



Lithium Iron Phosphate, Nickel Manganese Cobalt, and Sodium-Ion Batteries: A Life Cycle Perspective on Battery Choices for Electric Vehicles

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Abstract

A comparative Life Cycle Assessment was conducted to analyze the environmental impact of three electric vehicle batteries, viz., Sodium-ion Battery (NIB), Nickel Manganese Cobalt (NMC), and Lithium Iron Phosphate (LFP). The functional unit of 1 kWh of battery capacity was defined, with a cradle-to-grave boundary including the production of the batteries in China, usage in Thailand, and the recycling of the batteries at the end of the lifecycle in China. The ReCiPe 2016 life cycle assessment method was used considering both the midpoint and endpoint environmental impacts. The findings indicated that the production stage added much to the total environmental burdens, especially on the NMC battery, on account of the intensive mining and refining of nickel, cobalt, and manganese. Conversely, the LFP battery had overall moderate impact in most of the categories, as it is made of simpler materials and does not contain any critical metals. The NIB battery had the lowest impact and had greater chances of future development, bearing in mind the large resources of sodium and less reliance on the scarce minerals. Nevertheless, the use stage in Thailand caused rather similar high emissions for LFP and NIB and lower emission for NMC battery as the electricity mix is dominated by fossil fuels. In general, the paper concludes that LFP is now the most environmentally appropriate choice, and NIB represents a promising alternative that should be optimized. To reduce the environmental impacts of future battery systems, a focus on clean energy, low-impact manufacturing, and effective recycling strategies is essential.

Keywords : Electric vehicle batteries; sustainable transportation; life cycle assessment (LCA); nickel sodium-ion battery (NIB); nickel manganese cobalt (NMC); lithium iron phosphate (LFP)

Introduction

Electric vehicles (EVs) have received significant attention as a developmental step towards reducing greenhouse gas emissions and climate change [1]. Over the years, the market demand for electric vehicles has grown as concern over the environment has increased and the need to eliminate the use of fossil fuels has also increased. The shift is underscored by worldwide carbon-neutral plans, as major economies, including Thailand, the United States, European Union, and Japan, aim to achieve carbon neutrality by 2050, while China has set a target of 2060. Governments and organizations eager to reduce carbon emissions by reducing dependence on Internal Combustion Engine (ICE) vehicles have implemented interventional policies, and now EVs have become a growing topic of interest as a viable form of transportation [2]. This has given a boost to the industry, as the world sold nearly 6.7 million EVs in 2021 [3]. Since battery is the primary energy source of an electric car, it affects the car's effective mileage, power consumption, and output [4]. At present, lithium nickel cobalt manganese oxide (NMC) and lithium iron phosphate (LFP) batteries are the most prevalent in the EV industry. However, the manufacturing of EV batteries poses significant ecological issues, such as the large quantities of different substances, including lithium, cobalt, and nickel, which are found only in a few places [5]. The increase in the EV industry at a high rate has added pressure on both resources and the environment in the battery industry. Some of the environmental issues associated with the mining of these materials include the depletion of natural resources and socio-economic issues that surround mining regions worldwide [6]. Additionally, a significant portion of the energy-intensive battery production makes batteries a key factor in production emissions, which can be offset by the environmental benefits of EVs during their lifetime [7]. Moreover, the world's lithium resources are scarce, thus posing a resource-based challenge and increasing prices.

Conversely, the resources of sodium are large, evenly distributed, and less expensive. The promising alternative to lithium-ion

batteries has therefore been gaining growing traction in the use of sodium-ion (NIB) batteries [8]. The first-generation NIB developed at Contemporary Amperex Technology Co., Limited (CATL) was as energy dense as LFP batteries and had excellent cost management and safety performance. Nonetheless, the current studies of NIB primarily concern the development of battery materials and the enhancement of their performance, and there are few studies available on the environmental impact assessment of NIB. One such methodology that is very crucial in analyzing these cumulative effects is the Life Cycle Assessment, which can be applied from the extraction of raw materials to disposal at the end of the life of an item [9, 10]. The use of LCA on EV batteries is thus important in supporting informed decision-making and in capturing the opportunities to reduce adverse environmental effects [11]. The seminal LCA studies have proven the outstanding environmental footprint of the production of lithium-ion batteries, driving the creation of greener chemistries [12, 13]. More recent studies have extended to examine other forms of battery technologies. Lithium iron phosphate, batteries are considered with greater attention due to safety considerations and reduced environmental influence [14]. At the same time, sodium-ion, batteries are now a promising option, and studies have shown that they are safer and more cost-effective as well, because sodium is abundant [15, 16]. In spite of these developments, an important gap exists in literature.

Although significant focus has been put on known battery chemistries, no complete life cycle analysis comparing NMC, LFP, and NIB, batteries have been conducted under consistent scenarios [17]. It is also necessary to evaluate the differences in resource and environmental effects of sodium-ion, batteries and lithium-ion, batteries to facilitate the green transformation of the global energy storage sector [12, 18]. Moreover, the inclusion of the principles of the circular economy, battery recycling, and resource recovery has not been fully investigated in comparative studies. Their regional impacts on the lifecycle, especially in regions with different energy grid compositions, are usually neglected,

but they also affect the total carbon footprint of EV battery production [19].

To fill this gap, this study has performed a comparative LCA of NIB, LFP, and NMC battery technologies. Their effects are compared in terms of the use of resources and emissions during the product life cycle. The results are expected to offer significant knowledge to manufacturers, consumers, and policymakers to encourage the creation of more sustainable practices and inform strategic imperatives creation of the electric vehicle sector.

The first objective of this study is to perform a detailed LCA of battery technologies of electric vehicles to promote sustainable mobility solutions. To achieve this goal, the research establishes some main objectives. To begin with, it aims to determine the environmental performance of EV batteries throughout their life cycle, including resource extraction and production, use, and disposal. Second, it intends to compare environmental performance of common and new battery chemistries, namely, NMC, LFP, and NIB batteries. A further objective is to identify the differences in environmental performance between established and new battery types, such as NIB, LFP AND NMC, focusing on resource efficiency, regional variance of the energy grids, and the implementation of recycling. Finally, the study seeks to provide, based on these findings, specific policy interventions and actionable recommendations for policymakers, producers, and scientists to make the EV battery supply chain more environmentally friendly.

Methodology

A comparative life cycle assessment was conducted following the methodology provided in ISO 14040 and ISO 14044 standards to evaluate the environmental impacts of three major electric vehicle battery chemistries: sodium-ion, lithium iron phosphate, and nickel

manganese cobalt, based on their production and recycling in China and assembly and use in Thailand [20].

1. Goal and Scope Definition

The functional unit was defined as 1 kWh of usable electrical energy delivered by the battery system, providing a consistent basis for comparison among battery chemistries. Each battery system was first modeled over its full operational lifetime, corresponding to a total driving distance of 200,000 km, from which the total lifetime energy delivered was obtained. All life-cycle inputs and outputs were then internally normalized into 1 kWh of delivered energy. Accordingly, the reference flow corresponds to the fraction of the complete battery system required to deliver 1 kWh of usable electricity [3, 13, 20]. The system boundary is set as cradle-to-grave, covering all major life cycle stages, including raw material extraction, cell production, battery pack assembly, use phase, and end-of-life treatment (Figure 1). The material production and recycling activities were modeled in China, while battery assembly and the use phase were modeled in Thailand. The value of 1 kWh is used only as the functional unit for environmental comparison among the three battery types. The end-of-life stage considered both hydrometallurgical and pyrometallurgical recycling routes. These methods allow recovery of valuable materials such as metals, which can reduce the overall environmental impacts of the battery life cycle. While the difference between the two routes was not the focus of this study, including both ensures that potential material recovery is accounted for in the LCA results. The inventory data mentioned below represents the inventories for major components. Inventory data for the inputs of these major components are attached as annexes. The comprehensive inventory data are provided in Tables A1–A43.

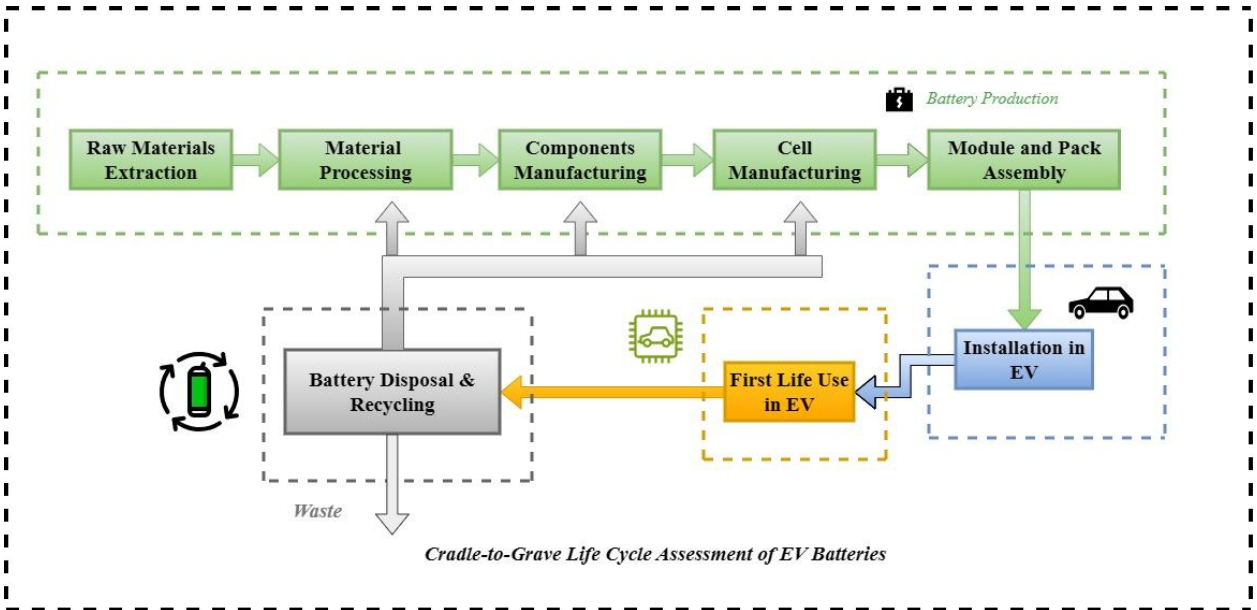


Figure 1 System boundary of the study

2. Data Collection and Life Cycle Inventory Analysis

The inventory data used in this study were collected from multiple authentic sources, such as peer-reviewed research articles and industry reports, to ensure completeness. All data are modeled in SimaPro (version 10.1.0.6), developed by PRé Sustainability, which serves as one of the mainstream platforms for life cycle modelling and impact assessment. The ecoinvent 3.10 database (compiled March 2024) is used to connect background processes such as material production, electricity generation, and transportation. Material and energy inputs for each battery chemistry, including anode, cathode, electrolyte, separator, and assembly processes, are modeled according to the cradle-to-grave approach. Each stage, from production to use and end-of-life, is analyzed to identify its contribution to the overall environmental performance. The collected inventory data is then used for the calculation of environmental impacts across all life cycle stages.

3. Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) is based on the ReCiPe 2016 method and provides a holistic assessment of the environmental pressures at both midpoint and endpoint levels. This analysis concentrates on the

most important impact indicators: global warming, fossil depletion, human toxicity, and terrestrial ecotoxicity. The Hierarchist (H) perspective, version 1.10, with the World 2010 baseline, was used for both midpoint and endpoint evaluations. In the midpoint impact category all 18 impact categories considered and for the endpoint level, results are aggregated into three areas: damage to human health, ecosystem quality, and resource depletion.

4. Sensitivity Analysis

To further assess the robustness of LCA results, a deterministic approach was adopted to perform a sensitivity analysis. All inventory flows associated with production-phase of battery life cycle were uniformly varied by -10% and $+10\%$ relative to the baseline, while keeping the functional unit, system boundaries and impact assessment method constant. Then, the endpoint impacts for human health, ecosystem quality, and resource scarcity for all the battery systems were considered and compared with baseline results. The $\pm 10\%$ variation was selected to represent typical variability in battery manufacturing inventory data as this approach enabled evaluation of the influence of production-phase assumptions on result stability and comparative ranking of the considered batteries.

Results and Discussion

1. Midpoint results

The impact assessment revealed that significant differences existed in how the three battery chemistries of LFP, NIB, and NMC performed in the environment in all the categories rated (Figure 2). The disparities in the emissions and resource use were mainly defined by the chemical composition of the cathode materials, the energy intensity of the manufacturing, and the power of electricity used in the use phase. In general, the use stage was found to be the most prevalent in the majority of categories, and the production stage produced major effects in the material- and energy-intensive operations, including metal mining and cathode manufacturing. The recycling stage added a relatively smaller contribution because of minimal energy consumption and the possible positive impact on the environment regarding material recovery.

1.1 Fossil resource scarcity

The fossil resource scarcity impact assessment showed that the NMC battery had the maximum impact, followed by LFP and NIB as shown in (Figure 2a). The production stage dominated the NMC battery, which was mainly associated with the high energy demand of battery material processing, electrode manufacturing, and cell assembly, and the use of critical metals. For the LFP battery, the production stage also contributed considerably, driven by the energy-intensive processing of iron-based cathode materials, and battery manufacturing processes, although its total impact remained lower than that of NMC. In contrast, the NIB battery showed substantially lower production-related fossil resource scarcity, reflecting its reduced reliance on fossil-intensive material production. The use phase contributed similarly across LFP and NIB battery chemistries based on electricity consumption; the NMC contributed relatively less to this phase. The end-of-life of the NIB battery was related to a high use of fossil resources. This was simply because pyrometallurgical recycling consumes a lot of energy. Processed through hydrometallurgy, both LFP and NMC batteries exhibited a significantly

less substantial impact because their recycling process is less energy consuming.

1.2 Mineral resource scarcity

The effects on mineral resource scarcity were noted to be the greatest for the NMC battery, then LFP and NIB as illustrated in (Figure 2b). The production stage prevailed in NMC, as the extraction and refining of valuable minerals, including nickel, cobalt, and manganese, involved heavy energy demand and contributed significantly to the resource depletion. On the other hand, LFP and NIB batteries had significantly smaller impacts because of their compositions of more prevalent elements like iron and sodium. Nonetheless, there was a significant contribution to the recycling stage of NIB, which is explained by the metal recovery process and secondary resources consumption. Comparatively, the effects of the use phase were relatively negligible for all battery chemistries. The same concerns have been expressed, and it was emphasized that cathode composition and critical metal content are the most significant issues that can define the scarcity of minerals in nickel-based battery systems [13, 21]. The net impact of the end-of-life stage on the scarcity of mineral resources was minor. Although hydrometallurgical recycling was in general more efficient for recovering valuable metals and hence providing minor credit, the pyrometallurgical methods were not effective. In general, recycling had a minor impact on this category as compared to the original manufacturing of the batteries.

1.3 Water consumption

The most critical contribution to water consumption came from NMC battery, with LFP and NIB following at noticeably lower levels (Figure 2c). For NMC, the production phase contributed most to this impact, which makes sense since water-intensive processes are required for mining, chemical processing, and cathode synthesis cooling [22]. It is noted that the most water-intensive part of battery production is the mining of cobalt and nickel, especially in regions where fresh water is not available. For LFP and NIB, production phase

also remained the main contributor, while the use phase showed only a minor contribution, reflecting electricity generation impacts, as power plants supplying electricity often rely on water-intensive thermal systems. The recycling phase showed comparatively low contributions across all batteries, with LFP slightly higher than NMC, and NIB the lowest, which can be associated with wet hydrometallurgical recovery processes. It was reported that hydrometallurgical processes are generally more water-efficient than pyrometallurgical recycling, which explains the limited contribution

observed [21, 23]. The implementation of closed-loop water systems and dry processing techniques in battery manufacturing has the potential to substantially reduce the overall water footprint across the battery life cycle. The notable water use at the end-of-life stage was more evident for NMC and LFP, which was attributed to the requirement of aqueous solutions during chemical leaching processes, whereas the simpler material chemistry of NIB batteries resulted in comparatively lower water consumption during recycling.

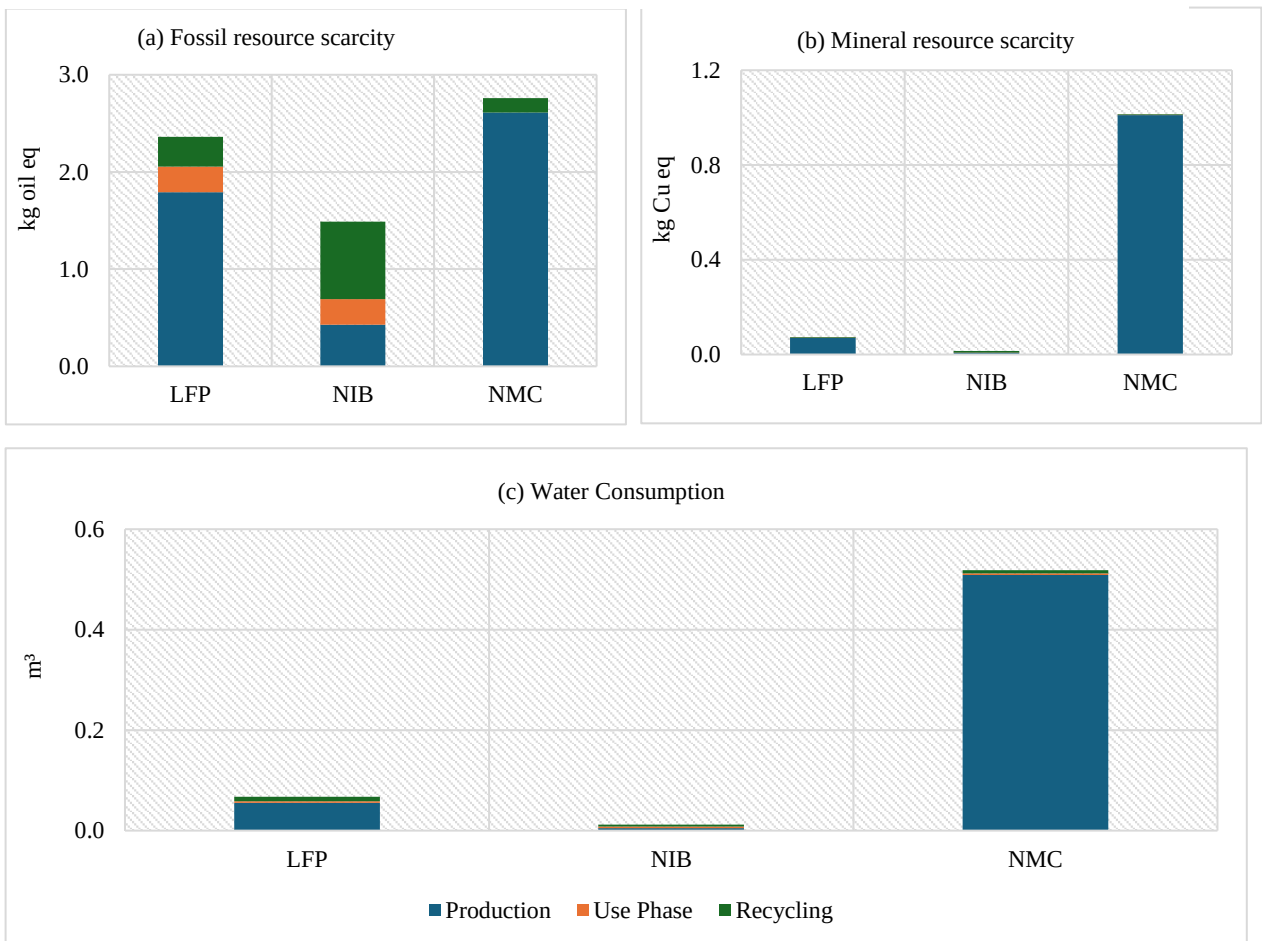


Figure 2 Resource depletion-related impact categories, (a) fossil resource scarcity, (b) mineral resource scarcity, (c) water consumption

1.4 Global warming

The findings showed that the production phase was the most significant contributor to global warming for all battery types, which represented the intensity of carbon intensity of electricity and material production processes. The NMC battery had the highest total global warming impacts, followed by LFP and NIB (Figure 3a). Such a trend implied that the overall global warming impact was strongly influenced by production-related emissions, while electricity use during charging remained similar across the batteries. The comparatively lower global warming of NIB was associated with its lower production-phase emissions, while the NMC battery showed highest production-related emissions, due to the energy-intensive mining and refining of nickel, cobalt, and manganese. The LFP battery demonstrated moderate impacts compared to the NMC battery, which can be explained by its simpler cathode chemistry and lower dependence on critical transition metals, although its energy-intensive production processes still contributed significantly. Similar results were presented, and raw material processing was identified as a major contributor to greenhouse gas emissions in NMC batteries. In addition, it was emphasized that the inclusion of cleaner energy sources to charge could significantly reduce the total greenhouse gas emissions, especially in LFP and NIB chemistries [21-24]. Thus, the effect of global warming was observed to be highly dependent on the carbon content of the electricity mix and the battery material composition. There was a significant difference in the end-of-life phase between battery chemistries. The NIB battery was identified to have the highest global warming impacts in the recycling process, which was mainly explained by the fact that it was processed through the pyrometallurgical process which requires a lot of energy, often from fossil fuels. However, the LFP and NMC batteries, which mostly undergo hydrometallurgical recycling, showed lower impacts, as this process is performed at lower temperatures with a reduced carbon footprint.

1.5 Fine particulate matter

The production phase was dominant in the formation of fine particulate matter because much of the particulate emissions were linked to energy-intensive manufacturing processes. The NMC battery had the greatest total

potential, followed by LFP and NIB (Figure 3b). The high impact of NMC was attributed to its production-related energy demand, which contributed to the emission of particulate matter. The LFP battery also showed notable impacts, mainly associated with material processing and manufacturing, while the NIB battery exhibited the lowest total particulate matter formation. The significantly larger contribution in the recycling stage of NIB originated from energy-intensive metal recovery and thermal treatment processes. Furthermore, the NIB battery was found to have lower overall particulate matter emissions, as its production phase required comparatively less energy. All these findings confirmed that the formation of particulate matter during battery production is highly sensitive to the energy source and processing methods [13, 23, 24]. The battery end-of-life stage for NIB remained a major source of particulate matter emissions, as the pyrometallurgical recycling process produces fine particles because of high-temperature applications, which are not safe for human respiratory health. The LFP and NMC recycling stages led to relatively lower particulate matter emissions.

1.6 Human carcinogenic toxicity

The most significant human carcinogenic toxicity effect was observed in the NMC battery, followed by LFP and NIB (Figure 3c). For the NMC battery, the production phase also contributed largest role, mainly due to the mining and processing of nickel and cobalt, which are known to be carcinogenic. In the case of LFP, the production phase played substantially, mainly because of energy-intensive material processing and upstream industrial activities associated with battery manufacturing. For the NIB battery, the end-of-life phase showed a relatively higher contribution, while the use phase contribution remained limited and was related to electricity generation during operation. The recycling phase also contributed to the overall impact, particularly for NIB, where pyrometallurgical recycling led to a higher potential for human carcinogenic toxicity. This was caused by the possible release and exposure to hazardous substances during high-temperature treatment. Overall, the production and recycling processes in battery systems were identified as the main sources of human carcinogenic toxicity,

depending on battery chemistry and recycling technology.

1.7 Non-human carcinogenic toxicity

The human non-carcinogenic toxicity impact was highest for the NMC battery, primarily driven by the production phase, including the production of nickel, cobalt, and manganese particulates, along with acid leachates and solvent residuals during cathode material preparation (Figure 3d). For LFP and NIB batteries, the production phase also contributed most to this toxicity, while the use phase contribution remained relatively small, as emissions from electricity generation were limited compared to manufacturing-related processes. The overall impact of recycling was small, although in the case of NIB, toxicity was slightly affected by energy-intensive recycling processes, rather than by material composition. These findings support the idea that metal extraction, material processing, and production-related energy emissions are the major non-carcinogenic toxicants in lithium- and sodium-based batteries [25].

1.8 Ionizing radiation

The examination estimated the effect of ionizing radiation and found that the contribution of the NMC battery was the highest, particularly during the manufacturing period, compared to other chemistries. This impact was primarily attributed to energy use and radioactive waste generation associated with nickel and cobalt extraction and processing. The LFP battery showed the second-highest impact, while the NIB battery had the lowest impact, mainly due to their lower dependence on these metals and relatively simpler manufacturing processes. The use stage also contributed to radiation effects, particularly when the share of nuclear electricity was high and the share of coal sources was minimum (Figure 3e), [26]. The LFP battery showed a relatively higher contribution in its end-of-life stage, primarily as a by-product of the hydrometallurgical recycling process, which is electricity-intensive. The primary contributor was the high-temperature treatment that requires substantial grid electricity. The NIB and NMC batteries, which were mainly associated with lower end-of-life radiation impacts, therefore exhibited a smaller footprint in this category.

1.9 Ozone formation, human health

The results indicated that ozone formation was mainly determined by the production and end-of-life treatment emissions. The NIB battery had the highest total contribution among the three chemistries, followed by LFP and NMC (Figure 3f). The main reason for this was the high end-of-life emissions of NIB, leading to higher releases of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) which are involved in the formation of tropospheric ozone. On the other hand, the production phase of NMC battery was a major contributor in this category, due to energy-intensive material processing, like aluminum foil, copper foil and rolling oil production, which are known sources of nitrogen oxides emissions. The higher total value of NIB reflected its higher recycling-related emissions, while the NMC battery showed a slightly higher impact than LFP, primarily associated with its production-related emissions. This trend has also been described, with NIB batteries exhibiting higher ozone formation potential on average than nickel-enriched cathode systems [27]. Overall, these results indicated that the electricity mix and energy efficiency are the most crucial factors affecting the impacts of ozone formation. The recycling of NIB battery contributed noticeably to the creation of ozone formation, as the pyrometallurgical process is a significant source of nitrogen oxides, which are precursors of smog and can cause respiratory problems. On the other hand, the end-of-life processes of LFP and NMC produced lower emissions, since their recycling relies on controlled hydrometallurgical processes.

1.10 Stratospheric ozone depletion

In the case of stratospheric ozone depletion, the production phase is found to be the leading contributor, primarily due to emissions of chlorofluorocarbons, halons, and nitrogen oxides. These emissions are generated during battery production through energy-intensive material processing and manufacturing activities. The NMC battery showed the highest potential for ozone depletion, followed by LFP, while NIB exhibited the lowest impact among the three batteries (Figure 3g). The relatively higher contribution of the recycling stage in NIB compared to its production phase was associated with emissions from the recycling process, which were related to energy utilization during metal

recovery and solvent evaporation. The ozone-depleting impact of NMC during production was substantially higher, due to the release of halogenated compounds and other ozone-depleting precursors during metal refining

processes. The results align with previous research, which shows that NMC batteries cause more stratospheric ozone depletion than LFP batteries because of their complex cathode manufacturing processes [28].

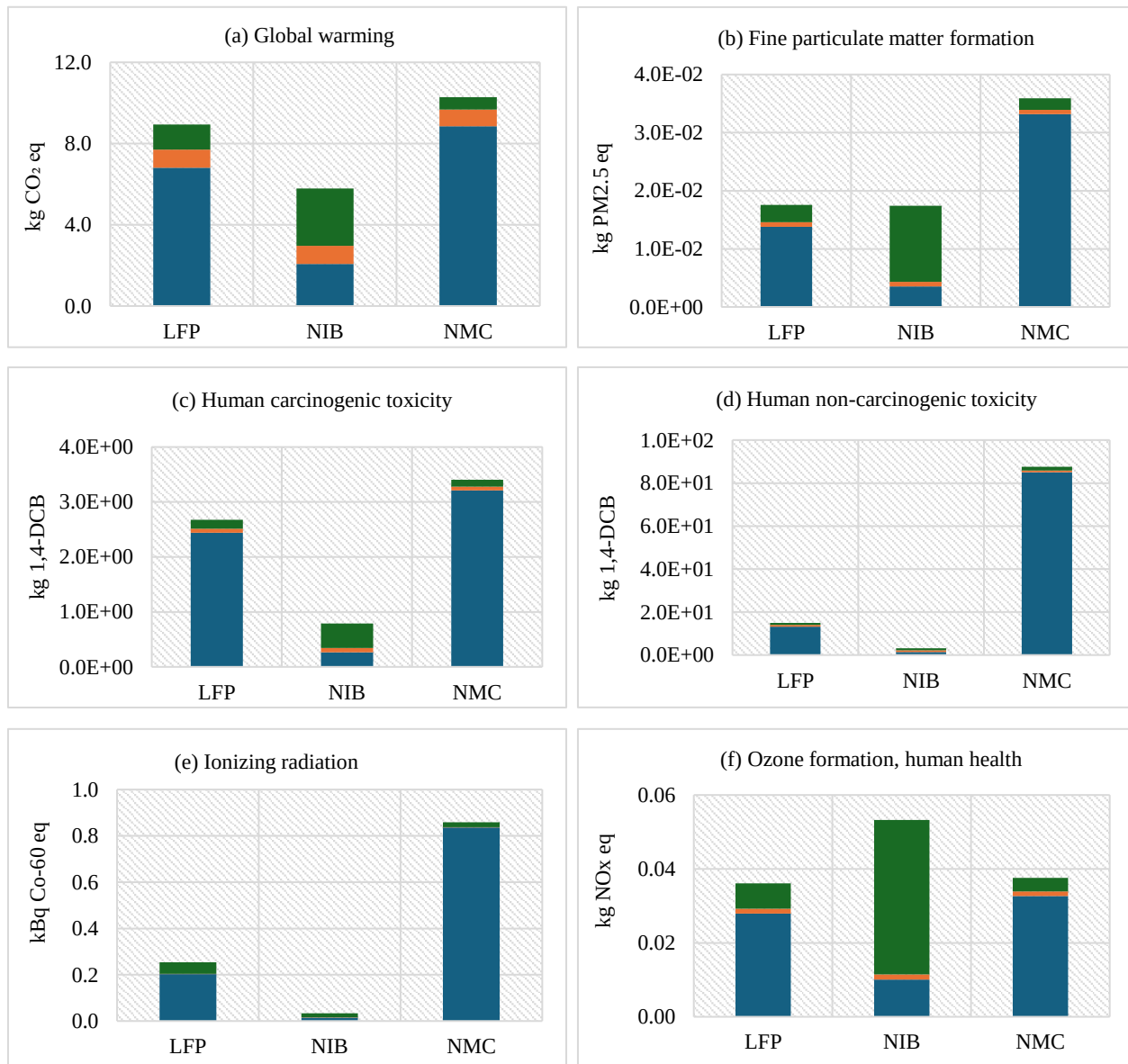


Figure 3 Human health-related impact categories, (a) global warming, (b) fine particulate matter, (c) human carcinogenic toxicity, (d) non-human carcinogenic toxicity, (e) ionizing radiation, (f) ozone formation terrestrial ecosystem, (g) stratospheric ozone depletion

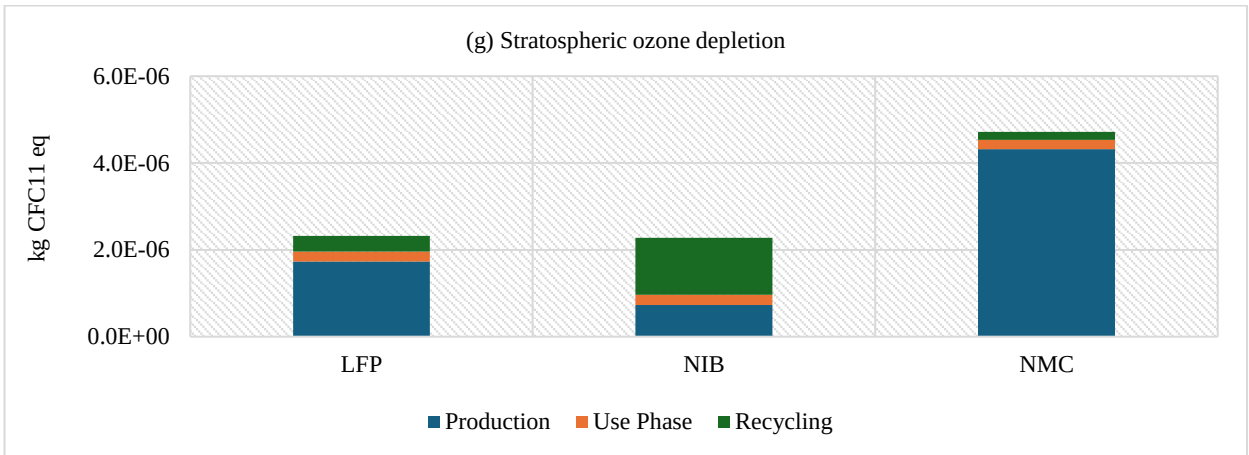


Figure 3 Human health-related impact categories, (a) global warming, (b) fine particulate matter, (c) human carcinogenic toxicity, (d) non-human carcinogenic toxicity, (e) ionizing radiation, (f) ozone formation terrestrial ecosystem, (g) stratospheric ozone depletion

1.11 Freshwater eutrophication

The largest contribution to eutrophication for all batteries occurred during the production phase, while the use phase showed a smaller contribution. This contribution was caused by phosphate emissions, which occurred during upstream fuel production and industrial activities in the electricity and material supply chains, specifically in fossil-based electricity generation and maintenance activities [29]. In NMC, the high impact of the production phase was due to wastewater discharge caused by effluent phosphorus from metal production [30, 31]. The highest total eutrophication was indicated by the NMC battery, followed more distantly by LFP, while NIB showed the lowest impact (Figure 4a). The lower total impact of NIB was associated with its reduced material intensity and lower phosphorus-related emissions across the life cycle. Similarly, it was mentioned that batteries were associated with varying rates of eutrophication depending on grid dependency and water management practices for sodium-ion and lithium-ion batteries [15, 32]. Their results revealed that further development of wastewater treatment has the potential to lessen freshwater eutrophication throughout battery life cycles, given that upstream phosphate emissions are minimized.

1.12 Marine Eutrophication

In the case of marine eutrophication, the production and end-of-life phases were the most

identified as the dominant contributors, while the use phase showed a relatively minor contribution across all battery chemistries. The NMC battery showed the highest overall impact, while the LFP battery showed a moderate impact and the NIB battery exhibited the lowest net emissions (Figure 4b). The lowest impact observed for the NIB battery was mainly attributed to lower nitrogen-related emissions across all life-cycle stages, particularly during the production and recycling phases. In contrast, the NMC battery demonstrated the highest marine eutrophication potential, which was primarily driven by its production and especially recycling stage, as reflected by its substantially higher recycling contribution compared to LFP and NIB. The moderate impact of the LFP battery was mainly associated with emissions from the production phase, while its recycling-related contribution remained considerably lower than that of NMC. The higher impacts observed for the NMC battery during production and recycling were associated with metal mining, chemical leaching, and recovery processes, which release nitrogen- and ammonia-related compounds into aquatic environments. These findings confirm that nutrient-based emissions originating from energy- and material-intensive battery production and recycling processes are the primary contributors to marine eutrophication. In comparison, LFP batteries demonstrate lower water-related environmental burdens than NMC batteries, while NIB batteries provide the most

environmentally favorable performance, thereby reducing the marine eutrophication potential in EV battery systems [30, 33].

1.13 Terrestrial Acidification

The production phase dominated terrestrial acidification, especially in NMC and LFP batteries, while the recycling phase played a major role for NIB batteries. This dominance was largely linked to the emission of sulfur dioxide and nitrogen oxides through energy-intensive material processing and electricity production from fossil fuels. The highest total impact was obtained with the NMC battery, followed by NIB, while LFP showed the lowest overall impact, which highlights the importance of material intensity and production-related emissions (Figure 4c). In the case of the NMC battery, the production stage played a significant role, since the extraction of metals and the refining of nickel and cobalt lead to the generation of acidifying emissions. The LFP battery showed a comparatively lower total impact, mainly because of its lower material intensity and reduced reliance on highly acidifying metal refining processes. The trend observed shows that the nature of acidifying emissions is mainly determined by manufacturing energy demand, as well as the chemical nature of the cathode materials [34]. The NIB battery was a significant contributor to acidifying emissions during the end-of-life stage, as the pyrometallurgical process caused emissions of sulfur oxides, which lead to acid rain and soil acidification. In comparison, recycling of the NMC and LFP batteries produced lower effects, because their hydrometallurgical processes operate at lower temperatures and use controlled chemical leaching instead of burning, which limits the release of these pollutants.

1.14 Ozone Formation (Terrestrial Ecosystems)

The formation of tropospheric ozone was mainly contributed by the production and recycling phases. Similar to the ozone formation (human health), the NIB battery had the highest impacts in terms of ozone formation (terrestrial ecosystem), whereas the difference between the LFP and NMC results is negligible (Figure 4d). The NIB battery exhibited a higher potential for ozone formation, which can be attributed to its

significantly higher recycling-related emissions, particularly from pyrometallurgical treatment, compared to NMC and LFP across its life cycle. In NMC and LFP, the production phase was playing a crucial role. This finding indicates that the formation of tropospheric ozone was strongly influenced by the raw material extraction, processing, and transformation in these two batteries. Similar conclusions were made, and it was emphasized that NIB batteries can show higher ozone formation potential when recycling-related emissions are substantial, whereas batteries generally exhibit lower impacts due to lower material intensity and more controlled recycling processes [25, 27, 34].

1.15 Terrestrial Ecotoxicity

The terrestrial ecotoxicity results show a different variation among the three battery chemistries. The NMC battery posed the highest overall impact, followed by NIB and LFP (Figure 4e). The most influential contribution to NMC occurred at the production stage, primarily because of the large amounts of toxic metals (nickel, cobalt, and manganese) used and the environmental costs of mining and refining. Another phase affecting all types of batteries was the use phase, which was responsible for airborne metal emissions during the production of electricity, although its contribution was minor compared to production and recycling. The recycling stage in the NIB battery showed a notable effect, which was mainly caused by operations involving the processing of sodium salts and chemical recovery, resulting in its total recycling-related ecotoxicity being higher than both LFP and NMC. Recent research established that NMC cathode manufacturing is the primary contributor to terrestrial ecotoxicity throughout EV battery life cycles due to the toxicity of metals and the release of waste [34, 35]. On the other hand, the impact of toxicity in LFP batteries was significantly lower because cobalt and nickel, which have severe effects on soil quality and ecotoxicology, are not present in the structure.

1.16 Freshwater ecotoxicity

The NMC battery shows the highest freshwater ecotoxicity during the production stage. It was determined that the production phase was the dominant contributor for the NMC

battery, suggesting that manufacturing and extraction of raw materials had significant impacts on freshwater ecosystems (Figure 4f). The production-related impacts were largely due to metal refining operations and chemical washing involved in the production of nickel and cobalt. Meanwhile, the use phase represented a comparable contribution in LFP and NIB batteries, mainly because of electricity production and grid emissions during the charging cycles, particularly from copper and zinc compounds released due to wear and corrosion in the electricity grid, which contribute to freshwater ecotoxicity. Although smaller than production impacts, the recycling phase contributed a relatively small amount to freshwater ecotoxicity across all chemistries. These findings were also observed in other studies pointing to the prevalence of transition metals and electrolyte residues as the primary sources of freshwater toxicity during battery production [18, 36].

1.17 Marine ecotoxicity

The maximum marine ecotoxicity was observed in the NMC battery, followed by LFP and NIB, respectively (Figure 4g). The production stage was predominant in the case of NMC, indicating that metal processing and solvent releases influenced marine ecosystems. The use and recycling stages of the NIB battery showed noticeable contributions despite its low production impact, indicating that electricity consumption and material recovery processes can continue to release toxic substances into water bodies. The LFP battery showed moderate production-related impacts but relatively low contributions from the use and recycling stages, which confirms that its iron-based chemistry is less harmful to marine

systems when compared to nickel- and cobalt-based alternatives [13, 36].

1.18 Land use

The NMC battery showed the highest effect on land use followed by LFP and NIB, respectively (Figure 4h). The production phase stands as the main contributor to NMC's environmental effects because mining for nickel and cobalt leads to large-scale land usage and results in deforestation and soil degradation [2]. In the case of LFP batteries, the production phase remained dominant, while for NIB batteries, the recycling phase prevailed, reflecting the impact of sodium recovery and associated material processing on land use. The impact of recycling was not very significant overall, but it was more evident in NIB because of the treatment of sodium and other metals. These findings indicate that the main factors driving land transformation in the life cycle of lithium- and sodium-based batteries are material extraction and end-of-life material processing, along with energy generation [3, 36].

2. Endpoint results

The endpoint assessment revealed that the indicators of human health, ecosystem quality, and resource availability showed significant differences across NMC, NIB, and LFP batteries. The variations were mostly attributed to material composition, energy consumption in the mining process, and recycling efficiency. In general, the end-of-life phase had a moderate impact, where hydrometallurgical recycling minimized effects, whereas pyrometallurgical recycling, especially that of NIB, posed larger risks to human health and resources.

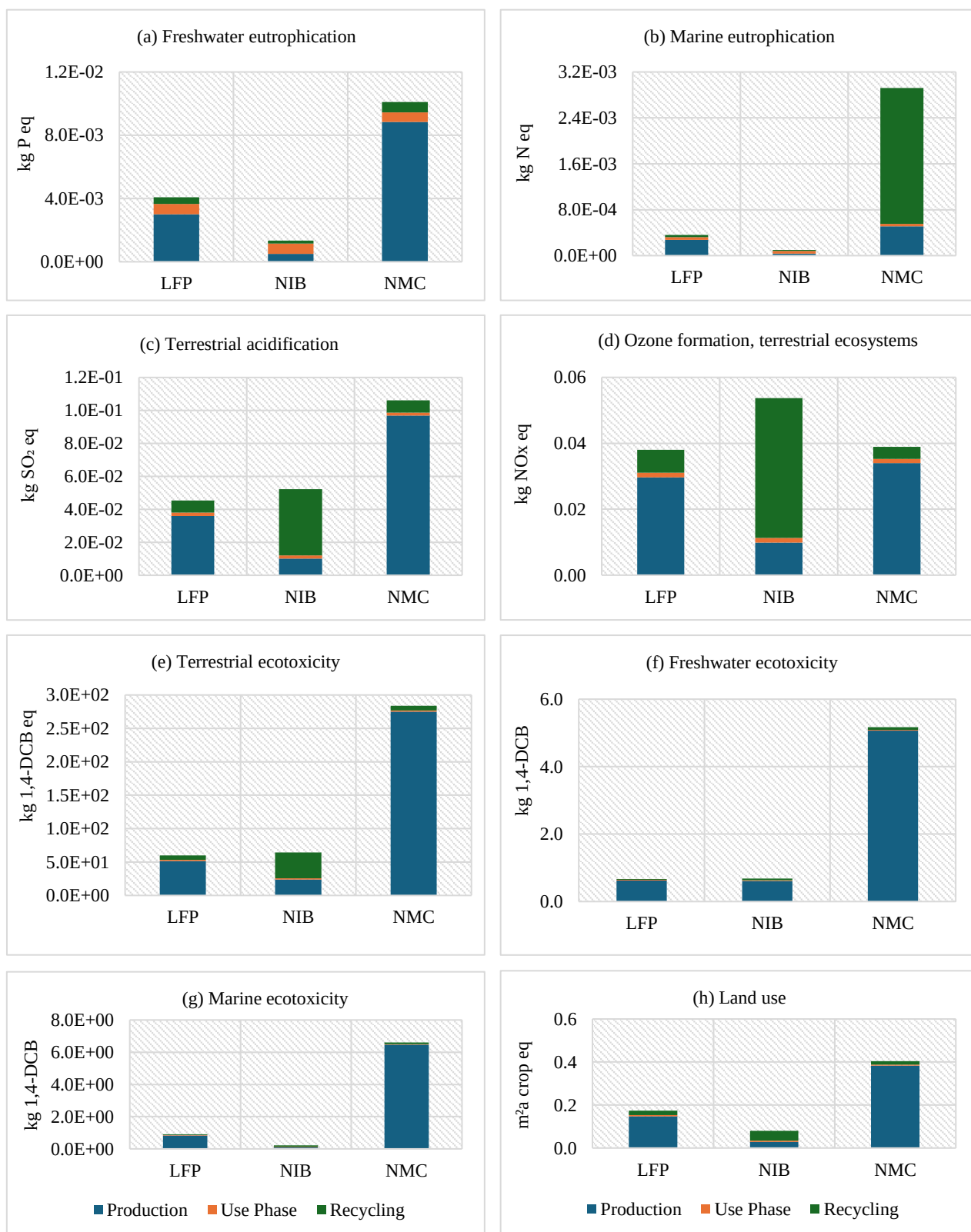


Figure 4 Ecologically related impact categories, (a) freshwater eutrophication, (b) marine eutrophication, (c) terrestrial acidification, (d) ozone formation, terrestrial ecosystems, (e) terrestrial ecotoxicity, (f) freshwater ecotoxicity, (g) marine ecotoxicity, (h) land use

2.1 Human health damage

The findings indicated that the production of the NMC battery made the greatest contribution in the human health category compared to the other stages (Figure 5a). This is explained by the fact that electricity-intensive manufacturing processes are widely used, and the production stage dominates the total impact. The energy demand associated with material processing and cell manufacturing contributes to releases of toxic compounds and greenhouse gases, which further endanger human exposure. These processes are associated with emissions of sulfur dioxide, particulates, and volatile organic compounds, all of which are linked to respiratory diseases and cardiovascular diseases. The NMC battery showed the highest total human health impact while LFP exhibited the second-highest total impact, and NIB the lowest, with its production phase still remained the main contributor, reflecting the influence of material processing and energy use. The NIB battery exhibited the lowest total impact, while its effects were relatively higher at the recycling stage, predominantly due to electricity consumption during recycling. Indirect emissions exacerbate human health risks in regions that primarily rely on fossil fuels for electricity production. The NIB battery exhibited higher impacts at the end-of-life stage, mainly because recycling processes contributed more to the total impact, even though it has a simpler material composition, does not contain toxic transition metals, and consumes less energy in its production. The end-of-life phase had the greatest contribution for NIB because of energy-intensive pyrometallurgical recycling, under which process-related emissions and residue handling may emit harmful gases unless properly managed [25, 27, 37]. In contrast, hydrometallurgical recycling is more efficient, trapping metals safely and minimizing possible human exposure. LFP and NMC showed lower end-of-life contributions, and the recycling processes are not complicated.

2.2 Ecosystem quality damage

The production phase was found to be the largest contributor in the ecosystem damage category for NMC and LFP batteries, whereas the recycling phase was the largest contributor for NIB [13, 34, 38]. This predominance is due to the

extraction and refining of metals and material-intensive manufacturing, which cause emissions leading to acidification, eutrophication, and ozone formation. For NMC, the production phase contributed the highest ecosystem damage among all batteries, while LFP showed lower but still noticeable production-related effects, (Figure 5b). Nickel and cobalt mining activities lead to heavy metal run-off, soil erosion, and contamination, causing degradation of aquatic and terrestrial ecosystems and disturbing biodiversity. The results also indicate that the geographical origin of resources and the carbon intensity of the local power network are significant factors in causing ecosystem harm. In addition, inadequate EV battery end-of-life regulatory frameworks, particularly the absence of biodiversity protection measures and clear recycling mandates, may further negatively affect ecosystem quality [3, 39]. NIB has shown a noticeable effect on the ecosystem at the end-of-life stage, which is caused by metal residues and process effluents during the pyrometallurgical treatment. The recycling effects of LFP and NMC are also minimal, indicating that the recycling of these materials, particularly via hydrometallurgical processes, does not release significant amounts of toxic substances into the soil or water.

2.3 Resource Depletion damage

The resource depletion category revealed that the NMC and LFP battery was by far the most resource-intensive, especially at the production stage, because it relied on scarce metals such as lithium, nickel, cobalt, and manganese (Figure 5c). The mining and subsequent handling of these metals not only increase the rates of depletion but also require high energy inputs, which cause other environmental burdens [13, 21, 40]. The LFP battery showed the second-highest resource depletion impact, mainly driven by the production phase, although its total impact remained lower than NMC and higher than NIB. The NIB battery presented greater contributions to the recycling stage, mainly because of increasing energy demands and underdeveloped recycling technologies. The existing approaches to sodium-ion recycling have low recovery rates, resulting in higher losses and additional strain on resource extraction. Conversely, the NIB battery

was least affected by resource depletion in the production stage because it is based on abundant natural resources, such as sodium and iron-based materials. The recycling stage contributed most to NIB, due to the pyrometallurgical recovery

process, which is less efficient and leads to greater resource loss. The end-of-life stage of NMC and LFP contributed minimally because hydrometallurgical recycling efficiently reclaims metals, reducing resource depletion.

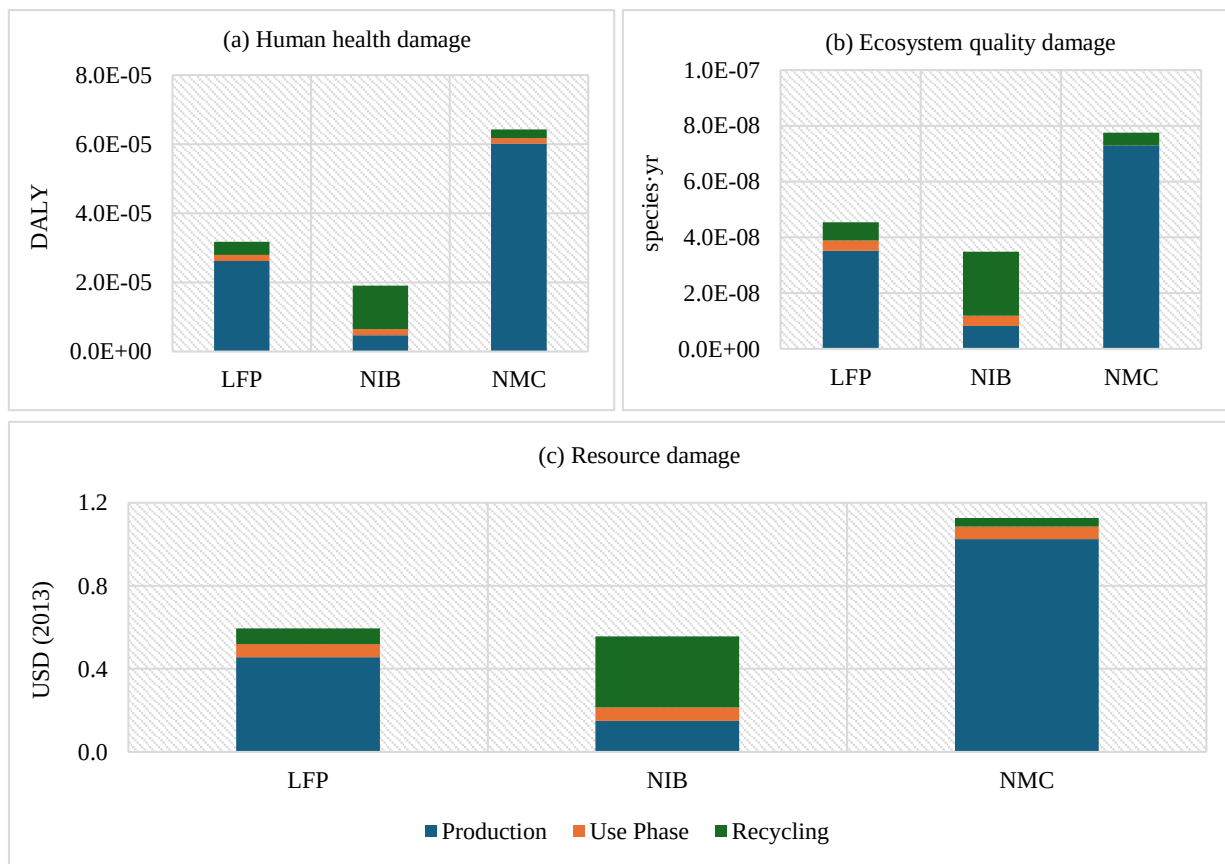


Figure 5 Comparison of endpoint results: (a) damage to human health damage, (b) ecosystem quality damage, (c) resource damage

3. Sensitivity Analysis

The sensitivity analysis was performed by considering a variability of $\pm 10\%$ percent in the battery production phase indicates a steady and almost linear response of endpoint impacts for all battery technologies (see Figure 6). In the case of the human health endpoint, the effects were proportional to the production burdens, where NMC had the highest and NIB the lowest values in all scenarios. The same linear patterns were observed in terms of damage to the ecosystem quality with NMC

showing the greatest potential impacts, then LFP and NIB respectively. The impacts in terms of resource scarcity showed NMC having the most pronounced impacts and NIB the least. Notably, the relative ranking of battery technologies did not change in any of the sensitivity cases, which implies that variability in the production phase influences the magnitude of the impact considerably but does not change the comparative conclusions of the study.

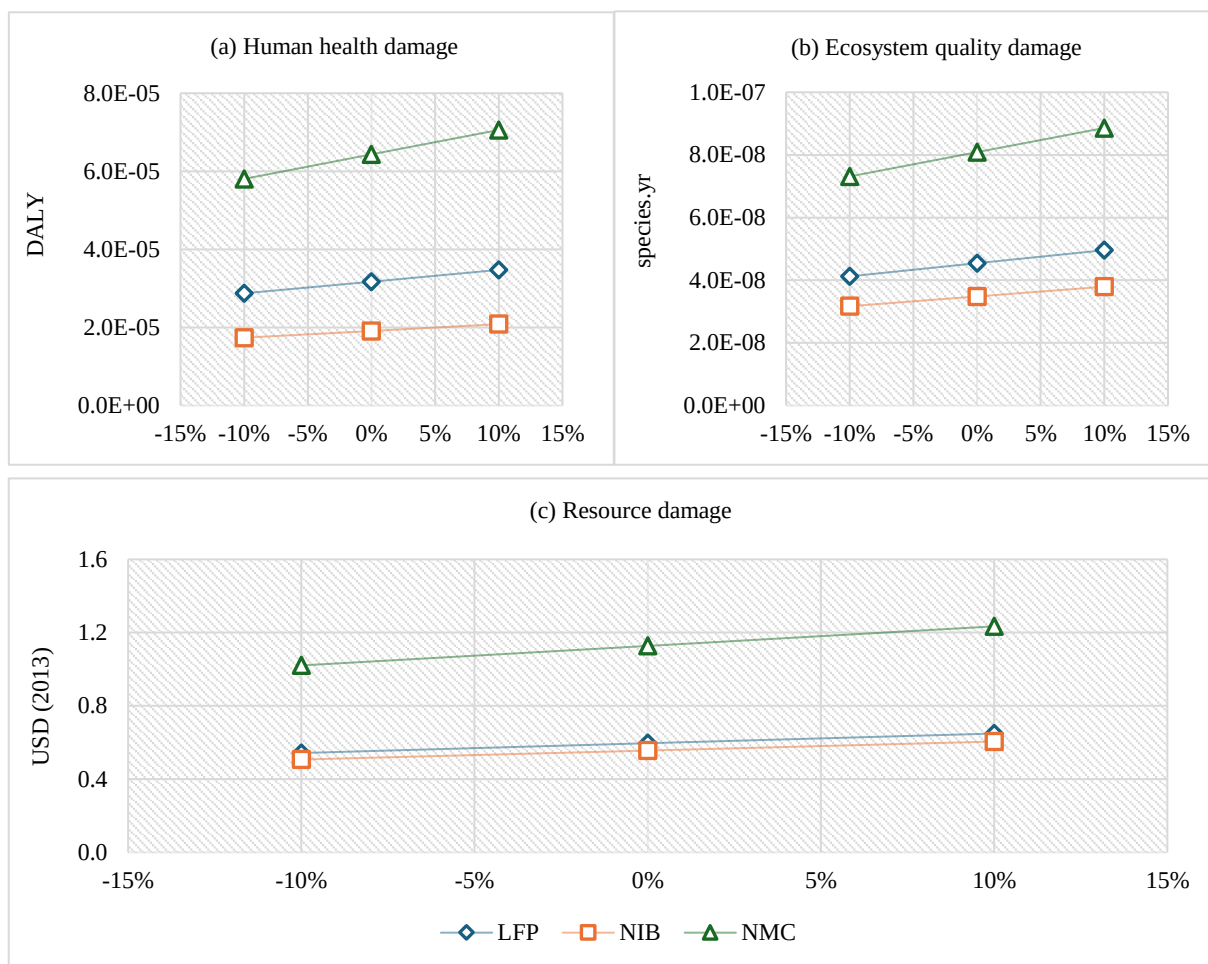


Figure 6 Sensitivity analysis of endpoint impact results considering $\pm 10\%$ Change in Battery Production Phase

Conclusions

In this study, the life cycle assessment methodology is employed to compare the environmental effects of NMC, LFP, and NIB batteries in their entire life cycle, beginning with the extraction of raw materials in China, their use in Thailand, and finally the recycling in China. Comparison analysis has been done to establish the major causal factors of environmental effects, as well as to determine the trade-offs between the three battery chemistries.

The findings indicate that the production stage is the primary cause of environmental impact of all types of batteries, especially for NMC, as it requires a lot of energy to extract and refine nickel, cobalt, and manganese. LFP

exhibits moderate environmental performance in the process of production, and it owes this quality mainly to its simpler material composition and a lesser dependence on critical minerals. NIB has better environmental effects in the production process and has a higher future adoption potential as it utilizes the abundant resources of sodium and does not use any critical metals. There is a need to optimize production technologies to minimize the environmental burdens further.

In use phase, both NIB and LFP have similar increased emissions particularly because of the extensive consumption of fossil fuels as a form of electricity, and NMC experiences relatively lower emissions because of the reduced energy usage due to its high energy density. NIB has the most significant

effects at the end-of-life stage due to the application of pyrometallurgical recycling, as residual sodium-based compounds, process slag, and high-temperature combustion emissions may emit toxic gases and particulate matter unless the process is closely monitored.

On the other hand, hydrometallurgical recycling is more effective, allowing safer recovery of metals and reducing human and ecological exposure. The effects of NMC and LFP in recycling are not very high, as they contain fewer hazardous metals and are easier to recycle. Additionally, classification of batteries and selective recycling to improve recovery efficiency and lower environmental burdens for all chemistries can be further enhanced.

Finally, the sensitivity analysis revealed that the considered variability in battery production phase ($\pm 10\%$) does not affect the environmental ranking of NMC, LFP, and NIB batteries, confirming the reliability of the comparative LCA results. The future studies may focus on quantitative uncertainty analyses to further assess the robustness of the LCA results.

Recommendations

Based on the results of this assessment, it is proposed that the manufacturing processes of NMC, LFP, and NIB batteries should be optimized to reduce water consumption, energy consumption and emissions, especially during the extraction and purification of critical material for NMC batteries. The increased use of renewable energy in battery manufacturing and operation in Thailand and China should be prioritized to reduce the impact of fossil fuels, related impacts, particularly for NMC and LFP chemistries. The recycling strategies should emphasize hydrometallurgical processes, as they exhibit lower emissions and better product recovery compared to pyrometallurgical, especially for the LFP and NMC batteries. Furthermore, selective classification of batteries prior to recycling could enhance resource recovery efficiency and mitigate ecological and human health risks. In addition, incorporating LFP and NIB batteries whenever possible will reduce the overall environmental impact as

they reduce the dependence on critical raw materials extraction, lightweight synthetic materials, and low energy consumption, which will facilitate sustainable EV adoption in Thailand and similar regions.

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Annexes - Inventory Data for the Life Cycle Assessment

The life cycle inventory of this study, which includes production, use, and end-of-life stages, was obtained from scientific literature. Inventory data for nickel-manganese-cobalt (NMC) batteries were taken from [3], While sodium-ion (NIB) and lithium iron phosphate (LFP) batteries were derived from [13].

1. Inventory data for NIB batteries

A1. Inventory data for NIB battery pack

	Parameter name	Amount	Unit
Input	Electricity	3.53E+01	kWh
	NIB battery cell	8.03E-01	kg
	BMS	5.60E-02	kg
	Shell	1.90E-1	kg
	Natural gas	3.65E-01	kg
Output	NIB Battery pack	1.00E+00	kg
	Waste heat	1.27E+1	MJ

A2. Inventory data for NIB battery cell

	Parameter name	Amount	Unit
Input	Cathode	2.16E-01	kg
	Anode	2.92E-01	kg
	Separator	1.69E-02	kg
	Electrolyte	1.17E-01	kg
	Cell container	1.97E-01	kg
	Nitrogen	8.39E-03	kg
	Infrastructure	3.20E-10	p
	Electricity	2.91E+00	kWh
	Heat	2.10E+01	MJ
Output	NIB Battery cell	7.99E-01	kg
	Waste heat	4.69E-01	MJ

A3. Inventory data for NIB Cell container

	Parameter name	Amount	Unit
Input	Casing	4.84E-01	kg
	Nylon ₆ for sealings	5.21E-03	kg
Output	Cell container	2.47E-01	kg

A4. Inventory data for NIB Electrolyte

	Parameter name	Amount	Unit
Input	Ethylene carbonate	1.04E-01	kg
	DMC	2.60E-02	kg
	NaPF ₆ (salt)	1.72E-02	kg
Output	Electrolyte	1.47E-01	kg

A5. Inventory data for NIB NaPF₆ (salt)

	Parameter name	Amount	Unit
Input	Sodium fluoride production	3.73E-02	kg
	Phosphorus pentachloride	2.32E-01	kg
	Hydrogen fluoride	4.73E-01	kg
	Nitrogen	1.46E-04	kg
	Lime	8.70E-01	kg
	Electricity	6.33E-02	kWh
Output	limestone residue	1.02E+00	kg
	Wastewater	4.22E-04	kg
	Phosphorus trichloride	3.08E-02	kg
	NaPF ₆	1.17E-01	kg
	NaF recycled	4.96E-03	kg
	Waste heat	2.28E-01	MJ

A6. Inventory data for NIB DMC

	Parameter name	Amount	Unit
Input	Electricity	4.66E-04	kWh
	Ethylene carbonate	1.73E-01	kg
	Methanol	1.26E-01	kg
	Heat	1.79E-02	MJ
	DMC	1.77E-01	kg
Output	Ethylene glycol	1.22E-01	kg

A7. Inventory data for NIB Cathode

	Parameter name	Amount	Unit
Input	Active material	2.31E-01	kg
	Carbon black	4.91E-03	kg
	Tetrafluoroethylene	4.78E-03	kg
	Polyethylene	4.85E-03	kg
	N-methyl-2-pyrrolidone	8.59E-04	kg
	Heat	7.21E-02	MJ
	Aluminum foil	4.92E-02	kg
Output	Electricity	5.40E-04	kWh
	1-Methyl-2-pyrrolidinone	8.59E-04	kg
	Cathode	2.70E-01	kg
	Waste heat	7.21E-02	MJ

A8. Inventory data for NIB Active material

	Parameter name	Amount	Unit
Input	Na ₂ CO ₃	4.70E-01	kg
	MnO ₂	3.50E-01	kg
	NiCO ₃	2.87E-01	kg
	Mg(OH) ₂	2.35E-02	kg
	N-methyl-2-pyrrolidone	8.59E-04	kg
	Heat	9.05E+00	MJ
	TiO ₂	3.22E-02	kg
	Electricity	2.63E-02	kWh
Output	Active material	8.54E-01	kg
	Carbon dioxide	3.01E-01	kg
	Waste heat	9.15E+00	MJ

A9. Inventory data for NIB Mg(OH)₂

	Parameter name	Amount	Unit
Input	Electricity	4.90E-02	kWh
	Sodium chloride	2.91E+00	kg
	Hydrated lime	3.30E-02	kg
	Magnesium mineral extraction	1.79E-02	kg
	Mg (OH) ₂	2.75E-02	kg
Output	Waste heat	1.77E-01	MJ

A10. Inventory data for NIB NiCO₃

	Parameter name	Amount	Unit
Input	NaHCO ₃	4.77E-01	kg
	NiSO ₄	4.37E-01	kg
	Water	2.68E+00	kg
	Heat	8.80E-01	MJ
	Electricity	3.76E-03	kWh
Output	NiCO ₃	3.36E-01	kg
	NiCO ₃ in effluent	4.27E-03	kg
	Na ₂ SO ₄ in effluent	6.52E-02	kg
	Carbon dioxide	3.01E-01	kg
	Waste heat	7.69E-01	MJ

A11. Inventory data for NIB Anode

	Parameter name	Amount	Unit
Input	Hard carbon	2.92E-01	kg
	Carbon black	9.45E-03	kg
	Carboxymethyl cellulose (CMC)	8.83E-03	kg
	Styrene-butadiene rubber (SBR)	3.80E-03	kg
	Water	1.26E-01	kg
	Heat	4.05E-01	MJ
	Aluminium foil	1.02E-01	kg
	Electricity	7.52E-07	kWh
Output	Anode	3.65E-01	kg
	Waste Water	1.26E-01	kg
	Waste heat	4.09E-01	MJ

A12. Inventory data for NIB Styrene-butadiene rubber (SBR)

	Parameter name	Amount	Unit
Input	Butadiene	7.82E-03	kg
	Styrene	2.61E-03	kg
	Emulsifier	2.84E-04	kg
	Cyclohexane	1.04E-04	kg
	Water	1.87E-02	kg
	Cooling water	2.60E-03	m ³
	Heat	1.43E-01	MJ
	Sodium persulfate	5.24E-05	kg
	Electricity	5.72E-03	kWh

Output	SBR	1.04E-02	kg
	Waste Water	1.87E-02	kg
	NM VOC	1.50E-04	kg
	Waste heat	1.64E-01	MJ

A13. Inventory data for NIB Hard carbon

	Parameter name	Amount	Unit
Input	Coke	9.13E-01	kg
	Nitrogen	7.21E-01	kg
	Water	1.43E-01	kg
	Heat	1.51E+00	MJ
	Electricity	1.47E-02	kWh
Output	Hard carbon	8.01E-01	kg
	CO ₂	6.72E-02	kg
	NO	3.73E-02	kg
	NO ₂	3.01E-03	kg
	SO ₂	4.03E-02	kg
	Waste heat	1.56E+00	MJ

2. Inventory data for LFP batteries

A14. Inventory data for LFP battery pack

	Parameter name	Amount	Unit
Input	Electricity	2.67E+01	kWh
	Water	7.95E-03	kg
	LFP battery cell	8.03E-01	kg
	BMS	1.66E-02	kg
	Shell	1.33E-01	p
Output	LFP Battery pack	1.00E+00	kg

A15. Inventory data for LFP battery cathode material

	Parameter name	Amount	Unit
Input	Iron phosphate	2.41E+00	kg
	Water	5.78E-01	kg
	Lithium carbonate	6.02E-01	kg
	Glucose	2.41E-01	kg
	Nitrogen	2.42E-02	kg
Output	CO ₂	4.12E+00	g
	Dust	2.31E-01	g
	Suspended solids	1.64E-02	g
	Phosphorus	1.20E-04	g
	Cathode material	2.41E+00	kg

A16. Inventory data for LFP battery Iron Phosphate

	Parameter name	Amount	Unit
Input	Electricity	8.43E+00	kwh
	Steam	1.93E+01	kg
	Iron powder	8.99E-01	kg
	Sulfur acid	1.62E+00	kg
	Phosphoric acid	1.84E+00	kg
	Ammonia	4.26E+00	kg
	Hydrogen peroxide	9.04E-01	kg
	Desalted water	2.05E+01	kg
	Ammonia	2.22E+00	g
	Dust	7.93E-01	g
Output	Sulfuric acid mist	4.89E-01	g
	Chemical Oxygen Demand (COD)	2.22E-00	g
	Biological Oxygen Demand (BOD)	2.23E-01	g
	Ammonia nitrogen	3.13E-03	g
	Suspended solids	8.87E-02	g
	Iron phosphate	2.41E+00	kg

A17. Inventory data for LFP battery Lithium carbonate

Parameter name		Amount	Unit
Input	Steam	3.71E+00	kg
	Hard coal	1.28E+00	kg
	Sulfuric acid	1.19E+00	kg
	Sulfur acid	4.76E-01	kg
	Limestone	4.46E-01	kg
	Sodium hydroxide	1.21E-01	kg
	Sodium carbonate	1.12E+00	kg
	Ultrapure water	1.07E+00	kg
Output	SO ₂	4.80E+00	g
	CO ₂	1.89E+02	g
	Dust	7.49E-01	g
	Sulfuric acid mist	7.68E-03	g
	Chemical Oxygen Demand (COD)	9.63E-03	g
	Suspended solids	9.36E-01	g
	Lithium carbonate	6.02E-01	kg

A18. Inventory data for LFP battery anode material

Parameter name		Amount	Unit
Input	Electricity	9.36E-01	kWh
	Natural gas	1.99E-02	kg
	Natural Graphite	9.94E-01	kg
	Water	7.68E-01	kg
	Asphalt	1.11E-01	kg
Output	Non-methane hydrocarbons	7.46E-01	g
	Dust	4.39E-01	g
	Benzopyrene	1.48E-06	g
	Soot	1.76E-01	g
	Anode material	1.05E+00	kg

A19. Inventory data for LFP battery Electrolyte

Parameter name		Amount	Unit
Input	Electricity	2.76E+00	kWh
	Natural gas	1.57E-01	kg
	Steam	1.15E+01	kg
	Pure water	6.70E-01	kg
	Nitrogen	4.89E-01	kg
	Sodium hydroxide	7.08E-02	kg
	Water	1.24E+00	kg
	CO ₂	8.45E+02	g
Output	Dust	4.96E-02	g
	Fluoride	8.82E-03	g
	Hydrogen fluoride	7.42E-02	g
	Hydrogen chloride	1.94E-01	g
	Volatile Organic Compounds (VOC)	3.40E-01	g
	Chemical Oxygen Demand (COD)	1.30E-01	g
	Fluoride	4.32E-03	g
	Suspended solids	1.25E-01	g
	Ammonia nitrogen	1.27E-02	g
	Electrolyte	1.88E+00	kg

A20. Inventory data for LFP battery separator

Parameter name		Amount	Unit
Input	Electricity	4.22E+00	kWh
	Polypropylene	1.88E-01	kg
	Polyethylene	9.44E-05	kg
	Aluminum oxide	3.75E-01	kg
	Carboxymethylcellulose sodium	3.75E-06	kg
	Aqueous acrylic acid	4.69E-02	kg
	Water	4.83E-01	kg
	Volatile Organic Compounds (VOC)	9.36E-01	g
Output	Dust	1.78E-02	g
	Chemical Oxygen Demand (COD)	5.76E-03	g
	Battery Separator	2.82E+01	m ²

A21. Inventory data for LFP battery copper foil

	Parameter name	Amount	Unit
Input	Electricity	1.12E+01	kWh
	Natural gas	2.49E-04	kg
	Copper	9.04E-01	kg
	Concentrated sulfuric acid	1.46E-02	kg
	Hydrochloric acid	1.21E-04	kg
	Tartaric Acid	1.02E-04	kg
	Active carbon	3.02E-04	kg
	Cobalt Sulphate Hexahydrate	6.04E-04	kg
	Zinc Sulphate Heptahydrate	6.04E-04	kg
	Carboxyethyl cellulose	1.21E-04	kg
	3-Carboxy-1-propanesulfonate	6.04E-05	kg
	Water	1.01E+01	kg
Output	Sulfuric acid mist	6.38E-01	g
	Copper	3.38E-04	g
	Cobalt	4.47E-05	g
	Copper foil	9.04E-01	kg

A22. Inventory data for LFP battery aluminum foil

	Parameter name	Amount	Unit
Input	Electrolytic aluminum	7.97E-01	kg
	Water	1.72E+00	kg
	Diatomite	2.48E+00	kg
	Rolling Oil	7.84E+00	kg
Output	Non-methane hydrocarbons	1.79E+00	g
	Chemical oxygen demand (COD)	2.98E-02	g
	Suspended solids	5.93E-04	g
	Ammonia nitrogen	5.86E-04	g
	Aluminum foil	6.02E-01	kg

A23. Inventory data for LFP battery Shell foil

	Parameter name	Amount	Unit
Input	Electricity	6.58E-01	kWh
	Stretching oil	5.26E-02	kg
	Water	2.88E-03	kg
	Aluminum	1.32E-01	kg
Output	Shell	1.75E+00	P

3. Inventory data for NMC batteries

A24. Inventory data for NMC battery cathode materials

A2.1. Inventory data for NMC battery cathode materials				
	Parameter name	Unit	Amount	
Input	Energy and Power	Electricity	kWh	
	Materials	Ternary precursor	kg	4.32E+00
		Water	kg	6.21E+00
		Lithium carbonate	kg	1.77E+00
		Oxygen	m³	2.76E-01
		Nano-alumina	kg	4.54E-02
Output	Atmospheric Pollutant	CO₂	kg	1.05E+00
		Dust	g	3.19E-01
		Cobalt	g	1.01E-01
		manganese	g	1.52E-01
		Nickel	g	2.35E-01
	Water pollutants	Biological Oxygen Demand (BOD)	g	1.93E-01
		Chemical Oxygen Demand (COD)	g	7.45E-01
		Suspended solids	g	5.87E-01
		Ammonia nitrogen	g	1.16E-01
	Production	Cathode material	Kg	4.62E+00

A25. Inventory data for NMC battery Ternary precursor

	Parameter name	Unit	Amount
Input	Energy and Power	Electricity	4.35E+00
		Natural gas	m ³
		Nickel sulfate	kg
	Materials	Cobalt sulfate	kg
		Manganese sulfate	kg
		Water	kg
		Ammonia	kg
		Sodium hydroxide	Kg

Output	Atmospheric Pollutant	Nitrogen	kg	1.04E-01
		SO ₂	g	3.52E-01
		Dust	g	7.20E-01
		Nitrogen oxides	g	3.43E-01
	Water pollutants	Ammonia	g	6.88E+01
		Chemical Oxygen Demand (COD)	g	3.89E+00
		Suspended solids	g	3.11E-01
		Ammonia nitrogen	g	5.63E-01
		Production	Ternary precursor	kg

A26. Inventory data for NMC battery Manganese sulfate

		Parameter name	Unit	Amount
Input	Energy and Power		Electricity	kWh
	Materials	Manganese dioxide	kg	1.64E+00
		Pyrite	kg	1.64E-01
		Concentrated sulfuric acid	kg	9.26E-01
		Hydrogen peroxide	kg	5.52E-04
		Sodium sulfate	kg	2.71E-02
		Sodium sulfide	kg	1.08E-02
		Biomass fuel	kg	3.25E-01
		Sodium hydroxide	kg	1.42E+01
		Water	kg	1.62E+00
		Manganese carbonate	kg	5.41E-02
Output	Atmospheric Pollutant	CO ₂	g	2.30E+01
		Dust	g	1.42E-02
		Sulfuric acid mist	g	1.15E-02
		Nitrogen oxides	g	3.32E-01
	Water pollutants	Chemical Oxygen Demand (COD)	g	3.30E-02
		Suspended solids	g	1.62E-03
		Ammonia nitrogen	g	5.59E-02
	Production		Manganese sulfate	kg

A27. Inventory data for NMC battery Nickel sulfate

		Parameter name	Unit	Amount
Input	Energy and Power		Electricity	kWh
	Materials	Hard coal	kg	3.42E+01
		Laterite nickel ore	kg	2.47E+02
		Calcium hydroxide	kg	1.30E+01
		Sodium hydroxide	kg	2.01E+01
		Water	kg	1.52E-02
		Flake alkali	kg	1.82E+00
		Extracting agent	kg	5.06E-02
		Calcium carbonate	kg	3.55E-01
		Hydrogen peroxide	kg	8.87E-01
		Sulfuric acid	kg	4.91E+00
		Concentrated sulfuric acid	kg	1.68E+02
Output	Atmospheric Pollutant	SO ₂	g	7.84E+01
		Dust	g	8.65E+01
		Nitrogen oxides	g	7.37E+01
		Sulfuric acid mist	g	9.39E+00
	Water pollutants	Chemical Oxygen Demand (COD)	g	5.70E+00
		Ammonia nitrogen	g	7.50E-01
	Production		Nickel sulfate	kg

A28. Inventory data for NMC battery Cobalt sulfate

		Parameter name	Unit	Amount
Input	Energy and Power		Electricity	kWh
	Materials	Hard coal	kg	1.11E+01
		Cobalt concentrate	kg	3.57E+01
		Concentrated sulfuric acid	kg	6.76E+00
		Sodium sulfite	kg	2.18E+00
		Water	kg	1.83E+02
		Sodium carbonate	kg	3.11E-01
		Calcium triple superphosphate	kg	8.51E-01
		Sodium chlorate	kg	1.04E-01
		Hydrochloric acid	kg	2.40E+01
		Sulfuric acid	kg	4.91E+00
Output	Water pollutants	Sodium hydroxide	kg	2.36E+01
		Ammonia	kg	1.50E-01
		Oxalic acid	kg	3.73E-01
		Ammonium bicarbonate	kg	4.79E+00
		Sodium sulfide	kg	2.45E-01

Output	Atmospheric Pollutant	Extracting agent	kg	5.54E-02
		Calcium oxide	kg	3.68E+00
		SO ₂	g	7.09E+01
		Dust	g	2.27E+01
		Nitrogen oxides	g	3.00E+01
		Ammonia	g	3.77E-01
	Water pollutants	Sulfuric acid mist	g	3.37E+00
		Chemical Oxygen Demand (COD)	g	7.86E+00
		Suspended solids	g	2.55E+00
		Biological Oxygen Demand (BOD)	g	1.11E-01
		Ammonia nitrogen	g	5.57E-02
	Production	Cobalt sulfate	kg	2.75E+00

A29. Inventory data for NMC battery Lithium carbonate

		Parameter name	Unit	Amount
Input	Energy and Power	Steam	kg	1.09E+01
		Hard coal	kg	3.77E+00
	Materials	sulfuric acid	kg	3.50E+00
		Sulfur acid	kg	1.40E+00
		Limestone	kg	1.31E+00
		Sodium hydroxide	kg	3.56E-01
		Sodium Carbonate	kg	3.56E+00
		Ultrapure water	kg	3.13E+00
Output	Atmospheric Pollutant	SO ₂	g	1.41E+01
		CO ₂	g	5.56E+02
		Dust	g	2.20E+00
		Nitrogen oxides	g	7.86E+00
	Water pollutants	Sulfuric acid mist	g	2.24E-02
		Chemical Oxygen Demand (COD)	g	2.83E-02
		Suspended solids	g	2.83E-02
	Production	Lithium carbonate	kg	1.77E+00

A30. Inventory data for NMC battery anode material

		Parameter name	Unit	Amount
Input	Energy and Power	Electricity	kWh	2.74E+01
		Natural gas	kg	4.50E-02
	Materials	Natural Graphite	kg	2.25E+00
		Water	kg	1.74E+00
		Asphalt	kg	2.51E-01
Output	Atmospheric Pollutant	Non-methane hydrocarbons	g	1.69E+00
		Dust	g	9.94E-01
		Benzo[a]pyrene	g	3.36E-06
		Soot	g	3.98E-01
	Production	Anode material	Kg	2.37E+00

A31. Inventory data for NMC battery Electrolyte

		Parameter name	Unit	Amount
Input	Energy and Power	Electricity	kWh	3.01E+01
		Natural gas	kg	1.71E-01
		Steam	kg	1.25E+01
	Materials	Pure water	kg	7.30E-01
		Nitrogen	kg	5.32E-01
		Sodium hydroxide	kg	7.71E-02
		Water	kg	1.35E+00
Output	Atmospheric Pollutant	SO ₂	g	7.84E+01
		CO ₂	g	9.20E+02
		Dust	g	5.40E-02
		Fluoride	g	9.61E-03
	Water pollutants	Hydrogen fluoride	g	8.08E-02
		Hydrogen chloride	g	2.11E-01
		Volatile Organic Compounds (VOC)	g	3.70E-01
		Chemical Oxygen Demand (COD)	g	1.42E-01
		Fluoride	g	4.70E-03
		Suspended solids	g	1.36E-01
		Ammonia nitrogen	g	1.38E-02
	Production	Electrolyte	kg	2.05E+00

A32. Inventory data for NMC battery separator

		Parameter name	Unit	Amount
Input	Energy and Power	Steam	kg	1.09E+01
	Materials	Polypropylene	kg	2.17E-01
		Polyethylene	kg	1.09E-05
		Aluminum oxide	kg	4.33E-01
		Carboxymethylcellulose sodium	kg	4.35E-06
		Aqueous acrylic acid	kg	5.41E-02
		water	kg	5.57E-01
	Atmospheric Pollutant	Volatile Organic Compounds (VOC)	g	1.08E-01
		Dust	g	2.06E-02
		Chemical Oxygen Demand (COD)	g	6.68E-03
		Suspended solids	g	1.45E-02
Output	Production	Battery Separator	m ²	3.25E+01

A33. Inventory data for NMC battery copper foil

		Parameter name	Unit	Amount
Input	Energy and Power	Electricity	kWh	1.40E+01
		Natural gas	kg	3.12E-04
	Materials	Copper	kg	1.13E+01
		Concentrated sulfuric acid	kg	1.83E-02
		Hydrochloric acid	kg	1.57E-04
		Tartaric Acid	kg	1.52E-03
		Active carbon	kg	3.78E-04
		Cobalt Sulphate Hexahydrate	kg	7.56E-04
		Zinc Sulphate Heptahydrate	kg	7.64E-04
		Carboxyethyl cellulose	kg	1.51E-04
		3-Carboxy-1-propanesulfonate	kg	7.54E-05
	Atmospheric Pollutant	Water	kg	1.26E+01
		Sulfuric acid mist	g	8.54E-01
	Water pollutants	Volatile Organic Compounds (VOC)	g	1.20E-01
		Copper	g	4.23E-04
		Cobalt	g	5.59E-05
Output	Production	Copper foil	kg	1.13E+00

A34. Inventory data for NMC battery aluminum foil

		Parameter name	Unit	Amount
Input	Materials	Electrolytic aluminum	kg	6.18E-01
		Water	kg	1.33E+00
		Diatomite	kg	1.92E+00
		Rolling Oil	kg	6.08E+00
	Atmospheric Pollutant	Non-methane hydrocarbons	g	1.53E+00
		Chemical Oxygen Demand (COD)	g	2.31E-02
	Water pollutants	Suspended solids	g	4.63E-04
		Ammonia nitrogen	g	4.62E-04
Output	Production	Aluminum foil	kg	4.67E-01

A35. Inventory data for NMC battery shell

		Parameter name	Unit	Amount
Input	Materials	Electricity	kWh	2.35E+00
		stretching oil	kg	1.88E-01
		Water	kg	1.03E-02
		Aluminum	kg	4.70E-01
	Production	Shell	P	6.27E+00

A36. Inventory data for the LFP batteries assembly phase

		Parameter name	Unit	Amount
Input	Materials	Electricity	kWh	3.75E-02
		Battery cell	P	1.75E+00
		Battery management systems	P	1.75E-02
		Water	kg	1.05E-01
		Shell	P	1.75E-02
	Production	LFP Battery	P	1.57E-02

4. Inventory data for use phase

A37. Background Parameters of NIB, LFP, and NMC battery life cycle models

Parameter name	NIB	LFP	NMC	Unit
Vehicle mass	1625	2,380	2,021	kg
Battery mass	558	600	531	kg
Battery capacity	57.0	57.0	63.8	kWh
Energy density	102	95	120	Wh/kg
Electricity consumption (Pv)	19.5	19.5	19.94	kWh/100km
Total mileage (Dv)	200000	200000	200000	km
Battery charge and discharge efficiency	90	90	95	%
Energy input to deliver 1 kWh of energy (loss from charge-discharge)	1.1	1.1	1.05	kWh
Total energy (use phase)	24,400	39,000	39,880	kWh
Grid mix electricity (use phase)	27,111	43,333	41,052	kWh

5. Inventory data for the recycling phase NIB, LFP & NMC

A38. Inventory data for hydrometallurgical recycling process of NIB

	Parameter name	Amount	Unit
Input	Electricity	1.41E-01	kWh
	Reagent	2.50E-02	kg
	Used battery of NIB	1.00E+01	kg
	Water	7.20E-01	kg
	H ₂ SO ₄	2.13E-01	kg
	Lime	1.16E-01	kg
Output	Non-Fe-Co-metals	1.05E-01	kg
	Aluminum	9.59E-02	kg
	Copper	9.38E-03	kg
	NiCO ₃	8.71E-02	kg
	MnO ₂	1.07E-01	kg
	Mg (OH) ₂	6.74E-03	kg
	TiO ₂	1.09E-02	kg
	SO ₂	4.50E-06	kg
	VOC	2.50E-06	kg
	Solid suspension	1.20E-05	kg
	Chemical Oxygen Demand (COD)	3.00E-05	kg
	Total hydrocarbon	1.00E-08	kg
	Plastic to refining	5.82E-02	kg
	Residue to landfill	2.02E-01	kg

A39. Inventory data for pyrometallurgical recycling process of NIB

	Parameter name	Amount	Unit
Input	Electricity	8.00E-01	kWh
	Used battery of NIB	1.00E+00	kg
	NaOH	2.10E-01	kg
	Water	1.10E+00	kg
Output	Non-Fe-Co-metals	1.05E-01	kg
	Aluminum	9.57E-02	kg
	Copper	9.36E-03	kg
	NiCO ₃	8.71E-02	kg
	MnO ₂	1.07E-01	kg
	TiO ₂	1.09E-02	kg
	SO ₂	4.80E-05	kg
	Dust	1.04E-05	kg
	CO ₂	2.03E+00	kg
	Plastic to refining	5.82E-02	kg

A40. Inventory data for hydrometallurgical recycling process of LFP batteries

	Parameter name	Amount	Unit
Input	Energy and Power		
	Natural gas	3.40E-02	kg
	Used battery of LFP	1.75E-02	P
	Hydrochloric acid	4.04E+00	kg
	Thick water	5.61E+00	kg
	Magnesium hydroxide	5.85E-01	kg
Output	Sodium hydroxide	4.26E-01	kg
	Dust	3.03E-01	g
	Sulfuric acid mist	8.11E-02	g
	Hydrogen chloride	5.43E-02	g
	Production		
	Lithium chloride solution	8.90E+00	kg

A41. Inventory data for Physical recycling process of LFP batteries

		Parameter name	Amount	Unit
Input	Energy and Power	Electricity	3.65E+01	kWh
		Used battery of LFP	1.75E-02	P
	Materials	Liquid Nitrogen	3.80E+01	kg
		DMC Solvents	1.93E+00	kg
		Lithium carbonate	1.53E-01	kg
		Nitrogen	4.92E-01	kg
		Glucose	1.45E-03	kg
	Atmospheric Pollutant	Hydrogen fluoride	2.10E-01	g
		Dust	6.51E+00	g
		Volatile Organic Compounds (VOC)	2.44E+00	g
Output	Production	Graphite	1.05E+00	kg
		Aluminum	5.26E-01	kg
		Copper	8.42E-01	kg
		Battery Separator	4.52E-01	kg
		Plastic Parts	1.11E-01	kg
		Shell	1.75E-02	P
		Electrolyte	1.04E+00	kg
		Cathode material	2.32E+00	kg

A42. Inventory data for hydrometallurgical recycling process of NMC batteries

		Parameter name	Unit	Amount
Input	Energy and Power	Electricity	kWh	1.86E+01
		Steam	kg	1.20E+01
	Materials	Used battery of NMC	P	1.57E-02
		Sodium chloride	g	6.75E+01
		Water	kg	8.31E+01
		Sulfuric acid	kg	1.27E+00
		P ₂ O ₄	kg	3.94E-03
		P ₅ O ₇	kg	1.45E-03
		Hydrochloric acid	kg	2.40E+01
		Sulfonated kerosene	kg	1.37E-02
		Sodium sulfide	kg	1.33E-02
Output	Atmospheric Pollutant	Ammonia	kg	4.17E-01
		Sodium hydroxide	kg	8.84E-01
		Hydrogen fluoride	g	4.38E-01
		Dust	g	4.38E-01
		Hydrogen sulfide	g	2.29E-02
		Ammonia	g	8.59E-02
	Water pollutants	Sulfuric acid mist	g	3.75E-02
		Chemical Oxygen Demand (COD)	g	1.03E+01
		Suspended solids	g	1.24E+02
		Biological Oxygen Demand (BOD)	g	3.64E+00
		Nickel	g	4.75E-02
		Cobalt	g	4.38E-02
		Manganese	g	4.75E-02
		Lithium	g	3.98E+00
		Ammonia nitrogen	g	5.96E-01
	Production	Cathode material	kg	1.25E+00

A43. Inventory data for pyrometallurgical recycling process of NMC batteries

		Parameter name	Unit	Amount
Input	Energy and Power	Electricity	kWh	6.67E+00
		Used battery of NMC	P	1.57E-02
	Materials	Sodium hydroxide	kg	2.92E+00
		Coke	kg	1.10E+00
		Limestone	kg	1.00E+00
		Slag Agent	kg	1.00E+00
Output	Atmospheric Pollutant	Hydrogen chloride	g	1.67E+01
		Sulfuric acid	g	2.50E+01
		Dust	g	4.17E-02
		Soot	g	3.86E-02
		SO ₂	g	2.00E-02
	Production	CO ₂	kg	2.03E+00
		Nickel	kg	1.39E+00
		Cobalt	kg	1.42E+00