

From aluminium to composites: A comparative social life cycle assessment of automotive lightweight components

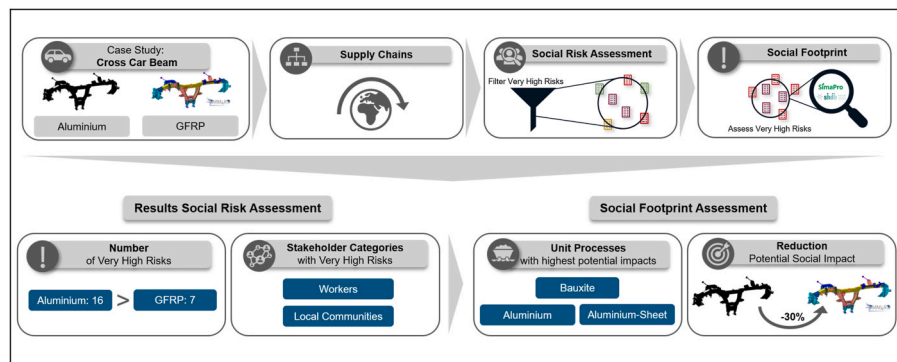
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HIGHLIGHTS

- First S-LCA of aluminum and composite automotive cross-car beam components.
- Case study identifies lower quantities of social risks for composite cross-car beams.
- Workers and local communities are most impacted in both material supply chains.
- Composites reduce potential social impacts by 24–36 % compared to aluminum beams.
- Social hotspots include bauxite mining, aluminum production, and sheet manufacturing.

GRAPHICAL ABSTRACT



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ABSTRACT

This study applies a Social Life Cycle Assessment (S-LCA) to compare the social sustainability of conventional aluminum cross-car beams (CCBs) with composite alternatives in which approximately 50 % of the aluminum is replaced by a glass fiber-reinforced polymer (GFRP). A two-step methodological framework, aligned with UNEP S-LCA guidelines and ISO 14075, was implemented: first, a social risk assessment identified very high risk (VHR) subcategories affecting specific stakeholder categories; second, a social footprint analysis quantified potential impacts through the Social Hotspot Index (SHI), which integrates labor intensity with social risk levels. Workers and local communities emerged as the only stakeholder categories associated with VHR subcategories in both CCB supply chains. The social footprint analysis quantified significant hotspots in aluminum-related processes, particularly bauxite extraction, aluminum manufacturing, and sheet production. Substituting aluminum with GFRP composites reduced cumulative SHI values by 24–36 % across VHR subcategories, with residual aluminum processes remaining major contributors to the social footprint of the composite variant. While the method is broadly applicable, the findings are case-specific - reflecting, e.g., a cradle-to-gate system boundary - and are not generalizable to the entire automotive sector. As the assessment partially relies on secondary supply chain data and proxy unit processes from established S-LCA databases, the results are not intended for direct supply-chain decision-making. However, the study informs the prioritization of stakeholders, subcategories, and unit processes

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for future CCB S-LCAs as technical development progresses and primary data becomes available. Overall, it highlights the potential of composites to reduce social impacts in automotive lightweight products.

List of abbreviations

Al ₂ O ₃	alumina	LCV	light commercial vehicle
B ₂ O ₃	boron oxide	MgO	magnesium oxide
BR	Brazil	MM4R	recycling-ready multi-material lightweight
CaO	calcium oxide	mrheq	medium risk hours equivalent
CCB	cross car beam	nec	not elsewhere classified
CFRP	carbon fiber reinforced polymers	OEC	Observatory of Economic Complexity
CN	China	OECD	Organization for Economic Co-operation and Development
CSDDD	Corporate Sustainability Due Diligence Directive	OEM	original equipment manufacturer
CSRD	Corporate Sustainability Reporting Directive	PP	polypropylene
DE	Germany	PSILCA	database Product Social Impact Life Cycle Assessment database
EoL	end-of-life	RS S-LCA	Reference Scale Approach S-LCA
FU	functional unit	SHDB	Social Hotspot Database
GF	glass-fiber	SHI	Social Hotspot Index
GFRP	glass fiber-reinforced polymer	SiO ₂	silica
GN	Guinea		
GTAP	Global Trade Analysis Project	<i>S-LCA</i>	<i>Social Life Cycle Assessment</i>
HALS	Hindered Amine Light Stabilizers	S-LCI	Social Life Cycle Inventory
HR	high risk	S-LCIA	Social Life Cycle Impact Assessment
ILO	International Labor Organization	TRL	Technology Readiness Level
IN	India	UN	United Nations
IP S-LCA	Impact Pathway Approach S-LCA	UNEP	United Nations Environment Programme
ISO	International Organization for Standardization	USD	United States Dollar
LCA	Life Cycle Assessment	UV	ultraviolet
LCC	Life Cycle Costing	VHR	very high risk
LCSA	Life Cycle Sustainability Assessment	ZA	South Africa

1. Introduction

Automotive lightweight components have emerged as a key solution for enhancing environmental sustainability in the transport sector. By significantly reducing vehicle weight, these components contribute to lower fuel consumption and, consequently, to a reduction in CO₂ emissions, which is crucial as road transport alone accounts for roughly 25 % of the EU's total CO₂ emissions, with passenger cars and light commercial vehicles (LCVs) responsible for about 15 % (Suarez Corujo et al., 2023). Composites, particularly carbon fiber reinforced polymers (CFRP) and glass fiber reinforced polymers (GFRP), present a considerable potential for achieving substantial weight reductions in the automotive lightweight sector (Njuguna et al., 2011; Wegmann et al., 2022). These materials offer additional weight savings compared to steel and the current dominating lightweight aluminum in the automotive industry (Mohammadi et al., 2022), potentially further reducing the overall vehicle weight by up to 10 % (Mohammadi et al., 2022; Pervaiz et al., 2016). This becomes especially important for future e-mobility, where the added mass of electric vehicles due to battery systems increases energy consumption, making weight reduction essential for optimizing range efficiency (Liu et al., 2021; Ou et al., 2023).

Yet, assessing the sustainability of automotive lightweight solutions requires addressing not only environmental but also social and economic dimensions, particularly in light of recent research underscoring the necessity of multidimensional sustainability frameworks in industry (Falcone and Tutore, 2025; Valdivia et al., 2021). Current assessments of automotive composite lightweight materials have predominantly focused on environmental and economic aspects, including evaluations

of carbon footprint (Deng et al., 2019; Ghosh et al., 2021; Oliver-Ortega et al., 2019; Sun et al., 2019), comprehensive Life Cycle Assessments (LCAs) (Koffler, 2014; Tadele et al., 2020) and LCAs coupled with Life Cycle Costing (LCC) assessments (Delogu et al., 2016; Witik et al., 2011). These studies consistently show that composite-based solutions often outperform aluminum in terms of embodied energy, greenhouse gas emissions (Oliver-Ortega et al., 2019; Sun et al., 2019), and, in some cases, cost-performance trade-offs (Delogu et al., 2016; Witik et al., 2011) - particularly when considering their contribution to vehicle lightweight and use-phase efficiency (Koffler, 2014; Tadele et al., 2020). However, while these findings highlight the environmental and economic advantages of composites, often based on aggregated impacts that overlook institutional or country-specific supply-chain variability (Barra and Falcone, 2024), they also do not account for potential trade-offs in the social dimension. Furthermore, this limitation is not solely limited to lightweight materials: even recent life-cycle-based assessments within the wide-ranging automotive sector - including comparisons of future battery electric and internal combustion engine vehicles - omit social impacts (Golkaram et al., 2025).

As a result, within both the broader automotive sector and the specific context of lightweight material innovation, the social dimension has been largely overlooked despite the critical social implications associated with conventional aluminum materials, particularly in their upstream supply chain. Existing literature highlights that the extraction and processing can lead to severe social impacts, such as forced community displacement, loss of livelihoods, and health issues from environmental damage like water pollution and toxic sludge - known as "red mud". (Human Rights Watch/Inclusive Development International, 2021) Additionally, mining operations have proven to pose substantial occupational health and safety risks (Di Giorgio et al., 2024; Dibattista

et al., 2023), including hazardous substance exposure (Georgitzikis et al., 2021) and high accident rates (Human Rights Watch/Inclusive Development International, 2021; Luthin et al., 2024).

These social consequences emphasize the need for a comprehensive sustainability assessment that integrates social considerations when shifting to alternative lightweight materials in the automotive industry. A holistic evaluation must evaluate trade-offs between social, environmental, and economic considerations to ensure that advancements in vehicle technology do not come at the expense of societal well-being, thereby preventing further burden-shifting to other sustainability dimensions (Falcone and Hiete, 2019; UNEP/ SETAC, 2011).

Social Life Cycle Assessment (S-LCA), a core component of Life Cycle Sustainability Assessment (LCSA), evaluates social impacts throughout a product's life cycle, from raw material extraction to end-of-life (EoL) (UNEP, 2020). As one of the most recognized methods for assessing social sustainability, S-LCA adheres to standards 14,040 and 14,044 published by the International Organization for Standardization (ISO) and follows the same four phases as traditional LCA (Ostojic and Traverso, 2024). Besides, ISO 14075 now establishes a standardized framework for conducting S-LCA, providing a structured approach for practitioners. While the S-LCA guidelines from the United Nations Environment Programme (UNEP) continue to offer valuable insights and guidance, ISO 14075 formalizes the methodology, marking a significant advancement in S-LCA practice (ISO, 2024; UNEP, 2020). The evolving method aims to support decision-making that enhances social conditions across life cycles and value chains globally (UNEP, 2020).

The UNEP guidelines indicate that S-LCA can be utilized to quantify social impacts, identify social hotspots, and evaluate the potential effects of policies or investment decisions (UNEP, 2020). Nevertheless, the early stages of product development often face challenges due to the limited availability of social data, complicating primary data-intensive social assessments. This study addresses these limitations considering an early-stage product development case study of a vehicle cross car beam (CCB) composed of an innovative recycling-ready multi-material lightweight (MM4R) design (FOREL, 2021). Initially, the study compares the social risk hotspots in the supply chains of conventional aluminum lightweight materials and the MM4R project-developed GFRP lightweight materials. The supply chains for each variant are built using where available primary data (sourced from MM4R project partners) and complemented with secondary data (sourced from literature). Based on these supply chains, the Social Hotspot Database (SHDB) is utilized to determine the highest social risks and, subsequently, the social footprint, quantifying social impacts through labor intensity and risk levels of the most material impact subcategories (UNEP, 2020).

Although limited S-LCA literature exists within the automotive sector on identifying social hotspots of aluminium components (Luthin et al., 2024) and developing methods for implementing S-LCA in complex industrial settings (Karlewski et al., 2019; Luthin et al., 2024), no prior study has focused specifically on lightweight materials or a comparative product evaluation. The study by Luthin et al. (2024), for instance, focuses on generic hotspot analysis in aluminium value chains using the Product Social Impact Life Cycle Assessment (PSILCA) database but is limited to single-material components from a supplier and does not address comparative material assessment or complete product system modeling relevant to automotive applications (Luthin et al., 2024).

This study is the first to conduct a comparative S-LCA of different lightweight automotive CCB components, specifically comparing conventional aluminium components with GFRP composites, evaluated on a functionally equivalent basis. The approach is methodologically novel in combining a social risk assessment with a subsequent quantitative social footprint analysis and in its application to comparing lightweight automotive components. Additionally, for the first time, its implementation draws on primary data from the MM4R research project (FOREL, 2021) for early-stage material composition and supply chain information, supplemented by secondary literature sources and SHDB proxy unit processes for impact assessment. This study, therefore,

addresses a critical gap in the literature, advancing holistic sustainability assessment in the automotive lightweight sector by incorporating the underrepresented social dimension and proposing a transferable methodological approach for evaluating alternative materials and technologies under real-world early design-phase conditions.

The remainder of this manuscript is structured as follows: Section 2 outlines the applied S-LCA methodology, including the normative framework, definition of system boundaries, functional unit (FU), and data sources. It also details the modeling of the aluminum and composite CCB supply chains and the two-step analytical approach comprising the social risk assessment and the social footprint analysis. Section 3 presents the results, highlighting identified stakeholder categories and subcategories affected by very high risk (VHR), as well as quantifying cumulative social impacts across the supply chain. Section 4 discusses the findings in relation to existing S-LCA literature, contextualizes methodological limitations, and outlines implications for future studies and practice. Section 5 concludes the paper with key insights and recommendations for integrating social sustainability in automotive lightweight product development.

Ultimately, this research is highly relevant in the context of growing automotive lightweight product development and increasing corporate social responsibility requirements at the product level. Identifying social hotspots aligns with the requirements of the Corporate Sustainability Due Diligence Directive (CSDDD), which mandates large companies to address human rights impacts across their operations and supply chains (Bueno et al., 2024). Ensuring policy implementability is particularly important, as recent research shows that uncertainty in economic, climate, and energy policies can hinder sustainability progress and undermine the effectiveness of regulatory frameworks (Barra et al., 2025). A social hotspot analysis, assessing risks by country and sector, helps companies identify and mitigate human rights and environmental liabilities (Benoît Norris et al., 2018). Additionally, S-LCA supports compliance with the Corporate Sustainability Reporting Directive (CSRD) and EU Taxonomy, aligning with international business and human rights guidelines from the Organization for Economic Co-operation and Development (OECD), the United Nations (UN), and the International Labor Organization (ILO) (Benoît Norris et al., 2018; Ostojic et al., 2024b).

2. Methods

This study conducts a comparative S-LCA using a developed two-step approach in alignment with established standards (ISO 14075) and international guidelines (UNEP Guidelines for S-LCA), which are broadly aligned in structure and intent. For instance, both frameworks adopt the four-phase life cycle model, recognize the two major Social Life Cycle Impact Assessment (S-LCIA) approaches, and permit the use of both primary and secondary data depending on context and availability. While ISO 14075 formalizes the procedural framework to promote standardization, consistency, and broader acceptance within life cycle methodologies, the UNEP guidelines provide more operational granularity - most notably by defining stakeholder categories, subcategories, and specific S-LCA outputs such as social risks, social hotspots, and social footprint (ISO, 2024; UNEP, 2020). This integration allows for a consistent yet detailed evaluation, enhancing transparency and relevance for stakeholders.

To enhance methodological clarity, Fig. 1 provides a visual overview of the research design implemented in this study.

The methodological approach is centered on a comparative case study of a CCB, where a conventional aluminum-based component is benchmarked against a within the MM4R project developed GFRP-based composite alternative. The sequential methodological flow is illustrated, beginning with the definition of the case study and the modeling of material-specific supply chains for both CCB variants. These modeled supply chains serve as the analytical foundation for a two-step S-LCA. First, a qualitative social risk assessment is conducted to identify and

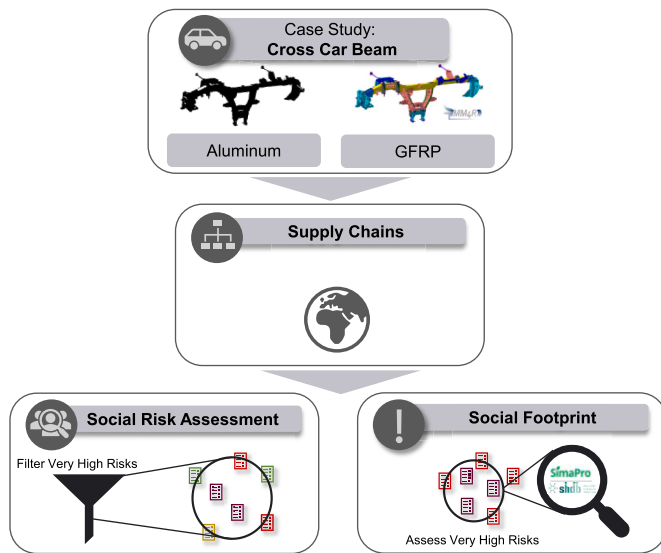


Fig. 1. Overview of the applied S-LCA methodological framework.

filter very high social risks along each supply chain based on country- and sector-specific risk levels. Second, a social footprint analysis is carried out using SimaPro and the SHDB to quantify the potential social impacts associated with the identified risk hotspots.

Accordingly, this section is structured into four subsections. The first outlines the theoretical foundation of S-LCA, elaborating on key methodological decisions - such as the definition of system boundaries and the selection of S-LCA outputs (e.g., social risk or social footprint) - where normative flexibility permits practitioner discretion. The second subsection describes the case study component and development of the modeled supply chains, which serve as the foundation for both the risk and footprint assessments. This includes a detailed explanation of methodological approaches taken in regard to different data sources - primary project data and secondary data from established databases. Finally, the third and fourth subsections present the specific methodological procedures for conducting the social risk assessment and the social footprint analysis, respectively, including data inputs, evaluation methods, and the software tools applied.

2.1. Social life cycle assessment

This study adopts the S-LCA methodology, comprising the standard four phases: Goal and Scope, Social Life Cycle Inventory (S-LCI), S-LCIA, and Interpretation. Within this framework, critical methodological choices are required, including the definition of the system boundaries and the FU, as well as the selection between the S-LCIA types - either the Reference Scale Approach (RS S-LCA), which evaluates social performance and risks or the Impact Pathway Approach (IP S-LCA), which characterizes consequential social impacts along a cause-effect chain (ISO, 2024; UNEP, 2020). Furthermore, the UNEP guidelines also define core S-LCA outputs, including social footprint, social handprint, materiality assessment, social hotspot, and social risks, which assess potential or actual social impacts. Social risks refer to the probability of socially adverse conditions - such as child labor or wage inequality - occurring in specific country-sector contexts, typically assessed using proxy indicators. A social hotspot, as defined by UNEP, is a life cycle stage or unit process where such risks or potential impacts are both elevated and materially relevant to the product system. Besides, the social footprint provides a quantified estimate of potential impacts by linking risk levels with labor intensity, expressed in medium risk hour equivalents (mrheq.); thus, a high footprint in a process can substantiate its classification as a hotspot. In contrast, a social handprint reflects relative improvements over a baseline scenario and materiality assessment

guides prioritization by identifying the most stakeholder-relevant issues (UNEP, 2020). Ultimately, differentiating each output between potential and actual impact, potential impacts refer to the probable presence of a social issue arising from organizational activities (Bouillass et al., 2021), while actual social impacts represent the positive or negative outcomes resulting from a relationship between an activity and human well-being (UNEP, 2020). Assessing actual impacts requires verified primary stakeholder data, as proxy indicators and predictive models are inadequate (UNEP, 2020).

The selection of S-LCA outputs and methodological approaches, including impact assessment type, is strongly influenced by the product development stage and data availability. Technology Readiness Level (TRL) frequently serves as a proxy for product maturity, with lower TRLs typically associated with limited and lower-quality data. This constraint has been noted in prior LCA studies on emerging technologies (Mahmud et al., 2021; van der Giesen et al., 2020; Zimmermann et al., 2022). Similar challenges exist for S-LCA, where emerging technologies often lack robust inventory data to support accurate assessments of actual impacts (Lobsiger-Kägi et al., 2018; Padilla-Rivera et al., 2023; Pucciarelli et al., 2021). To bridge data gaps, practitioners may rely on secondary sources, though this reliance increases uncertainty (Karlewski et al., 2019; Tokede and Traverso, 2020).

To provide conceptual guidance for practitioners and improve methodological transparency, this study introduces a novel classification and mapping of S-LCA outputs in relation to key parameters - such as data availability and design costs - that shape socially sustainable product design. This is illustrated in Fig. 2 and aims to clarify how different S-LCA outputs - namely social risk, social hotspot, materiality assessment, social footprint, and social handprint - can be positioned along product design stages.

In early design phases, data is often scarce, leading to higher uncertainty (Argoti et al., 2019; Zimmermann et al., 2022). Nonetheless, these stages provide flexibility to implement low-cost design changes that can significantly enhance social performance throughout the product life cycle (Argoti et al., 2019; Fröhling and Hiete, 2020). Despite the limited availability of primary data, early-stage S-LCA applications can still generate meaningful outputs - such as social hotspots, risks, footprint, and materiality assessments (see Fig. 2) - by integrating primary and generic data sources (Mármol et al., 2023; Padilla-Rivera et al., 2023; Sala et al., 2015). Such outputs inform decision-making, mitigating potential social risks in subsequent stages of product development.

Building on this mapping, the present case study applies two S-LCA outputs to systematically assess and compare the potential social impacts associated with a CCB manufactured from lightweight aluminum and a GFRP-based composite. First, a social risk assessment is conducted to identify stakeholders as well as subcategories classified as VHR, followed by a social footprint assessment to quantify the associated potential social impact values. This enables the characterization of critical social impacts linked to labor-intensive processes in the supply chain. Furthermore, the analysis explores how social impacts may shift under alternative supply chain configurations, such as changes in sourcing countries. The outcomes will highlight the most critical subcategories as well as unit processes requiring further assessment as primary data becomes available and uncertainty decreases.

The FU is considered a structural cockpit CCB with a lifespan use of 200,000 km. Functional equivalence between the conventional aluminum and composite (GFRP-based) variants is ensured, as both designs meet identical structural and mechanical performance requirements for integration within the same vehicle platform. These equivalencies are based on validated design data provided by the MM4R project (FOREL, 2021). This FU, however, is not always reflected in the risk assessment and social footprint analysis, which are based on the producing countries and a related sector.

Furthermore, the system boundary for this study is defined as cradle-to-gate, encompassing all upstream supply chain activities up to the final

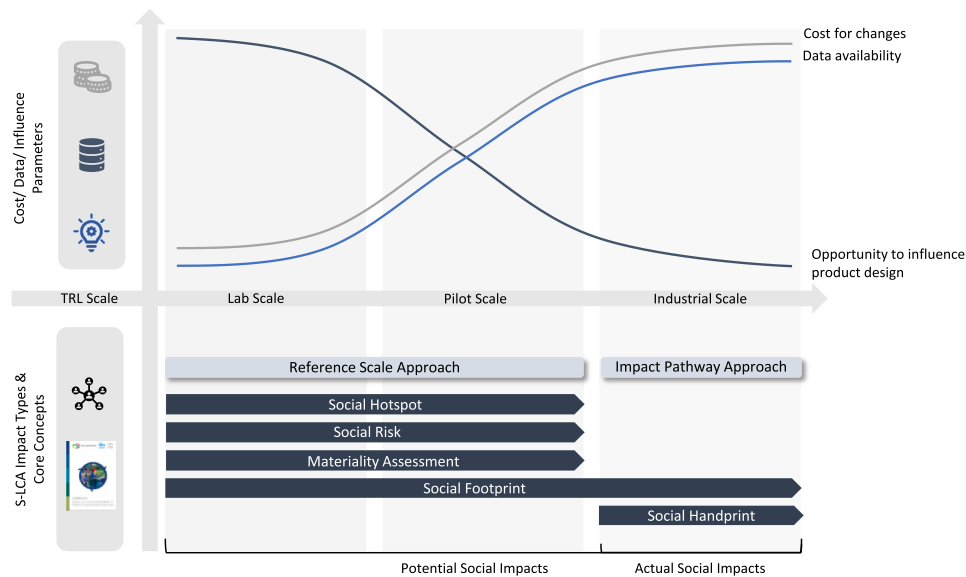


Fig. 2. Mapping S-LCA Outputs and the course of cost, data availability, and design influence across different product TRLs.

manufacturing stage of the CCB. The use phase is excluded, as the component is integrated into the vehicle interior and does not involve direct human interaction or maintenance during its operational life. Furthermore, savings in fuel or energy consumption linked to reduced component weight cannot be methodologically and reliably traced to a saving in social risks at the unit process level. The EoL phase is also excluded, based on the following considerations: (i) High uncertainty regarding future recycling technologies and treatment pathways. Given the early development stage of the CCB, its EoL lies far in the future. Over this extended time horizon, substantial changes in recycling technologies, infrastructure, and regulatory frameworks - especially for composite materials such as GFRP - are expected, rendering current modeling highly speculative and unreliable (Clavreul et al., 2012). (ii) Lack of reliable primary and secondary data. No primary data are available on the allocation of country-specific end-user distributions or recycling routes, as the GFRP CCB is still in development and not yet in serial production. Moreover, the secondary databases used for identifying the dominant geographic location in supply chain modeling do not include the geographic prevalence of different recycling activities. The SHDB also lacks unit processes for specific recycling operations. The only fitting relevant recycling unit process - categorized under the sector "manufacturing nec" - is not sufficiently granular to distinguish between recycling methods and assess their respective difference in social impacts. As a result, a methodologically consistent and meaningful comparative assessment of aluminium vs. GFRP EoL processes, aligned with the upstream modeling approach, is not feasible. (iii) Relatively low labor intensity and social risk potential of current recycling practices, especially when compared to upstream extraction and production. Current recycling operations, especially for automotive materials like aluminium and polymers, are typically conducted in developed countries with high labor standards and are largely mechanized, leading to lower labor intensity and minimal social risk potential (Behera et al., 2014; Jiang and Bateer, 2025; Yi et al., 2022; Zambrano et al., 2024). In contrast, primary extraction is frequently associated with elevated social risks and impacts, as these also often occur in regions with weaker labor and human rights enforcement (Sovacool et al., 2020). Thus, the most socially pertinent processes are comprehensively covered within the cradle-to-gate boundary, ensuring robustness and decision-usefulness regarding relevant stakeholders and impact subcategories of the assessment.

Within a cradle-to-gate system boundary, this study focuses on the foreground system, analyzing processes where the cockpit CCB original

equipment manufacturer (OEM) has decision-making authority over suppliers. Background processes such as electricity generation and water supply were excluded based on ISO 14075 and UNEP S-LCA guidelines, as they lack sufficient data granularity and social relevance (ISO, 2024; UNEP, 2020). This is particularly relevant given that the initial social risk assessment is based solely on country-sector data without accounting for material or energy flows, meaning energy intensity differences between the material systems would not be reflected. Furthermore, these processes are characterized by low labor intensity and limited traceability, being embedded in national infrastructure systems with generally lower exposure to social risks (Benoit Norris et al., 2018; Sovacool et al., 2020). Including them would require compounding proxy assumptions and would not meaningfully affect outcomes, as both material systems rely on similar utility inputs. Moreover, background utilities fall outside the influence of the OEM and its suppliers, whereas upstream material sourcing can be guided or specified in procurement, making it more relevant to supply chain decision-making. A visual representation of the system boundaries and corresponding supply chain breakdowns for both product systems is provided in Figs. 4 and 5 in the following subsection.

2.2. Supply chains

A CCB supports critical automotive components such as the steering column, airbags, and instrument dashboard, enhancing safety and comfort by absorbing impact energy and minimizing vibrations (Li and Kim, 2015). Building on the advancements in producing functionalized hollow profiles from glass fiber-reinforced thermoplastics (Müller et al., 2019), the MM4R project is developing a scalable manufacturing process for recyclable multi-material cockpit CCBs composed of GFRP composites integrated with metallic load introduction elements.

The conventional CCB is primarily composed of aluminum and steel sheets, whereas the MM4R CCB features a more complex structure, incorporating a hollow profile, organic sheets, and injection-molded granulate composed of glass-fiber (GF) and polypropylene (PP).

Fig. 3 illustrates these mass-based material differences between the conventional and the MM4R CCB product systems. Both variants contain comparable steel content, which was excluded from the analysis as the social risks associated with steel are identical for both. The study focuses on material substitution in the MM4R component, evaluating the potential social risks and impacts considering both supply chains. Notably, the MM4R product system replaces approximately 50 % of aluminum

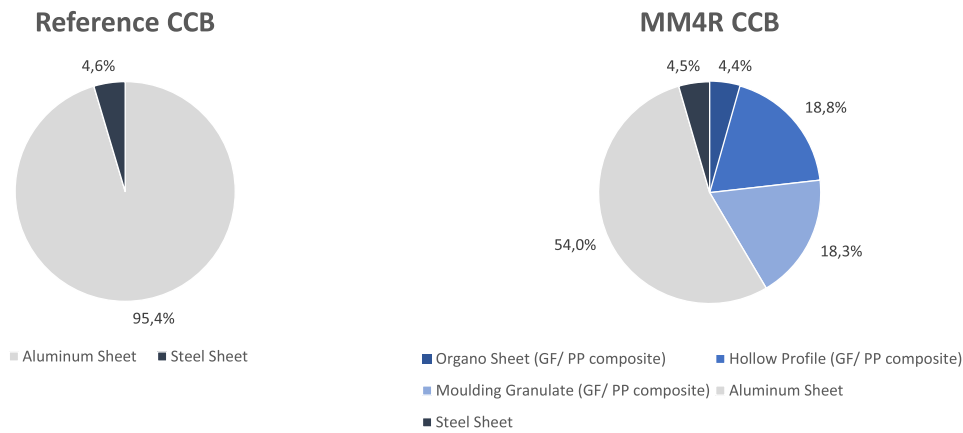


Fig. 3. Mass-based material composition of reference CCB vs. MM4R CCB.

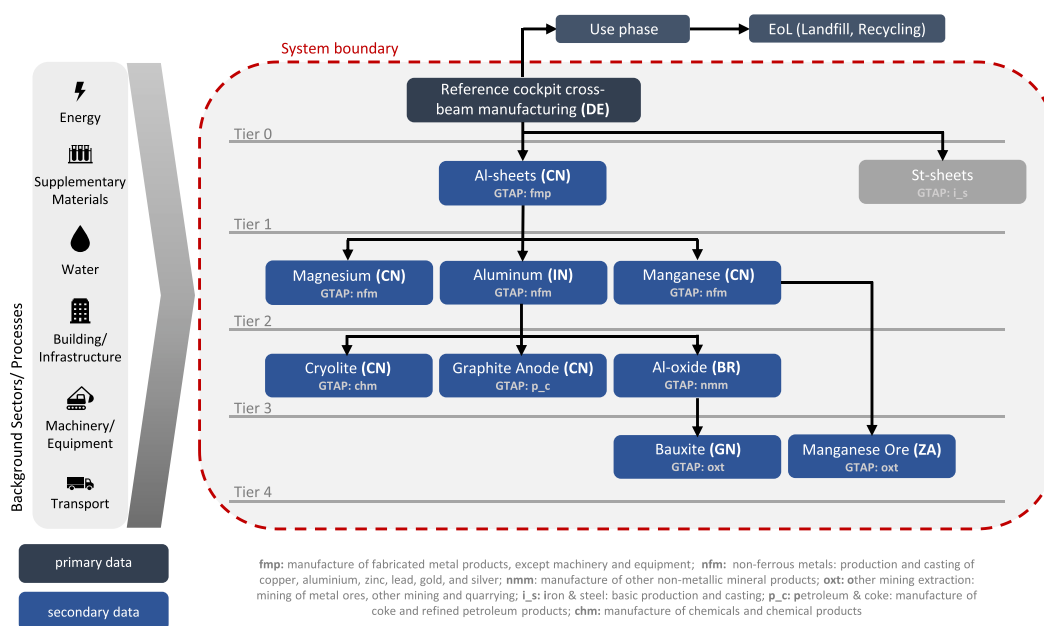


Fig. 4. Aluminum sheet supply chain.

with GF/PP composites while retaining residual aluminum for essential mechanical properties. The supply chains were developed using material manufacturing literature, export and production statistics, and collaboration with MM4R project partners, with the prototype manufacturer identified as the final actor.

2.2.1. Aluminum sheet supply chain

The reference CCB is composed of approximately 95 % aluminum sheet, specifically an aluminum-magnesium-manganese alloy known for its high strength and long-standing application in internal structural automotive components (Fang, 2023b).

As indicated in Figure A.1, which presents the material process flow, aluminum sheet production involves two primary process steps (Tabereaux and Peterson, 2014; Tripathi, 2022):

3. Bayer Process: Bauxite ore is processed to extract aluminum oxide (alumina), requiring caustic soda, water, lime, and energy inputs (Balomenos et al., 2011; Brough and Jouhara, 2020; Du Plessis et al., 2021; Raahauge and Williams, 2022).
4. Hall-Heroult Electrolytic Process: Alumina is smelted into aluminum via electrolysis, requiring cryolite, graphite, and substantial energy (Kvande, 2014; Padamata et al., 2023; Ratvik et al., 2022).

Overall, these processes are highly energy and resource-intensive, requiring approximately 4 tons of bauxite to produce 1 ton of liquid aluminum (Brough and Jouhara, 2020; Tabereaux and Peterson, 2014).

The resulting smelter-grade aluminum is alloyed with magnesium and manganese (Wagiman et al., 2020). Magnesium is typically produced via the Pidgeon process, where dolomite is reduced to metallic magnesium using ferrosilicon as a reducing agent (Wu et al., 2021). Manganese is obtained through electrolysis, requiring significant energy and sulfuric acid to leach the raw ore (Tsurtsumia et al., 2019; Wang et al., 2023). The alloyed aluminum is then cast into ingots, preheated, and rolled into aluminum sheets used for CCB production (Fang, 2023a).

Based on this process flow (illustrated in Figure A.1), a country- and sector-level supply chain model was developed to support the social hotspot assessment (see Fig. 4). This model focuses on foreground unit processes with significant country-specific dependencies. In contrast, materials with globally diversified supply chains - due to widespread geographic availability - were excluded from the analysis (see Table A.1). Emphasis was placed on materials with geographically concentrated supply chains, where regional dependencies are known to potentially elevate both social and geopolitical risk potentials. The illustrated supply chain (see Fig. 4) was segmented into the following Tiers:

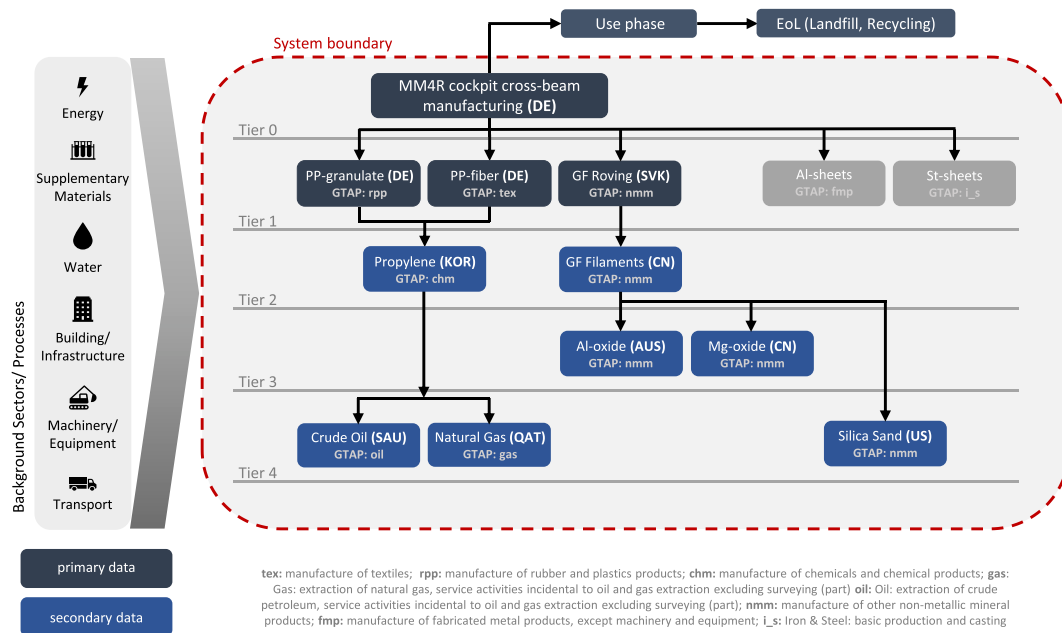


Fig. 5. GFRP composite supply chain.

- **Tier 0:** Product assembly and finishing;
- **Tier 1:** Material manufacturing;
- **Tier 2:** Material processing;
- **Tier 3:** Raw material conversion; and
- **Tier 4:** Raw material extraction.

For all Tiers and unit processes included in the supply chain model, country-specific sector data were compiled based on a combination of primary and secondary data sources. Primary data collection was attempted through collaboration with project partners and supplier questionnaires, but no primary data for the aluminum supply chain could be obtained. As a result, a bottom-up approach using secondary data was employed (see Table A.1), leveraging 2022 country-level export statistics from the Observatory of Economic Complexity (OEC) web tool (OEC, 2025). This approach was taken, given that, within a globalized trading system, there is a high likelihood that materials are sourced from countries with the highest export shares. The OEC, a platform for international trade data visualization, provides detailed export country distributions for specific materials (Qayyum et al., 2021). To develop the country-specific aluminium sheet supply chain illustrated in Fig. 4, exporting countries with the highest share were initially identified using the OEC database and reference year 2022. However, the highest exporters were not always selected as the representative countries for the social hotspot assessment. For instance, aluminium oxide was attributed to South America rather than Australia, based on the geographic origins of key input materials such as bauxite and caustic soda (see Table A.1). The final selection of assessed countries for each unit process is indicated by country codes in Fig. 4, while the underlying rationale - based on trade export statistics and material flow considerations - is detailed comprehensively in Table A.1.

Additionally, Table A.1 details the selected sectors from the Global Trade Analysis Project (GTAP) and their corresponding sectors within the SHDB risk-mapping tool (GTAP, 2025). Further details are provided in Section 2.3, which outlines the methodological approach adopted in the social risk assessment. This comprehensive analysis of the country-sector level aluminium sheet supply chain - from raw material extraction to product assembly - lays the groundwork for evaluating the social risks associated with the reference CCB production.

2.2.2. GF/PP composite supply chain

In the MM4R cockpit CCB design, 41.5 % of the aluminum is replaced with a GFRP composite, used in different structural components, including organo sheets, molding granulates, and a hollow hybrid yarn profile. Organo sheets and hybrid yarns are made from GF roving and PP fibers, while the molding granulate combines GF roving with PP pellets (see process flow diagram illustrated in Figure A.2). PP, widely used in automotive applications (Greene, 2021), is synthesized through desalting and distillation of crude oil, steam cracking, polymerization, and granulation. Steam cracking, the dominant method for producing propylene (Corma et al., 2017; Da Wagner Silva, op. 2023), involves processing desalted and distilled crude oil into naphtha, which is cracked using energy, steam, and sodium hydroxide to produce propylene (Baerns et al., 2023; Hsu and Robinson, 2019; Lv et al., 2021; Mukhopadhyay and Deopura, 2017; Spallina et al., 2017). Propylene is then polymerized into PP using hydrogen, nitrogen, and a Ziegler-Natta catalyst, with additional energy inputs (Fernandez et al., 2024; Gahleitner and Paulik, 2017). The obtained PP is pelletized with stabilizers like antioxidants and ultraviolet (UV) protectants, typically Hindered Amine Light Stabilizers (HALS), before undergoing melt-spinning to create fibers (Fried, 2014; Karger-Kocsis and Bárány, 2019; Mukhopadhyay and Deopura, 2017; Russell, 2022; Tolinski, 2015). The GF production involves melting, fiberization, and winding (melt spinning). E-glass, commonly used in automotive applications, is produced from silica (SiO₂), alumina (Al₂O₃), calcium oxide (CaO), magnesium oxide (MgO), and boron oxide (B₂O₃), which together enhance strength, durability, and ease of fiber formation (Chawla, 2019; Li, 2021). The molten glass is drawn into fibers, coated with sizing agents for protection and processing, and wound onto spools (Cevahir, 2017; Martynova and Cebulla, 2018; Zu et al., 2021).

Consequently, the GF/PP inventory supply chain model was developed using the same tiered structure as the aluminum supply chain, focusing on key foreground processes and dominant export countries (see Fig. 5). In contrast to the aluminium-based CCB, primary data for Tier 1 was obtained through collaboration with project partners and direct supplier-specific questionnaires. This supplier-specific information remains anonymous and was only available for Tier 1 processes, thus, secondary data were used to model the remaining Tiers. The overall supply chain model was developed using the same bottom-up approach, combining 2022 country-level export data from the OEC

and mapping the unit process steps to the GTAP and SHDB sectors. Detailed background information - including the rationale for the selection of representative countries and sectors used for the risk assessment - is provided in Table A.2. Based on the compiled supply chain inventory data, a social hotspot assessment was carried out for both the aluminium and GF/PP supply chains to identify and compare the number of very high social risks.

2.3. Social risk assessment

The SHDB evaluates social risks in global supply chains and calculates social footprints (Benoit-Norris et al., 2012), making it a leading S-LCA database alongside PSILCA (Luthin et al., 2024). Available as an online tool or licensed integration in LCA software like OpenLCA and SimaPro (Bennema et al., 2022), the SHDB combines a GTAP-based global trade model, a worker-hour model, and social risk data (Sala et al., 2015). Utilizing the GTAP multi-regional input-output model, the SHDB covers 57 sectors across 244 countries, with 2011 as the reference year, enabling sector-specific social risks at the country level (Bennema et al., 2022). The online tool assesses social risks via a color-coded system based on selected countries and sectors (Backes and Traverso, 2023; Bennema et al., 2022). Within this study, the SHDB online risk mapping tool is used to assess the social risk hotspots in both CCB supply chains. Thus, the SHDB was chosen over PSILCA due to its unique online risk mapping tool - which enabled a transparent and interactive identification of VHR - as well as its compatibility with SimaPro, which allowed for a consistent integration of both the qualitative social risk assessment and the subsequent quantitative social footprint analysis within a single database framework.

For assessing the social risks, the country and sector specified for each unit process in both supply chain inventories (see Figs. 4 and 5; Tables A.1 and A.2) was evaluated using the SHDB online risk mapping tool. The classification of social risk levels (low, medium, high, very high) follows the SHDB methodology, which combines statistical data distribution, expert judgment, and benchmarking against internationally recognized standards such as minimum wages, living wages, and core labor conventions (e.g., ILO standards), as detailed in the SHDB background documentation (Bennema et al., 2022). The assessment encompasses all stakeholder categories embedded in SHDB, and - based on mapping methodologies from recent literature (Krekel et al., 2024) - these were aligned with the established stakeholder groups defined in the UNEP S-LCA guidelines, thus including workers, local community, value chain actors, consumers, society, and children, along with all respective subcategories.

In the first step, the raw SHDB data were screened and filtered for high risks (HR) and VHR within all unit processes to identify and compare the number of potential social risks per CCB product system. In the second step, all unit processes containing VHR levels were analyzed in more detail to identify the affected stakeholders and subcategories, thereby highlighting potential social hotspots. The stakeholder and subcategory mappings from SHDB to UNEP terminology were made explicit to enhance transparency and are further elaborated in the results chapter. Finally, the proportional distribution of VHRs across stakeholder groups and subcategories was calculated on this basis and visualized for both product systems to enable a comparative analysis of potential social hotspots.

2.4. Social footprint assessment

To complement the risk hotspot identification, a social footprint assessment was conducted to quantify the potential social impacts of both CCB supply chains. This step provides a more differentiated and material flow-specific analysis, accounting also for labor intensities. For this purpose, the license-based version of the SHDB was used within the SimaPro software. This version applies a worker-hour model, converting GTAP wage data into country- and sector-specific labor hours per United

States Dollar (USD) of process output (Sala et al., 2015). These worker-hours are then multiplied by risk characterization factors - low (0.1), medium (1), high (5), and very high (10) - to calculate the Social Hotspot Index (SHI), expressed in mrheq. (UNEP, 2020).

The SHI evaluation was limited to stakeholder category-subcategory combinations identified as VHR during the previous social risk assessment. This ensures methodological consistency and focuses on the quantification of the most relevant impact subcategories. To operationalize this assessment, an input-output inventory was developed based on the tier-specific supply chain processes of each product system. The MM4R project provided material masses for the final manufacturing step of each CCB variant, and due to project confidentiality, these are not publicly disclosed. These data served as a basis for reconstructing the upstream material flows throughout both CCB supply chains, using secondary literature sources to derive a comprehensive mass balance. The resulting flows were then translated into economic values (value added) using 2011 reference prices obtained from the same literature sources.

The resulting value-added flows were subsequently assigned to SHDB country-sector proxy unit processes (e.g., metal products from China), as defined during the previous risk mapping. These assignments formed the S-LCI modeled in SimaPro. Based on this inventory, SHI values were calculated for each unit process, and cumulative SHI scores were evaluated per VHR subcategory across each Tier unit process and for both supply chains.

Within this study, the SHDB online tool was used for qualitative hotspot screening, while the license-based SimaPro version enabled quantitative SHI modeling.

3. Results

The detailed social risk assessment results for each component variant are available in the supplementary materials Excel files: Sheet 1 (*Social Risk Assessment Aluminum*), Sheet 2 (*Social Risk Assessment Composite GF*), and Sheet 3 (*Social Risk Assessment Composite PP*). Despite isolated data gaps in certain issues, subcategories, countries, and sectors, the analysis effectively identified critical risk hotspots across all unit processes. A comparative analysis of these social risk hotspots for both CCB variants was conducted, followed by a social footprint assessment for the most material subcategories. Additionally, the raw SHI calculation results, including calculations from SimaPro, are provided in another Excel file in the supplementary materials: Sheet 4 (*SHI Results*).

3.1. Social risk hotspots

Building on the results of the SHDB risk mapping tool (given within the supplementary materials), the total number of HR and VHR was identified for the conventional aluminum part (see Fig. 6) and the MM4R component (see Fig. 7). The analysis illustrates the number of HR and VHR subcategories across all unit processes, categorized by Tier levels to highlight the distribution of risks within each supply chain.

For the aluminum CCB, the highest amount of social risks was identified in manganese ore mining, bauxite mining, and aluminum production, with 16, 21, and 17 HR and VHR subcategories (see Fig. 6). In contrast, processes like aluminum oxide production in Brazil had a substantially lower amount of risks (5 HR and 2 VHR subcategories). Aluminum sheet, magnesium, manganese, and graphite anode production in China also showed a lower number of HR ($n = 6$) and VHR ($n = 3$) subcategories. Tier 4, though containing only two unit processes, exhibited the highest concentration of HR and VHR subcategories, marking it as the primary source of social hotspots in the aluminum supply chain.

For the GFRP composite CCB, crude oil, Mg-oxide, and natural gas extraction posed the highest number of social risks, each with 10–11 HR and VHR subcategories (see Fig. 7), significantly lower than the aluminum component's amount of highest risk categories. Other unit

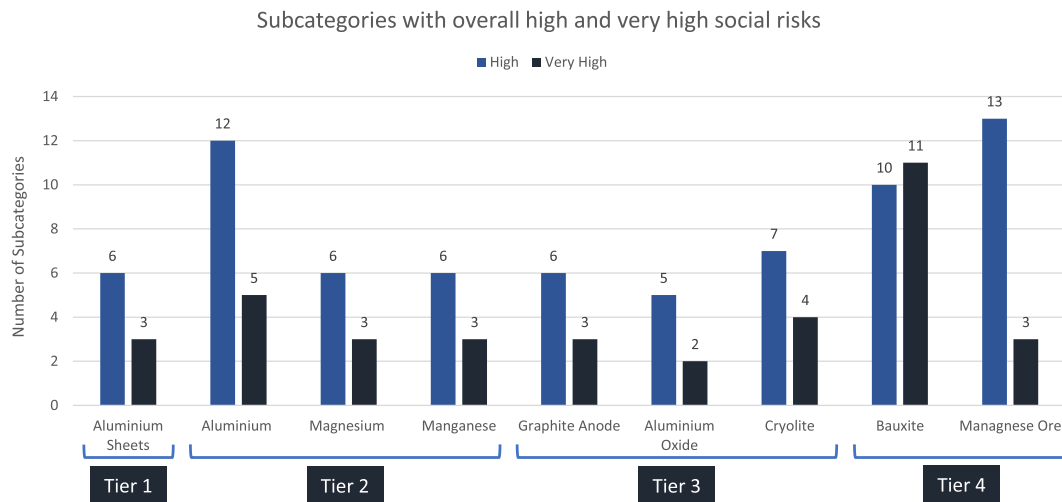


Fig. 6. Number of Subcategories with overall social HR and VHR in the aluminium supply chain.

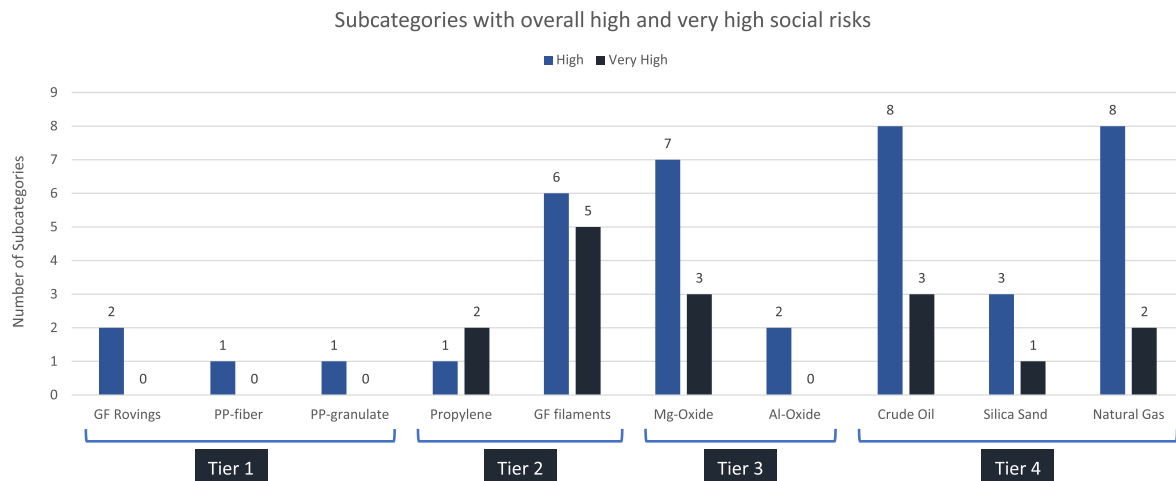


Fig. 7. Number of Subcategories with overall social HR and VHR in the GF/PP composite supply chain.

processes, such as GF rovings, PP-fiber, PP-granulate, and aluminum oxide production, revealed no subcategories assessed with VHR. Tier 4 again showed the highest concentration of HR and VHR risks. However, this elevated risk concentration is partly attributable to the larger number of unit processes included within this Tier. The analysis underscores significant social risk concentrations in both aluminium and GFRP composite CCB supply chains, particularly in Tier 4.

Moreover, the most critical social hotspots - defined as unit processes with stakeholder categories and associated subcategories classified as VHR - are presented in [Tables 1 and 2](#). To ensure transparency and enable alignment with the UNEP S-LCA Guidelines, as well as to facilitate cross-comparability with other S-LCA studies, the VHR subcategories identified through the SHDB risk assessment were systematically mapped to the corresponding social stakeholder categories and impact subcategories defined in the UNEP framework. This mapping followed a tailored allocation based on [Krekel et al. \(2024\)](#), which integrates SHDB subcategories into the UNEP framework using case studies and prior research ([Krekel et al., 2024](#)).

[Tables 1 and 2](#) thus serve a dual purpose: (i) they provide the allocation logic from SHDB stakeholder categories and subcategories to those defined by the UNEP guidelines, and (ii) they summarize the distribution of VHR impact subcategories within specific stakeholder categories and associated unit processes for both supply chains - aluminium and GFRP composite, respectively. The analysis focuses

exclusively on VHR classifications, providing a targeted view of the most severe social risks.

The results indicate 16 VHR subcategories in the aluminum CCB supply chain, according to the SHDB classification, compared to 7 in the GFRP composite supply chain. [Table 1](#) highlights a notable concentration of VHR classifications in the aluminum CCB supply chain, particularly related to freedom of association, collective bargaining, the right to strike, as well as occupational toxics and hazards - with bauxite extraction emerging as a key hotspot. In contrast, [Table 2](#) reveals a more evenly distributed pattern of VHRs across unit processes and subcategories, indicating a different social risk profile for the composite CCB component.

Ultimately, based on [Tables 1 and 2](#), the proportional distribution of VHR stakeholder categories and impact subcategories were visualized within [Figs. 8 and 9](#) to enable a comparative analysis of potential social hotspots across the two CCB product system supply chains.

For the conventional aluminium CCB supply chain, VHR classifications were limited to only two of the six stakeholder categories defined by UNEP: workers and local communities (see [Fig. 8](#)). Notably, the majority of VHR subcategories were concentrated within the workers category (~70 %), signifying this category as the most impacted in terms of social risks. Within the workers category, health and safety represented the largest share at 27 % of VHR occurrences, followed by freedom of association, collective bargaining, the right to strike at 19 %.

Table 1

SHDB assessment results for aluminum CCB supply chain: VHR subcategories mapped to UNEP guideline subcategories.

UNEP Stakeholder Categories	Local Communities							Workers									
UNEP Subcategories	Access to immaterial resources		Access to material resources				Secure living condition	Forced labor	Freedom of association, collective bargaining, right to strike	Health & Safety		Social benefits/ social security	Fair salary		Child labor	Equal opportunities/ discrimination	
SHDB Subcategories	Legal system	Democracy & freedom of speech	Access to improved source of sanitation	Access to health care	Access to electricity	Property rights	High conflict zones	Forced labor	Freedom of association, collective bargaining, right to strike	Occupational toxics & hazards	Occupational injuries & fatalities	Social benefits	Wage assessment	Workers in poverty	Child labor	Discrimination & equal opportunity	
Cryolite (China)	High	Very High	Medium	Medium	Low	Medium	High	Very High	Very High	Very High	Medium	High	Low	Medium	High	High	
Graphite Anode (China)	High	Very High	Medium	Medium	Low	Medium	High	Medium	Very High	Very High	Medium	High	Medium	Medium	Medium	High	
Bauxite (Guinea)	Very High	High	Very High	Very High	Very High	High	High	Very High	No data	Very High	Very High	Medium	Very High	Very High	Very High	Very High	
Manganese Ore (South Africa)	Medium	Medium	High	High	Medium	Very High	Medium	High	High	Very High	Very High	Medium	Low	High	Medium	High	
Aluminum Oxide (Brazil)	High	Medium	Medium	Medium	Low	High	Medium	Medium	Very High	Medium	Very High	Medium	Low	Medium	Medium	Medium	
Aluminum (India)	Medium	Medium	High	High	Medium	High	Very High	Very High	Very High	High	High	Very High	Low	High	Very High	High	
Alu-Sheets (China)	High	Very High	Medium	Medium	Low	Medium	High	Medium	Very High	Very High	Medium	High	Low	Medium	Medium	High	
Magnesium (China)	High	Very High	Medium	Medium	Low	Medium	High	Medium	Very High	Very High	Medium	High	Low	Medium	Medium	High	
Manganese (China)	High	Very High	Medium	Medium	Low	Medium	High	Medium	Very High	Very High	Medium	High	Low	Medium	Medium	High	

The GFRP composite CCB supply chain (see Fig. 9) exhibited fewer VHR classifications overall, with seven subcategories identified compared to ten in the aluminum supply chain. Similar to aluminum, VHRs in the GFRP supply chain were also confined to the workers and local communities' categories. The workers category again accounted for the majority of VHR subcategories (~69 %), with freedom of association, collective bargaining, the right to strike comprising 25 % of risks. Forced labor followed at 19 %, significantly higher than the 8 % observed in the aluminum supply chain.

These findings highlight that VHRs were confined to only two stakeholder categories - workers and local communities - in both supply chains. Despite differences, the VHR subcategories in both supply chains overlapped entirely, suggesting shared vulnerabilities in critical areas. Remarkably, the GFRP composite CCB supply chain is associated with a lower quantity of subcategories classified with VHR compared to the conventional aluminum supply chain.

Since all VHR subcategories in the GFRP composite supply chain overlap with those in the aluminum supply chain, the aluminum supply chain is the primary driver for the subcategory selection in the social footprint assessment.

3.2. Social footprint results

The calculated SHI values provide a quantitative perspective on the social risks identified in the prior hotspot analysis. The results illustrate how labor intensity and supply chain configuration influence potential social impacts across stakeholder categories and impact subcategories. SHI values are reported in mrheq, and allow for a direct comparison between the reference aluminum CCB and the MM4R composite CCB variants, considering the quantitative material flows of both variants.

The social footprint analysis focused exclusively on the 16 stakeholder subcategories previously identified as VHR in the risk assessment.

Material masses were first translated into economic value added (in USD), based on secondary 2011 reference year pricing, to align with the SHDB modeling structure. Where 2011 prices were unavailable (e.g., GF-roving, PP-fiber, cryolite), more recent market prices were used and validated for low volatility (Manson, 2021; Statista, 2024). Yet, cryolite prices remained uncertain due to the limited availability of secondary data, leading to the assumption of stability over time. Table A.3 contains the full breakdown of the input-output model, including country-sector selections and values added across all Tiers. The aggregated total values added up to \$44.83 for the conventional aluminum CCB and \$62.16 for the MM4R composite CCB, reflecting the economic contributions of intermediate products without considering regional price adjustments.

Cumulative SHI values were calculated for both CCBs and visualized for each VHR subcategory, disaggregated across the four supply chain Tiers and unit processes (Fig. 10). To ensure a fair comparison between the conventional CCB and MM4R CCB SHIs, an alternative scenario for the MM4R CCB was modeled using an Asia-based Tier 2 supply chain (derived from bottom-up export statistics and given within Table A.2), complementing the Europe-based configuration.

The results identify key social hotspots in each Tier, considering the unit processes with the highest SHI values. However, while cumulative SHI values highlight tier-specific hotspots, they do not fully capture overarching supply chain dynamics, such as the comparative impact quantity of bauxite extraction at Tier 4 versus aluminum sheet manufacturing at Tier 1. Instead, the findings emphasize aggregated hotspots at each Tier, pinpointing unit processes driving the respective social impacts. This tier-specific approach provides the nuanced understanding necessary for evaluating complex supply chains.

The social footprint assessment reveals a divergence in cumulative SHIs between the aluminum and MM4R composite CCB components. The aluminum CCB consistently shows higher aggregated SHIs across all Tiers, reflecting greater potential social impacts. Even with the Asia-

Table 2

SHDB assessment results for GFRP composite CCB supply chain: VHR Subcategories Mapped to UNEP guideline subcategories.

UNEP Stakeholder Categories	Local communities		Workers				
UNEP Subcategories	Access to immaterial resources	Access to material resources	Forced labor	Freedom of association, collective bargaining, right to strike	Health & Safety	Social benefits/ social security	Child labor
SHDB Subcategories	Democracy & freedom of speech	Property rights	Forced labor	Freedom of association, collective bargaining, right to strike	Occupational toxics & hazards	Social benefits	Child labor
GF Roving (SVK)	Low	Medium	High	Medium	High	Low	Low
GF Filaments (CN)	Very High	Medium	Very High	Very High	Very High	High	Very High
Magnesium Oxid (CN)	Very High	Medium	Medium	Very High	Very High	High	Medium
Aluminium Oxide (AUS)	Low	Medium	Low	High	Medium	Medium	Low
Silica Sand (US)	Medium	Medium	Low	High	Medium	Very High	Medium
PP Fibers (DE)	Low	Medium	Medium	Low	High	Low	Low
Polypropylene (DE)	Low	Medium	Medium	Low	High	Low	Low
Propylene (KOR)	Low	High	Very High	Very High	Medium	Medium	Low
Natural Gas (QAT)	Very High	No Data	Very High	High	Low	Medium	Medium
Crude Oil (SAU)	Very High	Very High	Medium	Very High	Low	Medium	Medium

based supply chain scenario for the MM4R component, the composite's overall impact remains lower, with reductions exceeding 30 % across all subcategories compared to the aluminum CCB. Exceptions include wage assessment; freedom of association, collective bargaining, right to strike (limited to the Asia-based composite supply chain); occupational toxics and hazards (limited to the Asia-based composite supply chain); democracy and freedom of speech; and access to electricity, where reduction potentials are slightly lower but still within 24–30 %. The most significant reduction is seen in occupational injuries and fatalities, with the MM4R composite achieving a 36 % reduction, underscoring its effectiveness in improving workplace safety. Conversely, the lowest reduction is observed in democracy and freedom of speech, with reductions of 27.8 % and 24.2 % for EU- and Asia-based supply chains, respectively.

Furthermore, the cumulative SHI assessment reveals that both the conventional aluminum and GFRP composite CCB components share the same unit process hotspots. However, the MM4R composite consistently exhibits a proportionally smaller quantity of impacts for these processes. Aluminum-based supply chain processes remain the dominant drivers of social impacts across all Tiers, with significant contributions from raw material extraction (Tier 4) and processing stages (Tier 2).

The potential social impact patterns are particularly pronounced in specific subcategories. Hotspots for the subcategories forced labor; workers in poverty; child labor; access to an improved source of sanitation; access to health care; and property rights, are concentrated in Tier 4 (bauxite extraction) and Tier 1 (aluminum sheet production). Similarly, subcategories such as occupational toxics and hazards; wage assessment; discrimination and equal opportunity; occupational injuries and fatalities; legal systems; democracy and freedom of speech; and high conflict zones exhibit main hotspots across Tier 4 (bauxite extraction), Tier 2 (aluminum processing), and Tier 1 (aluminum sheet manufacturing). A smaller set of subcategories - freedom of association, collective bargaining, and the right to strike; social benefits; and access

to electricity - show significant contributions from unit processes at Tier 2 (aluminum production) and Tier 1 (aluminum sheet manufacturing).

Notably, access to electricity stands out as the only subcategory with hotspots across all Tier levels, linked to distinct unit processes such as crude oil extraction (Tier 4), graphite anode production (Tier 3), aluminum processing (Tier 2), and aluminum sheet manufacturing (Tier 1). While Tier 3 typically contributes lower quantities to the overall cumulative SHI, graphite anode production emerges as the primary impact driver in this Tier, though its impacts remain significantly lower than those in Tiers 4, 2, and 1. Yet, all these hotspots remain directly connected to the aluminum supply chain.

Overall, the social footprint assessment complements the risk hotspot analysis by adding quantitative depth and material flow specificity, thereby facilitating a robust and comparative evaluation of both product systems' social sustainability profiles. The MM4R GFRP composite CCB consistently demonstrates lower social impacts compared to the aluminum reference CCB, reducing cumulative SHIs across the supply chain. These results also highlight specific subcategories and unit processes where targeted interventions could further enhance social outcomes.

4. Discussion

This study advances the field of sustainability assessments in the automotive industry by employing S-LCA to compare social risks and potential impacts between aluminum and GFRP composite CCB components. By applying the UNEP S-LCA guidelines as well as the ISO 14075 standard and using the SHDB, this research offers new insights into the social sustainability implications of transitioning from light-weight aluminum to composite products. Combining social risk hotspot analysis with a social footprint assessment, the study provides a comprehensive understanding of how material substitution influences social sustainability across supply chains. While prior literature has

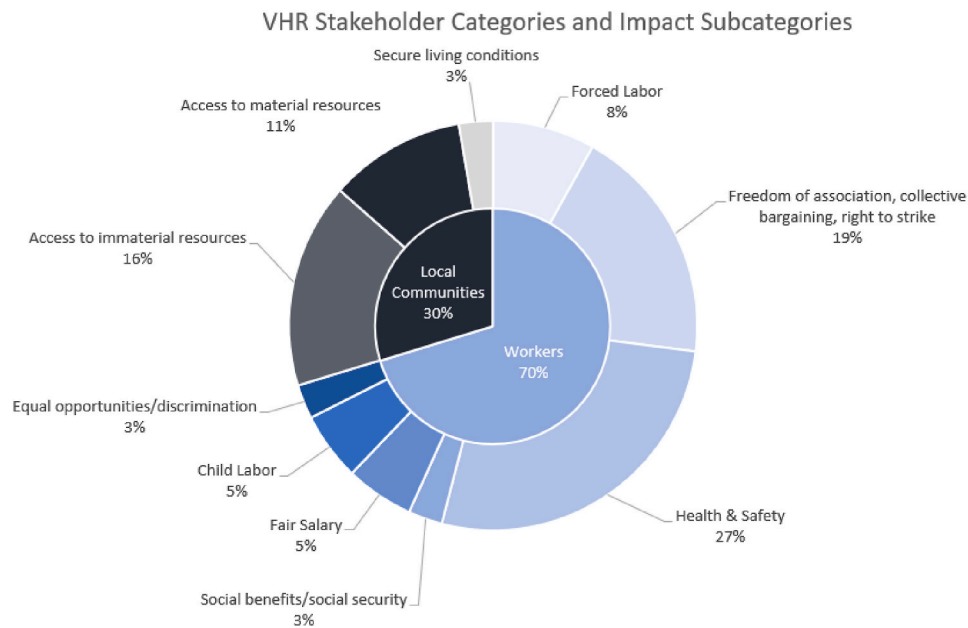


Fig. 8. Mapping of VHR categories and subcategories in the aluminum CCB supply chain to UNEP guidelines.

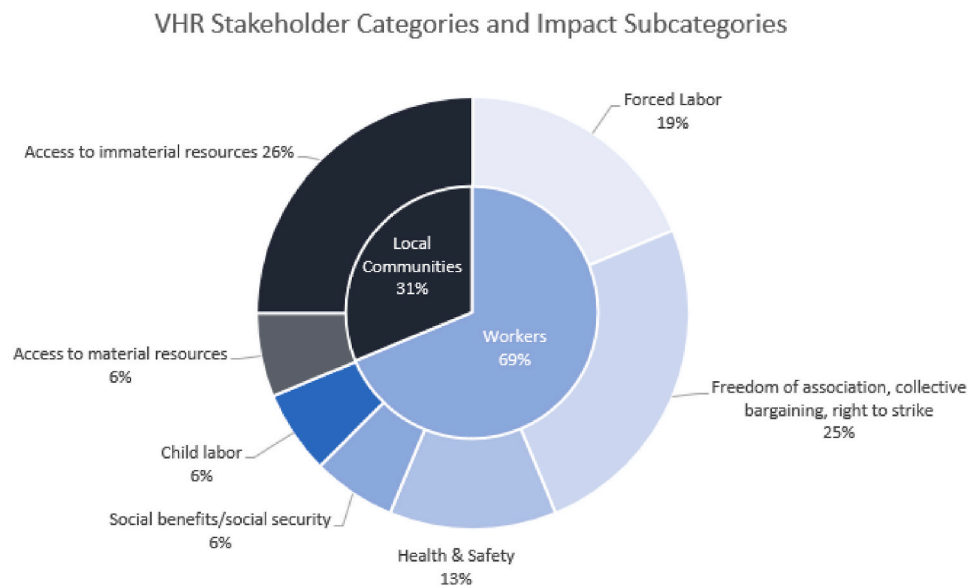


Fig. 9. Mapping of VHR categories and subcategories in the GFRP composite CCB supply chain to UNEP guidelines.

assessed individual component materials or supply chain actors in the automotive sector (Luthin et al., 2024), this study contributes the first comparative S-LCA focused on functionally equivalent lightweight products in an early design-phase automotive context.

The social risk hotspot analysis identified workers and local communities as the only stakeholder categories with VHR subcategories in both supply chains. This outcome is consistent not only with prior automotive-related S-LCA studies (Luthin et al., 2024), but also with sector-overlapping assessments of aluminum supply chains, including window (Di Giorgio et al., 2024) and bicycle frames (Chang et al., 2012), which similarly reported elevated risks for these stakeholder groups in relation to aluminum processing and sourcing. This study additionally complements existing evidence by extending the same findings to the GFRP supply chain, highlighting the overall centrality of these stakeholder groups in automotive S-LCAs. The alignment with existing research enhances the robustness of these findings while addressing a

gap in S-LCA literature, where comparative analyses of aluminium and composites for automotive components have not been performed.

Moreover, the social footprint assessment demonstrated significant quantitative reductions in cumulative SHI values (24 %–36 %) across VHR subcategories when aluminum was partly replaced by GFRP composites. This reduction was consistent across both Europe- and Asia-based supply chains, emphasizing composites' broad potential to mitigate social impacts. Notably, all SHI hotspots in the composite component supply chain were linked to the residual aluminum-related unit processes, as some aluminum remains necessary for mechanical properties. This highlights aluminum's labor-intensive nature as a key driver of social hotspots and underscores the need for interventions in aluminum-related processes. Interestingly, while no studies comparing SHIs exist, these findings diverge from some prior studies suggesting composites could exhibit higher labor intensity due to supply chain immaturity (Atescan-Yukseket al., 2024; Hasan and Wuest, 2022). This

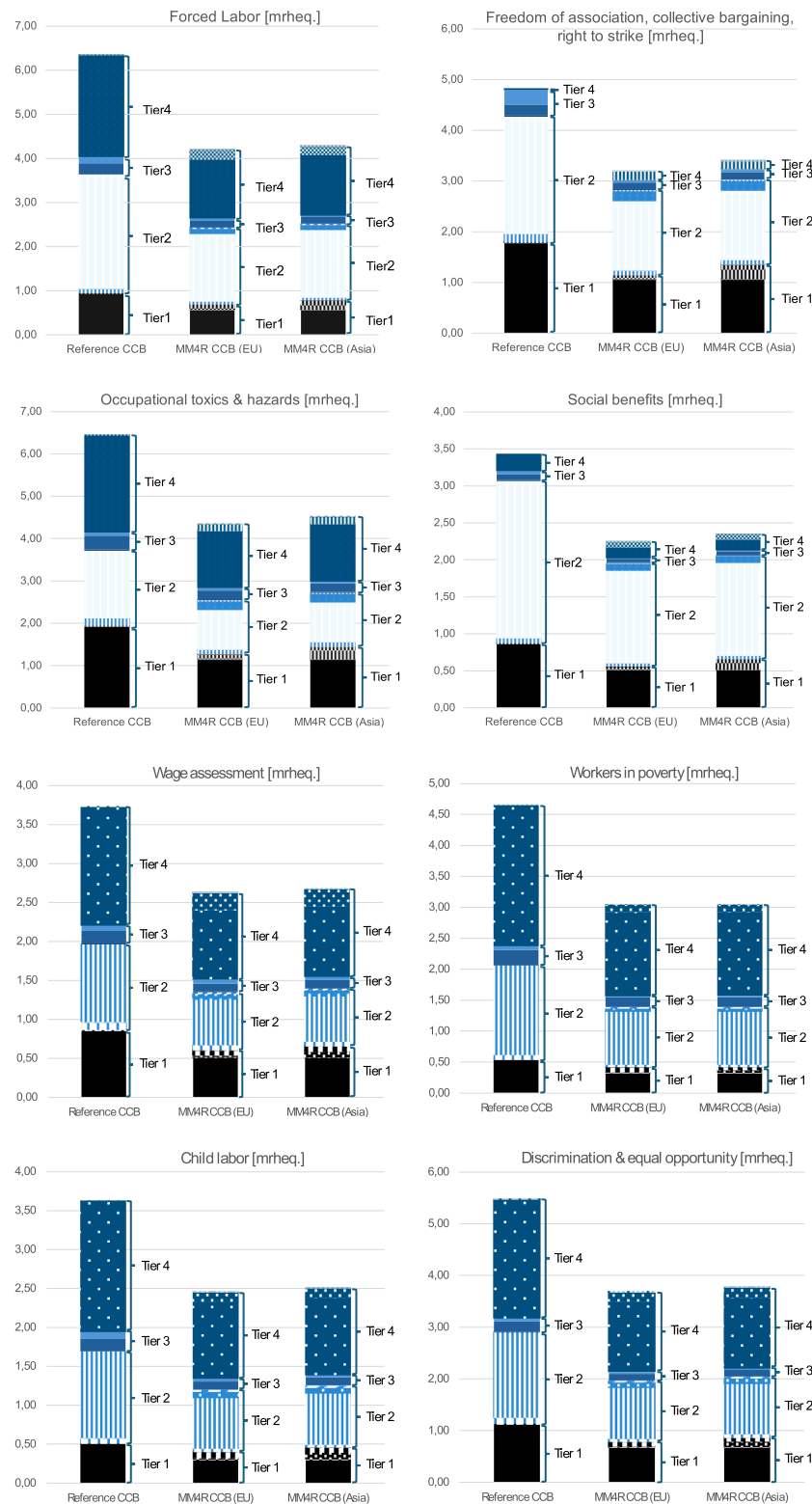


Fig. 10. SHI results for VHR subcategories in different CCB supply chains.

contrast highlights the importance of modeling supply chains using sector- and region-specific data, as applied in this study, to reflect plausible sourcing scenarios and to generate insights that are relevant to the specific product and industry context.

Given the limited availability of directly comparable S-LCA studies,

the identified potential social impact hotspots in the aluminum supply chain, particularly related to the unit processes of bauxite extraction (Tier 4), aluminum manufacturing (Tier 2), and aluminum sheet production (Tier 1) are consistent with existing qualitative findings. [Dibattista et al. \(2023\)](#) highlighted the severe health, social, and

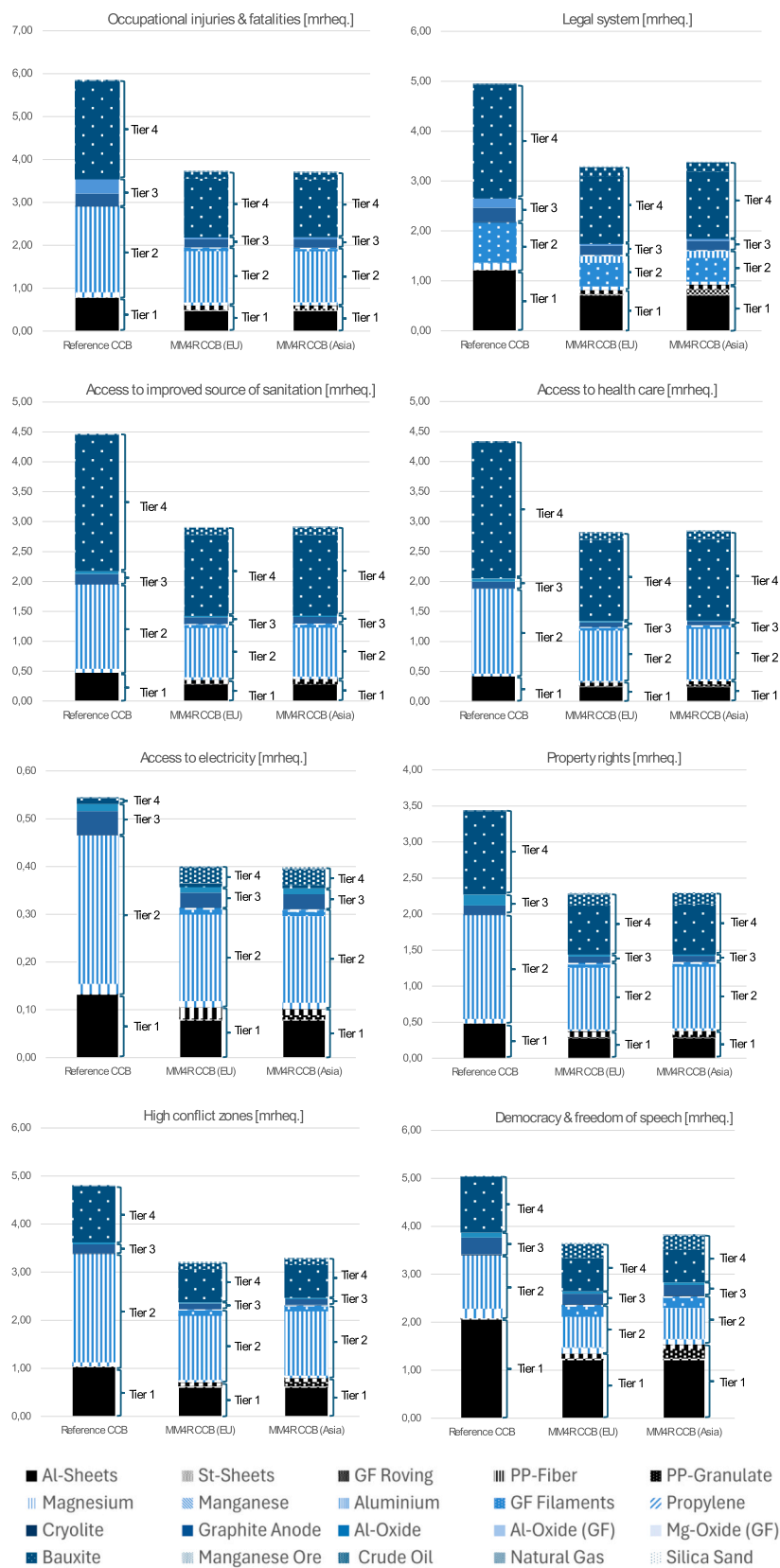


Fig. 10. (continued).

governance challenges associated with unregulated bauxite mining, including social inequalities, corruption, and lack of regulation (Dibattista et al., 2023). In contrast, no prior studies were identified that qualitatively or quantitatively assess the social impacts of GFRP production. Thus, by quantifying these risks and placing them within a comparative tiered supply chain framework, this study builds on prior research and provides actionable insights for stakeholders aiming to address these potential hotspots.

When considering whether patterns commonly emphasized in general S-LCA literature - such as geographic variability a factor often emphasized in the broader context of S-LCA studies (Tokede and Traverso, 2020; Krekel et al., 2024) - could be validated, we found that these played a minor role in this case study. Europe- and Asia-based GFRP composite supply chains exhibited only marginal differences in cumulative SHI values. Instead, material substitution was the primary driver of social impact reduction, with composite supply chains consistently outperforming aluminum. In this case study, material choice had a more pronounced influence on social risk profiles than regional supply chain differences, though geographic localization remains a key determinant of social sustainability in other contexts and should not be understated.

Overall, the findings highlight that substituting aluminum with GFRP composites in lightweight automotive CCBs can enhance social sustainability by lowering exposure to labor-intensive and high-risk supply chains, demonstrating the potential of material innovation to mitigate social impacts. While other studies have demonstrated the environmental and economic advantages of composite materials in automotive applications (Delogu et al., 2016; Witik et al., 2011), this research extends prior analyses by providing quantitative evidence of potential social impact reductions across specific subcategories, addressing an important gap in S-LCA literature.

Despite the promising results, several methodological limitations must be acknowledged, many inherent to the tools and datasets employed.

A key methodological limitation lies in the evaluated number of unit processes explicitly modeled, which may appear to underrepresent the inherent complexity of global automotive supply chains (Karlewski et al., 2019). However, this streamlining was necessary to ensure methodological coherence, as only processes with a material or functional contribution to the CCB - and for which country-sector risk data could be reliably obtained - were included. This prioritization reflects established guidance under ISO 14075 and the UNEP S-LCA guidelines, which allow for cut-off criteria based on system relevance, decision-making stakeholder influence, and data granularity (ISO, 2024; UNEP, 2020). While background and globally diversified processes were excluded, these would have introduced assumptions and contributed little to differentiating social hotspots across the two product systems, especially given their typically low labor intensity (Sovacool et al., 2020) and limited traceability from an OEM perspective. Importantly, the selected unit processes account for the dominant share of social risks observed in the results, particularly within aluminum extraction and processing, indicating that the most decision-relevant hotspots were captured. Nonetheless, we acknowledge that a more comprehensive inventory - especially incorporating upstream background processes and site-specific supplier data - would enhance the resolution of future S-LCA studies and support more granular social performance evaluations.

Another limitation arises from the use of aggregated country-sector-level inputs in the SHDB, which, while ensuring scalability, fails to capture country- and process-specific differences within broad economic sectors. This limitation is particularly pronounced within unit processes like bauxite mining aggregated to mining extraction processes, where results can vary substantially across geographic regions and even among different mineral extraction operations. It also contributes to the lack of sufficiently detailed data on recycling operations, which are not distinctly represented within the current SHDB structure and partly led to the exclusion of EoL processes. As Karlewski et al. (2019) suggest,

integrating site-specific data is essential to enhance S-LCA accuracy (Karlewski et al., 2019). However, due to limited availability, this study relied on secondary data with multiple layers of aggregation, mapping unit processes to OEC export statistics and GTAP sectors. Although necessary for harmonization, this approach may over- or under-represent specific social risks, limiting analytical precision. Addressing these aggregation challenges in future research will be critical for improving the reliability and applicability of S-LCA methodologies.

Besides, the SHDB's estimation of risk hours is based on work hours derived from sector-level added value, which can be altered by price variations between countries, independent of actual production or social context changes, which introduces further limitations. Such fluctuations, outside the authors' control, can affect the reliability of risk estimates, particularly in multi-regional assessments. Additionally, the reliance on 2011 as the SHDB reference year is also a constraint. Economic and regulatory conditions have likely evolved, potentially leading to discrepancies in risk assessments. As noted in previous studies, utilizing static data introduces challenges in representing dynamic changes within supply chains (Tokede and Traverso, 2020). In this context, another constraint lies in the assumptions regarding the stability of material prices over time when no secondary data could be identified. While price fluctuations were minimal for most materials, the absence of recent data for cryolite may have introduced biases. Incorporating dynamic or updated datasets in future research would improve the relevance and accuracy of assessments.

Furthermore, this study acknowledges the inherent uncertainties in early-stage S-LCA, particularly those arising from reliance on secondary data sources, proxy modeling, and country-sector level assumptions. In line with the UNEP S-LCA guidelines and ISO 14075, a deterministic modeling approach was employed, prioritizing transparency and relevance over quantitative uncertainty propagation. Although a formal sensitivity analysis was not conducted, the study design incorporated multiple measures to mitigate uncertainty. These include the use of conservative country allocation strategies based on dominant trade flows, exclusion of globally diversified materials with low social differentiation, and a tiered process prioritization to focus on VHR stakeholder-subcategory combinations only. Also, an alternative sourcing scenario was modeled for the GFRP composite supply chain using Asia-based suppliers to test the robustness of the findings against geographic variability in risk profiles. This comparison confirmed the persistence of potential impact differences between the two material systems and minimized the likelihood of overestimating social performance improvements. A formal parametric or probabilistic sensitivity analysis was deemed infeasible given the categorical structure of the SHDB social risk data, the absence of underlying statistical distributions, and the lack of process-specific uncertainty ranges. This limitation is consistent with current practice in S-LCA research, where transparency in assumptions, scenario testing, and hotspot prioritization are widely applied in lieu of full-scale uncertainty modeling (Backes and Traverso, 2023; Luthin et al., 2024). Thus, while uncertainty remains a relevant consideration, the measures taken in this study ensure that the most socially material hotspots are captured and the comparative findings remain robust and decision-relevant within the defined goal and scope.

Overall, it is also important to note that as the results are not intended for direct supply chain decision-making but to identify stakeholder categories and impact subcategories requiring further investigation during composite CCB development. Actual impacts require primary data from specific suppliers, which was beyond the scope of this study. Thus, the findings emphasize the need for supplier-specific, granular data to transition from generalized insights to actionable strategies. This study's results guide the prioritization of stakeholder categories, particularly worker-related subcategories like occupational safety and labor rights, which emerged as predominant VHR occurrences. These priorities align with recent calls to focus on workers as a critical stakeholder category in automotive supply chains (Luthin et al.,

2024), emphasizing the importance of addressing systemic risks through corporate and industry-wide initiatives.

In light of evolving regulatory frameworks, such as the CSDDD as well as the CSRD (Bueno et al., 2024), and the recent calls for more integrated sustainability frameworks (Falcone and Tutore, 2025), the findings underscore the importance of addressing social sustainability proactively. Identified hotspots in aluminum and composite supply chains can inform corporate as well as industry-wide initiatives to assess and reduce social risks effectively. Moreover, as recent research suggests, enhancing social performance transparency through S-LCA can also support sustainable finance strategies by informing investors and regulators about material social risks and due diligence efforts (Falcone and Sica, 2024; Ostojic et al., 2024a).

Future studies should prioritize collecting site-specific data from high-risk unit processes, such as bauxite mining and aluminum manufacturing, to enhance the granularity and accuracy of the social sustainability assessment. Additionally, expanding system boundaries to include the EoL phase would require improvements either in primary data availability or in secondary data coverage, as current S-LCA databases like SHDB lack sufficiently detailed unit processes for recycling. Once such data becomes available, including EoL processes could provide a more holistic perspective on the social impacts of lightweight automotive components. However, this is unlikely to alter the main findings, as current recycling processes - especially for aluminum and polymers - are typically mechanized, regulated, and low in social risk compared to the upstream extraction and production stages, which remain the dominant sources of social impact (Behera et al., 2014; Jiang and Bateer, 2025; Yi et al., 2022; Zambrano et al., 2024).

Ultimately, while this study compared primary aluminum to composite materials under early-stage design conditions, future work should also explore the social sustainability implications of using secondary aluminum in automotive applications. As recycled aluminum avoids the socially intensive processes of bauxite extraction and primary smelting, it could potentially offer a lower-risk alternative. However, this would require consistent traceability of recycled sources, access to region-specific data, and database integration capable of distinguishing secondary from primary aluminum - limitations currently not addressed within SHDB. Additionally, assessing secondary aluminum within an S-LCA would require the application of allocation methods, analogous to those employed in environmental LCA. Numerous allocation approaches exist, often giving rise to contentious discussions within the field (Allacker et al., 2017). Therefore, it would be essential to integrate such methodologies in the evaluation of social impacts associated with EoL recycling processes. Moreover, recycling material modeling would also need to include GFRP materials to enable a balanced comparison. While environmental LCA studies consistently show that aluminum recycling provides substantial environmental advantages over polymers and composites (Accardo et al., 2023; Atescan-Yuksekk et al., 2024), this assumption cannot be directly translated to S-LCA. To date, there is no empirical evidence suggesting that higher recycling rates (Baldassarre et al., 2025; European Aluminium, 2022) and the associated environmental burdens of landfilling (Atescan-Yuksekk et al., 2024), as identified in previous LCAs, also correlate with reduced social risks. On the contrary, increased labor intensity in certain recycling streams - especially under informal or weakly regulated conditions - may elevate social risks (Sovacool et al., 2020). Therefore, whether secondary aluminum outperforms recycled GFRP composites from a social sustainability perspective remains uncertain and cannot be assumed without robust, case-specific evidence. Nonetheless, such future analyses are critical to better understand the social trade-offs between circular economy strategies and innovation-driven material substitution.

Finally, integrating these advancements with social, environmental, and economic assessments under the LCSA framework would enable more comprehensive evaluations of product sustainability, supporting robust decision-making in the automotive industry.

Nevertheless, future research can build on the two-step approach

developed in this study by applying it to additional automotive components and other sectors to understand potential social hotspots and prioritize relevant social indicators to be assessed in the further development stages. Additionally, the study also showed that further methodological development of S-LCA databases is needed to address data aggregation challenges and improve the granularity of social impact modeling. This includes improving database coverage for more detailed unit process-level data and better regional differentiation. Most importantly, coupling the social assessment with environmental and economic life cycle models to enable full LCSA is crucial to providing a holistic basis for evaluating new CCB lightweight product systems. Such integration is essential for identifying trade-offs between sustainability dimensions and for supporting comprehensive decision-making in early design phases.

5. Conclusions

This study contributes to the advancement of S-LCA methodologies by conducting a comparative case study of the social sustainability of aluminum and multi-material GFRP composite automotive products. Through the integration of UNEP S-LCA guidelines and the ISO 14075 standard, the research assessed social risk hotspots and quantified potential social impacts using a social footprint approach. The analysis offers new insights into the role of material substitution in reducing potential social impacts and enhancing social sustainability performance within automotive supply chains.

The research aimed to achieve three main objectives: (i) to compare potential social risk profiles across two materially distinct CCB supply chains; (ii) to quantify potential social impacts using the SHI; and (iii) to assess the methodological feasibility and relevance of this approach for early-stage product development.

In line with these goals, the study found that social risks are more concentrated in the aluminum-based supply chain - particularly processes such as bauxite mining, aluminum manufacturing, and aluminium sheet production - whereas the GFRP-based component exhibited a lower number of VHR subcategories. The results reveal that workers and local communities are the most relevant stakeholder categories across both CCB component supply chains. These findings align with prior studies, highlighting persistent challenges in aluminum production, including labor-intensive operations and governance deficits. The social footprint assessment, based on SHI values, confirmed that substituting aluminum with GFRP composites demonstrated significant reductions in potential cumulative SHI values, ranging from 24 % to 36 % across critical VHR subcategories, irrespective of geographic supply chain configurations.

The results demonstrate the feasibility of applying a two-step S-LCA framework during early product development to identify socially relevant hotspots and support decision-making for future S-LCA studies on relevant stakeholders, impact subcategories, and supply chain unit processes. From a practical perspective, these insights can support OEMs and suppliers in the automotive sector in prioritizing workers and local communities when assessing social risk profiles, thereby informing targeted sustainability reporting and aligning with emerging due diligence requirements. Importantly, the findings presented reflect potential social risks and impacts based on generalized, aggregated country- and sector-level data derived partly from secondary and primary sources using the SHDB. While valuable for identifying stakeholder categories and impact subcategories requiring further attention, these results are not suitable for direct supply chain decision-making, altering supplier choices. For this purpose, actual impacts must be assessed using granular, company-supplier-specific primary data, which was beyond the scope of this study. Nonetheless, this study provides a screening-level foundation that can support broader corporate social risk management efforts and compliance with regulatory frameworks such as the CSRD or CSDDD. Future assessments must address this limitation by integrating site-specific data to enable actionable strategies.

Beyond its immediate findings, this research identifies key opportunities for improving S-LCA methodologies. While excluded from this case study due to methodological and data limitations, expanding system boundaries to include downstream lifecycle stages - particularly EoL recycling processes - represents a critical avenue for future studies aiming to achieve a more holistic understanding of social sustainability. Additionally, incorporating dynamic models to account for temporal and regional variability in social, economic, and regulatory conditions will enhance the granularity and relevance of S-LCA outcomes. Moreover, improving social performance transparency can be an enabler for sustainable investment decisions, linking S-LCA insights to broader sustainable finance frameworks.

Future research should also investigate the broader applicability of the two-step assessment approach used in this study to evaluate potential social hotspots in other automotive components or different industries. Given the early design stage of the cockpit CCB case study, this approach has proven particularly valuable for identifying potential stakeholder- and process-specific risk hotspots before finalizing design and sourcing decisions. Such early-phase assessments can be instrumental in integrating social sustainability into product innovation, procurement, and financial risk evaluation frameworks. Most importantly, future studies should aim to integrate social, environmental, and economic assessments within an LCSA framework. Such integration would enable a more comprehensive evaluation of sustainability trade-offs, supporting decision-making during the early development phases of advanced lightweight components.

In conclusion, this study provides a robust assessment of the social sustainability benefits of transitioning from aluminum to GFRP composites in automotive lightweight applications. It highlights the critical role of material innovation in reducing social risks and potential impacts. The findings are not only relevant to engineering and supply chain

decisions but also carry implications for ESG reporting, responsible investment practices, and policy development. Future research and industry initiatives can build on these findings by addressing methodological limitations and leveraging the opportunities identified to drive meaningful progress toward socially responsible and sustainable supply chains.

CRedit authorship contribution statement

Suzana Ostojic: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marzia Traverso:** Writing – review & editing, Validation, Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The MM4R research and development project is funded by the Federal Ministry for Economic Affairs and Energy (BMWE) under the funding code 03LB3026 and supervised by Project Management Jülich (PTJ). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2025.146361>.

Appendix

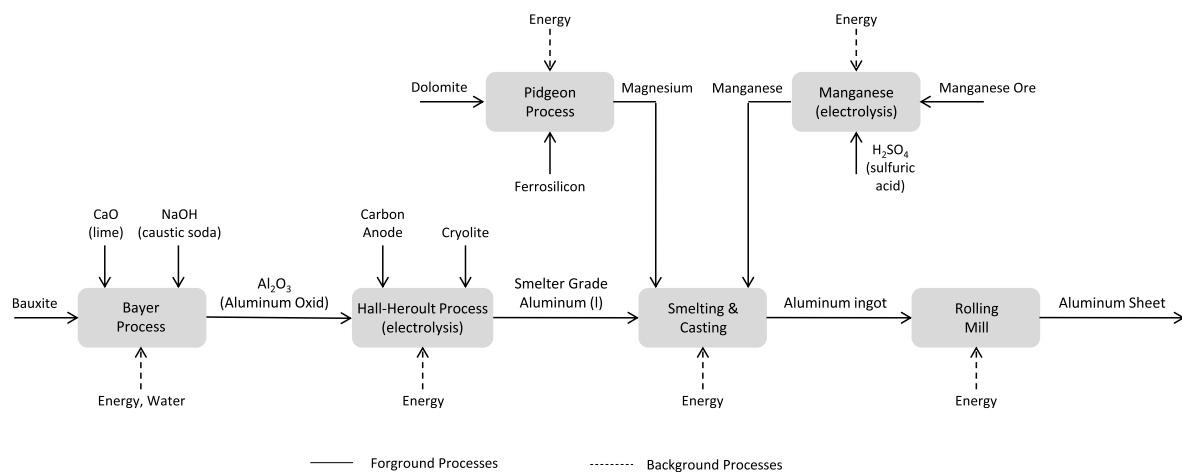


Fig. A. 1. Aluminum sheet production process flow diagram.

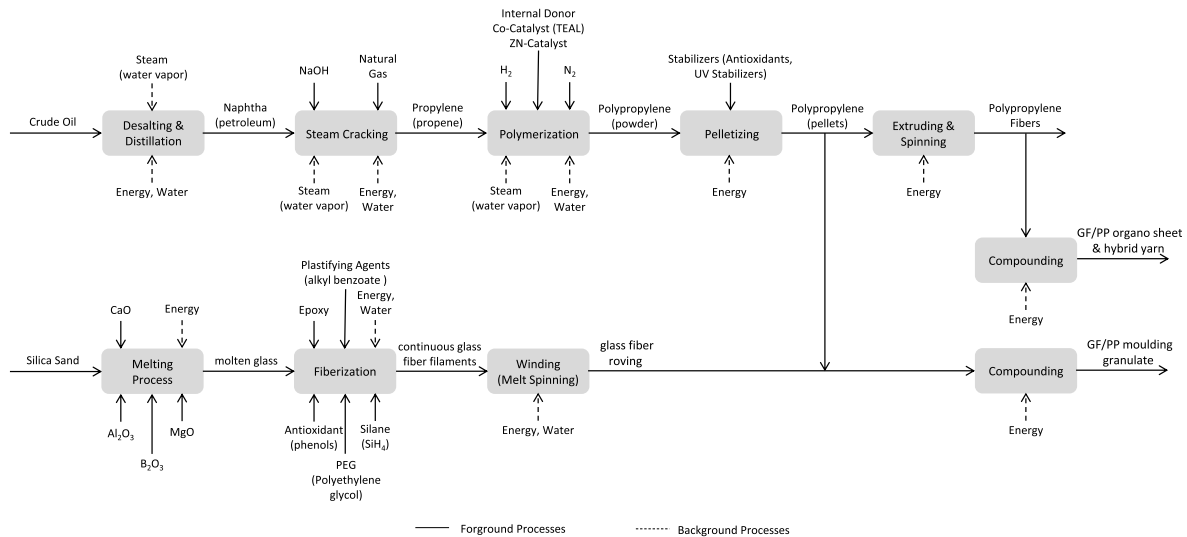


Fig. A. 2. GF/PP composite production process flow diagram.

Table A.1
Aluminum supply chain data

Product	OEC	Export Countries	GTAP	SHDB sector
Aluminum sheet	Aluminium alloy plate, sheet, strip	China (20,8 %) , South Korea (8,05 %), Saudi Arabia (8,03 %)	fmp	Metal products
Aluminum	Aluminium unwrought, not alloyed	India (16,6 %) , Russia (12,7 %), Australia (8,15 %)	nfm	Metals nec
Magnesium	Magnesium	China (59,2 %) Israel (5,57 %), Turkey (3,66 %)	nfm	Metals nec
Manganese	Manganese	China (66,1 %) , Indonesia (9,25 %), South Africa (6,68 %)	nfm	Metals nec
Aluminum oxide	Aluminium Oxide	Australia (32 %) , Brazil (17,3 %), China (9,39 %)	nmm	Mineral products nec
Cryolite	Sodium hexafluoroaluminate (synthetic cryolite)	China (27,3 %) , Denmark (11,4 %), Germany (10,7 %)	chm	Chemical, rubber, plastic products
Graphite Anode	Graphite	China (51,3 %) , Mozambique (10,5 %), Madagascar(9,81 %)	p_c	Petroleum, coal products
Bauxite	Aluminium Ore	Guinea (64,3 %) , Australia (12 %), Indonesia (9,33 %)	oxt	Minerals nec
Lime (CaO)	Quicklime	France (14,2 %), Germany (8,74 %), Malaysia (6,8 %)	nmm	Mineral products nec
Dolomite	Dolomite	Belgium (13,5 %), Greece (7,26 %), Bhutan (7,17 %)	nmm	Minerals nec
Ferrosilicon	Ferro silicon (<55 % silicon)	Canada (14,3 %), Norway (13 %), China (11,2 %)	i_s	Ferrous metals
Manganese Ore	Manganese Ore	South Africa (39,7 %) , Gabon (24,5 %), Australia (18,6 %)	oxt	Minerals nec
H ₂ SO ₄	Sulfuric Acid	China (19,3 %), South Korea (9,71 %), Japan (9,13 %)	chm	Chemical, rubber, plastic products

Table A.2
GF/PP composite supply chain data

Product	OEC	Export Countries	GTAP	SHDB sector
Polypropylene Fibers	Fibres: synthetic filament tow, of polypropylene	Primary data: Germany Secondary Data: South Korea (39,4 %) , China (21,7 %), South Africa (12,5 %)	tex	Textiles
Polypropylene (powder & pellets)	Polypropylene	Primary data: Germany Secondary Data: Saudi Arabia (18,5 %) , South Korea (8,66 %), United States (6,6 %)	rpp	Chemical, rubber, plastic products
ZN-catalyst	n.d.	n.d.	—	—
Antioxidant Stabilizers	Phenols	South Korea (11,4 %), Japan (10,2 %), Chinese Taipei (9,52 %)	chm	Chemical, rubber, plastic products
UV Stabilizers	Amine Compounds	China (26,2 %), United States (13,6 %), Belgium (11,4 %)	chm	Chemical, rubber, plastic products
Hydrogen (H ₂)	Hydrogen	China (18,1 %), Germany (13,2 %), United States (12,7 %)	chm	Chemical, rubber, plastic products
Nitrogen (N ₂)	Nitrogen	Belgium (24,3 %), Germany (10,1 %), United States (7,67 %)	chm	Chemical, rubber, plastic products
Propylene	Propylene (Propene)	South Korea (21,6 %) , Netherlands (9,84 %), China (8,53 %)	chm	Chemical, rubber, plastic products
Caustic Soda (NaOH)	Sodium hydroxide (caustic soda) in aqueous solution	United states (23,8 %), China (14,3 %), Germany (8,95 %)	chm	Chemical, rubber, plastic products
Natural Gas	Natural gas, liquified	Australia (20,2 %), United States (19,7 %), Qatar (18,3 %)	gas	Gas
Naphtha (petroleum)	Refined petroleum	United States (12,8 %), India (8 %), Netherlands (6,32 %)	p_c	Petroleum, coal products
Crude Oil	Crude petroleum	Saudi Arabia (16,2 %) , Russia (9,14 %), Canada (8,48 %)	oil	Oil

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Table A.2 (continued)

Product	OEC	Export Countries	GTAP	SHDB sector
Glass Fiber Roving	Glass fibers	Primary data: Slovakia Secondary Data: China (24 %) , United States (8,54 %), Germany (6,89 %)	nmm	Mineral products nec
Continuous Glass Fiber Filaments	Glass Fibre Fabric: Lightweight & Fine Filaments	Chinese Taipei (93,4 %) , Japan (2,97 %), China (1,86 %)	nmm	Mineral products nec
PEG (Polyethylene glycol)	Artificial and prepared waxes, of polyethylene glycol	South Korea (31,1 %), Germany (23,5 %), China (9,8 %)	chm	Chemical, rubber, plastic products
Silane (SiH ₄)	n.d.	n.d.	–	–
Epoxy (Film Former)	Epoxides, epoxy -alcohols, -phenols, -ethers nes, derivs	Netherlands (27 %), China (23,7 %), Japan (16,6 %)	chm	Chemical, rubber, plastic products
Antioxidant Stabilizers	Phenols	South Korea (11,4 %), Japan (10,2 %), Chinese Taipei (9,52 %)	chm	Chemical, rubber plastic products
Plastifying agents (alkyl benzoate)	n.d.	n.d.	–	–
Glass (molten)	Glass and glassware	China (28,1 %), Germany (8,81 %), United States (7,12 %)	nmm	Mineral products nec
Magnesium Oxide (MgO)	Magnesia, fused, dead-burned etc and magnesium oxide	China (44,2 %) , United States (7 %), Netherlands (4,5 %)	nmm	Mineral products nec
Lime (CaO)	Quicklime	France (14,2 %), Germany (8,74 %), Malaysia (6,8 %)	nmm	Mineral products nec
Boron Oxide (B ₂ O ₃)	n.d.	n.d.	–	–
Aluminum Oxide (Al ₂ O ₃)	Aluminium Oxide	Australia (32 %) , Brazil (17,3 %), China (9,39 %)	nmm	Mineral products nec
Silica Sand	Silica sands and quartz sands	United States (34,6 %) , Australia (14,6 %), Belgium (5,7 %)	nmm	Mineral products nec

Table A. 3

S-LCA Inventory Data for CCB case study

Tier 1							
Reference CCB				MM4R CCB			
Output	Value Added [USD]			Output	Value Added [USD]		
Aluminium Reference CCB	17.98			GFRP Composite CCB	13.7		
Input	SHDB Sector	Value Added [USD]	Country Code	Input	SHDB Sector	Value Added [USD]	Country Code
Aluminium Sheet	Metal products (fmp)	17.75 (IMF, 2024)	CN	Aluminium Sheet	Metal products (fmp)	10.52(IMF, 2024; IMF, 2024)	CN
Steel Sheet	Ferrous metals (i_s)	0.23 (Survey and Interior Dept, 2012)	CN	Steel Sheet	Ferrous metals (i_s)	0.22 (Survey and Interior Dept, 2012)	CN
				GF roving	Mineral products nec (nmm)	1.81 (Sola and Trinch, 2023)	SVK
				PP fiber	Textiles (tex)	0.84 (Choudhury and Hashmi, 2020)	DE
				PP granulate	Chemical, rubber, plastic products (crp)	0.31 (IKB, 2011)	DE
Tier 2							
Output	Value Added [USD]			Output	Value Added [USD]		
Aluminium Sheet (AlMg4,5Mn0,7)	17.75			GFRP Composite Materials including residual Aluminium Sheet (AlMg4,5Mn0,7)	13.11		
Input	SHDB Sector	Value Added [USD]	Country Code	Input	SHDB Sector	Value Added [USD]	Country Code
Aluminium	Metals nec (nfm)	16.09 (IMF, 2024)	IN	Propylene	Chemical, rubber, plastic products (crp)	0.78 (IKB, 2011; Moretti et al., 2020)	KOR
Manganese	Metals nec (nfm)	0.07 (USGS, 2024e)	CN	GF Filaments	Mineral products nec (nmm)	1.81 (Sola and Trinch, 2023)	CN
Magnesium	Metals nec (nfm)	1.59 (USGS, 2013)	CN	Aluminium	Metals nec (nfm)	9.53 (IMF, 2024)	IN
				Manganese	Metals nec (nfm)	0.04 (USGS, 2024e)	CN
				Magnesium	Metals nec (nfm)	0.95 (USGS, 2013)	CN
Tier 3							
Output	Value Added [USD]			Output	Value Added [USD]		
Aluminium Production	8.17			GF Filaments Production including residual Aluminium Production	5.111		

(continued on next page)

Table A. 3 (continued)

Tier 3							
Output	Value Added [USD]			Output	Value Added [USD]		
Aluminium Production	8.17			GF Filaments Production including residual Aluminium Production	5.111		
Input	SHDB Sector	Value Added [USD]	Country Code	Input	SHDB Sector	Value Added [USD]	Country Code
Input	SHDB Sector	Value Added [USD]	Country Code	Input	SHDB Sector	Value Added [USD]	Country Code
Cryolite	Chemical, rubber, plastic products (crp)	0.13 (Asif et al., 2005; Nurdin et al., 2015; Procurement Resource, 2023)	CN	Al-Oxide (for GF)	Mineral products nec (nmm)	0.01 (USGS, 2024a; Varshneya, 2016)	CN
Graphite Anode	Petroleum, coal products (p_c)	2.98 (Asif et al., 2005; Chakraborty, 2022; Nurdin et al., 2015; USGS, 2024b)	CN	Mg-Oxide (for GF)	Mineral products nec (nmm)	0.001 (USGS, 2024d; Varshneya, 2016)	CN
Al-oxide	Mineral products nec (nmm)	5.06 (Asif et al., 2005; Nurdin et al., 2015; USGS, 2024a)	BR	Cryolite	Chemical, rubber, plastic products (crp)	0.08 (Asif et al., 2005; Nurdin et al., 2015; Procurement Resource, 2023)	CN
				Graphite Anode	Petroleum, coal products (p_c)	1.86 (Asif et al., 2005; Chakraborty, 2022; Nurdin et al., 2015; USGS, 2024b)	CN
				Al-oxide (for Al)	Mineral products nec (nmm)	3.16 (Asif et al., 2005; Nurdin et al., 2015; USGS, 2024a)	AUS
Tier 4							
Output	Value Added [USD]			Output	Value Added [USD]		
Raw Materials for Reference CCB	0.9301			Raw Materials for GFRP Composite CCB	30.24204		
Input	SHDB Sector	Value Added [USD]	Country Code	Input	SHDB Sector	Value Added [USD]	Country Code
Bauxite	Minerals nec (omn)	0.93 (Asif et al., 2005; Engh et al., 2022; USGS, 2024a)	GN	Crude Oil	Oil (oil)	28.68 (IKB, 2011; Lavrenov et al., 2015; REN et al., 2006)	SAU
Manganese Ore	Minerals nec (omn)	0.0001 (Consolidated Minerals, 2011; Hagelstein, 2009)	ZA	Natural Gas	Gas (gas)	0.97 (IKB, 2011; Lavrenov et al., 2015)	QAT
				Silica Sand	Minerals nec (omn)	0.042 (USGS, 2024c; Varshneya, 2016)	US
				Bauxite	Minerals nec (omn)	0.55 (Asif et al., 2005; Engh et al., 2022; USGS, 2024a)	GN
				Manganese Ore	Minerals nec (omn)	0.00004 (Consolidated Minerals, 2011; Hagelstein, 2009)	ZA

Data availability

Data will be made available on request.

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