Politecnico di Torino

Corso di Laurea Magistrale in
March 2025
ENVIRONMENTAL AND LAND ENGINEERING
(DIATI)

Social-LCA and Sustainable Strategies of Critical Raw Material Supply Chains in the Battery Sector

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ABSTRACT

The transition to electric vehicles (EVs) and lithium-ion batteries (LIBs) is a critical pathway to reducing global greenhouse gas (GHG) emissions and enhancing sustainability. However, beyond their environmental benefits, LIBs introduce significant social implications throughout their life cycle. These materials are often sourced from a limited number of countries, raising concerns about supply stability and social risks such as labor exploitation and poor working conditions. Addressing these issues is vital for a sustainable and responsible battery supply chain.

One of the methods to evaluate the social impact is Social Lifecycle Assessment (S-LCA) which is a methodology to evaluate the social impacts of lithium battery production. S-LCA provides a systematic approach to identifying and evaluating these social impacts, covering key stages such as raw material extraction, refining, and cell production.

One of the critical features of lithium batteries is the reliance on raw materials such as cobalt, nickel, lithium, and graphite. These elements are not only scarce but also unevenly distributed globally. Moreover, many of the countries where these mines are located face severe social challenges. Due to these issues, this study aims to conduct a detailed Social Life Cycle Assessment (S-LCA) of the NCA (Nickel-Cobalt-Aluminum) lithium battery system, focusing on the social risks in non-EU and EU scenarios. The case study, performed using OpenLCA software and the PSILCA database, evaluates social impacts across various stages of the battery supply chain, from raw material extraction to cell assembly.

This study focuses on the Social Life Cycle Impact Assessment (S-LCIA) of lithium-ion batteries (LIBs), emphasizing the measurement and understanding of social impacts related to the product system across two supply chain scenarios: Non-European and European. By examining the extraction, refining, and processing of materials, the study aims to identify potential social risks associated with various stakeholder categories. The findings will provide insights into the social implications of LIB adoption and contribute to the development of a sustainable battery supply chain. The potential social impacts are evaluated through the PSILCA database, which multiplies worker hours for each process step by characterization factors according to risk and opportunity levels, resulting in medium risk hours (mrh).

In the EU scenario, indicators related to category of worker such as "Fair Salary," "Association and Bargaining Rights," "Trafficking in Persons," and "Violations of Employment Laws and Regulations" are significantly lower. In contrast, the non-EU scenario exhibits higher social impacts due to the concentration of critical raw materials in specific geographic regions. The findings emphasize the importance of considering social risks in supply chain design and the need for continuous improvement in social standards, particularly in regions with concentrated raw material extraction.

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1. Introduction

There is a global consensus on the urgent need to reduce greenhouse gas (GHG) emissions to address the climate crisis, especially in the transport sector, which is a major contributor to these emissions[1]. The 2015 Paris Agreement identified the shift from fossil fuels to electrified transportation as a key strategy in the global fight against climate change. The transition to electric vehicles (EVs) is now well underway [2]. The transport sector accounts for 25% of all energy-related emissions, with road vehicles alone contributing 75%. To combat the high emissions from road vehicles, there is a strong global push to transition from internal combustion engine vehicles (ICEVs) to electric vehicles (EVs). Ongoing advancements in renewable energy and battery technology are driving this transition. According to the International Energy Agency (IEA), the number of EVs is projected to increase significantly, reaching between 124 million and 199 million by 2030[1].

Currently, transportation responsible for 12% of the EU's total GHG emissions, and car manufacturers are tasked with reducing fleet emissions by 37.5% between 2021 and 2030 to align with Green Deal goals. The electrification of mobility systems (e-mobility) is pivotal, with electric vehicles (EVs) expected to drive a sharp increase in demand for resources like cobalt, graphite, and lithium. By 2050, cobalt and graphite demand could rise tenfold, while lithium demand may grow 40 times higher than today's levels. These materials are crucial for lithium-ion batteries (LIBs), which are the preferred energy storage systems for EVs. While alternative battery chemistries, such as lithium-sulfur and lithium-air, are being explored, LIBs remain a key focus due to their current relevance[3].

Lithium-ion batteries (LIBs) are critical in achieving zero-emission electric mobility due to their high energy and power density, cost-effectiveness, and long lifespan, making them essential for the shift to sustainable transportation[1], [4]. The production of lithium-ion batteries (LIBs) presents significant environmental challenges, primarily due to their chemical composition, material degradation over time, and the need for high-demand materials such as aluminum, cobalt and copper[5].

The primary materials used in batteries are largely obtained from a small number of countries, raising significant concerns about supply stability. The extraction of these materials is not only energy-intensive but also requires considerable water resources, which can lead to environmental challenges, including eutrophication and soil contamination. Furthermore, sourcing these materials from developing countries with unstable political conditions poses serious social risks, including labor exploitation and poor working conditions. Addressing these concerns is essential for fostering a sustainable and responsible battery supply chain[6].

The Social Lifecycle Assessment (S-LCA) methodology provides a systemic perspective to evaluate the positive and negative social impacts of products, processes, and services throughout their lifecycles. S-LCA examines social themes such as Human Rights and Working Conditions linked to production and consumption systems. Given the LIB lifecycle's multi-scalar nature, applying S-LCA principles can reveal potential social injustices and clarify the adverse social impacts associated with LIB adoption [9].

This thesis aims to analyze the social life cycle of lithium battery production by examining the extraction, refining, and processing of materials across two different supply chain scenarios, the Non-European and the European.

In the non-European scenario, it is assumed that the extraction and refining of raw materials such as cobalt, lithium, and nickel predominantly occur in non-European countries. These regions often face significant social challenges, including labor exploitation, poor working conditions, and limited regulatory oversight. The concentration of these critical raw materials in specific geographic areas worsens these social risks.

Conversely, in the EU scenario, it is assumed that the production and refining of raw materials are distributed across various European countries. This distribution helps mitigate some of the social risks associated with raw material extraction and processing. European countries generally have stricter labor laws, better working conditions, and more robust regulatory frameworks, which contribute to lower social impacts. The decentralized nature of raw material production in the EU scenario also allows for more equitable distribution of economic benefits and improved oversight of labor practices, ultimately leading to a more sustainable and socially responsible supply chain.

The goal is to identify potential social risks associated with various stakeholder categories, the database for assessing social risks is PSILCA or "Product Social Impact Life Cycle Assessment".

In the first chapters, the importance of critical raw materials and their supply chain is explained.

This chapter introduces the urgent need to reduce greenhouse gas emissions and the role of electric vehicles (EVs) and lithium-ion batteries (LIBs) in achieving this goal. It highlights the environmental and social implications of LIB production and the importance of addressing these issues through comprehensive assessments.

Chapter two outlines the methodology used for Social Life Cycle Assessment (S-LCA), including the goal and scope definition, inventory analysis, impact assessment, and results interpretation. It introduces the PSILCA database, which provides social impact data for various economic activities and supply chains and explains how it is used to analyze raw material supply chains and compare international scenarios.

In the third chapter, the focus is on critical raw materials and explaining the scenarios. This chapter focus on the case study describing the goal and scope, system boundaries, and critical raw materials involved. It includes a literature review, data requirements, and stakeholder analysis. The chapter presents the social life cycle inventory for both non-EU and EU production scenarios, followed by an impact assessment and comparison of social indicators between the two scenarios.

In the fourth chapter, discusses the major findings related to worker impacts, local community impacts, and societal impacts. It highlights the differences between the EU and non-EU scenarios, the chapter also addresses the limitations of the study, such as the use of national data instead of sector-specific information and the challenge of assessing broader societal contributions.

Conclusion summarizes the key findings of the study. It emphasizes the importance of considering social risks in the supply chain design of LIBs and the need for continuous improvement in social standards.

2. Social Life Cycle Assessment Methodology (S-LCA)

Social Life Cycle Assessment (S-LCA) is a recent methodology designed to evaluate the potential positive and negative social impacts associated with all activities from raw material extraction to final disposal. Managing social issues requires specific evaluation tools, and life cycle methodologies have become widely accepted for assessing the impacts of a product or service throughout its entire life cycle[7].

Social life cycle assessment (S-LCA) evaluates the social and socio-economic impacts of products and services across their life cycle. S-LCA involves four phases: goal and scope definition, social life cycle inventory (S-LCI), social life cycle impact assessment (S-LCIA), and interpretation[8].

The general methodology of Social Life Cycle Assessment (S-LCA) is similar to environmental life cycle assessment (LCA) since both methods are based on the ISO 14040 framework, they share the processes of goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation. The sustainability assessment community defined life cycle assessment (LCA) by ISO 14040 and 14044 standards, LCA analyzes the environmental aspects and potential impacts throughout a product's life cycle, from raw material acquisition to disposal and considers general environmental impact categories such as resource use, human health, and ecological consequences[8]. However, SLCA differs in the type of data which is collects. While LCA focuses on physical quantities of natural resources and emissions, S-LCA emphasizes the socio-economic interactions of activities and examines their organizational and societal context within the supply chain. This makes S-LCA a complementary tool to LCA, offering a more comprehensive view of product sustainability. Social impacts in S-LCA depend on the specific context of the product's supply chain, necessitating the collection of site-specific data. Depending on the study's objective, it may also be feasible to use data at a broader spatial level to identify social hotspots in the supply chain. Social hotspots are defined as activities in regions where situations occur that could be considered problems, risks, or opportunities concerning a social theme of interest[9].

To encourage the adoption of S-LCA, the United Nations Environment Program (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) developed guidelines for conducting S-LCA studies. These guidelines introduce six stakeholder categories: workers, local community, society, consumers, value chain actors, and children. Each category represents individuals or groups involved in or affected by the product system throughout its life cycle.[10] Supporting the guidelines, Methodological Sheets describe 40 social impact subcategories to assess potential social and socio-economic impacts. These impact categories detail how each stakeholder group can be affected by the product system's activities. Evaluations are conducted using various inventory indicators, collecting quantitative, semi-quantitative, and qualitative data[11].

There are various methods to conduct impact assessments in S-LCA (S-LCIA). Typically, S-LCIA is categorized into two main types: type I is Reference Scale Approach and type II is

Impact Pathway Approach, both of these approches aiming to quantify social impacts. The reference scale approach evaluates the social performance of companies by comparing them to legal norms, industry best practices, or stakeholder opinions. It relies on qualitative data, expert judgments, and performance reference points (PRPs) rather than quantitative impact pathways. Impact Pathway Approach assesses the potential short- and long-term social consequences of an activity using cause-effect model chains, with human well-being as the area of protection. [12].

S-LCA involves four phases: goal and scope definition, social life cycle inventory (S-LCI), social life cycle impact assessment (S-LCIA), and interpretation [8]:

2.1. Goal and Scope:

The first phase of creating social LCA is defining the purpose of the study and creating the system boundaries. In this phase, the main methodological approaches are the functional unit, cutoff criteria. and impact assessment method are planned, along with the stakeholder groups and impact subcategories.

In this process, the stakeholders such as workers, value chain actors, consumers, children, local communities, or society will be selected and based on the social issues categorize into different impact categories such as fair wages for workers.

The next step is defining the system boundaries for the product or services by planning a product system that is the composition of different flows and processes, for each component. Every component has its own input and output, and each process has its own potential for positive or negative social impact on every stockholder. Other critical information for modeling the product is includes the location of every component or process. [7].

2.2. Social Life Cycle Inventory (S-LCI):

The second phase of a S-LCA is collecting and creating the social life cycle inventory. In this phase every component will be defined and all the data related to their material composition and production process will be gathered. There is different type of data which reflect the entire process chain, Primary sources, literature, and other references can be used. These physical flows are complemented by social data, which indicate social impacts, this social data can be quantitative, semi-quantitative, or qualitative[13].

By identifying all input and output flows, the social inventory indicators could be evaluated. Then Data for each product system is normalized for a specific output process. The link between Input/output flows is an activity variable, which reflects the relevance of social impact subcategories related to the process output. This variable helps prioritize data collection and quantify social inventory indicators, with “working hours” being the most common activity variable[10],[13].

2.3. Social Life Cycle Impact Assessment (S-LCIA):

The third step is measuring and understanding of social impact related to the product system. The potential social impact is the probable presence of social impact which is result from conducting an activity and behavior of an organization [13][10].

In the impact assessment phase of PSILCA, the worker hours for each process step are multiplied by the characterization factors according to the risk and opportunity levels. Aggregating these results across all processes in the product system yields results in medium risk hours (mrh)[7].

2.4. Results Interpretation:

The interpretation of results is the final phase of S-LCA. In this phase all the previous phases will be reviewed and will be discussed to identify the social hotspots and according to the goal and scope. ISO 14044 defines this phase as: "analysis phase in which the findings of the inventory analysis or impact assessment, or both, are evaluated in relation to the defined objective and scope, in order to reach conclusions and recommendations".

2.5. PSILCA Database

In Social Life Cycle Assessment (S-LCA), OpenLCA enables users to integrate social impact data into traditional LCA models. This is particularly important for evaluating the social aspects of supply chains, such as labor rights, human health, and working conditions.

PSILCA (“Product Social Impact Life Cycle Assessment”) is a comprehensive database designed for social LCA. It provides regionalized social impact data for thousands of economic activities and supply chains.

GreenDelta GmbH introduced and developed PSILCA database, and this is a comprehensive repository for social LCA data. This database offers insights into the social aspects of products throughout their life cycles. PSILCA combines social indicators with a global input/output model that reflects the world economy's structure. The EORA Multi-Regional Input/Output (MRIO) database serves as the input-output model, demonstrating the interdependencies between various branches of national or regional economies, covering 187 countries and 15,909 sectors, EORA uses monetary flows in US dollars to link processes across different sectors and countries. PSILCA's extensive data on global industry sectors makes it valuable for sustainability policies. Governments can use it to identify potential social risks in specific sectors of their trading partners or pinpoint high-risk sectorial flows contributing to production in individual countries[14].

The PSILCA database has gone through several updates, each enhancing its data quality, coverage, and methodological approaches, until now there are several updates of PSILCA, each version of PSILCA builds upon its predecessor, refining methodologies and expanding datasets to provide more accurate and detailed social impact assessments[15].

The first version v1 released in 2015, and it introduced a set of social indicators based on globally frameworks, numerous economic sectors and countries, another version of this database which released in 2017 added more social indicators and increased to 65 qualitative and quantitative social indicators across 19 subcategories also it improved the data quality and regional specificity.

The latest version of PSILCA which released in 2023 and updated with more current values and a better country or sector coverage. for enhancing the accuracy updated most indicators also added 14 new indicators like Risk of conflicts and Violations of mandatory health and safety standards. This version is introduced new method to calculate the social risks based on initial indicator values. also 4 indicators were removed or changed because of lack of reliable sources. Also in this version, an indicator related to positive impacts known as “Contribution of the sector to economic Development” were added. An innovation in this version is introducing direct impact assessment method, which allows to calculate social risks based on the initial values of the indicator without the intermediate layer of working hours[16].

2.5.1. Stakeholders, impact subcategories and indicators in PSILCA

During the life cycle stages of a product, there are individuals and groups which might be affected positively or negatively, and UNEP classifies this groups of stockholders in different categories[8]. They are largely defined by the international community through its policy frameworks and other social responsibility references, and in respect to the best available science. To research and assess the potential social and socio-economic impacts the social LCA guideline guidelines define 31 impact subcategories. these subcategories capture different social and socio-economic aspects relevant to each stakeholder group. Data for their evaluation is collected through inventory indicators, which can be quantitative, semi-quantitative, or qualitative[10]. There are five stockholder categories which represents individual: workers, value chain actors, local communities, consumers, society.

PSILCA offers social indicators for various stakeholders and impact subcategories, based on UNEP/SETAC Guidelines. Each subcategory is represented by a set of social indicators, totalizing 88 qualitative and quantitative indicators, which are applied to all Country-Sector combinations in the Eora database. PSILCA could conduct the SLCA in two different software, OpenLCA and SimaPro also this database has different version which each version differs in the level of details. The comprehensive version is Developer version which contains 15000 process dataset within a single system model.

The definitions, units of measurement, and data sources for each indicator are detailed in PSILCA's documentation [16], which is also available online The database compiles data from various sources, including international organizations like the World Bank, International Labor Organization, World Health Organization, and Organization for Economic Cooperation and Development. Additional sources include governmental databases, public records on Environmental Health and Safety violations, and company or industry databases.

For all indicators, raw, unassessed values are provided along with an indication of their quality (Table 1). In some cases, only proxies are available, while in others, values have been adjusted through normalization, attribution, and extrapolation. Normalization is used when values depend on the system's size, and attribution and extrapolation are applied when there is a different level of detail between sources and the Eora database. This can occur when raw data is available for only a few sectors of a country in the Eora database or when raw data is not available for a country or any of its sectors[14].

Table 1. PSILCA database structure: stakeholders, subcategories and indicators

Stakeholder	Subcategory	Indicator
WORKERS	Child labor	Children in employment, male Children in employment, female Children in employment, total
	Forced labor	Goods produced by forced labor Frequency of forced labor Trafficking in persons
	Fair salary	Minimum wage, per month Living wage, per month Sector average wage, per month
	Freedom of association and collective bargaining	Right of Association Right of Collective bargaining Right to Strike Trade union density
	Working time	Hours of work per employee, per week
	Discrimination	Women in the labor force Men in the labor force Gender wage gap
	Health and Safety	Accident rate at workplace Rate of fatal accidents at workplace Rate of non-fatal accidents at workplace DALYs due to indoor and outdoor air and water pollution Presence of sufficient safety measures Workers affected by natural disasters
	Social benefits, legal issues	Social security expenditures Evidence of violations of laws and employment regulations
SOCIETY	Contribution to economic development	Contribution of the sector to economic development Embodied value-added total Illiteracy rate, female Illiteracy rate, male Illiteracy rate, total Public expenditure on education Adult illiteracy rate (15+ years), total Youth illiteracy rate, total Youth illiteracy rate, male Youth illiteracy rate, female
	Health and Safety	Health expenditure, total Health expenditure, domestic general government Health expenditure, external resources Health expenditure, out-of-pocket Life expectancy at birth Global Peace Index
LOCAL COMMUNITY	Access to material resources	Level of industrial water use (related to total withdrawal) Level of industrial water use (related to renewable water resources) Extraction of biomass (related to area) Extraction of biomass (related to population) Extraction of fossil fuels Extraction of industrial and construction minerals Extraction of ores Certified environmental management systems (CMEs)
	Environmental footprints	Embodied agricultural area footprint Embodied forest area footprint Embodied water footprint

		Number of threatened species
	GHG footprints	Embodied CO2 footprint Embodied CO2-eq footprint
	Respect of indigenous rights	Indigenous People Rights Protection Index Presence of indigenous population
	Safe and healthy living conditions	Pollution level of the country Drinking water coverage Sanitation coverage
	Local employment	Unemployment rate in the country
	Migration	International migrant workers in the sector International Migrant Stock Net migration rate Immigration rate Emigration rate Number of asylum seekers in relation to total population
VALUE CHAIN ACTORS	Fair competition	Presence of anti-competitive behavior or violation of anti-trust and monopoly
	Corruption	Active involvement of enterprises in corruption and bribery Public sector corruption
	Promoting social responsibility	Membership in an initiative that promotes social responsibility along the supply chain

2.5.2. Risk Assessment and Data Quality

Each Country-Specific Sector (CSS) is evaluated using raw data from various sources, such as "number of fatal accidents" for a specific country and sector. These raw values are connected to social risk level, based on assessment schemes.

There are six risk levels identified on a negative scale: "no risk", "very low risk", "low risk", "medium risk", "high risk", and "very high risk". For some indicators, a positive scale is also used to reflect positive social impacts, with levels such as "high opportunity", "medium opportunity", and "low opportunity". If data are unavailable or the processes are not applicable, the indicator is marked as "no data".

Risk levels are assigned based on international conventions, standards, labor laws, expert opinions, and internal evaluations. Due to the subjective nature of these assessments, risk levels can be adjusted to better align with the specific goals and scope of a study.

Based on "reliability of the source", "completeness", and "temporal", "geographical", and "technical conformance", PSILCA provides data quality information for each data point. Data quality is assessed using the "pedigree matrix" (Table 2) introduced for quality assurance in LCA.

Table 2. The pedigree matrix for data quality assessment of social data, used in PSILCA[16]

core	Indicator	1	2	3	4

Reliability of the source(s)	Statistical study, or verified data from primary data collection from several sources	Verified data from primary data collection from one single source or non-verified data from primary sources, or data from recognized secondary sources	Non-verified data partly based on assumptions or data from non-recognized sources	Qualified estimate (e.g., by expert)	Non-qualified estimate or unknown origin
Completeness conformance	Complete data for country-specific sector/country	Representative selection of country-specific sector/country	Non-representative selection, low bias	Non-representative selection, unknown bias	Single data point / completeness unknown
Temporal conformance	Less than 1 year of difference to the time period of the dataset	Less than 2 years of difference to the time period of the dataset	Less than 3 years of difference to the time period of the dataset	Less than 5 years of difference to the time period of the dataset	Age of data unknown or data with more than 5 years of difference to the time period of the dataset
Geographical conformance	Data from same geography (country)	Country with similar conditions or average of countries with slightly different conditions	Average of countries with different conditions, geography under study included, with large share, or country with slightly different conditions	Average of countries with different conditions, geography under study included, with small share, or not included	Data from unknown or distinctly different regions
Further technical conformance	Data from same technology (sector)	Data from similar sector, e.g., within the same sector hierarchy, or average of sectors with similar technology	Data from slightly different sector, or average of different sectors, sector under study included, with large share	Average of different sectors, sector under study included, with small share, or not included	Data with unknown technology/sector or from distinctly different sector

As an example of social indicator analyzing by this risk level assessment in the following section, fair salary indicator is explained. “Fair salary”, is One of the most important categories and it means ensuring workers receive enough wage across the supply chain. Assessing this indicator depend on qualitative data such as wages paid in different sectors and regions, but fairness is a complex concept to define[17]

Based on PSILCA manual the fair salary is “Fair wage means a wage fairly and reasonably commensurate with the value of a particular service or class of service rendered, and, in establishing a minimum fair wage for such service or class of service”; For this subcategory these indicators considered. “Living wage per month”, “minimum wage per month” and “sector average wage per month”[18]

The “living wage” is the income necessary for living in a decent standard and covering essential needs such as food, water, shelter, education, and healthcare. Sources of PSILCA for living wage data extracted from WageIndicator.org and converted to USD for comparison among 70 countries. In case of unavailability of data in the scale of countries, regional averages could be used. In the stage of Risk level, they could be assigned to base on by the probability that living costs exceed the minimum wage or sector average wage, in case of with higher living wages indicating a greater risk of unfair salaries[18].

The “minimum wage” is the lowest wage required legally for a worker, who works full-time in a country; Although, there are some countries which do not have a uniqe minimum wage, and the rate of these wages can vary based on different factors like; skill level and region. In PSILCA, minimum wage data is also sourced from WageIndicator.org, converted to USD, and evaluated based on its ratio to the living wage, if the ratio is high, PSILCA suggests a higher risk and because of that, the minimum wages are not sufficient for a decent life.

The “sector average wage” represents the monthly earnings of employees in each industry. This data is mainly extracted from ILOstat, and converted average to US dollars, and align with sector classifications. The risk assessment is based on the sector wage-to-living wage ratio, where a low ratio indicates a higher risk that workers in each sector cannot afford a decent standard of living. Only wages that are at least twice of living wage are considered to provide a secure and sustainable livelihood. These wage indicators in PSILCA help assess the fairness of salaries across countries and sectors, highlighting potential social risks in supply chains related to low wages and inadequate living conditions[18].

In risk assessment is indicate if the cost of living is high, for this assumption living wage value is used as a proxy to evaluate “Minimum wage” and “Sector average wage per month”, in this case, living wages indicates the cost of living, and the higher the living, the higher is the risk. This value represented in Table 3.

Table 3. Risk levels for range of years,” Fair salary”

Indicator value y, USD	Risk level
Y<100	Very low risk
$100 \leq y < 200$	Low risk

$200 \leq y < 500$	Medium risk
$500 \leq y < 1000$	High risk
$1000 \leq y$	Very High Risk
-	No data

2.5.3. Activity Variables

An activity variable measures process activity or scale in relation to process output. These variables, scaled by the output of each relevant process, "reflect the share of a given activity associated with each unit process".

For labor conditions, a relevant activity variable is worker-hours. It represents "the time workers spend to produce a certain amount of product" in the given process or sector. Worker hours are assigned to each process or sector based on 1 USD of output. This means that for each unit of output produced in a specific process, there is an estimated number of worker-hours required. These coefficients help determine how much labor (in terms of worker-hours) is involved in each step of a production process within a life cycle assessment (LCA). By summing up the worker-hours from all unit processes in a product's life cycle, it is possible to estimate the total labor input and analyze social impacts such as fair wages, working conditions, or labor rights compliance[8].

Currently, worker hours are the only activity variable, but other options are being explored. In the PSILCA database, worker hours are related to 1 US$ of process (or sector) output. These worker hours are calculated for the database using the following formula:

$$Working\ Hours = \frac{Unit\ Labour\ Costs}{Mean\ labour\ cost\ per\ employee\ per\ hour} [14]$$

$$Unit\ Labour\ costs = \frac{Compensation\ of\ employee(US\$\ per\ country\ specific\ sector\ and\ year)}{Gross\ output(in\ US\$\ per\ country - sector\ and\ year)} [14]$$

Data for "compensation for employees" come from the Eora satellite accounts, defined as the total remuneration payable by an enterprise to an employee for work done during the accounting period.

According to UN SNA, "gross output" is calculated from Eora, representing intermediate consumption plus value added for each industry group.

Data on "mean nominal hourly labor cost per employee" are available from the International Labor Organization. Labor cost includes remuneration for work performed, payments for time not worked, bonuses, in-kind payments, social security expenditures, vocational training costs, welfare services, and other miscellaneous items. In cases where data for mean labor costs were only available for years before 2011, the most recent value was extrapolated to 2011, assuming a 3% annual wage increase. All values were converted to US$ using the exchange rate from December 31, 2011. Eora sectors without an equivalent in "mean hourly labor cost per employee" were assigned an average value of hourly labor cost across all other sectors within the country. A simple impact assessment method summarizes risk-assessed indicators, and users can create their own impact assessment methods [14].

3. Social Life Cycle Assessment of Lithium Nickel Cobalt Aluminum oxides (NCA) battery

In the context of electric vehicles (EVs), Lithium battery sales are projected to grow significantly. More than 14 million Electric cars registered in 2023 and about 95% of these were in China, Europe and USA and approximately 40 million are on the roads, the rate of sale of Electric vehicle increases around 35% each year[19] (Figure 1). While most production is concentrated in Asian countries, with 40% in Japan followed by South Korea and China, the highest consumption occurs in the USA (28.4%) and the EU (27.2%)[20].

The European Green Deal outlines the EU's strategy for achieving sustainable economic growth while aiming for net-zero greenhouse gas (GHG) emissions by 2050[21]. A key priority is to ensure a stable and independent supply of battery materials, reducing reliance on non-EU countries and minimizing associated GHG emissions[22].

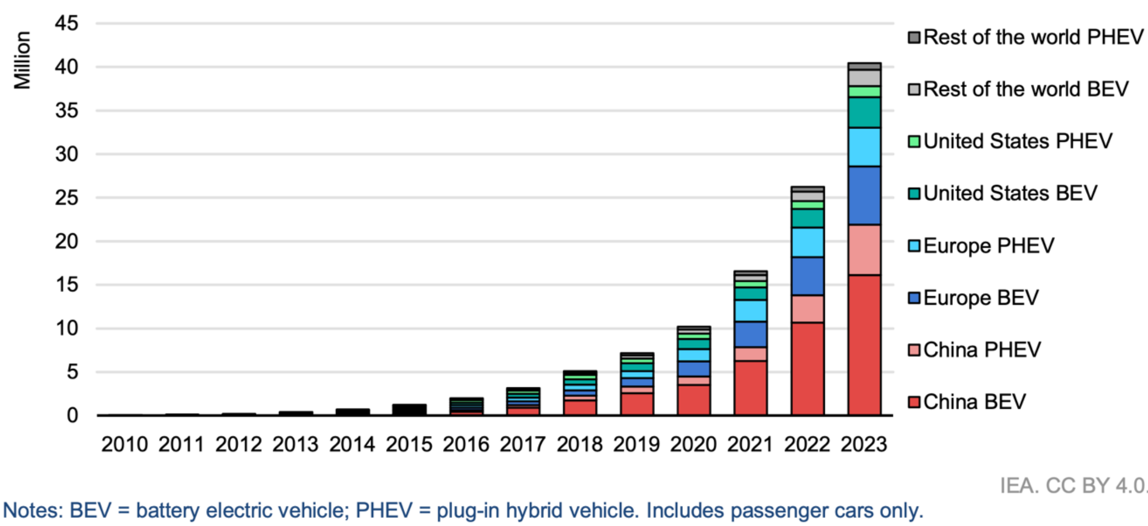

Figure 1. Global electric car stock trends, 2010-2023[19]

3.1. Goal and scope

3.1.1 Goal

In this section the focus is on the production system of a NCA lithium-ion battery and its social impacts throughout the supply chain. This chapter consolidates previously illustrated information and fundamentals to demonstrate the construction of a social LCA case study. In the subsequent chapters, the SLCA methodology will be applied following the UNEP/SETAC Guidelines[8] and other published case studies.

The Goal of this study is conducting a Social Life Cycle Assessment (SLCA) of Nickel-Cobalt-Aluminum (NCA) lithium-ion battery with different supply chain scenario and focusing on its social impacts. The objective is to identify social risks and hotspots associated with the battery supply chain, particularly under two different scenario, Non-European scenario which where key production stages—refining, active material production, and battery assembly—occur entirely outside of Europe, which is close to the current situation of producing and assembly of electric battery; and the second, European scenario which aligns with the European Green Deal's ambition to secure a stable and sustainable battery material supply and reducing dependency on non-EU countries, and minimize negative social and environmental impacts.

3.1.2. Scope

3.1.2.1 Functional unit

The functional unit is 1 USD of NCA Lithium Battery. A comparison will be conducted between EU scenario and non-EU scenario production of NCA Lithium Battery. scope of this research is Cradle-to-Gate, within this scope the following phase will be assessed; extraction of raw material, refining of material, manufacturing of positive and negative active material, at the end, production of the NCA cell. In the Figure 2 These processes are shown.

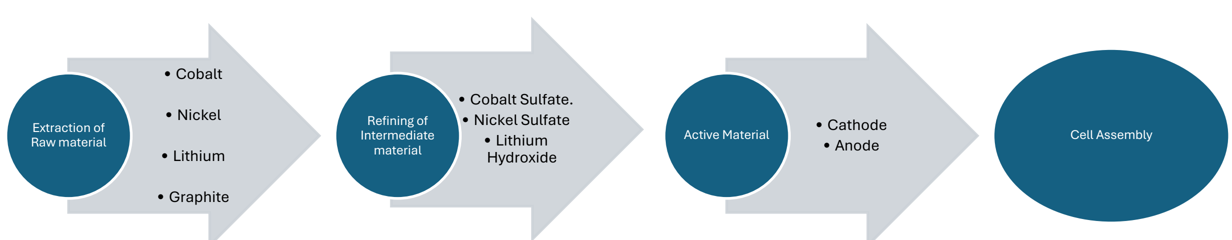

Figure 2. Streamlined representation of the battery cell product system

3.1.2.2. Description of NCA batteries

Lithium-ion batteries (LIBs) are composed of cells that rely on the movement of lithium ions between the negative electrode (anode) and the positive electrode (cathode) via a medium called electrolytes, which gives them their name[23].

The assembly process for cell and battery production requires a steady supply of anodes, cathodes, separators, and electrolytes. These components are often the result of complex manufacturing processes and are typically produced separately from cell production, both organizationally and geographically. Consequently, battery production depends on a variety of mineral elements and compounds that are primarily sourced from the earth rather than through recycling. Most of the material demand in a battery, by value, pertains to the cathode. The key elements for cathodes include lithium, nickel, cobalt, manganese and aluminum. Anode production involves the use of graphite, copper, silicon, and lithium, while electrolytes contain lithium, phosphorus, fluorine, and solvents[24].Common cathode types include lithium nickel-cobalt-manganese oxide (NMC), lithium iron phosphate (LFP), lithium nickel-cobalt-aluminum oxide (NCA), and lithium manganese oxide (LMO)[25].

One of the most effective Li-ion systems involves nickel aluminum cobalt oxide (NAC) cathodes, composed of 7.2% Lithium, 49% nickel, 1.4% aluminum, and 9% cobalt[26]. In Table 4, the composition of NCA lithium cell battery is shown.

Table 4. NCA Li-Battery Material Composition, % by weight, Battery weight and pack specific energy [29]

Battery Material Composition, % by wt	
Active Material	28.0%
Graphite/Carbon	15.8%
Binder	0.9%
Copper	8.1%
Aluminum Sheet (Automotive)	12.0%
Electrolyte: Ethylene Carbonate	2.9%
Electrolyte: Dimethyl Carbonate	2.9%
Plastic: Polypropylene	1.7%
Plastic: Polyethylene Terephthalate	0.3%
Steel	16.1%
Stainless Steel	6.5%
Coolant: Glycol	2.3%
Electronic Parts	1.1%

3.1.2.3. NCA Critical Raw Materials (CRM)

Lithium-ion batteries (LIBs) contain several Critical Raw Materials (CRMs), including cobalt (used in cathodes), lithium (found in cathodes and electrolytes), and graphite (utilized in anodes)[27](Figure 3). CRMs are metals and resources essential for economic stability and development, which also face supply risks[28].

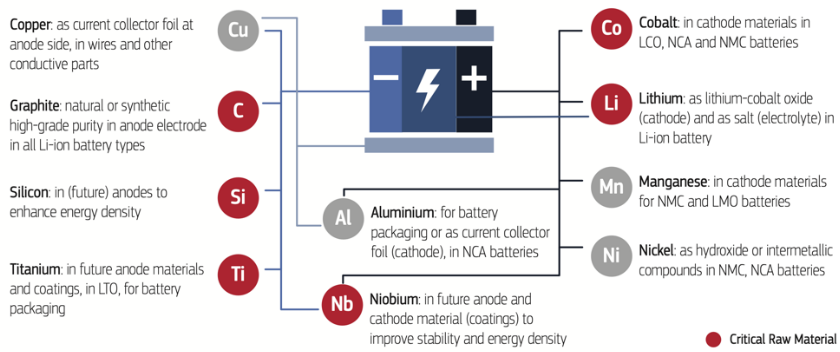

Figure 3. Raw material used in batteries [37]

Raw materials play a crucial role in enabling various sectors within the EU economy. Certain raw materials, especially those identified as critical raw materials (CRMs), are indispensable for the growth of key industries such as renewable energy, electric mobility, defense, aerospace, and digital technologies. Increasing consumption, along with shifts in the global economic, financial, and political landscape, has led to imbalances in the supply and demand of certain raw materials. This has caused price fluctuations in material markets, creating uncertainties for technologies and their market entry strategies[29].

The supply chains for lithium-ion battery (LIB) materials involve extensive global trade, with energy-intensive activities like ore extraction, processing, and refining spread across various countries. Key materials in LIBs include nickel, cobalt, manganese, graphite, and lithium. Nickel is mined in over 25 countries, with Indonesia and Russia being the largest producers, supplying 38% and 11% of the global output, respectively. The Democratic Republic of Congo provides 63% of the world's cobalt. Manganese is mainly sourced from South Africa (30%) and Australia (12%). China dominates the production of graphite, accounting for 62%, and lithium is primarily mined in Australia (52%), Chile (22%), and Argentina (7%). China also leads in LIB refining and manufacturing, with over half of the global refining capacity for cobalt, graphite, and lithium and producing more than 75% of all LIBs[30].

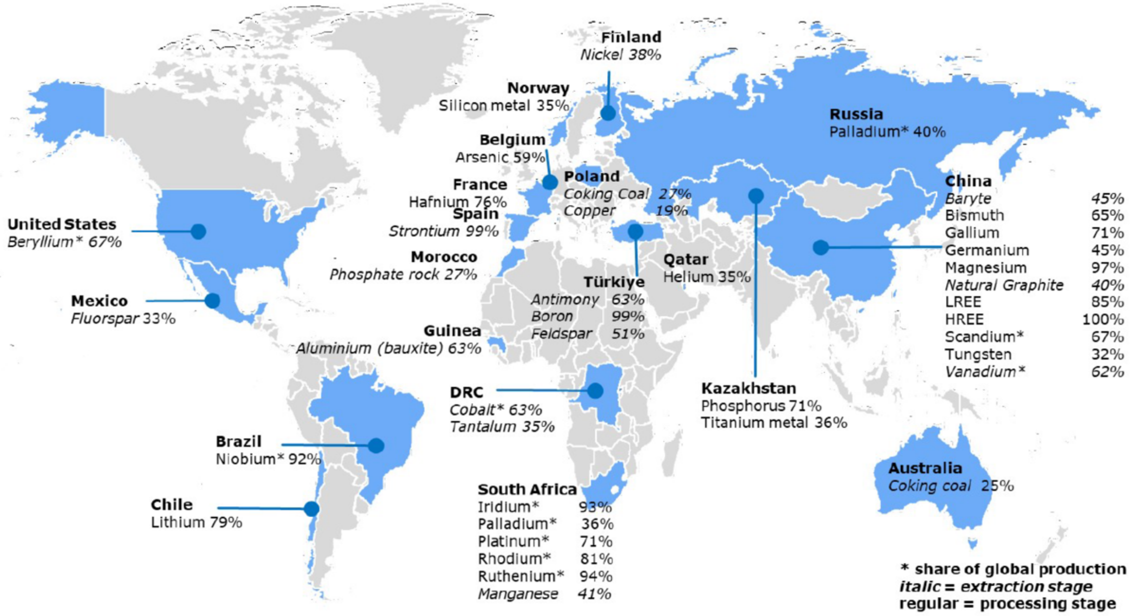

Figure 4. The world map of the main CRMs suppliers to the EU [39]

At present, the EU industry heavily relies on imported raw materials (Figure 4), which exposes it to significant supply chain vulnerabilities. With the ongoing global transition towards sustainable energy, the demand for metallic raw materials essential for manufacturing is on the rise[31].

The European Union faces significant challenges in the supply chain for battery production, particularly in the raw materials and Li-ion cell manufacturing stages (Figure 5). China, alongside Africa and Latin America, dominates the market by supplying 74% of all battery raw materials. Specifically, China alone is responsible for producing 66% of the world's finished Li-ion batteries. In contrast, the EU currently contributes to less than 1% of global Li-battery production[31].

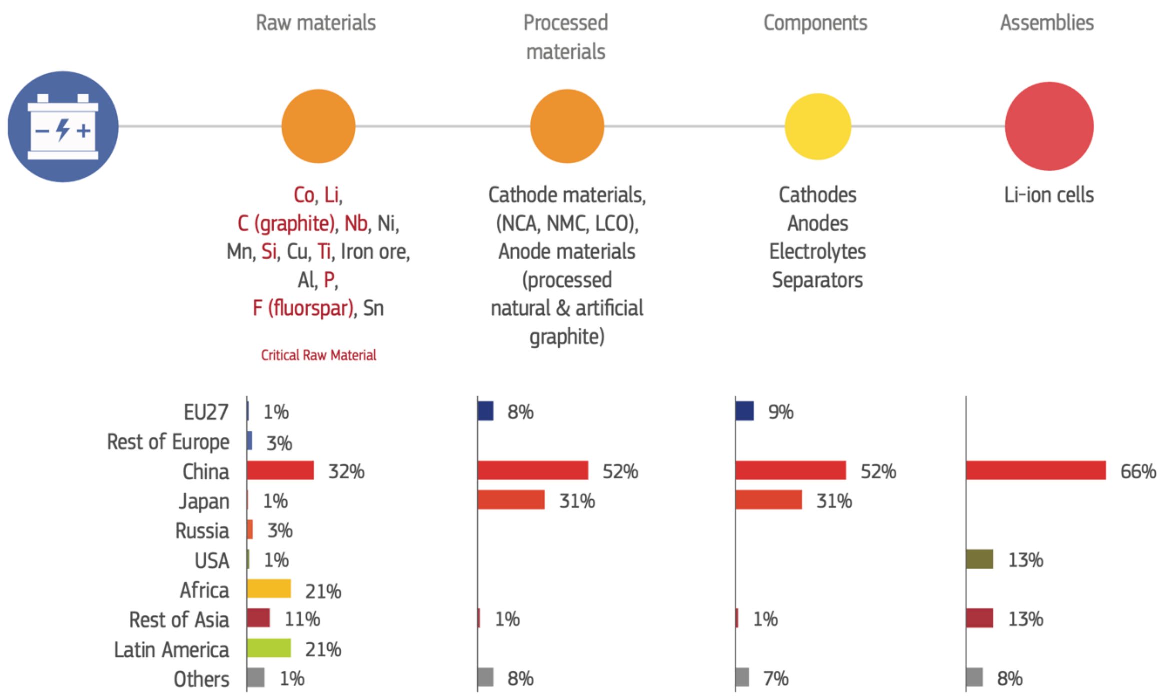

Figure 5. An Overview of supply risks in Lithium batteries [37]

Europe currently contributes about 10% to global LIB manufacturing but aims to boost this to 25% by 2030. The United States holds 6% of the production capacity, while Japan and South Korea together account for 5%. It is expected that electric vehicles (EVs) will dominate vehicle sales post-2030, with Bloomberg New Energy Finance predicting over 60 million EV sales by 2040, increasing to over 190 million by 2050. Each electric car typically requires more than 25 kg of critical materials, such as cobalt and lithium[32]. In figure 1 forecast of Li-ion battery market is shown [30].

In this thesis the considered critical raw materials to produce lithium battery are Cobalt, Lithium, Nickel, Graphite, Aluminum.

Cobalt

Cobalt (chemical symbol Co) is a lustrous, silver-grey metal known for its wide range of applications owing to its distinct properties. This hard metal maintains its strength at elevated temperatures, boasts a high melting point, and is ferromagnetic, retaining magnetic properties at the highest temperatures compared to other metals. It is multivalent, forms alloys with other metals to enhance high-temperature strength and wear resistance and is essential as a trace element in living organisms. Additionally, cobalt is notable for producing vivid blue colors.[33].

Cobalt is a key ingredient in lithium-ion batteries (LIBs). The cobalt supply chain is predominantly controlled by a limited number of countries. In 2020, for instance, the Democratic Republic of the Congo (DRC) was responsible for 69% of the global cobalt mine production, which is ten times higher than that of Russia, the second-largest producer in figure 6 the geographical distribution of Cobalt mining is showed. Similarly, the refined cobalt market is highly centralized, with China producing 67% of the global capacity for refined battery-grade cobalt sulfate (CoSO4) in 2020[34]. In Table 6 the cobalt content for NCA Li-battery is shown.

Table 5. NCA Li-battery and its properties [43]

Name	Abb.	Chemical Formula	Cobalt Content	Properties and Applications
Lithium Nickel Cobalt Aluminum Oxide	NCA	LiNiCoAlO2	10–15%	High capacity; gaining importance in electric powertrain and grid storage; industrial applications, medical devices

The DRC possesses roughly half of the world's cobalt reserves and contributes over 70% to the global cobalt production[35], Upstream cobalt processing and refining in the DRC produce cobalt concentrates, primarily cobalt hydroxide, for export. Other significant producers include Russia, the Philippines, Cuba, and Australia in Figure 6.

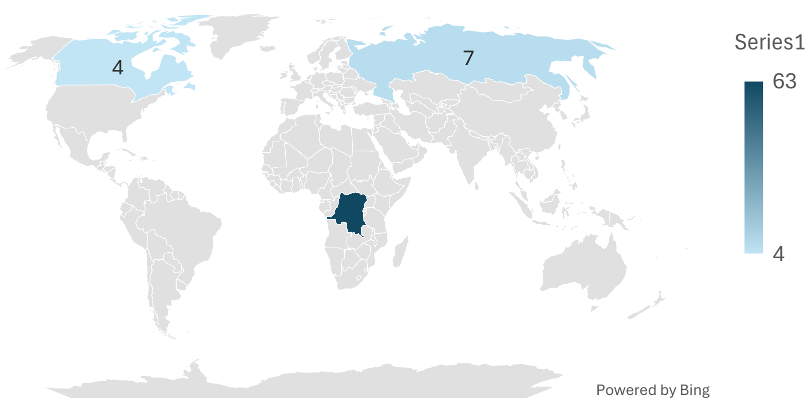

Figure 6. The geographical distribution of Cobalt mining

The DRC is producing an estimated 60-70% of the world's cobalt, 20-30% of which is artisanal production. Large-scale mining (LSM) is the primary method of copper and cobalt production in the DRC, accounting for 70-80% of cobalt output. And artisanal and small-scale mining with formal features constitutes the smallest share of copper and cobalt production, Artisanal mining in the DRC involves miners working without modern tools, technology, or safety equipment, relying instead on their hands, pickaxes, and chisels. About 30% of all cobalt mined in the DRC is extracted through artisanal mining, involving shifts of 5,000 people working consecutively under hazardous conditions such as collapsing mineshafts. In 2014, nearly 40,000 children, some as young as seven, were found working in these mines[36]. Reports from NGOs and media outlets have brought global attention to hazardous working conditions and the presence of child labor in mining activities such as collecting, sorting, washing, crushing, and transporting minerals[37]. multinational mining companies in and around mining sites have forcibly evicted communities from their homes and farmlands to facilitate energy transition mining. These communities often find themselves surrounded by mining projects, compelled to leave their homes and livelihoods with no effective means of seeking redress[38]. Also, other issues around the mining sites like birth defects by High toxic metal exposure is reported[37].

Table 6. the extraction and production of cobalt 2022[41]

Global production	Global producer	EU consumption	EU share	EU suppliers	Import reliance
136385	Congo 63%	10946(ext.)	8%	Russia 25%	81%
	Russia 7%			USA 16%	1%
	Canada 4%			Finland 16%	
	Others 26%			Congo9%	
				Madagascar 5%	
				Canada 5%	
				Norway 4%	

In the non-EU scenario, the initial step involves considering the share of each country in the global production of cobalt, as outlined in Table 6. This data provides a comprehensive overview of the contributions made by various countries to the total cobalt supply. Next, the input flow for the production of cobalt sulfate is analyzed. This involves calculating the amount of cobalt required for this process, taking into account the production shares of each country. And in EU scenario, the production of cobalt sulfate assumed to be in Finland as a main country.

Nickel

Nickel (chemical symbol Ni) is a lustrous white metal known for its characteristic metallic properties. In nature, nickel primarily exists in compound form and predominantly as isotopes with mass numbers 58 (68%) and 60 (26%). It has a relatively high melting point of 1,455°C and a density of 8.908 g/cm³. The abundance of nickel in the Earth's crust is moderate, with an upper crustal concentration of 47 parts per million (ppm). Economically significant nickel deposits are primarily found in geological settings such as magmatic sulfides and laterite deposits. Currently, nickel concentrations in sulfide ores, which are the main source of mined nickel, range from 0.15% to approximately 8%, although 93% of known deposits typically contain between 0.2% and 2% nickel[39].

Table 7. Nickel Extraction Stage

Global Production	Global Producers		Main EU sources (%)		Import Reliance (%)
2331612	Indonesia	26	Canada	59	31
	Philippines	14	South Africa	19	
	Russia	10	USA	9	
	New Caledonia	9	Guatemala	6	
	Canada	8	Norway	3	
	Australia	8			

From 2016 to 2020, global nickel ore production averaged 2,332 kilotons per year. The leading producers of nickel ore during this period were Indonesia and the Philippines, contributing 26% and 14% of global production, respectively, which translates to average annual outputs of 613 kilotons and 327 kilotons (Table 7). Other notable producers include Russia (10%; 231 kt), New Caledonia (9%; 209 kt), Canada (8%; 198 kt), and Australia (8%; 175 kt).

Nickel exists in numerous forms, and despite its extensive use, it is not classified as a critical material by the European Union [40].

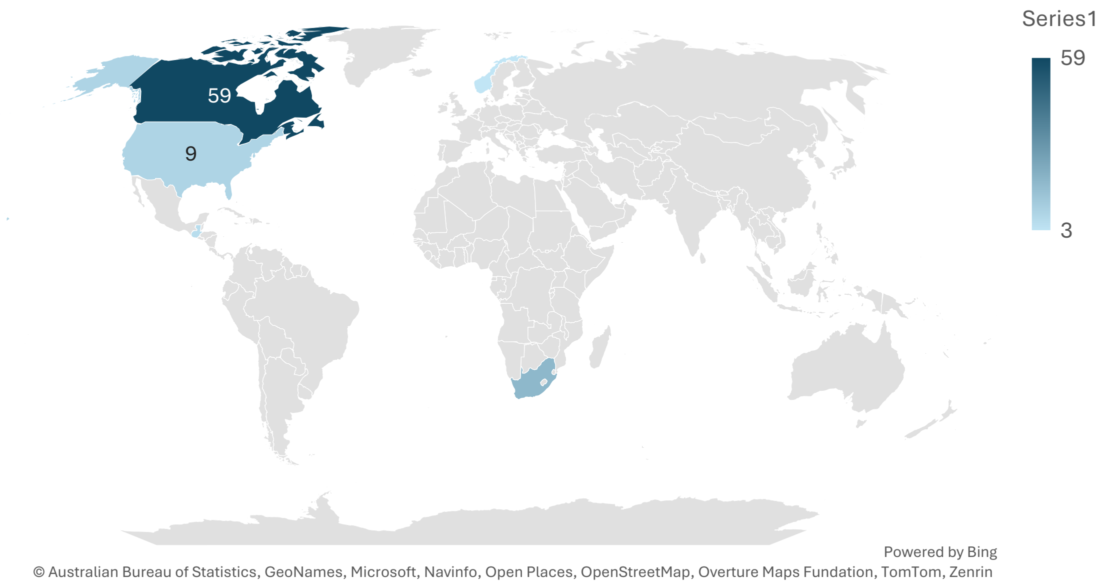

Figure 7. The geographical distribution of Nickel mining based on table 7

The EU was heavily reliant on nickel ore imports during this period, with an average import dependency of 71%, calculated as the ratio of net imports (imports minus exports) to domestic material consumption. Between 2016 and 2020, EU production of refined nickel averaged 161 kt (in nickel content) per year. Globally, smelter and refinery production of nickel reached an annual average of 2,298 kt, with China supplying 30% (701 kt)[41].

For non-EU scenario, production of nickel sulfate is assumed to take place in Russia, Indonesia and China according to Table 7. And in EU scenario it assumed to produce in Norway.

Graphite

Natural graphite (C, atomic number 6) is a carbon allotrope with distinct metallic and non-metallic characteristics. It appears as a soft, grey-black mineral with a hardness of 1-2 on the Mohs scale and exhibits perfect basal cleavage. Graphite's structure consists of planar sheets of three-coordinated carbon atoms. These sheets are bonded strongly within the plane but are held together by weak forces, allowing them to slide over each other easily. Graphite is known for its high thermal resistance, lubricity, corrosion resistance, chemical inertness, and non-toxicity, making it a versatile raw material used in various applications.

Global recoverable graphite reserves exceed 800 million tons, with China being the leading producer. Other significant holders of graphite resources include Brazil and Turkey. In 2022, the total worldwide mine production of natural graphite was approximately 1 million tons. Natural flake graphite must undergo additional processing to meet market requirements, which involves a combination of thermal, milling, and chemical techniques. Following these processes, spherical graphite is purified through hydrometallurgical or pyrometallurgical methods to attain a purity level of 99.99%[42].

Anode materials are chosen based on their ability to effectively collect charge. Currently, graphite is the most widely used material for the anode in most lithium-ion batteries. However, some manufacturers opt for lithium titanate as an alternative to graphite[7].

High-purity flake graphite, essential for lithium-ion batteries (LIBs), is relatively scarce. In 2017, flake graphite accounted for 30% of the natural graphite produced. During the same year, North America contributed 3% to the global graphite supply, although two graphite mining projects were underway in Alabama and Alaska. Due to the supply risk, natural graphite is classified as a critical raw material by the European Union[40].

Table 8. Natural Graphite at production supply

Global Production	main global producers		main EU sourcing countries (%)		import reliance (%)
1019167	China	67	China	40	99
	Brazil	8	Brazil	13	
	Mozambique	5	Mozambique	12	
	India	5	Norway	8	
	North Korea	5	Ukraine	7	

Chinese companies are the main supplier of the anode material (graphite)[43]. Social impacts on workers have been reported in bauxite mining, graphite, and steel refining. Natural graphite production in China is also associated with forced labor in the Xinjiang Uyghur region. Additionally, exposure to graphite dust during mining can harm workers' health, causing conditions like cough, reduced lung function, and lung fibrosis[44].

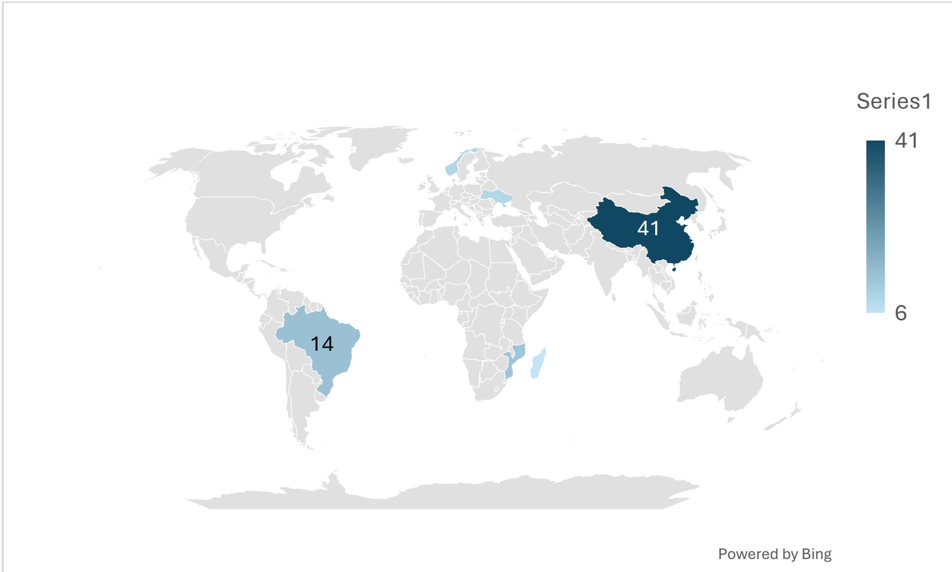

Figure 8. The geographical distribution of Graphite mining based on table 8

In non-EU scenario, and according to table 8the process of Graphite takes place in China and in the model, it was assumed accordingly. In EU scenario, Austria chosen for Graphite.

Lithium

Lithium (Li) is a soft, silver-white metal that belongs to the alkali metal group on the periodic table. It stands out as the lightest metal and has the lowest density among solid elements at room temperature, with a density of only 0.53 g/cm³. Lithium is also noted for its superior electrical conductivity and possesses the highest electrochemical potential of all metals. Due to its high reactivity, lithium is not found in its free form in nature. Instead, it exists in stable mineral compounds such as silicates, or commonly as lithium chloride in brines and seawater. Major lithium mining activities are concentrated in Australia, Chile, and Argentina, with Australia primarily mining lithium from spodumene and Chile and Argentina from brine (Table 9). Hard rock lithium is extracted from ore, while lithium from continental brines is often a byproduct of potassium production [45].

Table 9. Lithium at production supply

Global Production	Global producers		EU source (%)		import reliance (%)
76213	Australia	53	Others	81	81
	Chile	24	Portugal	19	
	China	10			
	Argentina	8			

Despite its higher cost, lithium hydroxide is essential for popular lithium battery chemistries like NCA and NMC. The current market dynamics for lithium-ion batteries (LIBs), especially in electric vehicles (EVs), reveal a growing demand. The compound annual growth rates for EVs and PHEVs are projected to be 42% and 56%, respectively (Table 10). In 2016, global LIB manufacturing capacity exceeded 31 GWh, with demand expected to surpass 90 GWh by 2020, necessitating increased lithium battery production. By 2025, the demand for lithium in batteries is predicted to double, making up approximately 70% of the total lithium market. Despite this, current lithium mining capacities are underutilized, and production capacity must quadruple to meet future demand.

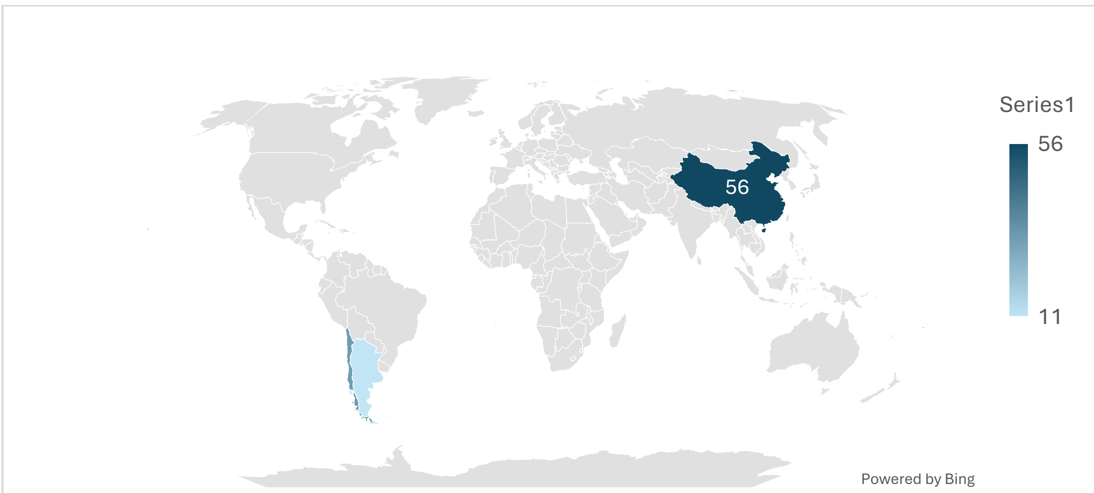

Figure 9. The geographical distribution of Lithium mining based on table 10

Supply risks need to be managed to meet the increasing demand for LIBs, due to the concentration of lithium production in Australia, Argentina, and Chile. China, despite mining less than 15,000 metric tons annually from 2014 to 2016, produces an average of 75,000 metric tons of lithium carbonate annually, primarily by importing unprocessed lithium from Australia. Unlike Australia, Chile is a leading exporter of tracked lithium carbonate, with significant exports to China, South Korea, and Japan.

Table 10. Lithium at mining stage

Global Production	Global producers		EU source (%)		import reliance (%)
57159	China	56	Chile	79	100
	Chile	32	Switzerland	7	
	Argentina	11	Argentina	6	
			United States	5	

Lithium brine extraction has significant social impacts, particularly for indigenous communities in the Atacama Desert, which supplies over a third of the world's lithium. These communities are concerned about water resources, as companies withdraw large amounts of water from aquifers to extract lithium, up to 2 million gallons per day. Although brine water is not drinkable or used for agriculture, there is concern that the aquifers containing brine are connected to freshwater sources. Continuous brine extraction may cause freshwater to flow into the depleted brine aquifers, reducing the water available for the indigenous Atacama[41].

In non-EU scenario, for processing Lithium China, Chile and Argentina were chosen for input flow and in EU scenario, Portugal was selected as main country of Lithium production.

3.1.3. System boundaries

The life cycle of NCA battery begins with the extraction and processing of essential raw materials (shows in Figure 10). In the positive active material of NCA, there are Lithium, Nickel, Cobalt, Aluminum, the most important negative active material is graphite (with copper for the negative electrode), and the electrolyte is made from lithium salt, the separator from polymers, and the cell packaging from plastic[32].

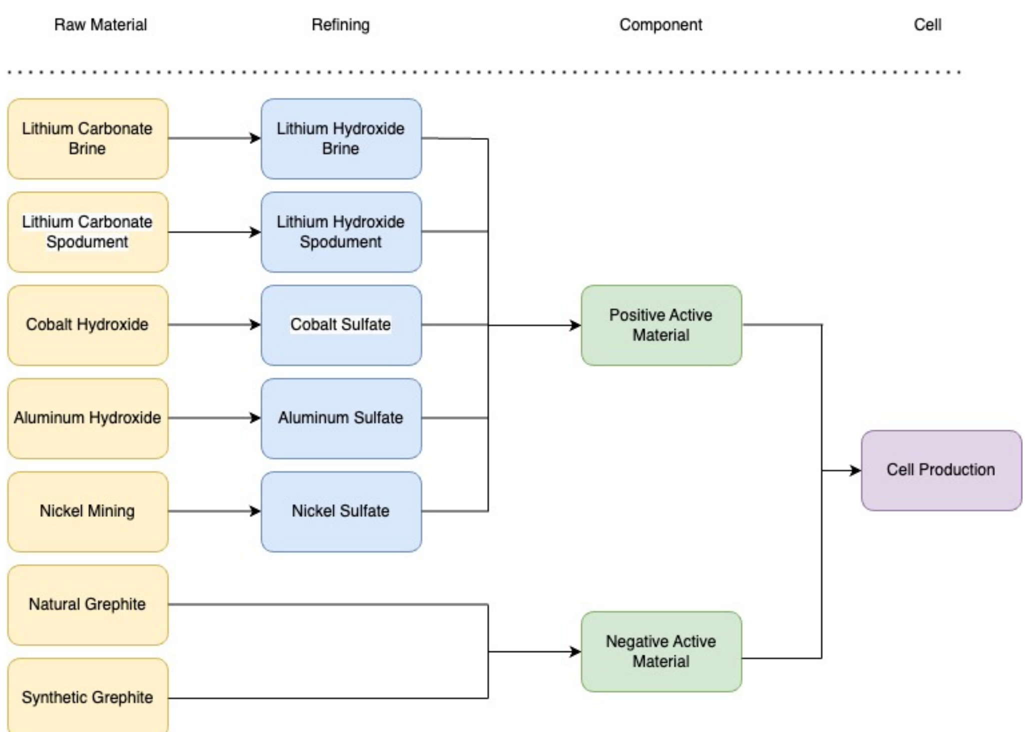

Figure 10. Cradle-to-gate product system for NCA lithium-ion batteries [32]

After the battery cells are manufactured, they can be assembled into a LIB pack. The number of cells within a pack varies depending on the desired performance, typically measured in terms of energy capacity. Key metrics used to evaluate LIB performance include specific power, specific energy, and round-trip efficiency. Specific power is calculated by dividing the rated power of the LIB by its weight, and the same approach is applied to determine specific energy. Round-trip efficiency, on the other hand, measures the actual amount of electrical energy transferred during a single charge-discharge cycle as a percentage of the theoretical maximum[32], [46].

3.1.4 Literature review and data requirements

Despite the environmental and social advantages of using lithium-ion batteries, their production involves significant impacts. The technology behind Li-ion batteries for electric vehicles relies on raw materials like lithium, cobalt, and natural graphite, which have notable environmental consequences. Extracting these critical raw materials involves processes such as brine evaporation, mining, and oil and gas extraction. Additionally, mining operations and material manufacturing can expose workers and local environments to toxic chemicals, unregulated effluents, and pollution, potentially causing serious health issues and threatening the well-being of nearby communities and ecosystems. Cobalt mines contain substantial amounts of uranium, resulting in high levels of radioactivity in these regions[11].

"New rush for energy transition technologies" increased the raw material mining and Lithium batteries production in different countries. In the case of location for of producing lithium battery, about 52 countries were involved in its the life cycle which were spreads in developed countries like Europe or North America or developing countries in South America or Asia, and also poor countries in Africa[47]. Some of these countries with weak institutional environment cannot guarantee the respect to human rights and the global distribution of raw material extraction create challenges to tracking its origins and make sure of the transparency of government[47].
For example, in an study which conducted analyze the short term social impacts, indicates that mining cobalt light have some social risks. Cobalt known as a critical raw material for producing NCA Lithium battery. The pressure for developing production of electric vehicle leads to more extraction of cobalt, which takes place mostly in DR Congo, and mining in DR Congo has many negative social impacts such as "child labor", "poor health", "safety of workers", "stress", and "violent conflicts"[12].

Geographical analysis of lithium batteries allows to highlight the countries with highest social risks, for example by conducting a social LCA on electric vehicle, the researchers found out that production of those car has a highest social risk in Russia, but producing electric machinery and equipment has higher social risk in China[10], [47].

In addition to environmental impacts, the production of battery materials and components can have significant social impacts on the communities involved in their production. For instance, 71% of cobalt is mined in the Democratic Republic of Congo (DRC), where child labor and hazardous working conditions are prevalent. Many children in the DRC work as artisanal miners for 10 to 12 hours without basic protective equipment, often carrying heavy loads. These children have been observed working in extreme climate conditions and facing abuse from security guards. Thus, it is essential to develop technologies that are both environmentally and socially responsible[11].

A comparative study of Lithium-Ion Batteries (LIB) and Vanadium Redox Flow Batteries (VRFB) revealed that social risks in battery supply chains are predominantly concentrated in the raw material extraction stage. For LIBs, these risks are notably lower in Germany compared to China. Additionally, the chemical sectors involved in battery production pose significant social risks, underscoring the need for targeted mitigation strategies. Battery Energy Storage System (BESS) manufacturers can address these risks through measures such as vertical integration of suppliers and rigorous supply chain due diligence. Key social issues, including poor working conditions, environmental pollution, and community conflicts, are particularly pronounced in countries like China and Chile—major contributors to battery supply chains. Identified social hotspots include fair wages, human trafficking, labor rights, and pollution levels. One effective mitigation approach is substituting high-risk materials. For instance, LIBs with LMO cathodes exhibit lower social risks compared to NMC cathodes, which rely on cobalt mining in the Congo—a major hotspot for social issues[48].

In a study, a hotspot analysis performed to identify the risks and for every sector and country and based on defining two scenarios, “European supply chain” and “Global supply chain”. This research indicates that in the sector of mining there are high risks regarding to violation of human rights which reported in extraction phase in DC Congo. But medium risks were related to refining phase regarding to governance, fragile state, and human hazard taking place in China and Poland[3], [49].

Among the affected stakeholder groups, workers face the highest social risks, followed by the local community, while societal impacts are comparatively smaller. These findings are consistent across supply chains in both China and Germany. However, for nearly all examined indicators, social risks are substantially lower in Germany than in China. Variations in LIB composition also influence social risks. LIBs with NMC cathodes exhibit significantly higher risks than those with LMO cathodes due to the use of cobalt, a material associated with severe social issues. Similarly, for VRFBs, an increased vanadium price exacerbates social risks, highlighting the cost sensitivity of the methodology. These findings emphasize the importance of material selection and supply chain management in mitigating social risks within battery production[48].
In another study which conducted a social LCA on different supply chain scenario, China scenario, Japan scenario and South Korea scenario, and based on medium risk hours equivalent. Based on this research in Chinese scenario has the highest total risk regarding to all the material and most high-risk indicators were "Labor Rights & Decent Work" and "Human Rights" in an comparison to Chinese and Korean scenario[49].

Table 11 represents the findings from various papers on the social life cycle of lithium batteries, which are utilized in this thesis.

Table 11. Studies on the social life cycle of lithium batteries

Author	Year	Field of Application	Objectives	Methods	Social Categories or Indicators
Virah-Sawmy et al.	2025	Renewable energy	Socio-economic and environmental impacts of renewable energy deployments: A review	systematic literature review	Not available
Domingue et al.	2024	Li-ion batteries	Lifecycle social impacts of lithium-ion batteries: Consequences and future research agenda for a safe and just transition	systematic review approach guided by the PRISMA protocol	Human Rights, Working Conditions, Cultural Heritage, Governance, and Socio-economic repercussions
Lígia da Silva et al.	2024	Li-ion batteries	The role of raw materials to achieve the Sustainable Development Goals: Tracing the risks and positive contributions of cobalt along the lithium-ion battery supply chain	Hotspot analysis	Worldwide Governance Indicator (WGI), Resource Governance Index (RGI), INFORM Human Hazard, Fragile States Index (FSI) Global Peace Index (GPI), Child Labor, Fair Salary, Forced labor, Environmental Performance Index, Water Risk Index
Shi et al.	2023	Li-ion batteries	Social life cycle assessment of lithium iron phosphate	S-LCA by using SHDB	labor Rights & Decent Work, Health & Safety, Human Rights

			battery production in China, Japan and South Korea based on external supply materials	and PSILCA database	
Koese et al.	2023	Li-ion batteries	A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage	S-LCA by using PSILCA database	Workers, society, local community
Pucciarelli et al.	2021	antimicrobial keyboard cover	Social hotspots life cycle assessment: A case study on social risks of an antimicrobial keyboard cover	S-LCA by using Social Hotspot Data Base (SHDB)	Labor rights and decent work condition, health & safety, human rights, governance, community
Mancini et al.	2021	Responsible sourcing initiatives for cobalt	Comparing the situation of two pilot projects about the general situation at cobalt small-scale mining sites in Congo (DRC). Providing the basis to discuss the lessons learned for the assessment and monitoring of responsible sourcing programs and possible implications for policy	s-LCA	Local community: health and safety, local employment and economy, social benefits/losses, cultural heritage and land rights, discrimination, forced migration/resettlement and land rights, poverty. Workers: health and social well-being, wages, social benefits, working conditions, discrimination, freedom of association and collective bargaining, training and education, job satisfaction and engagement
Muller et al.	2021	Flexible and modular mining plant (MMP)	The goal of this study is to assess the social implications of a new mining paradigm, small-scale 'switch-on switch-off' (SOSO) mining, which is based on the design of a flexible and modular mining plant (MMP) and aims at exploiting quickly and safely European small high-grade deposits of raw materials, including critical (e.g., battery manufacturing)	s-LCA (PSILCA v2.0 database)	Society: contribution to economic development, value chain actors, corruption, fair competition, and promoting social responsibility. Local community: access to raw material resources, safe and healthy living conditions, local employment and migration, respect of indigenous rights. Workers: health and safety, fair salary, social benefits, working time, child labor, and freedom of association
Maarten Koese and et al.	2020	Li-ion batteries	A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage	LCA	Local community: health and safety, local employment and economy, social benefits/losses, cultural heritage and land rights, discrimination, forced migration/resettlement and land rights, poverty. Workers: health and social well-being, wages, social benefits, working conditions, discrimination, freedom of association and collective bargaining, training and education, job satisfaction and engagement

Guo	2020	Lead-acid battery, Li-ion battery, Nas battery, and NiMH battery	Developing a life cycle sustainability decision-making framework for the prioritization of electrochemical energy storage under uncertainties	LCA, LCC, s-LCA,	Social acceptance, electric power system reserve capacity reduction
Wilken et al.	2020	Electric vehicles and internal combustion engine vehicles	Presenting a novel approach to analyze ICEV-, BEV-, and FCEV-type (fuel cell electric vehicle) passenger cars on a multidimensional basis	LCA, LCC, PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations)	Not available
Thies et al.	2019	Lithium-ion batteries	Assessing the social sustainability hotspots of lithium-ion batteries with a spatially differentiated resource flow model of the supply chain. Comparing three supply chain configurations	s-LCA: Social Hotspots Database in openLCA	Child labor, corruption, occupational toxics and hazards, poverty
Wang et al.	2019	Battery Electric Vehicle(BEVs)	To assess the life cycle sustainability of BEVs in China and compare results with internal combustion engine vehicles (ICEVs) to analyze developmental advantages and problems of BEVs	LCA, LCC, s-LCA, TOPSIS	Freedom of association and collective bargaining, child labor, fair salary, forced labor, equal opportunities/discrimination, health and safety for workers and consumers, feedback mechanism, access to material resources, local employment, contribution to economic development, technology development, policy and subsidy
Sansa et al.	2017	Batteries	Proposing a new model for the selection of sustainable design options, dealing with uncertainties and imprecisions due to technological choices and their impacts since the early design phase of the product	Environmental LCA (ELCA), economic LCA (ELCA), s-LCA, and the fuzzy analytic network process	Experts, involved to confirm results
Egbue	2015	Electric vehicle (EV) Li-ion batteries	To assess the social and socio-economic impacts along some parts of the lithium life cycle, particularly extraction and production impacts	s-LCA	Not available

3.1.5 Stakeholders

In this study, the focus is on the supply chain of raw materials. To demonstrate the risks related to people and resources in the target countries and based on previous studies the subcategories and indicators from the categories of Workers, and Local Community, value Chain Actors and Society were chosen. The selected indicators and subcategories were assessed to evaluate these risks are in Table 12

Table 12. Selected stakeholder for case this study

Stakeholders	Subcategory	Indicators
Workers	Health and Safety	Rate of non-fatal accidents at workplace Rate of fatal accidents at workplace DALYs due to indoor and outdoor air and water pollution Presence of sufficient safety measures Workers affected by natural disasters
	Freedom of association and collective bargaining	Trade union density Right of Association Right of Collective bargaining Right to strike
	Child labor	Child labor, Total
	Fair salary	Living wage, per month Minimum wage, per month Sector average wage, per month
	Working time	Hours of work per employee, per week H
Local Communities	Respect of indigenous rights	Human right issues faced by indigenous People Presence of indigenous population
	Migration	International migrant workers in the sector International Migrant Stock Net migration rate
Value Chain Actors	Corruption	Public sector corruption Active involvement of enterprises in corruption and bribery
Society	Contribution to economic development	Contribution of the sector to economic development Public expenditure on education illiteracy

3.1.6 Assumptions

In this work primary data were used for the assessment of NCA battery and the production location for every product were assumed based on the import and export of material or based on growth trend of battery production in Atlas of Battery 2024[50]

Data related to inventory list of NCA Lithium battery was gathered mainly from GREET 2024. The Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET®) model is a tool which developed by the U.S. Department of Energy's Argonne National Laboratory. GREET use a life cycle assessment framework to assess the environmental impacts associated with all stages of a technology or product's supply chain[51].

For the EU Scenario data and information was based on Thies and et al (2019)[9] study and Lima et al (2023)[51] for the information related to the social LCA of lithium Battery used Koese et al (2020)[3], [48].

3.2. Social Life Cycle Inventory

In this section and after collecting data and modeling the system, conducting LCI of two scenario to the PSILCA is illustrated. For life cycle inventory process was done at first on the non-EU scenario production and then on EU Scenario production, which will be described in the next sections.

The quantification of social risk will be done by using activity variable and in this case using worker hours. Worker hours mean the needed working time to produce 1USD of the product. To demonstrate the social risk related to production of 1USD of output, it needs to change it to medium risk hours and this risk scales and link with the price of the input in every sector and the amount of this work hours leads to the impact risk result.

These prices extracted mostly from alibab.com and GREET 2024.

3.2.1. Non-EU production scenario

In this scenario, the Social LCA of Lithium battery based on the non-EU scenario is going to be analyzed. In the non-EU scenario, the extraction of raw materials is based on the present supply chain which means that the first phase of battery production, extraction of raw material such as Cobalt, Nickel, Lithium and Graphite are from Congo, Indonesia, Australia and China, respectively. Then refining the intermediate material like Cobalt Sulfate, Nickel Sulfate, Lithium Hydroxide and Graphite is from China and at the end, the assembly and production of cell in China.

The inventory list of the NCA battery for this research is based on Argonne National Laboratory's R&D version of GREET (2024)[51]. Following the PSILCA method, these inventories (inputs and outputs of materials, products, and services) were translated to economic sectors by using the best available match in the PSILCA database in the most likely country of origin. The inputs and outputs from each sector were expressed as monetary values using cost data from Alibaba website.as an example, the inventory list of the Cobalt Sulfate with the monetary value is shown in Figure 11.

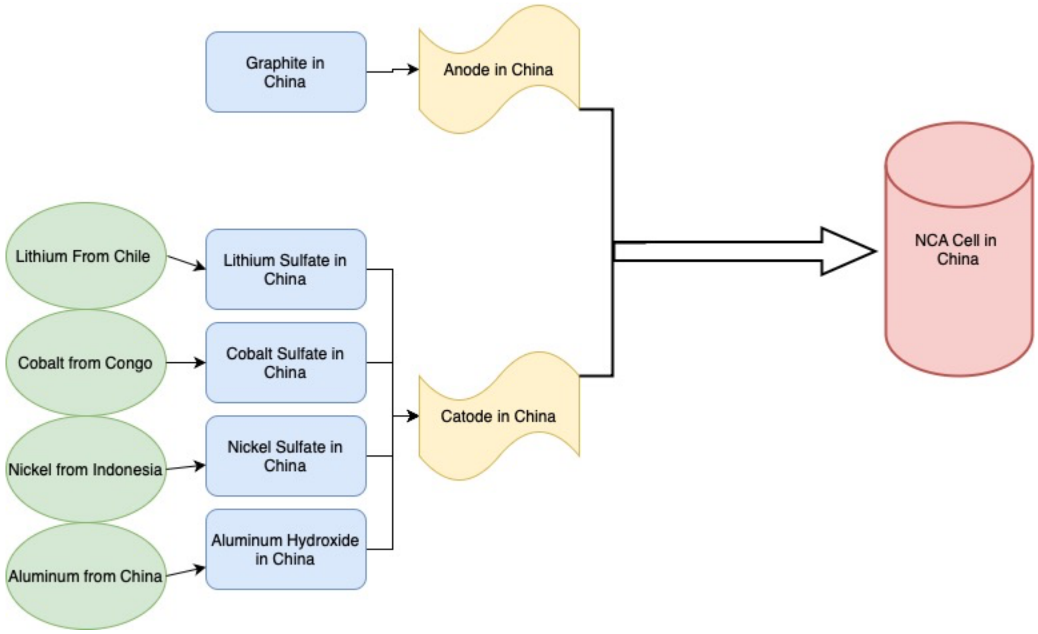

Figure 11-Streamlined representation of the battery cell supply chain

3.2.1.1. Intermediate Material Stage: Cobalt Sulfate (Co_2O_3) in China

Cobalt (Co) is the most expensive raw material used in lithium-ion batteries (LIBs). It is often mined under inhumane conditions, including child labor, and is also ecotoxic. Therefore, it is crucial to focus on recycling cobalt in the coming decade and aim to eliminate it from cathode materials entirely[52].

Oxides and sulfates of cobalt are recognized as suitable precursor materials for cobalt in lithium-ion battery (LIB) production. Cobalt sulfate (CoSO4) is the primary precursor for battery-grade cobalt, predominantly produced in China, which accounts for 80% of global CoSO4 and cobalt oxide production. The remaining 20% is mainly produced in Finland. China is expected to continue dominating the global CoSO4 supply chain.

Two significant cobalt production routes originate from ores in the Central African Copperbelt, located in the southeastern Democratic Republic of Congo (DRC) and northern Zambia. These ore deposits consist of an upper layer of oxide ores and a lower layer of sulfide ores. Sulfide ores are processed both pyrometallurgically and hydrometallurgically, while oxide ores are processed hydrometallurgically, including the precipitation of cobalt hydroxide. Currently, processing oxide ores yields cobalt chemicals, whereas processing sulfide ores produces Class I cobalt. Another type of cobalt ore, cobalt arsenide, also yields Class I cobalt but is mined and processed exclusively in Morocco, with low production volumes.

Additional processing methods include bioleaching and other hydrometallurgical techniques for sulfide ores, hydrometallurgical refining of nickel laterite matte into cobalt chemicals, separation of cobalt as a co-product in the platinum group metals (PGM) industry, and pyrometallurgical and hydrometallurgical processing of cobalt-containing slags and tailings, primarily from Central Africa[53].

The growing demand for electric vehicles (EVs) and consumer electronics is expected to increase the demand for cobalt significantly. By 2030, the demand for cobalt for LIBs alone is estimated to reach approximately 285,000 tons, which is double the total world output of cobalt in 2019, about 145,000 tons. Despite significant efforts by international government agencies, including a major initiative by the Department of Energy (DOE) called the "Next Generation Cathode Deep Dive," to reduce or eliminate cobalt use in LIB cathodes, this trend is anticipated to continue[54].

From the PSILCA database, and For Nickel sulfate the process which is chosen for foreground system regarding to evaluating the social risk and worker hours is "chemicals excluding Pharmaceuticals" in Russia. For the foreground system regarding to evaluation of social risk and worker hours is in PSILCA as the name of "Petroleum, Chemical and Non-Metal Mineral Production". The amount and details of input/output flow are shown in Table 17.

Table 13. Input and Output for Cobalt Sulfate production process

Flow	Amount	Unit	Source Input	Price	Source Price	Location	Reference on PSILCA database
			Input flows				
Crude petroleum products and Natural gas products	0.0069573	KWh	GREET2024	0.139724	Alibaba.com	China	market group for heat, district or industrial, natural gas
Electricity and steam production and supply	1.0693E-5	kg	GREET2024	0.019950	Alibaba.com	China	market group for electricity, medium voltage
Kerosene	0.006324	kg	GREET2024	0.240000	Alibaba.com	Australia	Kerosene
Limestone	7.6067E-6	kg	GREET2024	0.100000	Alibaba.com	Australia	Limestone
Mining and Quarrying	0.438825	kg	GREET2024	30	Alibaba.com	Congo	Cobalt hydroxide-
Mining and quarrying (energy	0.0278690	kg	GREET2024	30	Alibaba.com	Canada	Cobalt Hydroxide
Mining and quarrying (energy	0.0487708	kg	GREET2024	30	Alibaba.com	Russia	Cobalt Hydroxide

Raw chemical material	0.0604459	kg	GREET2024	1.57	Alibaba.com	China	Chemical factory, organics
Raw chemical materials	0.0604458	kg	GREET2024	1.350000	Alibaba.com	China	Disodium desulphated
Raw chemical materials	0.0347770	kg	GREET2024	4.410000	Alibaba.com	China	Hydrochloric acid, without water, in 30% solution state
Raw chemical materials	0.0172606	kg	GREET2024	1.200000	Alibaba.com	China	Sulfuric acid
				Output			
Cobalt Sulfate	1	Kg	GREET2024	72.60	GREET2024	China	

3.2.1.2. Intermediate Material Stage: Nickel Sulfate in Russia

Nickel is utilized in the cathode material for NCA, usually obtained as nickel sulfate (NiSO4), which is derived from refined nickel. The production involves several stages: mining, beneficiation, primary extraction, and refining.

Nickel refining, the most energy-demanding stage due to the high temperatures required. This can be produced from high-purity Class I nickel (at least 99.8% nickel) or from lower-purity intermediates such as nickel matte and mixed sulfide precipitate (MHP). Class I nickel is mainly derived from sulfide ores found in countries like Russia, Canada, and China. The other main type of nickel ore, laterite ore, is found in countries such as Indonesia, the Philippines, and New Caledonia, and is usually used to produce ferronickel and nickel pig iron. The largest class I nickel refining regions by production volume are China, Russia, and Canada. Russia and Canada together account for 35% of the market and a significant portion of the US market, while China holds 22% of the global market share but is less represented in the US. Canada and Russia are key boundary scenarios[55]. About 70% of Class I nickel comes from sulfide ores, while 30% comes from intermediates like MHP and mixed sulfide precipitate. MHP, derived from limonite ores (a layer in laterite ore), is used to produce Class I nickel through high-pressure acid leaching. The production of Class I nickel from sulfide ores involves several stages: ore mining, beneficiation, primary extraction, and refining. The primary extraction stage is the most energy intensive. The Class I nickel pathway represents global production, while the MHP pathway involves ore mining and beneficiation in Papua New Guinea and MHP refining in China[56].

Demand for nickel in lithium-ion batteries is projected to grow from about 70,000 tons in 2020 to 700,000 tons in 2030, necessitating a stable nickel supply as efforts to reduce cobalt content continue[57].

From the PSILCA database, and For Nickel sulfate the process which is chosen for foreground system regarding to evaluating the social risk and worker hours is “chemicals excluding Pharmaceuticals” in Russia. In Table 16 the amount and details of input/output flow are shown.

Table 14. Input and Output for Nickel Sulfate production process

Flow	Amount	Unit	Source Input	Price [USD/Unit]	Source Price	Location	Reference on PSILCA
				Input flows			
Chemical Fertilizers	0.002949611	kg	GREET 2024	3.6	Alibaba.com	China	market for nitrogen, liquid
Crude petroleum products and Natural gas products	9.33634E-4	MJ	GREET 2024	0.010600	Alibaba.com	China	market group for heat, district or industrial, natural gas
Electricity and steam production and supply	0.001704	KWh	GREET 2024	0.019950	Alibaba.com	China	market group for electricity, medium voltage
Manufacture of steam generators, except central heating hot water boilers	9.33634E-4	MJ	GREET 2024	0.139724	Alibaba.com	Grand Britania	market for heat, from steam, in chemical industry
Non-ferrous metal castings and forgings	0.035931667	kg	GREET 2024	1.38	Alibaba.com	Japan	Nickel Mining
Non-ferrous metals	0.047908889	kg	GREET 2024	15	Alibaba.com	Indonesia	Nickel Mining
Non-ferrous metals	0.027946852	kg	GREET 2024	15	Alibaba.com	Russia	Nickel Mining
Non-ferrous ore mining	0.131749444	kg	GREET 2024	15	Alibaba.com	China	Nickel Mining
Raw chemical materials	0.032185	kg	GREET 2024	1.172607	Alibaba.com	China	market for sulfuric acid
Raw chemical materials	2.57E-11	unit	GREET 2024	1.57	Alibaba.com	China	market for chemical factory, organics
Water production and supply	0.032185	kg	GREET 2024	0.000544	Alibaba.com	China	market group for tap water
				Output			
Nickel Sulfate	1	kg		24.41	GREET2024	China	

3.2.1.3. Intermediate Material Stage: Lithium Hydroxide

two main cathode materials are used in lithium-ion batteries are lithium hydroxide and lithium carbonate; Lithium Carbonate: Preferred economically because it requires fewer production steps; Lithium Hydroxide: Favored technically because it decomposes at lower temperatures, improving material use and performance. High-quality lithium hydroxide is essential for nickel-rich cathodes like NMC622, NMC811, and NCA. Both mineral and brine deposits can supply lithium-ion battery material. By 2030, the lithium needed for the EV market is estimated to be 2.3 times the total mined in 2018, which is emphasizing the importance of recycling[57].

Lithium carbonate (Li_2CO_3) is widely used in glass and ceramics, pharmaceuticals, and as a cathode material for lithium-ion batteries (LIBs), with over 74% of its usage in these applications. The primary market for lithium and LIBs is electric vehicles (EVs). In the upstream LIB value chain, mining and refining are highly concentrated in a few countries. The Lithium Triangle in South America holds 52% of global reserves, while Australia, Chile, and China account for 94% of global lithium production. Processing and refining lithium into lithium hydroxide and lithium carbonate is crucial for adding value in the upstream supply chain, with most capacity currently in China[52].

The foreground system for Lithium Hydroxide is the same as previous and the process that is chosen for evaluating social risk indicators and worker hours is “Metal Products” in China.

Amount and details of input/output flow for Lithium Hydroxide presented in Table 15

Table 15. Input and Output for Lithium Hydroxide production process

Flow	Amount	Unit	Source Input	Price [USD/unit]	Source Amount	Location	Reference on PSILCA
			Input flows				
Crude petroleum products and Natural gas products	0.017117	MJ	GREET 2024	0.1397	Alibaba.com	China	market group for heat, district or industrial, natural gas
Electricity and steam production and supply	4.73E-4	KWh	GREET 2024	0.0199	Alibaba.com	China	market group for electricity, medium voltage
Manufacture of lime	0.34701	kg	GREET 2024	6.09	Alibaba.com	Great Britain	Directly for lime,

Manufacture of steam generators, except central heating hot water boilers	0.005193	MJ	GREET 2024	0.016	Alibaba.com	Great Britain	Directly for heat, from steam, in chemical industry
Metal Products	0.21200288	kg	GREET 2024	11.627	Alibaba.com	Chile	Proxy for Lithium hydroxide
Non-ferrous ore mining	0.37100504	kg	GREET 2024	11.627	Alibaba.com	China	Proxy for Lithium hydroxide
Raw chemical materials	1.82E-4	unit	GREET 2024		Alibaba.com	China	proxy for chemical factory, organics
Water production and supply	1.0E-6	kg	GREET 2024	0.00054	Alibaba.com	China	proxy for tap water
Output							
Lithium hydroxide	1	kg	GREET 2024	28.480	Alibaba.com	China	

3.2.1.4. Intermediates material stage

The second stage in a battery material value chain is the Intermediate Material Stage. Generally, "intermediate" means "coming between two things." At this stage, materials undergo further processing while remaining somewhat application independent. The feedstock for this stage is the concentrate material from the Raw Material Stage. Depending on the concentrate type, smelting, purification, or refining steps may be applied. Smelting, a metallurgical process for chemically reducing metal from its ore, is typically involved, leading to the chemical modification of the material. The aim of the Intermediate Material Stage is to produce a precursor material that meets all qualitative or chemical requirements for the next stage. For metals in the group of mineral commodities, this product is commonly known as refinery production. The precursor material from the Raw Material Stage is not in a usable form for final applications. Processes at this level are typically handled by mining or chemical companies, which may operate either at both stages or separately[54].

In this part, the foreground system for Positive Active material and Graphite (for Negative Active material) will be explained and for the containing components of Positive Active material, just those which have the CRMs element such as Cobalt Sulfate, Nickel Sulfate and Lithium Hydroxide will be described.

3.2.1.4.1 Positive Active Material in China

The NCA cathode is significant due to its growing use in Tesla electric vehicles. This battery type features a crystal structure with alternating layers, where octahedral sites of nickel and cobalt (Ni-Co), aluminum and cobalt (Al-Co), and lithium atoms are arranged. Typically, NCA consists of 80% nickel, 15% cobalt, and 5% aluminum ($LiNi_{0.8} Co_{0.15} Al_{0.05}$), though these ratios might change in the future. The key innovation in this cathode is the inclusion of aluminum, which enhances thermal stability and discharge capacity. NCA's advantages include high energy density, especially when paired with a graphite and silicon anode. However, it also shows increased cell resistance and reduced capacity at high temperatures due to the growth of the solid electrolyte interphase (SEI) at the anode. Additionally, NCA is less safe compared to other cathode materials, as its initial thermal runaway temperature is below 150°C[58].

The process was modeled within PSILCA data, and it was not primary data, and all the data related to input and output was based on GREET 2024. By using PSILCA, social risk evaluation related to social indicators and Worker hours was extracted and for the Product system for positive active material, process of "Metal products in China" were chosen. Table 15 shown the input, output flows.

Table 16. Input and Output for Positive Active Material Production Process

Flow	Amount	Unit	Source Input	Price [USD/unit]	Source Price	Location	Reference on PSILCA
			Input flows				
Aluminum Sulfate	0.0017784	Kg	GREET2024	1.44	Alibaba.com	China	
Cobalt Sulfate	0.179322	Kg	GREET2024	72.60	Alibaba.com	China	
Crude petroleum products and Natural gas products	0.010028	Kg	GREET2024	0.139724	Alibaba.com	China	market group for heat, district or industrial, natural gas
Electricity and steam production and supply	0.01774	Kg	GREET2024	0.019950	Alibaba.com	China	market group for electricity, medium voltage
Lithium Hydroxide	0.0607	Kg	GREET2024	28.48	Alibaba.com	China	
Nickel Sulfate	0.3153772	Kg	GREET 2024	24.41	Alibaba.com	China	
Raw chemical materials	0.003434	Kg	GREET2024	0.380000	Alibaba.com	China	ammonium hydroxide
Raw chemical materials	0.0039	Kg	GREET2024	0.191000	Alibaba.com	China	Sodium Hydroxide
			Output				
Positive Active Material	1	kg		85	Alibaba.com	China	

3.2.1.4.2. Negative Active Material in China

For Negative Active material of the Lithium Battery the most component is Graphite. Global graphite mining is highly concentrated, with China producing nearly 59.1% of the world's supply in 2020. The next four largest producers together accounted for 26.9% of global output. From 2015 to 2020, global mine output of natural graphite declined, notably dipping in 2017.

However, global reserve estimates for graphite ore deposits increased from 230 million metric tons in 2015 to 320 million metric tons by 2020, based on new data from graphite-producing companies and government agencies. The processing of refined graphite for Li-ion battery anodes is concentrated in industrialized regions. China leads this industry, followed by Japan and South Korea, which together accounted for over 95% of global market sales in 2019. The United States and Western Europe are newer but rapidly growing entrants. Additionally, emerging graphite firms in Australia, Canada, and India are integrating upstream mining with downstream processing to produce battery-grade anode material[55]. Foreground system for Graphite the assumption is the same as Positive Active material. Table 17 Shows the amount and details of input/output flow.

Table 17. Input and Output for Negative Active Material Production Process

Flow	Amount	Unit	Source Input	Price [USD/unit]	Source Price	Location	Reference on PSILCA
				Input flows			
Coal mining and processing	0.659261	USD	GREET2024	1.2	Alibaba.com	China	Carbon Black
Electricity and steam production and supply	0.05712	USD	GREET2024	0.019950	Alibaba.com	China	market group for electricity, medium voltage
Graphite	0.484937	USD	GREET2024	0.43	Alibaba.com	China	Directly
				Output			
Negative Active Material	1	Kg	GREET2024	8.02		China	

3.2. 1.1. Nickel Cobalt Lithium Cell in China

Lithium-Ion Batteries (LIBs) are composed of Critical Raw Materials (CRMs) such as cobalt (in cathodes), lithium (in cathodes and electrolytes), and graphite (in anodes), which pose significant supply risks in Europe. The supply chain for LIBs is also concerning due to geopolitical uncertainties and the high environmental impacts of mining activities. Material Flow Analysis is often used to study supply networks and the recycling potential of CRMs across different regions and time periods. Globally, there are concerns that the rapid growth in demand is outstripping the supply capacity, and the locations of mining sites, manufacturing plants, and markets for lithium-ion batteries are not well-aligned[59].

In the following chapter, the foreground processes will be described in detail. The input and output data have been collected from GREET 2024. The remaining materials will be described in the appendix. shows the input and output flow for the NCA cell within the product system. This table is used to evaluate social risk by obtaining worker hours and risk levels of various indicators. The process of "Electronic computer and manufacturing" in China, as documented in PSILCA, has been utilized. Table 18 represent the inputs and output in OpenLCA

Table 18.Input and Output for NCA Cell production Process based on Non-EU Production Scenario

Flow	Amount	Unit	Source Input	Price [USD/unit]	Source Price	Location	Reference on PSILCA Database
			Input flows				
Crude petroleum products and Natural gas products	0.065	Kg	GREET 2024	0.139724	Alibaba.com	China	market group for heat, district or industrial, natural gas
Electricity and steam production and supply	0.092185	Kg	GREET 2024	0.019950	Alibaba.com	China	market group for electricity, medium voltage
Electronic element and device	0.029327	Kg	GREET 2024	1.57	Koese et al[48]	China	separator
Manufacture of plastic products	0.064117	Kg	GREET 2024	0.154	Koese et al[48]	China	plastic Film
Negative Active Material	0.395338	Kg	GREET 2024	8.26	Alibaba.com	China	
Positive Active Material	0.437155	Kg	GREET 2024	85	Alibaba.com	China	
			Output				
NCA Cell	1	Kg	GREET 2024	93.7	GREET2024	China	

3.2.2. EU Production Scenario

In the European scenario, the selection of countries was based on their potential role in the future supply chain within Europe, considering factors such as resource availability, production capacity, and strategic importance in the supply chain. Although, while most supply chain stages are modeled based on potential European sources, the mining stage is still linked to the country of origin, for example Cobalt in Congo or Nickel in Indonesia, and Lithium in Chile. In the case of Cobalt Finland is the biggest supplier for Europe.

The European scenario in this study is developed as a hypothetical scenario based on reports from the European Federation for Transport and Environment [60], and the European Carbon and Graphite Association[60], [61]. These sources provide insights into the potential evolution of Europe's battery production and material supply chain. By relying on these authoritative reports, this scenario aims to construct a plausible representation of how the social impact of the European battery supply chain could be under specific assumptions. The selection of key production locations for different battery components is guided by industrial capacity, resource availability, and strategic positioning within the European market.

According to these references, Germany is assumed to be the largest hub for cell battery assembly in Europe. This assumption is based on Germany's advanced technological infrastructure, strong automotive sector, and significant investments in battery manufacturing facilities. Major industry players are expanding their operations in Germany, positioning it as a central player in the hypothetical European battery supply chain. The presence of well-established supply chain networks further supports this assumption.

Poland is identified as having the greatest potential for cathode production, a crucial component in lithium-ion batteries. This assumption is based on Poland's increasing industrial capacity (Umicore), attractive investment environment, and strategic location within Europe. The country has already attracted significant investments in battery material processing, particularly for cathode active materials, making it a logical choice in this scenario.

For the anode component in this hypothetical scenario, Norway is considered a key supplier of active anode material. This assumption is based on the ongoing development of an anode material production facility by Mineral Commodities, which is strategically positioned to supply European battery plants. The company's investment in Norway aligns with Europe's efforts to establish a more localized and sustainable battery supply chain.

For the supply chain of intermediate materials, different European countries are assumed to play specialized roles. The United Kingdom (UK) is considered the primary source for lithium intermediate materials, reflecting its growing interest in lithium refining and processing. Norway is assumed to be the leading supplier of nickel sulfate, benefiting from its well-developed mining sector and commitment to sustainable resource extraction. Meanwhile, Finland is identified as the main supplier of cobalt sulfate, given its expertise in cobalt processing and expanding investments in battery material supply. Figure 12 have been draw based on the EU assumption scenari.

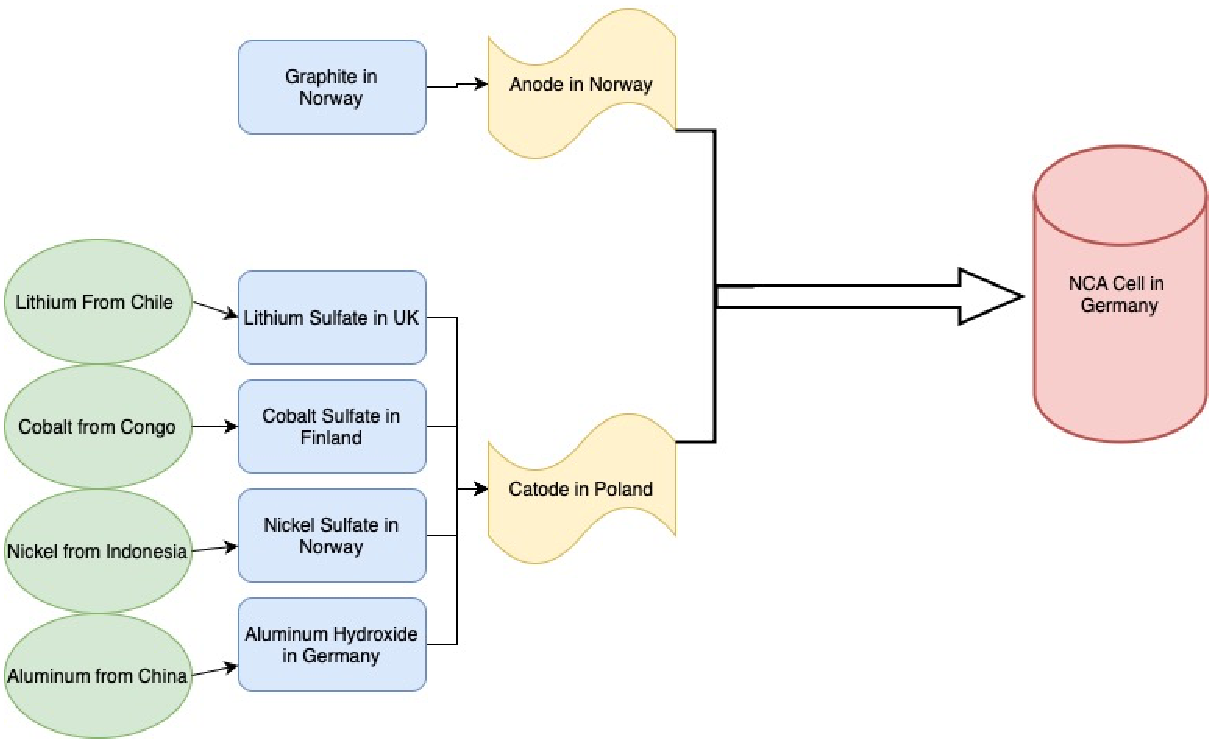

Figure 12. Foreground and background processes for NCA in EU scenario Production

The analysis follows the UNEP/SETAC Guidelines and leverages the PSILCA database implemented in OpenLCA to identify high-risk areas and critical social issues along the supply chain.

3.2.1. NCA Lithium battery social inventory

The manufacturing of lithium-ion batteries (LIBs) is still dominated by East Asia. European automakers have faced challenges securing adequate battery supplies from this region.

With the anticipated surge in EV adoption, European policymakers have underscored the critical importance of developing a robust local battery industry to maintain competitiveness in the automotive sector. Currently, Europe's LIB production accounts for just 6% of the global battery capacity (450 GWh). However, projections suggest that Europe's share will rise to 16% of the global market by 2029, with an estimated capacity of 2550 GWh.

Driven by various EU initiatives to advance lithium-ion battery (LIB) production within Europe, efforts extend beyond securing access to raw materials and mitigating environmental impacts. These initiatives aim to establish a fully competitive European battery value chain, emphasizing research, innovation, and the development of a highly skilled workforce. In alignment with the battery supply goals and the objectives outlined in the European Green Deal, a comparative analysis was conducted to evaluate European and global LIB supply scenarios[3]. The inventory for the described scenario involves key activities, processes, and materials along the NCA lithium battery supply chain.

3.2.2.6. Cobalt Sulfate in Finland

The similar assumption was considered for Cobalt Sulfate and the process which was extracted from PSILCA is "Chemical, chemical product and man-made fiber". Table 19 shows the input and output of Cobalt sulfate in EU scenario

Table 19. Input and Output for Cobalt Sulfate production process EU-Scenario Production

Flow	Amount	Unit	Source Input	Price	Source Price	Location	Reference on PSILCA Database
			Input Flows				
Crude petroleum and natural gas; services incidental to oil and gas extraction excluding surveying	0.00695733	KWh	GREET 2024	0.139724	Alibaba.com	Finland	market group for heat, district or industrial, natural gas
Electrical energy, gas, steam and hot water	0.001695733	kg	GREET 2024	0.019950	Alibaba.com	Finland	market group for electricity, medium voltage
Kerosene	6.31324E-5	kg	GREET 2024	0.240000	Alibaba.com	Australia	
Limestone	7.66097E-7	kg	GREET 2024	0.100000	Alibaba.com	Australia	
Metal ores	0.696726707	kg	GREET 2024	30	Alibaba.com	Finland	Cobalt Refining

Chemicals, chemical products and man-made fibers	0.034777042	kg	GREET 2024	1.57	Alibaba.com	Finland	proxy for hydrochloric acid, without water, in 30% solution state
Chemicals, chemical products and man-made fibers	0.017260661	kg	GREET 2024	1.350000	Alibaba.com	Finland	proxy for sulfuric acid
Chemicals, chemical products and man-made fibers	6.04459E-4	kg	GREET 2024	4.410000	Alibaba.com	Finland	proxy for disodium disulphite
Chemicals, chemical products and man-made fibers	1.02E-9	kg	GREET 2024	1.2	Alibaba.com	Finland	proxy for chemical factory
				Output			
Cobalt Sulfate		kg	GREET 2024	72.60	Alibaba.com		

3.2.2.4. Lithium Hydroxide in UK

All the assumption and social risks for Lithium Hydroxide taking place in Germany and from PSILCA and the social risk and worker hours are extracted from "Manufacture of Basic Metal" in Germany. Table 20 shows the input/output of Lithium hydroxide.

Table 20. Input and Output for Lithium Hydroxide production process in EU- Scenario Production

	Amount	Unit	Source Input	Price [USD/unit]	Source Price	Location	Reference on PSILCA Database
				Input flows			
Manufacture of other chemical products - GB	0.58304	kg	GREET2024	11.627000	Alibaba.com	GB	Lithium Hydroxide
Manufacture of other organic chemicals - GB	1.82E-04	kg	GREET2024	0.019950	Alibaba.com	GB	market for chemical factory, organics
Manufacture of lime - GB	0.34701	kg	GREET2024	6.090000	Alibaba.com	GB	lime, hydrated,
Electricity by gas - GB	4.73E-04	KWh	GREET2024	0.019950	Alibaba.com	GB	electricity, medium voltage
Gas oil - GB	0.017117	MJ	GREET2024	0.139724	Alibaba.com	GB	heat, district or industrial, natural gas
Collection, purification and	1.00E-06	kg	GREET2024	0.000544	Alibaba.com	GB	Tap water

distribution of water - GB							
			Output				
Lithium Hydroxide	1	kg	GREET2024	28.480000	Alibaba.com	GB	market for chemical factory, organics

3.2.2.5. Nickel Sulfate in Norway

As it said Finland is the Europe biggest supplier of Cobalt and Nickel, so for evaluating the social risk and worker hours the process which extracted from PSILCA is “Chemicals, Chemical Products and Man-made Fibers” in Norway. Table 21 demonstrate the Input and Output process of Nickel Sulfate production.

Table 21. Input and Output for Nickel Sulfate production process EU-Scenario Production

Flow	Amount	Unit	Source Input	Price [USD/Unit]	Source Amount	Location	Description
			Input Flows				
Metal ores	0.243537	Kg	GREET2024	24.41	Alibaba.com	Norway	Nickel Mining
Crude petroleum and natural gas; services incidental to oil and gas extraction excluding surveying	9.34E-04	Mj	GREET2024	0.010600	Alibaba.com	Norway	heat, district or industrial, natural gas
Electrical energy, gas, steam and hot water	0.001704	KWh	GREET2024	0.019950	Alibaba.com	Norway	Electricity, medium voltage
Chemicals, chemical products and man-made fibers	2.57E-11	kg	GREET2024	1.57	Alibaba.com	Norway	market for chemical factory, organics
Chemicals, chemical products and man-made fibers	0.032185	kg	GREET2024	1.172607	Alibaba.com	Norway	market for sulfuric acid
Chemicals, chemical products and man-made fibers	0.00295	kg	GREET2024	3.6	Alibaba.com	Norway	nitrogen, liquid
Collection, purification and distribution of water	0.032185	kg	GREET2024	0.000544	Alibaba.com	Norway	market group for tap water
			Output Flows				
Nickel Sulfate	1	Kg	GREET2024	24.41	Alibaba.com		

3.2.2.2. Positive Active Material in Poland

Similar to Non-EU Scenario Production in Positive active material, evaluating social risk and worker hours take place in PSILCA and the process of "Computer and related services" in Poland. Table 22 Shows the input and output flow.

Table 22. Input and Output for Positive Active Material Production Process based on EU Production Scenario

Flow	Amount	Unit	Source Input	Price [USD/unit]	Source Price	Location	Reference on PSILCA
			Input flows				
Aluminum Sulfate	0.0017784	Kg	GREET2024	1.44	Alibaba.com	Spain	
Cobalt Sulfate	0.179322	Kg	GREET2024	72.60	Alibaba.com	Finland	
Nickel Sulfate	0.315377	Kg	GREET2024	24.41	Alibaba.com	Norway	
Lithium Hydroxide	0.0607	Kg	GREET2024	28.48	Alibaba.com	Uk	
Chemicals, chemical products and man-made fibres	0.00733	Kg	GREET2024	28.48	Alibaba.com	Poland	Sodium Hydroxide
Chemicals, chemical products and man-made fibres	0.0039	Kg	GREET2024	0.380000	Alibaba.com	Poland	Ammunium Hydroxide
Chemicals, chemical products and man-made fibres	0.003434	Kg	GREET2024	0.191000	Alibaba.com	Poland	Sodium Hydroxide
Crude petroleum and natural gas; services incidental to oil and gas extraction excluding surveying	0.010028	MJ	GREET2024	0.139724	Alibaba.com	Poland	market group for heat, district or industrial, natural gas
Electrical energy, gas, steam and hot water	0.01774	KWh	GREET2024	0.019950	Alibaba.com	Poland	market group for electricity, medium voltage
			Output Flows				
Positive Active Material	1	kg	GREET2024	85	Alibaba.com	Poland	

3.2.2.3. Negative Active Material in Norway

For Negative active material also the same process as Positive active material was chosen and the data for evaluating social risk and worker hours extracted from PSILCA and "Computer and related services" in Norway. Table 23 Shows the input and output flow.

Table 23. Input and Output for Negative Active Material Production Process in EU-Scenario Production

Flow	Amount	Unit	Source Input	Price [USD/unit]	Source Price	Location	Reference on PSILCA
			Input Flows				
Crude petroleum and natural gas; services incidental to oil and gas extraction excluding surveying	0.659261	Mj	GREET2024	0.010600	Alibaba.com	Norway	heat, district or industrial, natural gas
Electrical energy, gas, steam and hot water	0.005712	KWh	GREET2024	0.019950	Alibaba.com	Norway	Electricity, medium voltage
Graphite	0.484937	USD	GREET2024	0.43	Alibaba.com	Norway	
			Output Flows				
Negative Active Material	1	Kg	GREET2024	8.02		Norway	

3.2.1.1. NCA Cell in Germany

In this scenario the production and assembly of cell changed from China to Germany. For this scenario, the information related to social indicators and worker hours are extracted from the PSILCA database and process of "Passenger cars and parts" in Germany. Table 24 shows the input and output of NCA cell

Table 24. Input and Output for NCA Cell production Process based on EU Production Scenario

Flow	Amount	Unit	Source Input	Price [USD/unit]	Source Amount	Location	Description
			Input flows				
Crude petroleum and natural gas	0.065	Kg	GREET 2024	0.139724	Alibaba.com	Germany	Proxy for Heat
Electricity and district heat	0.092185	Kg	GREET 2024	0.019950	Alibaba.com	Germany	Proxy for Electricity
Electricity generating equipment	0.029327	Kg	GREET 2024	1.57	Koese et al[48]	Germany	Proxy for Separator

Manufacture of plastic products	0.064117	Kg	GREET 2024	0.154	Koese et al[48]	Germany	Proxy for Plastic Film Extruded
Negative Active Material	0.395338	Kg	GREET 2024	8.26	Alibaba.com	Norway	
Positive Active Material	0.437155	Kg	GREET 2024	85	Alibaba.com	Poland	
Output Flows							
NCA Cell	1	Kg	GREET 2024	93.7	GREET2024	Germany	

3.3 Social Life Cycle Impact Assessment

In this section the social impact assessment of two scenarios: Non-EU production and EU production going to be analyzed. OpenLCA software was used to carried out this analysis and modeled the system by using PSILCA database and using "Social impact Weighting Method" to run and calculate the method. Because of using personal computer and due to computational limit, a cut-off criterion 10^{-4} was considered, with this assumption all the analysis related to flow and process with contribution of less than 0.01% not considered.

The result which are obtained from OpenLCA could be analyzed in different ways. Each of the social risk indicators can be analyzed based on different supply chain of different scenario.

In the following section, at first, a comparison between two scenarios on different stages of producing Lithium cell battery, positive and negative active material and CRMs components will be generated; then, contribution analysis on two different scenarios will be conducted on different stages of Cell production. And at the end of this section, two most impact riskiest impact categories on each scenario will be compared and analyzed.

3.3.1. Comparison Social Impact of NCA cell production in Different Scenarios

NCA cell production is include of many stages from extraction of raw material, refining, manufacturing of active cathode and anode material and at the end assembly of cell. Table 25 presents the LCIA results including the impacts from upstream activities. The rows represent the selected social impact categories and two scenarios, and the columns correspond to the cell typologies based on medium risk hours. In Table 25 The impacts are quantified using the unit defined by the LCIA method which is medium risk hours for a specific impact.

Table 25. LCIA result of NCA cell production

Impact category	EU Scenario	Non-EU Scenario
Association and bargaining rights	7.343433	63.42462
Certified environmental management system	0.054626	0.055217
Child Labor, total	0.000691	0.008658
Contribution of the sector to economic development	0.676246	4.440587
DALYs due to indoor and outdoor air and water pollution	0.006707	0.804032
Fair Salary	7.002404	59.25499
Fatal accidents	0.006708	0.058522
Health expenditure	1.403953	12.30173
Illiteracy, total	0.067653	1.324563
Indigenous rights	0.133932	1.165658
Industrial water depletion	0.403288	1.246455
International migrant stock	0.027194	0.021226
International migrant workers (in the sector/ site)	0.006938	0.060653
Life expectancy at birth	0.001863	0.086079
Migration flows	0.532694	0.178211
Non-fatal accidents	0.014686	0.074521
Public sector corruption	0.926301	5.841298
Safety measures	0.070033	0.536383
Social security expenditures	0.668349	6.577626
Trade unionism	0.325968	1.440729
Trafficking in persons	6.676924	58.51598
Violations of employment laws and regulations	6.679364	57.94203
Weekly hours of work per employee	0.07062	0.577254
Workers affected by natural disasters	0.66876	5.775103
Youth illiteracy, total	0.00679	0.803982

The LCIA results for NCA cell production reveal severe contrasts between the EU and non-EU scenarios across various social and environmental impact categories. The non-EU scenario generally exhibits significantly higher risks in areas such as association and bargaining rights (63.42 vs. 7.34), child labor (0.0086 vs. 0.00069), fatal accidents (0.0585 vs. 0.0067), and forced labor (4.60 vs. 0.66). These figures suggest weaker labor protections, higher exploitation risks, and less workplace safety in the non-EU scenario.

Conversely, the EU scenario performs significantly better in terms of education expenditures (0.092 vs. 0.66), fair salary (7.00 vs. 59.25), and health expenditure (1.40 vs. 12.30), reflecting stronger social welfare systems and worker protections. while the EU scenario generally fares better, the presence of Migration flows (0.59 vs. 0.17) and minor but existing child labor values highlight that challenges persist in both contexts. Overall, the EU scenario offering more sustainable and ethical conditions, while the non-EU scenario carries significantly higher risks across multiple impact categories.

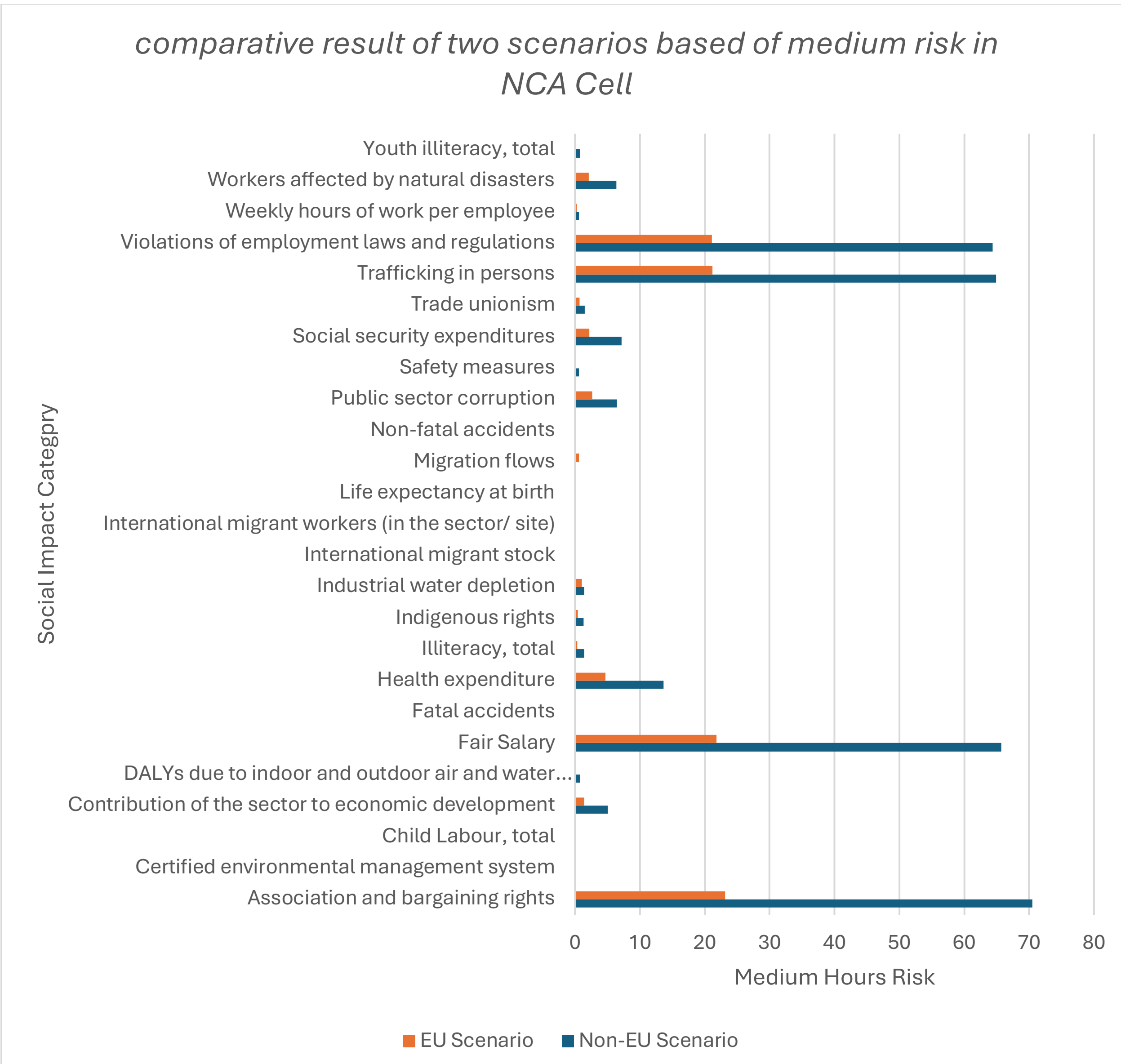

Figure 13. comparative result of two scenarios based of medium risk in NCA Cell

Figure 13, visualized Table 25 for better understanding, as it could be seen green bars are the indicators in non-EU scenario and orange bars represent the EU scenarios.

3.3.2. Comparison Social Impact of the Active Material in two Different Scenarios

Figure 14 compares the social impact of producing positive active material in two scenarios: one where production happens entirely in China (non-EU scenario) and another where production occurs in Poland (EU scenario). The comparison results are derived from OpenLCA software, and the medium risk hours are shown as percentages.

Key categories include association and bargaining rights, child labor, fatal accidents, public sector corruption, and industrial water depletion. The graph highlights differences in risk levels, showing that some categories have higher risks in one scenario compared to the other. For instance, the EU Scenario may exhibit lower risks in public sector corruption but higher risks in industrial water depletion compared to the Non-EU Scenario.

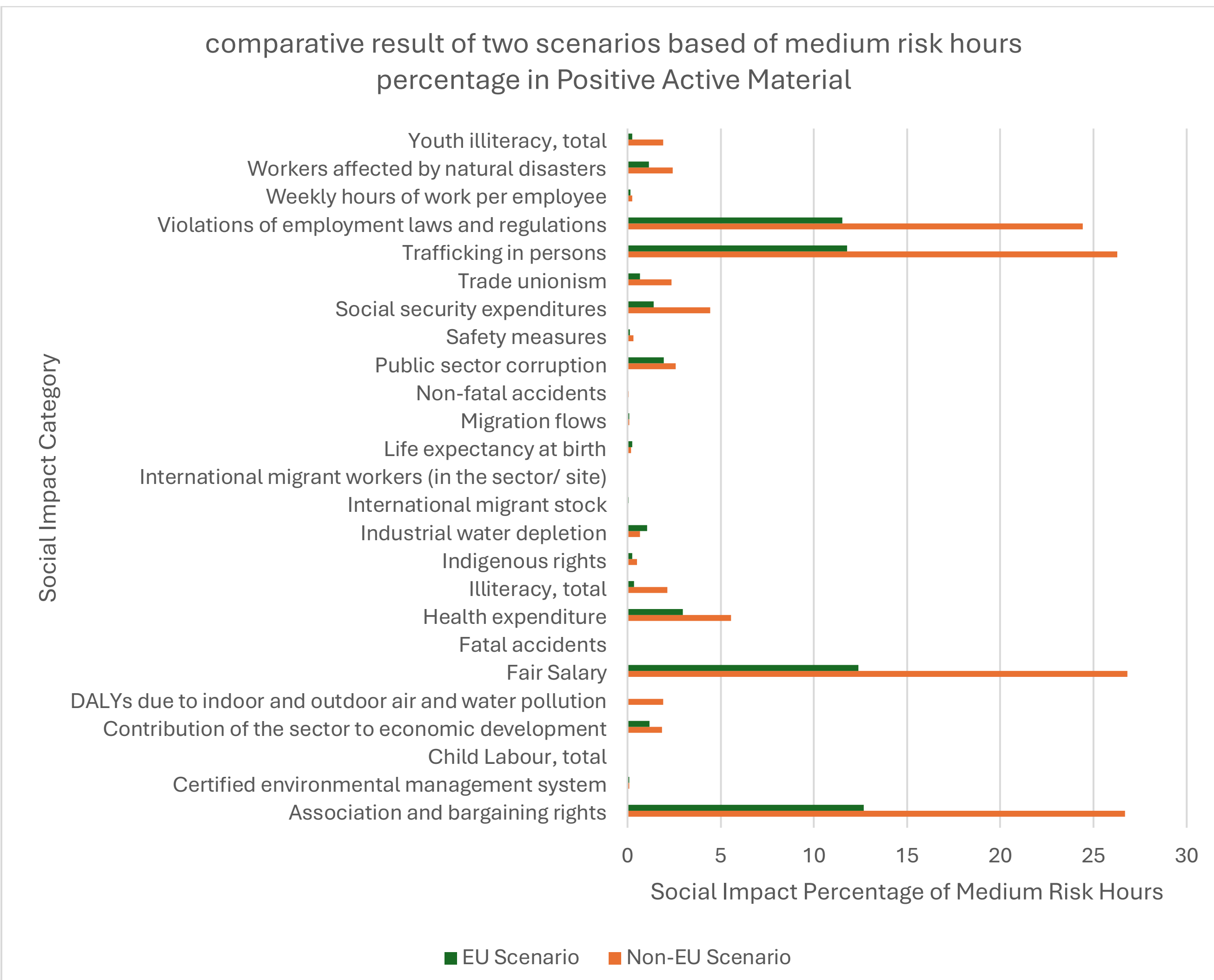

Figure 14. comparative result of two scenarios based of medium risk hours percentage in Positive Active Material

In this figure as can be clearly seen, in the stage of positive active material, in non-EU scenario the social risk of indicators is higher.

3.3.3. **Comparison Social Impact of the Component in Two Different Scenarios**

In this section, between the material which are used in the production of active material, Cobalt sulfate is chosen for further analysis. In the Figure 15 the result related to social risk level extracted from OpenLCA software have been shown.

Cobalt is the most problematic component for production of Lithium Battery cell, as it can be seen in the figure the problem related to cobalt is going to moderate if the process stage take place in a country with sustainable social impact. With refining of Cobalt in Finland the risk level related is reduced about 50%.

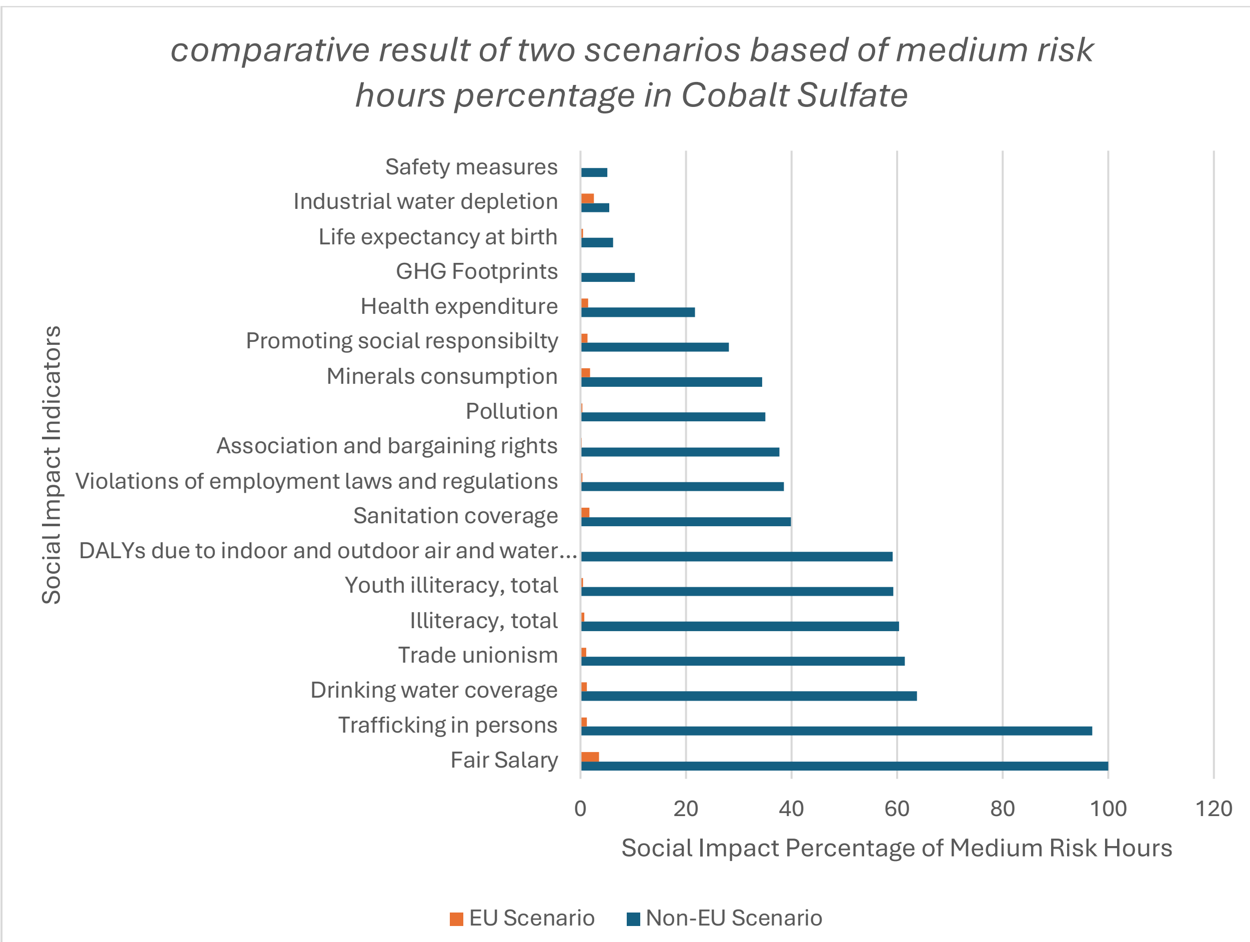

Figure 15. comparative result of two scenarios based of medium risk hours percentage in Cobalt Sulfate

3.3.4. Social impacts of cell production in Two Scenario: contribution analysis

In this part, the contribution analysis for two scenarios and different stage of producing NCA cell were conducted, this process in the analysis refer to production phases and the relative countries in two scenarios, where these stages assumed to be conducted. In Figure 17 represents the contribution of NCA cell battery production under the Non-EU Scenario. It demonstrates that the materials with the most significant contributions to social impacts are the positive active material and negative active material which produced in China. These materials play a crucial role in various social impact categories, such as certified environmental management systems, economic development, fair salary, health expenditure, indigenous rights, and safety measures. The figure highlights how these materials influence the overall social impact of NCA cell production, emphasizing their importance in the production process and their substantial effect on different social indicators.

3.3.4.1. NCA Cell Contribution Analysis

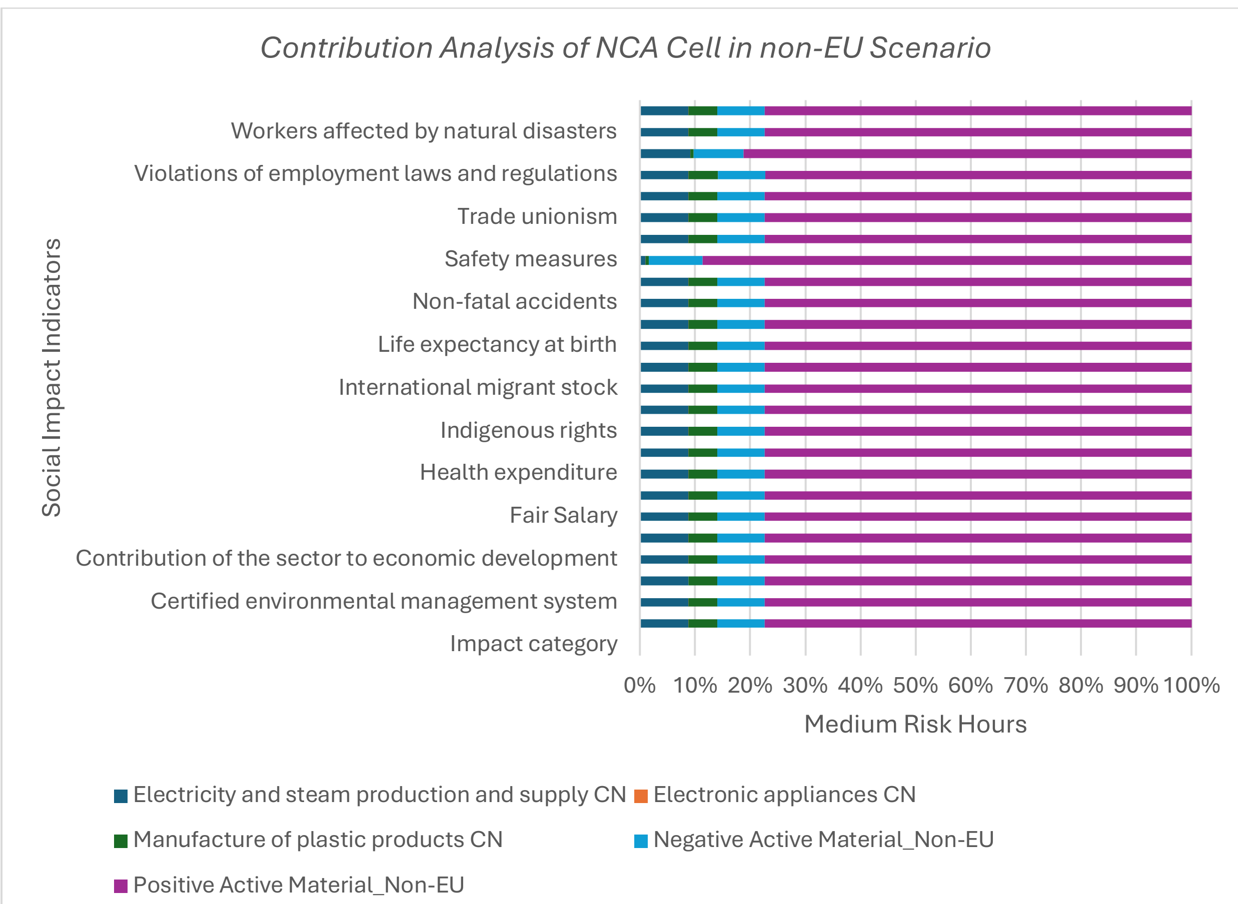

Figure 16. Contribution Analysis of NCA Cell in non-EU Scenario

Figure 17 shows the contributions of NCA cell battery production in the EU Scenario. Similar to the Non-EU Scenario, the positive and negative active materials are the main contributors. The social impact indicators include fair salary, industrial water depletion, international migrant workers, and non-fatal accidents, among others.

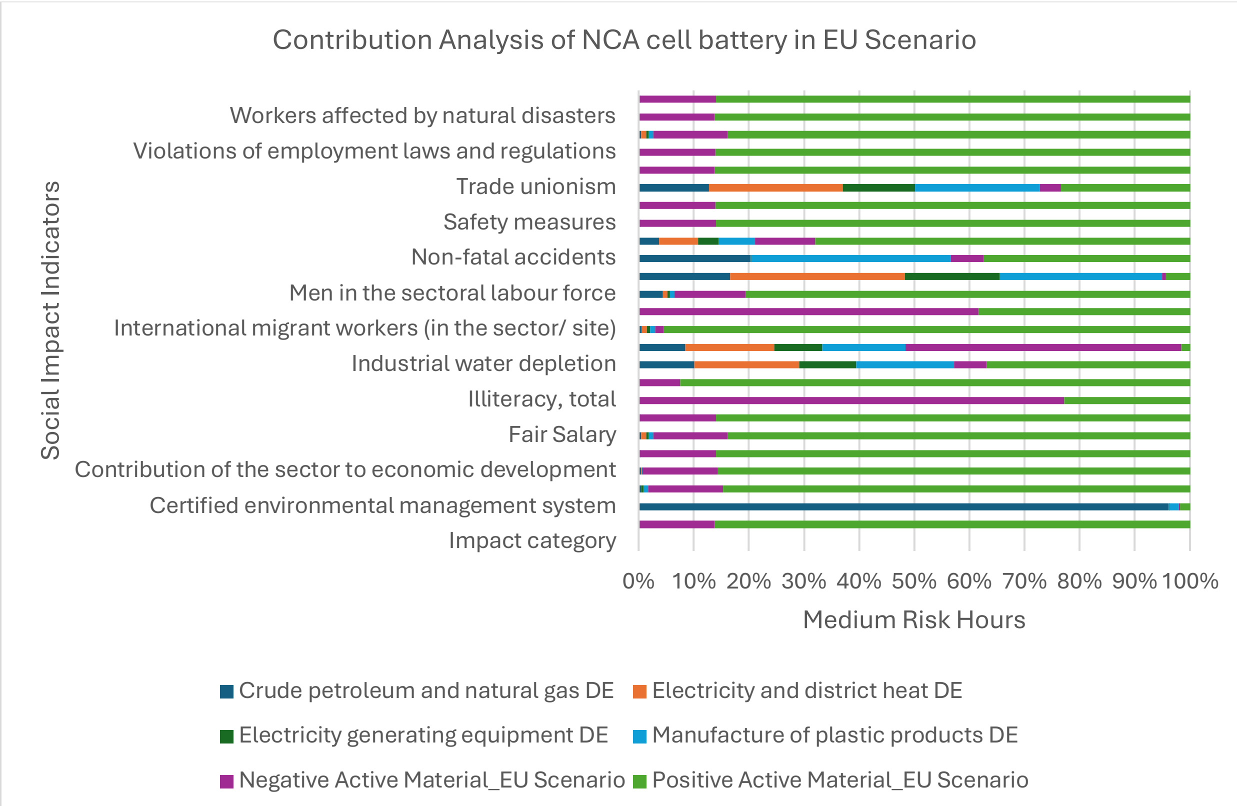

Figure 17. Contribution Analysis of NCA cell battery in EU Scenario

Both figures demonstrate that the positive and negative active materials are the primary contributors to the social impacts of NCA cell battery production. However, the percentage for each material input is different.

3.3.4.2. Positive Active Material Contribution Analysis

Figure 18 illustrates the social risks associated with different materials used in the production of positive active material in non-EU scenario, measured in Medium Risk Hours across various social impact indicators. The most significant risks are connected to Nickel sulfate and Cobalt and Lithium Hydroxide.

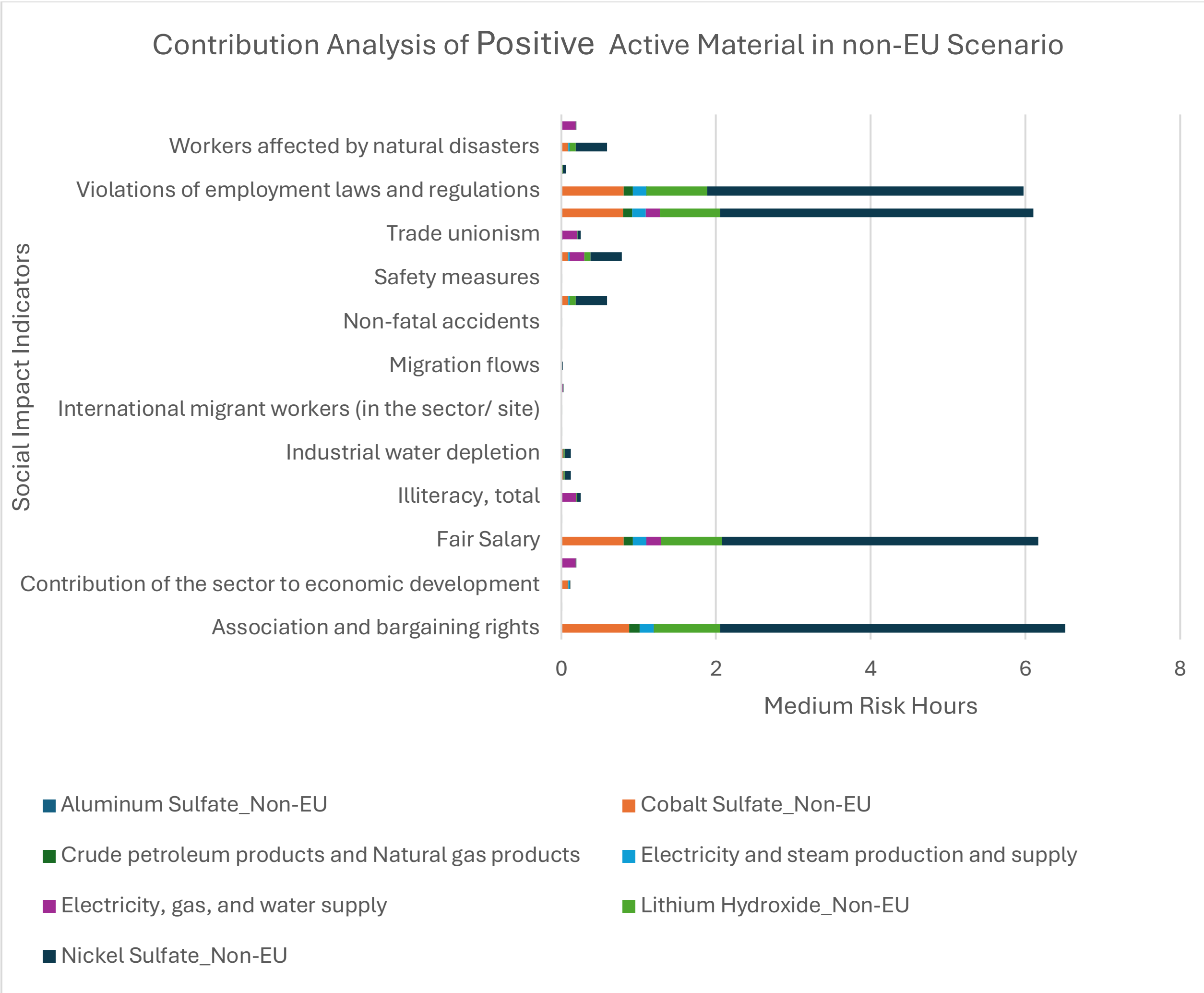

Figure 18. Contribution Analysis of Positive Active Material in non-EU Scenario

Figure 19, shows the similar result related to EU scenario, and contribution of Nickel sulfate and Cobalt sulfate is much higher in compared to other material.

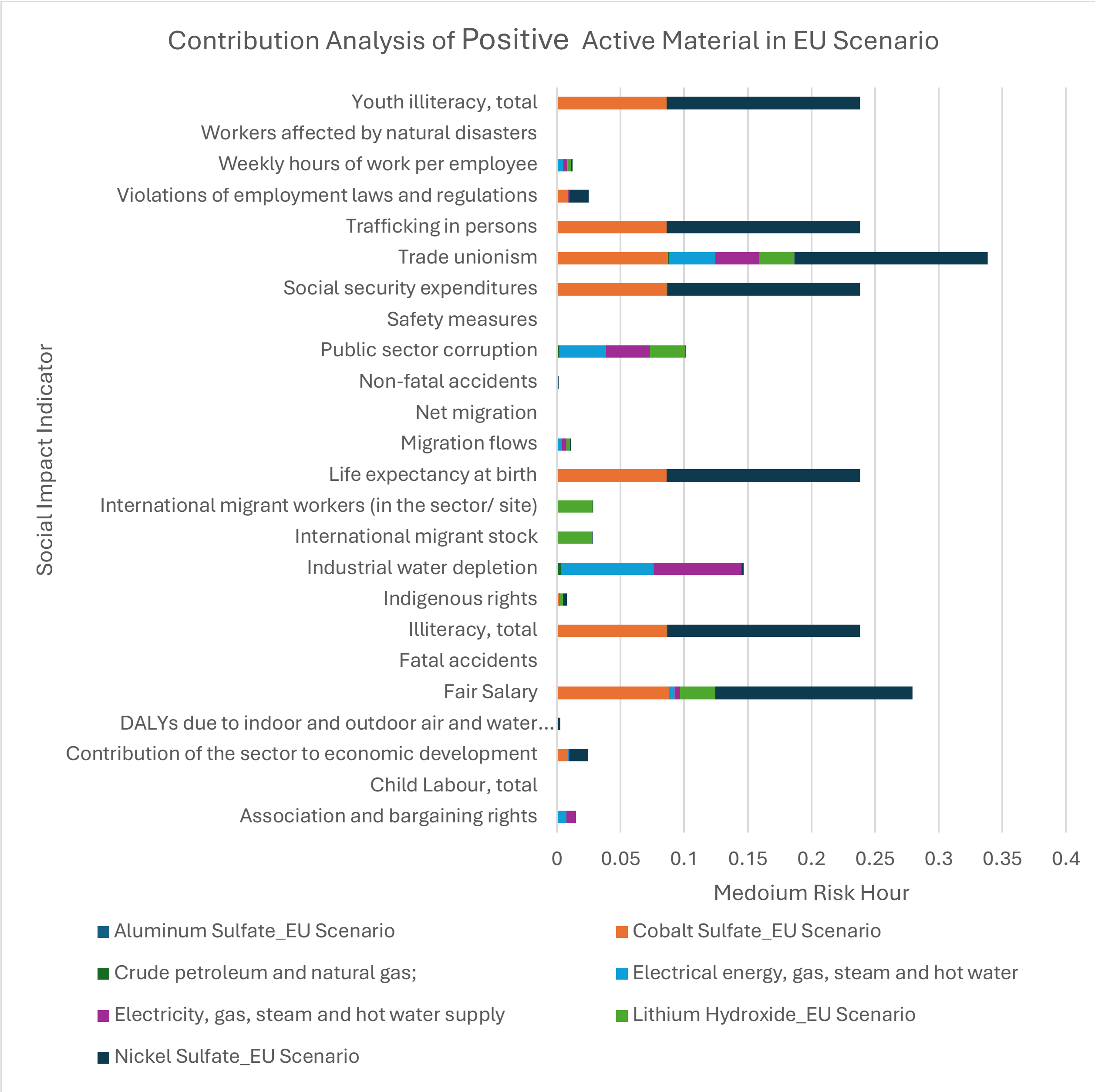

Figure 19. Contribution Analysis of Positive Active Material in EU Scenario

3.3.5. Comparison of Social Indicators between Non-EU and EU Scenario

The comparison between two scenarios was conducted based on four key risk categories that are more connected with the supply chain of lithium-ion batteries: fair salary, association and bargaining rights, trafficking in persons, and violations of employment laws and regulations. For each risk category, the Non-EU and EU scenarios were compared, analyzing the contribution of production processes. This section examined the different supply chains of NCA cell, positive active material and critical raw materials such as cobalt sulfate, nickel sulfate, lithium hydroxide, and graphite by comparing the total risk hours related to the different supply chain configurations. In figure 17 the medium risk hours of NCA cell compared in two different scenarios, and as it can be clearly seen, the differences between the non-EU scenario and EU scenario are significant.

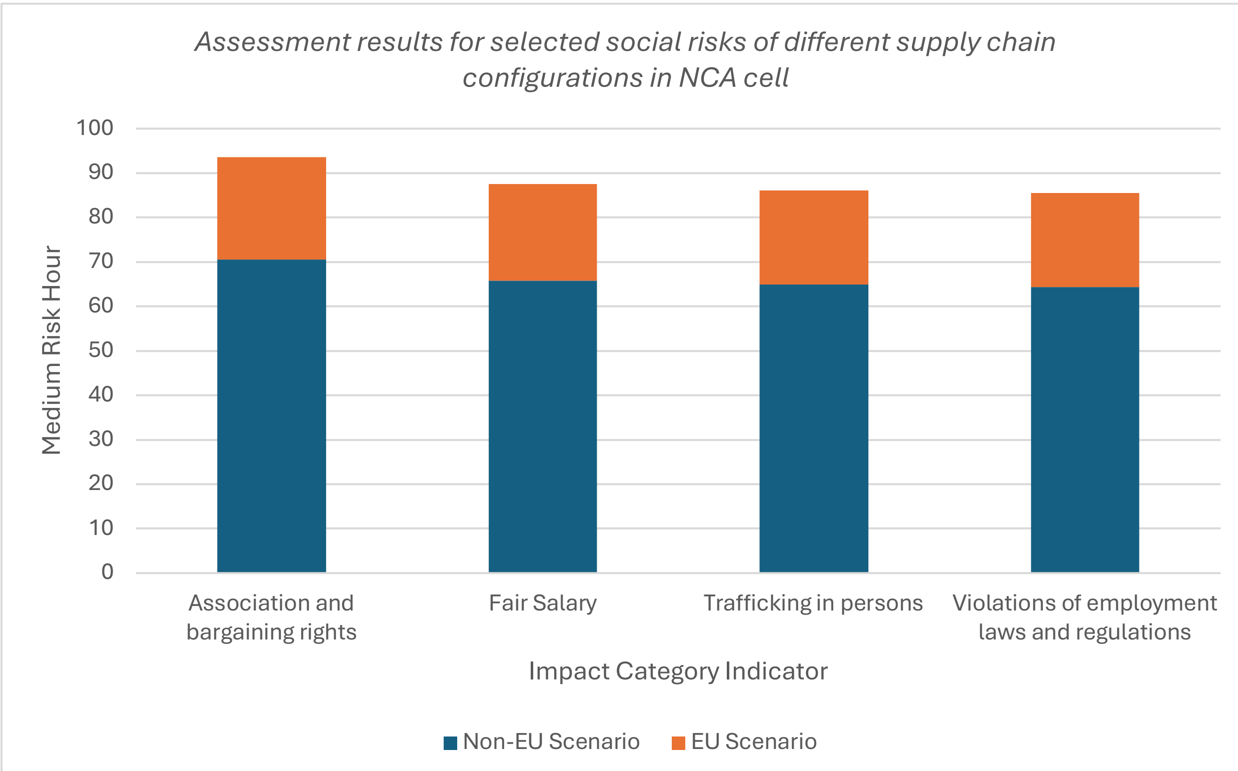

Figure 20. Assessment results for selected social risks of different supply chain configurations in NCA cell

As it can be clearly seen in this figure the whole process of production of NCA Cell has a significant difference in these two scenarios, and in non-EU scenario the level of social risk is high, also in each social indicator as a comparison, in EU scenario decreased.

Figure 21 demonstrates the different scenarios of Positive active material, as it clears that in non-EU scenario the medium risk hours is very higher.

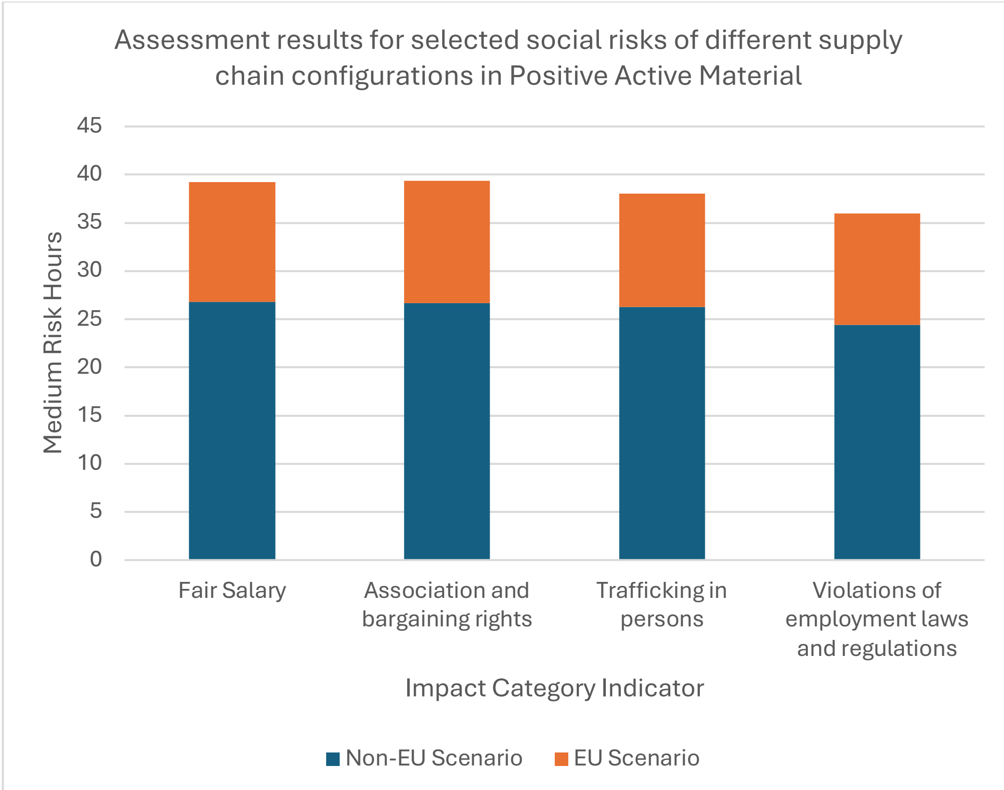

Figure 21. Assessment results for selected social risks of different supply chain configurations in Positive Active Material

In Figure 22, the assessment compares the cumulative medium risk hours for four social risk categories: Association and Bargaining Rights, Fair Salary, Trafficking in Persons, and Violations of Employment Laws and Regulations. The comparison is made between the EU Scenario and non-EU scenarios. For Fair Salary, there is a significant reduction in medium risk hours in the EU scenario. For Trafficking in Persons, the EU scenario indicates lower medium risk hours than the non-EU scenario. For Violations of Employment Laws and Regulations, the non-EU scenario has higher medium risk hours compared to the EU scenario.

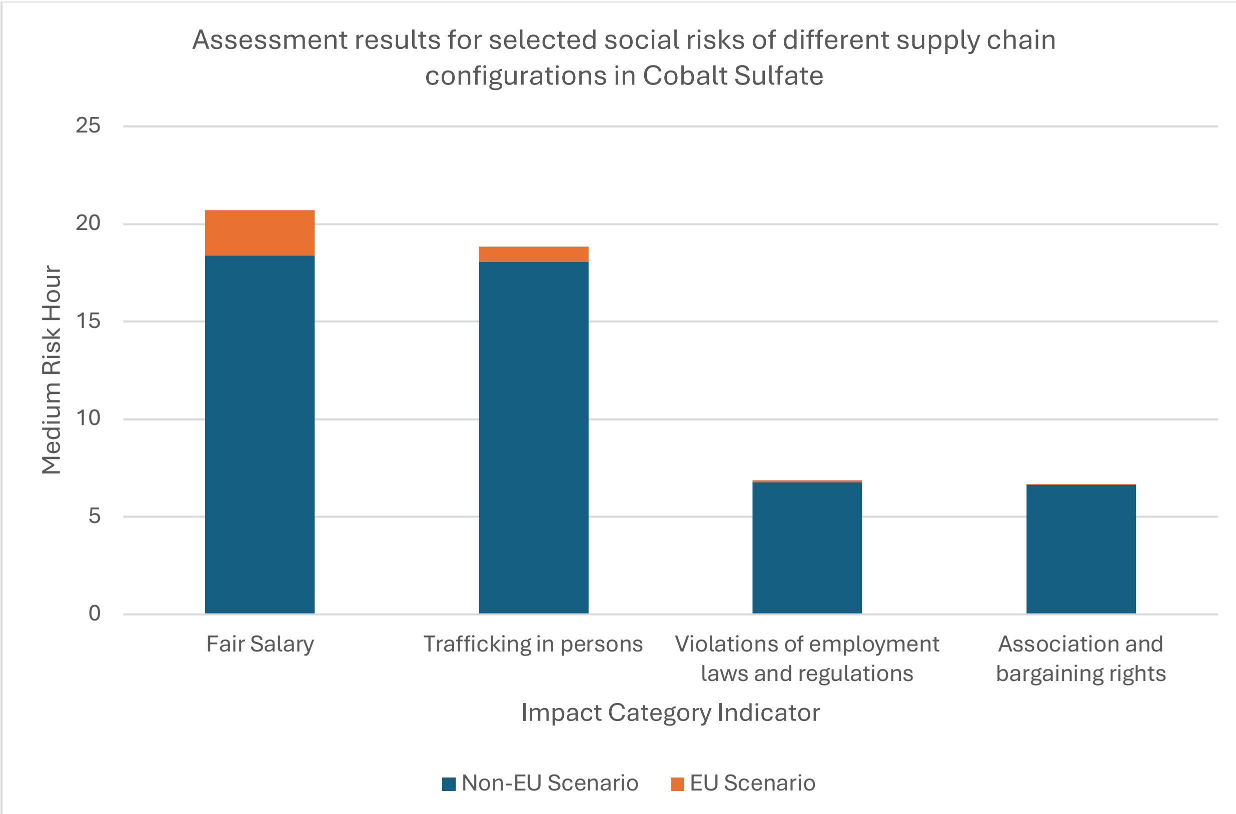

Figure 22. Assessment results for selected social risks of different supply chain configurations in Cobalt Sulfate

Overall, the EU scenario shows a reduction in medium risk hours across all four social risk categories, indicating an improvement in social conditions in the supply chain of Cobalt Sulfate.

3.3.6. Analysis of a social impact category: Fair Salary

Another way of analyzing the result is based on a specific subcategory. The reason to choose this social impact category is because, first the category of worker influenced the most between the other category and second, the quality of data is high and for battery production shows highest impact.

The result in this section will be analyzed related NCA cell production and the comparison of this production in different countries based on the assumed scenarios.

Subcategory of fair salary, focused on three standards; “the minimum wage required by law”;” the local ‘prevailing industry wage” and “The ‘living wage”.

Figure 23 illustrates the social impact indicators contributions of various countries and highlight’s locations where social hotspots occur within the EU scenario. The countries shown in red indicate regions that contribute significantly to the “Fair salary” indicator and identified as areas where social sustainability concerns exist.

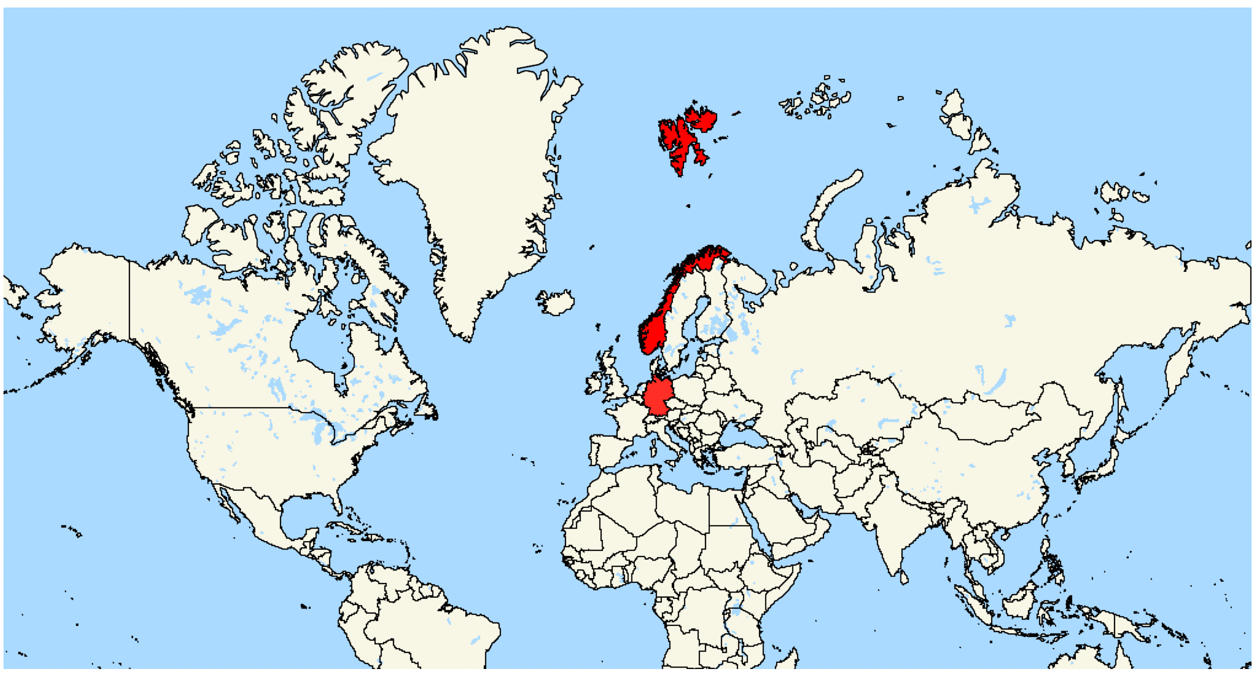

Figure 23. Social Hotspot in EU scenario

In Figure 24 presents the social hotspots identified in the non-EU scenario to produce NCA cells, highlighting the regions where significant social risks are concentrated. As depicted in the figure, two countries, China and the Democratic Republic of Congo, stand out as critical locations in terms of social sustainability concerns.

Figure 24. Social Hotspot in non-EU scenario

3.4. Social Life Cycle Interpretation

For social life cycle of NCA lithium battery in both scenario, different steps of producing battery and different critical raw material were analyzed. Between different steps and in both scenarios, the production of cell is more connected to social risk indicators. between critical raw material Nickel and Cobalt are more connected to social risk indicators and as a comparison between two scenarios, non-EU scenario supply chain is more connected to social impact indicators.

In the concept of social subcategories indicators: Fair salary, Association and bargaining rights, Trafficking in person and Violations of employment laws and regulations, were the most frequent category with the highest medium risk hours in both scenario although as a comparison in non-EU scenario these four subcategories were higher.

Based on contribution of different input flows for NCA cell, Positive and Negative active material had the most percentage of contribution with more than 70 percent, for Positive active material Cobalt and Nickel had the highest part. In Negative Active Material Graphite had the most contribution percentage.

In critical raw material, the most contribution percentage belongs to the extraction of raw material.

4. Discussion

A shift to electric vehicles (EVs) and lithium-ion batteries (LIBs) is considers as a critical pathway to reducing global greenhouse gas (GHG) emissions and improving sustainability. However, beyond their environmental benefits, LIBs introduce significant social implications throughout their life cycle. Social Life Cycle Assessment (S-LCA) provides a systematic approach to identifying and evaluating these social impacts, covering key stages such as raw material extraction, refining, cell production. This discussion evaluates the primary social risks associated with NCA Lithium battery, with a focus on critical raw material such as cobalt, lithium, nickel, and graphite, as well as production of positive active material and NCA cell production.

For the discussion, the research could be discussed in different levels, for this research the comparison between EU scenario and non-EU scenario were done by comparing different subcategories which are at the highest risk. The SLCA results for the cradle to gate analysis of the two different scenarios of battery production were conducted.

4.1. Worker

In non-EU scenario, as it was expected, the extraction of critical raw materials such as cobalt, lithium, and nickel, which are predominantly concentrated in a few geographic regions have higher social impact.

The subcategories which have the most connected risks in the production of NCA cell in both scenarios are "Association and bargaining rights, Fair Salary, Trafficking in persons, Violations of employment laws and regulations". Although in non-EU scenario, the percentage of social impact for Fair salary is 20 percent more than EU scenario, the percentage of "Association and bargaining rights" in non-EU scenario is about 50 percent more than EU scenario, in subcategory of "Trafficking in persons" and in non-EU scenario is 30 percent higher and in subcategory of "Violations of employment laws and regulations" the distance between two scenarios is about 50 percent. Also, in the stage of active material production and cell assembly the EU scenario has the lower risk, this result is corresponded to the finding of Thies et al.[9] and Koese et al.[62].

4.2. Local Community

For the local community category, the subcategories which have the highest risks include sanitation coverage, pollution, access to drinking water, mineral consumption. These risks are most pronounced in the EU scenario, particularly during the cell assembly stage, followed by the production of positive and negative active materials and finally, the raw material extraction phase.

Among battery components, the anode and cathode have the greatest risks, primarily due to the extraction of raw materials. Currently, social risks for local communities are most significant in sectors with supply chains based in China. However, in EU scenarios, these risks are expected to shift towards components sourced from Europe. This finding aligns with the research conducted by da Bouillass et al[10], [63] on EV vehicles.

4.3. Society

The societal category shows the lowest risks, especially in the non-EU scenario where components are manufactured in China. These risks fall under the subcategories of "Contribution to Economic Development" and "Health and Safety". The indicators, such as "illiteracy" and "health expenditure", are mainly linked to the extraction of raw materials, as reflected by their contribution percentages. These findings align with Koese et al. (2023) [41] on NMC lithium cathodes, where the "contribution of the sector to economic development" indicator was also analyzed and found to have a low score.

4.4. Limitation

The PSILCA database often uses national data instead of sector-specific information, raising concerns about its relevance to the battery supply chain's social conditions. Social risks, particularly in raw material extraction, may be less severe than suggested by S-LCA results and can vary significantly between companies or locations based on their policies and management. While the results indicate risks associated with a battery supply chain in China, this may change over time. According to World Bank projections, China's technological advancements will rapidly transform its industrial structure, improving standards for quality, safety, and the environment. Therefore, social risks related to a product's life cycle may change due to developments in the associated countries.

Another limitation is the attention to positive social risk, although there is positive indicators like "contributions to economic development", but social LCA results mainly highlight negative social risks. Assessing the broader societal contributions of products like batteries remains challenging, especially when negative impacts affect low socio-economic status countries and positive impacts benefit wealthier nations.

5. Conclusion

The transition to electric vehicles (EVs) is a crucial strategy in mitigating climate change, but it presents significant social sustainability challenges. Social Life Cycle Assessment (S-LCA) provides a systemic approach to evaluating these challenges across the lithium-ion battery (LIB) supply chain. By examining social themes such as human rights, working conditions, fair wages, and labor rights, S-LCA highlights the social risks associated with LIB production and usage.

This study starts with an introduction the importance of EV vehicle and electric battery specially lithium batteries and highlight the critical raw material which are used in battery, and then it continued with introduction of social life cycle assessment and PSILCA database. In the concept of social impact, the category and subcategory for assessment of social impacts were explained and chosen based on the relevance to the study, and NCA battery modeled in OpenLCA software, and the result was extracted.

With this methodology the social hotspot in the supply chain could identified. Based on this study and by some recommendation on supply chain design and the location of production and process could decreased the social impacts in every stage.

In conclusion, while the transition to electric vehicles and lithium-ion batteries is essential for reducing greenhouse gas emissions and enhancing sustainability, it is crucial to address the significant social implications throughout their life cycle. The Social Life Cycle Assessment (S-LCA) methodology provides a comprehensive framework for identifying and evaluating these social impacts, from raw material extraction to cell production. The comparison between EU and non-EU scenarios highlights the varying social risks, with non-EU scenarios generally exhibiting more connected risks in categories such as fair salary, association and bargaining rights, and trafficking in persons. Conversely, the EU scenario shows less connected risks in active material production and cell assembly stages.

The findings underscore the importance of considering social risks in supply chain design and the need for continuous improvement in social standards, particularly in regions with concentrated raw material extraction. Future advancements in technology and industrial standards, especially in countries like China, may alter these social risks over time. Therefore, it is essential to approach S-LCA results with caution, considering temporal variability and future trends. Incorporating positive social effects into S-LCA methodology and databases like PSILCA could provide a more holistic view of the societal contributions of products like batteries, ultimately supporting a more sustainable and equitable transition to electric mobility.

Conducting a social LCA has some limitation.; for instance, the PSILCA database often uses national data instead of sector-specific information, raising concerns about its relevance to the battery supply chain's social conditions. Social risks, particularly in raw material extraction, may be less severe than suggested by S-LCA results and can vary significantly between companies or locations based on their policies and management. Temporal variability and future trends, such as China's industrial advancements, can also affect these risks. Therefore, generalizing S-LCA results from the past to the present or future should be done with caution.

While there are positive indicators like contributions to economic development, the S-LCA results in PSILCA mainly highlight negative social risks. Assessing the broader societal contributions of products like batteries remains challenging, especially when negative impacts affect low socio-economic status countries and positive impacts benefit wealthier nations. Some authors advocate for a greater focus on positive social effects in S-LCA methodology, suggesting that incorporating these into databases like PSILCA would provide a more comprehensive view of the societal contributions of products.

Reference

[1] Q. Chen *et al.*, “A critical comparison of LCA calculation models for the power lithium-ion battery in electric vehicles during use-phase,” *Energy*, vol. 296, Jun. 2024, doi: 10.1016/j.energy.2024.131175.

[2] Trafigura, “Meeting the EV challenge: Responsible sourcing in the electric vehicle battery supply chain,” Nov. 2018. Accessed: Sep. 28, 2024. [Online]. Available: https://www.trafigura.com/news-and-insights/publications/white-papers/2018/meeting-the-ev-challenge-responsible-sourcing-in-the-electric-vehicle-battery-supply-chain/

[3] L. da Silva Lima, L. Cocquyt, L. Mancini, E. Cadena, and J. Dewulf, “The role of raw materials to achieve the Sustainable Development Goals: Tracing the risks and positive contributions of cobalt along the lithium-ion battery supply chain,” *J Ind Ecol*, vol. 27, no. 3, pp. 777–794, Jun. 2023, doi: 10.1111/jiec.13336.

[4] A. Khan *et al.*, “A state-of-the-art review on heating and cooling of lithium-ion batteries for electric vehicles,” Jan. 15, 2024, *Elsevier Ltd*. doi: 10.1016/j.est.2023.109852.

[5] J. Meegoda, G. Charbel, and D. Watts, “Second Life of Used Lithium-Ion Batteries from Electric Vehicles in the USA,” *Environments - MDPI*, vol. 11, no. 5, May 2024, doi: 10.3390/environments11050097.

[6] V. Rizos and P. Urban, “Barriers and policy challenges in developing circularity approaches in the EU battery sector: An assessment,” *Resour Conserv Recycl*, vol. 209, Oct. 2024, doi: 10.1016/j.resconrec.2024.107800.

[7] S. Passerini, L. Barelli, M. Baumann, J. F. Peters, and M. Weil, “The Materials Research Society Series Emerging Battery Technologies to Boost the Clean Energy Transition Cost, Sustainability, and Performance Analysis.”

[8] United Nations Environment Programme, “Guidelines for Social Life Cycle Assessment of Products,” 2020.

[9] C. Thies, K. Kieckhäfer, T. S. Spengler, and M. S. Sodhi, “Assessment of social sustainability hotspots in the supply chain of lithium-ion batteries,” in *Procedia CIRP*, Elsevier B.V., 2019, pp. 292–297. doi: 10.1016/j.procir.2018.12.009.

[10] G. Bouillass, I. Blanc, and P. Perez-Lopez, “Step-by-step social life cycle assessment framework: a participatory approach for the identification and prioritization of impact subcategories applied to mobility scenarios,” *International Journal of Life Cycle Assessment*, vol. 26, no. 12, pp. 2408–2435, Dec. 2021, doi: 10.1007/s11367-021-01988-w.

[11] A. Sánchez, G. Benveniste, V. J. Ferreira, I. Bulfaro, L. Igualada, and C. Corchero, “Methodology for social life cycle impact assessment enhanced with gender aspects applied to electric vehicle Li-ion batteries,” *International Journal of Life Cycle Assessment*, 2024, doi: 10.1007/s11367-024-02329-3.

[12] A. Orola, V. Uusitalo, and J. Levänen, “Implications of mineral price volatility on the outcome of social life cycle assessment interpretation—a battery material case study,” *International Journal of Life Cycle Assessment*, 2024, doi: 10.1007/s11367-024-02310-0.

[13] S. K. Springer, C. Wulf, and P. Zapp, “Potential Social Impacts regarding working conditions of Fuel Cell Electric Vehicles,” *Int J Hydrogen Energy*, vol. 52, pp. 618–632, Jan. 2024, doi: 10.1016/j.ijhydene.2023.04.034.

[14] L. Mancini, “Social assessment of raw materials supply chains,” 2018. doi: 10.2760/470881.

[15] S. Passerini, L. Barelli, M. Baumann, J. F. Peters, and M. Weil, "The Materials Research Society Series Emerging Battery Technologies to Boost the Clean Energy Transition Cost, Sustainability, and Performance Analysis," 2024. doi: 10.1007/978-3-031-48359-2.
[16] M. Loubert, K. Maister, C. Di Noi, L. Radwan, A. Ciroth, and M. Srocka, "The Product Social Impact Life Cycle Assessment database," 2023.
[17] M. R. Hall, "The living wage gap—a quantitative measure of poverty in global supply chains," *International Journal of Life Cycle Assessment*, vol. 26, no. 9, pp. 1867–1877, Sep. 2021, doi: 10.1007/s11367-021-01945-7.
[18] K. D. N. C. Maister, "PSILCA v.3 Database documentation," 2020.
[19] I. Energy Agency, "Global EV Outlook 2024 Moving towards increased affordability," 2024. [Online]. Available: www.iea.org
[20] E. Mossali, N. Picone, L. Gentilini, O. Rodrìguez, J. M. Pérez, and M. Colledani, "Lithium-ion batteries towards circular economy: A literature review of opportunities and issues of recycling treatments," *J Environ Manage*, vol. 264, Jun. 2020, doi: 10.1016/j.jenvman.2020.110500.
[21] J. Garche, Eckhard. Karden, P. T. . Moseley, and D. A. J. . Rand, *Lead-acid batteries for future automobiles*. Elsevier, 2017.
[22] R. Ginster *et al.*, "Circular battery production in the EU: Insights from integrating life cycle assessment into system dynamics modeling on recycled content and environmental impacts," *J Ind Ecol*, Oct. 2024, doi: 10.1111/jiec.13527.
[23] C. Aichberger and G. Jungmeier, "Environmental life cycle impacts of automotive batteries based on a literature review," Dec. 01, 2020, *MDPI AG*. doi: 10.3390/en13236345.
[24] National Renewable Energy Laboratory, "The JRC battery raw materials and value chain tool and ongoing RMIS modeling work."
[25] F. Arshad *et al.*, "Life Cycle Assessment of Lithium-ion Batteries: A Critical Review," May 01, 2022, *Elsevier B.V.* doi: 10.1016/j.resconrec.2022.106164.
[26] L. V. Thomas, O. Schmidt, A. Gambhir, S. Few, and I. Staffell, "Comparative life cycle assessment of lithium-ion battery chemistries for residential storage," *J Energy Storage*, vol. 28, Apr. 2020, doi: 10.1016/j.est.2020.101230.
[27] M. Bruno and S. Fiore, "Review of lithium-ion batteries' supply-chain in Europe: Material flow analysis and environmental assessment," May 01, 2024, *Academic Press*. doi: 10.1016/j.jenvman.2024.120758.
[28] H. Lehtimäki *et al.*, "Sustainability of the use of critical raw materials in electric vehicle batteries: A transdisciplinary review," *Environmental Challenges*, vol. 16, Aug. 2024, doi: 10.1016/j.envc.2024.100966.
[29] M. Hofmann, H. Hofmann, C. Hagelüken, and A. Hool, "Critical raw materials: A perspective from the materials science community," Sep. 01, 2018, *Elsevier B.V.* doi: 10.1016/j.susmat.2018.e00074.
[30] A. Mayyas, K. Moawad, A. Chadly, and E. Alhseinat, "Can circular economy and cathode chemistry evolution stabilize the supply chain of Li-ion batteries?," Jun. 01, 2023, *Elsevier Ltd*. doi: 10.1016/j.exis.2023.101253.
[31] S. . Bobba, S. . Carrara, J. . Huisman, F. . Mathieux, and C. . Pavel, *Critical raw materials for strategic technologies and sectors in the EU : a foresight study*. Publications Office of the European Union, 2020.

[32] J. A. Llamas-Orozco *et al.*, "Estimating the environmental impacts of global lithium-ion battery supply chain: A temporal, geographical, and technological perspective," *PNAS Nexus*, vol. 2, no. 11, Nov. 2023, doi: 10.1093/pnasnexus/pgad361.

[33] European Commission, "RMIS – Raw Materials Information System- COBALT-1," 2024.

[34] J. Das, A. Kleiman, A. U. Rehman, R. Verma, and M. H. Young, "The Cobalt Supply Chain and Environmental Life Cycle Impacts of Lithium-Ion Battery Energy Storage Systems," *Sustainability (Switzerland)* , vol. 16, no. 5, Mar. 2024, doi: 10.3390/su16051910.

[35] A. P. Dias, P. Alves Dias, and D. Blagoeva, "Cobalt: demand-supply balances in the transition to electric mobility," doi: 10.2760/97710.

[36] K. Hill-Tout, L. Nguyen, C. Pereira, E. Nelson, and H. Hunter, "Global Encounters: New Visions," Apr. 2024.

[37] D. Van Brusselen *et al.*, "Metal mining and birth defects: a case-control study in Lubumbashi, Democratic Republic of the Congo," *Lancet Planet Health*, vol. 4, no. 4, pp. e158–e167, Apr. 2020, doi: 10.1016/S2542-5196(20)30059-0.

[38] "POWERING CHANGE OR BUSINESS AS USUAL?," 2023. [Online]. Available: www.amnesty.org

[39] the European Union's Horizon 2020 research and innovation programme, "Solution for Critical Raw Materials- a European Expert Network:Nickel," 2021.

[40] N. Sharmili, R. Nagi, and P. Wang, "A review of research in the Li-ion battery production and reverse supply chains," Sep. 15, 2023, *Elsevier Ltd*. doi: 10.1016/j.est.2023.107622.

[41] S. S. Sharma and A. Manthiram, "Towards more environmentally and socially responsible batteries," *Energy Environ Sci*, vol. 13, no. 11, pp. 4087–4097, Nov. 2020, doi: 10.1039/d0ee02511a.

[42] European Union's Horizon 2020 research and innovation programme, "Solution for Critical Raw Materials- a European Expert Network: Natural Graphite," 2021.

[43] F. Maisel, C. Neef, F. Marscheider-Weidemann, and N. F. Nissen, "A forecast on future raw material demand and recycling potential of lithium-ion batteries in electric vehicles," *Resour Conserv Recycl*, vol. 192, May 2023, doi: 10.1016/j.resconrec.2023.106920.

[44] A. M. Domingues, R. G. de Souza, and J. V. R. Luiz, "Lifecycle social impacts of lithium-ion batteries: Consequences and future research agenda for a safe and just transition," Dec. 01, 2024, *Elsevier Ltd*. doi: 10.1016/j.erss.2024.103756.

[45] the European Union's Horizon 2020 research and innovation programme, "Scrreen solution for critical raw material_LITHIUM-update," 2020.

[46] M. Falcone, N. F. Quattromini, C. Rossi, and B. Pulvirenti, "Life Cycle Assessment of a Lithium-Ion Battery Pack Unit Made of Cylindrical Cells," *Batteries*, vol. 8, no. 8, Aug. 2022, doi: 10.3390/batteries8080076.

[47] A. M. Domingues, R. G. de Souza, and J. V. R. Luiz, "Lifecycle social impacts of lithium-ion batteries: Consequences and future research agenda for a safe and just transition," Dec. 01, 2024, *Elsevier Ltd*. doi: 10.1016/j.erss.2024.103756.

[48] M. Koese, C. F. Blanco, V. B. Vert, and M. G. Vijver, "A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage," *J Ind Ecol*, vol. 27, no. 1, pp. 223–237, Feb. 2023, doi: 10.1111/jiec.13347.

[49] Y. Shi, X. Chen, T. Jiang, and Q. Jin, "Social life cycle assessment of lithium iron phosphate battery production in China, Japan and South Korea based on external supply

materials," *Sustain Prod Consum*, vol. 35, pp. 525–538, Jan. 2023, doi: 10.1016/j.spc.2022.11.021.
[50] Kampker, Heimes, Frank, and Plumeyer, "Battery Atlas 2024 (2nd Edition) Shaping the European Lithium-ion Battery Industry," *PEM of RWTH Aachen University (own print), 2nd edition*, no. 2, Jun. 2024, Accessed: Feb. 28, 2025. [Online]. Available: https://www.researchgate.net/publication/381773894
[51] S. Shukla, T. Sykora, J. C. Kelly, and H. Cai, "R &D GREET Battery Module," 2024.
[52] M. D. Sanchez-Lopez, "Geopolitics of the Li-ion battery value chain and the Lithium Triangle in South America," *Lat Am Policy*, vol. 14, no. 1, pp. 22–45, Mar. 2023, doi: 10.1111/lamp.12285.
[53] T. Schmidt, M. Buchert, and L. Schebek, "Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries," *Resour Conserv Recycl*, vol. 112, pp. 107–122, Sep. 2016, doi: 10.1016/j.resconrec.2016.04.017.
[54] L. Weimer, T. Braun, and A. vom Hemdt, "Design of a systematic value chain for lithium-ion batteries from the raw material perspective," *Resources Policy*, vol. 64, Dec. 2019, doi: 10.1016/j.resourpol.2019.101473.
[55] J. C. Kelly, Q. Dai, and M. Wang, "Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries," *Mitig Adapt Strateg Glob Chang*, vol. 25, no. 3, pp. 371–396, Mar. 2020, doi: 10.1007/s11027-019-09869-2.
[56] O. Winjobi, J. C. Kelly, and Q. Dai, "Life-cycle analysis, by global region, of automotive lithium-ion nickel manganese cobalt batteries of varying nickel content," Jul. 01, 2022, *Elsevier B.V.* doi: 10.1016/j.susmat.2022.e00415.
[57] I. Belharouak *et al.*, "Operation, Manufacturing, and Supply Chain of Lithium-ion Batteries for Electric Vehicles," 2020. [Online]. Available: www.ornl.gov
[58] A. M. Nunes de Oliveira Lima, D. C. R. Espinosa, A. B. Botelho Junior, and J. A. S. Tenório, "NCA-Type Lithium-Ion Battery: A Review of Separation and Purification Technologies for Recycling Metals," Sep. 01, 2024, *Springer Science and Business Media Deutschland GmbH*. doi: 10.1007/s40831-024-00859-6.
[59] M. Bruno and S. Fiore, "Review of lithium-ion batteries' supply-chain in Europe: Material flow analysis and environmental assessment," May 01, 2024, *Academic Press*. doi: 10.1016/j.jenvman.2024.120758.
[60] A. Racu and J. Poliscanova, "An industrial blueprint for batteries in Europe How Europe can successfully build a sustainable battery value chain Transport & Environment Further information," 2024. [Online]. Available: www.transportenvironment.org
[61] C. Hebestreit, "THE IMPORTANCE OF CRITICAL RAW MATERIALS THROUGH THE EYES OF ORGANISED CIVIL SOCIETY: THE CASE OF GRAPHITE," May 2023.
[62] M. Koese, C. F. Blanco, V. B. Vert, and M. G. Vijver, "A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage," *J Ind Ecol*, vol. 27, no. 1, pp. 223–237, Feb. 2023, doi: 10.1111/jiec.13347.
[63] A. A. Pesaran, M. Mann, V. Putsche, and J. Greenberger, "NAATBatt North American Lithium-ion Battery Supply Chain Database Documentation and User Guide," Feb. 2023.