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Screening for social risks of raw materials for Sodium-Ion Batteries

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Keywords

Lithium-ion battery, social impact, S-LCA, raw material, child labour, DALY

Abstract

Lithium-ion batteries (LIBs) are considered a key technology for the energy and mobility transition. But the high demand for LIBs causes an increasing demand for critical raw materials (CRMs), like lithium, cobalt, graphite and nickel. Furthermore, there are concerns that the well-established LIB technology is falling short on environmental and social expectations, pointing out issues of human exploitation, including forced- and child labour. Currently, sodium-ion battery (SIB) technology is promoted as complementary to LIBs, but based on abundant resources. While SIBs are considered a promising alternative in some applications, with potential environmental advantages in the future, little is known regarding their potential social risks and impacts. This study uses Social Life Cycle Assessment (S-LCA) methodology to explore the potential social impacts of a representative emerging SIB in comparison to LIB. The focus is on the raw material extraction phase, and the investigated impact categories include child labour, trafficking in persons, fair salary, trade union density, disability-adjusted life years (DALY) due to indoor and outdoor air and water pollution, and the contribution of the sector to economic development. Except for the DALY, SIBs portrayed a better potential social performance, mainly due to the absence of CRMs such as cobalt and lithium.

1. Introduction

Currently, lithium-ion batteries (LIB) are being scrutinised for their ecological and potential social impact along the supply chain, depending on their chemistry. Ecosystem destruction during mining, high pollution from metal extraction and high energy requirements are some major environmental concerns.[1] But all technologies which rely on primary raw materials cause significant environmental and social impacts.[2,3] In general, mining is a critical sector when it comes to social aspects, due to the absence of strict monitoring and regulatory environments.[4,5] Consequently, there is a scarcity of reliable up-to-date data for this sector. This is reinforced by several factors, e.g., labour-intensive conditions in remote areas with limited infrastructure, often located in the global south, and volatile boom-and-bust economics for raw materials (e.g., cobalt, nickel or gold).[6,7] A 2019 report by the International Labour Organization (ILO) estimates that approximately 1 million children are engaged in child labour in the mining sector, particularly within artisanal and small-scale mining.[8] Studies indicate that residents in regions converted into cobalt mining areas in the Democratic Republic of Congo (DRC) have up to 10 times higher cobalt levels in their blood and urine than those in nearby control areas, with children being most vulnerable to these health risks.[9] Moreover, there are reported cases of children being buried alive in collapsed mines. In 2019, companies such as Tesla, Apple and Google faced for the first time legal challenges over Congolese child deaths caused by cobalt mining.[10] Thus the green transition in industrial countries is often connected not only to child labour, but also to forced labour, poor wages, corruption and health hazards.

LIBs rely on geographically concentrated critical minerals such as lithium, nickel, cobalt, and graphite, leading to supply-chain vulnerabilities and energy-intensive refining. In contrast, sodium ion batteries (SIBs), an emerging technology, shift material demand toward more abundant resources, including sodium salts and common transition metals like iron and manganese, being considered more sustainable and lower in cost. [11,12] A number of types of cathode materials are under development for SIBs, the three most prominent being: layered metal oxides, polyanionic materials, and Prussian blue analogues/ Prussian whites (see Table 1). While the manufacturing steps for LIBs and SIBs closely resemble, there are significant differences in the battery composition of SIBs and LIBs.[13,14] Especially Prussian whites and layered metal oxides are synthesized from widely available precursors, while avoiding high-nickel or cobalt chemistries. In addition, the copper in the current collectors of LIB can be substituted by aluminium when shifting from LIBs to SIBs, and the graphite anode active material is replaced by hard-carbon, produced from biomass or pitch-based materials, reducing dependence on high-risk mining regions. [15]

Due to these differences in the battery composition and therefore in the supply chain, SIBs are considered to be a promising alternative to LIBs, already available as a drop-in technology at high technology readiness level (refer Table 1). Even if their energy density is lower compared to LIBs, SIBs are gaining attention for their potential to reduce reliance on rare and critical raw materials (CRM).[16] Several start-ups as well as established battery manufacturing companies are currently investing in different SIB-chemistries.[17,18] However, while SIBs have the potential for a lower environmental impact along their life cycle,[19,20] the social risks are not yet known. The aim of this article is to explore potential social implications for this emerging technology in comparison with one reference LIB technology. The Social Life Cycle Assessment (S-LCA) methodology is used in this study. The findings will be useful for battery and automobile manufacturers as a basis to identify potential social hotspots in supply chains and to promote social responsibility and sustainability. Finally, the study focuses on the raw material extraction phase because the primary motivation for considering SIB technology lies in addressing the social and sustainability challenges associated with the material requirements of current LIB systems. Furthermore, the most critical social risks in LIB supply chains originate upstream, particularly in the extraction and processing of cobalt, nickel, and lithium. Therefore, this study specifically evaluates, in a explorative way, whether substituting these materials with the more abundant and less socially contentious inputs used in SIBs can lead to measurable improvements in social sustainability.

Table 1: Emerging Sodium ion battery chemistries, differentiated by type with corresponding technology readiness level (TRL) (Based on: [21–26])

Cell chemistry (Na-ion)	Typical cathode / anode pairing	Status & typical applications	Approx. TRL range*
PB/PW + hard carbon	Prussian blue / Prussian white cathodes with amorphous hard-carbon anodes	First commercial SIBs for stationary storage and low-cost mobility (e.g. grid, e-scooters, low-speed EVs) from multiple Chinese and European suppliers.	8–9 (early commercial, scaling)
Layered oxides (O3/P2/P3) + hard carbon	Sodium layered transition-metal oxides (e.g. NaNiMn, NaMnFe, NaMMT systems) with hard-carbon anodes	High-energy SIBs targeting LFP-class energy density; in demo EV packs and industrial pilot lines, including high-nickel O3-type oxides benchmarked versus LFP.	6–8 (pilot to niche commercial)
Polyanionic cathodes + hard carbon	NASICON-type, fluorophosphates, and other polyanionic Na cathodes with hard-carbon anodes	Focused on high voltage and thermal stability; mainly prototype cells and limited pilot production for stationary storage where safety and lifespan dominate.	5–7 (advanced lab to early pilot)
Alloying anodes (Sn, Sb, P, etc.) + layered/PB cathodes	Alloying-type Na anodes (Sn, Sb, P, sometimes Na metal composite) with conventional Na cathodes	R&D on higher energy density and fast-charge; cycling, expansion and safety still constrain scale-up; so far limited to research cells and small prototypes.	3–5 (proof-of-concept to early prototype)
Na metal or Na solid-state	Metallic sodium anodes with sulfide/oxide solid electrolytes and high-voltage cathodes	Long-term “beyond SIB” option with very high theoretical energy; currently facing interface stability and manufacturability challenges, with a few early pouch-cell demos.	2–4 (lab concept to early proof-of-concept)

2. S-LCA Methodology and the PSILCA database

Social impact can be defined as the consequences of socio-economic pressures on human wellbeing. It can either be positive or negative, such as creating social amenities or exploiting children. The S-LCA methodology is an assessment technique used to capture both positive and negative impacts of products and services from a life cycle perspective. S-LCA enables the screening of social risks associated with products and services across their life cycle, helping to avoid burden shifting along the supply chain within sustainability assessment. This methodology builds on the commonly known Environmental Life Cycle Assessment (E-LCA), the ISO 14040 methodological framework **(see Figure 1)**, now complemented by the new ISO 14075.[27,28] Although the S-LCA methodology is not yet fully established, it has been gaining maturity as a standalone methodology that can be integrated with other sustainability methods.[29] Using both aggregated and site-specific data, it can quantify both social and socio-economic impacts through the whole lifecycle, including raw material extraction, processing, manufacturing, usage and end-of-life/recycling.

Unlike the E-LCA, inventory data and impact assessment for S-LCA studies is drawn in relation to different stakeholders, which may include workers, children, local communities, society etc. Social impacts are quantified by an activity variable called e.g., worker hours or value added, which reflects the measure of share of a given process in a life cycle. In the social impact assessment phase, both positive and negative impacts are assessed using performance reference points and thresholds. There are only two existing databases for S-LCA, the Product Social Impact Life Cycle Assessment (PSILCA) and the Social Hotspot Database (SHDB). Both derive inspiration from the S-LCA guidelines by the UNEP/SETAC Life Cycle Initiative.[30] These guidelines provide a technical framework through which a larger group of stakeholders can engage toward social responsibility. According to the S-LCA guidelines, PSILCA falls under the first type of impact assessment approach, known as a Reference Scale Approach,[30] which is generally recommended for conducting S-LCA. In this study, the PSILCA professional version 3 developed by Green Delta in June 2020 is used, based on its more recent data as well as its data quality pedigree matrix.

PSILCA is based on three main units composed of an input-output model, a worker-hour model and a database on social aspects. The input-output model uses a multi-regional input-output (MRIO) database called Eora to provide insights into the global supply chain. It covers the entire world economy on an industrial sector basis with a representative of 15000 sectors and 189 countries.[31] A heterogeneous classification is adopted to follow the so-called sector harmonisation, where some countries are represented by industries and commodities. The social aspects characterise social indicators that impact five stakeholder groups, namely workers (including children), local communities, society, consumers, and value chain actors. Nineteen subcategories such as child labour, and about 70 qualitative/quantitative indicators assess social and environmental risks and impacts. PSILCA uses the worker-hours activity variable which describes the working time needed to produce 1 USD output from a sector. The social risks are then translated and aggregated into medium-risk hours, specifying the observed risks related to producing 1 USD of output from an economic sector. The overall social risks are scaled by the price input, amount of work hours and characterisation factors, which then leads to the risk results per impact category.

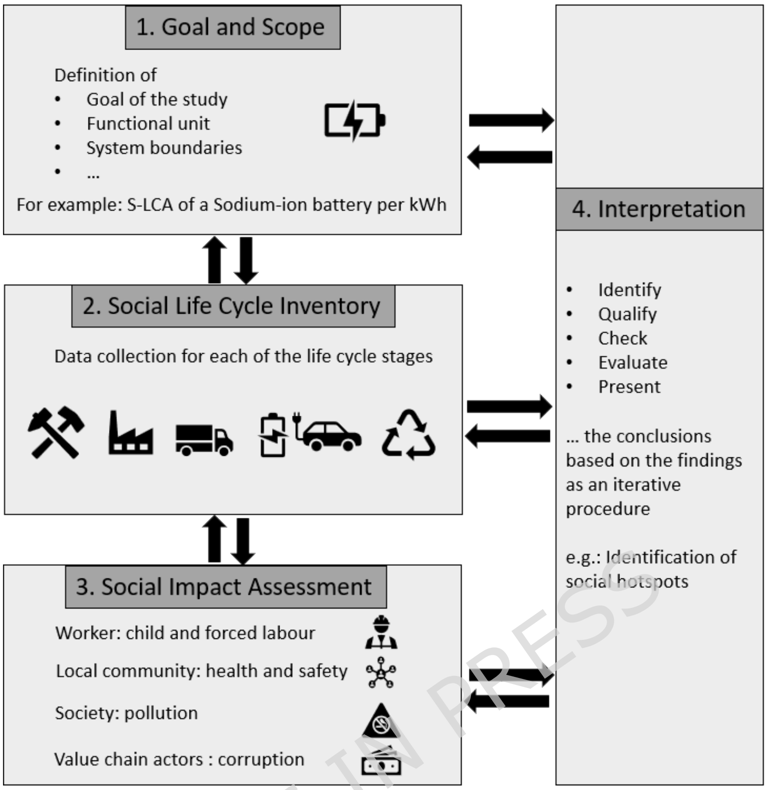


Figure 1: S-LCA framework

3. Literature Review and Research Question

3.1 Literature Review

Several works exclusively quantify the environmental aspects of the emerging SIB technology,[32–37] but no existing publication addresses the prospective social impacts of emerging SIBs. For the conducted review Google Scholar and Science Direct were used with the search terms 'S-LCA,' 'social life cycle assessment,' 'social impact,' 'social sustainability,' and 'sustainability assessment,' in combination with the terms 'SIB,' 'sodium-ion battery,' 'LIB' 'lithium-ion-battery,' 'VRFB,' and 'vanadium redox flow battery,'. Therefore, to widen the scope beyond SIBs **Table 2** presents, to the best of the authors´ knowledge, all social assessment studies of batteries published until 2024.

Table 2: Comparison of S-LCA studies on LIB

Authors	Title/Context	Methodology/Database	Social Indicators	Results
Marc Heydt[38]	**Ecological and social sustainability of LIB for electric vehicles**. This thesis evaluated the full life cycle of two Li-ion battery chemistries,_NMC 111 and NMC 811. The study emphasised the importance of assessing both environmental and social impacts across the batteries' life cycle, highlighting the need for a holistic approach to sustainability.	openLCA software, Ecoinvent (E-LCA) and PSILCA database.	Child labour, fatal work accidents and violations of workers' rights.	The S-LCA revealed that NMC111 performed worse socially than the NMC 811. In particular, cobalt mining in D R Congo was linked to a high risk of child labour. Additionally, Chinese production processes were associated with elevated risks of fatal occupational accidents and violations of workers' rights.
Benjamin Reuter[39]	**Assessment of sustainability issues for the selections of materials and technologies during product design: a case of Li-ion batteries for electric vehicles**. The assessment compared two cathode chemistries—lithium nickel manganese cobalt oxide (Li-NMC) and lithium iron phosphate (LiFeP)— and evaluated the sustainability considerations in the selection of materials and technologies during the product design phase.	E-LCA, Life Cycle Costing Assessment (LCCA), S-LCA, SHDB.	Indicators related to working conditions, community, and legal systems.	The results indicated that the Li-NMC battery was advantageous in terms of global warming potential and life cycle costs. The LiFeP battery, however, turns out to be more beneficial regarding the other emission-related impact categories. Also, the use of cobalt in Li-NMC posed social risks of a supply shortage, and the risk of negative social aspects.
Shi et al.[40]	**Social life cycle assessment of lithium iron phosphate battery production in China, Japan and South Korea based on external supply materials**. This study combined supply concentration analysis with S-LCA to examine the social risk profile of LFP battery production in China, Japan, and South Korea. Using data from external material supply chains and the Social Hotspot Database, the assessment was conducted within a cradle-to-gate scope, covering the production phases of key input materials.	Supply concentration, S-LCA, SHDB.	Labour rights and decent work, health and safety, human rights.	The S-LCA based on multiple supply sources generated weighted risk values for each material, outlining the material-specific social risk profiles encountered by LFP battery producers in China, Japan, and South Korea. The resulting social footprint analysis revealed that materials sourced from developed countries generally carry lower social risks per unit of USD value compared to those sourced from developing countries.
Barke et al.[41]	**Life cycle sustainability assessment of potential battery systems for electric aircraft**. This study evaluated the environmental, economic, and social impacts of eight potential battery systems for electric aircraft. The	E-LCA, LCCA, S-LCA, SHDB.	Risk of poverty, risk of corruption, risk of child labour.	The LSBs were advantageous compared to lithium-ion batteries in terms of environmental, social, and economic impacts. LSBs were found to be socially

	assessment considered five lithium-ion batteries based on lithium nickel manganese cobalt oxide (NMC), one LIB based on lithium iron phosphate (LiFeP), one LIB based on lithium nickel cobalt aluminium oxide (NCA), and one lithium-sulfur battery (LSB). The analysis covered the full life cycle from raw material extraction to component manufacturing, battery cell production, and battery pack assembly.			beneficial across all impact categories assessed, outperforming the LIB variants.
Koese et al.[42]	**A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage.** The aim was to assess the social risks associated with these two different stationary batteries for energy storage from cradle-to-use life cycle.	S-LCA, PSILCA.	Indicators related to workers, local communities and society were assessed.	For both the LIB and the VRFB, the majority of social risks were associated with the raw material extraction phase, with risks being lower in Germany compared to China. The extraction phase had the highest social risks, with workers being the most affected. The study highlighted that S-LCA, using the PSILCA database, can provide valuable insights into the potential social risks across a product's life cycle.
Mancini et al.[43]	**Responsible and sustainable mining of battery raw materials.** This report from the JRC Publications Repository provided insights into responsible and sustainable mining practices for battery raw materials. From a hotspot analysis, corporate disclosures, and field research, the report highlighted key challenges and opportunities in ensuring ethical sourcing and minimising environmental and social impacts across the supply chain.	Hotspot screening, Sustainability report analysis, reviews of initiatives.	Risk of conflicts. Child labour.	This study represented an initial step toward understanding and quantifying the main risks in battery supply chains during the mining stage, as well as assessing the impact of current on-the-ground initiatives aimed at addressing these risks.
Sánchez et al.[44]	**Methodology for social life cycle impact assessment enhanced with gender aspects applied to electric vehicle Li-ion batteries.** A cradle-to-grave approach was applied to evaluate the social concerns associated with the design of Li-ion battery packs. This methodology is enhanced by incorporating gender aspects, providing a more comprehensive assessment of social impacts throughout the entire life cycle.	S-LCA, a questionnaire based on UNEP guideline, is complemented by a gender	Children, workers, local community, society, value chain actors, consumers.	Based on the results of this study, the design of Li-ion battery packs for electric vehicles demonstrated a positive social impact on the stakeholders evaluated.

		assessment.		
Domingues et al.[45]	**Lifecycle social impacts of lithium-ion batteries: Consequences and future research agenda for a safe and just transition.** This study presented a comprehensive review of peer-reviewed literature, grey literature, and conflicts in the Global Atlas of Environmental Justice, focusing on the social impacts associated with the life cycle of lithium-ion batteries.	Peer-reviewed literature and conflicts in the Global Atlas of Environmental Justice associated with LIBs lifecycle.	A total of 238 social impacts were mapped to broad social themes, including health, water and air pollution, education, governance, human rights.	The main findings showed that workers, local communities, and society are the most investigated stakeholders, while consumers, value chain actors, and children are often overlooked. The continued business-as-usual production of lithium-ion batteries could hinder the achievement of a safe and just transition.
Zimmermann et al.[46]	**Social Life Cycle Assessment as a pillar of sustainability analysis of batteries: The case of LiFePO4**. This study explored the potential of S-LCA of $LiFePO_4$ batteries. The operationalisation of S-LCA using the Social Hotspot Database and the openLCA software is described and critically reviewed. The approach is compared with traditional LCA and LCC methodologies.	SHDB, openLCA.	Collective bargaining, corruption, toxic and hazards.	Social repercussions associated with battery production are more complex, dynamic, and regionally fragmented than many environmental impacts. Moreover, Social Life Cycle Assessment faces limitations due to the lack of precision and detailed datasets for the battery production process chain.
Theis et al.[47]	**Assessment of social sustainability hotspots in the supply chain of lithium-ion batteries.** An assessment of the social sustainability hotspots of lithium-ion batteries carried out based on a spatially differentiated resource flow model of the supply chain taking into consideration raw materials, cells, components, cells and pack production.	SHDB.	Child labour, corruption, occupational toxics and hazards, poverty.	The results showed that China-focused production posed the highest risk across all access categories. However, shifting cell and pack production to Germany, along with the responsible sourcing of raw materials, led to a significant reduction in risk hours.

3.2 Research question

Based on the background and literature review, most social impacts are embedded in the battery technology supply chain and affect various stakeholder groups. Additionally, many social issues and risks stem from problematic practices in the LIB supply chain, particularly concerning cobalt.[38–41] No literature was found detailing the social effects of SIB technology or comparing it to other technologies; therefore, the potential social and socio-economic impacts of SIB remain unknown. As a first step to address this gap, this study aims to identify potential social impact hotspots in the supply chain of emerging SIBs and highlight high-risk social issues. Accordingly, it analyses the social performance of a SIB (sodium nickel manganese magnesium titanite oxide-based cathode (NaMMT)) in comparison to low-cobalt NMC (lithium nickel magnesium cobalt (NMC 811)) and the corresponding limitations of the PSILCA database. This leads to the following research question: What are the potential high-risk social issues in the supply chain of the emerging SIB and how do they compare to those of NMC battery technology?

The NMC811-graphite LIB chemistry was selected because NMC-based batteries are consistently identified in the literature as the most socially critical due to their reliance on cobalt, nickel, and manganese sourced from high-risk regions such as the D.R. Congo and China. [38,39,41–43] NMC811 represents the current industrial benchmark for high-energy LIBs and remains central in EV and with a decreasing trend in stationary storage applications, making it the most relevant reference system for social hotspot comparison.[48]

In contrast, no studies currently examine the social impacts of SIB, creating a significant knowledge gap. To address this, the NaMMT-hard carbon chemistry was chosen as it is a technologically plausible next-generation SIB composition that is cobalt-free, lithium-free, and based on more abundant materials. This configuration aligns with ongoing European research and development efforts and offers a realistic basis for evaluating how emerging SIBs may avoid the major social risks highlighted for LIBs in previous studies. Selecting these two systems therefore enables a meaningful and future-oriented comparison of social hotspots while directly addressing the gap identified in the literature.

4. Application of S-LCA

4.1 Goal

In accordance to **Figure 1,** first the goal of the study is defined by assessing the potential positive and negative impacts along the supply chain of a SIB cell and to contrast them with those of an existing LIB. The results are analysed, and a critical review and limitations of the database is provided. In particular, a SIB based on NaMMT and hard carbon is compared with a LIB with NMC 811 cathode and a graphite anode. The NaMMT has an energy density of 138.8 Wh/kg, whereas the NMC811 has an energy density of 233 Wh/kg.

4.2 Functional unit, scope and system boundary

The potential social impact is assessed per 1 kWh of battery energy storage capacity, tracing raw materials from top suppliers to the EU. As the global supply chain for battery production is very complex and difficult to trace, the scope of this work is limited to the extraction phase of the supply chain. This allows identification of the social hotspots during material extraction, since the social burdens are more concentrated in the mining stage of the battery raw material. [42] Additionally, the manufacturing of SIBs and LIBs closely match, therefore an assessment would lead to only very small differences, when compared. The analysis focuses on the top three EU sourcing countries for the main raw materials of a battery cell, including the active materials of cathode and anode, the current collectors, electrolytes and the cell casing, using the background data from PSILCA. The corresponding system boundary is shown in **Figure 2**.

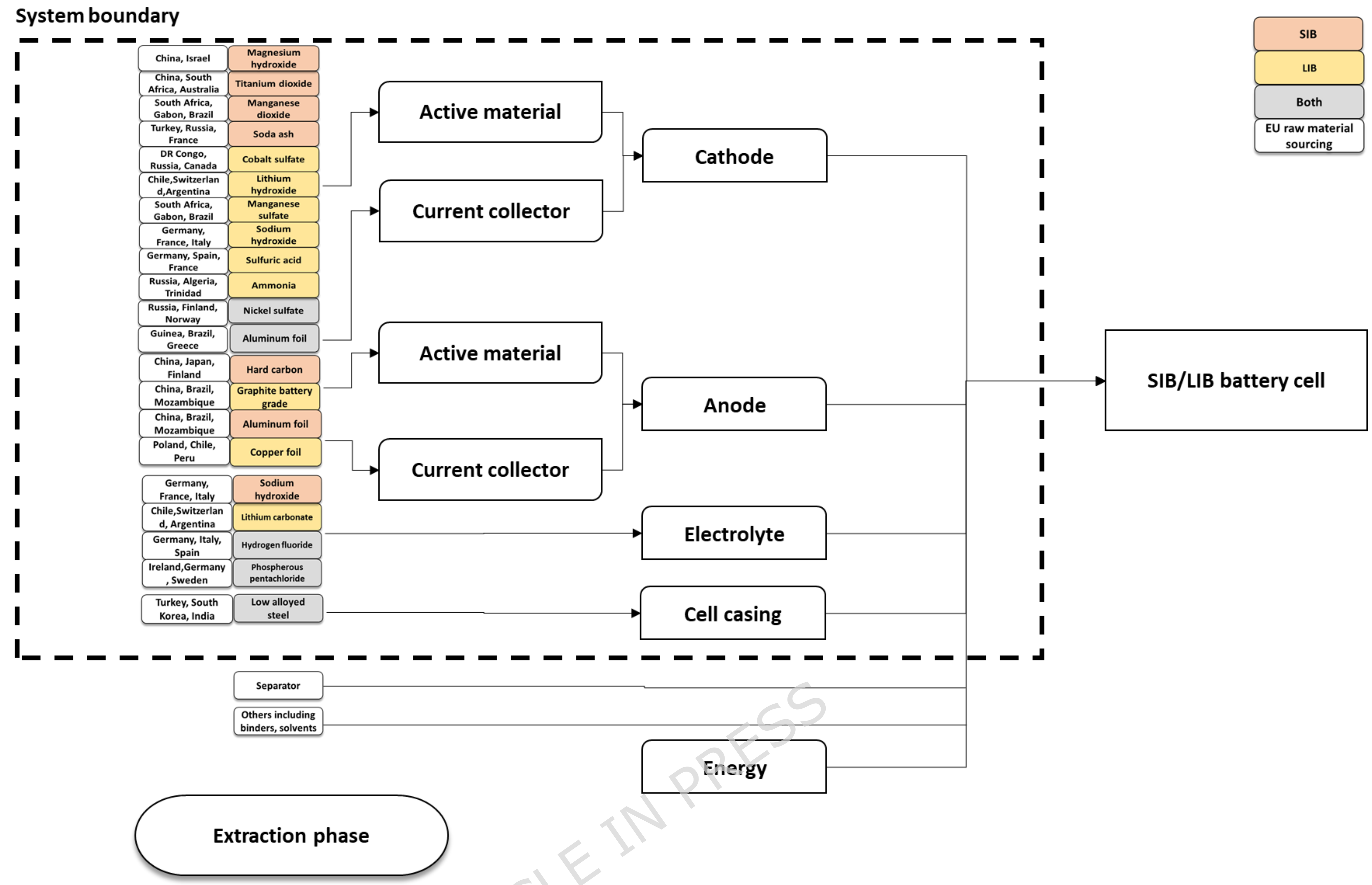


Figure 2: Product system and system boundary

4.3 Social Life Cycle Inventory

For most raw materials, the EU economy has low domestic production and relies heavily on importing raw materials from international markets that are produced and supplied by third countries. To trace where the EU sources its raw materials, data is collected from sources such as the EU Raw Material Information Systems, and EU CRM reporting.[49–53] For this study, the top three countries supplying each material are considered, with the shares normalised to 100%. For each material used, the three countries are listed in the supplementary information (SI), in Tables S2 and S3. In cases where data did not reflect the EU, global data is used. For example, from the existing data sources it was difficult to identify the EU's importing countries for cobalt as the countries were anonymised, hence global suppliers are used instead. Equal shares are assumed when no specific contribution can be determined. The daily average price between April 2021 and April 2024 of the raw materials per kWh are taken mainly from the Shanghai Metals Market Database and converted to 2015 US dollar rates to reflect the economic value of the PSILCA database, **Table 3**.[54]

For the SIB and LIB models, inventories are taken from previous publications.[55,56] **Table 3** shows the mass of material inputs required per 1 kWh of energy storage for the two batteries analysed. Here the difference in energy density between the two analysed cells are taken into account. Since PSILCA does not provide a list of all the raw materials, the products from the inventories were converted into the PSILCA logic. That is, all the products were accounted based on monetary value per corresponding sector rather than mass. For example, a product system that contains 1 kg of cobalt sulfate, would be $1.65 from the mining and quarry industry in DR Congo. Finally, the social risks are scaled by price (inputs), working hours and characterisation factors to give the final results in terms of medium risk hours (mrh). A mrh is a normalised, risk-weighted unit calculated by multiplying labour hours by a certain factor. It is used to aggregate the potential social risk exposure of all working hours throughout a product's life cycle onto a common scale.

Table 3: Material mass input per 1 kWh of storage battery capacity. Material prices are sourced from the Shanghai Metals Market Database, converted in USD.[54]

	Component	Item	Mass(g)/kWh	Input price USD/kWh
SIB	Cathode	Magnesium hydroxide	57.30	0.169
		Manganese dioxide	854.33	1.345
		Nickel sulfate	700.14	2.653
		Titanium dioxide	78.56	0.134
		Soda Ash	1146.05	0.309
		Aluminium foil	249.59	0.482
	Anode	Hard carbon	1458.13	0.004
		Aluminium foil	256.16	0.496
	Electrolyte	Sodium hydroxide	396	0.081
		Hydrogen fluoride	5015.67	8.067
		Phosphorous pentachloride	2453.58	2.685
	Cell casing	Steel	1527.10	1.884
LIB	Cathode	Cobalt sulfate	295.88	1.946
		Lithium hydroxide	448.05	11.117
		Nickel sulfate	2603.73	9.867
		Manganese sulfate	295.88	0.180
		Sodium hydroxide	3381.47	0.693
		Sulfuric acid	1653.54	0.177
		Ammonia	41.25	0.015
		Aluminium foil	165.19	0.320
	Anode	Battery grade graphite	1281.64	7.801
		Copper foil	372.47	0.712
	Electrolyte	Lithium carbonate	24.23	0.625
		Hydrogen fluoride	376.78	0.606
		Phosphorous pentachloride	163.78	0.180
	Cell casing	Steel	701.38	1.140

4.4 Assessed social indicators

The scope of this study is limited to the worker stakeholder category. This is mainly based on the conducted literature review, which confirms that the majority of severe social issues in battery supply chains originate in the mining sector, particularly in low-income countries, where many critical raw materials are extracted. As this study aims to assess and potentially mitigate these upstream social risks by comparing them with those associated with emerging SIB technologies, focusing on these mining-related indicators provides a meaningful basis for understanding how social burdens may be reduced.[42] Moreover, PSILCA provides social impacts under 55 different impact categories. Using all the categories can hinder the significant and frequently analysed ones and would be beyond the scope of the paper. Accordingly, sectors that reveal very high-risk social issues are selected; child labour, trafficking in persons, Disability-Adjusted Life Years (DALYs) due to indoor and outdoor air and water pollution, trade union density, and fair wages. [38,40,42] These categories are expressed on a negative scale measured in mrh. To capture a positive impact in this investigation, the positive social indicator, "contribution of the sector to economic development" pertaining to stakeholder society, is added. This is the only indicator in PSILCA expressed at opportunity level and on a positive scale. The following impact categories are considered:

I. Child labour according to the definition from the World Bank refers to "children involved in an economic activity for at least one hour…" aged 7-14. This category is assessed in PSILCA through the indicators "children in employment, male", "children in employment, female", "Children in employment, total".

II. Trafficking in persons is the recruitment of individuals for the purpose of exploitation. This may include forced labour, sexual exploitation and all sorts of slavery practices.

III. DALY (Disability-Adjusted Life Year) due to indoor and outdoor air and water pollution helps assess the health risks to workers affected by high air and water pollution at their place of work. One DALY refers to one lost year of a 'healthy' life. This social indicator measures the risk of unhealthy living caused by air and water pollution in the workplace.

IV. Fair salary refers to a wage reasonably commensurate with the value of a particular service. It is assessed through "Living wage, per month", "Minimum wage, per month", and "Sector average wage, per month" as codes of conduct for wages and benefits for a rendered service.

V. Trade union density, also known as trade unionism, is used to assess the degree of freedom of association. It considers the number of union members who are employees as a percentage of the total number of employees.

VI. Contribution of the sector to economic growth is currently the only social indicator in the PSILCA database that captures potential positive impact and is related to the society stakeholder. It is a measure of monetary contribution of a sector to the Gross Domestic Product (GDP) of a country.

4.5 Assumptions and limitations

A kWh of energy storage capacity cell, produced in the EU, is assumed for the bill of materials for cathode, anode, the two current collectors (positive and negative) and the cell casing. In the life cycle inventory, the three leading raw material-supplying countries to the EU are allocated per their percentage share of contribution. As stated above, in a case of lack of data, global data for origins of raw materials is used to depict the EU's supplier. The scope is limited to the extraction phase of the battery materials. Due to the lack of data granularity in the PSILCA database to identify industries for specific materials, intermediate products such as cobalt sulfate and lithium hydroxide are assumed for the EU raw materials market. As there are no specific material sectors in PSILCA, the entire mining and quarrying sector, for instance, is used as a monetary input to represent the economic sectors. All product material inputs of both SIB and LIB, such as nickel sulfate, are considered alongside the process inputs such as sodium hydroxide, sulfuric acid and ammonia used for the precipitation of metal sulfates. Hence, the high total mass (grams) in the total in-flow of materials per the mining/sourcing sectors for each of the battery cells as shown in **Figures 3 and 4** does not refer to the composition of the battery cells, but to the total input of materials required for their production.

Due to the assumptions and corresponding limitations, two different sensitivity analyses (section 5.3) are carried out to evaluate the robustness of the results. These quantify how medium-risk hours vary when changes occur in the corresponding supply chains.

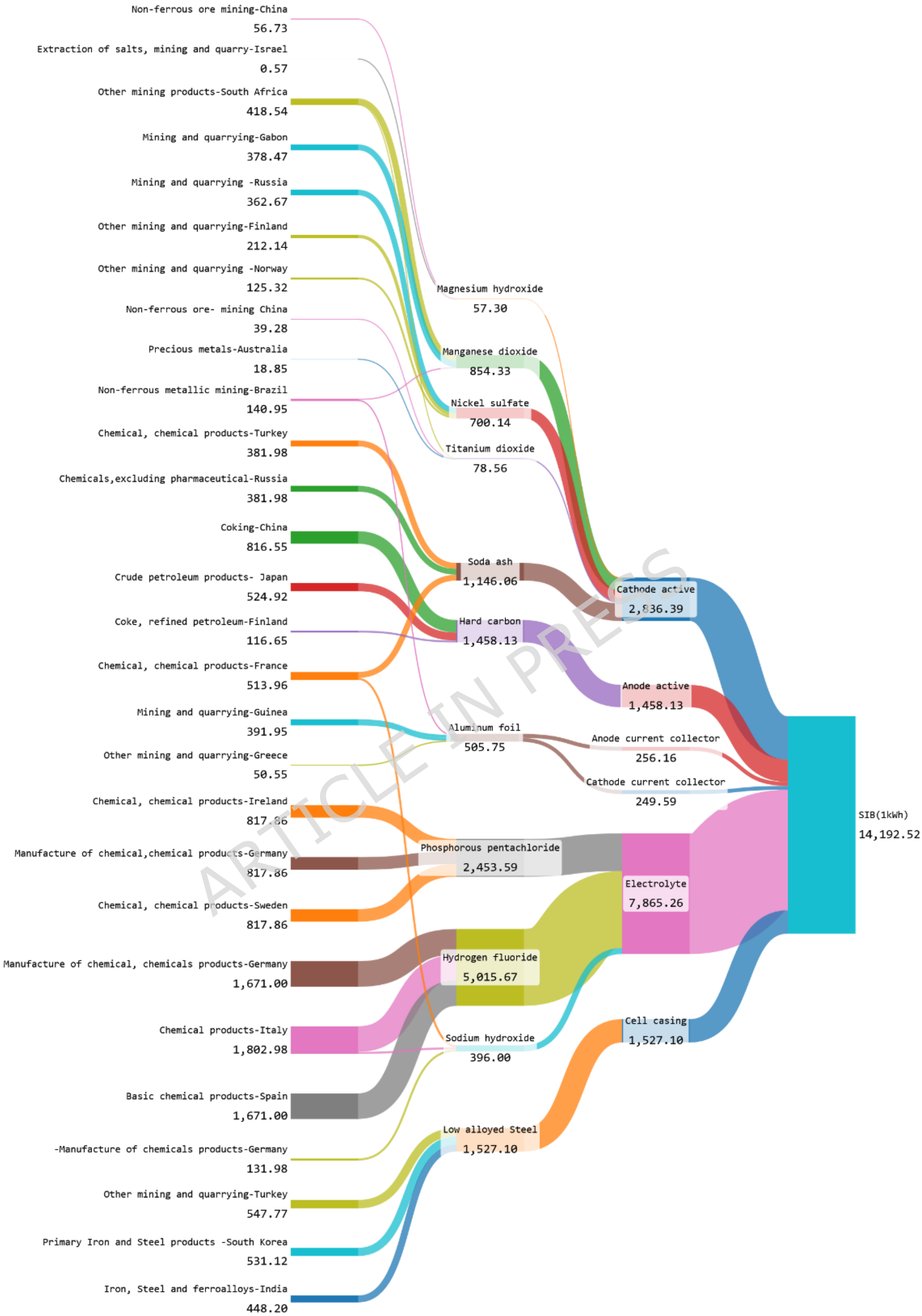


Figure 3: In-flow of materials per the mining sectors grams/ kWh SIB

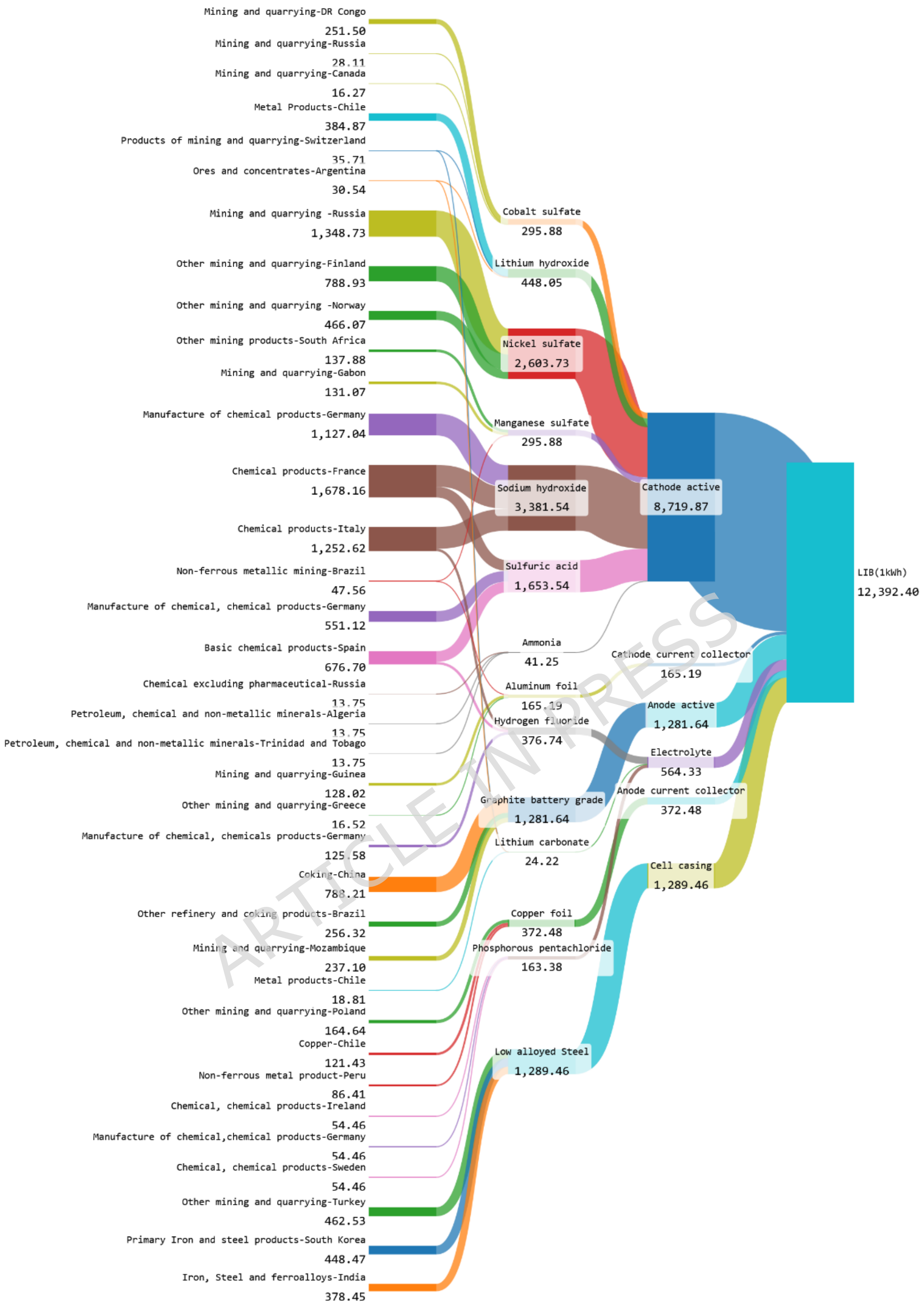


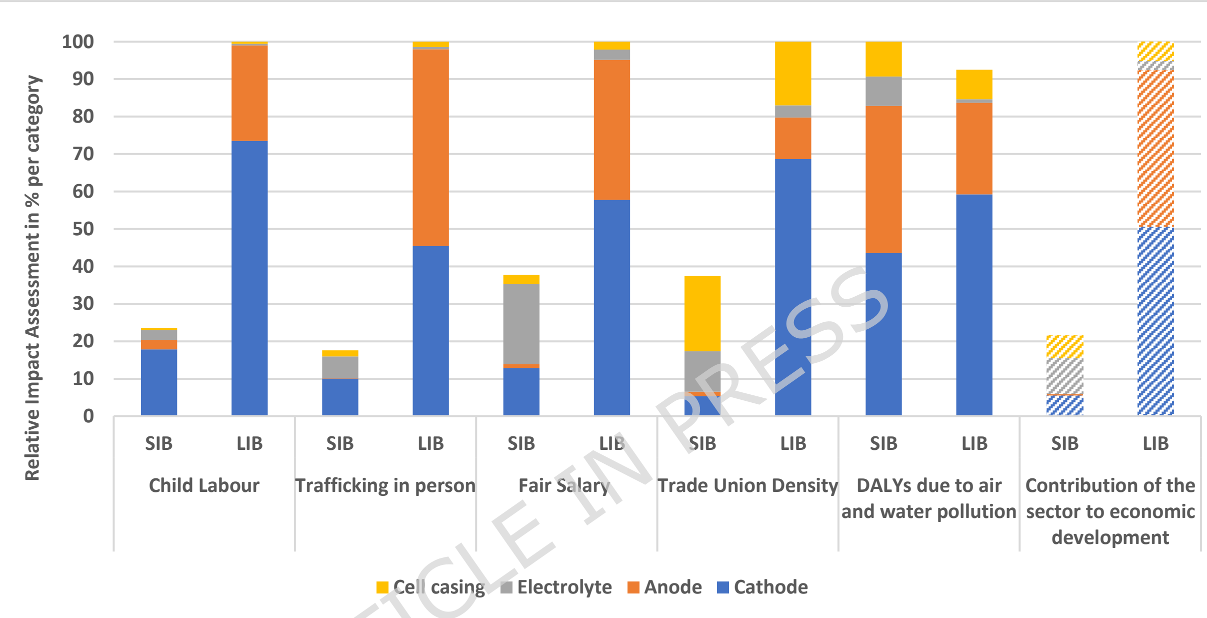
Figure 4: In-flow of materials per the mining sectors gram/ kWh LIB

5. Social impact assessment

5.1 Result overview

In the social impact assessment, the impact categories of child labour, trafficking in persons, fair wages, trade union density, DALY and contribution of the sector to economic development (the only positive indicator) are assessed. **Figure 5** shows the relative impact assessment of both batteries with a breakdown of impacts by component. The results across all the social impact categories (considering all stakeholders) are provided in the SI Table S.1. For the negative categories, it can be seen that SIB has lower social risk values in all the categories except DALY.

Figure 5: Relative social impact assessment results. The results are given in percentages based on medium



risk hours per kWh energy capacity. Contribution of the sector to economic development is hatched to highlight that higher values represent positive contributions rather than social risks.

From **Figure 5,** the category "Fair Salary" has the highest social risk hours for both the SIB (107 mrh) and the LIB (284 mrh), followed by "Trade union density" (SIB = 84 mrh and LIB = 224 mrh). For SIB, these associated social risks are mostly caused by the cathode, anode, and cell casing, whereas for the LIB, the cathode and anode are the main contributors of the impacts. A significant difference is found between SIB and LIB in terms of social risks associated with "Child labour" (SIB = 16 mrh and LIB = 69 mrh) and "trafficking in persons" (SIB = 27 mrh and LIB = 156 mrh), coming mainly from impacts from the LIB cathode and anode.

There is also a slightly higher social risk value in SIB compared to LIB for the category "DALYs due to indoor and outdoor air pollution"(SIB = 4.3 mrh, LIB = 4.0 mrh). The breakdown reveals that for the SIB, both anode and cathode possess higher risks in comparison to the LIB. "Contribution of the sector to economic development" is the only category assessed on a positive scale (pattern filled), thus the higher the value, the greater the potential positive impact on society. SIB displays lower value in this category compared to LIB.

5.2 Geographical analysis

In this section, an in-depth geographical result is shown for each of the impact categories to account for the contribution at country level. Each country is assigned a pattern for better visualisation. The top five contributing countries for each impact category for each technology are displayed, with the remaining countries grouped as "Others".

5.2.1 Child labour

It can be seen from **Figure 5** that the cathode component of the LIB reflects most of the social risk in the category child labour. Geographically, **Figure 6** traces this social risk mainly to the process activities of cobalt sourced from DR Congo with a value of 42 mrh, followed by Mozambique (8 mrh) and China (8 mrh) for LIB. In comparison, SIB has a significantly lower risk of child labour. Likely affected countries shown in this category for SIB are South Africa (7 mrh), Guinea (3 mrh) and Gabon (2 mrh), where titanium, manganese and aluminium are sourced.

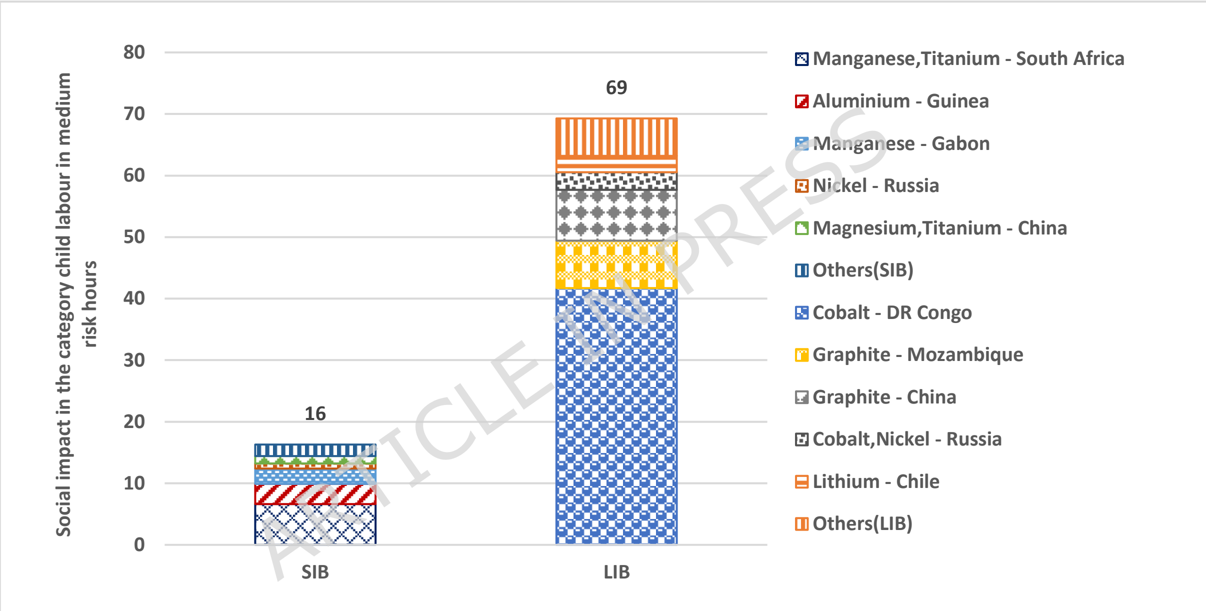


Figure 6: Social impact in the category child labour. Results are given in medium risk hours per kWh energy capacity.

As mentioned before, several studies have identified child labour issues in cobalt mining as a serious problem that occurs predominantly in artisanal mining in the DR Congo.[45,57–61] Our results confirm the existing publications by the JRC repository, which highlight social risks in raw materials supply chains—particularly those associated with severe human rights abuses and child labour in developing countries such as South Africa and the DR Congo.[43] From our analysis results, although SIB performs better, South Africa, Guinea and Gabon show hotspots for child labour and human trafficking issues. Already, several socioeconomic factors such as unemployment, limited livelihood strategies and poverty have been found as key drivers for artisanal mining in South Africa.[62] The US Department of Labor asserts that the Guinean Ministry of Labor fails to enforce child labour laws, and estimates that about 32.3 % of children under the age of 14 work in dangerous sectors like mining.[63] This indicates that the supply chain parts located in South Africa, Guinea and Gabon should be analysed in more detail for corresponding battery raw materials, as this could be a critical area in the evolution of the emerging SIB.

5.2.2 Trafficking in persons

Figure 7 shows the major contributors regarding LIB for the risk of trafficking in persons to be China, DR Congo and Russia, with social risk values of 80 mrh, 41 mrh and 19 mrh respectively, while the major contributors for the SIB are Russia, China and Gabon, with values of 6 mrh, 5 mrh and 2. mrh respectively. Previous studies have indicated that a high portion of the social risk in LIB production stems from graphite extraction linked to China.[47,64]

Notably, China is the world's largest producer of natural graphite and primarily meets its graphite demands through domestic reserves.[65] However, based on highly aggregated data of PSILCA, China potentially carries a high risk of contributing to human trafficking activities.

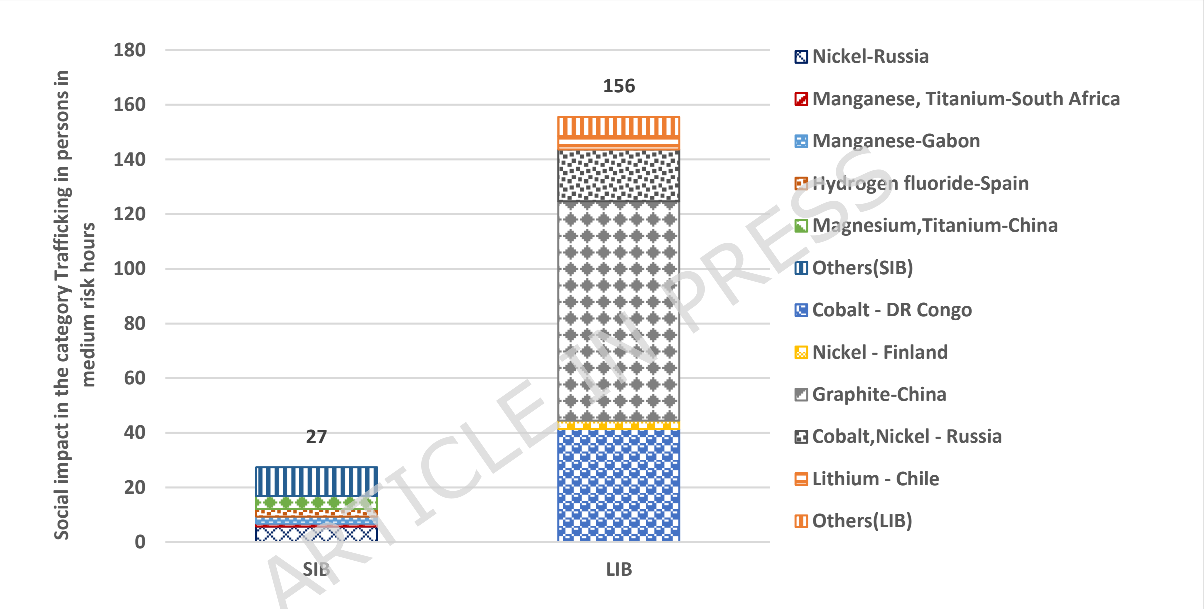


Figure 7: Social impact in the category trafficking in persons. Results are given in medium risk hours per kWh energy capacity.

According to the Global Organised Crime Index (GOCI), China has a criminality score of 6.37/10 (in 2023), and evidence suggests that forced labour and child labour is prevalent across the global LIB technology supply chain, with Chinese suppliers providing materials associated with these practices.[66–68] Here it has to be mentioned that named sources have also been discussed extensively and are viewed as controversial making it hard to verify named claims related to China. However, if valid, it can be recommended that, in addition to the measures implemented by the Chinese government, systematic top-down enforcement strategies should be combined with grassroots organisations' efforts to identify, prevent, and provide comprehensive social protections for both domestic and foreign victims.[69] Meanwhile, DR Congo, with a higher criminality score of 7.75, is a major source of conflict minerals like tin, tungsten, and tantalum, which are often extracted under exploitative conditions. Children are frequently forced to work for armed groups, perpetuating violence and contributing to modern slavery in these areas.[70,71] Both China and DR Congo are identified as potential hotspots for human trafficking risks in the supply chains of various technologies, necessitating enhanced measures to prevent exploitation and safeguard vulnerable populations.

5.2.3 Fair Salary

Fair salary displays the highest medium risk hours of the assessed impact categories for both battery types. **Figure 8** illustrates the risk of non-compliance with fair salary conditions for the worker stakeholder category of SIB and LIB. From the relative results, the cathode and anode are the main contributors for the LIB. As displayed in **Figure 8**, China (83 mrh), DR Congo (44 mrh) and Chile (39 mrh) are the countries with very high-risk values for the LIB technology. Relative to LIB, SIB has lower risk for this category. However, the cathode and electrolyte are the major contributors for SIB and this can be traced back to high amounts of hydrogen fluoride from the chemical industries of Italy (18 mrh), Germany (18 mrh) and Spain (14 mrh) due to the high cost of chemical products assigned in PSILCA. Although hydrogen fluoride is not used directly in cell production, it serves as an intermediate precursor for fluorine-containing materials such as electrolyte salts. hydrogen fluoride is highly corrosive and toxic, requiring strict safety measures and specialised protective equipment during handling. However, the relatively higher impact is arisen from the increase quantity of hydrogen fluoride usage in SIBs.

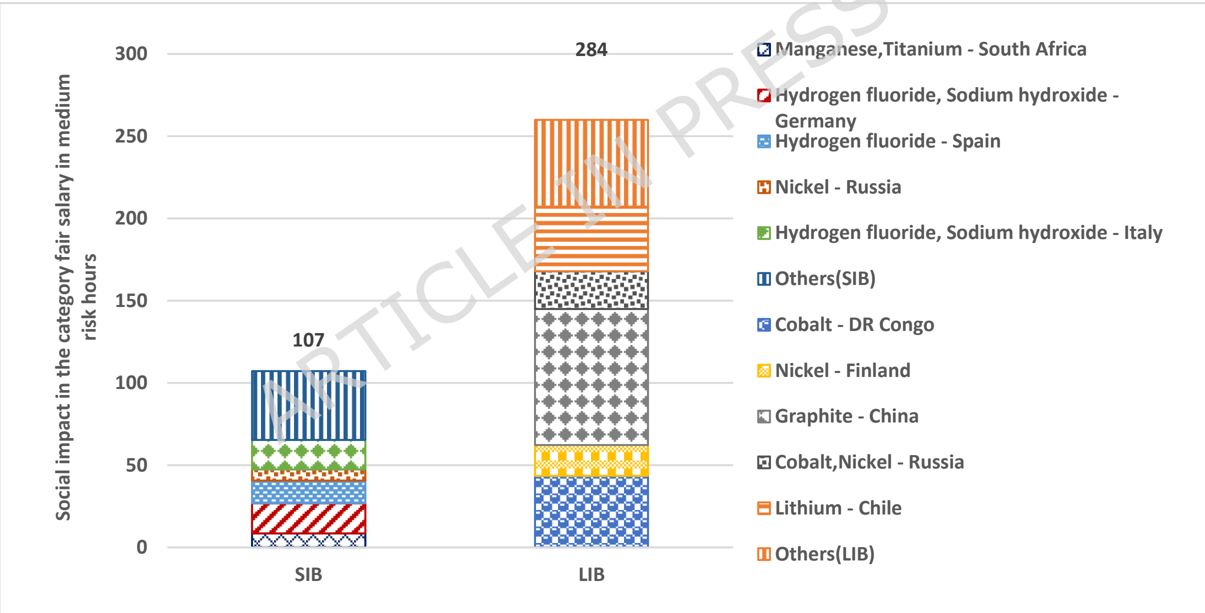


Figure 8: Social impact in the category fair salary. Results are given in medium risk hours per kWh energy capacity.

5.2.4 Trade union density

Figure 9 shows that for trade union density, lithium from Chile poses the highest risk (90 mrh), followed by cobalt from DR Congo (42 mrh) and India (29 mrh) for LIB. For SIB, India (35 mrh), Turkey (9 mrh) and Spain (9 mrh) are the main contributors. It is reported by the International Labour Organization that, although Indian employers' organisations are well-established, there are still major challenges facing trade unions, including the promotion of the right to organise and bargain collectively, gender equality, the lack of social security, and workers' safety and security.[72]

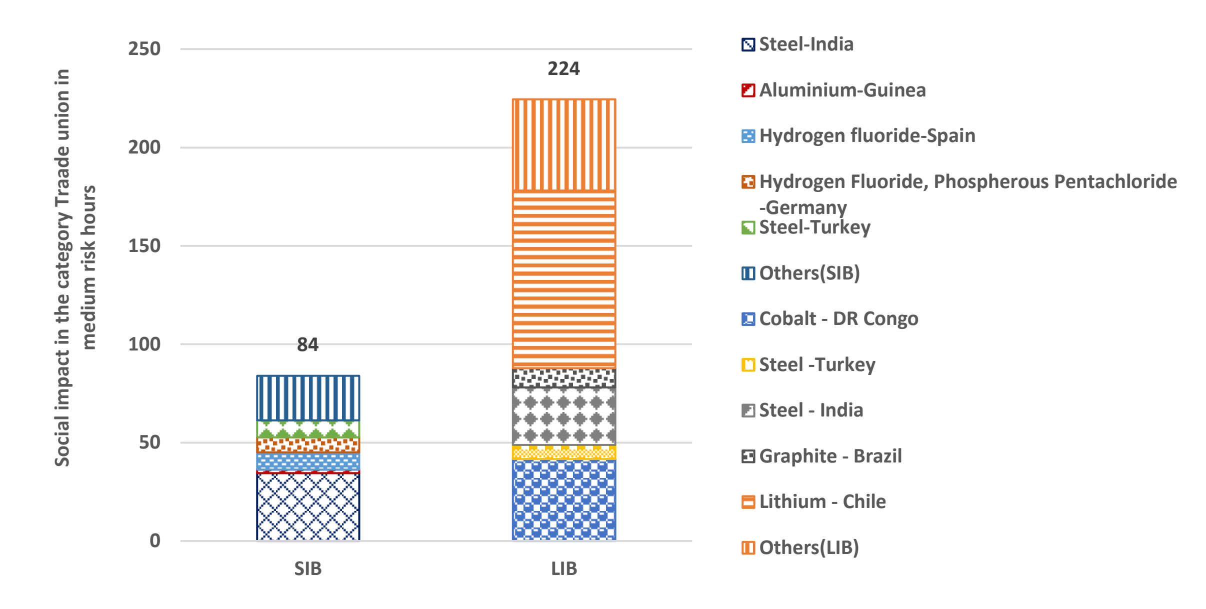


Figure 9: Social impact in the category Trade union density. Results are given in medium risk hours per kWh energy capacity.

Our investigation reveals that Chile is a major contributor to the risks of trade unionism for workers despite ranking as a flourishing economy among the Organisation for Economic Co-operation and Development (OECD) countries. This can be traced to the 1979 Chilean labour legislation, before the democratic era. The Labour Plan restricted creation of association trades unions, restricted collective negotiation processes by workers and allowed for the replacement of workers during a strike.[73] While the trade union density in Chile is currently increasing in the democratic era, the current labour laws are still shaped by the past. Turkey also has a history marked by waves of unauthorised strikes and labour legislation that does not fully align with ILO conventions.[74] Consequently, supply chain compliance issues in the country may have affected the findings of this investigation, leading to Turkey being identified as a potential hotspot for steel sourcing, particularly for LIB and SIB production

5.2.5 DALY due to indoor and outdoor air and water pollution

In the overall comparison between the two battery tapes, displayed in **Figure 5**, SIB shows a better performance for most of the social indicators except for the DALY, due to indoor and outdoor air and water pollution. From **Figure 10**, the main contributing factor can be linked to aluminium sourced from Guinea, as displayed for both SIB (3.4 mrh) and LIB (1.1 mrh). SIB has more social risk because of the higher content of aluminium in both the anode and cathode material, compared to the aluminium content in the LIB cathode only, as the current collector in the anode is made from copper.

A key social issue related to aluminium production is the insufficient implementation of health and safety measures for workers.[75] The operation of heavy machinery, which generates significant air pollution, has been found to adversely affect the environment in Guinea, particularly in regions where bauxite is extracted and processed into aluminium.[76] One study indicates that farmers in the Boké region of Guinea, a major bauxite mining area, face substantial health and social risks due to the unregulated nature of these activities.[76] These risks contribute to a higher potential health burden for mine workers, likely driven by the ineffective management of red mud, a hazardous by-product of aluminium refining. If bauxite extraction and aluminium production were confined to the EU, where more stringent labour and environmental regulations exist, then the DALY associated with these processes could be significantly reduced.

In addition, graphite mining and processing also may pose substantial occupational health risks. [77,78] The extraction and processing stages generate large quantities of dust, which are difficult to contain and control. Prolonged exposure to this dust can lead to serious respiratory problems for workers and surrounding communities. These risks are intensified in regions where workplace safety regulations are weak or poorly enforced, further compounding the social impacts of graphite production within the battery supply chain.

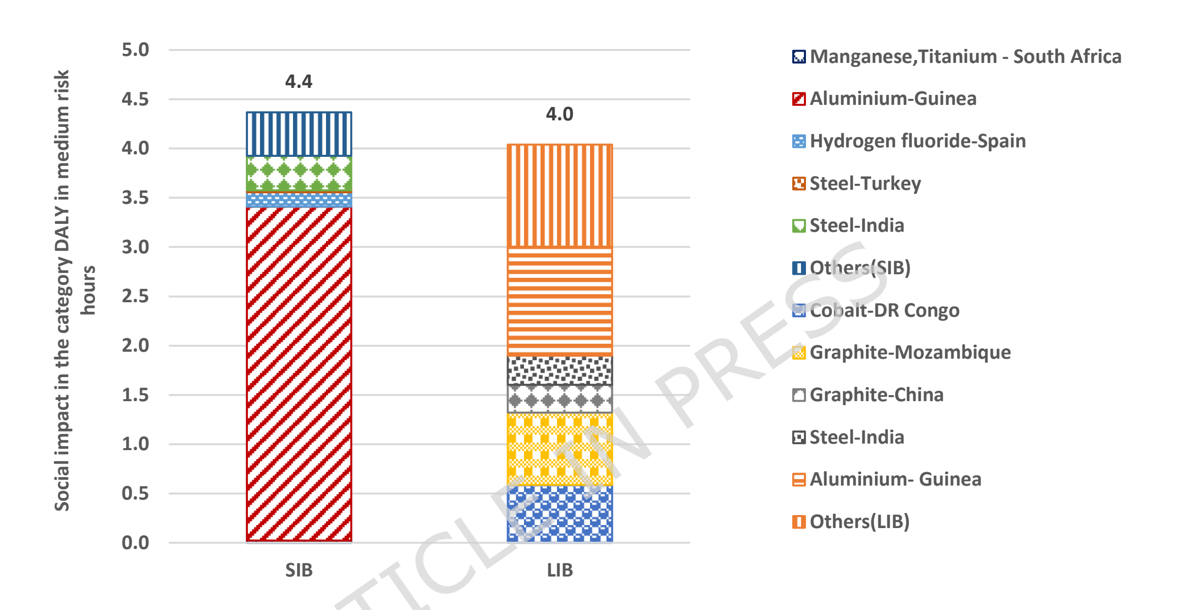


Figure 10: Social impact in the category DALY. Results are given in medium risk hours per kWh energy capacity.

5.2.6 Contribution of the sector to economic development

In the analysis for both SIB and LIB, the opportunity level for a positive impact is very small. Although the LIB performs better in this category than SIB, both technologies are marginally affected in terms of their opportunity to affect changes in the GDP of the respective countries. This is seen independently from their respective market presence, as this assessment is of attributional and not consequential nature. The major country contributors for this category for LIB are China, Chile, DR Congo, Argentina and Russia, while SIB includes India, Russia, Spain and South Africa, as shown in **Figure 11**. In recent developments, the mining sectors' contribution to the GDP of Chile, China, Russia and DR Congo show significant growth. In Chile, for example, the mining sector contributed 13.6% to the country's GDP in 2022.[79] This is even more promising under the new Mining Royalty Law passed in 2024, because

Chile's mining royalties will be used to improve the quality of life of its citizens and provide more funds for municipalities.[80]

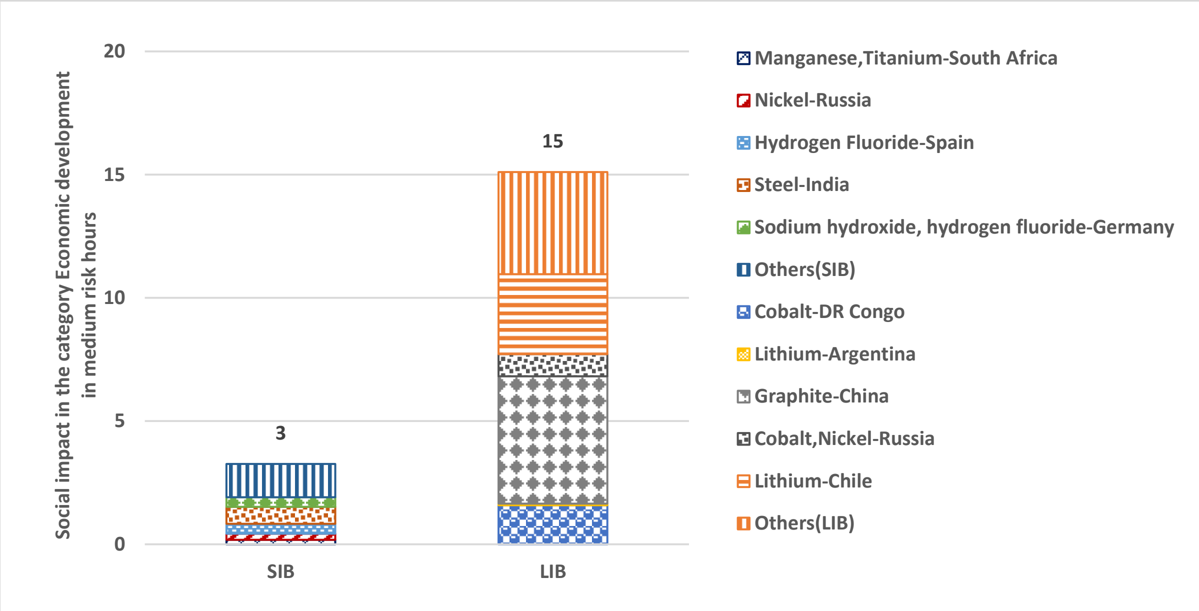


Figure 11: Social impact in the category economic development. Results are given in medium risk hours per kWh energy capacity.

5.3 Sensitivity Analysis

5.3.1 Impact of change in sourcing countries on social risk

Based on the assessed indicators, SIB displays greater medium risk hours for DALY due to indoor and outdoor air and water pollution, a factor heavily influenced by the use of aluminium in the cathode and anode current collectors. Aluminium from Guinea accounts significantly in the DALY category **(see Figure 10).** By exploring a scenario where instead of using global suppliers (Base-case), aluminium foil is sourced 100% from a supplier within Europe, in Greece (SIB-Al-Greece), the sensitivity analysis (**Figure 12)** shows a decrease in the risk for DALY for SIB-Al-Greece by around 77 %, mainly due to the absence of the mining sector in Guinea. The same reduction for LIB is at around 27%, which is significantly lower due to the lower amount of aluminium used in LIBs.

Several factors contribute to this result, including the regional social conditions of the involved countries. In developed European countries like Greece, better working conditions and labour regulations result in lower health risks, which is reflected in PSILCA's low-risk rating for Greece in the mining sector. This is likely due to the country's strong occupational health and safety framework, which is harmonised with EU standards.[81] Greece has established institutions and legal measures since the 19th century to exploit national mineral deposits while also protecting mine workers.[82] Data from the Greek Mining Enterprise Association (2010-2021) and interviews with health and safety managers in the sector highlight a commitment to worker safety and adherence to best practices.[83] The industry has implemented extensive health and safety training programs to improve the protection and wellbeing of miners. In contrast, artisanal mining workers face much higher health risks, with artisanal small mining having a health impact of 0.014 DALY/kg of cobalt, while large scale mining is below 0.0001 DALY/kg.[84] Since artisanal mining is prevalent in low- and middle-income countries like Guinea,[85] this may explain the higher risk of DALY observed in our study.

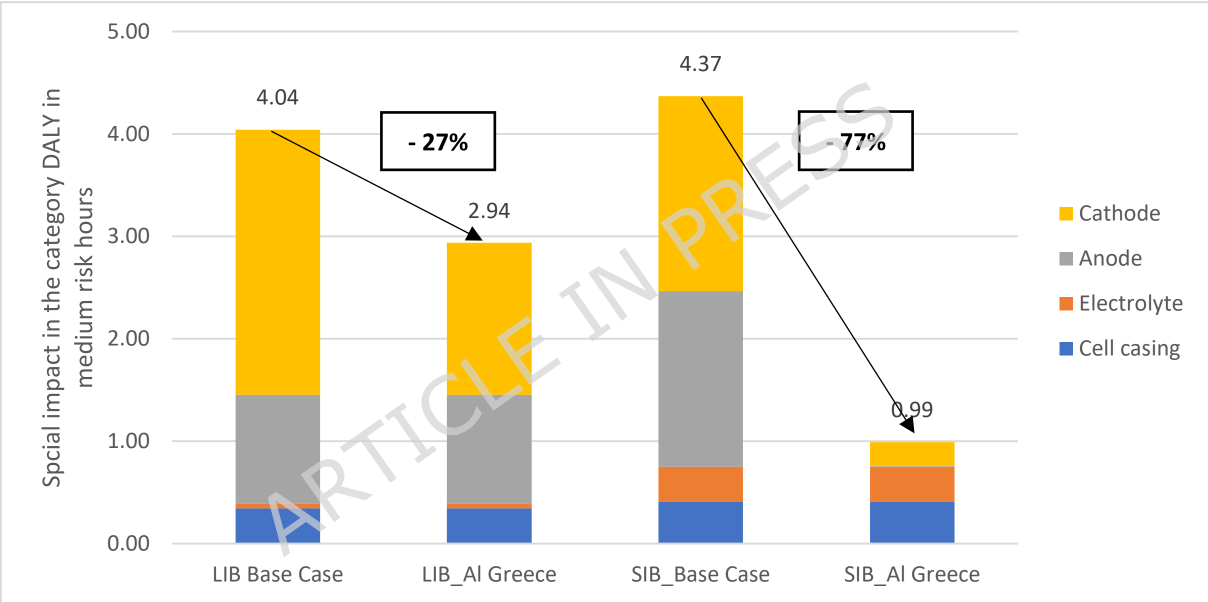


Figure 12: Social impact in the category DALY considering different sourcing countries for Al as current collectors. Results are given in medium risk hours per kWh energy capacity.

5.3.2 Impact of change in price on social risks

Second, the effects of price volatility are assessed, particularly in the context of the boom-and-bust cycles of the mineral sector, with a specific focus on cobalt. The price is an important factor in the social impact assessment, as it is used as a proxy for the value added, which in turn is used for determining the working hours. The baseline scenario considered an average cobalt price of USD 8,653 per tonne between 2021 and 2024. However, in light of a significant market downturn, the low-price scenario incorporates an updated 2024 average price of USD 3,614 per tonne. This leads to a 60% reduction in the impacts in the category child labour in DR Congo, leading to an overall reduction in this category of around 39%, as shown in **Figure 13**. Hence, fluctuations in mineral prices can significantly influence S-LCA results when monetary values are used as the reference flow. This confirms findings from other studies,[47,86,87] which indicate that a decrease in price can reduce the calculated social risks. Importantly, while the actual risk level of child labour may not vary directly with price changes, model outcomes are nonetheless affected due to the use of monetary-based flows in S-LCA databases. This highlights a critical limitation of applying monetary values in sectors characterised by high price volatility, and underscores the necessity of conducting sensitivity analyses to ensure robust and reliable interpretations.

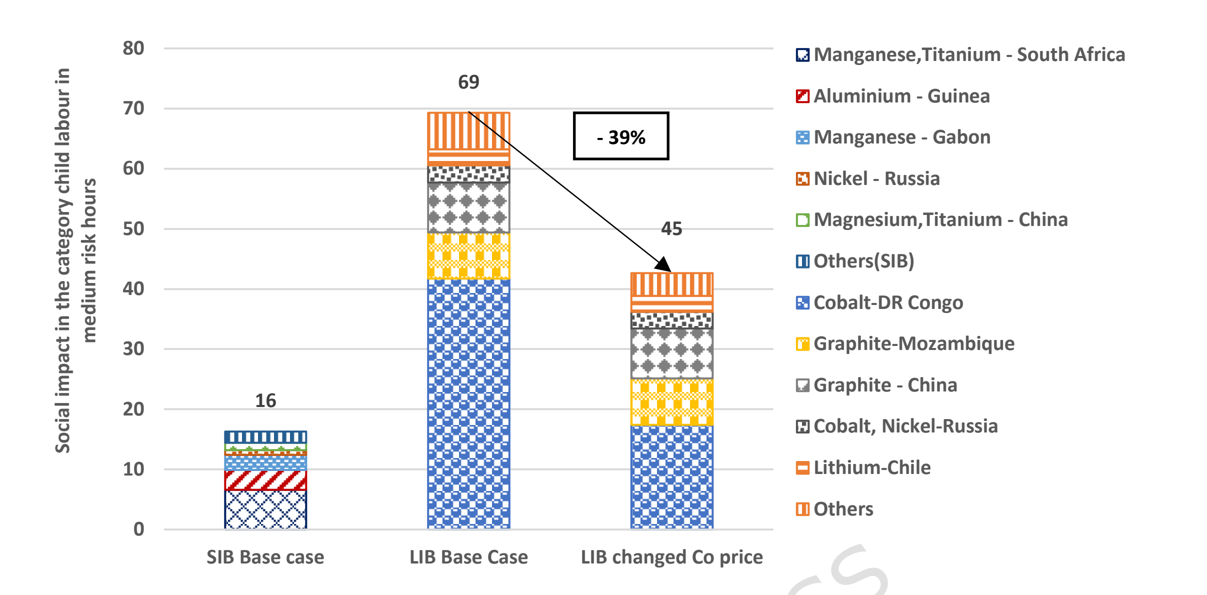


Figure 13: Social impact in the category child labour considering different co prices. Results are given in medium risk hours per kWh energy capacity.

6. Discussion

6.1 Reflection on Social-LCA method

Social impacts arise from societal pressures, which can be either positive or negative, and unlike many environmental or physical processes they do not adhere to natural laws. These impacts are driven by changes in human behaviour, socio-economic dynamics, and the broader context of human, cultural, and political capital, creating a complex and dynamic value chain that is difficult to quantify. This complexity highlights the challenges in measuring and addressing social impacts effectively across the supply chain, making the selection of social indicators a delicate task. Within PSILCA, there are so far about 70 qualitative and quantitative indicators, with only one positive impact category, and as a result, not all global issues can be addressed by the S-LCA methodology.

The PSILCA database faces challenges due to the lack of data granularity, as it relies on aggregated country-specific sector data which provides a general analysis of potential social impact hotspots. The input data from its so-called harmonised sectors still lacks detail, and most of the data gaps are filled by regional mapping or taking data from similar sectors. This approach links processes to country-specific sectors rather than to individual materials, resulting in social impact assessments that reflect the conditions of the entire mining sector in a country rather than for specific materials. For example, the entire mining and quarrying industry in DR Congo is used as a representation for cobalt, but other minerals are mined, including gold and bauxite, that may have different social conditions. The same comes true for graphite mining in China. Hence, the results of this S-LCA may not accurately reflect the social risks of using only cobalt as a material, and further investigation would be needed to supplement PSILCA's background data. It further needs to be stated that the version 3 of PSILCA was developed in 2020, however, it represents the newest available database for the analysis. To address these issues, improvements in data collection and evaluation in S-LCA databases like PSILCA are needed to provide more detailed, material-specific data that better captures regional and sectoral differences, as well as regular database updates..[88]

PSILCA relies on monetary values of products as input flows, making the model highly sensitive to market price fluctuations. This reliance can be problematic, as it implies that the more expensive a product, the higher working hours and, consequently, the higher social risks regardless of changes in physical quantities. For instance, the sensitivity analysis showed a reduction in cobalt price led to reduced social risks of child labour, even when the actual mass or volume of cobalt used remains constant. The key limitation of using monetary values as a reference flow is that market prices are influenced by multiple external factors beyond labour costs. These include supply and demand fluctuations, energy prices, geopolitical instability, natural disasters, global economic conditions, market speculation, and trade restrictions. As a result, sectors like the mining sector characterised by high price volatility, such as those involving CRMs pose particular challenges for consistent and reliable S-LCA outcomes. Therefore, interpreting social impacts using PSILCA in such contexts requires caution, as temporal price variations can significantly distort the assessment results.[86] Moreover, PSILCA cannot distinguish the underlying context behind child-labour statistics. For example, in some mining regions, children may be present at mining sites without formally engaging in labour activities, while in other cases informal or undocumented child labour may not be captured in official statistics. Because PSILCA relies on aggregated country-sector data expressed in monetary values, such nuances cannot be interpreted, and the model may either overestimate or underestimate actual child-labour risks.

Transparency in S-LCA results is crucial for addressing the sensitive nature of many social issues, which often carry political undertones.[89] Social issues such as human rights and labour conditions can have political implications and can be interpreted differently depending on the socio-political context rather than purely scientific criteria. This can be seen for studies and reports that have been discussed in a controversial way.[66–68] In any case, contrasting controversial studies with the results of an aggregated database like PSILCA can help to understand potential gaps and hotspots in battery value chains. In the end, it is hardly possible to validate claims without on-site data or the possibility of interviewing affected groups of workers or residents directly. However, transparent reporting of S-LCA results not only enhances the credibility of the assessment but also facilitates open discussion and critique. This, in turn, fosters a better understanding of the social impacts and creates opportunities to address potential biases or misinterpretations. This approach involves comprehensively evaluating both qualitative and quantitative social impacts on stakeholders across the product supply chain lifecycle. By safeguarding transparency, the credibility and integrity of S-LCA findings are strengthened, thereby promoting more informed and objective decision-making based on the integrity and reliability of the social findings.

This research focuses on the potential social impacts during the extraction phase of the battery supply chain, specifically by assessing the social footprints of raw materials. Expanding the system boundary in future studies to include intermediate production, manufacturing, transportation, and recycling phases could provide further valuable insights. To gain a more complete understanding, future research should also consider the effects on additional stakeholders. For a comprehensive sustainability assessment, future work should integrate social, environmental, and economic aspects.

6.2 Takeaways

The results indicate that a SIB, here a NaMMT, has a lower risk of social hotspots than the selected NMC811 LIB in the assessed categories using the very aggregated database and secondary data. Based on 1 kWh of storage capacity, the SIB seems to have a lower potential social impact for risks of child labour, trafficking in persons, trade union density and fair salary as compared to NMC811. The highest potential impact for both assessed battery types are shown in the category fair salary. This may be because a deficit in this category is considered less serious than in categories such as child labour. Consequently, less effort is made to eliminate it, potentially leading to higher risks. However, direct comparisons of medium-risk hours across different indicators are not recommended, as PSILCA employs distinct social impact assessments and reference scales for various indicators.[90] These results are context-dependent and are influenced by various factors like battery chemistry, material prices, and the mining conditions in the countries involved. Since battery energy density is a key parameter associated with environmental impacts, increasing the energy density minimises the environmental impact due to lower material demand.[32] This can also affect the outcomes of S-LCA. If less material is used, then prices may decrease, which could influence perceived social risks, as the PSILCA model uses prices to assess these risks. Therefore, changes in material demand and prices can either raise or lower reported social risks in the supply chain. Consequently, assessments can be prone to high uncertainty due to the varying market prices of the materials used.

The analysis identifies trade union density and DALY as potential high-risk social impacts for the sodium-ion technology by dint of materials imported from countries such as India, Turkey, South Africa and Guinea. The SIB also displays a significantly lower risk of child labour than LIB. However, companies importing raw materials from Guinea, South Africa, and Gabon should be aware of these issues, as they could become potential social impact hotspots since these countries already struggle with such issues on a minor scale. For instance, despite increasing governmental efforts to enhance anti-trafficking capacity, the Verité Trafficking in Persons Report highlights the persistence of trafficking risks within certain supply chains, including the mining sector in Guinea.[91] The report estimates that 32.3% of children under the age of 14 are currently engaged in labour, with a significant proportion working in hazardous sectors like mining. This points out the continued challenges in addressing child labour and trafficking, particularly in such high-risk industries, and indicates a need for strengthened interventions and enforcement to mitigate exploitation and protection of children in the corresponding sectors.

Due to a higher aluminium demand, partially met from Guinea, the SIB has a worse DALY performance compared to LIB. This is in line with a recent study that also identified the most social impact hotspots within the automotive industry in the Guinean aluminium supply chain.[92] As the current alumina-industry process suffers from the difficulty of mineral sorting and an economical use of the red mud complex structure,[93] finding and establishing efficient technologies for a sustainable environmental treatment of red mud could serve as a breakthrough for the aluminium supply chain. It follows, therefore, that if not properly addressed, the resulting environmental damage caused by bauxite extraction for aluminium can lead to both severe environmental consequences, as well as social and health problems, not only for the workers but also for the local inhabitants. However, this is also true at a lower magnitude for the LIB, where aluminium is used in the current collector. In light of the physically strenuous and dangerous working conditions these countries already face, the literature indicates that their mining industries do not meet significant sustainability goals.[94–96] They also fail to meet social and labour plan targets and create unsanitary working conditions which threaten their workers' health and safety.

The sensitivity analysis underscores the importance of sourcing materials such as aluminium from regions with stronger labour protections, as these areas generally rank lower in the PSILCA database, indicating reduced social risks. This highlights the potential benefits of prioritising materials from jurisdictions with robust labour standards. However, it remains equally critical to strengthen and enforce labour regulations at both regional and international levels––particularly in developing countries, where a significant portion of raw materials are extracted. Enhancing compliance with improved labour standards in these regions can foster better working conditions without compromising the economic contributions of mining activities. In some cases, continuing mining operations under improved labour conditions may result in more favourable socio-economic outcomes than halting operations entirely, given their role in supporting economic growth and sustaining local livelihoods.[97] While the analysis suggests that switching to suppliers from low-risk regions may help mitigate social risks, it is essential to approach this transition carefully. New suppliers may carry their own labour-related challenges.

An ideal model is the establishment of socially responsible mining operations in developing countries. Such a model would allow us to meet global demand for resources and support the UN Sustainable Development Goals by providing access to quality education, and good conditions and healthcare systems for the workers and the local communities at large. However, in practice mines are mostly operated by private companies from foreign countries, detached from local communities.[98] Therefore, there is a need for regulation at the EU level to ensure that companies, regardless of origin, adhere to high social and environmental standards. With respect to both SIB and LIB technologies, policies should bolster regional sourcing (e.g., lithium from the Rhine Valley, Germany) and strengthen requirements for traceability and accountability across the upstream supply chain. Companies should not only disclose the origin of their raw materials but also provide evidence that these materials meet established labour and social responsibility standards. This practice is central to fulfilling due diligence requirements and fostering sustainable sourcing in producer countries. Although our S-LCA results may not capture the precise local realities, they provide a valuable indication of potential social risks and burdens, offering a foundation for more targeted research and policy development.

SIBs, while gaining substantial momentum in the market and holding high potential in decarbonising both the electric mobility and stationary sectors, may bring some risks related to DALY, child- and forced labour, fair wages, trade union density, and human trafficking. Some of these social issues are already highlighted [99], are independent of technology features, and are shaped primarily by the policies and practices of mining companies. Thus, the performance of companies in addressing these social concerns will significantly influence the overall impact of the supply chain. Building up mining capacities for enabling technologies like SIBs is fraught with uncertainty due to the complex interplay of technological, social, economic, and environmental factors. Moreover, value chains for SIB production are not established on a large scale and can look very different to the assumptions made in this study. Additionally, raw material prices (which are based on a time frame), are difficult to predict, can impact the results strongly, and relate to both SIB and LIB.

The "contribution of the sector to economic development" is primarily based on the mining sector's impact on the overall GDP of countries. However, this does not provide much insight into the potential opportunities for the development of the two specific technologies of LIB and SIB. Despite LIB's better performance in this positive impact category, both technologies present very low opportunity values for economic growth compared with the negative social risks. This shows an imbalance between economic income and social burdens. It also reveals how most of the social burdens are borne by developing economies, yet with lower economic benefits.[41] Further studies illustrate that the negative impact of mining dwarfs the positive one, resulting in a slowdown in the progress of the Sustainable Development Goals on the African continent.[100]

This study constitutes an initial effort to address the often-overlooked social impacts of raw material extraction for battery production. It aims to promote a more sustainable supply chain that considers the working conditions of front-line labourers, who bear the social consequences of mining activities. In the context of sustainability initiatives, such as the EU Green Deal, it is pertinent that policymakers, Original Equipment Manufacturers (OEMs), and other stakeholders recognise and uphold the critical role of the working class in the raw material supply chain. Several regulatory frameworks, including the EU Supply Chain Due Diligence Directive, are already under development, requiring companies to prevent adverse environmental and human rights practices within their supply chains. It is hoped that the results will inform automobile and battery manufacturers as a procurement guideline for raw material sourcing, as well as for recognising social sustainability issues and the potential consequences of their choices of raw materials used for production. Exposing the grassroot problems can enable concerned institutions to know specifically which issues can be resolved by setting stricter regulations in the supply chains of these raw materials. Banning imports from already weak economies such as DR Congo and Guinea may further impair such economies. Instead, maybe aiding the facilitation of modernised waste management systems could be an option. In this way, the health risks to workers and local communities can be addressed directly. Summary of all the policy recommendations are given in the Table 4.

Table 4: Summary of policy recommendation for battery supply chains considering social aspects

Stakeholder Group	Key Risk Identified	Recommended Action
Policymakers	High social risks in mining regions (child labour, DALY, trafficking)	Strengthen due-diligence and traceability requirements for imported raw materials.
	Weak labour protections in supplier countries	Support international cooperation to improve labour standards and enforcement.
	Impacts from aluminium/bauxite supply chains	Promote cleaner extraction technologies and require environmental compliance.
Battery Manufacturers / OEMs	Exposure to high-risk materials (Co, Ni, Mn; Al for SIBs)	Prioritise sourcing from low-risk regions and certified responsible mining operators.
	Price-driven social risk fluctuations (PSILCA sensitivity)	Use long-term contracts with verified suppliers rather than spot-market sourcing.
	Uncertain SIB value chains	Integrate S-LCA in material selection and early design decisions.
Raw-Material Suppliers	Unsafe labour conditions and weak H&S performance	Comply with ILO standards and improve on-site worker protections.
	Limited transparency	Publish audited ESG data and join responsible mining initiatives.
All Stakeholders	Social risks concentrated upstream	Improve data quality and support development of material-specific S-LCA datasets.

7. Conclusion

This study utilises the Social Life Cycle Assessment methodology to evaluate the social impacts of emerging SIB technology (considered NaMMT), in comparison to LIB (considered NMC 811) technology, focusing specifically on the raw material extraction phase. It takes a first step to address a gap in the existing literature, which has primarily concentrated on the environmental and technological development of emerging SIB technologies, overlooking their possible social hot spots. The assessment considers the social categories of child labour, fair wages, trade unionism, trafficking in persons, disability-adjusted life years (DALY), and the contribution of the sector to economic development. While LIBs perform slightly better in the DALY, SIBs generally show lower risk values in the assessed categories, mainly due to the absence of raw materials like cobalt and lithium, which are linked to countries such as DR Congo and Chile. Based on 1 kWh of storage capacity, SIBs appear to have a lower risk for child labour, human trafficking, trade unionism, and fair wages. Potential hotspots for NaMMT include India, Turkey, China, Guinea, and South Africa due to the sourcing of materials such as steel, manganese, titanium, and aluminium. In contrast, hotspots for LIBs include DR Congo, Guinea, China, Chile, Mozambique, and India, driven by the sourcing of materials such as cobalt, lithium, steel, graphite, and aluminium. While the social risk values associated with SIBs are generally lower than LIBs, targeted interventions are still necessary to mitigate social impacts and ensure a socially responsible raw material supply chain for SIB technology. Stronger compliance measures and regulatory frameworks are needed to anticipate and address these risks, ensuring that SIBs do not simply shift the social burden to new suppliers like Guinea and South Africa. By doing so, emerging technologies can avoid transferring risks along global supply chains and instead contribute to reducing unintended social vulnerabilities. The findings from this study should be interpreted with caution, because only the top three importing countries for a raw material are considered, and the results are not representative for any specific activity, company or mine, but represent a sectorial approach. Additionally, the low data granularity for some mining countries within the PSILCA database needs to be considered, which hinders in many cases a raw material-specific evaluation. Still, despite the current limitations of the database, it enables an initial screening analysis, important for identifying hotspots and the relation to the origin countries of the raw material. This investigation can serve as a base for a more detailed study, which is potentially real battery producer-oriented (with the specific raw material sources).

In conclusion, the extractive mining industry is fundamental to the supply chain of green energy technologies, yet developing countries often disproportionately bear the associated social and environmental burdens with limited economic benefit. As SIBs are expected to play a pivotal role in the energy transition, both stationary and e-mobility, it is crucial to conduct further studies on the socio-ecological impacts of their production, to guide these further developments. These studies must consider local and global social and environmental effects, and guide the development of robust policies to ensure that the energy transition, supported by SIB technology, is equitable and sustainable. Rigorous supply chain due diligence, coupled with comprehensive Social Life Cycle Assessment, is essential to identify and mitigate social challenges and to promote corporate social responsibility. By integrating social, environmental, and economic assessments, decision-makers can foster the development of future battery technologies that are not only economically viable and environmentally sustainable, but also socially just. In the long term, SIB offer significant sustainability potential, particularly due to the use of abundant raw materials that avoid traditional mining practices. Their successful integration into the global energy transition will depend on the continued adoption of production practices, technological innovation, and sustainable resource extraction processes, ultimately positioning SIB as a key component of a more sustainable energy storage future.

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Author Contributions

Writing – original draft, Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization: BRH, FJ, DSP, MB, JP, MW. Supervision: MB, JP, MW.

Data Availability

All data generated or analysed during this study are included in the manuscript, or the supplementary information.

Declarations

Conflict of Interest

The authors declare no conflict of interest.

Consent for publication

Not applicable

Ethics approval and consent to participate

We confirm that all research was performed following relevant guidelines and regulations

Clinical Trial number

Not applicable

Declaration of Generative AI and AI-assisted technologies in the writing process

In the preparation of this manuscript, the author(s) utilized ChatGPT to assist in enhancing language clarity and readability. The author(s) thoroughly reviewed and revised the content as required and assume full responsibility for the accuracy and integrity of the final manuscript.

References

[1] S. Luckeneder, S. Giljum, A. Schaffartzik, V. Maus, M. Tost, *Surge in global metal mining threatens vulnerable ecosystems*, **2021**.

[2] C. Zinsius, *Resource use and its consequences*, Umweltbundesamt, **2019**.

[3] E. Berthet, J. Lavalley, C. Anquetil-Deck, F. Ballesteros, K. Stadler, U. Soytas, M. Hauschild, A. Laurent, *Assessing the social and environmental impacts of critical mineral supply chains for the energy transition in Europe*, **2024**.

[4] E. Smith, P. Rosenblum, *Government and Citizen Oversight of Mining_Enforcing the Rules*, Revenue Watch Institute, **2011**.

[5] M. Onifade, T. Zvarivadza, J. A. Adebisi, K. O. Said, O. Dayo-Olupona, A. I. Lawal, M. Khandelwal, *Advancing toward sustainability: The emergence of green mining technologies and practices*, **2024**.

[6] L. Mancini, S. Sala, *Social impact assessment in the mining sector: Review and comparison of indicators frameworks*, **2018**.

[7] F. W. Schwartz, S. Lee, T. H. Darrah, *A Review of the Scope of Artisanal and Small-Scale Mining Worldwide, Poverty, and the Associated Health Impacts*, **2021**.

[8] Child labour in mining and global supply chains | International Labour Organization, **2019**.

[9] C. Banza Lubaba Nkulu, L. Casas, V. Haufroid, T. De Putter, N. D. Saenen, T. Kayembe-Kitenge, P. Musa Obadia, D. Kyanika Wa Mukoma, J.-M. Lunda Ilunga, T. S. Nawrot, O. Luboya Numbi, E. Smolders, B. Nemery, *Nat Sustain* **2018**, *1*, 495.

[10] A. Kelly, *Apple and Google named in US lawsuit over Congolese child cobalt mining deaths*, **2019**.

[11] M. M. Mashfy, T. A. Alvy, N. Hossain, M. A. Haque, F. T. Mohsin, T. Sharmin, M. Nasim, *Next Energy* **2026**, *10*, 100478.

[12] M. Baumann, M. Häringer, M. Schmidt, L. Schneider, J. F. Peters, W. Bauer, J. R. Binder, M. Weil, *Prospective Sustainability Screening of Sodium-Ion Battery Cathode Materials*, **2022**.

[13] F. B. Jasper, M. J. Baumann, H. Ersoy, A. Smith, S. Büchele, N. Bohn, J. R. Binder, D. H. Neuhaus, M. Weil, *ChemSusChem* **2025**, *18*, e202500268.

[14] Q. Li, U. Ulissi, Z. Liang, X. Chen, B. Guo, X. Zhang, C. Ouyang, *Advanced Energy Materials* **2025**, e04877.

[15] R. Sun, Y. You, *ACS Appl. Mater. Interfaces* **2023**, *15*, 44599.

[16] A. Nekahi, M. Dorri, M. Rezaei, M. D. Bouguern, A. K. Madikere Raghunatha Reddy, X. Li, S. Deng, K. Zaghib, *Comparative Issues of Metal-Ion Batteries toward Sustainable Energy Storage: Lithium vs. Sodium*, Multidisciplinary Digital Publishing Institute, **2024**.

[17] C. Pegard, *Tiamat: revolutionizing the electric mobility landscape*, **2024**.

[18] New sodium-ion developments from CATL, BYD, Huawei, **2024**.

[19] M. Baumann, M. Häringer, M. Schmidt, L. Schneider, J. F. Peters, W. Bauer, J. R. Binder, M. Weil, *Prospective Sustainability Screening of Sodium-Ion Battery Cathode Materials*, **2022**.

[20] J. Peters, D. Buchholz, S. Passerini, M. Weil, *Life cycle assessment of sodium-ion batteries*, The Royal Society of Chemistry, **2016**.

[21] B. Song, Y. Cheng, G. Zhao, K. Jia, Q. Shi, X. Li, Z. Wang, Y. Zhou, G. Zou, X. Ji, *Adv Funct Materials* **2025**, e10872.

[22] Z. Cui, C. Liu, A. Manthiram, *Advanced Materials* **2025**, *37*, 2420463.

[23] E. D. Spoerke, V. Durvasulu, H. Balliet, *Technology Strategy Assessment - Sodium Batteries*, **2023**, p. 25.

[24] P. Voß, B. Gruber, M. Mitterfellner, J.-D. Plöpst, F. Degen, R. Schmuch, S. Lux, *Energy Environ. Sci.* **2025**, *18*, 8104.

[25] A. Rehman, S. Saleem, S. Ali, S. M. Abbas, M. Choi, W. Choi, *Energy Mater* **2024**, *4*.

[26] S. Roberts, E. Kendrick, *NSA* **2018**, *Volume 11*, 23.

[27] ISO 14075:2024(en), Environmental management — Principles and framework for social life cycle assessment, .

[28] ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework, **2006**.

[29] Guidelines for Social Life Cycle Assessment of Products and Organisations 2020 - Life Cycle Initiative, **2020**.
[30] U. N. Environment, *Guidelines for social life cycle assessment of products | UNEP - UN Environment Programme*, **2009**.
[31] K. Maister, C. Di Noi, M. Srocka, *PSILCA v.3 Database documentation*, **2020**.
[32] J. F. Peters, M. Baumann, J. R. Binder, M. Weil, *On the environmental competitiveness of sodium-ion batteries under a full life cycle perspective – a cell-chemistry specific modelling approach*, The Royal Society of Chemistry, **2021**.
[33] S. Wickerts, R. Arvidsson, A. Nordelöf, M. Svanström, P. Johansson, *Prospective life cycle assessment of sodium-ion batteries made from abundant elements*, **2024**.
[34] H. Liu, Z. Xu, Z. Guo, J. Feng, H. Li, T. Qiu, M. Titirici, *A life cycle assessment of hard carbon anodes for sodium-ion batteries*, Royal Society, **2021**.
[35] S. F. Schneider, C. Bauer, P. Novák, E. J. Berg, *A modeling framework to assess specific energy, costs and environmental impacts of Li-ion and Na-ion batteries*, The Royal Society of Chemistry, **2019**.
[36] S. Zhang, B. Steubing, H. Karlsson Potter, P.-A. Hansson, Å. Nordberg, *Future climate impacts of sodium-ion batteries*, **2024**.
[37] X. Lai, J. Chen, Q. Chen, X. Han, L. Lu, H. Dai, Y. Zheng, *Comprehensive assessment of carbon emissions and environmental impacts of sodium-ion batteries and lithium-ion batteries at the manufacturing stage*, **2023**.
[38] M. A. von der Heydt, Ecological and social sustainability assessment of lithium-ion batteries for electric vehicles, **2022**.
[39] B. Reuter, *Assessment of sustainability issues for the selection of materials and technologies during product design: a case study of lithium-ion batteries for electric vehicles*, **2016**.
[40] Y. Shi, X. Chen, T. Jiang, Q. Jin, *Social life cycle assessment of lithium iron phosphate battery production in China, Japan and South Korea based on external supply materials*, **2023**.
[41] A. Barke, C. Thies, J.-L. Popien, S. Melo, F. Cerdas, C. Herrmann, T. Spengler, *Life cycle sustainability assessment of potential battery systems for electric aircraft*, **2021**.
[42] J. M. Koese, C. F. Blanco Rocha, V. B. Vert, M. G. Vijver, *A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage*, **2022**.
[43] L. Mancini, N. A. Eslava, M. Traverso, F. Mathieux, *Responsible and sustainable sourcing of battery raw materials*, **2020**.
[44] A. Sánchez, G. Benveniste, V. J. Ferreira, I. Bulfaro, L. Igualada, C. Corchero, *Methodology for social life cycle impact assessment enhanced with gender aspects applied to electric vehicle Li-ion batteries*, **2024**.
[45] A. M. Domingues, R. G. de Souza, J. V. R. Luiz, *Lifecycle social impacts of lithium-ion batteries: Consequences and future research agenda for a safe and just transition*, **2024**.
[46] B. Zimmermann, M. Baumann, J. Reiß, G. Rodriguez-Garcia, M. Weil, *Social Life Cycle Assessment as a pillar of sustainability analysis of batteries: The case of LiFePO4*, **2015**.
[47] C. Thies, K. Kieckhäfer, T. S. Spengler, M. S. Sodhi, *Assessment of social sustainability hotspots in the supply chain of lithium-ion batteries*, **2019**.
[48] SVLOT, *Trend reversal: LFP batteries set to fully displace traditional NMC storage*.
[49] Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (European Commission), M. Grohol, C. Veeh, *Study on the critical raw materials for the EU 2023: final report*, Publications Office of the European Union, **2023**.
[50] European Commission, *RMIS - Raw Materials Information System*.
[51] Cobalt Market Report 2021 - Cobalt Institute, **2022**.
[52] European Union Anhydrous ammonia imports by country |, **2022**.
[53] EUROPEAN CHEMICALS AGENCY| ECHA CHEMICALS DATABASE, .
[54] Steel,Aluminum,Nickel,Rare earth,new energy,Copper Prices Charts and news-Shanghai Metals Market, .
[55] J. F. Peters, M. Baumann, J. R. Binder, M. Weil, *Correction: On the environmental competitiveness of sodium-ion batteries under a full life cycle perspective – a cell-chemistry specific modelling approach*, The Royal Society of Chemistry, **2022**.

[56] M. Chordia, A. Nordelöf, L. A.-W. Ellingsen, *Environmental life cycle implications of upscaling lithium-ion battery production*, **2021**.
[57] B. CN, A. C. JD, *Bayer: Worst Forms of Child Labour in the Democratic Republic of the Congo*, **2019**.
[58] B. Faber, B. Krause, R. Sánchez de la Sierra, *Artisanal Mining, Livelihoods, and Child Labor in the Cobalt Supply Chain of the Democratic Republic of Congo*, **2017**.
[59] B. K. Sovacool, *When subterranean slavery supports sustainability transitions? power, patriarchy, and child labor in artisanal Congolese cobalt mining*, **2021**.
[60] F. W. Schwartz, S. Lee, T. H. Darrah, *A Review of Health Issues Related to Child Labor and Violence Within Artisanal and Small-Scale Mining*, **2021**.
[61] B. Flid, M. Kimbuila, *Analyzing Lithium- Ion Batteries in the Perspective of Social Sustainability of Crtitical Minerals*, **2024**.
[62] V. Bester, T. Uys, *Artisanal mining and its drivers in the South African context*, **2023**.
[63] U.S. Department of Labor: International Child Labor & Forced Labor Reports, .
[64] W. T. Gong, P. Dunuwila, X. Sun, I. Daigo, *Capturing potential social risks along the global supply chains for NCM batteries manufactured in China*, **2025**.
[65] X. Rui, Y. Geng, X. Sun, H. Hao, S. Xiao, *Dynamic material flow analysis of natural graphite in China for 2001-2018*, **2021**.
[66] Department of Labor United States of America, *List Required by the Trafficking Victims Protection Reauthorization Act of 2005*, **2025**.
[67] E. Halper, *EV makers' use of Chinese suppliers raises concerns about forced labor*.
[68] Global Organized Crime Index. Global Initiative Against Transnational Organized Crime, **2023**.
[69] T. Zheng, *Human trafficking in China*, **2018**.
[70] E. Umpula, M. Dummett, *The Blood Cobalt Narrative: Addressing Human Rights Concerns or Scaremongering?*, **2024**.
[71] A. L. Wardani, *Cobalt Red: How the Blood of the Congo Powers Our Lives*, Routledge, **2023**.
[72] Workers' and Employers' Organizations in South Asia | International Labour Organization, .
[73] P. P. Ahumada, *Why is it so difficult to reform collective labour law? Associational power and policy continuity in Chile in comparative perspective*, Cambridge University Press, **2021**.
[74] A. Birelma, *Trade Unions in Turkey 2022*, **2022**.
[75] Aluminum: The Car Industry's Blind Spot : Why Car Companies Should Address the Human Rights Impact of Aluminum Production | HRW, .
[76] I. Dibattista, A. R. Camara, I. Molderez, E. M. Benassai, F. Palozza, *Socio-environmental impact of mining activities in Guinea: The case of bauxite extraction in the region of Boké*, **2023**.
[77] S. Damm, *Rohstoffrisikobewertung - Graphit*, Datenstand: November 2021., DERA, Berlin, **25**.
[78] P. Dolega, M. Buchert, J. Betz, *Environmental and socio-economic challenges in battery supply chains: graphite and lithium*.
[79] Chile: mining sector's share of GDP, .
[80] Everything you need to know about the mining royalty in Chile - Gob.cl, **2024**.
[81] Greece-Commission on Sustainable Delevopment 18-19: Chapter II- Mining, .
[82] D. Lampou, G. Tsifoutidis, *MINLEX -Greece Country Report*, **2019**.
[83] K. Tsichla, K. Adam, *The Evolution of Health and Safety Training Needs of the Mining Sector in Greece and EU*, Multidisciplinary Digital Publishing Institute, **2022**.
[84] U. N. Environment, *Global Resources Outlook 2024 | UNEP - UN Environment Programme*, **2024**.
[85] S. Nordhagen, M. L. Fofana, A. O. Barry, S. Diallo, J. L. Songbono, R. Stokes-Walters, L. X. Zhang, R. Klemm, P. J. Winch, *Between the city and the farm: food environments in artisanal mining communities in Upper Guinea*, **2021**.
[86] A. Orola, V. Uusitalo, J. Levänen, *Implications of mineral price volatility on the outcome of social life cycle assessment interpretation—a battery material case study*, **2024**.
[87] S. K. Springer, C. Wulf, P. Zapp, *Potential Social Impacts regarding working conditions of Fuel Cell Electric Vehicles*, **2024**.
[88] M. Hannouf, G. Assefa, *Subcategory assessment method for social life cycle assessment: a case study of high-density polyethylene production in Alberta, Canada*, **2018**.

[89] E. Ekener Petersen, Tracking down Social Impacts of Products with Social Life Cycle Assessment. Doctotal Thesis, KTH Royal Institute of Technology, Sweden, **2013**.

[90] M. Martín-Gamboa, L. Mancini, U. Eynard, A. Arrigoni, A. Valente, E. Weidner, F. Mathieux, *Social life cycle hotspot analysis of future hydrogen use in the EU*, **2024**.

[91] Verité | Human Trafficking Risk Factors in Supply Chains in Guinea, .

[92] A. Luthin, J. Knacksterdt, M. Traverso, *Social hotspots in the automotive industry's aluminum value chains—combining primary and generic data*, **2024**.

[93] G. Zhou, Y. Wang, T. Qi, Q. Zhou, G. Liu, Z. Peng, X. Li, *Toward sustainable green alumina production: A critical review on process discharge reduction from gibbsitic bauxite and large-scale applications of red mud*, **2023**.

[94] N. Bulled, M. Singer, *The occupational syndemics of miners in South Africa*, **2024**.

[95] M. Ahmed, A. Hussain, S. M. Bouzgarrou, S. Nasr, *An Overview of Human Health Hazards in Indian Mining Industry*, **2023**.

[96] Y. Berberoglu, S. K. Mangla, Y. Kazancoglu, *Towards sustainable mining in an emerging economy: Assessment of sustainability challenges*, **2024**.

[97] M. Yousefian, M. Bascompta, L. Sanmiquel, C. Vintró, *Corporate social responsibility and economic growth in the mining industry*, **2023**.

[98] M. Ericsson, O. Löf, A. Löf, *Chinese control over African and global mining—past, present and future*, **2020**.

[99] M. B. Hannouf, A. Padilla-Rivera, G. Assefa, I. Gates, *Social life cycle assessment (S-LCA) of technology systems at different stages of development*, **2024**.

[100] F. Egunyu, J. Boakye-Danquah, Y. A. Boafo, E. K. Antwi, M. Abdelbaset, M. Bayatvarkeshi, A. A. Owinyi, G. Werikhe-Wanzala, B. Batbayar, C. Marfo, *The Socio-Economic Consequences of Mining in Africa: A Systematic Review of the Costs and Benefits*, Social Science Research Network, Rochester, NY, **2024**.