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Potentials and hotspots of post-lithium-ion batteries: Environmental impacts and supply risks for sodium- and potassium-ion batteries

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ABSTRACT

Lithium-ion batteries (LIBs) currently have the dominant market share in rechargeable batteries, a key technology reducing greenhouse gas emissions. However, concerns regarding the environmental impacts of manufacturing and requirements for critical resources result in the need for developing alternative battery technologies as well as improving LIBs. This study assessed environmental impacts and supply risks associated with three post-LIBs, namely two sodium-ion batteries (NMMT and NTO) and one potassium-ion battery (KFSF), and three LIBs (NMC, LFP, and LTO) using life cycle assessment and criticality assessment. Post-LIBs showed comparable environmental performances and lower supply risks compared with LIBs. The environmental hotspots were $NiSO_4$ production for cathode for NMMT and NMC, and TiO_2 production for anode for NTO and LTO. KFSF anode and cathode had no significant environmental impacts, achieving the best performance. LIBs had higher supply risks than the other batteries, mainly attributed to Li and Co used as electrode constituents.

1. Introduction

Rechargeable batteries are one of the key technologies used to reduce anthropogenic greenhouse gas (GHG) emissions. They enable electric energy storage to enhance the flexibility of power systems, consequently integrating a higher degree of renewables into the grid (Ram et al., 2019; Weil et al., 2020). Additionally, they form the basis for successful electric vehicle deployment (Dunn et al., 2011). The importance and demand for these technologies are projected to further increase in light of the need to achieve net-zero GHG emissions to limit the rise in global temperature below 1.5 °C relative to pre-industrial levels (IPCC, 2021; Rogelj et al., 2018). Among the various rechargeable battery technologies, lithium (Li)-ion batteries (LIBs) dominate the market share of rechargeable batteries and are widely used in various applications because of their high energy and power density, and long cycle life (shelf life) (IEA, 2020; Kim et al., 2012; Li et al., 2018; Zubi et al., 2018).

Although LIBs have the aforementioned advantages, some major concerns exist, particularly regarding their environmental impacts associated with manufacturing and requirements for scarce and critical resources (e.g., Dolganova et al., 2020; Nayak et al., 2018; Nitta et al., 2015; Peters and Weil, 2016). To avoid environmental burden shifting, that is, reducing GHG emissions by potentially increasing other environmental impacts, assessing all environmental impacts associated with battery manufacturing is essential. In addition, Li, which is a primary constituent of LIBs, is distributed in a limited number of countries and often considered a critical metal with a relatively high supply risk (e.g., Miatto et al., 2021; Prior et al., 2013; Schrijvers et al., 2020; Yokoi et al., 2021). Since the global demand for Li is expected to drastically increase in the future (Sovacool et al., 2020; Watari et al., 2020), this resource-related issue may become a source of price increases and constraints for expanding LIBs (Baumann et al., 2022; Lebrouhi et al., 2021). Accordingly, in addition to improving LIBs, developing alternative battery technologies is also essential for the large-scale adoption of rechargeable batteries.

Various post-LIBs have been explored as alternative battery technologies with the aim to be comparable to or even better than LIBs in

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terms of battery performance, cost, large-scale adoption, environmental impact, and material requirements (Amici et al., 2022; Choi and Aurbach, 2016; Duffner et al., 2021; Walter et al., 2020; Yu et al., 2020). In particular, sodium-ion batteries (SIBs) and potassium-ion batteries (PIBs) are considered potential alternatives to LIBs (Kubota et al., 2018; Pham et al., 2017). SIBs are considered one of the most promising and mature post-LIB technologies because of their economic efficiency, similar chemical properties to LIB, and abundance of sodium (Chen et al., 2018; Delmas, 2018; Deng et al., 2018; Hwang et al., 2017; Peters et al., 2019a; Slater et al., 2013; Vaalma et al., 2018; Yabuuchi et al., 2014). In addition, it was recently announced that SIBs are being implemented in electric vehicles (CATL 2023). At the same time, PIBs are another emerging technology also considered as a research-worthy alternative owing to their low cost, high operating voltages, fast rate capabilities (thus, high power density), and abundance of potassium (Dong et al., 2020; Hosaka et al., 2020; Hwang et al., 2018; Liu et al., 2023; Min et al., 2021; Wang et al., 2021; Zhang et al., 2019, 2021a). Besides, sodium and potassium do not form alloys with aluminum; hence, aluminum foil can be used as a current collector instead of the copper foil found in LIBs, which reduces not only the cost but also the weight of batteries (Hwang et al., 2018; Kubota et al., 2018; Min et al., 2021; Zhang et al., 2019). Substituting Li with sodium or potassium as the main battery component will change battery performance metrics in various environmental aspects, such as material use, energy consumption, and GHG emissions. Therefore, a comprehensive assessment regarding the environmental impacts of batteries is crucial to demonstrate the environmental performance of these batteries (LIBs, SIBs, and PIBs) by verifying that the alteration by sodium- or potassium-ion batteries does not result in the net increase in the total environmental impact of overarching environmental issues.

Life cycle assessment (LCA) is a standardized methodology for comprehensively quantifying and assessing a wide set of environmental impacts (e.g., global warming, acidification, and resource depletion) of products, services, and activities, considering the whole (or part of) life cycle (i.e., from resource extraction until the end-of-life treatment) (ISO, 2006a, 2006b). Although LCA studies on the environmental impact associated with LIB manufacturing have already been conducted (Aichberger and Jungmeier, 2020; Arshad et al., 2022; Chen et al., 2022; Ellingsen et al., 2017; Peters et al., 2017; Porzio and Scown, 2021; Tolomeo et al., 2020; Zhao et al., 2021), research on those associated with SIBs have been limited (Guo et al., 2023; Lai et al., 2023; Mohr et al., 2020; Peters et al., 2016, 2019b, 2021; Schneider et al., 2019; Sharma and Manthiram, 2020; Wang et al., 2020) and to the best of our knowledge, no study has assessed the environmental impact of PIBs. Besides, in the current LCA framework, resource-related issues are generally assessed in terms of resource depletion from a long-term perspective, rather than resource scarcity, accessibility, or supply risk issues from a short-term perspective, which are often the main concerns of stakeholders for resource use-related issues (Berger et al., 2020; Cimprich et al., 2019; Schulze et al., 2020; Sonderegger et al., 2020). Such short-term aspects of resource use are generally assessed using criticality assessment (Schrijvers et al., 2020). Despite resource-related issues associated with LIBs, including resource requirements, depletion, and criticality, have been discussed in several studies (Bongartz et al., 2021; Dolganova et al., 2020; Greenwood et al., 2021; Kiemel et al., 2021; Manjong et al., 2023; Pelzeter et al., 2022; Peters and Weil, 2016; Santillán-Saldivar et al., 2022; Simon et al., 2015; Sun et al., 2021), the raw material criticality associated with post-LIB technologies have been partly addressed in a very limited number of studies (Baumann et al., 2022; Vaalma et al., 2018; Wentker et al., 2019).

This study addressed these research gaps in the assessment of post-LIB technologies. We assessed the environmental impacts and supply risks associated with the production (cradle to gate) of 1 kWh of post-LIBs as well as LIBs using LCA and criticality assessment. This aimed to demonstrate the performance of the current and emerging batteries in both environmental impacts and supply risks in parallel and identify the hotspots to improve their performance towards the large-scale adoption of decarbonization. Six types of current and emerging batteries were analyzed in this study: $Na_{1.1}(Ni_{0.3}Mn_{0.5}Mg_{0.05}Ti_{0.05})O_2$—Hard carbon SIB (NMMT), $Na_2Fe_2(SO_4)_3$—$Na_3LiTi_5O_{12}$ SIB (NTO), $KFeSO_4F$-Graphite PIB (KFSF), $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$-Graphite LIB (NMC), $LiFePO_4$-Graphite LIB (LFP), and $LiFePO_4$-$Li_4Ti_5O_{12}$ LIB (LTO).

2. Methods

2.1. Functional unit and system definition

LCA is a method for quantifying the environmental impacts associated with products throughout their life cycle, allowing the comparison of the environmental performance of different products and identification of hotspots among different processes in their life cycle. As this study focused on the environmental impacts associated with battery production, the scope of assessment (i.e., system boundary) was cradle to gate, that is, from resource extraction to battery manufacturing. The functional unit, the quantified performance of a product system as a reference unit (ISO, 2006a), was defined as 1 kWh of a battery pack.

The production processes and weight composition of the six target batteries (cylindrical type) are illustrated in **Figs. S1–S7**. Batteries comprise a cathode, anode, electrolytes, separator, cell casing, battery management system (BMS), and pack casing. The battery design and key parameters, including mass balance, electricity and heat demand, and energy density, were calculated using a dimensioning tool developed by Peters et al. (2021) with assumptions of some parameters, such as active material capacity, cell open circuit voltage at full power, and open circuit voltage at 50% state of charge. The calculated energy densities for the NMMT, NTO, KFSF, NMC, LFP, and LTO battery packs were 137.4 Wh kg^{-1}, 88.8 Wh kg^{-1}, 136.1 Wh kg^{-1}, 217.4 Wh kg^{-1}, 157.7 Wh kg^{-1}, and 81.9 Wh kg^{-1}, respectively. Although reported energy densities for batteries are highly diversified and include uncertainty, the calculated energy densities may be comparable to the reported, estimated, or assumed values in the literature. For example, the energy density of SIB cells can be 75–150 Wh kg^{-1} (Abraham et al., 2020; Lai et al., 2023; Peters et al., 2016); that of NMC can be 115–300 Wh kg^{-1} (Akgunduz, 2022; Niu et al., 2019; Sun et al., 2020); and that of LFP can be 90–160 Wh kg^{-1} (Akgunduz, 2022; Oliveira et al., 2015). Regarding PIB, the theoretical energy density can be lower than LFP, whereas it has the potential to improve performances including energy density (Hosaka et al., 2019; Komaba, 2019; Lander et al., 2015).

2.2. Life cycle inventory of the target batteries

For the post-LIBs, two SIBs (NMMT and NTO) and one PIB (KFSF) were selected. NMMT is the most studied SIB in LCA and is composed of a hard carbon anode and $Na_{1.1}(Ni_{0.3}Mn_{0.5}Mg_{0.05}Ti_{0.05})O_2$ cathode. The foreground data of anode and cathode production for NMMT were based on Peters et al. (2021) and Ellingsen et al. (2014). The hard carbon anode was assumed to be produced from petroleum coke (Peters et al., 2016). NTO is a new type of SIB assessed in this study and is composed of a $Na_3LiTi_5O_{12}$ anode and $Na_2Fe_2(SO_4)_3$ cathode. The anode material is a recently developed single-phase spinel-type sodium titanium oxide with a $Li_4Ti_5O_{12}$-like structure, and is a promising anode material for constructing stable and safe SIBs (Kitta et al., 2020). The foreground data of anode and cathode production for NTO were developed based on Kitta et al. (2020) and Peters et al. (2021). KFSF is composed of a graphite anode and a $KFeSO_4F$ cathode. The foreground data of anode production for KFSF were based on Peters et al. (2021), whereas the foreground data of graphite production were updated based on Engels et al. (2022). The cathode material is produced by mixing, milling, and heating $FeSO_4$ and KF (Hosaka et al., 2019; Lander et al., 2015; Recham et al., 2012). The foreground data of electrolyte production for the post-LIBs were based on Peters et al. (2016).

Three types of LIBs were targeted in the assessment for comparison with the post-LIBs: NMC, LFP, and LTO. NMC is one of the most frequently assessed LIBs in LCA studies, in which graphite and $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ are used in the anode and cathode, respectively. The foreground data of anode and cathode production for NMC were obtained from Ellingsen et al. (2014), Engels et al. (2022), and Peters et al. (2021), whereas the foreground data of $CoSO_4$ production were updated based on Zhang et al. (2021b). LFP is also one of the commonly used types of LIBs, which is expected to be cheaper compared with LIBs requiring a Co-based cathode (Li et al., 2018). LFP is composed of graphite and $LiFePO_4$ in the anode and cathode, respectively. The foreground data of anode and cathode production for LFP were based on Ellingsen et al. (2014), Engels et al. (2022), Le Varlet et al. (2020), and Peters et al. (2016). LTO is composed of a $Li_4Ti_5O_{12}$ anode and $LiFePO_4$ cathode. Lithium-titanium oxide (i.e., $Li_4Ti_5O_{12}$) is known as a reliable anode material with improved chemical and crystal stability and safety (Takami et al., 2013; Wang et al., 2013; Zhao et al., 2015). This study included LTO in the assessment for comparison with NTO, one of the target SIBs in this study. The foreground data of anode and cathode production for LTO were based on Le Varlet et al. (2020), Peters et al. (2016), and Ellingsen et al. (2014). The foreground data of electrolyte production for LIBs were based on Notter et al. (2010).

The life cycle inventory of these six target batteries was developed based on the collected foreground data and background data from ecoincent 3.7 (Moreno Ruiz et al., 2020). A detailed inventory of the target batteries is provided in a full transparent manner in **the supplementary excel file 1**, which is highly recommended by experts in this field (Bauer et al., 2022).

2.3. Life cycle impact assessment

The ReCiPe 2016 endpoint method (hierarchist perspective) was used to quantify environmental impacts (Huijbregts et al., 2017). It assesses environmental impacts in terms of three endpoints: human health, ecosystems, and resources (Fig. 1). To determine the scores of these endpoints, the results of the corresponding midpoints were summed up. The impacts on human health were attributed to seven categories: global warming (GW), stratospheric ozone depletion (SO), ionizing radiation (IR), ozone formation (OF), particulate matter (PM), human toxicity (HT), and water use (WU). The impacts on ecosystems were attributed to seven categories: GW, OF, terrestrial acidification (TA), eutrophication (EP), ecotoxicity (ET), land use (LU), and WU. The impacts on resources were attributed to two categories: mineral resources (MR) and fossil resources (FR). The scores for the three endpoints were normalized using global normalization factors for the reference year 2010 and then aggregated into a single score (total environmental impact) with weighting factors from Eco-indicator 99 (Goedkoop and Spriensma, 2001). Weighting is effective in interpreting results when there is a trade-off between impact categories, although it includes uncertainty (Finnveden et al., 2009; Kalbar et al., 2017). In addition to the environmental impacts, the supply risks associated with material requirements were assessed, as described in the following section. The impact assessment was implemented using SimaPro 9 software developed by PRé Sustainability as well as the inventory analysis.

2.4. Supply risk assessment

Supply risks are the main concerns associated with raw materials and products. To quantitatively assess the supply risks of mineral resources associated with batteries, this study adopted the integrated method to assess resource efficiency: ESSENZ method. The ESSENZ method was developed to assess the risks associated with resource use for a product system in terms of sustainability including overarching aspects in economic, environmental, and social dimensions (Bach et al., 2016, 2019). This method has been applied to assess the criticality aspect of not only products but also companies (Manjong et al., 2023; Pelzeter et al., 2022; Yavor et al., 2021). This is a method recommended by the international

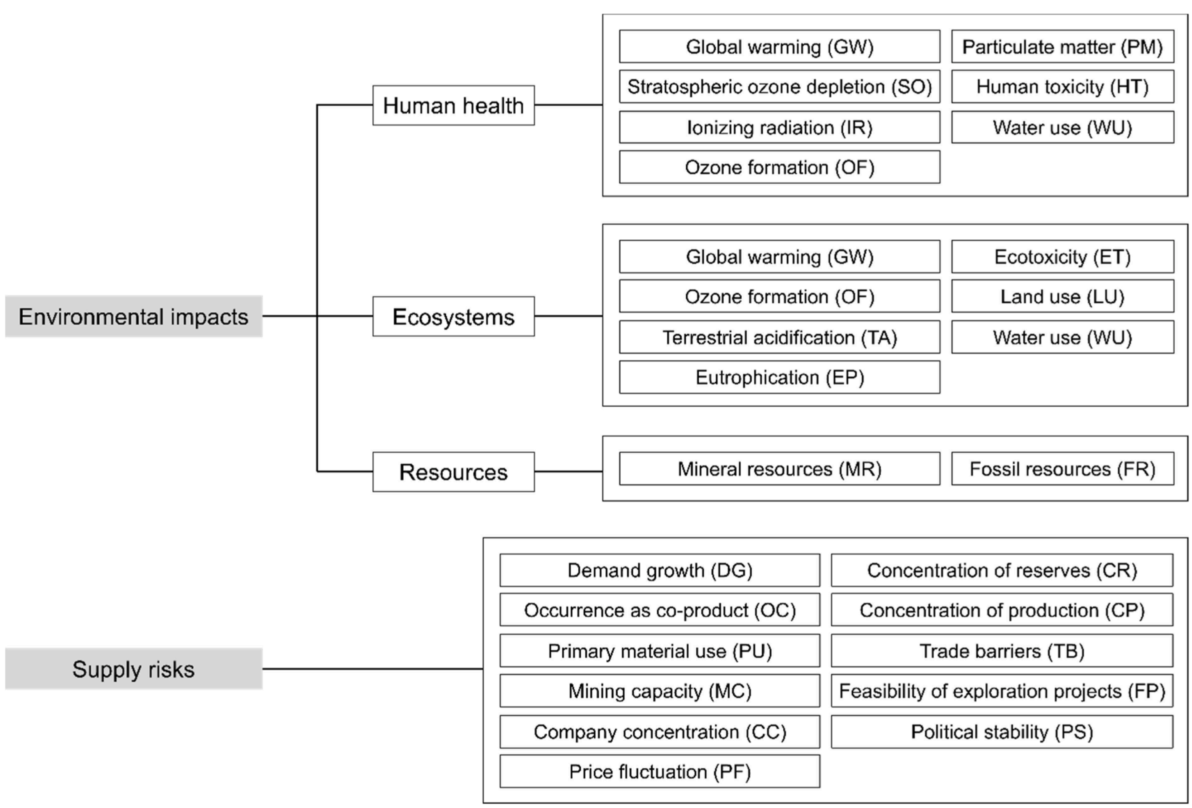

Fig. 1. Impact categories for assessing environmental impacts and supply risks. The ReCiPe 2016 endpoint and ESSENZ methods were adopted to assess environmental impacts and supply risks, respectively.

initiative, the Life Cycle Initiative hosted by UNEP, to assess potential accessibility issues for a product system within the LCA framework (Berger et al., 2020; UNEP, 2019).

According to the ESSENZ method, the supply risks of minerals for batteries were assessed in terms of 11 categories (Fig. 1): demand growth (DG), occurrence as co-product (OC), primary material use (PU), mining capacity (MC), company concentration (CC), price fluctuation (PF), concentration of reserves (CR), concentration of production (CP), trade barriers (TB), feasibility of exploration projects (FP), and political stability (PS). The method provides characterization factors for abiotic resources based on a distance-to-target approach, in which factors are calculated by setting the indicator result in relation to the target value for each category. If an indicator result is smaller than the target value (ratio below 0.8), the characterization factor is set to zero. A larger indicator result is reflected in a larger characterization factor. In addition, characterization factors are scaled up to 1.7×10^{13} for all categories to allow application also for big inventories. The resulting score for each category was calculated by multiplying the inventory data of resource use by the corresponding characterization factors. The overall supply risks were calculated by summing the scores of the 11 categories. This study adopted the updated characterization factors of ESSENZ in 2019 provided on the website of the Technical University of Berlin (Technische Universität Berlin, 2023). Note that the underlying data for calculating characterization factors for supply risks can vary from year to year; thus, updating characterization factors is required to assess supply risks based on the latest situations (Bach et al., 2019).

3. Results

3.1. Overview of the total performance in environmental impacts and supply risks

Post-LIBs have comparable environmental impacts and promising performance in terms of supply risks compared with LIBs (Fig. 2). In particular, KFSF exhibited the best performance for environmental impact, although it is still an immature technology compared with the other battery technologies. Although the LFP results were lower than those of the SIBs (NMMT and NTO) in terms of environmental impact, the SIBs showed lower scores for supply risks. Among the SIBs investigated, NMMT was better than NTO in both aspects. These results suggest that there is a trade-off among environmental, supply risk, and technological maturity aspects for current and emerging batteries.

The main contributors differed depending on the battery type and aspect. Regarding environmental impacts, the cathode was one of the main contributors to NMMT and NMC (Fig. 2), mainly because of the production of nickel sulfate ($NiSO_4$) for active materials (Fig. 3). In addition, cobalt sulfate ($CoSO_4$) production for active materials in the cathode also contributed significantly to the environmental impact of NMC. In contrast, NTO and LTO require neither $NiSO_4$ nor $CoSO_4$, resulting in a relatively low environmental impact of the cathode (Fig. 2). The anode and BMS were the main contributors to the environmental impacts of NTO and LTO. The environmental impact associated with the anode production of these batteries mainly arose from the production of titanium dioxide (TiO_2) (Fig. 3), which is a distinctive material used in these batteries. For KFSF and LFP, the BMS was the main contributor due to the production of the printed wiring board. Given that the BMS is a common part of all six batteries, the environmental impacts of BMS were more prominent for these batteries because the other parts exhibited relatively low environmental impacts.

Regarding the supply risks, Li was a key mineral for NTO, NMC, LFP, and LTO (Fig. 4). The cathode was the main contributor to the supply risks of LIBs owing to the use of lithium hydroxide (LiOH) for the active materials. In addition, the use of lithium carbonate (Li_2CO_3) for the anode of LTO also contributed significantly. Li_2CO_3 was also used for the anode of NTO, but its content was lower than that of LTO (approximately 35% of the content in 1 kWh of LTO), resulting in lower supply risks. For KFSF, the supply risks for anode were relatively high due to graphite use.

3.2. Hotspot materials for environmental impacts

This section explores environmental hotspots by breaking down the environmental impacts of the anodes and cathodes (Fig. 3**)**. We exhibit environmental hotspots based on the aggregated environmental impacts of all target impact categories, while the endpoint- and midpoint-level results for environmental impact are discussed in detail in **the supplementary material (Figs. S8–S12).** Substance-level results of the total environmental impacts are provided in **the supplementary excel file 2**. Environmental hotspots generally differ depending on the battery type and the corresponding anode and cathode materials, while they can be categorized into three groups according to the similarity of the hotspots: 1) NMMT and NMC, 2) NTO and LTO, 3) KFSF and LFP.

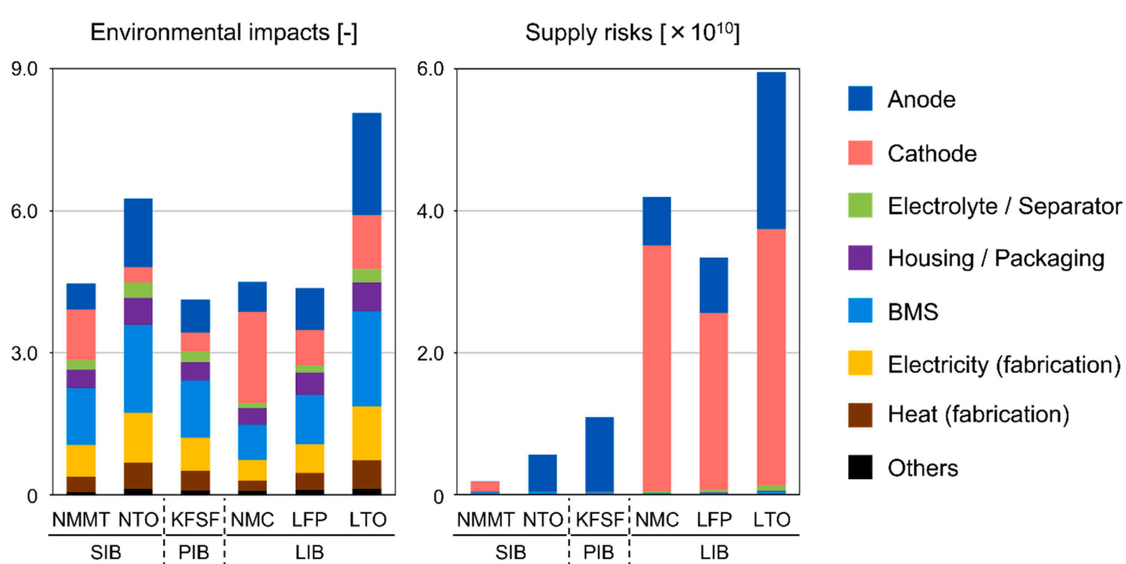

Fig. 2. Overall results for environmental impact and supply risk scores associated with the production of 1 kWh of the two sodium-ion batteries (SIBs), one potassium ion battery (PIB), and two lithium-ion batteries (LIBs). NMMT: $Na_{1.1}(Ni_{0.3}Mn_{0.5}Mg_{0.05}Ti_{0.05})O_2$—Hard carbon SIB; NTO: $Na_2Fe_2(SO_4)_3$—$Na_3LiTi_5O_{12}$ SIB; KFSF: $KFeSO_4F$-Graphite PIB; NMC: $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$-Graphite LIB; LFP: $LiFePO_4$-Graphite LIB; LTO: $LiFePO_4$-$Li_4Ti_5O_{12}$ LIB; BMS: battery management system.

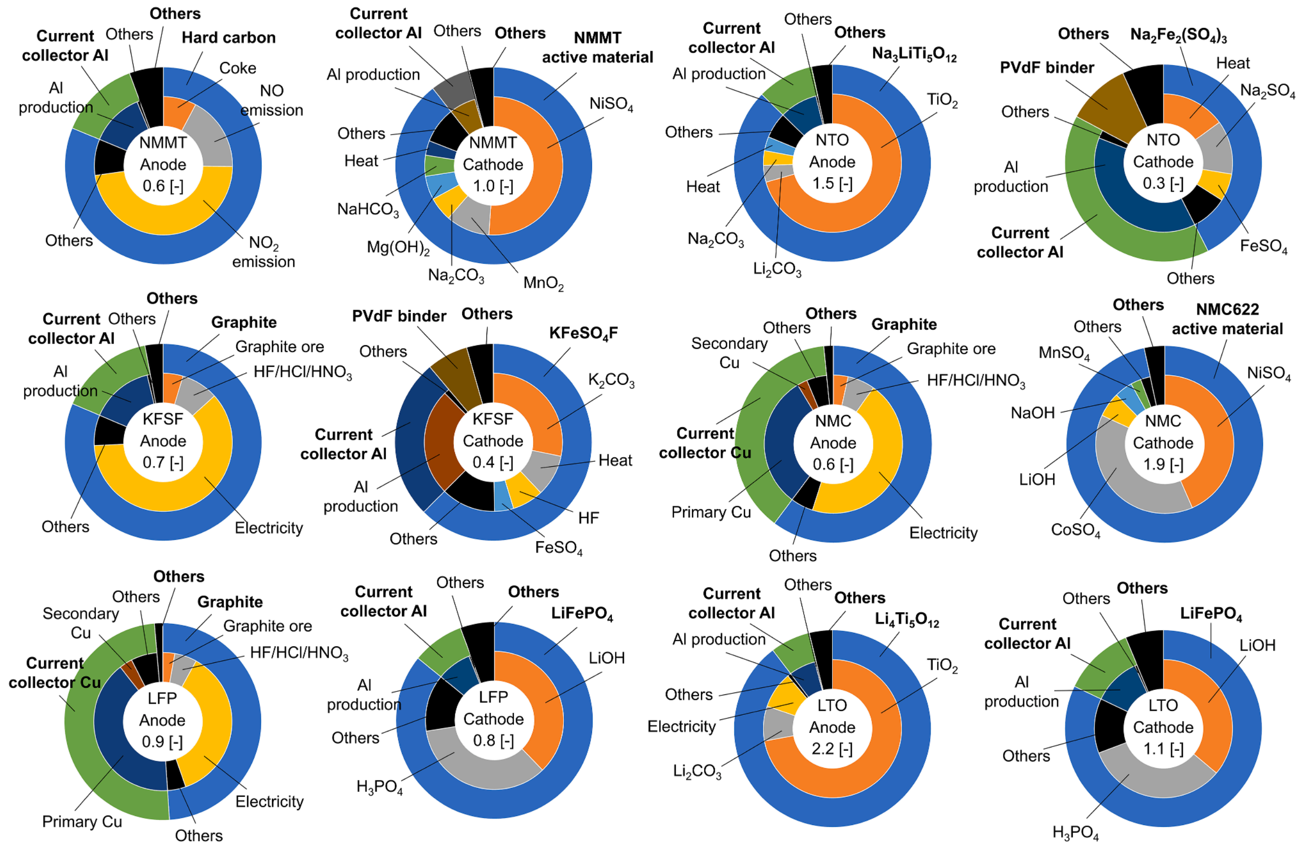

Fig. 3. Breakdowns of the environmental impact of the anode and cathode for the six batteries.

The environmental hotspot for the cathode of NMMT and NMC stemmed from the production of $NiSO_4$ for the cathode precursors, which accounted for 12.0 % and 18.6 % of the total environmental impacts of the battery pack, respectively. In addition, $CoSO_4$ for the cathode of NMC was also the hotspot material, which accounted for 16.4 %. In contrast, the hotspot materials for the anode differed between NMMT and NMC. For NMMT, hard carbon production (from petroleum coke) for the anode accounted for 19.1 %, which was the most significant environment hotspot of the anode. For NMC, graphite and copper current collector production were the hotspots for the anode, which accounted for 8.5 % and 5.4 %, respectively. A breakdown of the environmental impacts associated with $NiSO_4$ production suggests that nickel (Ni) mining and electricity consumption were its main contributors. The main impact category for environmental impact associated with Ni mining was particulate matter (PM), which was also the main impact category for the total environmental impact of the batteries (**Fig. S9**). The environmental impacts of $CoSO_4$ were mainly attributed to cobalt (Co) production, particularly its electricity consumption in China.

NTO and LTO had the same environmental hotspots: TiO_2 for the anode. TiO_2 production accounted for 16.3 % and 19.2 % of the total environmental impact of NTO and LTO, respectively. For the NTO cathode, $Na_2Fe_2(SO_4)_3$ and the aluminum current collector were also contributors, although the cathode contributed a minor share of the total environmental impact (5.1 %). Other contributors to LTO were the production of LiOH and phosphoric acid (H_3PO_4) for the cathode, which accounted for 5.1 % and 4.7 %, respectively. The aluminum current collector is used for the anode of LTO, unlike NMC and LFP, resulting in relatively small contributions of the current collectors for LTO. The environmental impact of TiO_2 production was mainly attributed to the treatment of waste gypsum at a sanitary landfill and sulfuric acid production, both of which mainly contribute to PM. TiO_2 production also contributes to global warming (GW), but its contribution to GW is less significant than that to PM.

The environmental hotspots for KFSF were graphite production for the anode and $KFeSO_4F$ production for the cathode, accounting for 13.9 % and 6.0 % of the total environmental impact of the battery pack, respectively. Graphite production was also the environmental hotspot for the anode of LFP, which accounted for 9.9 % of the total environmental impact of the battery pack. The environmental impact of graphite production mainly originated from electricity consumption. In addition, copper current collector for the anode and $LiFePO_4$ for the cathode were the main contributors to the environmental impact of LFP, accounting for 10.1 % and 14.8 %, respectively. The main contributors to the environmental impact of $LiFePO_4$ were production of LiOH and H_3PO_4. The environmental impact of LiOH production was mainly due to soda ash production for Li_2CO_3, contributing to GW and PM. The contribution of H_3PO_4 was mainly attributed to sulfuric acid production and treatment of H_3PO_4 purification residue. The former mainly contributed to GW and PM, while the latter mainly contributed to human toxicity (HT). $LiFePO_4$ was also used for the cathode of LTO, while TiO_2 for the anode was more significant in the case of LTO.

Electricity and heat consumption for battery fabrication and BMS, which are common processes for all batteries, were the main contributors to the environmental impact of all batteries, especially for KFSF. Although electricity and heat consumption for battery fabrication per 1 kg of battery packs are slightly different depending on battery types as shown in **the supplementary excel file 1**, their environmental impacts per 1 kWh of battery packs are mainly determined by energy densities. The environmental impacts associated with electricity and heat consumption for battery fabrication and BMS accounted for 49.4 %, 55.4 %, 56.2 %, 31.4 %, 46.0 %, and 46.4 % for NMMT, NTO, KFSF, NMC, LFP, and LTO, respectively. Although the energy density for KFSF is higher than those for NTO and LTO, contributions of the environmental impacts

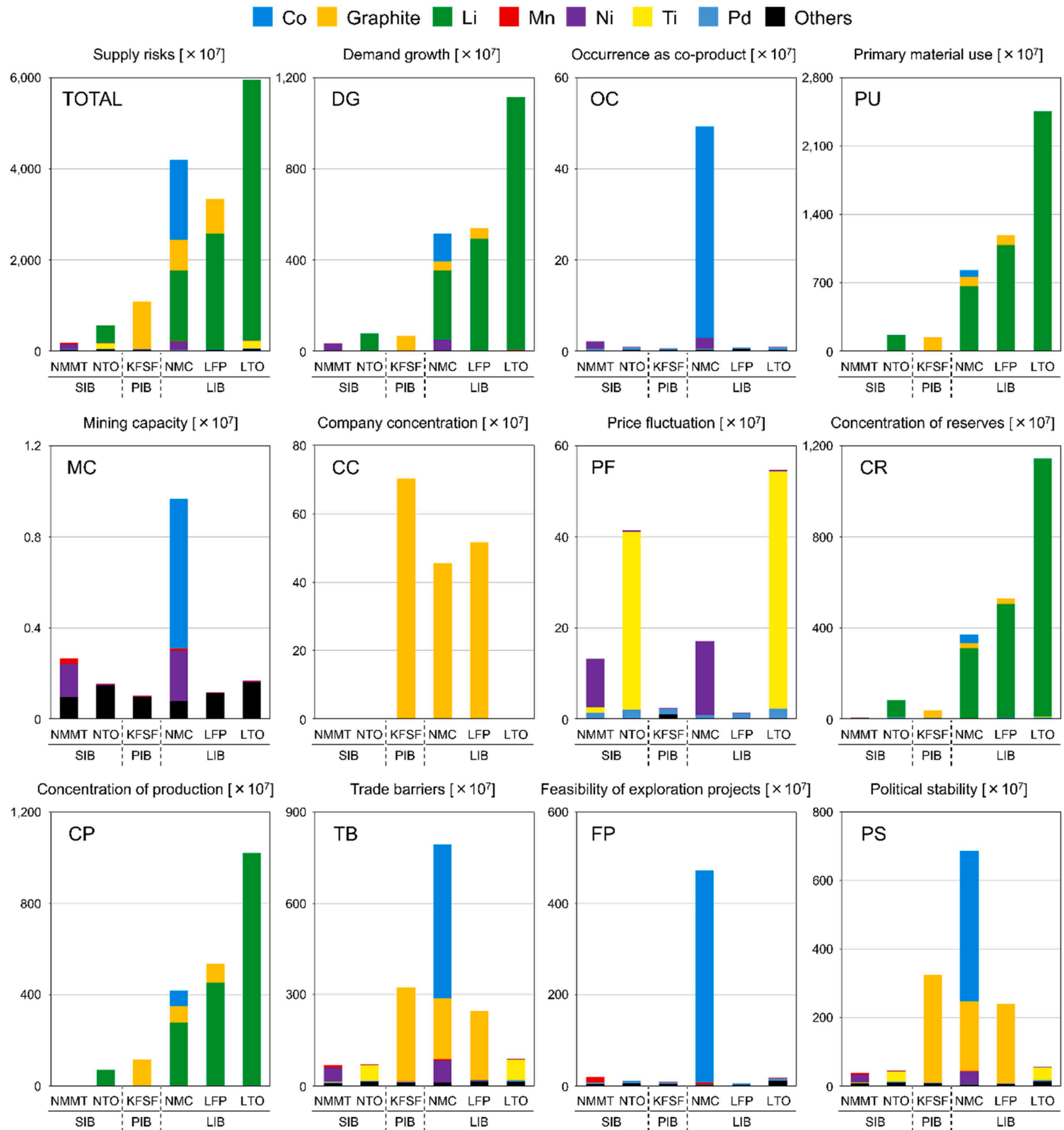

Fig. 4. Contributions of mineral resources to categories of the supply risks for the production of 1 kWh of the six batteries.

associated with these components were relatively high for KFSF because the environmental impacts associated with other components (i.e., anode, cathode) were smaller for KFSF. Similar trends were observed in the case of other next-generation batteries (Montenegro et al., 2021). The main contributor to BMS was printed wiring board, which accounted for 67.5 % of the environmental impact of BMS.

3.3. Supply risks

Supply risks were evaluated by summing the scores of the 11 categories according to the ESSENZ. Different trends were observed among categories (Figs. 4 and **S13**). For demand growth (DG), primary material use (PU), concentration of reserves (CR), and concentration of production (CP), LTO exhibited the highest scores, mainly attributed to Li use required for the production of Li_2CO_3 for the anode and LiOH for the cathode (Fig. 4). The scores for these categories were relatively high compared with the others; thus, Li was also the main contributor to the total supply risk score. As NMMT and KFSF do not require the use of Li, the scores for these categories were low. Meanwhile, the risks of Li for the other categories are assessed as zero by the ESSENZ, that is, indicator values are lower than target values (see Section 2.4); thus, Li use did not contribute to them.

For occurrence as co-product (OC), mining capacity (MC), trade barriers (TB), feasibility of exploration projects (FP), and political stability (PS), the NMC scores were noticeable, mainly attributed to Co use required for $CoSO_4$ production for the cathode. In particular, Co use was dominant in the OC and FP (Fig. 3). Co use for NMC was a major reason for the difference in supply risks between NMC and LFP. For MC, Ni use associated with $NiSO_4$ production for the cathode and gold (Au) use associated with printed wiring board for the BMS also contributed to the scores. Although the amount of Au used for the BMS was significantly small, the risk of Au for this category is assessed as relatively high by the ESSENZ. This resulted in a high Au contribution to the MC, although the share of the MC in the total score of the supply risks was less significant. Regarding TB and PS, graphite for the anode of KFSF, NMC, and LFP was also the main contributor.

Company concentration (CC) and price fluctuation (PF) showed different results from the other categories. KFSF, NMC, and LFP exhibited prominent scores for CC due to graphite use for the anode. This is because the risks of the other main materials required for battery production, including aluminum (Al), Co, copper (Cu), iron (Fe), Li, manganese (Mn), Ni, and titanium (Ti), are assessed as zero for the CC by the ESSENZ. NTO and LTO exhibited higher scores for PF due to Ti use associated with anode production.

As mentioned before, this study summed the scores of the 11 categories to calculate the total supply risk score of battery production, therefore applying equal weighting to all categories. Thus, analyzing these categories separately is necessary. The results in Figs. 4 and **S11** suggest that the total supply risk score can vary when specific categories would be considered more important.

4. Discussion

4.1. Technological potentials for improvement

The large-scale introduction of rechargeable batteries is one of the key elements for achieving decarbonization; however, the supply risks of critical materials are of high concern in this context. Our analysis demonstrated the high supply risks associated with LIBs, while the transition from LIBs to SIBs and PIBs will generally alleviate supply risks. However, this transition cannot be instantaneously achieved, and some challenges regarding the environmental impacts and technological immaturity of SIBs and PIBs exist, as suggested by our results. Therefore, technological improvements in all batteries, i.e., LIBs, SIBs, and PIBs, are crucial during the transition.

For NMMT and NMC, Ni use for a cathode is a major hotspot of the environmental impacts. Meanwhile, Co, graphite, and Li are key materials in terms of the supply risk for NMC. The present development of NMC goes in the direction of reducing dependency on Co and promoting Ni-rich layered oxide cathodes for the sake of higher energy density and safety (Kim et al., 2021; Li et al., 2020; Myung et al., 2017; Xia et al., 2018), which will reduce supply risks but may increase environmental impacts. Options to reduce the environmental impacts associated with $NiSO_4$ include utilizing secondary nickel (i.e., promoting recycling), developing production technologies of $NiSO_4$ with lower energy requirements, and using renewable energy. The technologies for recycling Ni in NMC are currently being developed (e.g., Baum et al., 2022; Zhang and Azimi, 2022). This is also effective for Co, which shows the second major environmental impact and high supply risk. In addition, battery recycling will be promoted according to the European Union battery directive (European Parliament, 2022), which requires improved recycling rates (Baum et al., 2022). Another hotspot of the environmental impact associated with NMMT is hard carbon production for the anode. This study assumed petroleum coke to be the source of hard carbon; however, it has other sources, such as sugar, starch, cellulose, and biowaste, which may have different environmental impacts (Liu et al., 2022; Peters et al., 2016, 2019b). Developing production technologies and hard carbon sources will be effective in improving the performance of NMMT.

For NTO and LTO, the improvement of the energy density is of high priority compared with other types of batteries. Their energy densities were less than half that of NMC, which also resulted in higher environmental impacts of the BMS and utilities for manufacturing battery packs (i.e., electricity and heat) in NTO and LTO (Fig. 2). In this analysis, the BMS and utilities were not specific to the type of anode and cathode; therefore, the environmental impacts of the functional unit were simply determined by the energy density. Battery performance, including energy density, of LIBs has improved substantially and still has potential for improvement (Ziegler and Trancik, 2021). Improving the energy density of other types of batteries (SIBs and PIBs) is an essential task. Simultaneous with the improvement in energy density, TiO_2 recovery for the anode can also alleviate the environmental impacts as the main contributor of NTO and LTO. Recovery technologies for Ti as well as Li (Larouche et al., 2020) are promising for the large-scale introduction of these batteries.

KFSF showed the best performance in terms of environmental impacts and fairly low supply risks, but it is still an early-stage technology as a new-generation battery; thus, the results are connected to higher uncertainties. The moderate energy density of KFSF indicates that its environmental impacts and supply risks could still be improved by increasing the energy density (Masese et al., 2018). Apart from the improvement in energy density, graphite use for the anode contributes to the environmental impacts and supply risks of KFSF, which is the same challenge for LFP. Recycling graphite and alternative anode development could be options to accelerate the benefits of KFSF and LFP (Abdollahifar et al., 2023).

4.2. Influence of background database for inventory analysis

The selection of a background database for inventory analysis is one of the sources of uncertainty in LCA results (Herrmann and Moltesen, 2015; Pauer et al., 2020). Therefore, we used in addition to ecoinvent (Moreno Ruiz et al., 2020), GaBi (Sphera, 2023) as the background database to calculate the environmental impacts of the main contributors (anode, cathode, and BMS) and compared the results (Fig. 5). The GaBi is one of the most widely used databases along with ecoinvent. The ReCiPe 2016 endpoint method (hierarchist perspective) was used for both in life cycle impact assessment.

The environmental impacts of all batteries were higher using ecoinvent, mainly due to the difference in the environmental impact of BMS production (particularly the printed wiring board) between ecoinvent and GaBi. Since BMS was one of the main components in terms of environmental impact, these results suggest that the selection of a background database has a considerable effect. Excluding BMS, environmental impacts of NMMT, LFP, and LTO were larger using GaBi, while those of NTO, KFSF, and NMC were comparable in both cases (**Fig. S14**). The cathode of NMMT showed a larger environmental impact based on GaBi mainly because the environmental impacts of nickel carbonate ($NiCO_3$) and manganese dioxide (MnO_2) were larger based on GaBi. Environmental impacts of cathodes for LFP and LTO, both of which are composed of $LiFePO_4$, were larger using GaBi mainly because the environmental impact of LiOH production was calculated larger based on GaBi. Meanwhile, anodes for KFSF, NMC, and LFP exhibited larger environmental impacts based on ecoinvent. This is because graphite, which is a main constituent for anodes of these batteries, showed larger environmental impacts based on ecoinvent. These results suggest that the environmental impact scores of batteries could change depending on the choice of background database for inventory analysis, which highlights the significance of collecting foreground data for a more accurate assessment. Although there were some differences in the results of the environmental impact assessment based on two different inventory databases, the identified hotspots were generally common in both cases. The comparative assessment based on different background databases can endorse the relevance of the identified hotspots, while any difference in hotspots between different background databases will prioritize processes and materials for collecting foreground data, which usually requires resources and time.

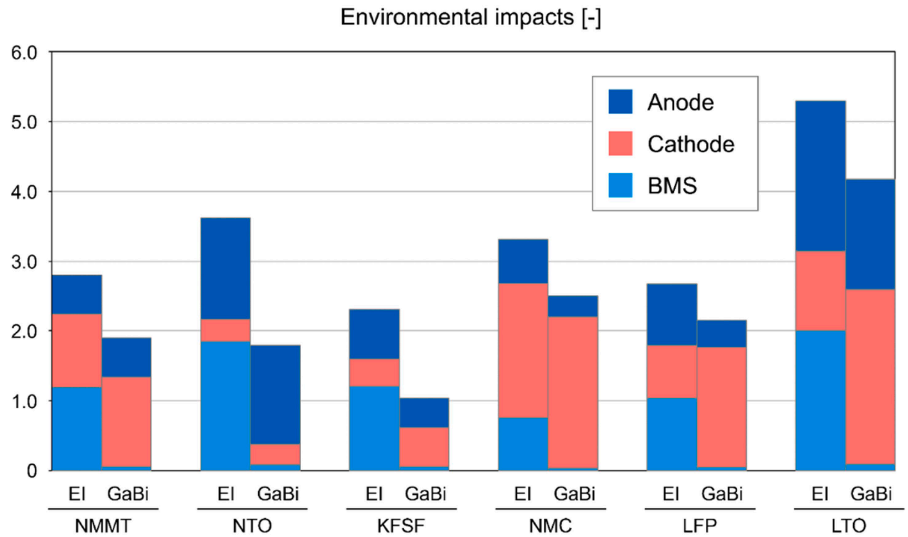

Fig. 5. Comparison of the environmental impacts associated with the production of 1 kWh of the six batteries calculated using ecoinvent and GaBi database. The ReCiPe 2016 endopoint method was used for life cycle impact assessment. EI: ecoinvent.

4.3. Limitations and future works

This study explored the environmental impacts of batteries considering only the production process, but the use phase and end-of-life treatment (e.g., recycling) are also relevant (Ellingsen et al., 2017; Pellow et al., 2020; Peters, 2023; Peters et al., 2021). Not only energy density but also battery cycle life is an important parameter that influences the life cycle environmental impact of batteries. Cycle life is one of the challenges that SIBs face, while research is ongoing to improve the cycle life of SIBs (Hasa et al., 2021; Jemesh et al., 2018; Xiang et al., 2015). PIBs also have the potential to show long cycle life (Deng et al., 2021; Hosaka et al., 2020; Onuma et al., 2020; Zheng et al., 2021). Assessing the environmental impacts throughout the full life cycle of batteries is an essential task in the future.

The recyclability of batteries is also a significant aspect in terms of both environmental impact and supply risk. Peters et al. (2021) demonstrated the potential to reduce the environmental impacts of NMMT and NMC by recycling. Our results also suggest that recycling Ni and Co will reduce the environmental impacts of NMMT and NMC, and recycling Li will substantially reduce the supply risks associated with LIBs. In addition, the recycling of TiO_2 will affect the environmental impacts of NTO and LTO. Our results also suggest that graphite recycling is an effective measure for reducing both the environmental impacts and supply risks of KFSF, NMC, and LFP. Recent studies have shown that graphite recycling can contribute to a reduction in environmental impact (Abdollahifar et al., 2023; Rey et al., 2021). In addition, other options to address end-of-life batteries are available, including reuse, remanufacturing, and second-use (Bobba et al., 2019; Kastanaki and Giannis, 2023). Collecting data on the recyclability of batteries and materials and the environmental impacts associated with the recycling process as well as considering scenarios for different options for end-of-life battery management are required to understand the net environmental impacts throughout the life cycle of batteries (Mousavinezhad et al., 2023). It is worth mentioning that recycling leads to lower environmental impact of battery chemistries that rely on critical metals which are related to higher efforts for raw materials extraction and processing. In contrast, low value materials used for SIBs and PIBs might lead to limited environmental benefits or even additional impact from advanced recycling methods (Peters et al., 2021).

This study assessed the environmental impacts and supply risks associated with the batteries, while other aspects are also relevant for the battery performance, including cost, safety, and technological maturity (Chen et al., 2021a; Pelomares et al., 2012; Vaalma et al., 2018). The quantitative assessment of these aspects will complement our findings to provide the overall picture of battery performance. Finally, we mention uncertainties associated with the assessment. This study adopted the ReCiPe 2016 endpoint method to calculate a single index (i.e., total environmental impact) by weighting endpoint-level scores in LCA, which are subject to uncertainty (Finnveden et al., 2009). Several methods are available for assessing environmental impacts and weighting the environmental impacts in LCIA (Chen et al., 2021b; Prado et al., 2020). Besides, various assumptions were set in collecting data and developing life cycle inventories, including production regions and battery performances. In particular, KFSF is an emerging and immature technology, including various uncertainties. Sensitivity and scenario analyses will be effective for addressing these uncertainties in future works. Even though uncertainties are included, this study is the first attempt to assess the environmental performance and supply risks of next-generation batteries including PIBs. Our results show the potential to develop sustainable battery systems based on SIBs and PIBs and support battery developers in identifying hotspots for developing new-generation batteries with lower environmental impacts and supply risks.

CRediT authorship contribution statement

Ryosuke Yokoi: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Riki Kataoka:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Titus Masese:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Vanessa Bach:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Matthias Finkbeiner:** Conceptualization, Methodology, Writing – review & editing. **Marcel Weil:** Conceptualization, Methodology, Writing – review & editing. **Manuel Baumann:** Conceptualization, Methodology, Writing – review & editing. **Masaharu Motoshita:** Conceptualization, Methodology, Investigation, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107526.

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