Power play: A multi-criteria analysis of present and future battery technologies

Aditya Anindito Widayat[1], Gregory J. Offer[2,3], Jacqueline S. Edge[2,3], Evangelos Kallitsis[2,3*]

[1] *Energy Futures Lab, Imperial College London, London, UK*

[2] *Department of Mechanical Engineering, Imperial College London, London, UK*

[3] *The Faraday Institution, Quad One, Becquerel Avenue, Harwell Campus, Didcot, UK*

[*] *Corresponding author email address: evangelos.kallitsis17@imperial.ac.uk*

This paper is a non-peer-reviewed preprint submitted to EarthArXiv.

Abstract

Advancing electrification requires batteries that combine high performance with sustainability, cost-effectiveness, and supply-chain resilience. Post lithium-ion batteries (PLIBs) such as sodium-ion (SIB), lithium-sulfur (LSB), and solid-state batteries (SSB) are widely discussed as alternatives to today's lithium-ion batteries (LIBs), yet discussion of their technical and sustainability benefits and drawbacks remains fragmented. Here we present an integrated, multi-criteria assessment of twelve battery chemistries, combining cradle-to-gate life cycle, raw material criticality and material cost analyses with performance metrics, specific energy and energy density into a unified comparison. On average, PLIBs exhibit 114 % higher global warming potential and up to 461 % higher material costs than LIBs, particularly when lithium metal or specialty lithium chemicals are required. SIBs achieve 94 % lower criticality and slightly lower cost than LIBs, although their specific energy and energy density remain comparatively low. SSBs deliver the highest specific energy, outperforming LIBs, but depend on costly and less scalable materials. LSBs exploit abundant sulfur and offer high theoretical specific energy, but today's reliance on lithium foil and electrolyte-intensive designs lead to elevated cost, criticality, and carbon footprint. A sensitivity analysis demonstrates how improvements in specific energies enhance PLIB competitiveness. By linking sustainability, cost and criticality hotspots with performance, this study identifies targeted areas of improvement to guide next-generation battery development.

Keywords: Post lithium-ion batteries, carbon footprint, criticality assessment, material cost, life cycle assessment, multi-criteria analysis

Highlights

- Holistic analysis of carbon footprint, cost, and criticality across 12 present and future battery technologies
- Sodium-ion batteries reduce material criticality by ca. 95 % relative to lithium-ion

- Lithium-sulfur batteries have 3x the carbon footprint and material cost under current designs
- Solid-state batteries surpass lithium-ion specific energy, but rely on critical and costly material inputs
- Improving specific energy narrows sustainability gaps across post lithium-ion technologies

1. Introduction

Battery demand is projected to grow at a 26 % compound annual growth rate (CAGR) until 2030, driven mainly by electric vehicles and grid storage (Placek, 2022). Lithium-ion batteries (LIBs) dominate the market due to their technological maturity and performance. However, concerns over resource availability, environmental impact, the need for higher specific energy (Wh kg^{-1}), and highly flammable liquid electrolytes surrounding current LIB technologies drive exploration for alternative technologies (Au et al., 2025; Duffner et al., 2021; McKinsey, 2021; C. Yang et al., 2025). Post-lithium-ion batteries (PLIBs) are gaining attention for using more abundant materials and potentially delivering specific energy benefits. However, realising these benefits at scale requires evaluating not only technical potential, but also environmental, economic, and supply-chain constraints.

Sodium- and sulfur-based systems have attracted particular interest due to the abundance of their constituent materials (USGS, 2024). Sodium-ion batteries (SIBs) and lithium-sulfur batteries (LSBs) are emerging as viable technologies, with the latter offering high theoretical specific energy (Duffner et al., 2021). Solid-state batteries (SSBs) use solid electrolytes to replace liquid electrolytes, potentially improving safety and both specific energy and energy density (Wh L^{-1}). Yet many of the advantages attributed to LSBs and SSBs remain theoretical, as both often rely on lithium metal anodes that are difficult to manufacture and stabilise (Duffner et al., 2021). Although commercial deployment of PLIBs remains limited, growing academic and industrial interest has motivated early assessments of their sustainability relative to LIBs, providing insights to guide the design and development of next-generation battery technologies (Degen et al., 2025; Yokoi et al., 2024).

Life cycle assessment (LCA) is widely used to quantify environmental burdens, and criticality assessment evaluates raw-material supply risks using socioeconomic and geopolitical indicators such as those incorporated in the ESSENZ method (Bach et al., 2016). However, when applied independently, these methods capture only part of the sustainability landscape. Economic viability, particularly raw material cost, remains a fundamental constraint for emerging chemistries but is often underrepresented in current analyses. A framework that integrates environmental impact, supply-chain criticality, and material cost, together with relevant performance metrics, is needed to provide a more comprehensive basis for comparing LIBs and PLIBs.

Numerous studies have performed LCAs on LIBs (Chordia et al., 2021; Kallitsis et al., 2020, 2024; Peiseler et al., 2024) and on selected PLIB chemistries (Deng et al., 2017; Peters et al., 2016; Troy et al., 2016; Wickerts et al., 2023, 2024). However, no study has yet provided a multi-criteria evaluation with broad methodological and technological scope, comparing various types of PLIBs and LIBs within a unified framework. Criticality assessments using the ESSENZ method exists, but they focus primarily on LIBs (Manjong et al., 2023; Pelzeter et al., 2022) and a limited subset of PLIBs (Yokoi et al., 2024), covering two SIB variants and one potassium-ion chemistry. Criticality aspects of LSBs and SSBs have not been studied yet, and the leading SIB cathode, Prussian white, has also not been included. Although Duffner et al. (2021) briefly discussed PLIB costs, detailed and comparative cost analyses across a wider set of chemistries are scarce.

Here, we address these gaps by conducting a multi-criteria assessment of twelve present and emerging battery chemistries. The analysis combines cradle-to-gate carbon footprint, supply-risk indicators, and raw-material costs derived from bill-of-materials (BoM) data with performance metrics such as specific energy and energy density. By bringing these dimensions together in a single framework, the study enables direct benchmarking of LIBs and PLIBs and provides a clearer understanding of sustainability-performance trade-offs that will influence the future development and deployment of next-generation battery technologies.

2. Methods

We investigate whether PLIBs can address key issues of LIBs (e.g. environmental impact and material criticality) while also addressing cost and performance considerations. The BoM for each battery provides the basis to calculate material and energy flows and to incorporate specific energy data. First, a LCA focusing on GWP is conducted for materials and energy use, followed by criticality assessment to evaluate socioeconomic supply risks at the elemental level. The cost of materials is estimated based on the material demand and latest market data. Finally, a multi-criteria comparison integrates all metrics for each battery.

2.1 Selection of lithium-ion and post lithium-ion batteries

While several LIB chemistries are currently commercialised, this study focuses on the three dominant chemistries, $LiNi_xMn_yCo_yO_2$ (NMC), $LiFePO_4$ (LFP), and $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA), which together represent 98 % of the global market: 60 % for NMC, 30 % for LFP, and 8 % for NCA (McKinsey, 2021). Among NMC variants, NMC811 is selected as it reflects the latest technology and is widely adopted by EV manufacturers such as CATL (CATL, 2024). Cradle-to-gate material demand per kWh for LIBs is taken from Kallitsis et al. (2024), while manufacturing energy inputs are sourced from Degen et al. (2023).

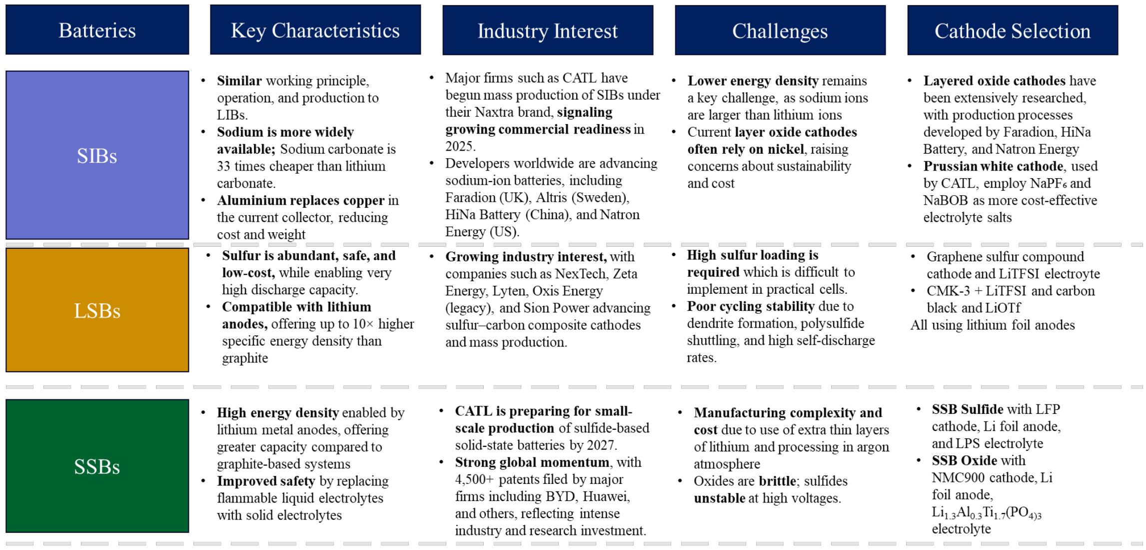


Figure 1. Overview of PLIB technologies summarising key characteristics, challenges and industry relevance (Duffner et al., 2021; Kulova et al., 2020; Zuo et al., 2023)

This research focuses on three PLIB categories: SIBs, LSBs, and SSBs, selected based on their mid-term commercialisation prospects as indicated by ongoing industrial development. Key characteristics, challenges, and industry relevance of PLIBs are highlighted in *Figure 1*. Key battery formulations, including cathode, anode, electrolyte, and energy metrics are summarised in **Table** 1 and detailed BoMs and cradle-to-gate material demand are provided in Supplementary Tables. Specific energy is reported at the cell level, excluding the battery pack. Energy densities were taken directly from literature when available (e.g. LSB - Graphene-Sulfur Composite (GSC) from Deng et al., 2017) or estimated via linear correlations (using the Faraday Institution's Cell Analysis and Modelling System, CAMS) based on specific energy values for cases where only such data were known.

Table *1*. Summary of battery technologies considered in this study.

Battery Type	Reference	Cathode	Anode	Electrolyte	Specific energy (Wh kg^{-1})	Energy density (Wh L^{-1})
LIB	Kallitsis et al. (2024)	NMC811	Graphite	$LiPF_6$	311	680
LIB		LFP	Graphite	$LiPF_6$	213	432
LIB		NCA	Graphite	$LiPF_6$	316	687
SSB Sulfidic	Popien et al. (2023)	LFP + CB + LPS	Lithium + TEOS	LPS	270	535
SSB Oxide	Degen et al. (2025)	NMC900	Lithium	$Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$	394	1,417
SIB	Peters et al. (2016)	Layered Oxide	HC (Petroleum Coke)	EC + DMC + $NaPF_6$	128	313
SIB		Layered Oxide	HC (Sugar Beet)	EC + DMC + $NaPF_6$	128	313
SIB	Wickerts et al. (2024)	Prussian White	HC (Resin)	EC + DMC + $NaPF_6$	160	284
SIB		Prussian White	Hard Carbon (Lignin)	NABOB + TEP	160	284
LSB	Deng et al. (2017)	GSC	Lithium	LiTFSI + LiNO3 + DOL + DME	333	298
LSB	Wickerts et al. (2023)	Sulfur + CMK-3	Lithium	LiTFSI + LiNO3 + DOL + DME	150	198
LSB		Sulfur + CB	Lithium	LiOTf	150	198

CB: Carbon black; LPS: Lithium thiophosphate; HC: Hard carbon; GSC: Graphene–sulfur composite; CMK-3: Ordered mesoporous carbon; LiPF6: Lithium hexafluorophosphate; TEOS: Tetraethyl orthosilicate; EC: Ethylene carbonate; DMC: Dimethyl carbonate; NABOB: Sodium bis(oxalato)borate; TEP: Triethyl phosphate; LiTFSI: Lithium bis(trifluoromethanesulfonyl)imide; DOL: 1,3-Dioxolane; DME: Dimethoxyethane; LiOTf: (lithium triflate)

2.2 Life cycle assessment

A streamlined LCA was used to calculate the carbon footprint of each LIB and PLIB chemistry, with a cradle-to-gate scope. Only production inputs were considered (materials and energy for cell manufacturing), with the use-phase, recycling, and transport being out of scope. The model excludes capital goods (facility construction, machinery) and end-of-life, and it is limited to production of a single battery cell (i.e. no pack components, such as battery management systems).

This study is not country specific, since most PLIBs have not yet reached large-scale commercialisation. Therefore, global averages emission factors are used: 0.74 kg CO_2-eq kWh^{-1} for electricity and 0.13 kg CO_2-eq MJ^{-1} for steam production. Similarly, material emission factors rely on global or rest-of-world datasets. The impact assessment focuses on the GWP with a 100-year horizon (GWP, in kg CO_2-eq) due to its relevance to battery technologies and the broader decarbonisation of transport. Emission factors covering both material and energy were sourced from Ecoinvent 3.10 (Wernet et al., 2016).

Given the focus on battery production, the functional unit is 1 kWh of battery cell produced, in kWh_{cell}, a standard in battery LCA studies (Chordia et al., 2021; Kallitsis et al., 2024). Total GWP for 1 kWh_{cell} is calculated by multiplying each material and energy input by its emission factor. This functional unit ensures comparability across all assessments beyond LCA performed herein.

2.3 Criticality assessment

We applied the ESSENZ methodology to evaluate socioeconomic supply risks using 11 impact indicators, namely: concentrations of reserves, concentration of production, company concentration, feasibility of exploration projects, political stability, occurrence as companion metals, mining capacity, primary material use, demand growth, price fluctuations, and trade barriers (Bach et al., 2016). After all indicator data were collected, they were further processed to calculate characterisation factors (CFs), as detailed in Supplementary Information. Each element is assigned with 11 CFs which quantify the element's specific socioeconomic and geopolitical supply risks, a higher CF value indicates higher potential risk (Bach et al., 2016).

We assessed 16 key elements commonly used in LIBs and PLIBs: Ni, Graphite, F, P, Cu, Li, Co, Na, Mn, Mg, Ti, S, Al, Fe, K, and Hard Coal. For each battery, compound masses from the BoM were converted to elemental masses, normalised per kWh, multiplied by CFs, and aggregated to obtain criticality scores.

Updated CFs were calculated expanding on the work of Bach et al. (2016) and Pelzeter et al. (2022). This was necessary because materials such as coal, fluorspar, sulfur, and sodium are not included in the existing CF databases, and to ensure the data reflects current state of materials used in the battery industry. Two ESSENZ indicators, co-product occurrence and company concentration, were excluded due to inconsistent or unavailable data. For feasibility of exploration projects and trade barriers, we replaced the policy perception index (PPI) and enabling trade index (ETI), with data from the worldwide governance indicators (WGI) (World

Bank, 2024). Full data sources and calculation details are provided in the Supplementary Information.

2.4 Cost analysis

Material costs were estimated by multiplying the kWh denominated cradle-to-gate material demand (kg kWh^{-1} cell) with bulk market prices (\$ kg^{-1}) obtained from public industrial sources. Price data reflect industrial-scale scenarios, although some PLIB-specific materials where industrial production is not yet established exhibited higher prices. The analysis captures only raw material costs and does not include labour, energy, manufacturing, or infrastructure. Detailed material prices for each chemistry are provided in Supplementary Tables. This study includes historical price of LIBs, compares the material cost structure between LIBs and PLIBs, and pinpoints the main cost hotspots for each battery.

2.5 Multi-criteria technology analysis

After the LCA, criticality, and cost calculations, all batteries are benchmarked using spider web charts incorporating specific energies and energy densities. Since each parameter has different values, normalisation is necessary to create a uniform scale. Normalisation is performed by dividing each individual value by the maximum value in its category, resulting in a consistent range between 0 and 1 for easier comparison. For specific energy and energy density, higher values are better. In opposite, for GWP, criticality, and cost, where lower values are preferred, the results are inverted by subtracting them from 1. This ensures higher normalised values consistently reflect better performance in all assessments.

3. Results

3.1 Carbon footprint of PLIBs

Figure 2(a) presents the GWP results for all batteries. While both LSBs and SSBs contain sulfur-based materials, their compositions differ significantly. LSB-GSC uses H_2SO_4 and Na_2SO_3 in its cathode preparation, whereas SSB-Sulfidic-LFP relies on Li_2S and P_2S_5 in its solid electrolyte (see Supplementary Tables). On average, PLIBs currently have substantially higher production emissions than LIBs with approximately 114 % higher GWP on average. Among PLIBs, SIBs show the smallest GWP increase relative to LIBs (52 %), while LSBs show the largest (217 %).

In LIBs, cathode materials are the main GWP contributors, particularly lithium salts and transition metal sulphates. For example, in LIB-NMC811, $CoSO_4$ constitutes only 3.7 % of the cell material demand but contributes 17 % of total GWP, whereas $NiSO_4$ is 30 % of the demand and only 24 % of GWP. LFP cathodes can reduce cathode GWP compared to NMC811 and NCA, but high energy demand offsets this benefit, resulting in similar overall GWP.

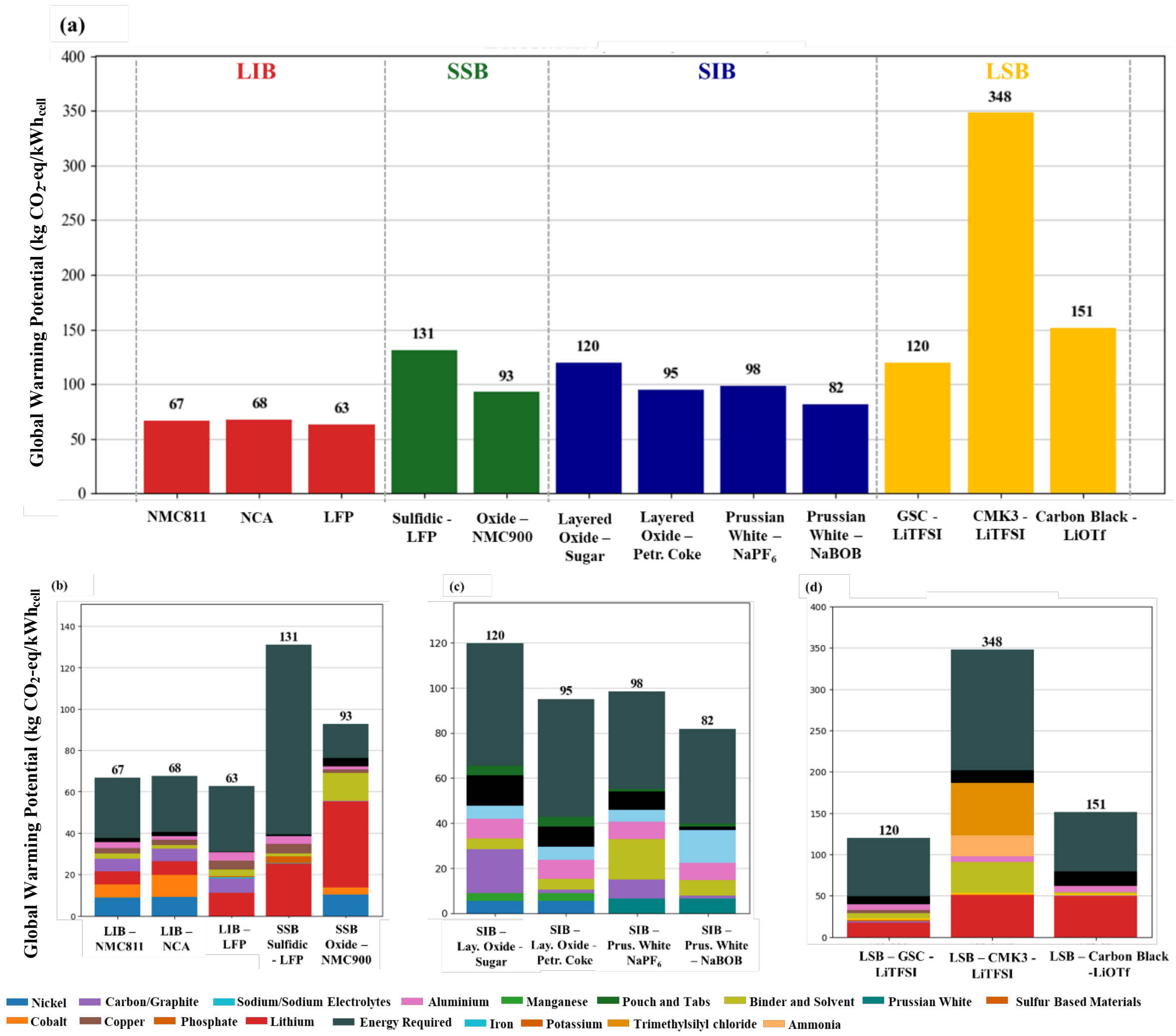


Figure *2***.** (a) GWP of LIBs and PLIBs, and contribution analysis for (b) SIBs, (c) LIBs and SSBs, and (d) LSBs.

Figure 2Many PLIBs avoid emission-intensive materials such as cobalt, but still show higher GWP due to other factors. Notably, chemistries using lithium metal anodes (all LSBs and SSBs) have significantly higher emissions from anode production. On average, the lithium metal anode batteries (LSBs and SSBs) have ~162 % higher GWP than LIBs.

Among PLIBs, SIBs have the lowest GWP, slightly above LIB levels as shown in Figure 2(b). Within SIBs, cells with layered oxide cathodes show higher GWP than those with Prussian white, mainly due to energy-intensive cathode production (the layered oxide cathode involves Ni and Mn precursors and high-temperature processing). The choice of anode precursor for SIBs also matters: hard carbon from sugar beets has 12x higher emissions than from petroleum coke, since it requires 17x more feedstock to produce equivalent hard carbon. For SIB-Prussian white cells, the choice of electrolyte affects the GWP with $NaPF_6$ resulting in 80 % lower GWP contribution than NaBOB.

LSBs show the highest GWP of all batteries assessed (Figure 2(d)), mainly due to the excessive electrolyte use and lithium metal anodes. Although LSB-GSC and LSB-CMK-3 use the same electrolyte composition (LiTFSI, DOL, DME, and $LiNO_3$), LSB-CMK-3 exhibits much higher electrolyte-related GWP due to using seven times more LiTFSI and a more complex production method as shown in Figure S4, requiring trimetylisyl chloride, additional binder and solvent, and ammonia. Consequently, LSB-CMK-3's electrolyte contributes disproportionately to GWP. The lithium metal foil usage also differs, with LSB-GSC using a thinner lithium anode (lower mass per kWh) than LSB-CMK-3, moderating its anode-related GWP.

SSBs likewise incur high anode-related emissions from lithium metal as illustrated in Figure 2(b). In SSB-Sulfidic-LFP, GWP is also driven up by energy-intensive cell production steps (e.g. sulfidic electrolyte handling). SSB-Oxide-NMC900's GWP, on the other hand, is dominated by its nickel- and cobalt-containing cathode. Notably, SSB-Oxide-NMC900 uses 35 % more lithium (in the anode and electrolyte) than SSB-Sulfidic-LFP (see Supplementary Tables), contributing to a higher GWP despite its more stable oxide electrolyte. SSB-Sulfidic-LFP requires more processing energy than SSB-Oxide due to steps including electrolyte sheet calendaring, high-pressure cell pressing, and stringent dry-room assembly to avoid moisture reacting with Li_2S/P_2S_5. These additional energy inputs, combined with the energy-intensive LFP cathode production and lower specific energy, make SSB-Sulfidic-LFP's total GWP higher than SSB-Oxide-NMC900 despite having a cobalt-free cathode.

3.2 Criticality of PLIBs

The per-element supply risk results are shown in Figure 3(a), calculated by summing all nine ESSENZ indicators; a detailed breakdown is provided in Figure S1. Lithium, cobalt and graphite stand out with particularly high criticality scores. These elements are key components in current LIBs, suggesting that switching to chemistries that reduce reliance on them could improve overall criticality.

Figure 3(b) shows the calculated criticality score for each battery, based on their composition and the CFs of Figure 3(a). While PLIBs are often promoted as solutions to LIB material criticality issues, not all PLIBs scored better than LIBs. In fact, the average SSB and LSB, which utilise lithium metal anodes, scored 22 % higher criticality than the average LIB. Elements such as sodium, sulfur, and manganese, though present in some PLIBs, have low individual scores and barely contribute to the total, therefore being grouped together in the same colour in Figure 3(b).

Among LIBs, cobalt- and nickel- containing cathodes unsurprisingly lead to the highest criticality. LIB-NCA and LIB-NMC811 show 46 % and 19 % higher criticality values than LIB-LFP, respectively. In LIB-NMC811, $CoSO_4$ is only 3.7 % while NiSO4 at 30 % of the overall material demand, yet, cobalt's criticality contribution is at 31 % while nickel is at 9 %. LIBs share common hotspots, lithium and graphite, which appear in all chemistries.

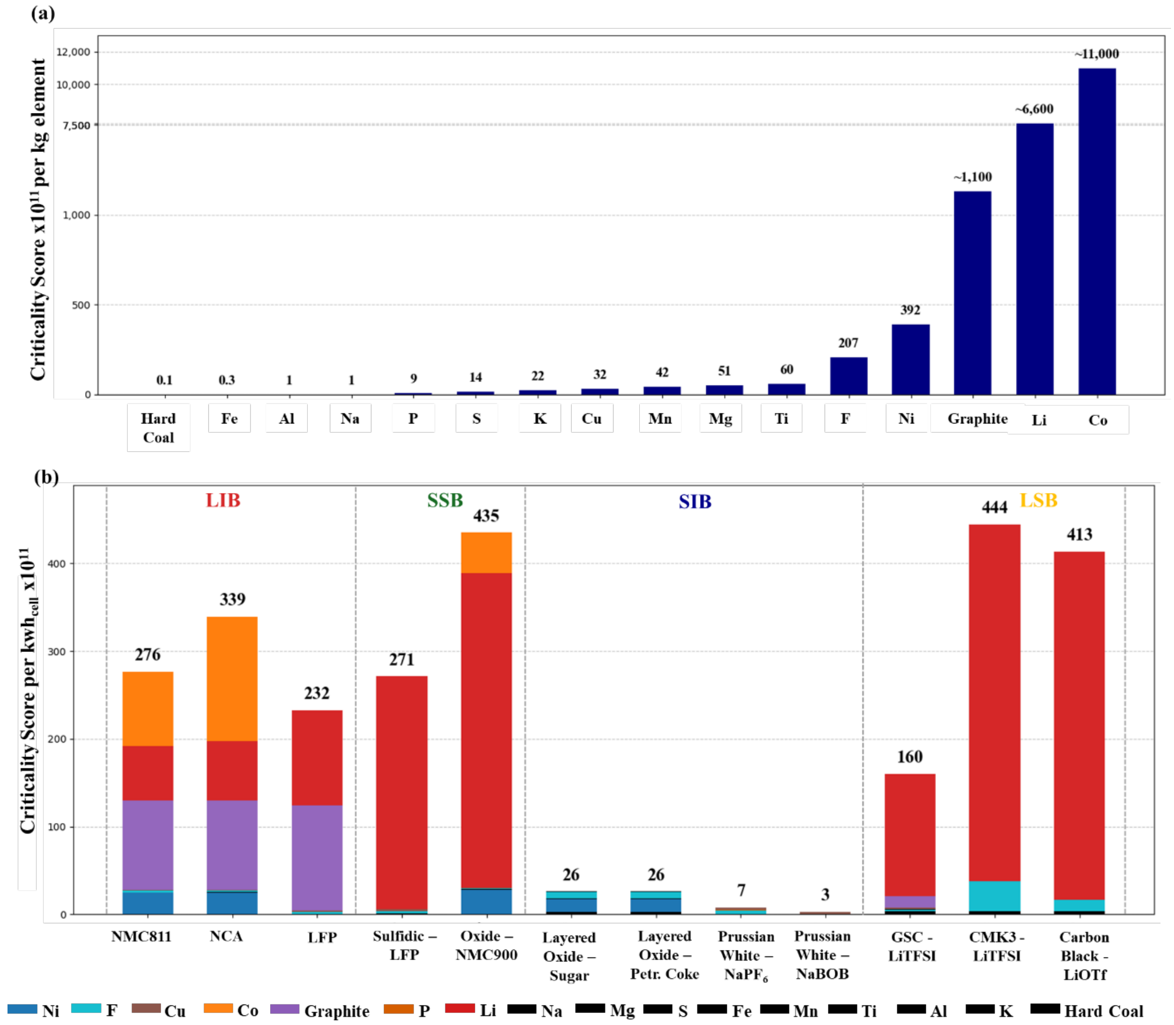


Figure *3* (a) Total ESSENZ characterisation factor for each element and (b) total LIB and PLIB ESSENZ criticality results together with key contributions.

Lithium is the main hotspot for all LSBs and SSBs, since these designs use metallic lithium in the anode, leading to up to four times higher lithium demand per kWh than in LIBs. As a result, the lithium-related risk is greatly amplified in those PLIBs. Another notable contributor in some LSBs is fluorspar (fluorine source for LiTFSI and LiOTf electrolytes, Figure S4), which has supply risks due to limited production sites. Despite this, LSB-GSC shows a lower criticality value than all LIBs and other LSBs. This is due to its lithium demand being three times lower than other LSBs, the use of low-criticality elements such as sulfur, sodium, aluminum, and the lowest overall material demand among other LSB. This is further supported by LSB-GSC's superior specific energy, which lowers material demand per kWh_{cell}.

SIBs have by far the lowest criticality scores, about 94 % lower than the average LIB. The dominant materials in SIBs, such as sodium, carbon, manganese, and aluminium are less critical than those used in LIBs. Among SIB variants, those with layered oxide cathodes have slightly higher criticality, related to their nickel content. The source of the SIB-layered oxide anode material, either petroleum coke or sugar beet, does not affect criticality, resulting in consistent values across SIB layered oxide variants.

3.3 Cost of materials

Figure 4 presents the overall material cost comparison across batteries, together with detailed contributions. Currently, only SIBs offer lower material cost per kWh than high-nickel LIBs (NMC811 and NCA). On average, batteries that use large amounts of lithium in the anode, such as SSB and LSB have more than 50 % higher material cost compared to the average for current LIBs.

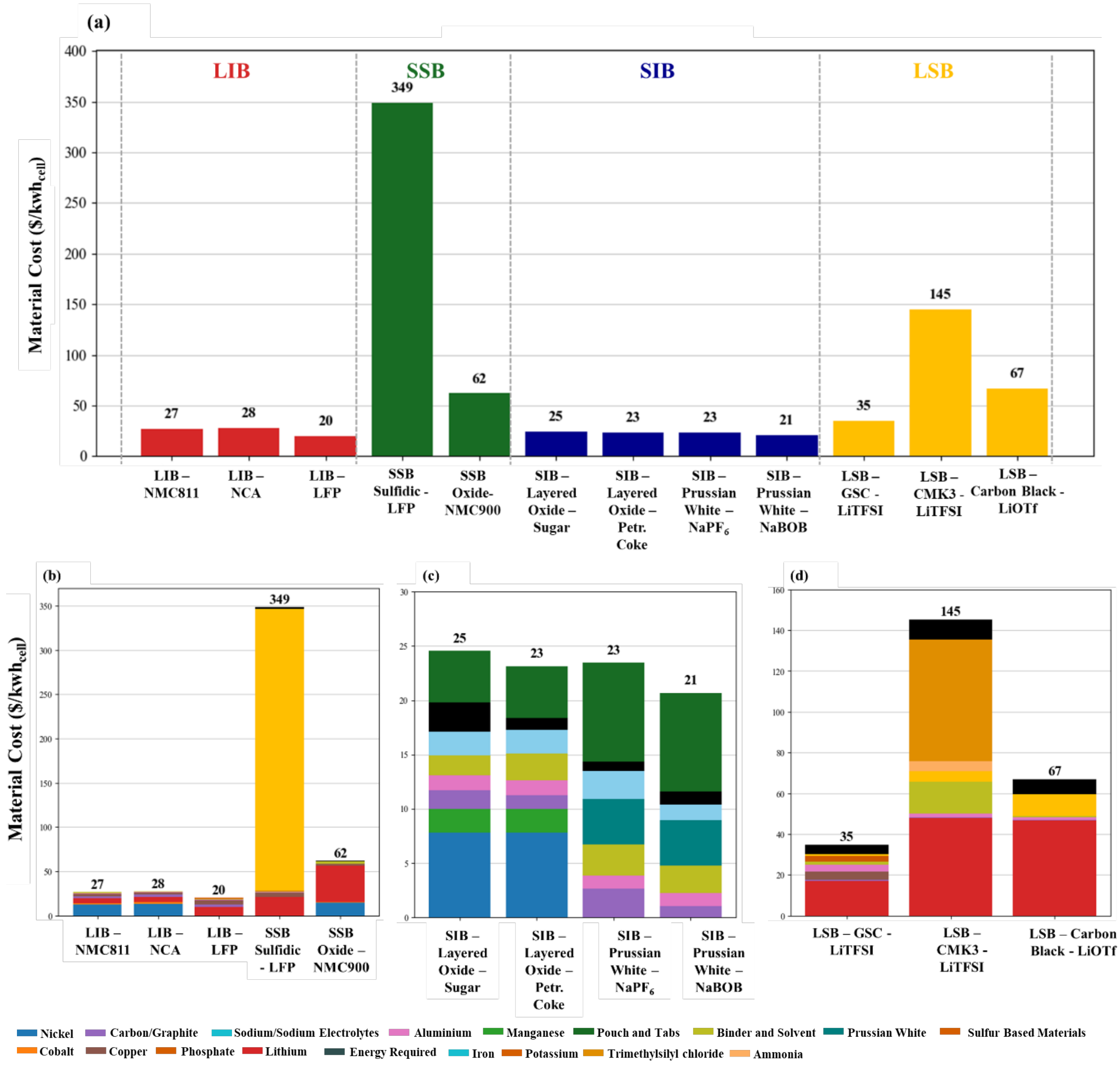


Figure 4. (a) Total cost of materials for LIBs and PLIBs and cost of materials breakdown for (b) SIBs, (c) LSBs, (d) LIBs and SSBs.

Compared to LIBs, SIBs avoid several expensive material inputs. Nickel, a major cost hotspot in NMC and NCA LIBs, is absent in SIB-Prussian white but is a hotspot in SIB-Layered oxides due to its high price. In fact, SIB-Prussian white cells have an extremely low cathode cost since Prussian white is made from inexpensive iron and sodium salts. The main costs of SIB-Prussian white come from non-cathode components, including aluminium and copper in the pouch and tabs. Excluding them makes it the least expensive option, even compared to LIBs.

LSB material costs are generally dominated by lithium. Lithium metal foil is used in the anode and lithium-based salts (LiTFSI or LiOTf), which are used in large quantities in the electrolyte. However, in LSB-CMK-3, an even bigger cost contributor than lithium is trimethylsilyl chloride, a specialty chemical used in the synthesis route of LiTFSI. Trimethylsilyl chloride costs 6 $/kg and is used in large amounts in LSB-CMK-3's LiTFSI production (9.94 kg kWh^{-1}). For LSB-GSC, using 85 % less LiTFSI at 0.18 kg kWh^{-1}, lithium foil is the top cost contributor.

While lithium remains a hotspot due to its use in the anode, the primary cost driver in SSB-Sulfidic-LFP are sulfur-based materials that include Li_2S and P_2S_5. Li_2S is a rarely used material in batteries or broader industry applications, has an underdeveloped supply chain resulting in a high price, making it the most expensive battery material in this study, with a price of 857 \$ kg^{-1} (Trunano, 2025). SSB-Oxide-NMC900 uses more conventional materials (oxide electrolyte, nickel-rich cathode), thus its cost drivers resemble those of LIBs plus the lithium foil anode. All SSBs use lithium foil, which we estimate at ~80 \$ kg^{-1} (Shanghai Metals Market, 2025b). The process to make battery-grade lithium foil (electrolysis, purification, rolling in inert atmosphere) is energy-intensive, contributing to its cost.

4. Discussion

4.1 Carbon footprint comparison amongst LIBs and PLIBs

Comparing the cathodes in SIB-Prussian white and SIB-Layered oxide, the latter consists of nickel, magnesium, sodium and others, with a total GWP of 14.29 kg CO_2-eq/kWh_{cell}. This is 220 % higher than for the Prussian white cathode, which consists of iron and sodium salts. Although both SIB-Layered oxide and SIB-Prussian white use $NaPF_6$ as the electrolyte, SIB-Prussian white requires twice the amount, resulting in a higher GWP from sodium electrolytes, binder and solvent. Additionally, SIB-Prussian white uses diethyl carbonate (DEC) as its solvent, with a GWP of 22 kg CO_2-eq kg^{-1}, whereas SIB-Layered oxide uses dimethyl carbonate (DMC) and ethylene carbonate (EC), having a much lower combined GWP of 3.5 kg CO_2-eq kg^{-1}. The high anode GWP in SIB-Layered oxide occurs from using 32 kg kWh_{cell}^{-1} sugar beets, whereas petroleum coke requires 70 % less feedstock. As shown in Supplementary Tables, using aluminium for both current collectors in SIBs can reduce costs, as aluminium is 70 to 80 % cheaper than copper. However, this comes with a climate-change trade-off, since aluminium's GWP is 80 % higher than copper's.

For PLIBs, lithium anodes are often considered as key enabler with a specific energy 10x that of graphite (Mo et al., 2020; Pasta, 2019). However, their GWP is 12x higher than graphite in LIBs as shown in Supplementary Tables. This presents a trade-off with the increased specific energy.

To fully unlock LSB specific energy advantages, the sulfur content in the cathode should be at least 50 % (Yang et al., 2018), a level only achievable in LSB-GSC, with other LSBs only having 27 %. LSB cathodes have the lowest GWP due to their lower kg kWh^{-1} material demand and lack of minerals such as nickel, cobalt, and iron. Instead, they rely on using carbon and sulfur in the cathode. LSB-GSC uses graphene oxide, sodium sulfite, and carbon black, while

LSB-CMK-3 uses sulfur and mesoporous carbon, and LSB-CB combines sulfur, carbon black, and polyethylene glycol.

While some LSBs use the same electrolyte, LiTFSI, they demonstrate significant differences in GWP. LSB-CMK-3 uses seven times more LiTFSI than LSB-GSC. Additionally, LiTFSI production in LSB-CMK3 is more complex, largely due to the production of CF_3SO_2F, which requires substantial energy and material demand (Wickerts et al., 2023) as shown in Figure S4. LiOTf, which also uses CF_3SO_2F, similarly contributes to the high GWP. The use of lithium foil in both LSBs and SSBs results in the highest anode GWP making it a key hotspot.

For instance, SSB-Oxide-NMC900 contains 35 % more lithium than SSB-Sulfidic-LFP (Supplementary Tables), driving its higher GWP. Additional impacts come from nickel- and cobalt-based cathode materials and 18x greater binder and solvent use. SSB-Sulfidic-LFP has a higher energy demand compared to SSB-Oxide-NMC900. This is due to complex production steps such as calendaring the electrolyte, cell pressing, and extended dry room processing (Duffner et al., 2021). These conditions are essential to prevent reaction between air, moisture and materials such as sulfidic electrolytes and lithium foil, which can release harmful gases such as H_2S (Duffner et al., 2021). These impacts are further increased by the LFP cathode, which require slightly more energy compared to nickel-based cathode, as shown in Figure 2**Figure** 2.

4.2 Criticality and cost hotspots of PLIBs

The shift towards PLIBs is often motivated by a desire to overcome the material limitations of current LIB chemistries, particularly around environmental impacts and supply risks. However, PLIBs introduce new challenges by relying on materials with their own criticality and supply issues. Here, we discuss criticality and cost hotspots across the assessed battery chemistries, highlighting how economic viability ad supply-chain risk often intersect.

Nickel's global reserves-to-production ratio suggest fewer than 50 years of remaining mining capacity. This is largely driven by a surge in production over the past five years, with a global CAGR of 7 %, and an extraordinary 21 % in Indonesia (USGS, 2025), the world's largest producer. While this expansion has resulted in a short-term oversupply and price deflation, it has also accelerated resource depletion, shortening mine lifespans and leading to closures of unprofitable sites such as Glencore's New Caledonia mine, and First Quantum's operation in Western Australia (Mining.com, 2024; MiningWeekly, 2024). Economically, nickel remains one of the most expensive major cathode metals, especially in sulphate form. $NiSO_4$ is approximately 70 times more expensive than $FeSO_4$, yet both make up similar fractions (20-30 %) of the active material mass in relevant battery chemistries. Thus, while specific benefits are gained, the economic and geopolitical risks compound, particularly for chemistries reliant on high nickel content.

Lithium lies at the heart of both conventional and next-generation batteries, yet its supply chain is increasingly exposed to volatility and strategic vulnerability. From 2021 to 2023, lithium demand grew at an average rate of 35 % per year, primarily driven by the widespread deployment of LIBs, which account for 87 % of lithium's end-use (USGS, 2024). This rapid growth triggered extreme price fluctuation. Prices increase eight-fold from early 2021 to late 2022, before dropping 72 % just six months later (Investing, 2024). This instability has direct implications for battery material costs, as reflected in the historical LIB material cost trends shown in Figure 5. Arguably, PLIBs relying heavily on lithium metal, such as SSBs and LSBs would exhibit even higher sensitivity to lithium prices, due to their higher lithium content.

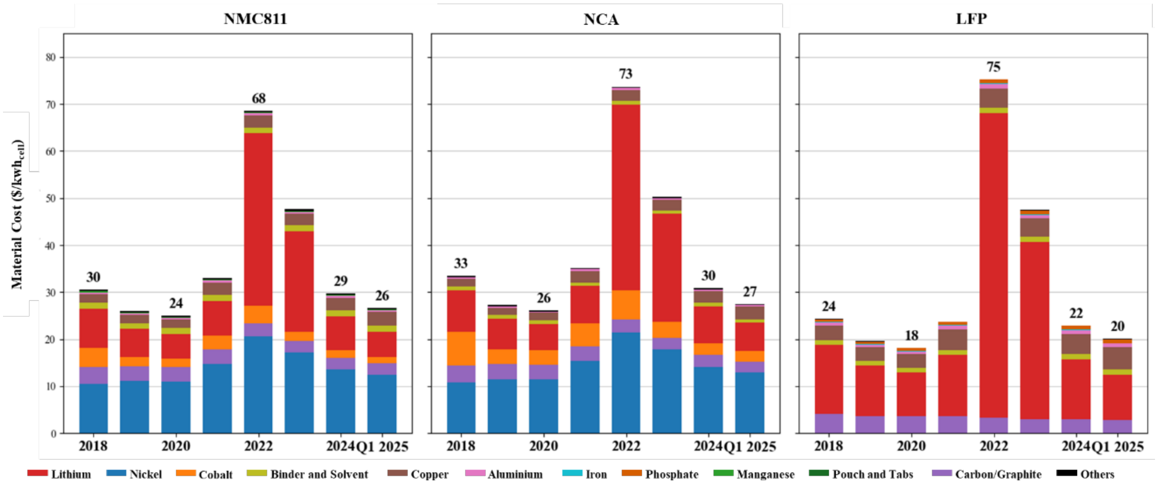


Figure *5***.** Historical LIB material costs over the past 7 years based on data from Winjobi et al. (2020) and USGS reports.

Criticality is further amplified by lithium's low recycling rate, with ca. 1 % coming from recycling batteries compared to ca. 30 % for nickel and cobalt (Graedel, 2011). This means all lithium demand must be met through primary extraction, increasing exposure to geopolitical, environmental and market risks. However, investment in lithium recycling is gaining traction; by 2023, around 90 companies in the U.S. and Canada were developing recycling infrastructure (USGS, 2024), suggesting a potential path toward greater circularity and cost stability in the long term. In addition, battery recycling has been shown to reduce the GWP of LIBs (Kallitsis et al., 2022), which would likely be the case if PLIBs get recycled at scale.

In PLIBs, lithium is also used in more costly and reactive forms, such as lithium foil (used in SSBs and LSBs) and Li_2S used in SSB-Sulfidic-LFP. Lithium foil production involves energy-intensive electrolysis and purification steps and must be handled in an argon environment due to its reactivity (Duffner et al., 2021), pushing costs to approximately 80 $\$\ kg^{-1}$ (Shanghai Metals Market, 2025). Li_2S, a specialty chemical not yet produced at scale, can range in price from 857 $\$\ kg^{-1}$ (Luoyang Tongrun Info Technology, 2025) to 3,000 $\$\ kg^{-1}$ (Sun et al., 2023), posing a substantial economic hurdle for commercialisation of sulfidic SSBs.

A further cost challenge for PLIBs arises from the use of specialty materials that lack mature supply chains. One example is trimethylsilyl chloride, used in the LSB-CMK-3 electrolyte. Though relatively inexpensive at ~6 $\$\ kg^{-1}$ (see Supplementary Tables), it is required in large quantities around 10 $kg\ kWh_{cell}^{-1}$, resulting in a disproportionately high contribution to total material costs (Wickerts et al., 2023). This highlights how PLIB cost is not only a function of unit price but also of mass intensity and battery design.

4.3 Multi-criteria assessment insights

The results of the multi-criteria assessment are summarised in Figure 6, highlighting how trade-offs between sustainability, cost, and performance emerge across both current and emerging battery technologies.

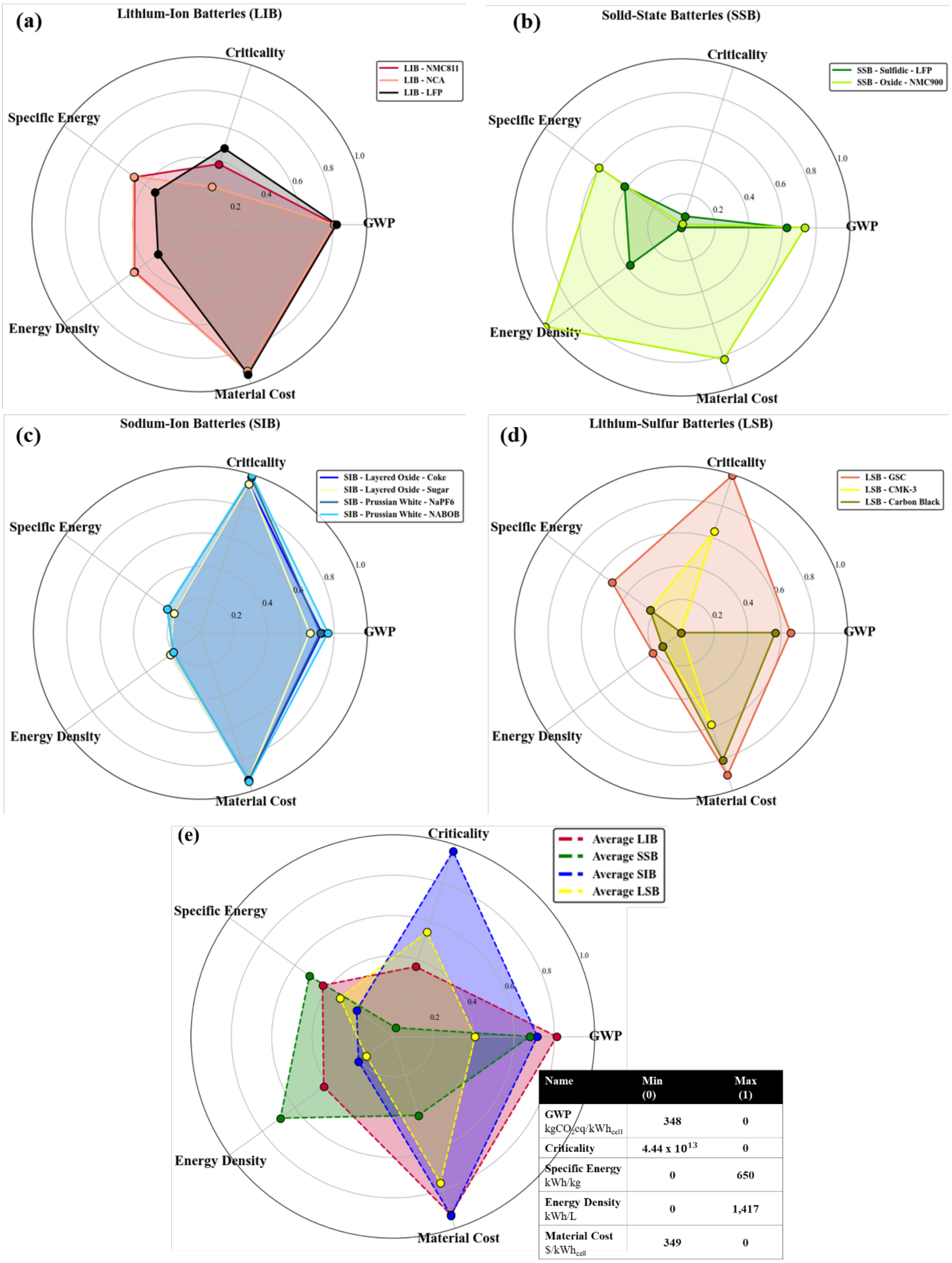
Among LIB chemistries, material cost and GWP are relatively similar, but LIB-LFP stands out for its significantly lower criticality due to the absence of nickel and cobalt. This comes at the expense of reduced specific energy and energy density. Solid-state designs could, in principle, address some of these energy limitations through lithium metal anodes, but such configurations introduce substantial trade-offs. The increased reliance on lithium foil and Li_2S raises both material costs and supply-chain vulnerability, offsetting the sustainability advantages that motivate the transition beyond conventional LFP cathodes.

When comparing solid-state technologies, SSB-Sulfidic-LFP and SSB-Oxide-NMC900 exhibit distinct profiles. The latter achieves higher specific energy, with comparable GWP and material cost to LIB-NMC811. However, its criticality score remains high due to heavy reliance on nickel and lithium metal. In contrast, SSB-Sulfidic-LFP benefits from LFP's low criticality but suffers from higher material costs due to the use of Li_2S and other specialty materials. These comparisons reveal a clear trade-off between specific energy and sustainability among SSBs, with no single variant achieving dominance across all metrics.

All SIB chemistries show favourable sustainability and cost performance, with lower material cost, GWP, and criticality compared to LIBs. Among these, SIBs based on Prussian white outperform layered oxide variants. However, the overarching challenge for SIBs remains their low specific energy and energy densities, which currently limit their viability for high-performance applications such as electric vehicles.

In contrast to the relative uniformity of SIBs, LSBs exhibit significant performance variability. LSB-CMK-3 is penalised by high GWP and material costs due to intensive LiTFSI use and a complex production process. In comparison, LSB-GSC benefits from a high sulfur content (>50 %), which drives exceptional specific energy, but its GWP remains high due to reliance on lithium foil and relatively high energy demand for manufacturing. These findings illustrate how increasing specific energy alone does not guarantee improved sustainability, especially when offset by greater material intensity or processing complexity.

Across both LSB and SSB chemistries, improving sustainability can be achieved by reducing reliance on lithium metal, due to its high CO_2 emissions, price volatility, and criticality, but also by achieving more effective utilisation of lithium. Despite their potential to enable exceptionally high theoretical specific energy, current designs often fall short of this promise. Practical implementations of lithium metal anodes are constrained by limited coulombic efficiency, dendrite formation, and high lithium excess, which undermine both specific energy and material efficiency. As a result, the promise for lithium metal remains suboptimal, raising questions about its scalability. Bridging this gap will require advances in lithium utilisation, such as thinner foils, protected interfaces, and lithium-excess-free (anodeless) concepts, to realise the full performance potential, without compromising sustainability. In parallel, alternatives such as graphite, silicon, or composite anodes offer promising, more scalable pathways, though further development is needed to balance performance with cost and environmental footprint.



Name	Min (0)	Max (1)
GWP $kgCO_2eq/kWh_{cell}$	348	0
Criticality	4.44×10^{13}	0
Specific Energy kWh/kg	0	650
Energy Density kWh/L	0	1,417
Material Cost $\$/kWh_{cell}$	349	0

Figure 6. Multi-criteria assessment results of (a) LIBs, (b) LIBs and SSBs, (c) SIBs, (d) LSBs, and (e) the average combination of LIBs, SSBs, SIBs, and LSBs

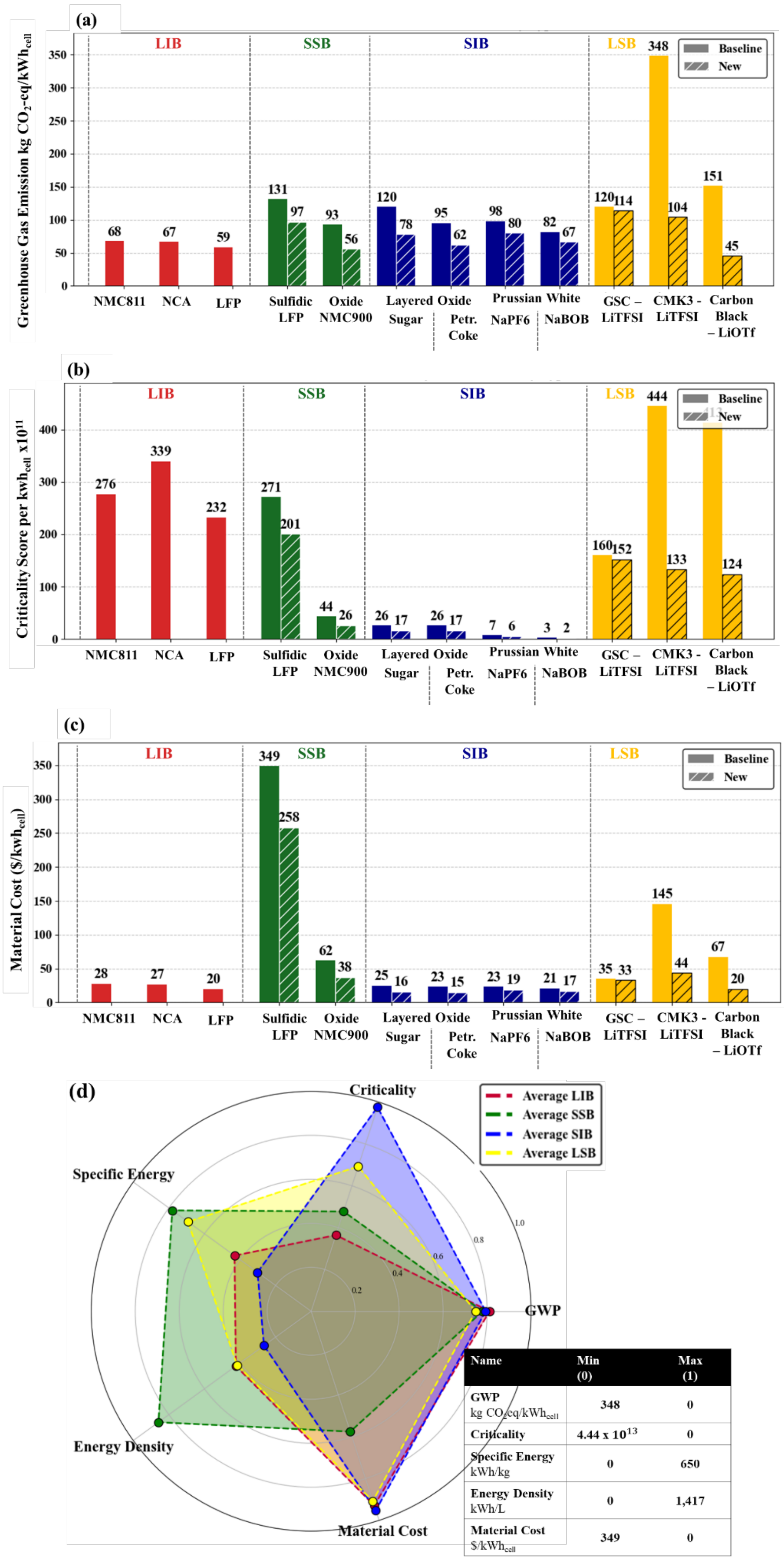
Figure 6(d) summarises the multi-criteria assessment across all LIBs and PLIBs, by compiling an average for each battery technology. While several PLIB chemistries show clear advantages over conventional LIBs on individual metrics, none currently offers a complete solution to the environmental and resource challenges facing battery technology. SIBs offer lower criticality and comparable cost and GWP to LIBs, but their low specific energy and energy density remains a significant drawback. SSBs help close the specific energy and energy density gap, offering performance on par with LIBs and a relatively low GWP, though their reliance on lithium raises concerns about cost and material criticality. Sulfur and lithium foil theoretically provide very high specific energy (Deng et al., 2017), but the average performance of LSBs still falls short of expectations.

4.5 Accounting for improvements in specific energy

Over the years, LIBs have consistently demonstrated improvements in specific energy alongside declining costs, driven by advances in materials science, cell design, and manufacturing scale. Although still emerging, PLIBs may follow a similar trajectory. To explore this possibility, a sensitivity analysis was conducted to assess how future specific energy improvements could reshape the sustainability, criticality, and cost profiles of PLIB chemistries.

Future specific energy and energy densities were estimated based on values reported in recent literature (Table S4). These projections represent plausible near- to mid-term improvements, under the assumption that increases in specific energy are achieved without altering the underlying bill of materials, i.e. improvements are attributed to more efficient cell design or enhanced electrode architecture. Based on these projected densities, the GWP, criticality score, and material cost per kWh_{cell} were recalculated for each chemistry as shown in Figure 7.

From an environmental perspective, SIB-Layered Oxide with Petroleum Coke, SIB-Prussian White -NaBOB, and LSB-Carbon Black, demonstrate similar or even lower GWP impacts than LIBs. From a criticality standpoint, SIBs remain the most resilient option, even under future scenarios. Notably, all PLIBs exhibit lower criticality values compared to LIBs, as the higher specific energy reduces material intensity per unit of stored energy. The improved specific energy also caused significant materials cost reductions for PLIBs, but SSB, LSB-CMK-3, and LSB-GSC still show higher material costs than LIBs. Among these, LSB-CMK-3, which previously ranked as the most critical and second-most expensive chemistry, exhibits the largest improvement in specific energy, rising from 198 Wh kg^{-1} to 660 Wh kg^{-1}. This increase not only narrows its gap with current LIB benchmarks but also demonstrates how targeted design advancements could make even complex PLIB systems competitive across multiple sustainability metrics.



Name	Min (0)	Max (1)
GWP kg CO_2eq/kWh$_{cell}$	348	0
Criticality	4.44 x 10^{13}	0
Specific Energy kWh/kg	0	650
Energy Density kWh/L	0	1,417
Material Cost \$/kWh$_{cell}$	349	0

Figure 7 Sensitivity results for improvements in specific energy and energy density of PLIBs in (a) GWP, (b) criticality, and (c) material cost together with (d) multi-criteria assessment results.

3.4 Limitations and future perspectives

This study provided a multi-criteria evaluation of LIB and PLIB technologies under current conditions, but it is important to acknowledge limitations and areas for future work. First, our analysis is production focused (cradle-to-gate) and does not capture use phase operation or end-of-life scenarios. In reality, battery technologies differ in cycle life, safety, and recyclability, which also affect their overall sustainability (Lander et al., 2021). For example, many PLIBs (especially LSBs and some SSBs) currently suffer from shorter lifespans and higher self-discharge than LIBs, meaning they might deliver fewer total kWh over their lifetime. Ideally, a cradle-to-grave assessment using a functional unit "per kWh delivered over the battery's life" would be used to compare technologies. However, data on cycle life for emerging batteries are often laboratory scale and not directly transferrable to real world conditions, so we focused on the production stage where data could be obtained or estimated. As PLIB prototypes improve, integrating lifespan and efficiency into the analysis will be crucial.

Second, our LCA results for PLIBs are likely conservative because we modelled current lab- or pilot-scale production. LIB manufacturing has benefited immensely from economies of scale and learning-by-doing, large factories have optimized processes, yielding lower energy use (Chordia et al., 2021; Kallitsis, 2022). PLIBs, not yet in mass production, have not had this advantage. We assumed generic energy inputs for manufacturing steps, but in reality a gigafactory producing SSBs or SIBs in the future might implement more efficient process steps, waste heat recovery, high-speed coating, etc., reducing energy and waste. For example, our SSB-Sulfidic model included energy-intensive vacuum drying and pressing steps that might be streamlined or run in parallel in a mature production line.

Third, in updating the ESSENZ methodology, we had to approximate some indicators and exclude others due to data limitations. While this provided a reasonable comparison of materials, criticality assessment inherently has uncertainties and subjective choices (e.g. which socio-political indices best represent mining risk). Our findings of lithium and cobalt being high risk align with other studies (Manjong et al., 2023), and the relative ease of sodium, sulfur, etc., is also intuitive. However, as the geopolitical landscape changes (for instance, new mining projects in different countries, or changes in trade policies), criticality scores can shift. It will be important to continuously update such assessments; for example, if large lithium projects in diverse locations (e.g. South America, Australia, even Europe) come online, lithium's concentration of production might decrease, reducing its criticality.

Fourth, we limited our cost analysis to raw materials. In reality, manufacturing costs (processing, yield losses, labor) vary widely between chemistries. PLIBs might require new equipment or dry rooms (for SSBs) that add cost. On the other hand, some PLIBs could simplify manufacturing. A full cost-of-ownership model for these batteries would be valuable future work, especially as more pilot production data becomes available. Here, we chose to compare material "hotspots" as a first step, and those are instructive, showing for instance that unless Li_2S cost drops by an order of magnitude, sulfidic SSBs will struggle to be cost-competitive.

4. Conclusions

This study presented a multi-criteria evaluation of PLIB technologies, benchmarking them against dominant LIB chemistries across carbon footprint, material criticality, raw material cost, specific energy, and energy density dimensions. Our findings reveal that while PLIBs offer clear opportunities to improve specific sustainability metrics, they also introduce new challenges and trade-offs, particularly related to material dependency and supply chain maturity. PLIBs currently exhibit, on average, 114 % higher production-related carbon emissions than LIBs. Within PLIBs, SIBs have the smallest carbon footprint increase (+52 %), while LSBs have the largest (+217 %), mainly due to the carbon intensity of lithium metal and electrolyte production. A key motivation for developing next generation battery systems is the reduced reliance on critical minerals, lithium, nickel and cobalt. However, we find that currently only SIBs reduce material criticality, by 95 % compared to LIBs. For solid-state and lithium-sulfur systems, lithium demand per kWh can be up to four times higher, amplifying material criticality and raw material costs. In addition, material costs for PLIBs are amplified due to the electrolyte-intensive designs of LSBs and dependence on specialty chemicals, such as lithium sulfide for sulfidic SSBs. SSBs and LSBs currently demonstrate more than 50 % higher material cost compared to the average for current LIBs. SIBs are competitive at current levels, albeit at the expense of reduced specific energy and energy densities. Among all chemistries assessed, LSBs with low specific energy performed the weakest, resulting in the highest GWP, high criticality, and the second-highest material cost. For such chemistries, if specific energy is tripled in line with theoretical predictions, they become competitive with LIBs across all criteria. Increasing specific energy helps narrow the sustainability gap between PLIBs and LIBs, but batteries relying on lithium metal still perform worse in terms of material costs.

CRediT author contributions statement: Conceptualization: A.A.W., E.K., Data curation: A.A.W., E.K., Investigation: A.A.W., E.K., Methodology: A.A.W., E.K., Software: A.A.W., Supervision: E.K., Visualisation: A.A.W., E.K., Writing-original draft: A.A.W., E.K., Writing-review & editing: A.A.W., E.K., G.J.O., J.S.E., Funding acquisition: G.J.O., J.S.E.

Acknowledgements: This work was partly supported by the Faraday Institution's ReLIB project (grant number FIRG057).

5. References

Au, H., Crespo-Ribadeneyra, M., Edge, J. S., Lander, L., Kendrick, E., & Titirici, M. M. (2025). Rethinking Sustainable Batteries. *Advanced Energy Materials*, e02829. https://doi.org/10.1002/AENM.202502829

Bach, V., Berger, M., Henßler, M., Kirchner, M., Leiser, S., Mohr, L., Rother, E., Ruhland, K., Schneider, L., Tikana, L., Volkhausen, W., Walachowicz, F., & Finkbeiner, M. (2016). Integrated method to assess resource efficiency – ESSENZ. *Journal of Cleaner Production*, *137*, 118–130. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.07.077

CATL. (2024). *CATL Innovative Technology*. Retrieved August 30, 2024, from https://www.catl.com/en/research/technology/

Chordia, M., Nordelöf, A., & Ellingsen, L. A.-W. (2021). Environmental life cycle implications of upscaling lithium-ion battery production. *The International Journal of Life Cycle Assessment*, *26*(10), 2024–2039. https://doi.org/10.1007/s11367-021-01976-0

Degen, F., Mitterfellner, M., & Kampker, A. (2025). Comparative life cycle assessment of lithium-ion, sodium-ion, and solid-state battery cells for electric vehicles. *Journal of Industrial Ecology*, *29*(1), 113–128. https://doi.org/10.1111/jiec.13594

Degen, F., Winter, M., Bendig, D., & Tübke, J. (2023). Energy consumption of current and future production of lithium-ion and post lithium-ion battery cells. *Nature Energy*, *8*(11), 1284–1295. https://doi.org/10.1038/s41560-023-01355-z

Deng, Y., Li, J., Li, T., Gao, X., & Yuan, C. (2017). Life cycle assessment of lithium sulfur battery for electric vehicles. *Journal of Power Sources*, *343*, 284–295. https://doi.org/https://doi.org/10.1016/j.jpowsour.2017.01.036

Duffner, F., Kronemeyer, N., Tübke, J., Leker, J., Winter, M., & Schmuch, R. (2021). Post-lithium-ion battery cell production and its compatibility with lithium-ion cell production infrastructure. *Nature Energy*, *6*(2), 123–134. https://doi.org/10.1038/S41560-020-00748-8;SUBJMETA

Graedel, T. E. (2011). *RECYCLING RATES OF METALS A Status Report*. https://www.resourcepanel.org/sites/default/files/documents/document/media/e-book_metals_report2_recycling_130920.pdf

Investing. (2024). *Lithium Carbonate 99%Min China Spot*. https://uk.investing.com/commodities/lithium-carbonate-99-min-china-futures-historical-data

Kallitsis, E. (2022). On the energy use of battery Gigafactories. *Journal of Cleaner Production*, *364*, 132573. https://doi.org/10.1016/J.JCLEPRO.2022.132573

Kallitsis, E., Korre, A., & Kelsall, G. H. (2022). Life cycle assessment of recycling options for automotive Li-ion battery packs. . *Journal of Cleaner Production*, 371, 133636. https://doi.org/10.1016/j.jclepro.2022.133636

Kallitsis, E., Korre, A., Kelsall, G., Kupfersberger, M., & Nie, Z. (2020). Environmental life cycle assessment of the production in China of lithium-ion batteries with nickel-cobalt-manganese cathodes utilising novel electrode chemistries. *Journal of Cleaner Production*, *254*, 120067. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.120067

Kallitsis, E., Lindsay, J. J., Chordia, M., Wu, B., Offer, G. J., & Edge, J. S. (2024). Think global act local: The dependency of global lithium-ion battery emissions on production location and material sources. *Journal of Cleaner Production*, *449*, 141725. https://doi.org/10.1016/J.JCLEPRO.2024.141725

Kulova, T. L., Fateev, V. N., Seregina, E. A., & Grigoriev, A. S. (2020). A Brief Review of Post-Lithium-Ion Batteries. *International Journal of Electrochemical Science*, *15*(8), 7242–7259. https://doi.org/10.20964/2020.08.22

Lander, L., Kallitsis, E., Hales, A., Edge, J. S., Korre, A., & Offer, G. (2021). Cost and carbon footprint reduction of electric vehicle lithium-ion batteries through efficient thermal management. *Applied Energy*, *289*, 116737. https://doi.org/10.1016/j.apenergy.2021.116737

Luoyang Tongrun Info Technology. (2025). *Factory Price 99.9% High Purity CAS 12136-58-2 Li2S Powder Price Lithium Sulfide Li2S Powder*. https://www.alibaba.com/product-detail/Factory-Price-99-9-high-Purity_1601044660910.html?spm=a2700.galleryofferlist.normal_offer.d_title.610813a0xhdD0N (Accessed 18 November 2025).

Manjong, N. B., Bach, V., Usai, L., Marinova, S., Burheim, O. S., Finkbeiner, M., & Strømman, A. H. (2023). A comparative assessment of value chain criticality of lithium-ion battery cells. *Sustainable Materials and Technologies*, *36*, e00614. https://doi.org/https://doi.org/10.1016/j.susmat.2023.e00614

McKinsey. (2021). *Building better electric batteries for battery electric vehicles | McKinsey*. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/building-better-batteries-insights-on-chemistry-and-design-from-china

Mining.com. (2024). *First Quantum to shut down Ravensthorpe nickel mine - MINING.COM*. https://www.mining.com/first-quantum-to-shut-down-ravensthorpe-nickel-mine/

MiningWeekly. (2024). *Glencore to close unprofitable New Caledonia nickel mine*. https://www.miningweekly.com/article/glencore-to-close-unprofitable-new-caledonia-nickel-mine-2024-02-12

Mo, R., Tan, X., Li, F., Tao, R., Xu, J., Kong, D., Wang, Z., Xu, B., Wang, X., Wang, C., Li, J., Peng, Y., & Lu, Y. (2020). Tin-graphene tubes as anodes for lithium-ion batteries with high volumetric and gravimetric energy densities. *Nature Communications 2020 11:1*, *11*(1), 1–11. https://doi.org/10.1038/s41467-020-14859-z

Pasta, M. (2019). *Anode-less Li-metal batteries*. https://www.materials.ox.ac.uk/article/anode-less-li-metal-batteries

Peiseler, L., Schenker, V., Schatzmann, K., Pfister, S., Wood, V., & Schmidt, T. (2024). Carbon footprint distributions of lithium-ion batteries and their materials. *Nature Communications* , *15*(1), 1–13. https://doi.org/10.1038/S41467-024-54634-Y;TECHMETA

Pelzeter, J., Bach, V., Henßler, M., Ruhland, K., & Finkbeiner, M. (2022). Enhancement of the ESSENZ Method and Application in a Case Study on Batteries. *Resources*, *11*(6). https://doi.org/10.3390/resources11060052

Peters, J., Buchholz, D., Passerini, S., & Weil, M. (2016). Life cycle assessment of sodium-ion batteries. *Energy Environ. Sci.*, *9*(5), 1744–1751. https://doi.org/10.1039/C6EE00640J

Placek, M. (2022). *Global battery demand by application*. https://www.statista.com/statistics/1103218/global-battery-demand-forecast/

Popien, J. L., Thies, C., Barke, A., & Spengler, T. S. (2023). Comparative sustainability assessment of lithium-ion, lithium-sulfur, and all-solid-state traction batteries. *International Journal of Life Cycle Assessment*, *28*(4), 462–477. https://doi.org/10.1007/S11367-023-02134-4/TABLES/5

Shanghai Metals Market. (2025). *Battery Grade Lithium Metal price today | Historical Battery Grade Lithium Metal Price Charts | SMM Metal Market*. https://www.metal.com/Lithium/202304250002 (Accessed 15 March 2025)

Sun, Y., Zhang, Q., Yang, S., Sun, X., & Yang, Y. (2023). Making the Unfeasible Feasible: Synthesis of the Battery Material Lithium Sulfide via the Metathetic Reaction between Lithium Sulfate and Sodium Sulfide. *Inorganic Chemistry*, *63*, 485–493. https://doi.org/10.1021/acs.inorgchem.3c03345

Troy, S., Schreiber, A., Reppert, T., Gehrke, H.-G., Finsterbusch, M., Uhlenbruck, S., & Stenzel, P. (2016). Life Cycle Assessment and resource analysis of all-solid-state batteries. *Applied Energy*, *169*, 757–767. https://doi.org/https://doi.org/10.1016/j.apenergy.2016.02.064

Trunano. (2025). *Factory Price 99.9% High Purity Cas 12136-58-2 Li2s Powder Price Lithium Sulfide Li2s Powder - Buy Li2s Powder lithium Sulfide Cas 12136-58-2 Product on Alibaba.com*. https://www.alibaba.com/product-detail/Factory-Price-99-9-high-Purity_1601044660910.html?spm=a2700.galleryofferlist.normal_offer.d_title.610813a0xhdD0N

USGS. (2024). Mineral commodity summaries 2024. *Pubs.Usgs.Gov*, *2024*. https://doi.org/10.3133/mcs2024

USGS. (2025). Mineral commodity summaries 2025. *Mineral Commodity Summaries 2025*, *2025*. https://doi.org/10.3133/mcs2025

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. https://doi.org/10.1007/S11367-016-1087-8/METRICS

Wickerts, S., Arvidsson, R., Nordelöf, A., Svanström, M., & Johansson, P. (2023). Prospective Life Cycle Assessment of Lithium-Sulfur Batteries for Stationary Energy Storage. *ACS Sustainable Chemistry & Engineering*, *11*(26), 9553–9563. https://doi.org/10.1021/acssuschemeng.3c00141

Wickerts, S., Arvidsson, R., Nordelöf, A., Svanström, M., & Johansson, P. (2024). Prospective life cycle assessment of sodium-ion batteries made from abundant elements. *Journal of Industrial Ecology*, *28*(1), 116–129. https://doi.org/https://doi.org/10.1111/jiec.13452

Winjobi, O., Dai, Q., & Kelly, J. C. (2020). Update of Bill-of-Materials and Cathode Chemistry addition for Lithium-ion Batteries in GREET 2020. *Systems Assessment Group, Energy Systems Division, Argonne National Laboratory, llinois, USA*.

World Bank. (2024). *Home | Worldwide Governance Indicators*. https://www.worldbank.org/en/publication/worldwide-governance-indicators

Yang, C., Singh, A., Pu, X., Mallarapu, A., Smith, K., Keyser, M., Haberman, M. R., Khani, H., Misztal, P., Spray, R., Ezekoye, O. A., & Finegan, D. P. (2025). Addressing the safety of next-generation batteries. *Nature*, *645*(8081), 603–613. https://doi.org/10.1038/S41586-025-09358-4;SUBJMETA

Yang, X., Li, X., Adair, K., Zhang, H., & Sun, X. (2018). Structural Design of Lithium–Sulfur Batteries: From Fundamental Research to Practical Application. *Electrochemical Energy Reviews*, *1*(3), 239–293. https://doi.org/10.1007/s41918-018-0010-3

Yokoi, R., Kataoka, R., Masese, T., Bach, V., Finkbeiner, M., Weil, M., Baumann, M., & Motoshita, M. (2024). Potentials and hotspots of post-lithium-ion batteries: Environmental impacts and supply risks for sodium- and potassium-ion batteries. *Resources, Conservation and Recycling*, *204*, 107526. https://doi.org/10.1016/J.RESCONREC.2024.107526

Zuo, W., Innocenti, A., Zarrabeitia, M., Bresser, D., Yang, Y., & Passerini, S. (2023). Layered Oxide Cathodes for Sodium-Ion Batteries: Storage Mechanism, Electrochemistry, and Techno-economics. *Accounts of Chemical Research*, *56*(3), 284–296. https://doi.org/10.1021/ACS.ACCOUNTS.2C00690