56	10.87	11.17
Encapsulation	4.52	3.91	4.02
Liquid injection	10.05	8.69	8.93
Pre-formation	6.35	5.49	5.64
Forming	1.51	1.30	1.34
Aging	1.26	1.09	1.12
Assigning	12.56	10.87	11.17
Drying	93.75	81.08	83.33
Total	261.75	226.38	232.67

Table 5 Optimization results of ternary lithium battery precursor materials

Impact category	Unit	NCM811 Total	NCM811 optimization	NCM622 Total	NCM622 optimization
AD	kg Sb eq	2.18E-02	9.93E-03	2.37E-02	1.02E-02
ADF	MJ	1.85E+04	1.90E+04	1.95E+04	2.01E+04
GWP	kg CO_2 eq	1.89E+03	1.80E+03	1.93E+03	1.83E+03
ODP	kg CFC-11 eq	9.15E-05	9.57E-05	1.31E-04	1.36E-04
HTP	kg 1,4-DB eq	1.98E+03	1.21E+03	2.12E+03	1.23E+03
FETP	kg 1,4-DB eq	1.93E+03	1.06E+03	2.01E+03	1.02E+03
METP	kg 1,4-DB eq	4.92E+06	3.56E+06	5.05E+06	3.50E+06
TETP	kg 1,4-DB eq	5.30E+00	3.83E+00	5.68E+00	4.00E+00
POCP	kg C2H4 eq	2.95E+00	1.41E+00	3.14E+00	1.38E+00
AP	kg SO_2 eq	7.43E+01	3.46E+01	7.90E+01	3.36E+01
EP	kg PO_4— eq	4.61E+00	3.25E+00	4.60E+00	3.05E+00

Figures

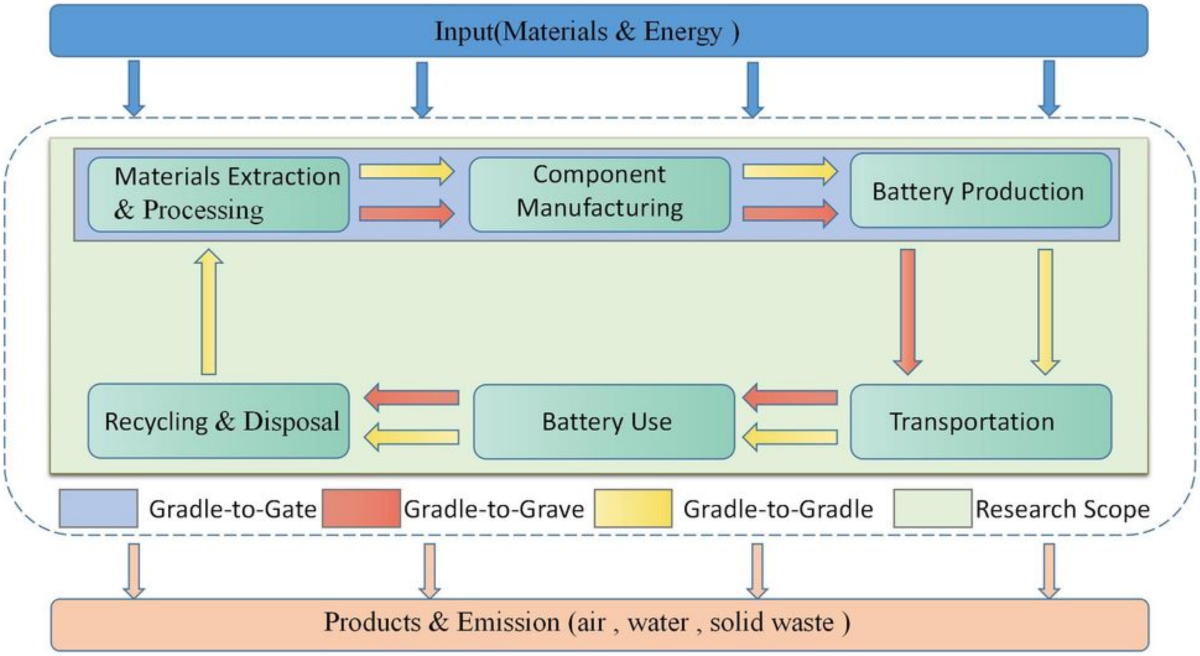
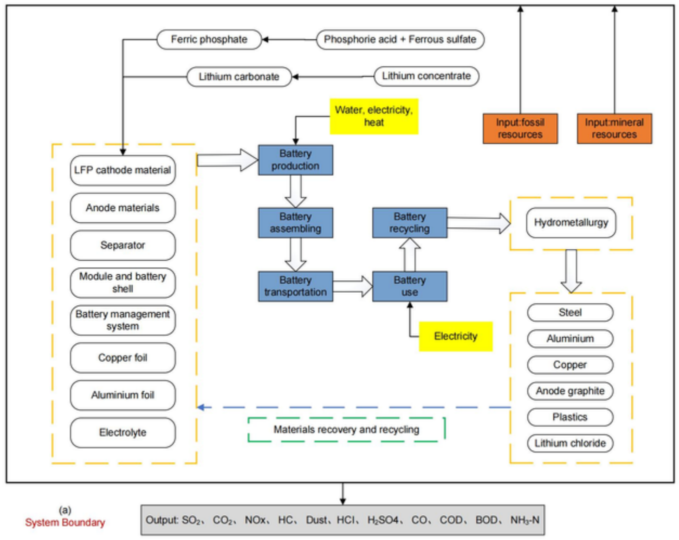


Figure 1

The battery's system boundaries during its entire life cycle



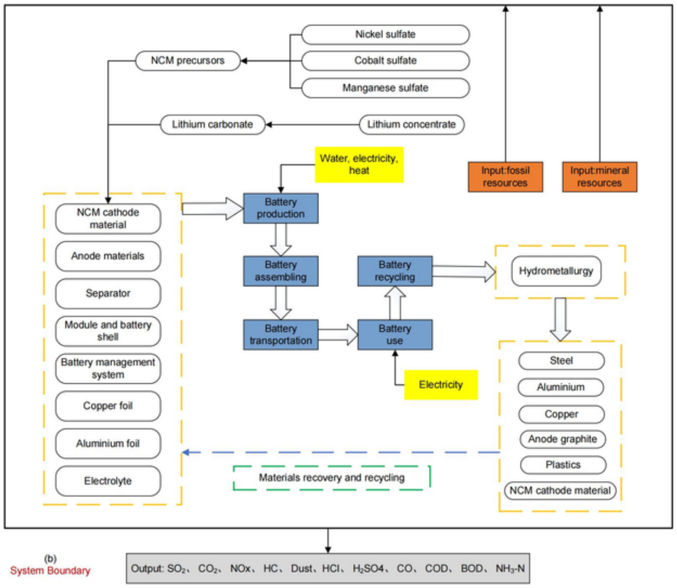
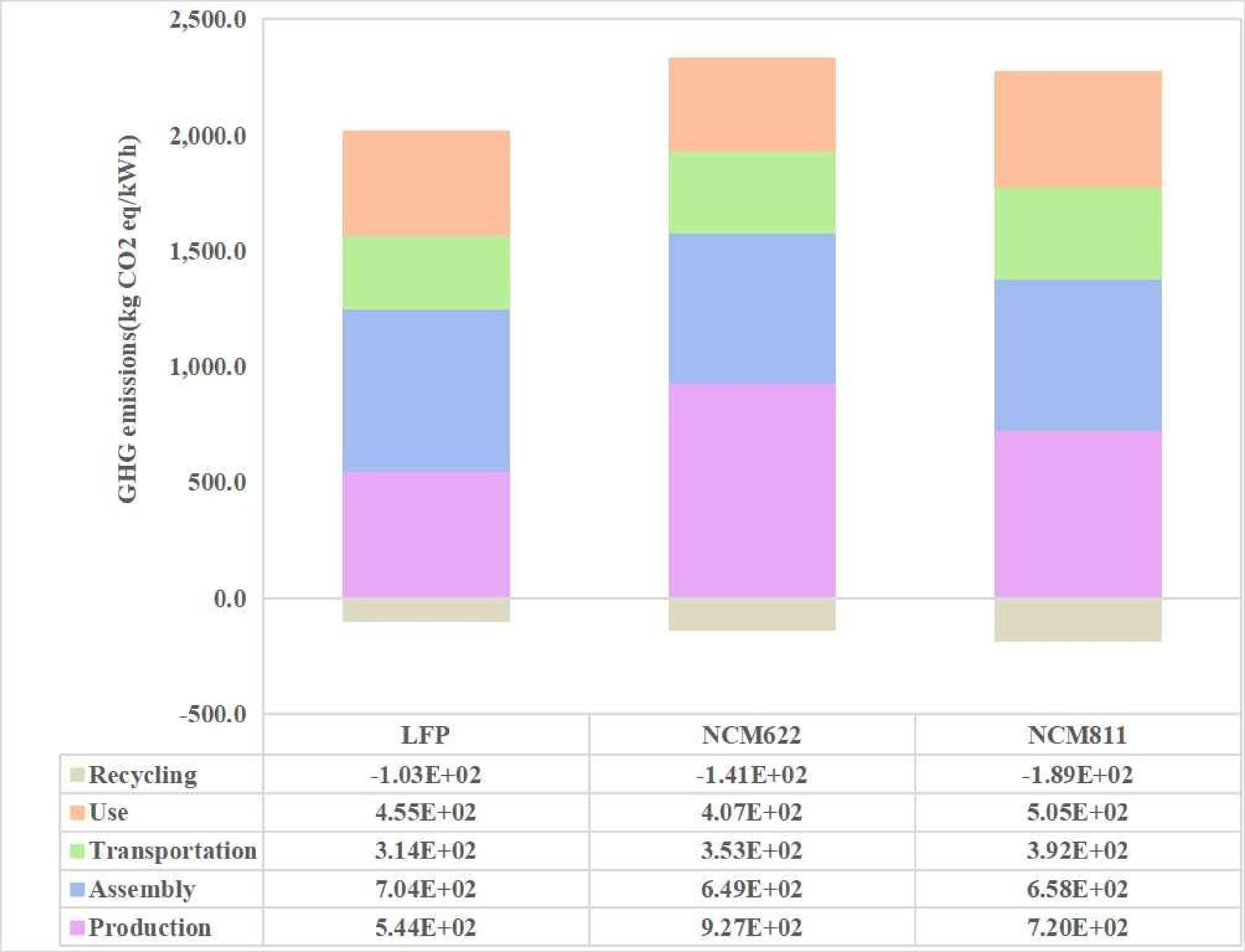


Figure 2

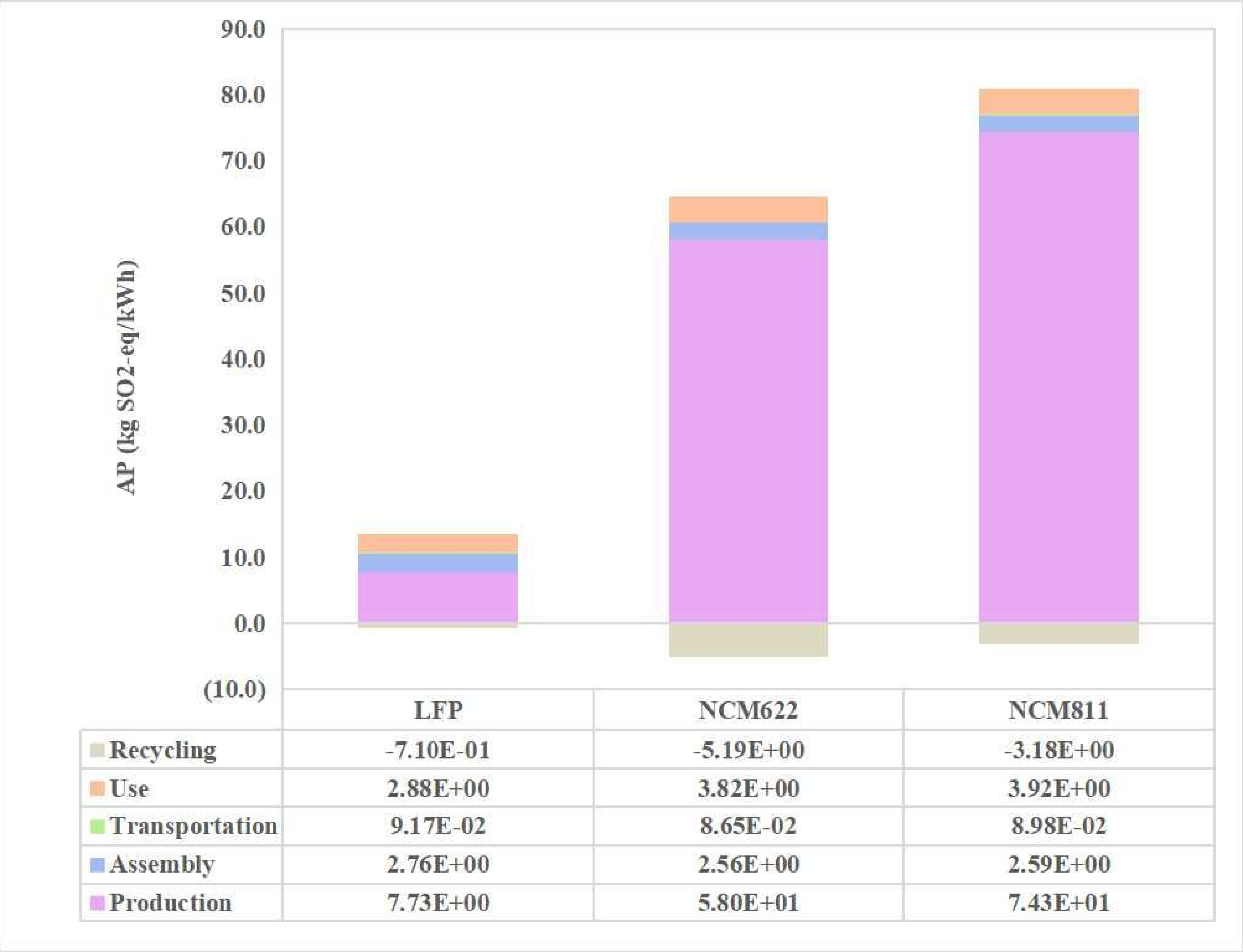
System boundaries of (a) LFP batteries and (b) NCM batteries



	LFP	NCM622	NCM811
Recycling	-1.03E+02	-1.41E+02	-1.89E+02
Use	4.55E+02	4.07E+02	5.05E+02
Transportation	3.14E+02	3.53E+02	3.92E+02
Assembly	7.04E+02	6.49E+02	6.58E+02
Production	5.44E+02	9.27E+02	7.20E+02

Figure 3

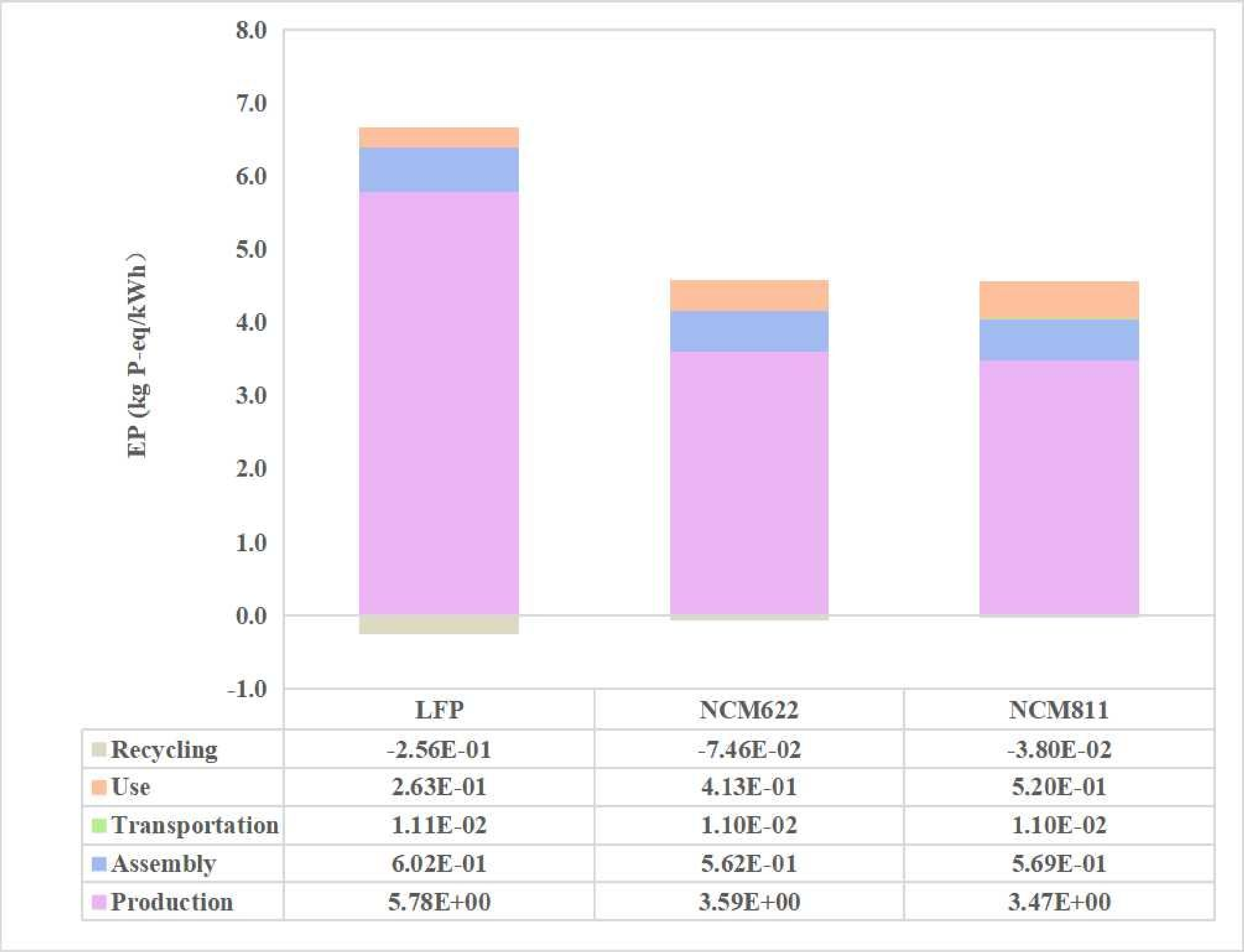
GHG emissions at all stages of LIBs



	LFP	NCM622	NCM811
⬜ Recycling	-7.10E-01	-5.19E+00	-3.18E+00
🟧 Use	2.88E+00	3.82E+00	3.92E+00
🟩 Transportation	9.17E-02	8.65E-02	8.98E-02
🟦 Assembly	2.76E+00	2.56E+00	2.59E+00
🟪 Production	7.73E+00	5.80E+01	7.43E+01

Figure 4

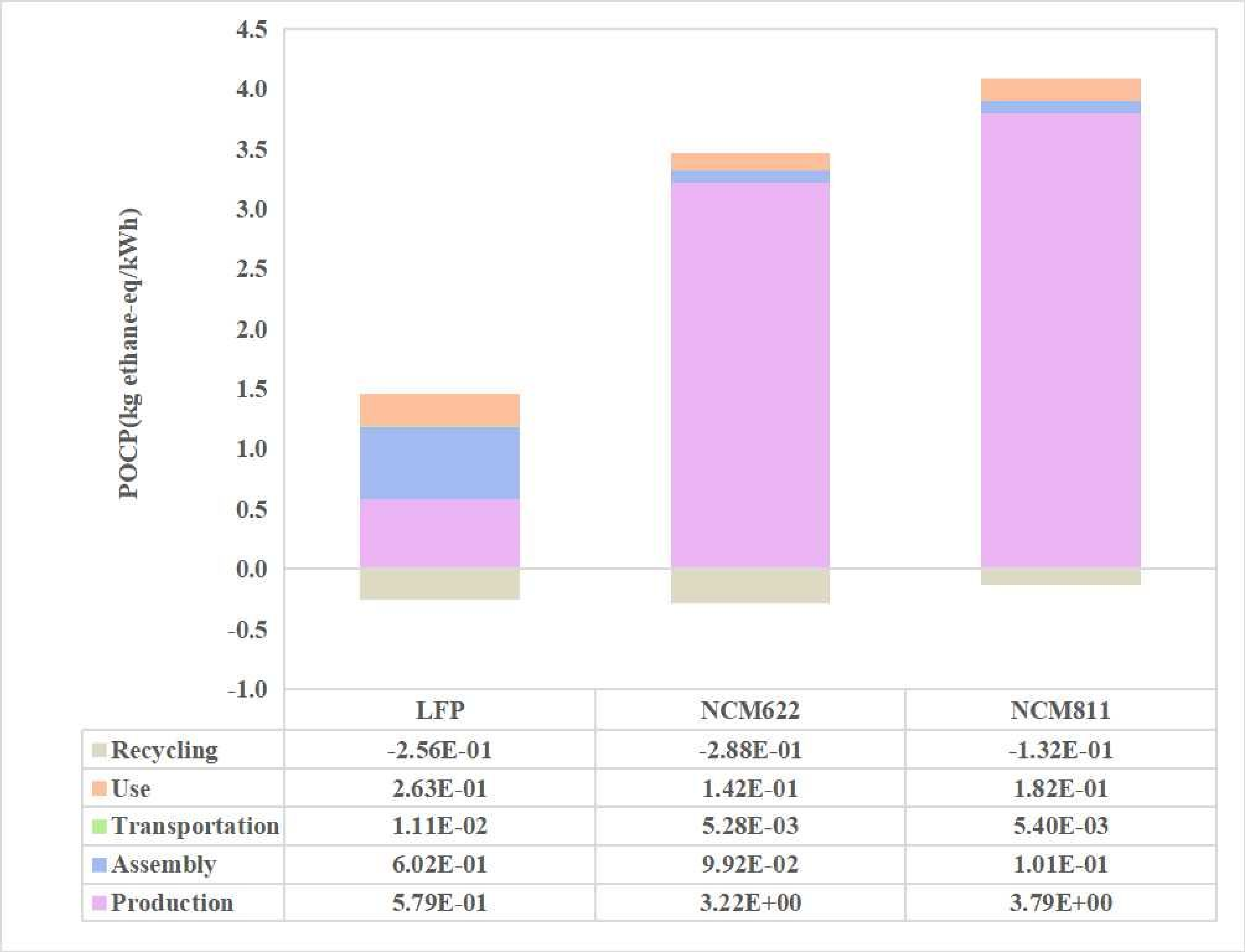
AP of three types of batteries during battery entire life cycle



	LFP	NCM622	NCM811
▨ Recycling	-2.56E-01	-7.46E-02	-3.80E-02
🟧 Use	2.63E-01	4.13E-01	5.20E-01
🟩 Transportation	1.11E-02	1.10E-02	1.10E-02
🟦 Assembly	6.02E-01	5.62E-01	5.69E-01
🟪 Production	5.78E+00	3.59E+00	3.47E+00

Figure 5

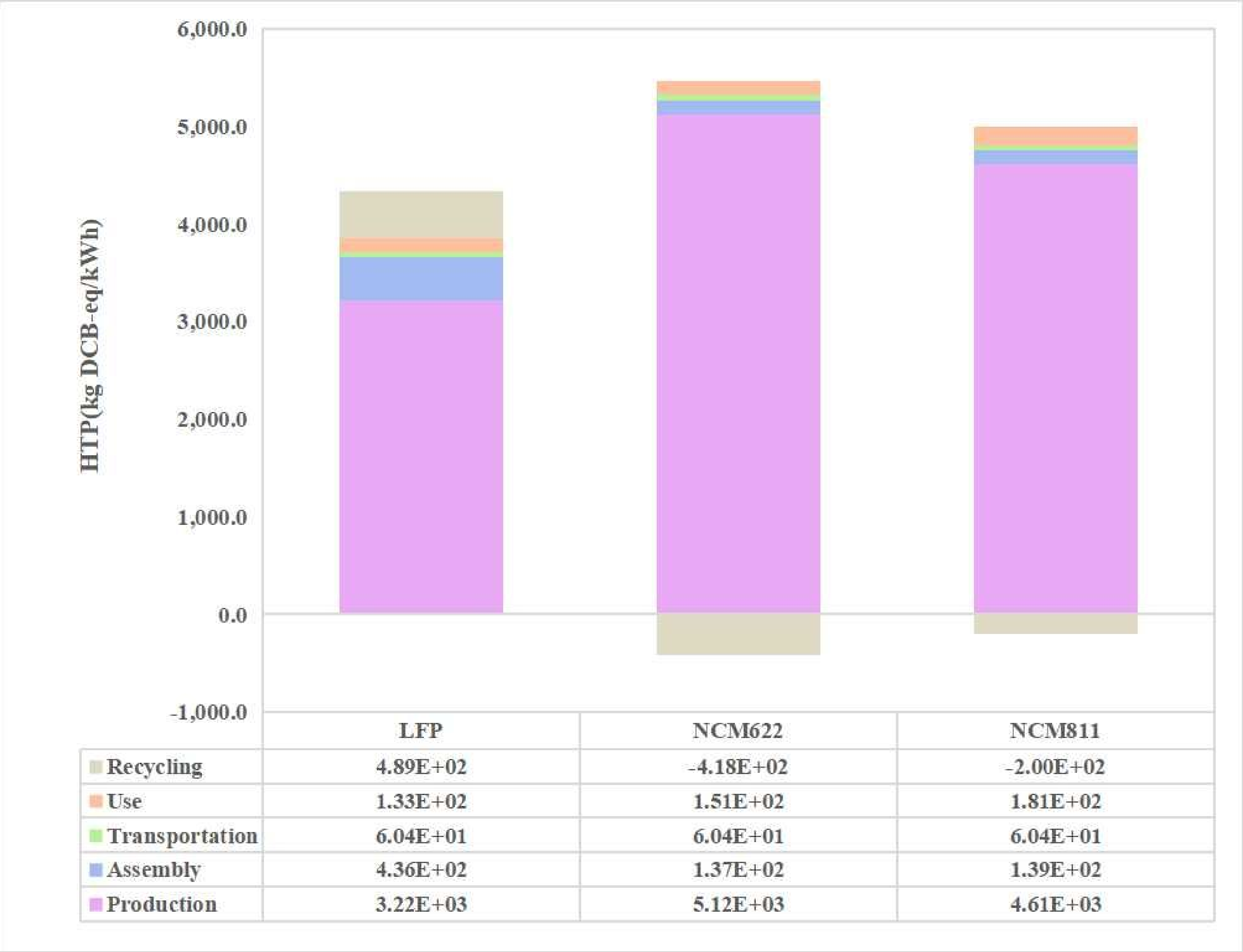
EP of three types of batteries during battery entire life cycle



	LFP	NCM622	NCM811
🟫 Recycling	-2.56E-01	-2.88E-01	-1.32E-01
🟧 Use	2.63E-01	1.42E-01	1.82E-01
🟩 Transportation	1.11E-02	5.28E-03	5.40E-03
🟦 Assembly	6.02E-01	9.92E-02	1.01E-01
🟪 Production	5.79E-01	3.22E+00	3.79E+00

Figure 6

POCP of three types of batteries during battery entire life cycle



	LFP	NCM622	NCM811
Recycling	4.89E+02	-4.18E+02	-2.00E+02
Use	1.33E+02	1.51E+02	1.81E+02
Transportation	6.04E+01	6.04E+01	6.04E+01
Assembly	4.36E+02	1.37E+02	1.39E+02
Production	3.22E+03	5.12E+03	4.61E+03

Figure 7

HTP of the entire life cycle for three LIBs

	LFP	NCM622	NCM811
Recycling	-1.39E-03	-3.24E-03	-2.12E-03
Use	8.37E-03	4.31E-03	5.17E-03
Transportation	2.82E-03	2.30E-03	2.40E-03
Assembly	5.30E-03	6.82E-03	6.90E-03
Production	3.91E-02	6.11E-02	5.23E-02

Figure 8

MEP of the entire life cycle for three LIBs

	LFP	NCM622	NCM811
Recycling	6.36E+01	-1.78E+01	-1.05E+01
Use	6.32E+00	6.49E+00	6.53E+00
Transportation	2.13E+00	2.13E+00	2.13E+00
Assembly	8.22E+00	1.01E+01	1.02E+01
Production	1.12E+02	2.29E+02	2.10E+02

Figure 9

METP of the entire life cycle for three LIBs

	LFP	NCM622	NCM811
Recycling	1.58E+01	-1.25E+01	-7.54E+00
Use	2.94E+00	3.17E+00	3.90E+00
Transportation	1.77E+00	1.77E+00	1.77E+00
Assembly	5.87E+00	7.45E+00	7.54E+00
Production	9.88E+01	1.61E+02	1.48E+02

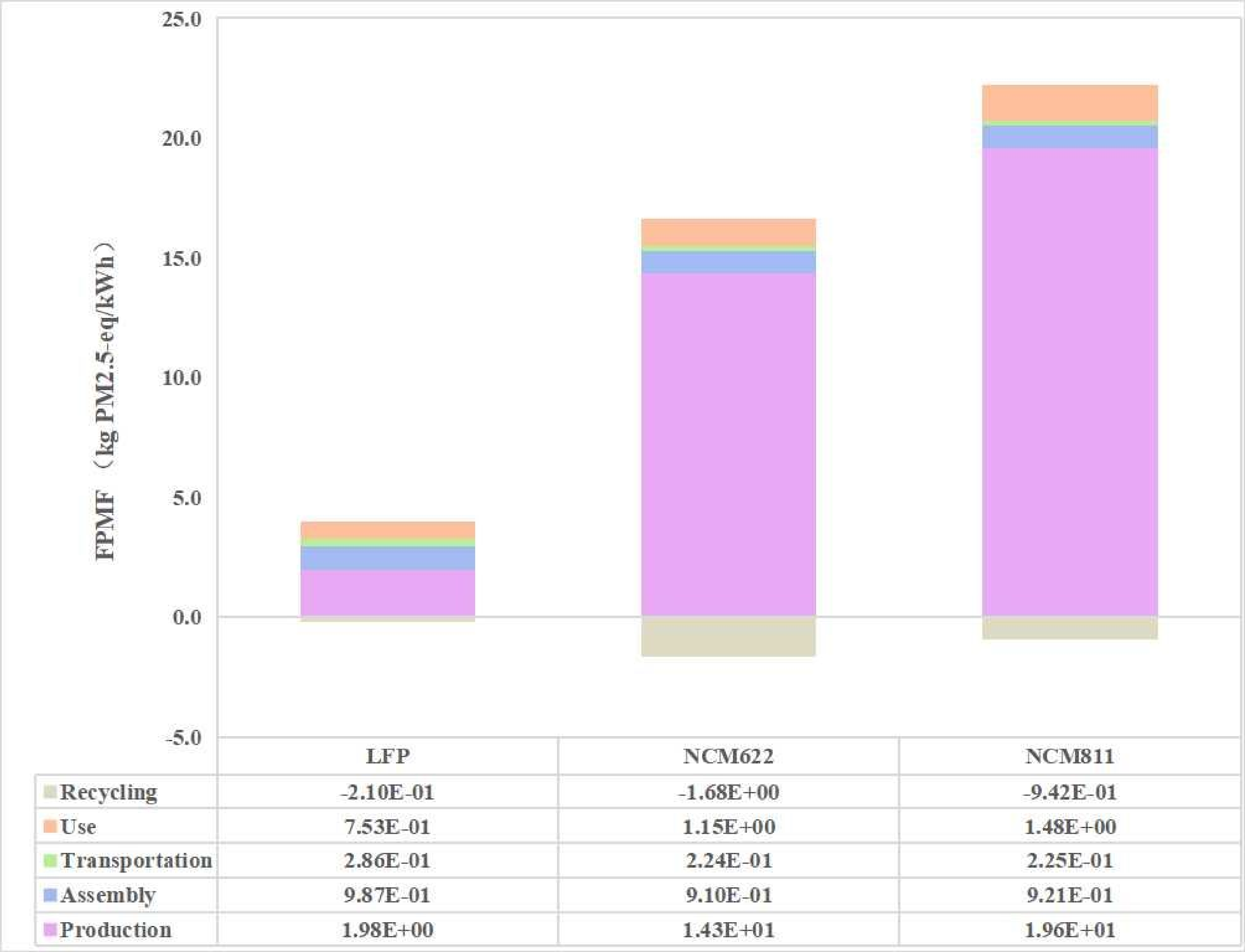
Figure 10

FETP of the entire life cycle for three LIBs

	LFP	NCM622	NCM811
Recycling	-3.42E+02	-3.45E+02	-3.97E+02
Use	1.29E+03	2.09E+02	2.48E+02
Transportation	5.92E+01	5.32E+01	5.02E+01
Assembly	3.15E+02	3.34E+02	3.38E+02
Production	6.08E+02	1.86E+03	1.06E+03

Figure 11

TETP of the entire life cycle for three LIBs



	LFP	NCM622	NCM811
🟫 Recycling	-2.10E-01	-1.68E+00	-9.42E-01
🟧 Use	7.53E-01	1.15E+00	1.48E+00
🟩 Transportation	2.86E-01	2.24E-01	2.25E-01
🟦 Assembly	9.87E-01	9.10E-01	9.21E-01
🟪 Production	1.98E+00	1.43E+01	1.96E+01

Figure 12

FPMF of the entire life cycle for three LIBs

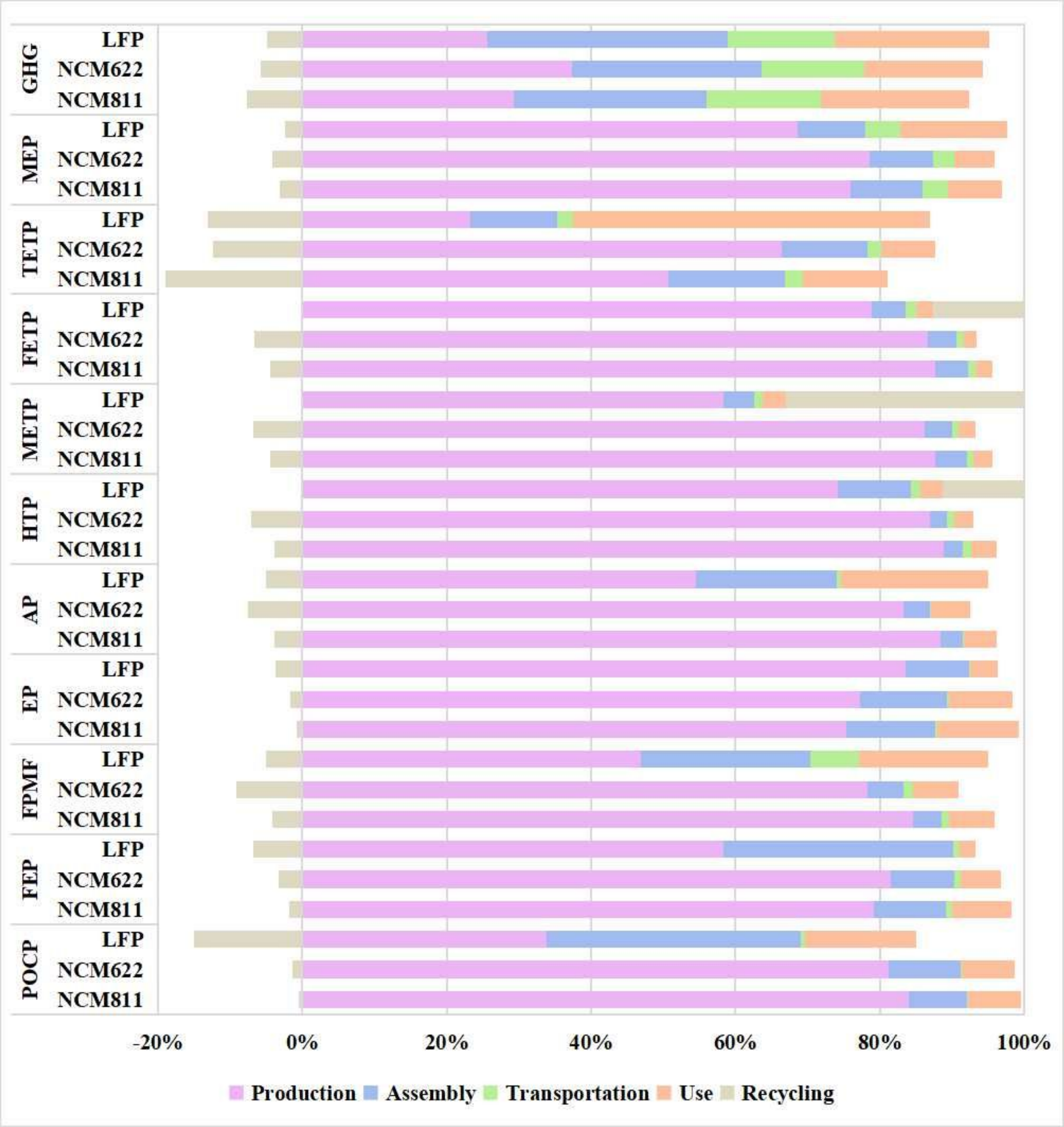


Figure 13

Comparison of 11 ecological metrics of three types of LIBs

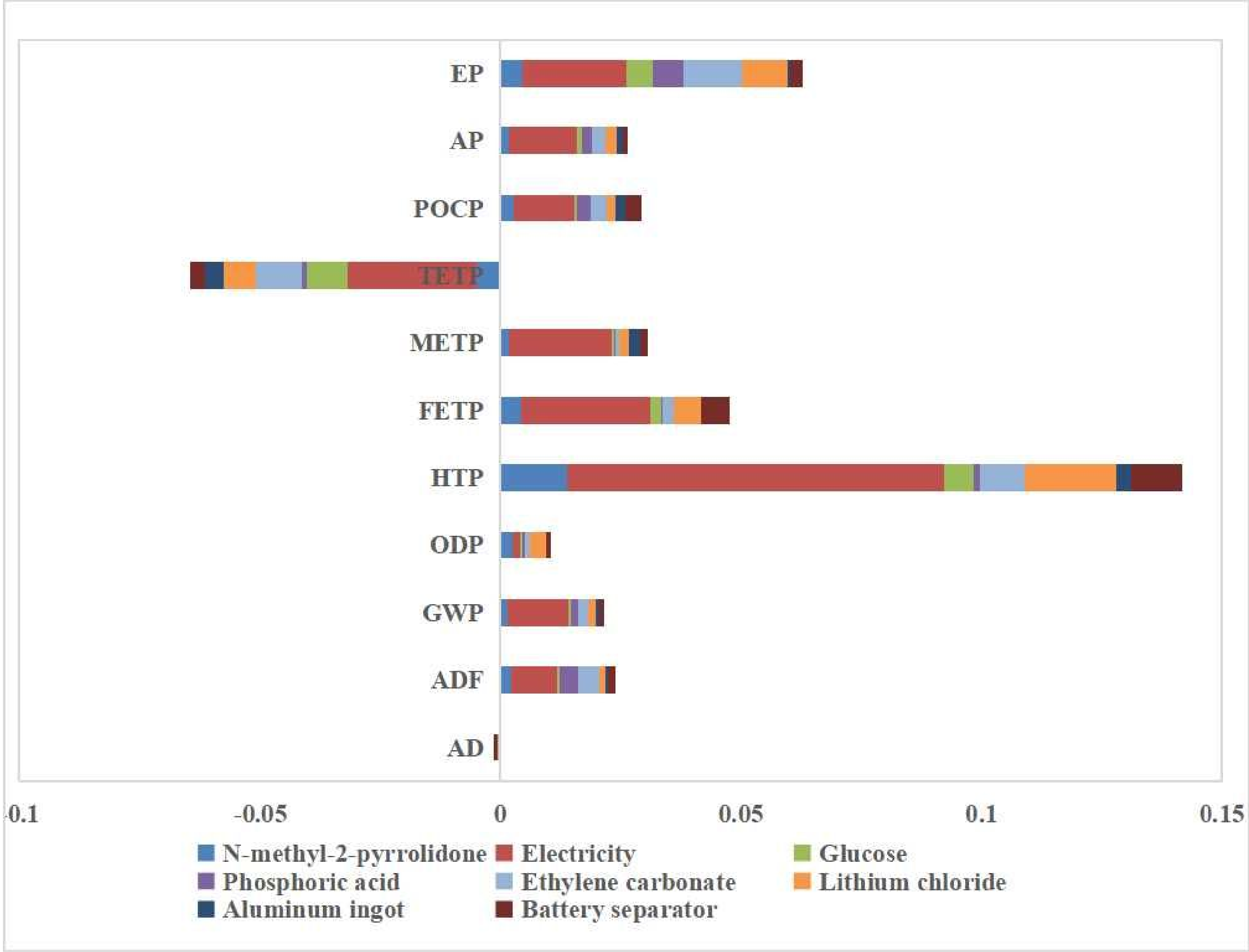


Figure 14

Sensitivity analysis diagram of LFP battery

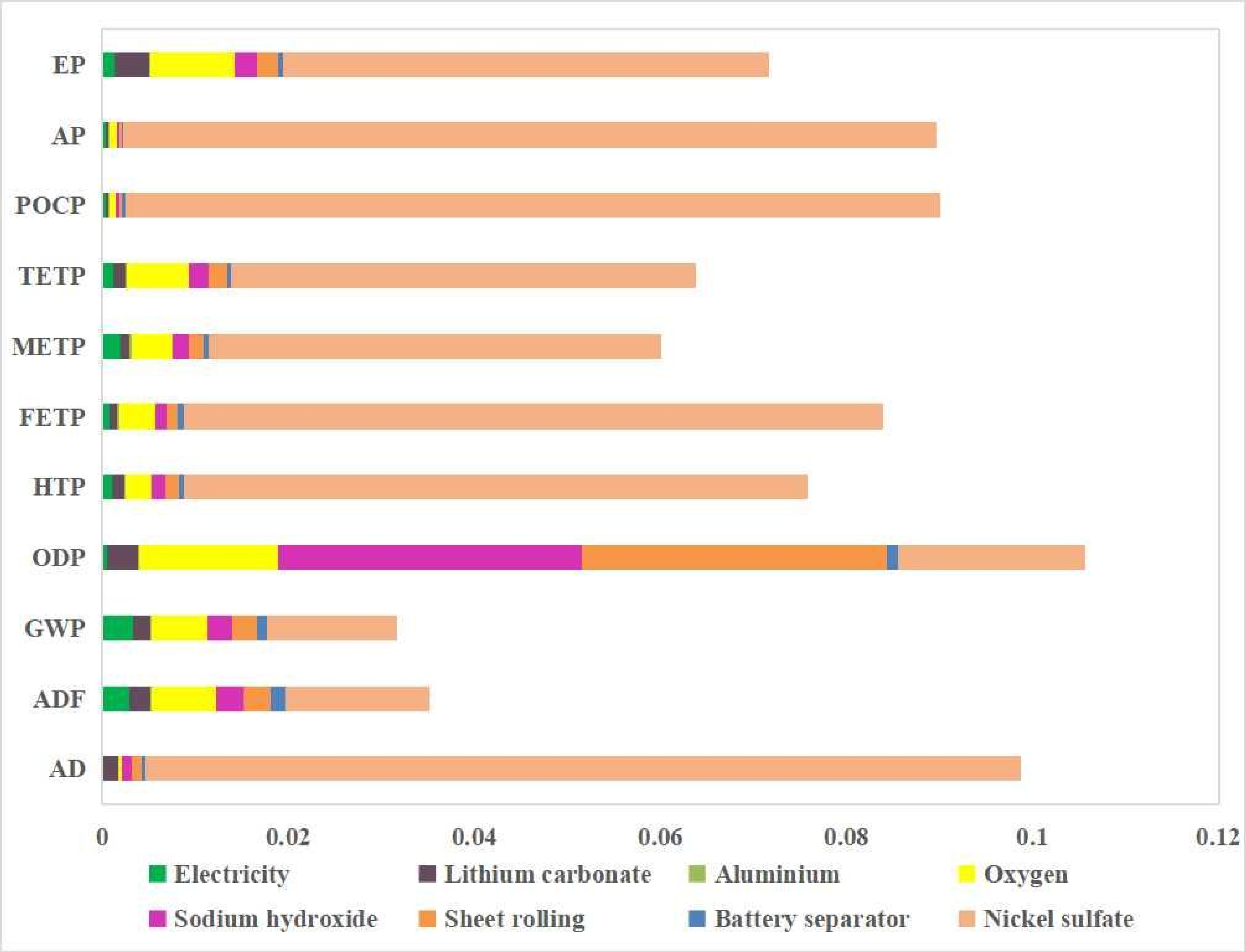


Figure 15

Sensitivity analysis diagram of NCM battery

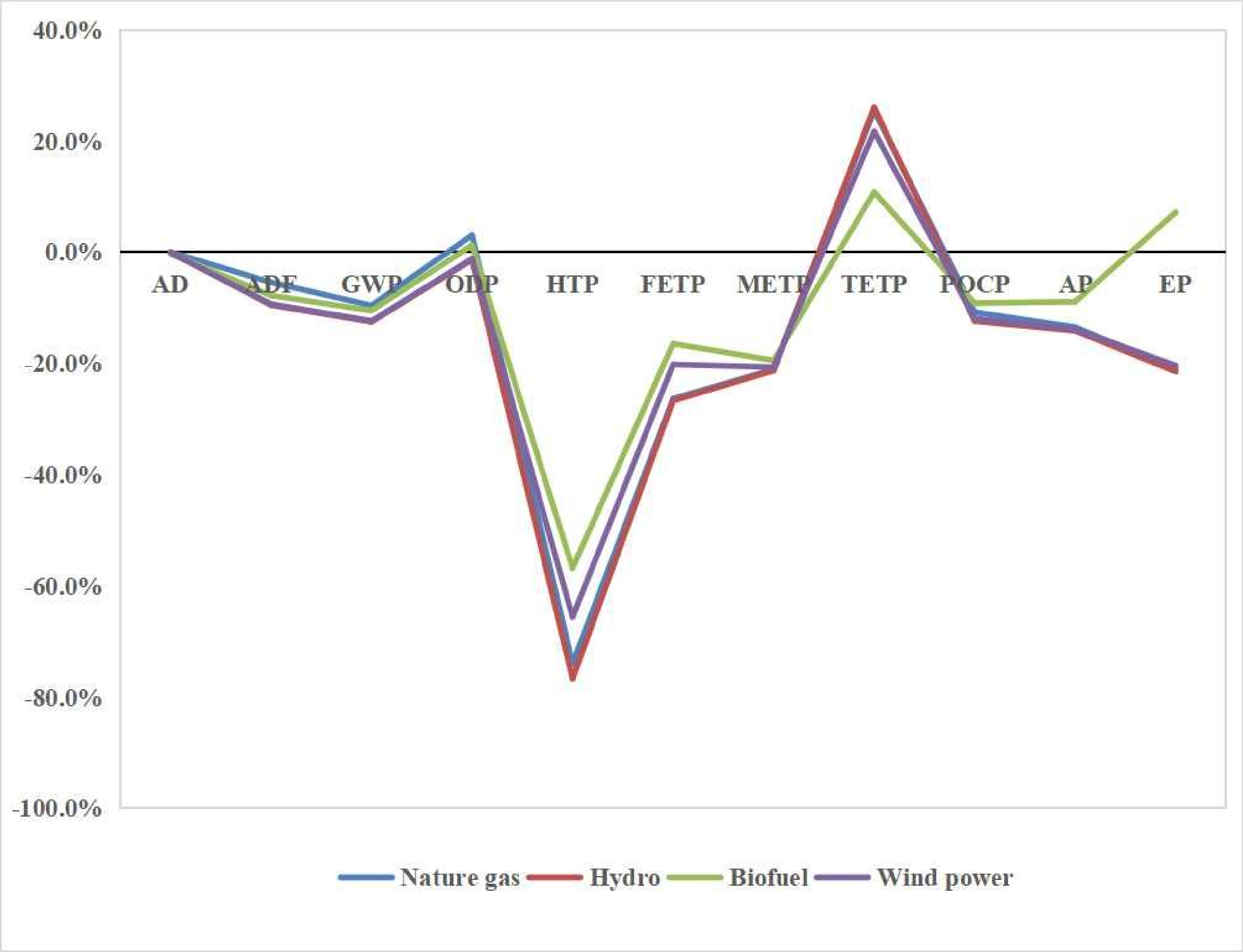
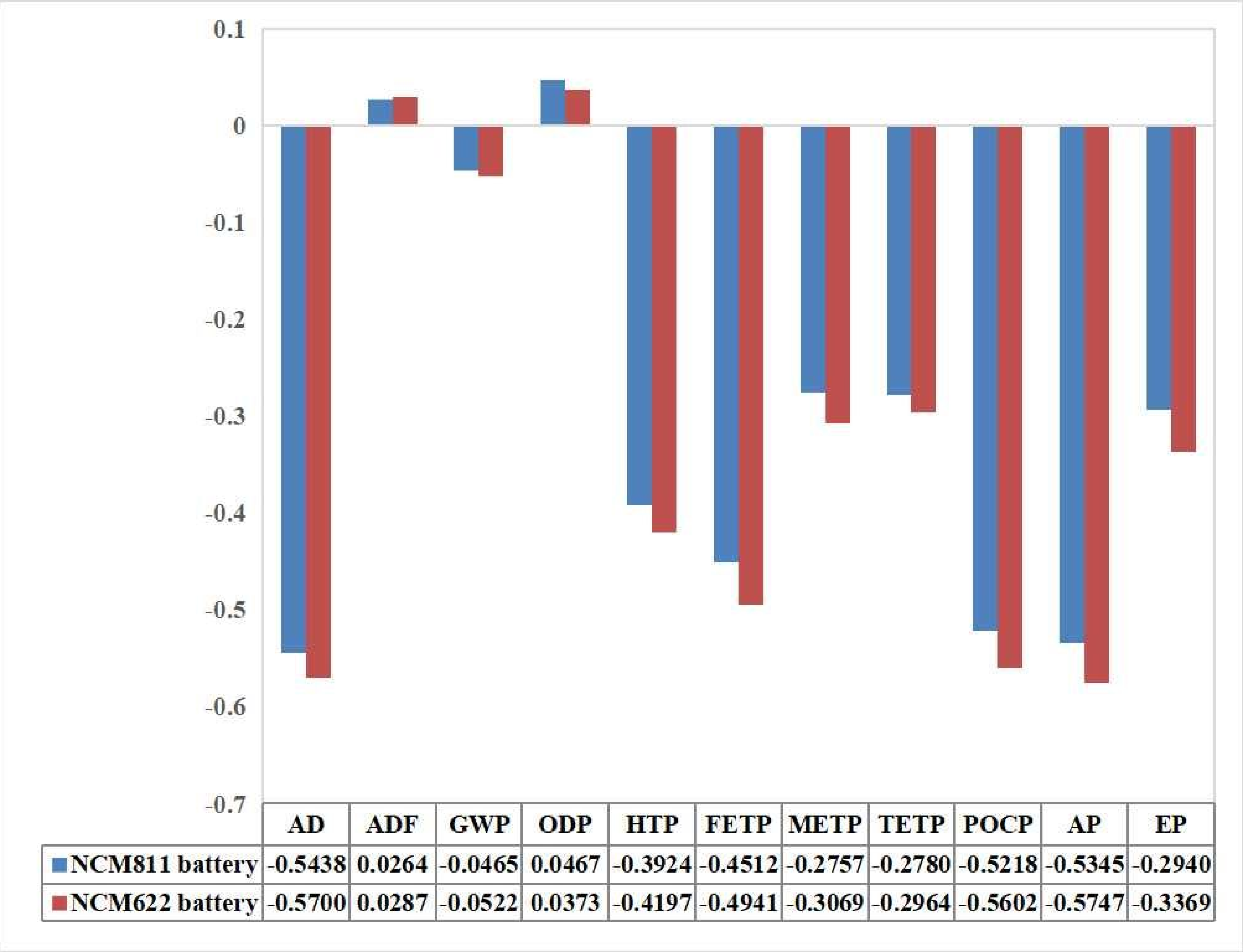


Figure 16

Four kinds of power optimization diagram of LFP battery



	AD	ADF	GWP	ODP	HTP	FETP	METP	TETP	POCP	AP	EP
🟦 NCM811 battery	-0.5438	0.0264	-0.0465	0.0467	-0.3924	-0.4512	-0.2757	-0.2780	-0.5218	-0.5345	-0.2940
🟥 NCM622 battery	-0.5700	0.0287	-0.0522	0.0373	-0.4197	-0.4941	-0.3069	-0.2964	-0.5602	-0.5747	-0.3369

Figure 17

Percentage diagram of material optimization for NCM battery precursors

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryInformation.docx
- Graphicalabstract.jpg