FACULTY OF
BIOSCIENCE ENGINEERING

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INTERNATIONAL MSc

LI/CO FOR BATTERIES IN ELECTRIC VEHICLES IN THE EU: LCSA APPROACH WITHIN THE CONTEXT OF A CIRCULAR ECONOMY.

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Abstract

The European Union (EU) aims to be climate-neutral by 2050, an economy with net-zero greenhouse gas emissions. This target helped to increase the electric car market, which raises doubts about how sustainable the global value chain of these products is, especially the lithium-ion battery which is the main component to make them less polluting during the use phase.

The thesis seeks to identify, understand, and evaluate the relevance of environmental and social risks involved in lithium and cobalt production for batteries. An Environmental Life Cycle Assessment (e-LCA) and a Social Life Cycle Assessment (s-LCA) were conducted, based on UNEP guidelines. The global value chain of lithium-ion batteries of electric vehicles was estimated and evaluated based on sector-level qualitative and quantitative indicators.

The thesis raises the following research question: What environmental and social risks are connected to the life cycle assessment of lithium and cobalt in batteries from electric vehicles? The outcomes reveal the environmental and social impacts and suggest circular improvements in the chain to prevent these impacts especially in the Democratic Republic of Congo and Chile.

Keywords: e-LCA, s-LCA, Life Cycle Assessment, Lithium-Ion Battery, Cobalt, Circular Economy.

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List of Abbreviations and Chemicals

1,4-DCB - 1,4-dichlorobenzene

3TG - Tin, tungsten, tantalum and gold

ADF – Allied Democratic Forces

Al - Aluminium

C – Carbon

$CaCl_2$ - Calcium chloride

CAGR - Compound Annual Growth Rate

CCCMC - Chinese Chamber of Commerce for Metals, Minerals & Chemicals

CH_4 - Methane

Co – Cobalt

CO_2- Carbon dioxide

CRMs- Critical Raw Materials

CSR - Corporate Social Responsibility

Cu - Copper

DRC – The Democratic Republic of Congo

EBA - European Battery Alliance

EC – European Commission

e-LCA – Environmental Life Cycle Assessment

EO - Explosive Ordnance

EOD - Explosive Ordnance Disposal

EoL - End of Life

EPR – Extended Producer Responsibility

EU – European Union

EVI – Electric Vehicles Index

EVs - Electric Vehicles

FARDC – Armed Forces of the Democratic Republic of the Congo

FDLR - Forces Démocratiques de Libération du Rwanda-Forces

FU - Functional Unit

GBA - Global Battery Alliance

GGE – Global Greenhouse Emissions

GHG – Greenhouse Gas
GLR - Great Lakes Region
GRI – Global Report Initiative
GTAP – Global Trade Analysis Project
ICE - Internal Combustion Engines
IEA – International Energy Agency
ILO - International Labour Organization
INDH – the Chilean National Institute of Human Rights
LCA – Life Cycle Assessment
LCC – Life Cycle Costing
LCI - Life Cycle Inventory
LCIA - Life Cycle Impact Assessment
LCSA – Life Cycle Sustainability Assessment
LFP – Lithium iron phosphate
Li – Lithium
LIBs - Lithium-Ion batteries
Mn – Manganese
MONUSCO - United Nations Organization Stabilization Mission in the Democratic Republic of the Congo
MRIO - Multi-Regional Input Output modeling
N_2O- Nitrous Oxide
Na_2CO_3 - Sodium carbonate
NCA – Lithium nickel cobalt aluminum
NCM – Lithium nickel cobalt manganese
NCX – Lithium nickel cobalt with X representaing Al or Mn
Ni – Nickel
OECD - Organization for Economic Cooperation and Development
RCI - Responsible Cobalt Initiative
RMI - Responsible Minerals Initiative
SASLAB - Sustainability Assessment of Second Life Application of Automotive Batteries
SHDB – Social Hotspot Database

Si – Silicon

s-LCA – Social Life Cycle Assessment

Sn – Tin

Ti – Titanium

TP – Toxicity Potential

UNEP – United Nations Environmental Programme

UNMAS - United Nations Mine Action Service

USA – United States of America

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1. Introduction

The transition to sustainable mobility is an essential step to tackle climate change and negative environmental impacts related to the current use of fossil fuel vehicles. Regulations and policies to reduce gas emissions from the transport sector are being promulgated around the world.

The 2030 Climate Target Plan proposed by the European Commission's proposed to reduce greenhouse gas emissions by at least 55% by 2030 to become climate neutral by 2050 (European Commission, 2021).

Electric vehicles (EVs) are seeing as an alternative to achieve this reduction, to replace combustion engines. This change requires the development of more durable and efficient electric batteries. Electric vehicles are considered an option due to fewer greenhouse gases and air pollutants emissions during the use phase than a fuel-powered car. In addition, they do not have the vibration, smell, and noise associated with gasoline cars (Moses, 2020).

Lithium-ion batteries power most EVs. Because of the increasing demand for electric cars encouraged by the public policies of the European Union, there is the same increase in battery demand, as shown in Figure 1. This demand comprises three main battery applications: electric mobility, energy storage, and consumer electronics; however, the most significant collaborator is the electric mobility sector.

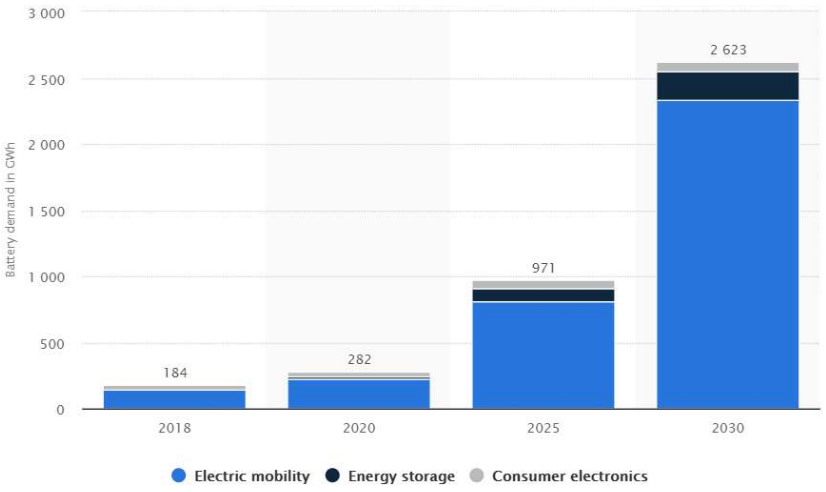


Figure 1: Global battery demand between 2018 and 2030, by application (in gigawatt hours). Extracted from Statista Research Department, 2020.

LIBs comprise four main components: cathode, anode, electrolyte, and separator (Samsung, 2016). Most of the raw materials used in battery production are imported from different countries. Therefore, the European Commission (EC) is setting up a European Raw Materials Alliance dedicated to ensuring a "sustainable supply of raw materials in Europe" where sustainable development, social and environmental externalities in the life cycle must be considered (European Commission, 2020).

The thesis aims to evaluate the lithium and cobalt production for LIBs from EVs following a life cycle sustainability assessment (LCSA) approach focusing on the environmental life cycle assessment (e-LCA) and social life cycle assessment (s-LCA). E-LCA and s-LCA will be carried out to identify hotspots along the supply chain of lithium-ion batteries for electric vehicles with the most significant social and environmental impacts. However, the economic effects will not be assessed as these are not the focus. Furthermore, this methodology allows the understanding of which parts of the lithium and cobalt supply chain need improvement. The functional unit considered will be one lithium-ion battery of one EV.

The thesis raises the following research question: What are the environmental and social risks associated with lithium production and cobalt production for batteries from electric vehicles? Therefore, the global supply chain for lithium-ion batteries from electric vehicles from Europe will be evaluated.

The expected outcomes of this thesis are the assessment of the environmental and social impacts of the lithium and cobalt production for batteries from electric vehicles; the identification of potential points of improvement in the chain to avoid or prevent these impacts, and a brief analysis of circular technologies to recovery lithium and cobalt at the end of life of lithium-ion batteries. The methodology used will combine literature study, e-LCA, and s-LCA.

To answer the research question, the thesis contextualizes the electric vehicles industry, the global value chain of lithium-ion batteries, the suppliers of the main components of a lithium-ion battery, the social aspects of cobalt in the Democratic Republic of Congo, and lithium in Chile. Next, the e-LCA and s-LCA methodologies are introduced. After that, the assessment design for the thesis is defined. Finally, the thesis will present the results and the discussion of the findings.

2. Contextualization and Literature Review

2.1. Battery Electric Vehicles Industry

Electric Vehicles (EV) are considered a solution for the mobility sector to tackle the greenhouse gas (GHG) emissions produced by fuel-powered cars. According to the International Energy Agency, the stock of global electric vehicles increased in the last decade, encouraged and supported by policies and technological advancements, as shown in Figure 2. As a result, the EV stock curve tends to increase, and policies to support the market transition for replacement of fuel-generated cars by EV (International Energy Agency, 2020).

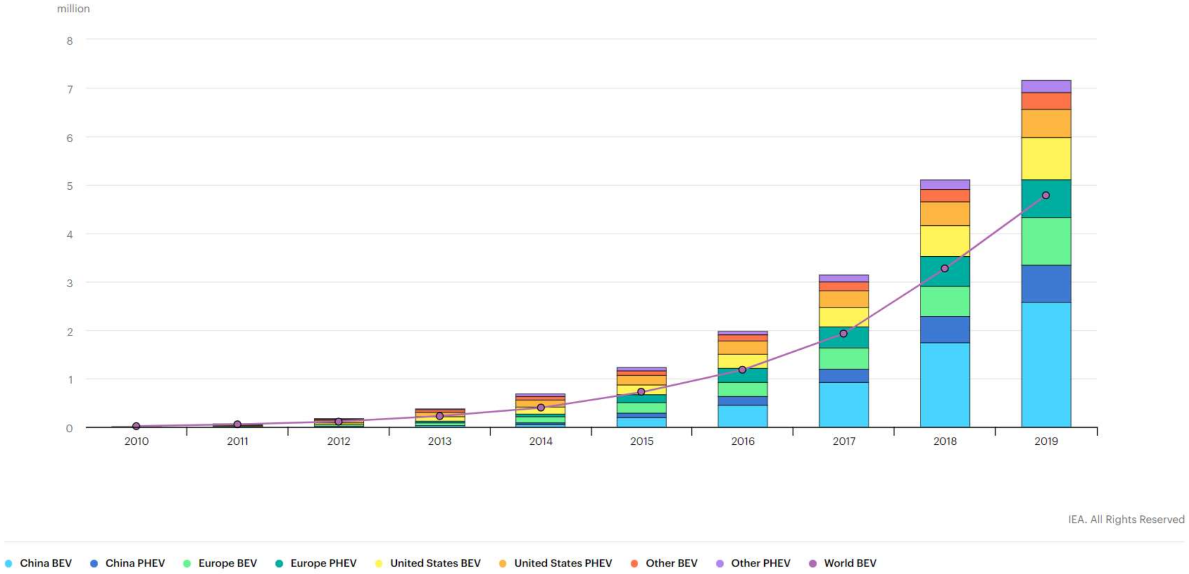
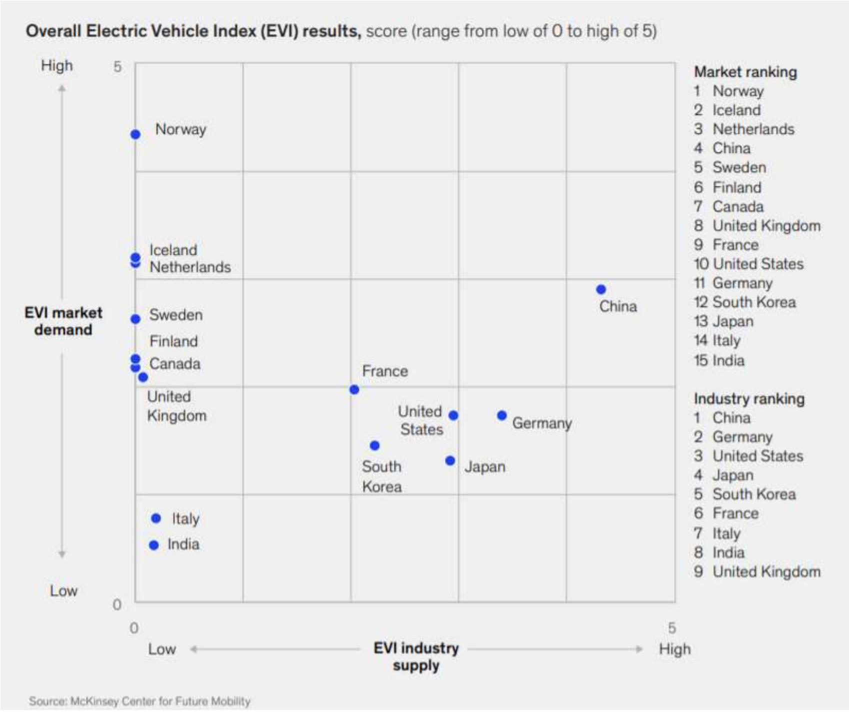


Figure 2: Global electric car stock, 2010-2019. Extracted from International Energy Agency, 2020.

The Electric Vehicle Index (EVI) published by McKinsey explores the market dynamics, the demand, and the industry supply for electric mobility, showing that Nordic countries are the leader market out demand although China and Germany dominate the industry supply, as shown in Figure 3, nine of the top ten markets for EV were in Europe, according to the EVI study from 2020 (Gersdorf et al., 2020).


Overall Electric Vehicle Index (EVI) results, score (range from low of 0 to high of 5)

Source: McKinsey Center for Future Mobility

Figure 3: Overall EVI results, score (range from low of 0 to high of 5). Extracted from Gersdorf et al, 2020.

With the increasing demand for electric cars, there is a consequent increase in the batteries of these vehicles. There are different types of batteries that have been used in EVs, such as Lithium-Sulfur (Li-S), Molten Salt (Na-NiCl$_2$), Lead Acid Batteries, Nickel Metal Hydride (Ni-MH), and Lithium-Ion Batteries (Mok, 2017). The complexity of batteries requires a wide range of raw materials. A generic battery scheme for EV cell packaging is shown in Figure 4.

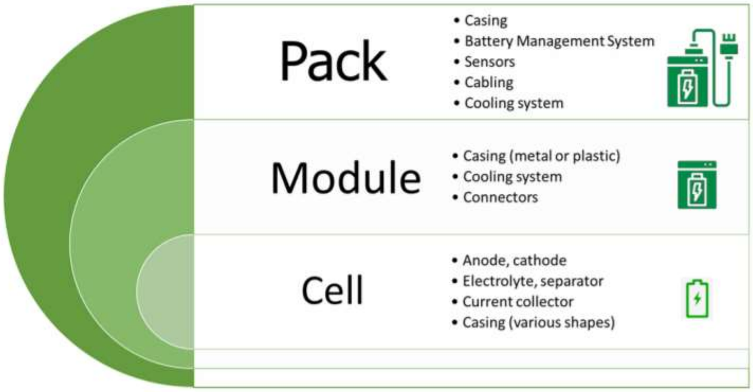


Figure 4: Battery packs, modules, and cells for EV applications. Extracted from Huisman et al., 2019.

Lithium-ion batteries represent the most used technology in EVs (Iclodean et al., 2017). Some examples of brands in the market that uses LIBs on their vehicles are Tesla, Renault, Hyundai, Nissan, and Volkswagen.

These batteries are rechargeable devices in which lithium moves from the negative to the positive electrode during the charging process. The main advantage of LIBs compared to other batteries, such as nickel-metal ones, is that they have lighter weights and smaller sizes (Iclodean et al., 2017 and Statista Research Department, 2020). The global Li-Ion battery demand is increasing due to electric vehicles and because they are widely used in devices like tablets, mobile phones, and cameras. However, even with several applications, the most increasing demand is related to electric mobility (Statista Research Department, 2020).

The Compound Annual Growth Rate (CAGR) is the rate of return of an investment (van Genuchten & Hatton, 2012). The automotive sector is expected to grow with a CAGR of 19.1% in the following years (Statista Research Department, 2020). This increasing demand in the electric vehicle sector is also motivated by the need to comply with the Paris Agreement (2015), which states that emissions from cars and vans will need to decrease by 37.5% to reach the ambitious goal set by the European Union (EU) by 55% by 2030 (Agreement, 2015 & Balch, 2020). Furthermore, this will have a directly proportional effect on the LIBs' global value chain.

2.2. The Lithium-Ion battery global value chain

To understand the impact of this ascending demand, it is necessary to evaluate the LIBs' global value chain. “A LIB is usually composed by a cathode and an anode that are separated by a liquid organic electrolyte, and inactive components such as a polymer separator, copper (Cu) and aluminum (Al) as current collectors, the casing and packaging materials” (Olivetti et al., 2017). Figure 5 shows the representation of a LIB and its cell components.

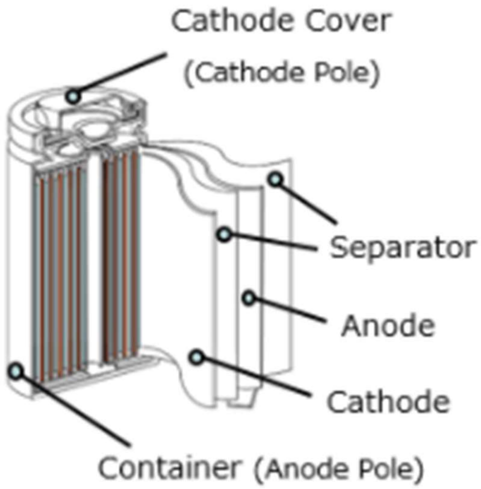


Figure 5: LIBs cell components. Extracted from Ineltek, 2021.

Various components used in Li-ion battery cells including lithium (Li), nickel (Ni), cobalt (Co), manganese (Mn), Al, Cu, silicon (Si), tin (Sn), titanium (Ti), and carbon (C) in a variety of forms such as graphite. These elements have correspondingly and increasing demand (Franco et al., 2014). A general LIB value chain is shown in Figure 6, and the generic supply chain structure is shown in Figure 7.

Figure 6: Automotive lithium-ion battery value chain. Adapted from Franco et al. 2014.

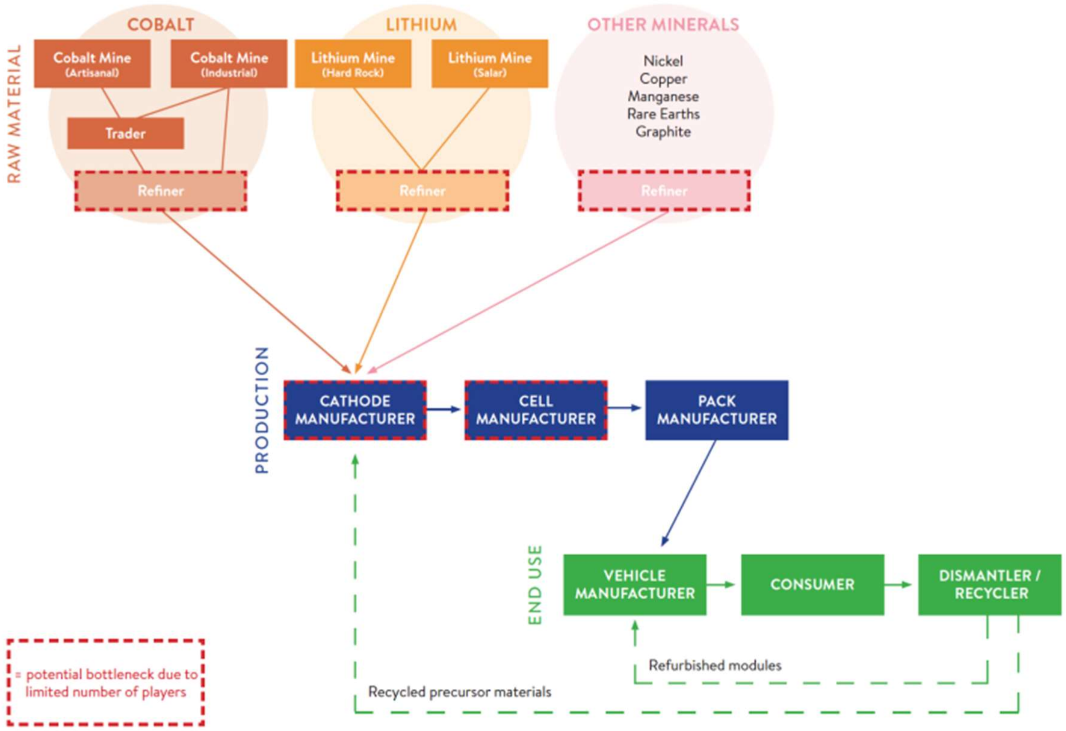


Figure 7: Supply Chain Structure: Extracted from Elkind et al., 2020.

Some of the materials used in the manufacturing process of LIBs are in the list of Critical Raw Materials (CRMs) published by the European Union in 2020, which means that they present economic importance and substantial supply risk (European Commission, 2020). Therefore, the Communication aims to "ensure resilience through a secure and sustainable supply of critical raw materials." Through this, "a major contribution to the recovery and the long-term transformation of the economy can be made" (European Commission, 2020).

The materials required for building a LIB that is considered critical (Appendix I) include Lithium, Cobalt, Silicon metal, Titanium, and Natural Graphite. Cobalt plays an important role improving the energy density and battery life as lithium ions are reversibly embedded and extracted from the cathode during battery operation (Patel, 2020). The most significant suppliers of CRMs to the EU can be observed in Figure 8.

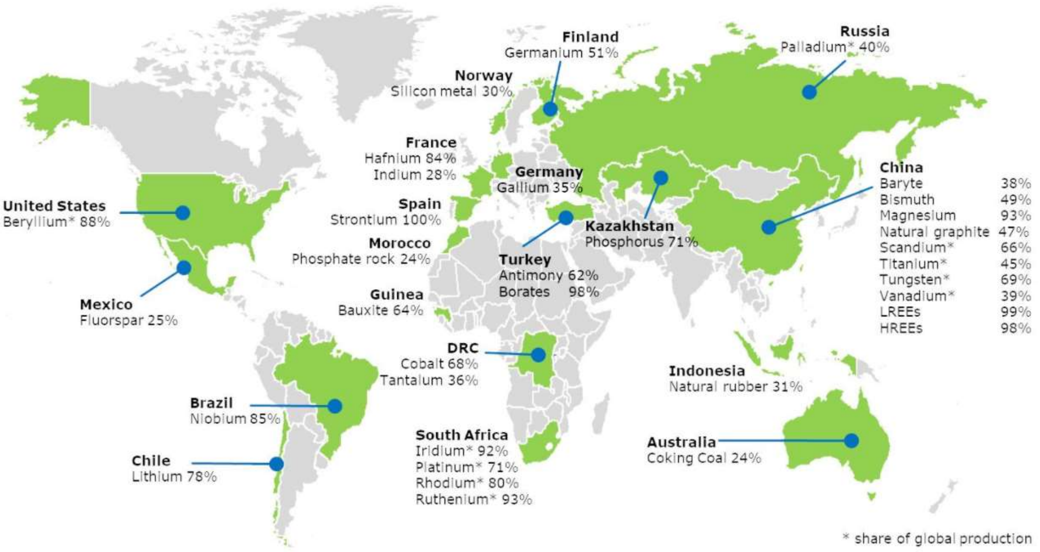


Figure 8: Biggest supplier countries of CRMs to the EU. Extracted from European Commission, 2020.

Considering the components in LIBs, the global demands for lithium and cobalt are expected to grow, as shown in Figure 9. Thus, one key mineral for battery application is lithium, which is expected to register significant demand growth (Statista Research Department, 2020). The leading global producers that are used in the production of LIBs are presented in Table 1.

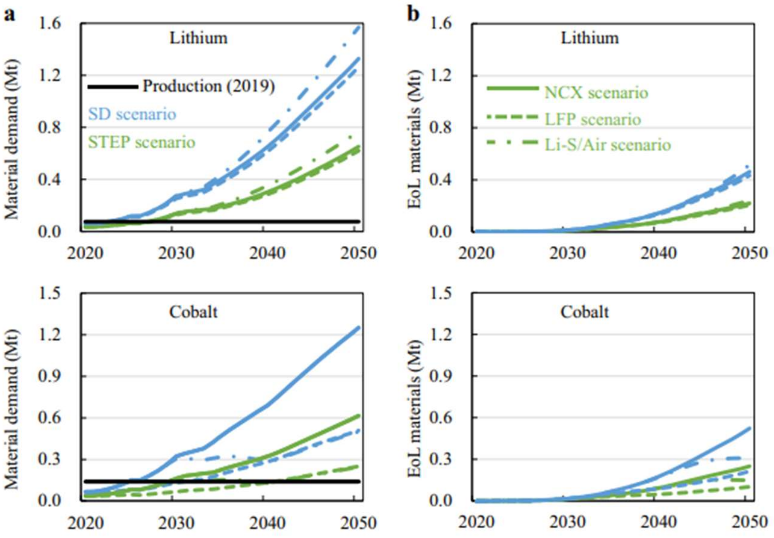


Figure 9: Battery material flows for Li and Co in the lithium nickel cobalt aluminum (NCA), and lithium nickel cobalt manganese (NCM) called NCX with X representing Al or Mn. Lithium iron phosphate (LFP) and Li-S/Air battery scenarios from 2020 to 2050. Extracted from Xu et al., 2020.

Table 1: Main global producers. Adapted from European Commission, 2020.

Raw Material	Main global producers
Cobalt	DRC (59%) China (7%) Canada (5%)
Lithium	Chile (44%) China (39%) Argentina (13%)
Natural Graphite	China (69%) India (12%) Brazil (8%)
Silicon metal	China (66%) United States (8%) Norway (6%) France (4%)
Titanium	China (45%) Russia (22%) Japan (22%)

Among these CRMs, several raised concerns regarding the environmental and social impacts of the production along their supply chain. To produce LIB, lithium and cobalt production are considered sensitive points through the value chain.

2.3. Social Responsibility throughout Global Value Chains

For LIBs to be considered fully sustainable, social responsibility throughout Global Value Chains must be addressed. It is necessary to account the main actors linked with the production process, such as corporations.

Corporate responsibility is defined by the firm's duties besides profit generation (ISO 26000, 2010 & Hahn, 2013). Corporate accountability can be shaped by the influence that external pressure can have on the company. This influence can be a result of social and governmental actors (ISO 26000, 2010).

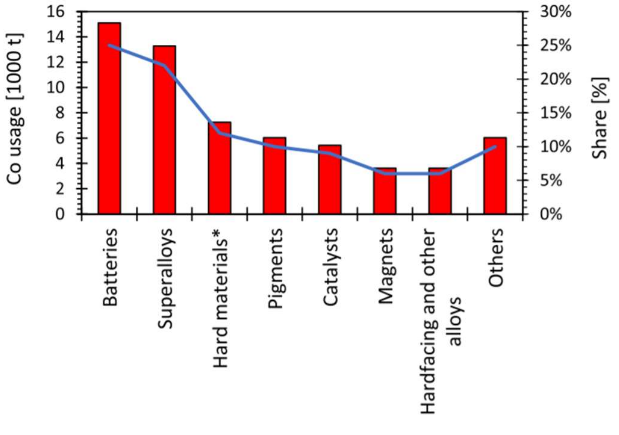
Corporate Social Responsibility (CSR) has goals beyond the legal requirements, and it is drive by extra-legal forces to integrate different concerns about social and environmental issues (European Parliament, 2020). Among the existing guidance, the Global Report Initiative (GRI) and the ISO 26000 (2010) are the most used for CSR. GRI Sustainability Reports are widely used because they created a common language for organizations and offer standards based on the principles of balance, comparability, accuracy, timeliness, clarity, and reliability (ISO 14040, 2006). The GRI Standards support organizations to understand their economic, environmental, and social aspects through a modular set that can be used by various stakeholders; they are also pertinent to other groups such as policymakers, investors, and civil society (Global Reporting, 2019).

Social obligations must include all parts of the company that produces the product discussed and confirm that these standards are being followed; this is necessary to carry due diligence studies focused on social responsibilities (ISO 14040, 2006). In addition, due diligence must evaluate the whole value chain to help identify which production stages are sensitive and have higher social impacts, and these will need to be addressed (Mazijn & Revéret, 2015).

This chapter presents a literature review of the environmental and social aspects resulting from the extraction of the LIB components that will be the focus of this thesis: Cobalt and Lithium.

a) Cobalt

Cobalt is usually obtained as a by-product of copper, nickel, and iron, and it has historical importance among various industrial sectors due to its physical properties (Tkaczyk et al., 2018). The global end uses of cobalt are batteries, superalloys, hard materials, pigments, catalysts, magnets, hard facing, and other alloys, as shown in Figure 10.



* Carbides and diamond tooling

Figure 10: Global end uses of cobalt. Extracted from Tkaczyk et al., 2018.

The Democratic Republic of Congo (DRC) is the leading producer of cobalt globally and the primary source of this material to the EU and China, as shown in Figure 11 (Schmidt et al., 2016).

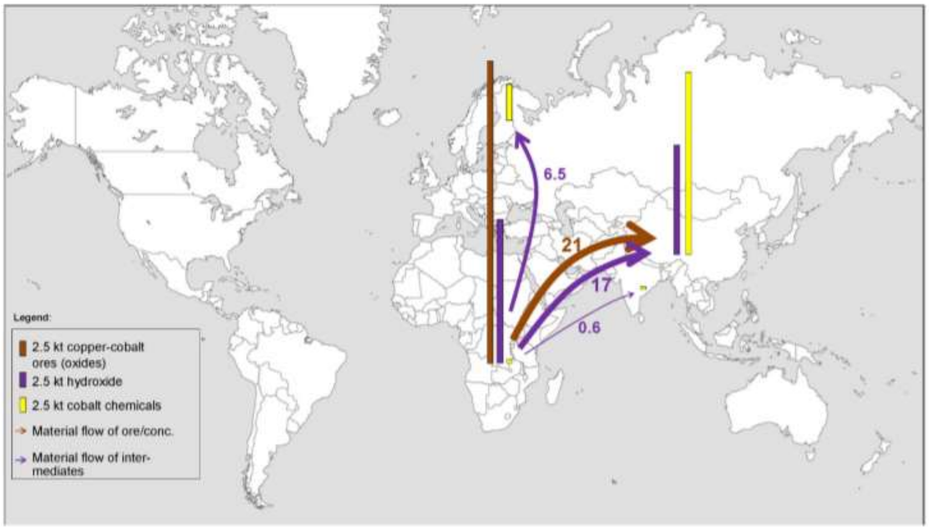


Figure 11: Global flow chart for the primary production of cobalt chemical with 2011 as a year reference. Extracted from Schmidt et al., 2016.

Cobalt is considered a critical raw material, more than half of the mine's worldwide production in 2018 originated from Cu-Co ores in the DRC, where there is an aggravating political instability and inhuman working conditions (Gourley et al., 2020).

In addition, the cobalt supply chain is controlled by China who acts as the main actor in the production, supply, and consumption phases (Gourley et al., 2020). Since 2000, China owns cobalt mining operations in the DRC, with that the country has decreased its dependence on the reliance of importing raw cobalt from 97% to 68% (Gulley et al., 2019 and Gourley et al., 2020). According to the documentary "Conflict Minerals, Rebels and Child Soldiers in Congo" produced by VICE (2011), mining activity combined with extreme poverty, lack of policies that reinforce legislation on mineral exploration, and internal conflicts resulted in the deaths of over 5 million people in Congo since 1990. In addition, colonization played a significant role in the political instability in DRC. The main drivers of European countries such as Belgium were the competition to find and control raw materials, including minerals. Between 1870 and 1929, the patterns of production and consumption were integrated into the local economy and were radically altered by colonial practice; with the technological development, the demand for minerals increased worldwide, making copper and cobalt – a vital mineral associated with the copper belt – be more exported (The Northern Miner, 2011).

The postcolonial theory is based on the political, social, economic, and historical impact caused by European colonial rule in the world (Elam, 2019). According to Lennerfors et al. (2015), communal violence is firmly related to colonialism. Belgian colonies like DRC experienced considered levels of inter-communal conflict. The distinction between ethnic groups was reinforced by the Belgians, promoting discrimination in the country. The weakness of DRC's state was unable to collaborate against this oppression, resulting in several uncontrolled regions that promoted violent regional rebellion due to its colonialism background.

In certain parts of the world, especially in Congo and Africa's Great Lakes Region (GLR), the growing global demand for mineral resources essential for high-tech electronic goods, has fueled more sinister societal impacts (Barume et al., 2016). For example, tin, tungsten, tantalum, and gold (often referred to as 3TG, or 'conflict minerals') can be directly linked to the promotion of armed conflicts and to the activities of armed groups that involves serious human rights abuses, especially for women and children (Mazalto, 2009).

The mineral industry usually operates in peripheral territories where life is generally different or has any relation with the global market and is institutionally fragile. In this context, the most challenging is sustainable local development from remote cities (Matlaba et al., 2017).

The impacts of mining on society in developing countries are mostly related to everyday work, child labor, weakness of environmental legislation, and the risk of hazards from unsound practices (Tsurukawa et al., 2011). Many informal workers are from marginalized populations, including the poor, migrants from rural areas, and ethnic and religious minorities (Spittaels & Hilgert, 2013). With a lack of regulation, the sector's informality means that such populations are subject to adverse health impacts and lack opportunities to develop skills, become socially mobile and even more marginalized (Matthysen & Montejano, 2013). They are not only exposed to the health risks posed by unsound practices but are also unable to attend school and therefore limit their opportunities later in life because of a lack of education (EIT Learning Climate-KIC, 2020).

Among these harmful effects, the unsafe activities imply the pollution of soil, air, and water; therefore, the degradation and loss of natural resources occur, impacting the environment.

b) Lithium

According to Table 1, 44% of the Lithium produced in the world is originated in Chile, located in the Lithium Triangle in South America, as shown in Figure 12 (Kozak, 2020).

It is likely that Bolivia and Argentina also make inputs to the amount imported by other countries, considering that approximately 60% of the global lithium deposits are concentrated in this triangle (McFarlane, 2018).

Figure 12: The Lithium triangle. Extracted from Me-metals, 2018.

Lithium processing represents a significant impact on the environment due to the consumption of water and waste generated and/or used in the process, such as organic solvents that can pose health and safety risks for mine workers and dependent populations; the pressure for mining expansion and lithium extraction in the Atacama Desert can increase the environmental and social impacts (McFarlane, 2018).

Regarding the explosion of workers and surrounding communities in mining regions, it is necessary to consider that Lithium does not occur naturally in its pure form because of its high reactivity. The effects of lithium in its pure form are related to the fact that lithium in metal form reacts with water and can be corrosive because of its alkaline properties. Lithium dust can irritate the respiratory tract. The prolonged exposure can cause fluid accumulation in the lungs leading to pulmonary edema; the metal has dangerous handling due to the caustic hydroxide produced when it reacts with water (Lithium Mine, 2018). Therefore, lithium mining carries high socio-environmental costs and can cause health impacts on human beings in contact with the operations and processing material (Schlosser, 2020).

Mining and extractive activities have been linked to the groundwater and surface water resources in the Atacama. The changes in the aquifers may not be identified immediately, but the requirement of water and brine can influence freshwater reserves from extraction from the brine aquifer (McFarlane, 2018).

2.4. EU and international initiatives in sustainable battery value chains

The LIBs supply chain presents environmental and social challenges, especially for lithium and cobalt, due to the leading suppliers' sensitive scenarios. These challenges motivated several global and European initiatives to tackle these challenges for this point of the chain.

The Responsible Minerals Initiative (RMI) was founded in 2008 have the mission is to provide "tools and resources to make sourcing decisions that improve regulatory compliance and support responsible sourcing from conflict-affected and high-risk areas" (RMI, 2008). That is the case for the DRC with cobalt.

Launched in 2016, The Responsible Cobalt Initiative (RCI) aims to promote cooperation with the Government of the DRC, civil society, and local communities to act addressing in the supply chain of Co (CCCMC & OECD, 2016).

The European Commission, concerned industries, and the scientific community launched the European Battery Alliance (EBA) in 2017 (Schuler et al., 2018). The main goal of EBA is to develop an innovative, competitive, and sustainable battery value chain in Europe through the segments shown in Figure 13. In addition, the community interfaces integrate other interests proposed by the Commission in the European Industrial Policy and EU Green Deal, such as reaching climate neutrality by 2050 and reducing transport emissions by 90% by 2050 (European Commission, 2018).

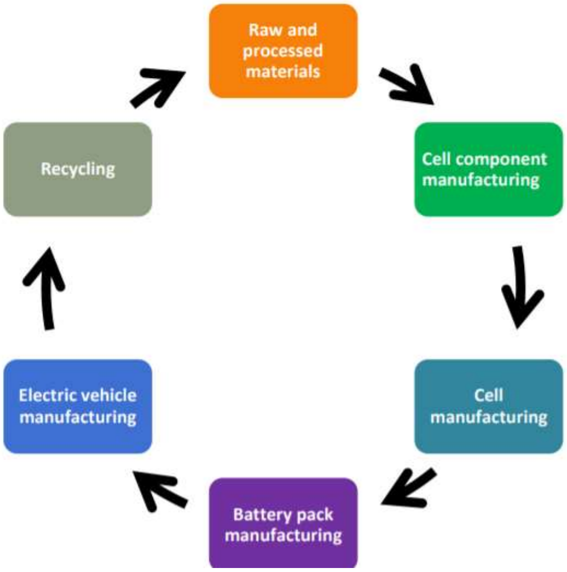


Figure 13: Battery value chain and priority areas for EBA. Extracted from European Commission, 2018.

In 2017 it was founded the Global Battery Alliance (GBA) to help establish a sustainable battery value chain (World Economic Forum, 2019).

According to the European Commission (2020) and to a study carried out by the US EPA in 2008, around 800,000 tons of automotive batteries enter the EU per year. However, these products are not all adequately recycled and collected at their end of life, resulting in this material disposed of in the environment and releasing hazardous substances. The EU legislation on waste batteries states that to guarantee environment protection, "it is desirable for the Member States to achieve a high collection and recycling rate for waste batteries and accumulators to achieve a high level of environmental protection and material recovery" (European Economic Community, 2020). Furthermore, the European Green Deal suggests that batteries should be repurposed, remanufactured, and recycled at their end of life (European Commission, 2020).

There are different EoL and recycling methods for each material within LIBs, as shown in Figure 14.

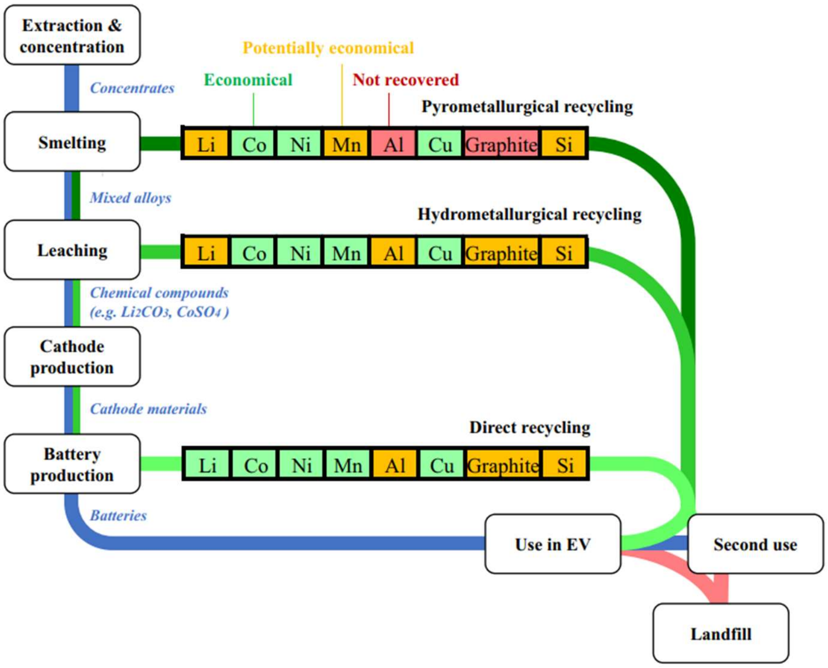


Figure 14: Scheme with the three considered recycling scenarios and which materials are recovered. Extracted from Xu et al., 2020.

The evaluation of lithium and cobalt showed that they have economic potential, so their recovery at the EoL can avoid unnecessary waste with a circular approach. Furthermore, the circular economy context within Li-Ion batteries could be integrated at the end of life with a second use for them instead of just dismantling and recycling them or even disposing on landfills.

According to the JRC Technical Report on Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB), there is increasing attention to LIBs and services where second use can be applied, such as households and commercial users, utilities, and grid. The same report considers Germany as the location for the post-consumer phase in which fourteen service batteries were identified, as shown in Figure 15.

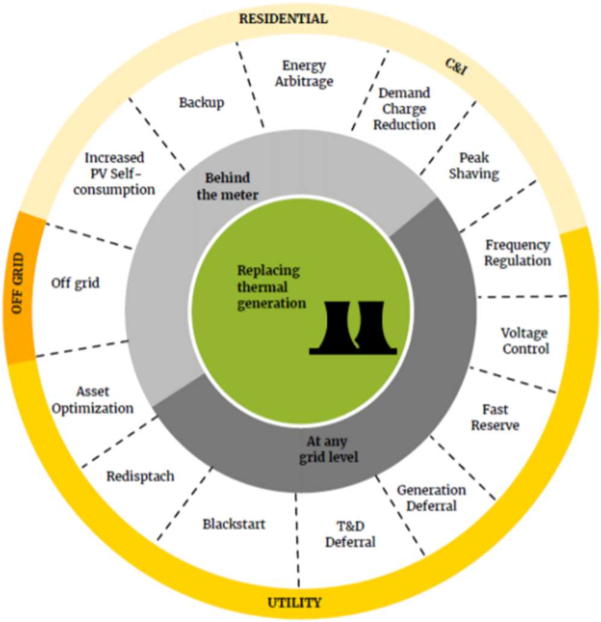


Figure 15: Fourteen battery services. Extracted from Bobba et al., 2018.

The initiatives regarding the batteries value chain show a need to score environmental and social impacts along the supply chain to understand better which points in the lithium and cobalt production can be improved and whether there are options for recovering these metals in a circular context. An assessment that effectively presents this result is the Life Cycle Assessment (LCA) with environmental and social focuses.

2.5. Methodological Framework: Life Cycle Sustainability Assessment

LCSA aims to evaluate the negative impacts and benefits through different techniques: environmental, social, and economic, as shown in Figure 16 (Kralisch et al., 2016). This approach was developed to stimulate awareness of the risks associated with products and consider environmental protection and climate change challenges (UNEP, 2011).

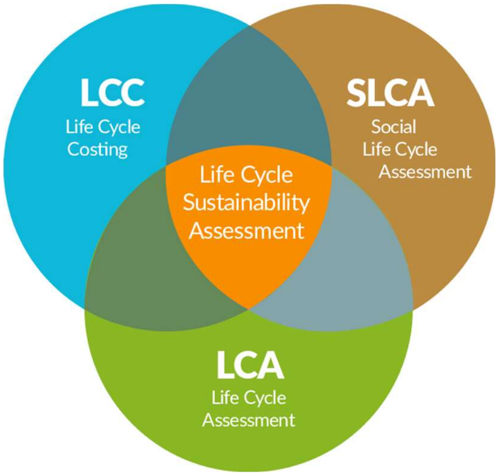


Figure 16: LCSA scheme. Extracted from Kralisch et al. (2016)

LCSA can support the consumer through the transparency of the results showing if the products are cost-efficient, socially responsible, and eco-efficient (UNEP, 2011).

This thesis was developed with a combination of environmental and social life cycle assessments. The Life Cycle Costing (LCC) was not considered because, in this case, sustainability is not focusing on the economic part since the results are not targeting cost reduction; nevertheless, the other niches were discussed.

2.5.1. Environmental Life Cycle Assessment

Environmental Life Cycle Assessment (e-LCA), also called LCA, is a technique developed to identify improvements opportunities of a product life cycle, and the need of enterprises and policymakers to comprehend the relative environmental effects in the value chain (ISO 14040, 2006).

It can be applied as a "cradle-to-grave" approach for assessing products, processes, industrial systems, and their end of life. "Cradle-to-grave" considers the whole product life cycle: the acquisition of raw material, production, use, end-of-life, recycling, and final disposal (ISO 14040, 2006). “LCA makes it possible to estimate the cumulative environmental impacts resulting from all stages of the product’s life cycle” (Klugmann-Radziemska, 2020). It allows the selection of the path or process that is more environmentally preferable (Department of Energy and Mineral Engineering, 2020).

As shown in Figure 17, a typical LCA study follows four stages: goal definition and scope, inventory analysis, impact assessment, and data interpretation, as shown in Figure 18 (ISO

14040, 2006). In the stage of goal definition and scope, the product or process evaluated is identified, the context and the system boundaries are established.

In the goal and scope definition stage, the Functional Unit (FU) is defined, and the system boundaries. In the Inventory analysis, the inputs and environmental releases as outputs are quantified. In the Impact Assessment stage, the potential human and ecological effects are assessed and quantified to measure their environmental significance. In the last stage, the Life Cycle Interpretation is made by comparing the Inventory Analysis and Impact Assessment stages (ISO 14040, 2006 & Department of Energy and Mineral Engineering, 2020).

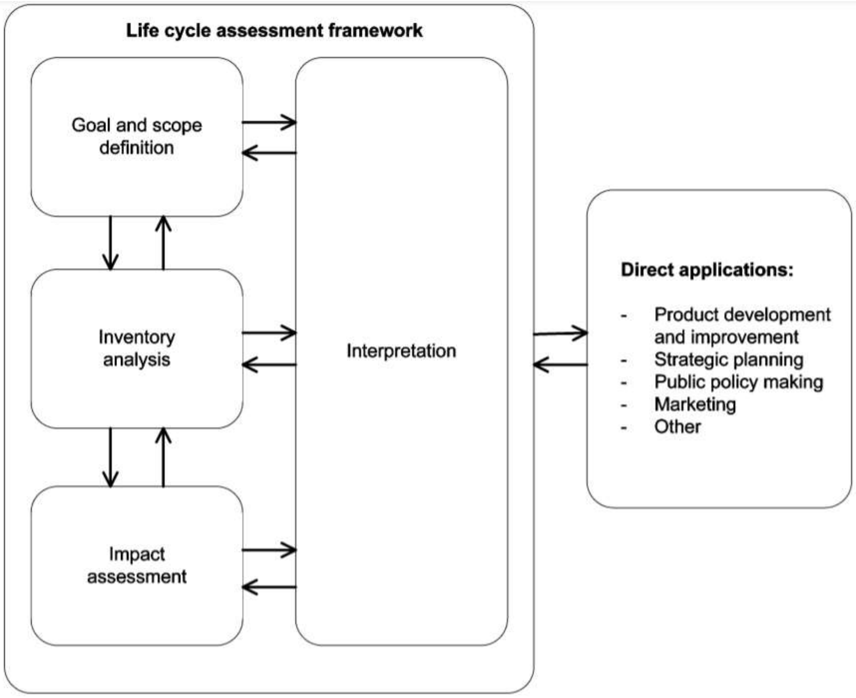


Figure 17: General phases of a life-cycle assessment, as described by ISO 14040. Extracted from ISO 14040 (2006)

LCA helps decision-makers select the product/process/technology that results in the most negligible impact on the environment. In addition, this technique identifies the transference of the environmental effects from one media to another and between different lifecycle stages (Department of Energy and Mineral Engineering, 2020).

The diagram in Figure 18 shows that the generation of a product requires an input of materials and energy at all steps, from raw materials acquisition to manufacturing, operation/use/maintenance, and final disposal; there are losses and co-products, which sometimes can be undesirable (Department of Energy and Mineral Engineering, 2020). LCA helps track all valuable and harmful outcomes such as atmospheric emissions, waterborne and solid wastes (Department of Energy and Mineral Engineering, 2020).

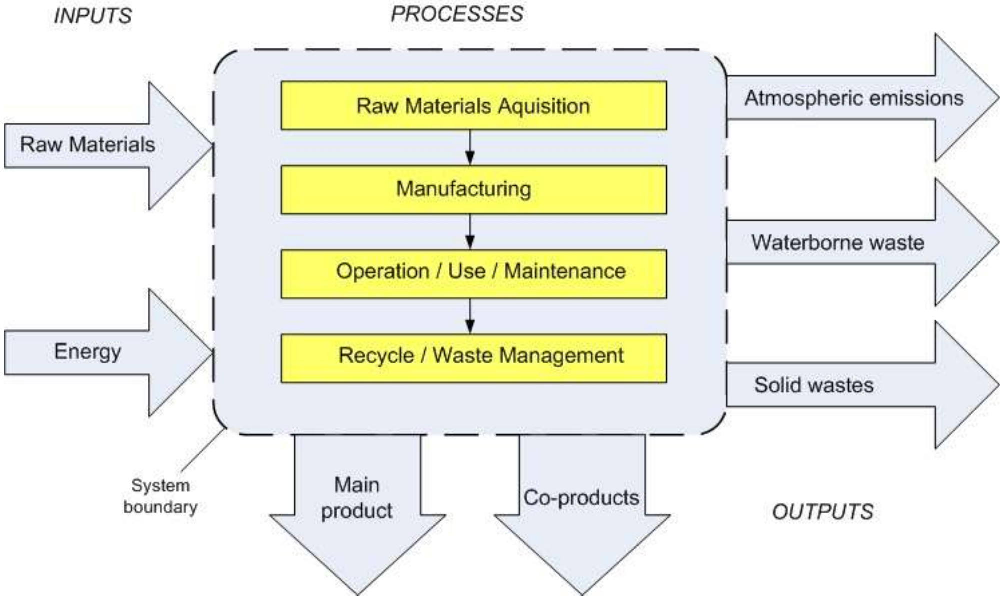


Figure 18: The commons inflows and outflows considered in lifecycle assessment. Extracted from Department of Energy and Mineral Engineering, 2020.

According to ISO 14040 (2006), LCA accuracy relies on the availability of data, and because of that, it is necessary to define the uncertainty and assumptions precisely. But this methodology does not address other impacts of the product such as social and economics (Agusdinata et al., 2018).

The combination of cost analysis, social and environmental metrics provides a fully sustainable analysis (Department of Energy and Mineral Engineering, 2020). LCA models are appropriate for comparisons regarding environmental aspects. Still, they may be insufficient only with an environmental approach, which was the primary motivation to include social elements in this thesis to improve the predictions of risks.

a) Goal and scope definition

In this first stage, it is necessary to state “the goal of the LCA, such as the rationale for carrying out the research, the product system to be studied, the functional unit, the system boundary, assumptions, and limitations” (ISO 14040, 2006).

The definition of a functional unit is the core factor of the study. "It will be the reference to which the inputs and outputs can be related, enabling a more realistic comparison between different systems" (ISO 14040, 2006). Furthermore, the FU used for a project should be determined by elaborating the collected data and study (ISO 14040, 2006).

In addition, potential restrictions concerning the study depth, the sources, and the data quality are determined during the study. In this stage, the system boundaries are also defined. Boundaries that can be considered are geographical area and time horizon (Ecoil, 2006).

To define the system boundary is necessary to set several life cycle stages, unit processes such as the acquisition of raw materials, inputs, and outputs in the processing, manufacturing, distribution, transportation, use, and disposal of products (ISO 14040, 2006).

To develop a study with results that can be interpreted appropriately, it is required to follow data quality requirements (ISO 14040, 2006).

b) Inventory Analysis

The Life Cycle Inventory (LCI) is defined as the material and energy flow calculations that quantify what goes in and out of a product life cycle (Department of Energy and Mineral Engineering, 2020). The general structure is shown in Figure 19.

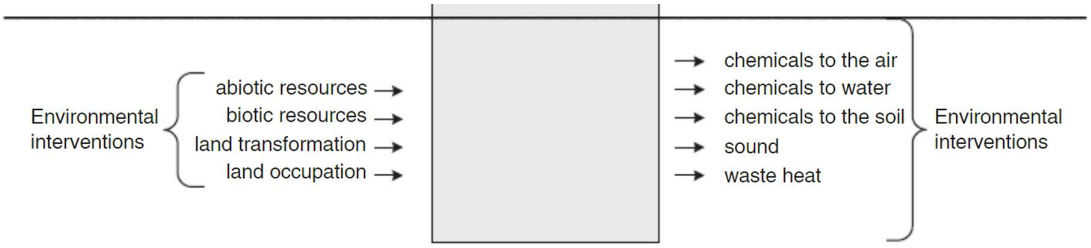


Figure 19: The general structure of a unit process. Extracted from Azapagic & Solberg-Johansen (1998).

In this stage, the product system and its processes are described, exchanges between the product system and the environment are summarized and analyzed; these exchanges include inputs from nature and outputs to nature (Ecoil, 2006; ISO 14040, 2006). Finally, the amounts of elementary flows exchanged by the product system and the environment are compared to the FU defined in the Goal and Scope stage (Curran, 2017).

c) Impact Assessment

The Life Cycle Impact Assessment (LCIA) shows the significance of environmental impacts associated with elementary flows compiled during inventory analysis (UNEP, 2020). This is done by associating the LCI results with environmental impact categories and category indicators (ISO 14040, 2006).

The elementary flows are identified in this stage, and their connection with the category indicators is determined. Therefore, "LCIA has mandatory elements: selection of impact categories, category indicators, and characterization models as well as assignment of the LCIA results to the various impact categories and calculation of category indicator results" (ISO 14040, 2006 and UNEP, 2020).

The elements of this stage are illustrated in Figure 20. The mandatory elements are the selection of impact categories, the definition of the category indicators, and the characterization models, followed by the classification of the results and category indicator results (ISO 14040, 2006). Although there is uncertainty that varies for each impact category, each model is in different development steps.

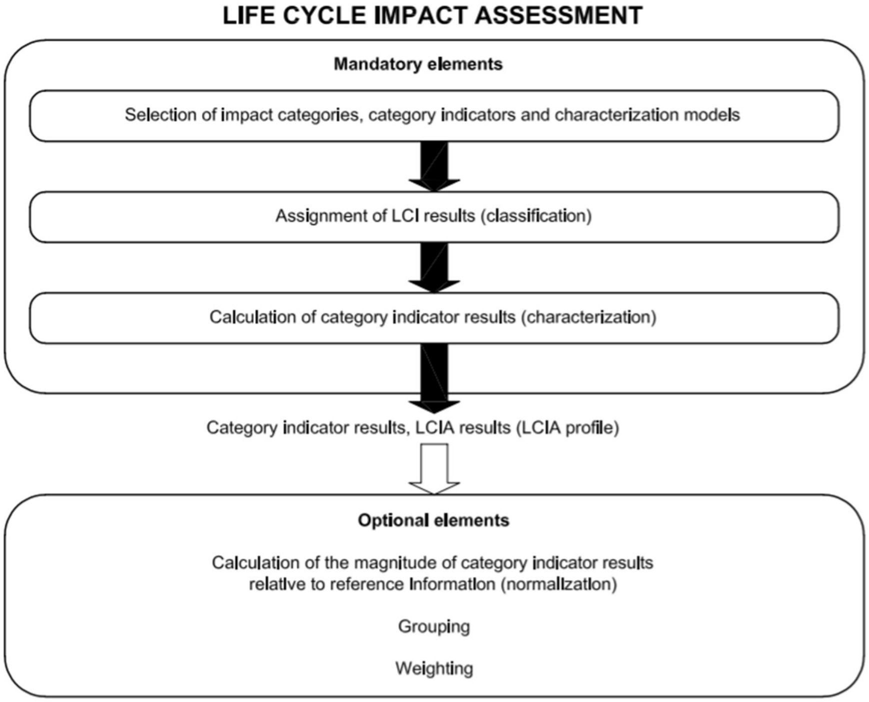


Figure 20: Elements of Life Cycle Impact Assessment. Extracted from ISO 14040 (2006).

d) Interpretation

In the interpretation phase, all procedures performed are reviewed and discussed. Finally, all limitations found in the results are considered to formulate conclusions and recommendations to decision-makers chosen in the goal and scope phase of the study (ISO 14040, 2006).

2.5.2. Social Life Cycle Assessment

A Social Life Cycle Assessment (s-LCA) is a tool used to complement the classic LCA to assess the impact of products and services from a social perspective and their life cycle, providing a broader vision of its life cycle impacts (UNEP, 2020).

It is highly recommended to inform in the goal and scope stage why it is relevant to conduct an s-LCA of a particular product. All steps along the chain can have a social impact and must be considered to provide the most accurate results to evaluate the harmful nature of the product to achieve a sustainable life cycle (UNEP, 2020).

According to UNEP (2020), the social impacts evaluated are mainly divided by stakeholders' categories: workers, local community, society, consumers, and value chain actors. Furthermore, the impact categories related to those stakeholders are linked to human rights, working conditions, health and safety, cultural heritage, governance, and socio-economic repercussions (UNEP, 2020).

According to UNEP (2020), an s-LCA is a tool that can provide crucial data about the social conditions of the manufacturer and consumption of products in a transparent manner. It also gives a critical understanding of the system and its impacts. However, there are some limitations in this methodology, such as the difficulty in accessing data; the use of qualitative data, methods, and indicators; the lack of knowledge about casual chains relations; the needed skills of practitioners, the need for developing indicators, the assessment of the use phase and the communication of the results that requires several assumptions (UNEP, 2020).

As well as for e-LCA, s-LCA follows the ISO 14044 framework, according to the stages previously mentioned: goal and scope, life cycle inventory, life cycle impact assessment, and interpretation. The system scope can be defined by the parts or complete life cycle and supply chain of products and services (UNEP, 2020). The s-LCA decision tree is shown in Figure 21.

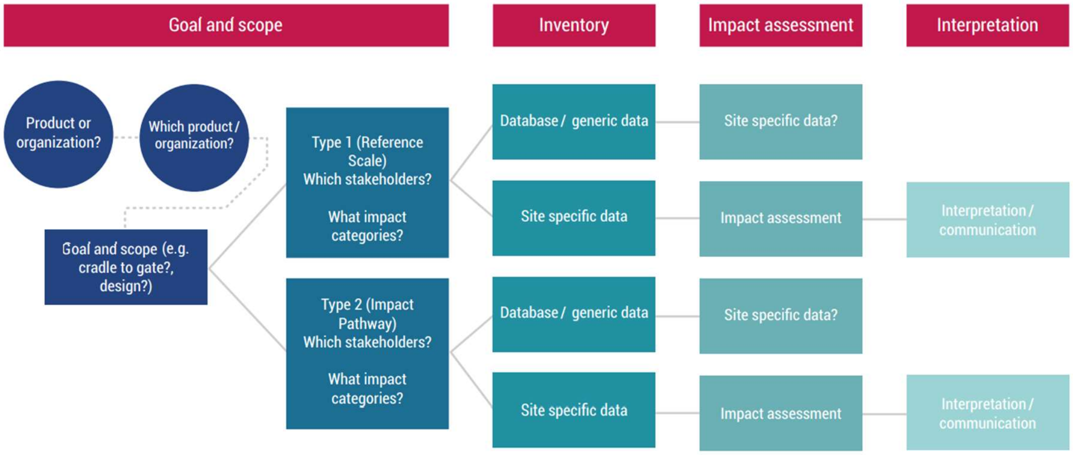


Figure 21: S-LCA decision tree. Extracted from UNEP (2020).

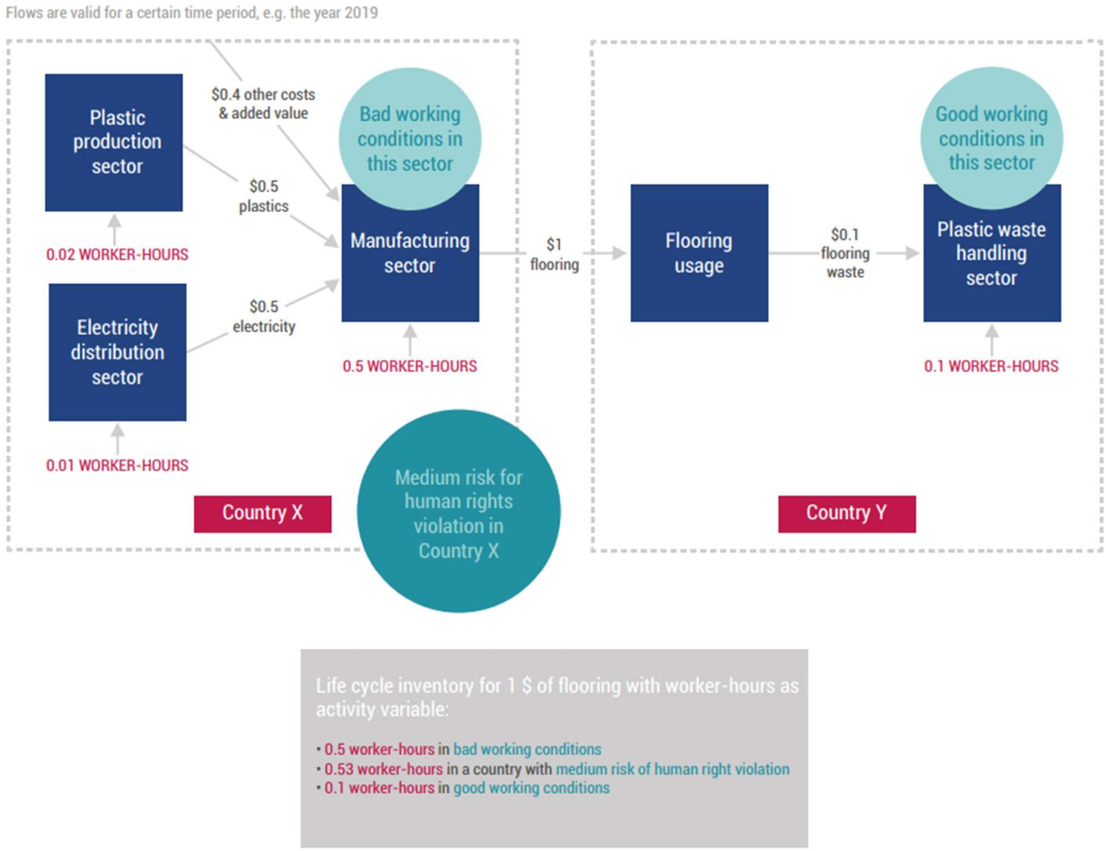
a) Goal and scope definition

At this phase, the goal of the study is defined based on different purposes such as "to support the sustainable design of products, to identify main social Hotspots of a product, to examine potential social improvement options along the life cycle, to assess the most relevant stages in the social value chain in terms of social impacts/hotspots, to communicate the potential social performance and/or social impacts of the product to the public, or to understand if the product value chain contributes to the social development of its stakeholders" (UNEP, 2020).

The scope definition is usually based on practical or theoretical factors such as data availability and quality. However, in this phase, for both e-LCA and s-LCA, defining a functional unit is a crucial step of the study that will guide the next ones. It will provide reference to which the data can be related, enabling a more realistic comparison between different systems (ISO 14040, 2006).

b) Inventory Analysis

The Life Cycle Inventory (LCI) is defined as the prioritization of the data set for collection and hotspot assessment for the relevant stakeholders and subcategories. Therefore, the database selection must consider the source's reliability (s), completeness/temporal/geographical/further technical conformances to guarantee data quality (UNEP, 2020). The generic example of a life cycle inventory approach often used in s-LCA is shown in Figure 22.



Life cycle inventory for 1 $ of flooring with worker-hours as activity variable:

- 0.5 worker-hours in bad working conditions
- 0.53 worker-hours in a country with medium risk of human right violation
- 0.1 worker-hours in good working conditions

Figure 22: A generic example for a life cycle inventory approach based on sectors. Extracted from UNEP (2020).

Unlike e-LCA, for s-LCA, the geographic location is needed to consider the socio-economic scenario of each country and identify the hotspots (UNEP, 2020).

c) Impact Assessment

The impact assessment is the phase where the magnitude of the social impacts of the product or process is evaluated. It needs to include the approach selected, the social topics of interest that are the stakeholders, and impact categories (UNEP, 2020). The s-LCA also shows the negative and positive impacts of the product life cycle, while the e-LCA shows adverse effects (UNEP, 2020).

LCIA typically follows the inclusion of inventory and impact indicators, definition and use of characterization models leading to impact indicators, description of impact pathways, and the presence of correlations and/or casual relations (UNEP, 2020).

The impact categories defined are “human rights, working conditions, health and safety, cultural heritage, governance, and socio-economic repercussions” (Benoît et al., 2013). This can be observed in five categories: workers/employees, local community, society, consumers, and value chain actors (Benoît et al., 2013).

d) Interpretation

In the interpretation phase, completeness, consistency, sensitivity, data quality, and materiality are checked and discussed. Finally, all limitations found in the results are considered to formulate conclusions and recommendations.

According to the ISO 14044 (2006) and UNEP (2020), this step must identify the significant issues, evaluate the study regarding completeness and consistency; conclusions and recommendations considering the most problematic social hotspots and impacts in the life cycle, and the participation of relevant stakeholders.

2.5.3. Software and databases

To automatize various steps from the assessment process, the software openLCA was used. It is open-source and free software for Sustainability and LCA. It provides insights into calculation and analysis results, help to identify the main drivers throughout the life cycle through the process, flow, or impact category (OpenLCA, 2021).

a) Ecoinvent version 3.4

For the e-LCA, the Ecoinvent version 3.4 was used for the assessment stage. This database provides a well-documented process for products supporting the understanding of their environmental impacts.

The Ecoinvent database comprises inventory data for most economic activities. The consistency and cohesion of the LCI datasets increase the credibility and acceptance of the results obtained using this database. The baselines of this database are LCI datasets that considers human activities and their interactions with the environment (Weidema et al., 2013). These components are partly based on the preceding work performed at ETH Zurich. The database consists of several sections that are presented in Figure 23.

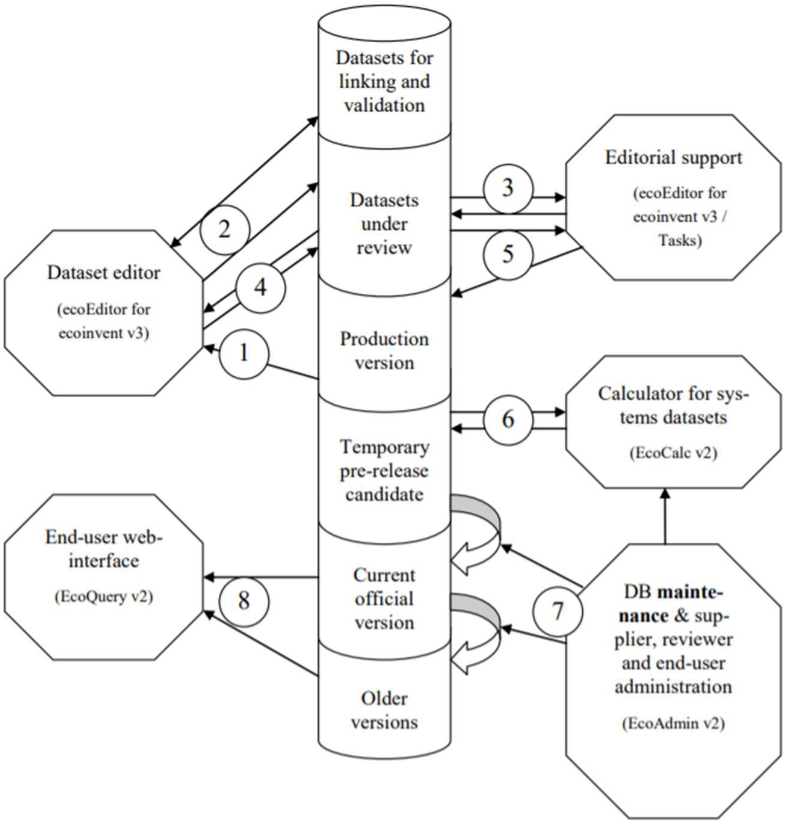


Figure 23: The basic structure of ecoinvent database system. Extracted from Weidema et al., 2013.

b) Social Hotspot Database (SHDB)

For the s-LCA, the SHDB was used for the assessment stage, using generic data from national and international organizations.

In 2009, the SHDB was launched to ensure complete transparency and access to information about working conditions and other social impacts that can occur in global supply chains, to collaborate with supply chain stakeholders to overcome issues on their management of social responsibility and drive progress (Benoît-Norris et al., 2020).

The access to SHDB can be done through a risk mapping tool or by a license to use the database in an LCA software such as openLCA. The risk mapping tool gives users information on social risks in 244 countries and territories. Thus, SHBD can be a valuable tool for companies who aim to conduct risk assessments around complex social issues (Benoît-Norris et al., 2020).

The SHDB is a modular system based on three components: information on the trade flows between the economic sectors of each country, information on the economic sector of labor intensity, and information on social risks and opportunities associated with each location. The method allows to set baselines, benchmarks, compare the effect of various types of social impacts and the impact of changes (places, materials or activities, management of risks).

The SHDB uses the Global Trade Analysis Project (GTAP) global economic equilibrium model version 9, the most recent and operates the 2011 reference year (Benoît-Norris et al., 2020). The current version of the GTAP model contains trade data for 57 economic sectors1 for each of 140 countries and regions (Benoît-Norris et al., 2020).

GTAP's Global Input-Output model provides the greatest country resolution while providing a more homogenous 57 sectors framework than any other MRIO. This safeguards the comparability of the results and gives a consistent view of supply chains (Benoît-Norris et al., 2020).

The data was selected bases on the legitimacy, reliability, combination of qualitative and quantitative indicators, meaningfulness, timeliness, variety of sources to increase robustness, and the number of countries/sectors of the economy in which the data was available. The categories and subcategories are shown in Figure 24.

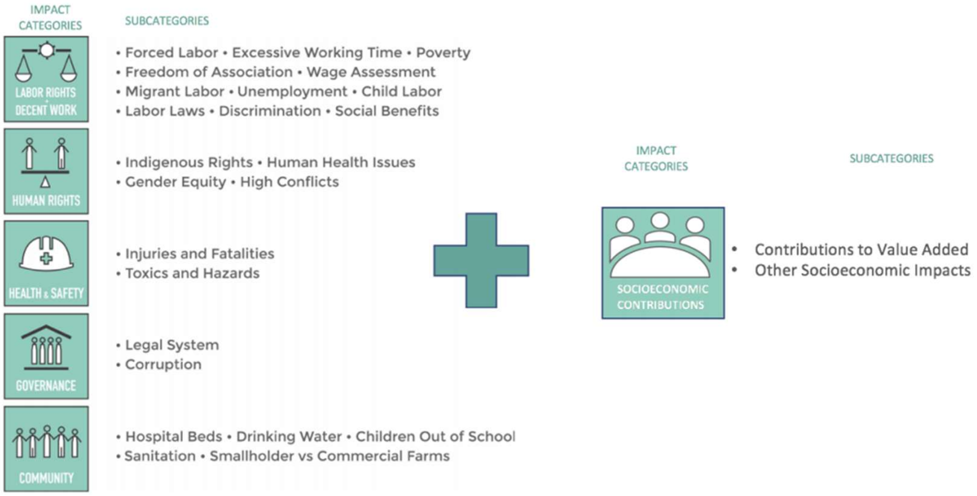


Figure 24: SHDB categories and subcategories. Extracted from Benoît-Norris et al., 2020.

3. Assessment Design

3.1. Goal and Scope Definition

The current thesis aims to evaluate mainly lithium and cobalt production processes to identify which stage of these processes needs improvements and attention to reduce the stage with higher environmental impact. In addition, this study also aims to understand the social and environmental risks involved in the production of Lithium and Cobalt for Lithium-Ion Batteries considering the global value chain. A third aim is to identify priorities regarding these risks and analyze what can enable policymakers and/or private actors to prioritize and avoid these risks.

The e-LCA and s-LCA were chosen to achieve these goals, whereby one LIB from the most common EV purchased by European Union will be the Functional United (FU) applied. This will enable the understanding of which part of the process has higher risks for the global value chain. Furthermore, this will also help to detect environmental and social risk hotspots across the value chain.

The functional unit considered was one LIB. The e-LCA will consider the amount of lithium and cobalt used as raw material in one lithium-ion battery from a Tesla Model 3 vehicle.

The approach considered will be the cradle to grave, which means that the life cycle will be evaluated from the resource extraction until the disposal phase. To define the system boundaries, the principal processes within a LIB life cycle considered will be: raw material and processed materials, cell component manufacturing, cell manufacturing, battery pack manufacturing, vehicle manufacturer, transport to the selling point, use of the battery in electric vehicles, and the possible end of life (EoL) of this product. The discussion will be around the different materials, but the focus will be on lithium and cobalt. The general core life cycle stages of a LIB are in Figure 25.

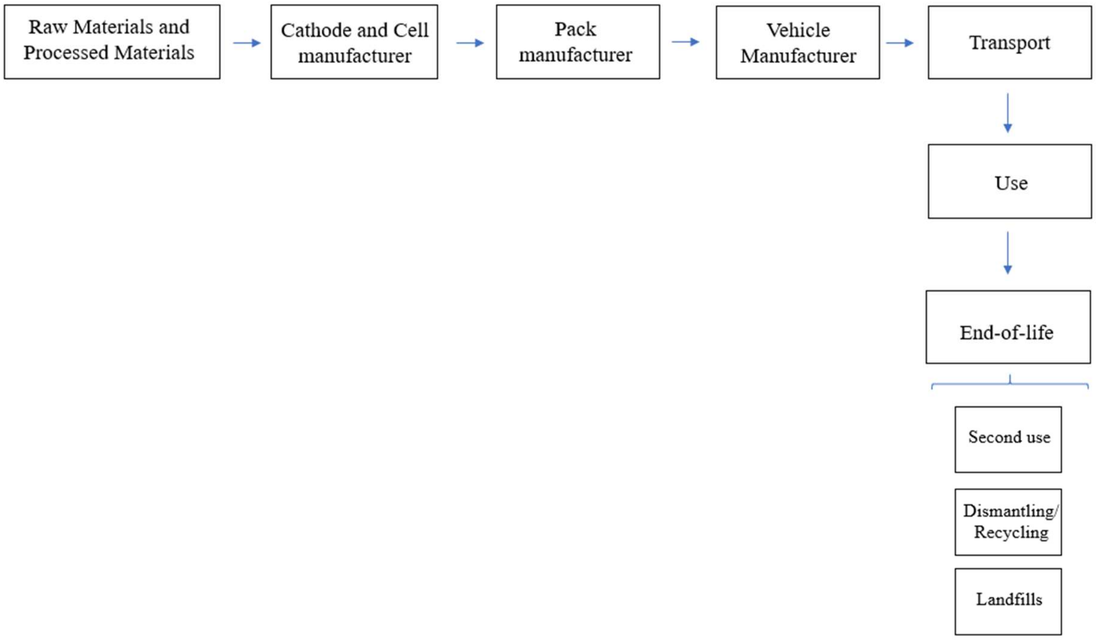


Figure 25: The general core life cycle stages considered for the LIB production.

A lithium-ion battery has more than 20 different raw materials across the supply chain. The assessment for the whole chain considering all materials involved in the production would require further studies. Thus, the risk assessment was carried out as qualitative and explorative research that aims to evaluate the environmental and social hotspots of lithium and cobalt production that are part of the raw materials and processed materials stage. Such analysis provides understanding of the risks associated with their production within the LIBs industry, their global value chain and how issues can be addressed considering circular economy at their EoL.

According to UNEP (2020), the use phase is not considered because the s-LCA was developed to assess the sustainability of organizations within a social focus because of that some steps were not considered. Therefore, the proposed indicators do not apply to individuals' users. However, the user's perspective will be discussed in the 'consumer' category at the use phase. Also, the transport between some life cycle stages was omitted.

3.2. Inventory Analysis

a) Geographic modeling of chain actors

For the Life Cycle Inventory Analysis (LCI), Ecoinvent 3.4 database was applied for the e-LCA, and SHDB was used for the s-LCA.

The assumptions were based on the supply chain of the Tesla Model 3 launched in 2017, the most selling plug-in electric vehicles in Europe, as shown in Figure 26.

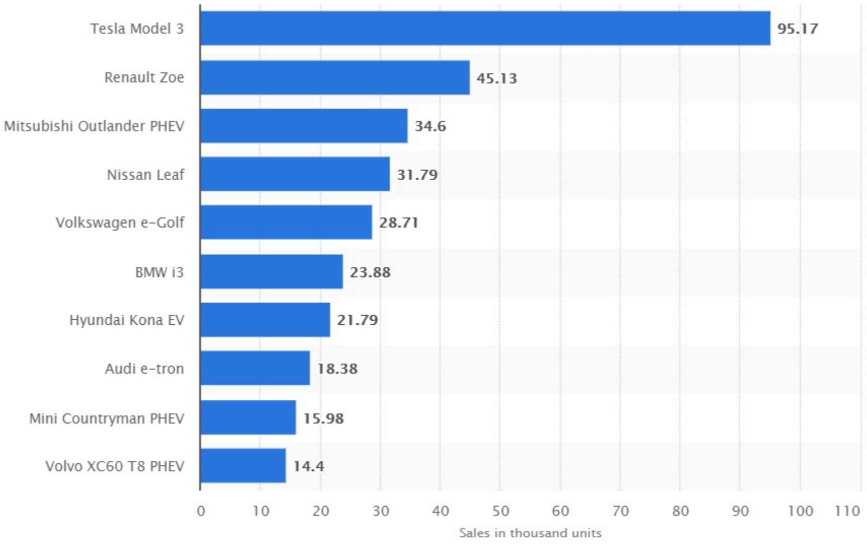


Figure 26: The most selling plug-in electric vehicle models in Europe. Extracted from Wagner, 2020.

The Tesla Model 3 leading battery supplier is Panasonic, located in Nevada, California (USA), The company works with the manufacture of lithium-ion batteries. Consequently, the battery manufacturer considered was the one found in California, USA.

The Tesla Model 3 vehicles are produced at the Gigafactory in Fremont, California (USA). Therefore, the transport package of battery between both cities in California was not considered, such as the package on that stage.

After transporting the lithium-ion battery to the Gigafactory, the batteries are placed inside the electric vehicle and then shipped to Europe. The Tesla Model 3 arrives in Europe through the Port of Zeebrugge in Belgium, and after that, they are transported to ‘pick-up’ points in 14 countries (Flanders Investment and Trade, 2019). Based on that literature review about the geographical route of a Tesla Model 3 from the factory to the final consumer, the assumptions were made.

The country in the EU that presents the higher numbers of newly registered electric cars is Germany, as shown in Figure 27 (European Environment Agency, 2020). The exact values of electric cars per country are attached to the present thesis as Appendix II.

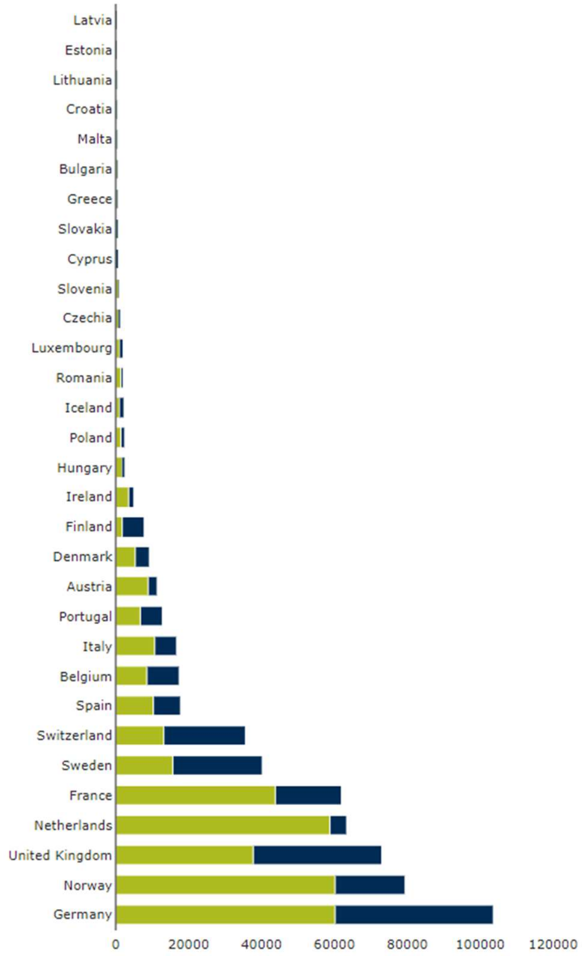


Figure 27: Absolut numbers of newly registered electric cars by country in December of 2020. In green – battery EVs, in blue – plug-in hybrid EVs. Extracted from European Environment Agency, 2020.

This thesis assumed that the LIB from the electric vehicle Tesla Model 3 was produced in California, the USA, transported to Belgium, transferred, and used in Germany, Europe. The end-of-life was processed in Belgium. This choice was made because this thesis accessed a European Union context.

Following the assumptions stated and the leading global producers of the Raw Materials needed for the cell manufacturer according to the European Commission (2020) presented in chapter 2.2, the core life cycle stages and their geographical location are shown in Figure 28.

The leading suppliers of the raw materials considered in the present thesis were the Democratic Republic of Congo for cobalt, Chile for lithium. Furthermore, the battery and vehicle manufacturer's cell manufacturer were defined to be made in California, USA. Finally, the use phase was designated to be in Germany. The EoL was considered to happen in Belgium due to the batteries recycling facility of Umicore located in Olen. The EoL was considered three options for the battery: second use, dismantling/recycling, and landfill.

Ideally, the second use is the best option, but it must be repaired or recycled if the direct re-use is not possible (Harper et al., 2019).

For dismantling/recycling, the refurbished process and enter the vehicle manufacturer stage, and the recycled precursor materials would enter the cathode manufacturer stage. Among the recycling methods are pyrometallurgical recovery, physical materials separation, and hydrometallurgical metals reclamation. The recycling stages were assumed to occur in Europe due to recycling companies such as Umicore (Harper et al., 2019).

On the other hand, if the two first options were not followed, this electronic waste has a high probability of ending up in landfills (Ikhlayel, 2017). The site in Agbogbloshie in Ghana is considered the largest world's e-waste dump; for the present thesis, it was assumed that if the LIB at their EoL were not correctly recycled or given a second use in Europe, it would end in a landfill. Therefore, Ghana was the location considered (Environmental Justice Atlas, 2020).

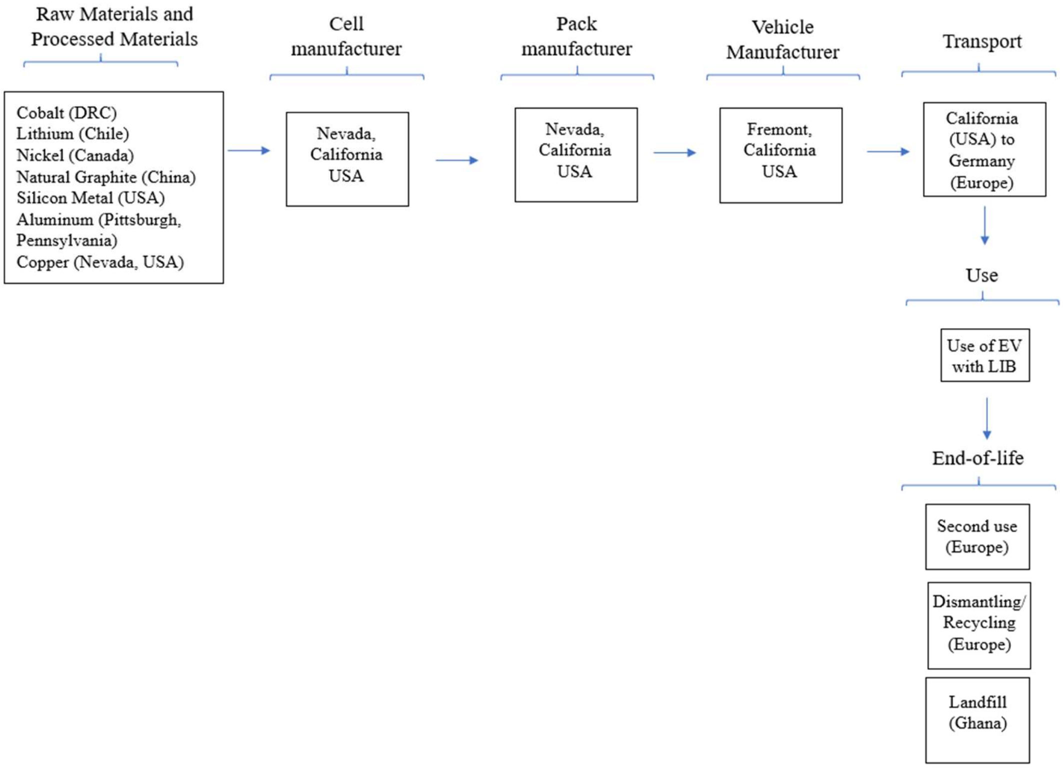


Figure 28: Chain actors with geographical location.

b) Selection of stakeholders

The stakeholders and risk categories selection were based on their significance for the objectives of the current thesis. Regarding business and products, the s-LCA guidelines state that the basis of an s-LCA are workers, local community, society, consumers, and value chain actors (Benoît-Norris et al., 2020).

Considering the literature review and the biggest suppliers of LIBs, this thesis focuses primarily on the environmental and social risks faced on the lithium and cobalt extraction/processed stage. The categories "**workers**", "**local community**" and "**society**" are the most sensitive point in the lithium and cobalt production of the electric vehicles industry due to the background of violation of human rights in countries where these raw materials are obtained, as mentioned on chapter 2.3. Therefore, the greatest attention will be directed to the most vulnerable groups in each category.

The '**society**' was considered a crucial stakeholder because one of this thesis's goals is to comprehend better how countries with raw materials of global interest are affected by economic relations. As the lithium-ion batteries of electric vehicles retailing in Europe focus on the present thesis, the ‘**consumer**’ will only be addressed for the final product.

The category “**value chain actors**” proposed by the methodology from UNEP (2020) aims to assess the relations between an actor, its suppliers, and their social responsibility, investigating power discrepancies that can result to social risk indicators. Furthermore, this approach indicates geographically where the social risks stand out, for example, where cobalt workers are at risk of suffering with their human rights being violated because of the country background in the mining sector.

c) Selection of risk categories & inventory indicators

The risk categories were chosen according to the methodological sheets for sub-categories in s-LCA. The selected categories aimed to assess social risks along the life cycle. The thesis focused more on the “**workers**” and the “**local community**.”

For “**value chain actors**”, the emphasis was placed on the promotion of social responsibility and wealth distribution to evaluate the influence and accountability of these actors.

For “**consumers**”, the EoL responsibility and transparency were discussed. These aspects are important to raise awareness among consumers regarding the acknowledgment of the products that are being buyed by them. They are considered to play a crucial role into the circular economy practices within closing the loop.

Regarding the “**society**”, the risk categories that will be proposed are public commitments to sustainability issues, prevention and mitigation of armed conflicts and corruption. Considering this stakeholder, the aim was to identify red flags concerning risks to human well-being and sustainable development.

The category “**children**” was placed because the production of the raw materials may have harmful effects, pose a risk to children exposed to the production process, and can often be associated with child labor. Finally, the risk category “education provided in the local community” was chosen to evaluate if companies are socially responsible and improve access to local communities' access to education.

The corresponding inventory indicators were identified for each of the impact and subcategories selected, as shown in Table 2. These indicators were compatible with the chosen approach of impact assessment.

Table 2: Summary of chosen stakeholders and risk categories. Adapted from UNEP (2020) and Rupp (2020)

Stakeholder	**Risk category**
Workers	Freedom of association and collective barganing
	Child labour
	Fair salary
	Working hours
	Forced labour
	Health and safety
	Social benefits/social security
	Equal opportunities/discrimination
Local community	Local employment
	Safe and healthy living conditions
	Secure living conditions
	Respect of indigenous rights
	Community engagement
	Delocalization and migration
	Cultural heritage
Value chain actors (not including consumers)	Promoting social responsibility
	Wealth distribution
Society	Public commitments to sustainability issues
	Prevention and mitigation of armed conflicts
	Corruption
Consumer	Transparency
	End-of-life responsibility

3.3. Impact Assessment and Results

a) Data collection

Ecoinvent 3.4 database was applied for the e-LCA combined with the information obtained from the literature review.

For the s-LCA, the data collection was based on desktop research and available data from public sources for the selected inventory indicators. The second included gathering literature around lithium-ion batteries, the chain actors and social risks linked with them. The Risk Mapping Tool by the Social Hotspots Database (SHDB) indicated the risk relevance level acting as a complement of the research. The most significant aim at this stage was to use sources as updated and transparent as possible.

b) Type of assessment

As stated previously, this study aimed at the identification of environmental and social risks connected with lithium and cobalt from batteries for the electric vehicles industry.

For the e-LCA, the LCIA was divided into two steps: classification and characterization. First, the inventory data was classified based on the selection of the relevant impact categories. Then, the assessment was made following the ReCiPe 2016 midpoint (H) method; there are 18 impact categories at the midpoint level. The present thesis discussion focused on terrestrial ecotoxicity, human non-carcinogenic toxicity, global warming, mineral resources scarcity, water consumption, and land use.

For the s-LCA, the data assessment was carried out in a narrative descriptive form. In parallel to this goal, quantitative data on statistics were used as indicators and further combined with the social aspects described within the literature review.

To assess the objective of this work, the LCIA was based on international standards: ILO labor standards, ISO 26000, the OECD Guidelines for Multinational Enterprises, and the s-LCA Methodological Sheets were used as performance reference points.

Based on the s-LCA methodological sheets, the definition of a color rating scales were carried out to illustrate the risk rating more homogeneously and provide more evidence around the researcher's choice. The color scale was based on qualitative and subject evaluation of the author, but it was also combined with quantitative indicators, and international standards. The rating criteria are summarized in Appendix III; they were based on Rupp (2020). The risks were evaluated according to the color scheme in Table 3.

Table 3: Color scheme for risk assessment. Adapted from Rupp (2020).

0	No evidence	🟦
1	Low risk	🟩
2	Moderate risk	🟨
3	Substantial risk	🟧
4	High risk	🟥
5	Very high risk	🟥
X	No data	⬜
Y	Does not apply	⬛

The indicators were rated according to the color scheme in Table 3. The ratings were aggregated when more indicators were used to evaluate one category. The same color scheme was applied to each actor. It must be emphasized that the aggregation loses precision and increases the subjective influence of the scale for a FU.

3.4. Interpretation

The interpretation phase for e-LCA is checked through critical review, analysis of data sensitivity if the conclusions were well substantiated. ISO 14044 standard describes several checks to test whether findings were supported by the data and procedures used.

For the s-LCA, the qualitative narrative description allowed context, synthesis, and explanation of the presented risks. The rating of the system provided an evaluation of relevant social risks and hotspots that were identified. A hotspot was considered where “high” or “very high” social risks were found.

The results were interpreted with the aim of an understanding on which risks are connected to the lithium and cobalt production within the LIB industry at the considered life cycle stages with the purpose to identify aspects of improvement and/or consider how risks can be banished and/or minimized.

a) Methodological reflections & limitations

A possible limitation is related to the data assessment and precise information among the other raw materials included in the process. In addition, the different life cycle stages presented various levels of data and sources' availabilities. For example, for extracting cobalt in the Democratic Republic of Congo, many sources are available but fewer with international recognition. On the other hand, in the SHDB, there was not enough data to specific mining of each metal but a general overview of mining in a determined country.

4. Analysis and Results

4.1. Raw Materials Production

The criticality of raw materials (CRMs) has become a meaningful discussion; the supply of certain raw materials is considered crucial for advancements in technology, such as in the mobility sector. Cobalt and lithium are relevant for specific interest in batteries which means that both will have increasing economic importance in parallel to the LIB market growth. The policies to guarantee reliable and controlled access to raw materials are being made by many institutions within the EU. Still, on the other hand, just fewer efforts are being made to understand the social risks embedded in their production (Tkaczyk et al., 2018).

a) Cobalt

The Democratic Republic of Congo in 2016 was responsible for 54% of the cobalt world mine production and 49% of the estimated reserves, as shown in Figure 29 (Tkaczyk et al., 2018).

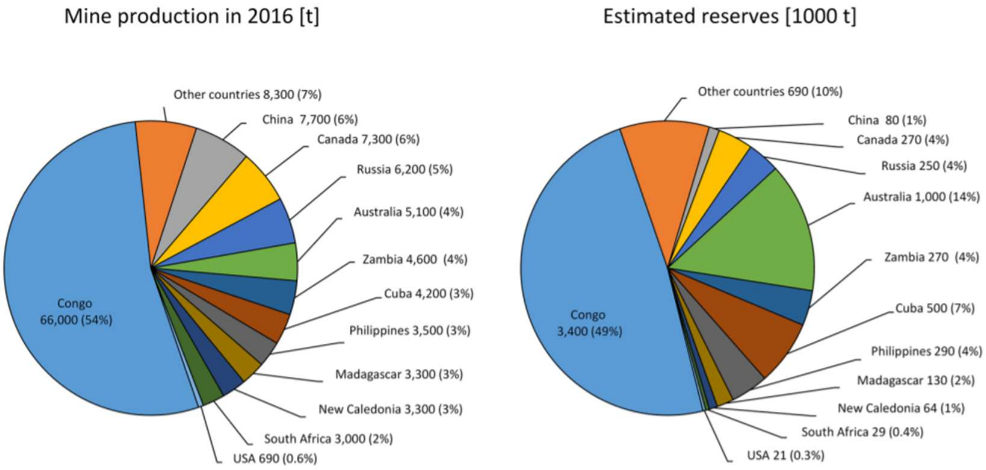


Figure 29: Global share of cobalt mining production and estimated reserves. Extracted from Tkaczyk et al., 2018.

Prevention and mitigation of armed conflicts

The conflict in DRC is motivated by the political instability background scenario. The 1994 genocide in Rwanda has effects until today, the intense refugee crisis that occurred at that time is one of the origins of the current violence in the DRC.

The 1994 genocide in Rwanda has effects until today, the refugee crisis occurred at that time when Hutu genocides fled to the east of the DRC and formed armed groups, opposing the Tutsis, and other opportunist rebel groups emerged, this is one of the origins of the current violence in the DRC (Council on Foreign Relations, 2021). Some armed groups directly threatened populations in neighboring countries, and war eventually broke out; the local government did not hold the power to control this conflicting scenario (Council on Foreign Relations, 2021).

The prevention and mitigation of armed conflicts are being done by some organizations such as the United Nations Mine Action Service (UNMAS) that supports the United Nations Organization Stabilization Mission in the Democratic Republic of the Congo (MONUSCO) that addresses Explosive Ordnance (EO) threats resulting from conflict in the east. The DRC's national security institutions reported that weapons management is followed under international standards (UNMAS, 2020).

Artisanal and industrial miners

The competition between artisanal and industrial miners is one of the social tensions in DRC. The coalition dynamics in the political sector pose a significant obstacle to change the mining sector.

Commonly, the interests of local politicians overcome the needs of artisanal miners and creates barriers to economic opportunities such as work on industrial mining, this ended up encouraging confronts (International Crisis Group, 2020).

The literature review analysis shows that an alternative to mitigate this problem is the creation of economic opportunities and the facilitating access of artisanal miners to industrial sites (International Crisis Group, 2020).

Environmental impacts and health risks to workers and local community

Artisanal and small-scale mining activities can pose risks to miners and the local community, usually using mercury and cyanide in the production resulting in environmental pollution due to the dumping of tailings and effluents into rivers and deforestation.

This damage can threaten people's livelihoods and well-being who rely on subsistence agriculture and food such as fishes due to their habitat destruction. In addition, this can lower the protein ingestion of people, and the lack of nutrients on their diets can aggravate health impacts due to other diseases common in mining areas, such as mercury contamination, sexually transmitted diseases, and malaria (Bannock Consulting Ltd, 2006).

A case study conducted in Kasulo, a hub of the Congolese mining area, showed that one of the biggest problems caused by mining activities is the dust that contains cobalt and other metals such as uranium. This study collected urine and blood samples from children who lived in Kasulo and children who lived in other places. The results showed that the children who lived in the district had ten times as much cobalt in their urine as the others. This value was exceedingly the limits accepted by workers at a European factory (Zaidi, 2019).

Amnesty International researchers found that cobalt miners in Congo generally lack essential protective equipment like face masks, work clothing, and gloves; this increases their exposure to contaminants (CBS, 2018). In addition, the same report interviewed miners, and many of them complained about lung problems (CBS, 2018).

Local communities: water distress and adverse effects of aggressive mining

The connection between the local community and aggressive mining is related to water distress. Most vulnerable groups from DRC society are engaged with artisanal mining with minimal access to Water, Sanitation, and Hygiene (WASH) and primary health care.

The development of the cities where mining activities are located usually occurs with little or no planning, resulting in workers building their houses next to the mines.

The lack of formal recognition of these settlements as villages makes it challenging to treat possible diseases generated by the lack of basic sanitation. This increases the exposure of these people to malaria, cholera, tuberculosis, and infectious diseases (Bannock Consulting Ltd, 2006).

Local employment, working hours, and fair wages

The selection of workers in DRC by mining companies is made by recruiting agents committed to giving preference to the local community within their CSR framework (Rubbers, 2020). However, no reports and evidence that showed that this was being followed were found.

To understand the labor market developed within the mining in the DRC is necessary to consider that mining project commonly outsource employees. Artisanal mining is considered a substantial part of the global cobalt supply chain (Rubbers, 2020). Tsurukawa et al. (2011) suggest that around 70,000 people were employed in artisanal mining in 2011.

Under the Congolese labor law, day laborers cannot be hired without breaks for more than 22 days over two months (Human Rights Watch, 2019). However, reports showed that during the pandemic workers had been confined over two months having no choice but to work or lose their jobs (Human Rights Watch, 2020). That shows the lack of social responsibility of these mining companies with their workers.

Regarding fair wages, some reports show the average monthly costs of living in the DRC and the salary of miners. For example, the report of Fairphone from 2020 showed that in Nzibira and Itebero, located in Eastern Congo, most miners earn between USD 84.37 and USD 115 per month. Most households in that region are composed of 6 people on average; if we consider a family where two adults are miners, their joint revenue is approximately USD 202 per month. On the other hand, according to the same report, the basic needs in this region are estimated to cost around USD 243 per month. That implies that the family’s incomes do not meet their basic needs, which can have many consequences such as hunger or even the need for children to work in the mines to increase their income (de Brier & Jorns, 2020).

Child labor and forced labor

Child labor is one of the issues related to non-industrial mining in the DRC, involving them in the precarious forms of work, including in the forced mining of cobalt (Human Rights Watch, 2020). According to the US Bureau of International Labor Affairs (2015), 35,000 of 255,000 artisanal miners at the DRC are children. This fact makes it difficult for these children to attend schools, directly affecting local educational development. Table 4 provides statistics on children's work and education.

Table 4: Statistics on children's work and education. Extracted from US Bureau of International Labor Affairs (2015).

Children	Age	Percent
Working (%)	5 to 14	35.8
Attending School (%)	5 to 14	77.3
Combining Work and School (%)	7 to 14	37.1
Primary Completion Rate (%)	-	69.9

The literature review on child labor by sector and activity showed that the mining industry and child labor are sometimes a result of debt bondage (US Bureau of International Labor Affairs, 2015). The children's work includes carrying heavy loads, digging, transporting, using explosives, washing, and working underground to produce cobalt and 3TG. The literature review showed that they often work in auto mechanics, carpentry, craft workshops, construction sites, and building roads (US Bureau of International Labor Affairs, 2011).

Among the many forms of child labor, the ones characterized as the worst forms under Article 3 of the International Labor Organization (ILO) are the engagement in prohibited activities like working for armed groups; transportation of stolen goods, and contraband of minerals, including tax collectors at mining sites (US Bureau of International Labor Affairs, 2011 and 2015).

Even with the conflict between military and the Forces Démocratiques de Libération du Rwanda-Forces (FDLR) and the Allied Democratic Forces (ADF), some non-state armed groups that operates in the region insists on recruiting children in armed conflict (US Bureau of International Labor Affairs, 2015 and 2019).

A comprehensive child labor inspection has never been managed in the DRC, despite the indication of children engaged in armed conflict and artisanal mining (US Bureau of International Labor Affairs, 2011).

Studies shows that there is no capacity to investigate and prosecute child labor violations from the justice system in DRC (US Bureau of International Labor Affairs, 2011 & United Nations, 2019). Additionally, the lack of investigations, data collection, and assistance to victims continues to hamper the government's ability to overcome child labor in the DRC (US Bureau of International Labor Affairs, 2011).

The Congolese law states the right of free education and school is mandatory until the age of 15 but this is not properly enforced. Consequently, children in the DRC have a high chance of ending up working in mining or other activities (US Bureau of International Labor Affairs, 2011).

b) Lithium

Lithium can be obtained from spodumene, “a complex silicate mineral found in pegmatites, and lithium chloride in brine lake deposits” (Agusdinata et al., 2018). That is the case of Chile, the country that holds the highest concentration in the world (Agusdinata et al., 2018).

The South American Lithium Triangle, an area that includes Chile, Bolivia, and Argentina, is estimated to hold more than 50% of the world’s lithium resources (Gruber et al., 2011 and Liu & Agusdinata, 2020). The Li- triangle embraces salt flats with extremely arid climates and scarce water; it is characterized by complex socio-ecological interactions (Agusdinata et al., 2018).

The focus on Chile is explained because it is the biggest lithium supplier in the world, as previously explained. Almost half of the world’s lithium reserve is in the Atacama Salt Flats in Chile. Many mining companies that are suppliers of producers of phones and cars depend on lithium extracted from Chile. Although, the impacts of this process have become a severe problem for Chile due to the excessive use of water during the extraction process affecting the environment and society (Southwell, 2020).

The environmental and social risks with lithium production are related to the consequences of aggressive mining activities, social injustice at the local community level, and the impacts on human health and potential toxicity.

Local communities: water distress and adverse effects of aggressive mining

Chile is one of the driest areas in the world, with a high-water scarcity followed by environmental negative impacts, and conflicts with local communities (Aitken et al., 2016).

In Chile, pools of saline water are the primary source to find lithium. The liquid from these lagoons is pumped out and then dried in the sun to collect sediment (Francis, 2020). According to the Nonmetallic Mining Committee, mining companies extract around 8,800 liters of brine per second in that region (Francis, 2020). The process uses water to remove the lithium, consequently drying out entire towns like San Pedro de Atacama and protected sites like the national monument of Peine and devastating the environment in general, causing increasing desertification in the region (Southwell, 2020).

Mapuche people belong to the largest indigenous group of Chile (INE, 2018). A field observation mission by the Chilean National Institute of Human Rights (INDH) showed that Mapuche communities from the Los Rios Region face water shortages and are being affected by pollution (van der Mark, 2019).

The primary source of income of the local community relates directly to agriculture, and the water distress is causing a significant effect on their water supply (Francis, 2020). This pushes local farmers to migrate and walk out on inherited settlements, contributing to negative environmental impacts such as landscape damage, soil and groundwater contamination (McCrae, 2020).

4.2. Battery Production and Vehicle Manufacturer in the USA

The production phase is divided into cell and pack manufacturing, followed by the junction of the vehicle and the battery. They are done in Nevada and Fremont, respectively, both in California, USA.

The literature review showed that the environmental impacts of cell manufacturing are essentially in GHG emissions and energy demand, and other effects are assessed per total battery pack. For some specific stages of production, the data is limited. For example, if there are more recycled materials are processed. the impact is lowered (Aichberger & Jungmeier, 2020).

The battery used in Tesla Model 3 is an NCA. The type of cathode paste with a higher GHG impact, as shown in Figure 30, compares the different types of cathode pastes from various battery models and raw materials. Figure 31 shows that the higher result in battery production is related to cathode production.

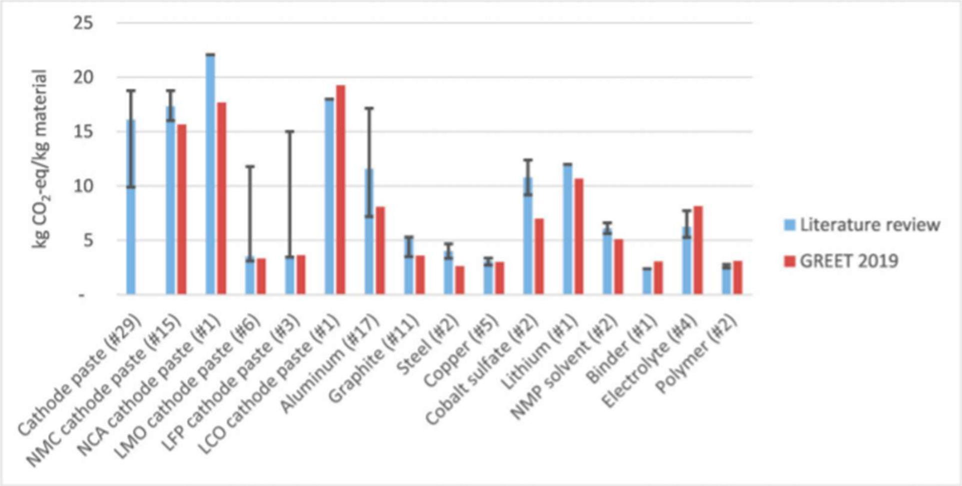


Figure 30: GHG emissions of battery materials from the LCA comparison. Extracted from Aichberger & Jungmeier, 2020.

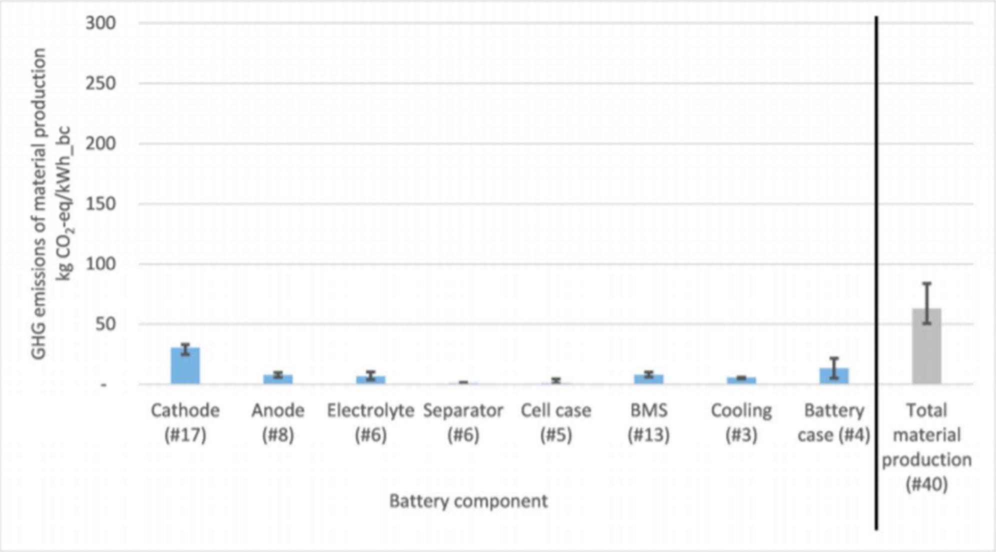


Figure 31: GHG emissions of material production per component. Extracted from Aichberger & Jungmeier, 2020.

Aichberger & Jungmeier (2020) show that the highest impact is related to the cathode portion connected to lithium and cobalt. According to the literature review, the social aspects of the manufacturing process that showed to be the most sensitives points in the USA are gender inequality and fair wages. On the other hand, Panasonic has a robust internal activity for occupational safety and health of their employees, which was one reason why this was not profoundly discussed in this thesis.

Gender inequality and fair wages

Gender inequality has been decreasing throughout history. There are some significant advancements towards equality, but the disparity is still persistent, especially in the technology sector that was the main subject of the present research.

The Global Gender Gap report released by the World Economic Forum (2021) establishes a score from 0-1 to evaluate the countries. The score closest to 1 shows less gender inequality while most relative to 0 shows the opposite. For example, the United States was scored with 0.763. In addition, it is known that the presence of women in senior and managerial roles represents 42% of the workforce, showing some progress compared to values from previous reports.

The discrepancies in salary regarding gender are still a significant issue. For example, the United States showed a 35% gap between men's and women's incomes (World Economic Forum, 2021).

4.3. Distribution in Belgium

In 2019 it was reported that at the retail stage it is estimated that 3,000 Tesla cars arrives in Belgium at the Port of Zeebrugge per week from the United States (Flanders Investment and Trade, 2019). With the new policies from the EU to decrease GHG emissions, the incentives for electric mobility, and information from the literature, the consumption tends to increase, and so the numbers of EVs arriving at the port.

Social risks in the sector

There are no significant social risks for workers related to this stage in Belgium. According to Eurostat, the Belgian minimum wage is 1593 euros. This value is above the estimated living wage of a family suggesting economic security to these families, showing security of the well-being of its workers such as the social security guarantee. The most considerable social risk that is reported in this sector is discrimination. This stands especially against non-white and non-European people, also in job recruitment processes (Verhaeghe, 2017 and Baert et al., 2015).

4.4. Use phase

As previously mentioned, the use phase was considered in Germany because it is the country from the EU with more EVs registered. However, the transport from Belgium to Germany was not considered for both environmental and social impacts.

Tesla's Model 3 battery pack has four battery modules and an average lifespan of 400,000 miles; considering that the average miles driven per year are 13,500, the lifespan of a lithium-ion battery from a Model 3 is approximately eight years (CarAdvice, 2020).

Consumers are well informed about the environmental aspects and economy related to that purchase during the use phase. For example, in Europe, they are willing to pay for a vehicle that will contribute to the decarbonization in the urban mobility sector (Burghard et al., 2020). However, there is a lack of information about social responsibility in the whole supply chain of raw materials used in these vehicles.

Social responsibility towards consumers

The general work conditions in Europe are considered good, and European consumers are well informed about the environmental advantages of the use phase of electric vehicles. However, it is difficult to assess the social risks of the supply chain connected to EVs when a consumer buy one.

The efforts to show that EVs are a better option than fossil fuel vehicles can be understood as "greenwashing" when there is an avoidance to discuss the whole value chain of the product. The claim is that EVs brands are putting more effort into marketing strategies, mainly considering the environmental impacts. At the same time, the social aspects are not being publicly discussed in the same proportion.

4.5. End-of-life

The EoL of the battery was considered to occur also in Belgium because it is the country where the Umicore battery recycling plant is located.

The EoL for improper disposal was also considered to highlight the need for a circular economy in the battery sector for electric vehicles. If the battery was not properly recycled or given a second use in Europe, it was considered that this battery ended up in a landfill in Ghana.

There are three broad options for lithium-ion batteries at the end of their first life, as shown in Figure 32, second life (reuse as an EV battery or repurpose, e.g., stationary storage); recycling; and disposal. Following waste management hierarchy principles, an effective regulatory and policy environment should promote the reuse and repurpose of lithium-ion batteries, and safe and effective end-of-life management, as shown in Figure 33.

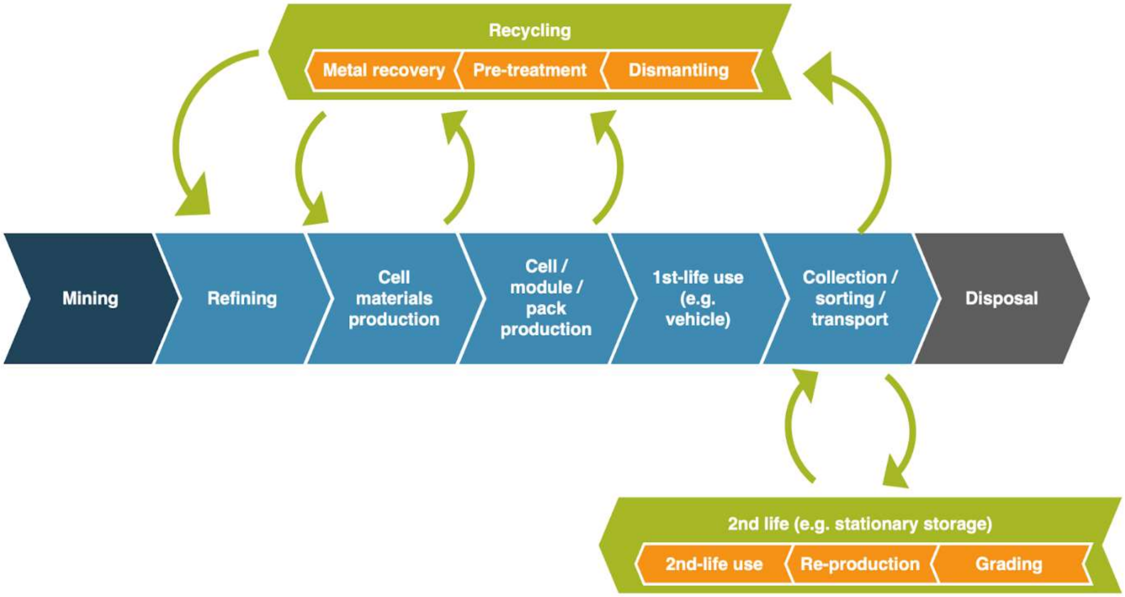


Figure 32: Options for lithium-ion batteries at the end of their first life.

Figure 33: Waste management hierarchy

Europe has many initiatives to recycle, dismantle, or even a second use of these batteries at the end-of-life stage. Three scenarios are being applied in Europe to repurpose for a second life, recycling and disposal.

The Sustainable Batteries Regulation launched by the EU in 2020 shows the efforts made towards increasing circularity and avoiding the electronic waste of these materials. This strategy established a comprehensive framework covering all types of batteries and addressing their life cycle from the production process to design requirements and EoL (second life, recycling, and incorporating recycled content), showing the strategic efforts made by the EU to help to close the batteries loop. The ambitious focus is on the final stage proposing 100% recycling to ensure that no metal and CRM are lost. Hence, all valuable materials that are part of batteries are feedback into the economy. Therefore, the primary purpose of the EoL management is to extend producer responsibility, collection targets, and obligations for recycling efficiencies and levels of recovered materials (European Commission, 2020).

The targets for recycling efficiency of LIBs and the specific recovery targets for CRMs such as cobalt, lithium, lead, and nickel are set to be achieved by 2025 and 2030. In Europe, only 10% of the lithium from LIBs is recycled, showing that the EoL of batteries is another sensitive point in the supply chain. Most of the recycling processes for used LIBs in the EU are currently pyro-metallurgical based, highly effective for cobalt (Bobba et al., 2018).

The major sorting firm in the market is Umicore, with a dismantling and recycling process that recovers almost all metals inside the batteries. The efforts to improve LIBs recycling are also concentrated in a non-significant numbers of research groups and companies (Jacoby, 2019).

The second uses for LIBs are the repurposed in a peak shaving configuration and the use to increase photovoltaic self-consumption (Bobba et al., 2018).

Social risks within end-of-life

Extended Producer Responsibility (EPR), as the name suggests, extends the responsibility of producers to embrace the whole life cycle of their products (Atasu & Subramanian, 2012). The producer partially pays responsibility for discarded products and the costs of collection and recycling. EPR is based on the principle of "the polluter pays" (Massarutto, 2014). The policy aims to create an incentive for producers to include recycling considerations early in the product design phase and take responsibility for managing their products from design and production to the end-of-use stage. The logic behind this is that if producers pay for collection and recycling, they will have an incentive to make their products easier to recycle.

Even with the EU legislation stating that EPR needs to be followed, the collection system of LIBs is not well defined in Europe. When recycling and second-use options are not applied, these batteries will likely end in landfills (Jacoby, 2019).

Improper collection and treatment approaches in some countries lead to severe environmental, societal, and health impacts. The flow of e-waste around the world is not only a story of dumping, but it also moves globally because it has value in terms of its materials, its components, and its reuse potential (Salahabedi, 2013). In addition, there are legitimate transboundary movements, also related to trade in reusable and repairable equipment.

When disposed of in landfills, e-waste can pose a risk due to its complexity and aggregation of many different materials fused in various combinations (EIT Learning Climate-KIC. (2020). Therefore, recycling and recovering materials must be managed carefully.

The threats to the environment and human health come from three groups of substances that can be released during recycling and material recovery: the original constituents of equipment, such as lead and mercury, substances that may be added to separate and extract materials, such as cyanide, substances such as dioxins that may be formed and released by unsound recycling operations, such as uncontrolled burning processes or open burning (Lundgren, 2012 and EIT Learning Climate-KIC, 2020).

Among the issues related to global electronic waste management, elevated concentrations of heavy metals in the air have been detected in high-tech facilities in developed countries (Lundgren, 2012). However, the most severe problems are found in developing countries with high-volume, informal (unregulated) recycling (Lundgren, 2012).

As the markets for second-hand electrical and electronic equipment can be more profitable than other types of waste, e-waste recycling has become an essential source of income for many people who lack different ways of earning a living (EIT Learning Climate-KIC, 2020). Many people who work in informal e-waste collection and recycling operate outside labor and environmental regulations and are therefore at risk from the hazards of unsound practices, their incomes are low despite the risks they are exposed to (EIT Learning Climate-KIC, 2020). In many countries, earning a living from e-waste recycling is not recognized as a formal occupation. Informal e-waste workers often have minimal access to social security and have little or no employment injury protection, unemployment protection, disability benefits, or access to healthcare, many of those working in the informal e-waste sector lack the benefits of formal employment, such as set working hours, membership of trade unions and other associations that protect workers' rights, and equitable rates of remuneration – for example, equal pay for men and women (EIT Learning Climate-KIC, 2020).

Many informal e-waste workers are from marginalized populations, including the poor, migrants from rural areas, and ethnic and religious minorities (Global E-Waste Monitor, 2017). Together with a lack of regulation, the informality of the sector means that such populations are subject to adverse health impacts and lack opportunities to develop skills and become socially mobile and become even more marginalized.

Children are a significant portion of the e-waste collection and recycling workforce. For example, in Bangladesh, over 50,000 children are involved in informal e-waste collection (Global E-waste Monitor, 2017). Children are engaged in finding and collecting manual sorting, burning, and manual dismantling of e-waste. Unfortunately, they are not only exposed to the health risks posed by unsound practices but are also unable to attend school and therefore limit their opportunities later in life because of a lack of education (Global E-waste Monitor, 2017).

4.6. Life Cycle Assessment results

The functional unit used for both assessments was one lithium-ion battery from a Tesla Model 3. However, the e-LCA considered the amount in kg of lithium and cobalt used to produce one battery, 10 kg, and 4.5 kg, respectively. While for the s-LCA, the global supply chain was assessed, but the discussion was a significant focus on lithium and cobalt production.

a) Environmental Life Cycle Assessment (e-LCA)

The current thesis will use a LIB as a functional unit, but the e-LCA was performed for lithium and cobalt production. In addition, the e-LCA results for a lithium-ion battery were gathered with a literature review to give a brief analysis of the environmental impact of the whole battery. For the assessment, it is necessary to point that Tesla Model 3 battery packs have a capacity of 82 kWh, 480 kg of weight, and the lifespan of a battery is about eight years on average (U.S. Environmental Protection Agency, 2017 and Lamber, 2020).

Some studies about the e-LCA of LIB were carried. Still, these results showed a significant discrepancy that is probably affected by the origin of the data inventory, calculation approach, energy sources, battery type, and refining methods (Hans et al., 2019). All these variables impacted the assessment results showing a wide range among the outcomes, especially for cumulative energy demand and amount of GHG emissions. In addition, 51% of the studies reviewed by Tolomeo et al. (2020) showed that the interpretation phase and the sensitivity analysis of these LCAs had not been performed.

The current thesis could not have access to precise information about all raw materials and processes of a lithium-ion battery Model 3 to carry the e-LCA, so the focus was mainly on lithium and cobalt productions.

The environmental sustainability and the hotspot analysis were performed with ReCiPe 2016 midpoint (H) method. The impact was calculated by multiplicating the characterization factor for resource or emission and the amount calculated over the lifecycle. Appendix IV shows the inputs and outputs analyzed by the software for Li and Co-production used in a lithium-ion battery in a Tesla Model 3.

Lithium Production

According to the Ecoinvent database, this dataset represents the production of 1 kg of lithium carbonate from concentrated brine. Therefore, the dataset can be used for preparing electrode base material for batteries. This dataset is based on an environmental survey from SEIA-CONAMA (2006) and environmental reports from a company in Chile (SQM).

The activity starts with raw materials entering the process and ends with 1 kg of lithium carbonate (Ecoinvent, 2020). The dataset includes the processing of the raw materials, the energy uses, and the estimated infrastructure. Emissions to air and water are not included. It was considered 10 kg of lithium production because it is the amount needed to produce one battery for an EV Tesla Model 3 (Clean Technica, 2019 & Root, 2020).

Cobalt Production

According to the Ecoinvent database, this dataset represents 1 kg of cobalt production from the reduction of gray and black cobalt oxide. Material and energy inputs, extraction processes, material, transport, and emissions are approximations based on nickel production. Infrastructure and auxiliaries are an estimation based on a large chemical plant. From cobalt in-ground, this activity ends with the production of 1 kg of cobalt. The dataset includes material and energy inputs, infrastructure, transport, and emissions to air and water. The dataset does not include overburden and tailing material from the process as well as losses of product. It was considered 4.5 kg of cobalt production because it is the amount needed to produce one battery for an EV Tesla Model 3 (Benchmark Mineral Intelligence, 2018).

Impact categories

In this work, the software analyzed five principal impact categories based on the high relation that they have with the production of cobalt and lithium. Figures 34 to 39 summarizes the contribution of both processes for each impact. The rationale behind the chosen categories was mainly which indicator showed higher results in both approaches. The impact categories analyzed were terrestrial ecotoxicity, human non-carcinogenic toxicity, global warming, mineral resources scarcity, water consumption, and land use.

Terrestrial ecotoxicity is the increasing hazard-weighted in natural soils; it is measured by kg 1.4-dichlorobenzene (1,4-DB) to industrial soil. For ReCiPe, this value is obtained through the toxicity potential (TP), 1,4-DB is used as a reference and divided by the chemical with potential impact on industrial soil. Figure 34 shows the lithium and cobalt production results, 143.02 and 192.08 kg 1,4-DCB, respectively. For lithium, the most significant contribution is 38.32% related to the soda production used in the Solvay process; for cobalt, the higher contribution is 65.94% pertaining to the mine construction with the biggest contribution of the market for copper, probably because cobalt is obtained as a byproduct of copper extraction (Crundwell et al., 2020).

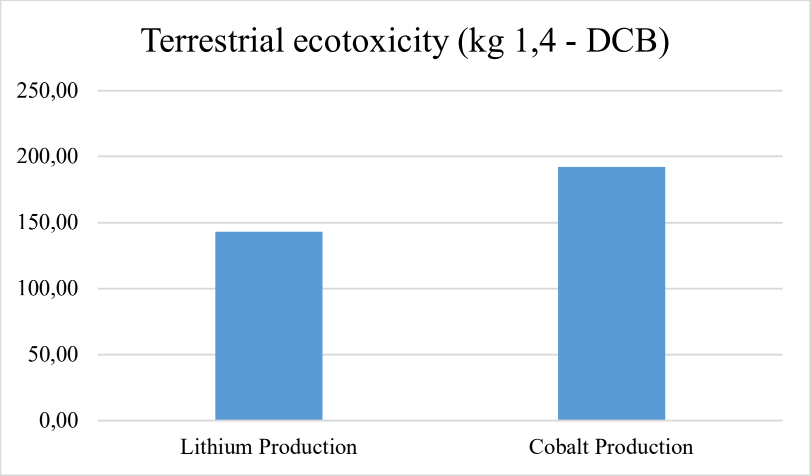


Figure 34: Contribution of lithium and cobalt production to Terrestrial Ecotoxicity

Human non-carcinogenic toxicity is defined by the risk of increasing a non-cancer disease incidence, and it is measured by kg 1,4-DCB to urban air. Figure 35 shows the lithium and cobalt production results, 35.76 and 89.89 kg 1,4-DCB, respectively. For lithium, in this impact category, the soda production for the Solvay process is the most enormous contribution with

48.99%; for cobalt, the higher contribution is 37.09 % related to the mine construction with the biggest contribution of the market for copper.

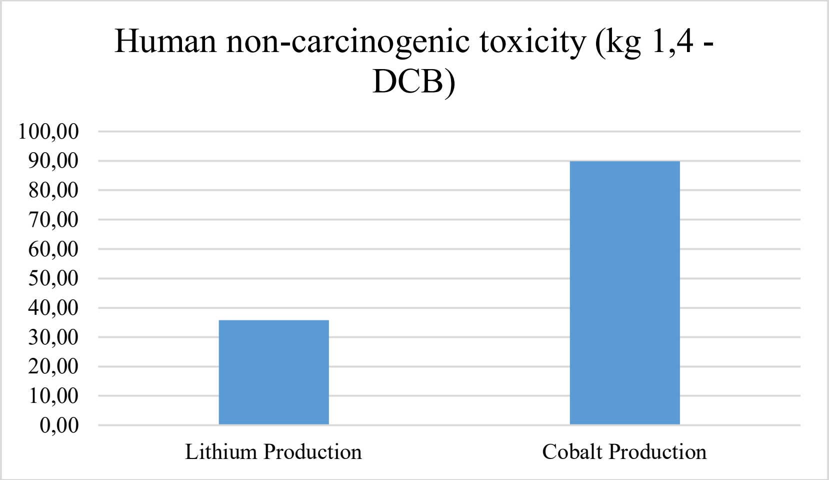


Figure 35: Contribution of lithium and cobalt production to Human non-carcinogenic toxicity

Global warming, defined as the increase in the average global temperature, is caused by greenhouse gases like CO_2, CH_4, N_2O emitted by human activities (MacDonald, 2019). According to the World Wild Foundation (2019), the principal causes of global warming are the burning of fossil fuels, deforestation, and agriculture and farming (European Commission, 2019). Global warming is one of the most critical impact categories since the effects can be felt on all continents (Huijbregts et al., 2016).

For one lithium-ion battery of a Tesla Model 3, the lithium and cobalt production contributions for global warming are 28.52 kg CO_2 eq and 48.06 kg CO_2 eq, respectively, as shown in Figure 36. According to the contribution tree, this value for lithium explains that 37.1% is related to soda ash production (sodium carbonate, Na_2CO_3) and calcium chloride ($CaCl_2$) through the Solvay process, followed by 19% of electricity. For cobalt, 35.37% of the total is mainly due to electricity and 21.81% for cement production. The electricity needed in mining activities is intense due to all machinery required in the process, having a negative effect on global warming.

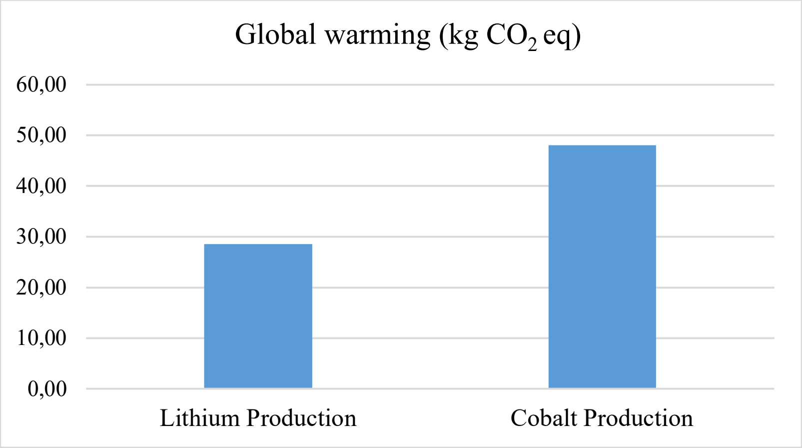


Figure 36: Contribution of lithium and cobalt production to Global warming

The mineral resource is the concentration or occurrence of solid material of economic interest in or on the Earth's crust in such form, grade or quality, and quantity that there are reasonable prospects for eventual economic extraction (Hore-Lacy, 2016). However, the scarcity of these resources worldwide can make their extraction harder in terms of energy used, generating a higher impact.

As shown in Figure 37, lithium production contributes with 0.13 kg Cu eq while cobalt production contributes with 39.26 kg Cu eq. This discrepancy is probably due to the lower risk of lithium supplies running low with the current demand; on the other hand, if the demand continues to increase as shown previously, this result will probably be different. This hypothesis is supported by Greim et al. (2020); the study assesses 18 scenarios and discussed that the short-lived, scenario-dependent, small deficit between now and 2050 can be managed with an adjustment for almost all scenarios, except for the procedure corresponding to low recycling, for which there is an initial supply deficit that continued until the end of the century due to the premature depletion of fresh Li supply (Greim et al., 2020). For cobalt, there seems to be enough cobalt to meet the demand for the foreseeable future. However, two key issues bear the significant potential to create supply bottlenecks, related to the nature and the location of cobalt deposits (Energy Storage World Forum, 2020)

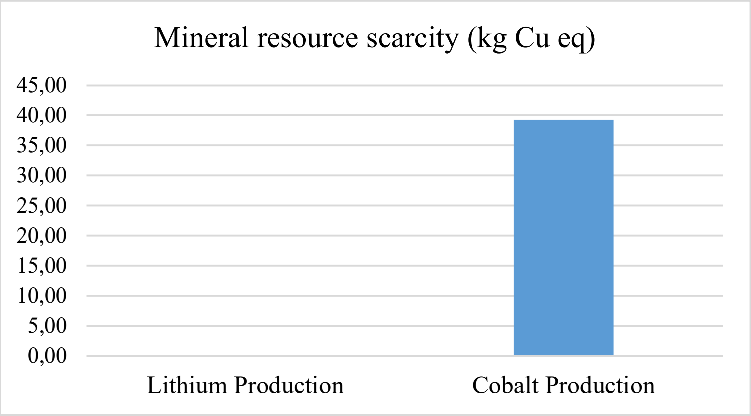


Figure 37: Contribution of lithium and cobalt production to mineral resource scarcity

The impact category water consumption is defined as water use in all processes in which water is used and can be transferred to different chemical or physical states through evaporation, incorporation into products, or even transferred to other water bodies, or disposed into the sea (Huijbregts et al., 2016). Once the water is used, it is not available anymore, and this can lead to the competition of different water uses. For example, mining uses water for the process of minerals, to suppress dust and particulate matter, to transport slurry, and in the facilities (ICMM, 2012). As a result, water is sought from groundwater, streams, rivers, and lakes or through water suppliers in most mining operations. But often, mining sites are located in regions distant from people where usually water is scarce and, because of that there is an opposition of local communities and authorities regarding the water use from these sources (Mining Technology, 2020).

Figure 38 shows that the water consumptions for lithium and cobalt production are 0.58 and 0.74 m^3, respectively. According to the contribution tree, the explanation of this value for lithium is that 81.47% is related to soda ash production. On the other hand, for cobalt production, 37.89% of the total is mainly due to the gravel and sand quarry operation and 16.23% for electricity.

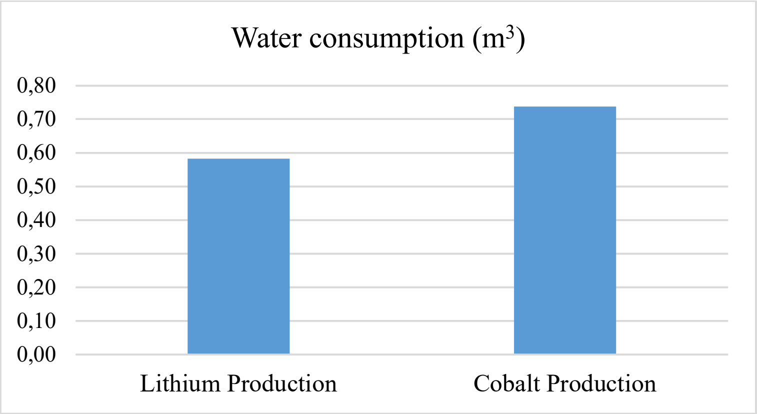


Figure 38: Contribution of lithium and cobalt production to water consumption

Land Use calculates the impact of land use on species losses because of land use, land transformation, land occupation, and land relaxation. It is considered that a natural situation (presence of species) would occur without any land usage. However, this use directly affects the cover of such land, causing loss of habitat and soil disturbance, which will cause severe consequences and damages to the local ecosystem. Biodiversity, for instance, can be affected indirectly.

Figure 39 shows that the land use impact category for lithium and cobalt production showed results of 2.00 and 3.49 m^2a crop eq, respectively. According to the contribution tree, this value for lithium is explained by 30.64% related to the lithium brine inspissation that pumps lithium-rich groundwater to the surface and injects in evaporation ponds to concentrate the brine (Schomberg et al., 2021). For cobalt production, 40.51% of the total is mainly due to the treatment of non-sulfidic tailing off-site, followed by 21.75% for the treatment of non-sulfidic overburden.

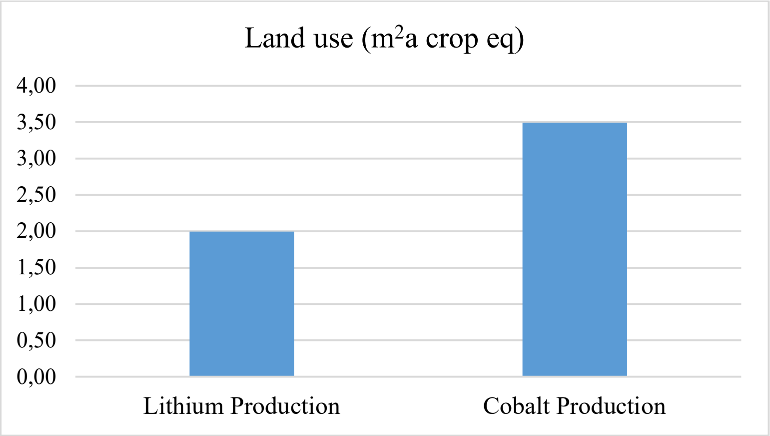


Figure 39: Contribution of lithium and cobalt production to land use

The results showed that the processes that have a higher impact for lithium is the soda ash production and for cobalt is the copper market because cobalt is obtained as a by-product of copper.

b) Social Life Cycle Assessment (s-LCA)

The social hotspot analysis disclosed social risks within the lithium and cobalt production stages of a lithium-ion battery life cycle from a Tesla Model 3 purchased in Germany. The s-LCA allowed the identification of red flags, and this section examined the hotspots. In addition, the specific social risks for each value chain actor were discussed.

The ratings per risk category are shown in Table 5. The categories marked with dark red can be considered social hotspots. It should be noted that this presentation in the form of a table is a visual overview. The interpretation and comparison of the categories must be carried out with attention considering that these results are a combination of a bibliographic review and the LCA results obtained with the support of the Social Hotspot Database. The analysis should serve as guidance for future investigations targeting the most sensitive points. The s-LCA approach provides a basis for future research to investigate the hotspots that were identified. To obtain more consistent conclusions from the red flags raised in the current study, site-specific studies can be conducted combined with interviews with the major suppliers of LIB companies.

The social hotspots tracked in table 5 show with clarity that workers are the most vulnerable among stakeholders. This results is associated with the social risks of the dynamics on exploitative working conditions that are unfathomable. However, these risks are not seen in

Belgium and Germany results. One comprehensive explanation is because both countries are part of the “consumption” stage.

One critique around the social hotspots in the production of lithium and cobalt is the absence of proper due diligence, social audits, and monitoring reports for those working conditions aspects. The lack of due diligence practices emphasizes the continued focus on decreasing costs instead of investing in social and environmental responsibilities.

Table 5: Risk rating summary per country

Stakeholder	**Risk category**	DRC	Chile	USA	Belgium	Germany	Ghana
Workers	Freedom of association and collective barganing	🟥	🟥	🟥	🟩	🟩	🟥
	Child labour	🟫	🟧	🟩	🟦	🟦	🟫
	Fair salary	🟫	🟧	🟩	🟩	🟩	🟨
	Working hours	🟫	🟥	🟨	🟩	🟩	🟥
	Forced labour	🟫	🟩	🟩	🟩	🟩	🟥
	Health and safety	🟥	🟧	🟩	🟩	🟩	🟧
	Social benefits/social security	⬜	🟧	🟥	🟩	🟩	🟥
	Equal opportunities/discrimination	🟫	🟧	🟧	🟨	🟨	🟫
	Gender inequality	🟫	🟧	🟧	🟩	🟩	🟥
Local community	Unemployment	⬜	🟩	🟨	🟨	🟩	⬜
	Safe and healthy living conditions	🟫	🟩	🟩	🟩	🟩	🟥
	Children out of School	🟫	🟥	⬜	🟩	🟩	🟥
	Respect of indigenous rights	🟧	🟧	🟨	🟦	🟦	🟧
	Community engagement	🟫	🟥	🟨	🟩	🟩	🟥
	Migration	🟫	🟥	🟧	🟩	🟩	🟥
	Cultural heritage	🟥	🟥	⬜	⬜	⬜	🟥
Value chain actors (not including consumers)	Fair competition	🟫	🟫	🟧	🟨	🟨	🟥
	Promoting social responsibility	🟫	🟧	🟩	🟩	🟩	🟥
	Wealth distribution	🟫	🟧	🟨	🟩	🟩	🟥
Society	Public commitments to sustainability issues	🟥	🟧	🟧	🟩	🟩	🟥
	Prevention and mitigation of armed conflicts	🟫	🟧	🟥	🟦	⬜	🟥
	Corruption	🟫	🟧	🟩	🟩	🟩	🟫
Consumer	Transparency	🟫	🟧	🟩	🟩	🟩	🟥
	End-of-life responsibility	⬛	⬛	⬛	🟨	⬛	🟫

The comprehensive analysis showed that high social to very high social risks were identified at the cycle stages that are the focus of the current study: lithium and cobalt production. The other raw materials and processed materials were not considered because there would not be enough data to evaluate all of them. The distribution from the USA to Belgium, the use phase in Germany, second use, and dismantling/recycling in Belgium, Europe showed low to substantial risk for some of these stages. Figure 40 provides an overview of chain actors along the life cycle and the respective colors of the risk rating scheme.

It is essential to highlight that this analysis needs to be comprehended as a part of a bigger picture. Due to the heterogeneous distribution of the risks in this system, it was essential to apply the color rating of the chain actors into perspective. The interpretation of this figure must consider that the risks that emerged result from a connection between the countries, actors, and the world production system.

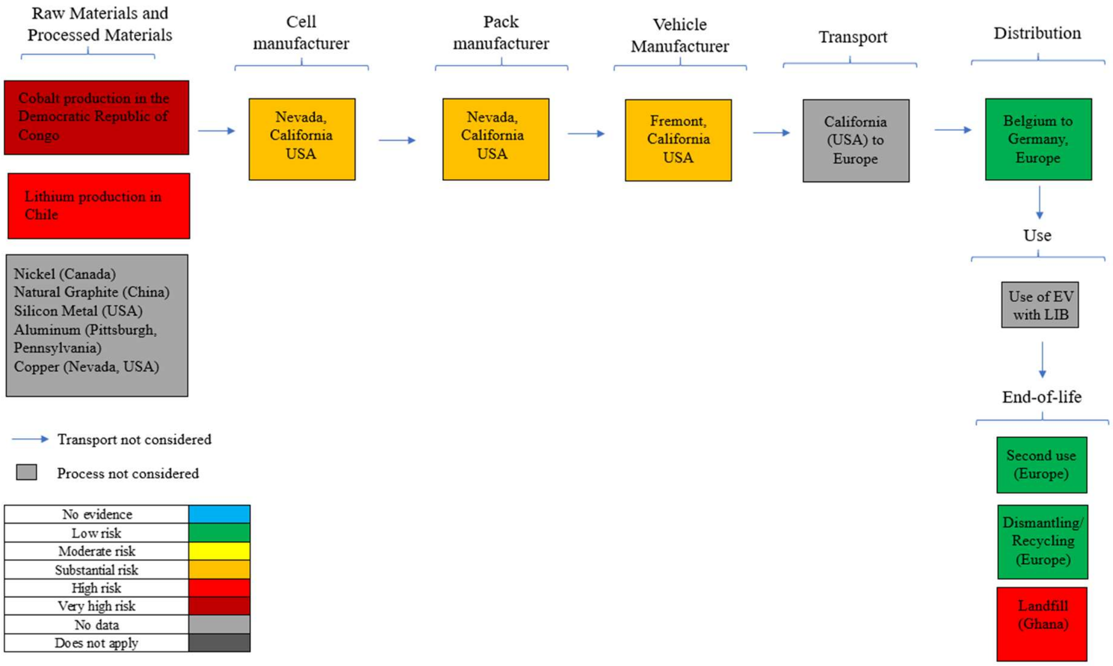


Figure 40: Chain actors with the risk rating

5. Discussion

5.1. Environmental Life Cycle Assessment

This chapter discusses the different environmental impacts across the various stages of cobalt and lithium production of lithium-ion batteries.

The results for the e-LCA for lithium and cobalt production were performed with ReCiPe 2016 Midpoint (H). The impact categories were selected based on the literature review and the higher results obtained on the report generated by the software openLCA. For the chosen categories, cobalt production showed to have a higher impact than lithium production.

For lithium, the results showed that the most significant contributor of impacts for the categories of terrestrial ecotoxicity, human non-carcinogenic toxicity, global warming, water consumption, and mineral resources scarcity for lithium is related to soda production in the Solvay process. The impact on land use was the only impact category for lithium that showed the significant impact related to the lithium brine inspissation; this process involves the salts harvesting and the transposition of them, causing an impact on land use; besides the environmental impact, this category is linked with the social risks for local communities.

The results also showed a more heterogeneous result for cobalt when it becomes the most significant impact contributor among the chosen categories, but all associated with some niche of the mining activity. As previously mentioned, cobalt is usually obtained as a by-product of copper and nickel mining, which implies that its environmental impacts are associated. For the categories terrestrial ecotoxicity and human non-carcinogenic, the major contributor was the copper market, emphasizing this association. The higher impact of cobalt on global warming is due to electricity and cement production needed for mining activities. Following the impacts of mining for water consumption, the major contributor is the gravel and sand quarry operation. Finally, the impact on land use is the treatment of non-sulfidic tailing off-site.

The analysis of these results allowed a better understanding of each stage of both CRM's production that needs improvement. It suggests that a recommendation to lower the environmental impacts on the production of lithium and cobalt would be to implement solutions for the stages that have a higher impact on their value chain; these stages are the Solvay process for lithium and the mining activities for cobalt production.

Circular economy solutions towards a more efficient resource recovery can act as a solution for both cases decreasing the environmental impact on these stages.

5.2. Social Life Cycle Assessment

This chapter discusses the different social impacts across the various stages of Co and Li production of LIBs, the life cycle for the main producers countries and their respective stakeholders.

To complement the e-LCA, an s-LCA was carried out to identify and understand the social risks of lithium and cobalt production. The results for s-LCA identify high social risks within both productions; one central aspect that is important to highlight is that the differences in the mining process and socio-political background of DRC and Chile greatly impacted these results. The highest social risks related to cobalt production in DRC were distributed with similar weight among the stakeholders, with sensitive points more linked to workers and the local community. The lithium production in Chile was assessed with high social risks within the local community. The other life cycle stages, such as the cell/battery manufacturing in the USA and the distribution in Belgium, did not pose any specific social risk. The end-of-life stage was evaluated for three different scenarios: second use, recycling, and landfill; it was assumed that the first two would occur in Belgium, while Germany was suggested for the use, the EoL in Belgium did not pose any social risk as well. On the other hand, it was discussed the likelihood of electronic waste ending up in landfills if EPR were not followed as expected and the consumers were not well guided to what to do with the battery after their use; so, the social risks involved in this stage were evaluated showing expressive social risks connected with this stage.

This study emphasizes the perpetuation of social risks associated with the global power-relations between countries with different socioeconomic scenarios and positions in the market. The market competition, political configuration of countries as the DRC and Ghana collaborates with the preservation of human rights violations such as child labor, fair wages, forced labor, extensive working hours among other types of health and safety risks, especially for workers and the local community. Furthermore, the mining activities in these regions showed how the environmental impacts are directly connected with the challenges of social development affecting the natural resources and, therefore, the local community, specifically in Chile, the indigenous people with water distress.

The comparison of social hotspots across the s-LCA showed that cobalt production presents the highest social risks. First, workers in mining in DRC are socio-economically forced to extensive working hours to have access to basic needs, food, and water. Secondly, they are under pressure for being the leading supplier of most countries globally, being exposed to an intense need to show results. Therefore, in this position, dominated by the low production costs, workers and the local community, especially children, are exposed to different risks.

For lithium production - the second social hotspot in the current study - the social risks are more related to locals' environmental and social effects due to the extensive use of water in the extraction, especially the indigenous community. As a result, social issues, such as water scarcity in local communities and the increasing displacement of local workers from mining jobs have generated an intensification of social activism against lithium mining (Agusdinata et al., 2018).

Regarding CSR, mining companies have focused attention on social development directed to education and guaranteeing children's access to primary school. However, the literature review showed that it is not being successful for DRC. Other less towards initiatives that can help develop economic independence of local communities, such as job training and tourism support. Increasing lithium demand will inevitably enhance Chile's social issues and generate economic dependency on lithium mining in the following decades. Hence, increasing Li-ion battery waste, an issue that will be enhanced as more EVs are produced in the world and as more users choose them in Chile.

Moreover, to the manufacturing stage in the USA, the most sensitive points observed were related to freedom of association and collective bargaining, social security, prevention, and mitigation of armed conflicts. Those results were highly likely related to the historically armed conflicts from the US in general but not specifically to the battery production.

The retail stage in Belgium does not pose any alarming risk in the chain. Belgium was evaluated considering the end of life and not the use phase, showed a higher EoL responsibility when compared to the other option of EoL in Ghana that offered a very high risk not only in the disposal phase but for all stakeholders selected in this study.

The EVs in the EU and the consumption behavior towards what is considered a more sustainable consumption in the transport sector are one of the crucial drivers of environmental and social risks associated with LIBs production in the Global South. While developed countries run with policies to reduce greenhouse gas emissions and push the use of electric vehicles to boost sustainable development to reach that goal, it is questionable the effects of the so-called development.

The mining sector was the principal actor of the DRC economy; however, the civil war and armed conflict boosted informal and artisanal mining, known for overexploiting the workers, children, and local communities in deplorable conditions (World Bank, 2008). In Chile, the mining sector is crucial to expose local communities to a lack of water and basic needs. At the same time, both sectors showed a high risk to workers and local communities, possibly hindering sustainable development in the long term. It is important to emphasize that these ruthless conditions are leaded and accepted by most stakeholders, especially by companies who lack transparency on how their raw materials are being obtained.

The perpetuation of social risks in these countries reinforces the need for CSR with a major focus in these locations. However, despite some improvements in terms of policies and transparency, the progress in the DRC and Chille cannot rely on these terms since they are intrinsic to the socioeconomic structure of these places.

The social risks across the life cycle show that sustainability initiatives fall short of sustainable development in the sector. The results showed the need to know and track the entire supply chain to avoid and mitigate these sensitive points. The assessment emphasize that batteries producing companies should frequently audit the supply chain actors to guarantee that no human rights are being violated and that companies comply with due diligence obligations. Upwards, on-site s-LCAs would be a requirement to do this more accurately.

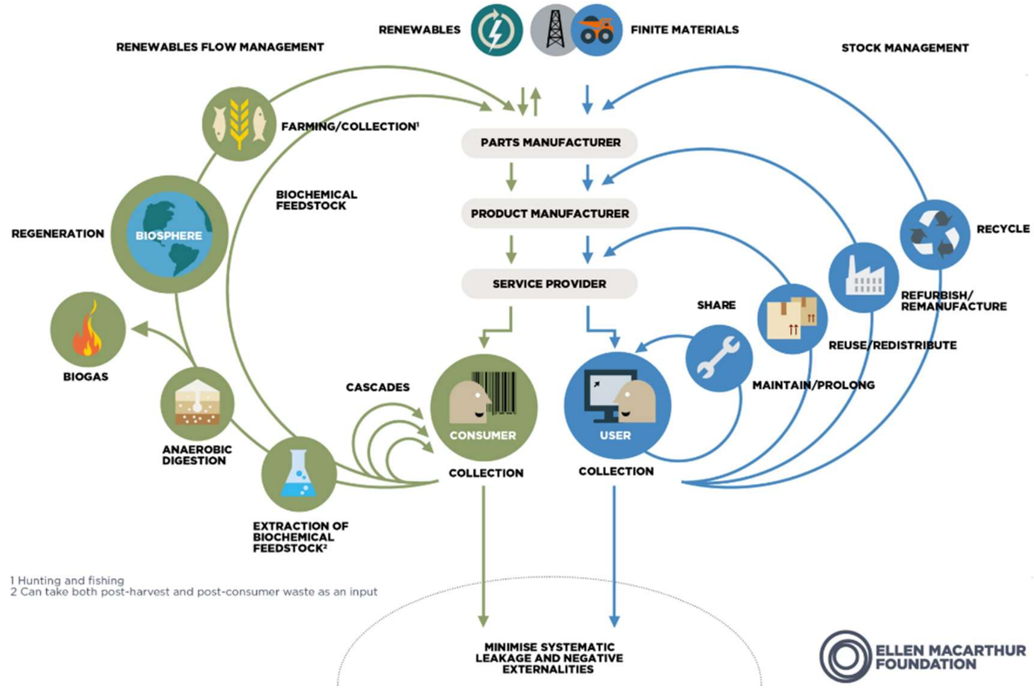
The results showed a need to implement circular strategies to mitigate the problems that will become more evident if the demand for electric cars with lithium batteries increases. Also the monitoring over new circular and recycling technologies within the EU is easier than the management of mining activities outside the EU.

5.3. Circular Economy Approach

The evaluation of the global supply chain of lithium-ion batteries highlighted the need to find a solution for the raw materials production stage and the EoL of lithium-ion batteries to reduce the environmental and social impacts caused by the extraction of lithium and cobalt in Chile and the DRC. With proper technology recoveries at the end of life is possible to decrease the number of raw materials processed and use the resources again in the manufacturing stage.

The possible scenarios for the end-of-life showed a need for a circular economy approach when it comes to batteries, considering that despite efforts to recycle and give a second use to the batteries, there are still challenges that need to be solved, such as preventing the LIBs from ending up in landfills and that dismantling process becomes more practical.

According to the Ellen MacArthur Foundation (2020), CE can be defined as a system that focuses on restoration and regeneration by designing it based on keeping the products/materials in use, designing out waste and pollution. Figure 41 illustrates the “value circle” system defined by the Ellen MacArthur Foundation.



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

Figure 41: Circular economy systems diagram. Source: Ellen MacArthur Foundation (2019).

The Circular Economy approach for LIBs is a topic that was analyzed by more than 3000 researchers in the last decade (Mossali et al., 2020). The CE approach must be implemented in the EoL through the innovative design of products to optimize the disassembly of products; however, it is necessary to analyze the current post-user collection, reuse/redistribute options, refurbish/remanufacture options, recycle, waste handling, landfills, and thermal recovery. With proper metal recovery, the environmental and social risks faced in the raw materials production stage could be avoided.

There are innovative initiatives by some companies and public policies that incentives the EU towards accelerating the transition to a circular economy. On the other hand, CE is insufficient to shift sustainable economic configurations with the several social risks discussed previously. Therefore, a transformative vision is needed towards a Circular Society (CS); this concept is connected to social sustainability and intergenerational social justice, combined with the environment and technology to create a resilient and sustainable society. The main goal of a CS is to establish a participatory, solidary, circular consumption and productions (Research Group Obsolescence, 2021).

To understand how the circular economy approach can play a role in the global value chain of LIBs is necessary to evaluate the right-wing of the butterfly diagram in Figure 41. First, the producer must arrange the collection of used batteries following the EPR to guarantee that the users will receive proper guidance on what to do after using LIBs for EVs, such as assistance to the maintenance of the product.

To overcome the recycling challenge of LIBs from electric vehicles, many policies are being implemented in an EU context by the European Battery Alliance, as briefly explained in chapter 2.4. The most likely option for EoL of batteries from EVs is reusing and remanufacturing for a second life. The residual capacity of LIBs from EVs is approximately 80%, equivalent to 6700 cycles representing a valuable opportunity for second use (Mossali et al., 2020).

Another issue related to the improper EoL briefly discussed is the possibility of LIBs ending up in landfills contaminating soil and groundwater through leaching processes, showing a need for a proper destination. Finally, regarding recycling, the typical recycling process for LIBs is presented in Figure 42.

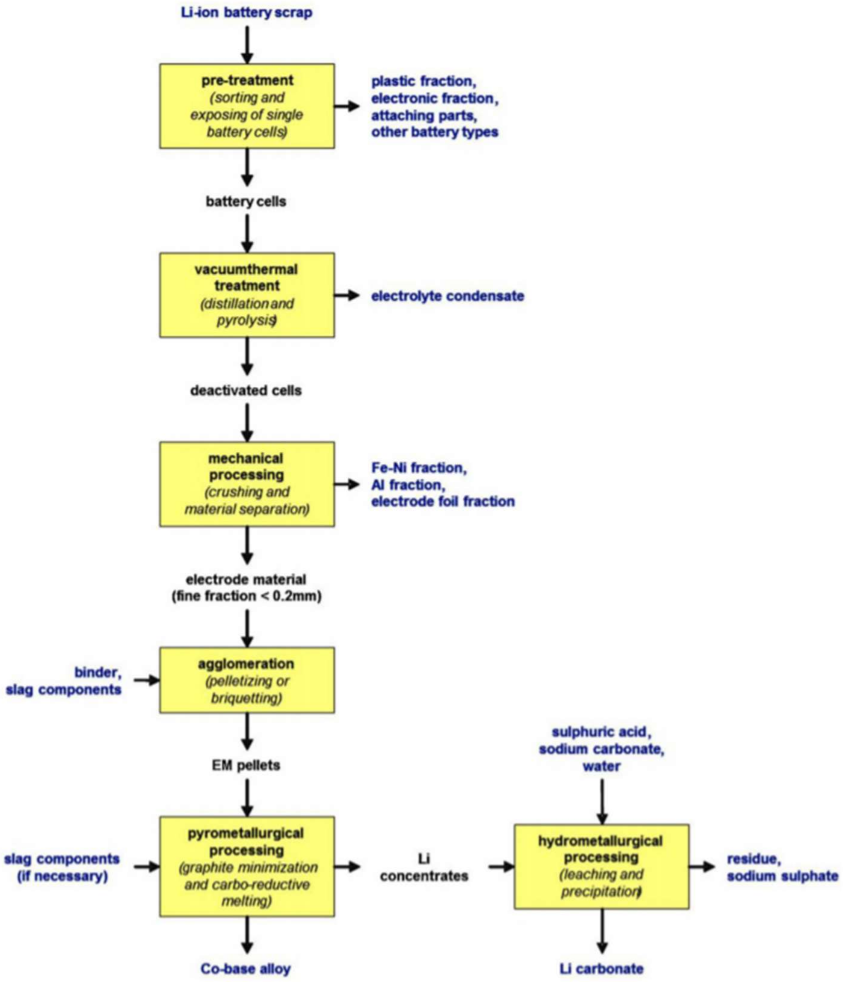


Figure 42:Typical recycling process for lithium-ion batteries. Extracted from Huang et al., 2018.

There are fewer companies in Europe that developed technologies to increase metal recovery from LIBs. This section discusses the different angles from maintain/prolong to waste handling, the recovering technologies that are being applied, and an overview of current policies. Both technologies show possibilities to recover cobalt and lithium, increasing the circularity of batteries.

Umicore

Umicore, a global player in materials technology, applied a process focused on the recovery of cobalt and nickel through the combination of pyro and hydrometallurgical steps (Velázquez-

Martínez et al., 2019). The simplified flowsheets of the processes used by Umicore are presented in Figure 43.

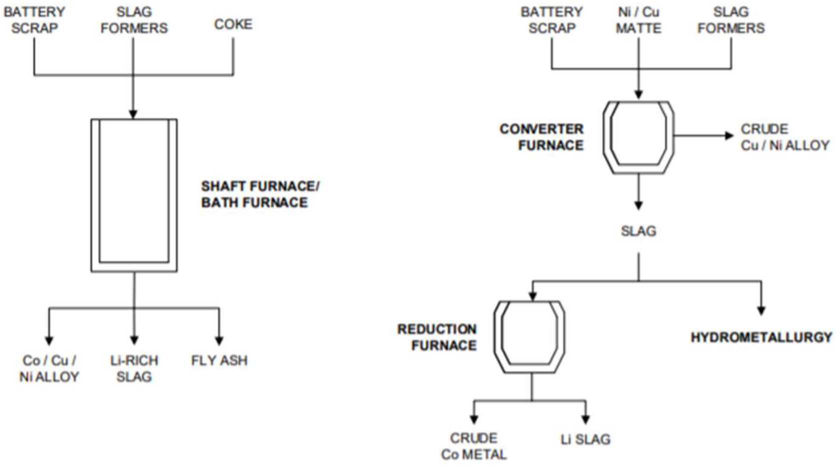


Figure 43: Simplified flowsheets of the process. Extracted from Brückner et al. (2020).

The pyrometallurgical phase converts the waste into three fractions: an alloy containing Co, Ni and Cu; a slag fraction which can be processed to Rare Earth Elements (REE) and refined with Solvay; and clean air that is released after a cleaning process (Umicore, 2020).

The pyrometallurgical step implements an ultra-high temperature (UHT) technology that can treat large volumes of different types of complex metal wastes; it has a higher metal recovery compared to other processes recovering strategics elements such as cobalt and lithium (Umicore, 2020).

The UHT furnace from Umicore is installed in Hoboken, in the Flemish Region of Belgium. It has a capacity of 7,000 metric tons per year, which is equivalent to approximately 35,000 EV batteries (Umicore, 2020).

After this, the hydrometallurgical process is applied to refine and convert the metals into active cathode materials to produce new rechargeable batteries (Umicore, 2020).

Group Renault, Veolia & Solvay

The Renault group is a top automotive player. Veolia is a global leader in resource management, while Solvay's is a global leader in materials, solutions, and chemicals; together, they aim to reduce the environmental footprint of EV batteries. The consortium between these actors with the support of the Ellen MacArthur Foundation was established to create a closed-loop for the EoL battery metals, as shown in Figure 44 (Groupe Renault, 2020 & Solvay, 2020). In addition, they plan to build a recycling plant in France.

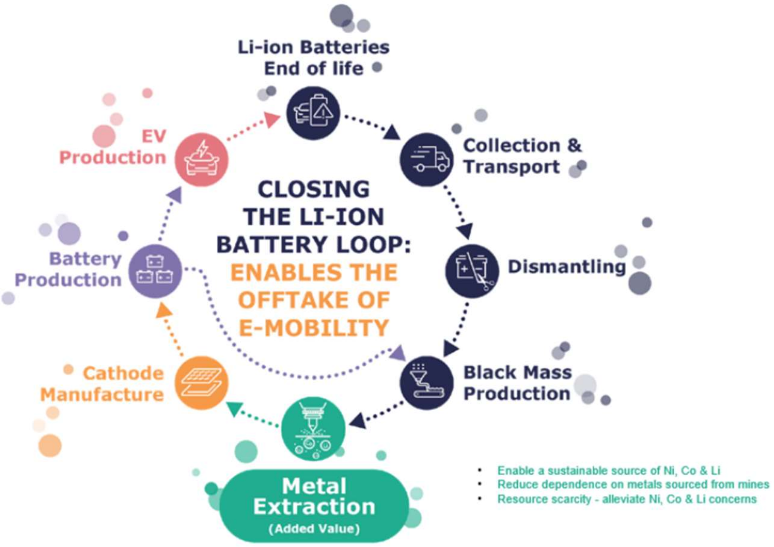


Figure 44: Closing the loop of Li-ion EV batteries. Extracted from Solvay, 2020.

The black mass production, showed in Figure 44, comprises electrode coatings and valuable elements such as cobalt, lithium, nickel, manganese, and graphite. The regular recovering process for this mass is done by hydrometallurgy, where there is a dissolution of the mass followed by chemical separation by precipitation or solvent extraction (Solvay, 2020)

The solution presented is based on an extractant for EV battery metals called CYANEX® 936P; it is a reagent for lithium that can be used to recover valuable metals (Solvay, 2020). The recovery process from a black mass leached liquor (pregnant leach solution – PLS) uses a sequence of solvent extraction circuits, as shown in Figure 45.

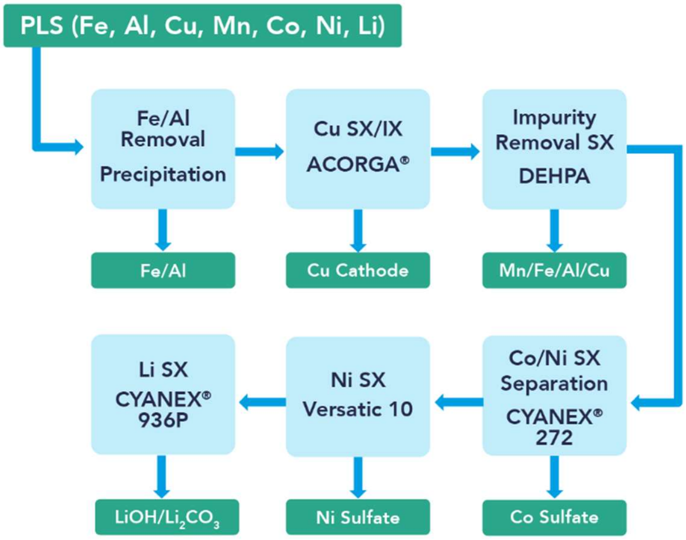


Figure 45: Flow diagram for recovery of value metals from LIBs. Extracted from Solvay, 2020.

European Commission batteries strategies

The report published in December 2020 by the European Technology and Innovation Platform on Batteries proposed three strategies to overcome challenges for 2030. The strategies are divided into three topics:

- Sourcing, sustainability, and traceability of raw materials
- Sustainable extraction and refining of battery-grade raw materials
- Raw Material LCA and material Flow Analysis

The strategies aim to reduce 50% CO_2 emission in lithium extraction and processing compared to the current state of the art; increase 25% in energy efficiency in graphite, battery chemical, and pCAM (precursor cathode active materials). For the third one, EC aims to rely on holistic LCA tools to understand societal sustainability and coherent measurement of the s-LCA (European Commission, 2020).

The CE-based business models that are discussed in this report are shown in Table 6. These projects aim to gain a clear vision of the actions taken for an EU climate-neutral and green recovery plan (European Commission, 2020).

Table 6: Circular Economy objectives and projects. Adapted from European Commission, 2020.

Objective	Projects
Securing a sustainable supply of minerals, base metals, and Critical Raw Materials	- Efficient primary mining - Resource assessment - Mapping of secondary sources and valorization of secondaries
Designing low lifecycle footprint material solutions.	- Design for sustainable recycling - New processes - Standards & eco-labels - Digital platforms
Enabling maximum value usage of products in the economy	- Ageing management and monitor as a service

CEWASTE project

CEWASTE was developed with the support of the European Union within the H2020 program. The project aims to address the challenges faced in the value chain of secondary raw materials from waste that contains valuable CRMs in economically relevant quantities. Furthermore, the project outcomes will contribute to and enhance the network between key players in the EU and improve the raw material recovering from waste (WRFA, 2021).

According to the WRFA (2021), if there will be a pyrometallurgical process, the batteries removed can be treated without dismantling and discharging, then processed in a smelter to reduce metal oxides into a metallic phase or an alloy; after the bullion is transferred to be refined in a hydrometallurgical process. The disassembly must be carried out into cells for hydrometallurgical or mechanical process, followed by shredding or thermally treatment and then shredding; this step will separate powder containing both cathode and anode materials to recover metals like cobalt and lithium. If these elements are economically feasible, they must be recovered, and landfilling should be avoided. All the wastewater from these processes must follow proper treatment. The CEWASTE project also recommends that the recycling process recover a minimum of 90% of cobalt from LIBs (WRFA, 2021).

6. Conclusion

This thesis evaluated the environmental and social risks connected to producing a lithium-ion battery from electric vehicles. To this end, the electric vehicles industry and its global supply chain discrepancies were contextualized within an LCSA methodology. In addition, an environmental and a social life cycle assessment were conducted. This method allowed the investigation of risks related to stakeholders involved in the LCA for lithium and cobalt production and their end of life in evaluating the global supply chain to identify hotspots that need improvements. The LCC was not considered in this study because cost reduction was not a target.

The objectives of this study were to understand the environmental and social risks associated with the production of lithium and cobalt, which bring attention to areas of improvement in their value chain and provide red flags for sequential research.

The contextualization of the global value chain showed that the sensitive aspects of LIBs from EVs are mainly associated with the production of the raw materials and with the end-of-life if the battery is not properly recycled.

Both e-LCA and s-LCA emphasized the need to incorporate a circular approach to minimize the impacts caused by the cobalt and lithium production.

The e-LCA showed the need to improve or find an alternative for soda production and the lithium brine inspissation due to the most significant contribution to the impact categories analyzed. For cobalt, the improvement recommendation is related to the mining activity that is the major contributor in different forms such as gravel and sand quarry operations, electricity and cement production, treatment of non-sulfidic tailing off-site, and activities related to the copper market since cobalt is obtained as a by-product of Cu. These results showed that circular approaches to obtain and recover these raw materials could be a solution to decrease the negative impacts during the production stage.

The s-LCA showed that social hotspots within the global value chain of LIBs are linked to the DRC and Chile. For the first, the results showed a very high risk, and for the latter, between substantial and high risks. It is challenging to assess the risk categories in the DRC due to many factors such as armed conflicts, corruption, and political instability. In Chile, the social impacts are mainly related to the effects on the locals, predominantly indigenous communities. The results also showed that if the collection, recycling, and recovery of the LIB is not made within the EU, there is a very social risk of improper disposal of the e-waste in Ghana.

The many aspects related to these sensitives aspects from the hotspots showed that a circular approach as a recommendation to avoid raw materials production in those countries due to the difficulty in managing all social and environmental risks related to their production outside the EU.

Regarding the EoL, the circular approach within the EU can be a solution due to the management of these activities taking place within the territory of the European Union besides all resource recovery technologies available in the same location. In addition, the implementation of these technologies would decrease the possibility of transboundary management of e-waste, with that overcoming the challenge to audit on-site to check legal compliances in the DRC, Chile and Ghana.

The results informed in this thesis can be incorporated to further research for life cycle management reasons and improve CSR efforts. Further research apart from this thesis can be conduct, such as an LCC to complement the sustainability assessment, on-site research and interviews on the social hotspots identified, and risk assessments.

Notwithstanding, the LCA methodology has several limitations, and it was sensitive to the assumptions made. First, this study is explorative. It is needed to highlight that for some life cycle stages and stakeholders, the information available was limited. Therefore, the outcomes of this thesis must be interpreted carefully. Secondly, the results are a combination of quantitative and qualitative data. Further research is needed to investigate site-specific environmental impacts and social hotspots; this thesis can be used as a foundation for future analysis.

While some improvements and initiatives from the EU are in progress, the life cycle of the assessed lithium-ion battery for EVs is riddled with risks, but, notably, those are being insufficient and/or inefficient in the production sites due to many social, economic, and political aspects. For example, the practices of corruption and armed conflicts often inhibit efforts needed to proceed on site. Furthermore, it is challenging to neutralize the global dynamic that results in the compression of labor rights in the Global South, being more practical and efficient to monitor the procedures that take place within the EU itself, such as the improvement of circular technologies for recovering lithium and cobalt. The following discusses the lessons learned and recommendations.

Lessons Learned and Recommendations

Regarding the environmental aspects, the biggest lesson was the need to find new ways of obtaining or retaining CRMs in the chain because the mining process in the countries evaluated cannot be controlled due to a challenging global dynamic. The efforts from the EU are being made to improve and optimize the obtention of raw materials, and circular economy is one of the solutions that can help move towards a more balanced use of natural resources. Considering the end-of-life stage being in Europe and the risks of this electronic waste face transboundary management, the first recommendation would be to stress the importance of companies to address what consumers should do with their products after they use to improve the recovering rate of these metals from the batteries within the EU and to take advantage of the current incentive policies for circularity of CRMs.

The intrinsic relationship between both sectors, environmental and social, show the importance of integrated approaches to lift the sustainability of products and avoidance of lithium and cobalt scarcities. The recommendation that can help to decrease the overexploitation of CRMs is to focus primarily on the EoL, increasing the circularity of products giving a proper second use, investing in innovative designs and technology that will help the dismantling and recycling, and mainly perform due diligence more frequently through the entire supply chain until the EoL. That is crucial to move towards a circular society. Another lesson learned with the circularity approach was the need to design batteries that can be reused and recycled easily with processes that do not make the dismantling stage even more complicated; this can also be done by decreasing the variety of metals used in the LIB production.

A final recommendation is the significance of the life cycle approach for environmental, social, and economic aspects to act as the foundation for improvements when considering a circular economy approach. Many of the existing initiatives of EVs mainly focused on the environmental impacts during the use phase. However, when the whole supply chain is assessed, it is understandable that electric vehicles are still far from a truly socially sustainable substitute for fossil fuel vehicles. This research has thus emphasized the need for a look beyond the unique environmental impact segment. Only with complete assessment will consumers be informed about the sustainability of a product and make a purchasing decision based on the transparency of the information available.

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8. Appendixes

Appendix I – List of Critical Raw Materials of 2020 by European Commission

Raw materials	**Stage**	**Main global producers**	**Main EU sourcing[33] countries**	**Import reliance[34]**	**EoL-RIR[35]**	**Selected Uses**
Antimony	Extraction	China (74%) Tajikistan (8%) Russia (4%)	Turkey (62%) Bolivia (20%) Guatemala (7%)	100%	28%	• Flame retardants • Defence applications • Lead-acid batteries
Baryte	Extraction	China (38%) India (12%) Morocco (10%)	China (38%) Morocco (28%) Other EU (15%) Germany (10%) Norway (1%)	70%	1%	• Medical applications • Radiation protection • Chemical applications
Bauxite	Extraction	Australia (28%) China (20%) Brazil (13%)	Guinea (64%) Greece (12%) Brazil (10%) France (1%)	87%	0%	• Aluminium production
Beryllium	Extraction	United States (88%) China (8%) Madagascar (2%)	n/a	n/a36	0%	• Electronic and Communications Equipment • automotive, aero-space and defence components
Bismuth	Processing	China (85%) Lao Pdr (7%) Mexico (4%)	China (93%)	100%	0%	• Pharmaceutical and animal feed industries • Medical applications • Low-melting point alloys
Borate	Extraction	Turkey (42%) United States (24%) Chile (11%)	Turkey (98%)	100%	1%	• High performance glass • Fertilisers • Permanent magnets
Cobalt	Extraction	Congo DR (59%) China (7%) Canada (5%)	Congo DR (68%) Finland (14%) French Guiana (5%)	86%	22%	• Batteries • Super alloys • Catalysts • Magnets
Coking coal	Extraction	China (55%) Australia (16%) Russia (7%)	Australia (24%) Poland (23%) United States (21%) Czechia (8%) Germany (8%)	62%	0%	• Coke for steel • Carbon fibres • Battery electrodes

Raw materials	Stage	Main global producers	Main EU sourcing[33] countries	Import reliance[34]	EoL-RIR[35]	Selected Uses
Fluorspar	Extraction	China (65%) Mexico (15%) Mongolia (5%)	Mexico (25%) Spain (14%) South Africa (12%) Bulgaria (10%) Germany (6%)	66%	1%	• Steel and iron making • Refrigeration and Air-conditioning • Aluminium making and other metallurgy
Gallium	Processing	China (80%) Germany (8%) Ukraine (5%)	Germany (35%) UK (28%) China (27%) Hungary (2%)	31%	0%	• Semiconductors • Photovoltaic cells
Germanium	Processing	China (80%) Finland (10%) Russia (5%)	Finland (51%) China (17%) UK (11%)	31%	2%	• Optical fibres and Infrared optics • Satellite solar cells • Polymerisation catalysts
Hafnium	Processing	France (49%) United States (44%) Russia (3%)	France (84%) United States (5%) UK (4%)	0%[37]	0%	• Super alloys • Nuclear control rods • Refractory ceramics
Indium	Processing	China (48%) Korea, Rep. (21%) Japan (8%)	France (28%) Belgium (23%) UK (12%) Germany (10%) Italy (5%)	0%	0%	• Flat panel displays • Photovoltaic cells and photonics • Solders
Lithium	Processing	Chile (44%) China (39%) Argentina (13%)	Chile (78%) United States (8%) Russia (4%)	100%	0%	• Batteries • Glass and ceramics • Steel and aluminium metallurgy
Magnesium	Processing	China (89%) United States (4%)	China (93%)	100%	13%	• Lightweight alloys for automotive, electronics, packaging or construction • Desulphurisation agent in steelmaking
Natural Graphite	Extraction	China (69%) India (12%) Brazil (8%)	China (47%) Brazil (12%) Norway (8%) Romania (2%)	98%	3%	• Batteries • Refractories for steelmaking

Raw materials	**Stage**	**Main global producers**	**Main EU sourcing[33] countries**	**Import reliance[34]**	**EoL-RIR[35]**	**Selected Uses**
Natural Rubber	Extraction	Thailand (33%) Indonesia (24%) Vietnam (7%)	Indonesia (31%) Thailand (18%) Malaysia (16%)	100%	1%	• Tires • Rubber components for machinery and household goods
Niobium	Processing	Brazil (92%) Canada (8%)	Brazil (85%) Canada (13%)	100%	0%	• High-strength steel and super alloys for transportation and infrastructure • High-tech applications (capacitors, superconducting magnets, etc.)
Phosphate rock	Extraction	China (48%) Morocco (11%) United States (10%)	Morocco (24%) Russia (20%) Finland (16%)	84%	17%	• Mineral fertilizer • Phosphorous compounds
Phosphorus	Processing	China (74%) Kazakhstan (9%) Vietnam (9%)	Kazakhstan (71%) Vietnam (18%) China (9%)	100%	0%	• Chemical applications • Defence applications
Scandium	Processing	China (66%) Russia (26%) Ukraine (7%)	UK (98%) Russia (1%)	100%	0%	• Solid Oxide Fuel Cells • Lightweight alloys
Silicon metal	Processing	China (66%) United States (8%) Norway (6%) France (4%)	Norway (30%) France (20%) China (11%) Germany (6%) Spain (6%)	63%	0%	• Semiconductors • Photovoltaics • Electronic components • Silicones
Strontium	Extraction	Spain (31%) Iran, Islamic Rep. (30%) China (19%)	Spain (100%)	0%	0%	• Ceramic magnets • Aluminium alloys • Medical applications • Pyrotechnics
Tantalum	Extraction	Congo, DR (33%) Rwanda (28%) Brazil (9%)	Congo, DR (36%) Rwanda (30%) Brazil (13%)	99%	0%	• Capacitors for electronic devices • Super alloys
Titanium[38]	Processing	China (45%) Russia (22%) Japan (22%)	n/a	100%	19%	• Lightweight high-strength alloys for e.g. aeronautics, space and defence • Medical applications

Raw materials	**Stage**	**Main global producers**	**Main EU sourcing[33] countries**	**Import reliance[34]**	**EoL-RIR[35]**	**Selected Uses**
Tungsten[39]	Processing	China (69%) Vietnam (7%) United States (6%) Austria (1%) Germany (1%)	n/a	n/a	42%	• Alloys e.g. for aeronautics, space, defence, electrical technology • Mill, cutting and mining tools
Vanadium[40]	Processing	China (55%) South Africa (22%) Russia (19%)	n/a	n/a	2%	• High-strength-low-alloys for e.g. aeronautics, space, nuclear reactors • Chemical catalysts
Platinum Group Metals[41]	Processing	South Africa (84%) - iridium, platinum, rhodium, ruthenium Russia (40%) - palladium	n/a	100%	21%	• Chemical and automotive catalysts • Fuel Cells • Electronic applications
Heavy Rare Earth Elements[42]	Processing	China (86%) Australia (6%) United States (2%)	China (98%) Other non-EU (1%) UK (1%)	100%	8%	• Permanent Magnets for electric motors and electricity generators • Lighting Phosphors • Catalysts • Batteries • Glass and ceramics
Light Rare Earth Elements	Processing	China (86%) Australia (6%) United States (2%)	China (99%) UK (1%)	100%	3%	

Appendix II - Number of electric cars per country in December 2020

Country	Battery electric vehicels	Plug-in hybrid electric vehicles	Battery electric vehicels	Plug-in hybrid electric vehicles	Total	Total registrations
Germany	60192	43370	1.72	1.24	103562	-
Norway	60008	19226	42.41	13.59	79234	141.496
United Kingdom	37724	35193	1.64	1.53	72917	-
Netherlands	58767	4561	14.9	1.16	63328	394.502
France	43678	18359	1.9	0.8	62037	-
Sweden	15570	24810	4.46	7.11	40380	348.931
Spain	10209	7451	0.76	0.55	17660	-
Belgium	8630	8937	1.58	1.64	17567	545.799
Italy	10643	6110	0.56	0.32	16753	-
Portugal	6880	5773	3.1	2.6	12653	222.033
Austria	9077	2156	2.77	0.66	11233	327.823
Denmark	5478	3754	2.46	1.69	9232	222.562
Finland	1887	5864	1.73	5.38	7751	108.924
Ireland	3451	1362	2.94	1.16	4813	117.369
Hungary	1623	748	1.15	0.53	2371	141.148
Poland	1443	891	0.27	0.17	2334	532.62
Iceland	913	1204	7.99	10.53	2117	11.43
Romania	1503	400	0.94	0.25	1903	160.622
Luxembourg	962	907	1.79	1.68	1869	53.878
Czechia	660	513	0.27	0.21	1173	242.019
Slovenia	628	167	0.9	0.24	795	70.088
Cyprus	8	581	0.07	4.84	589	12.002
Slovakia	170	399	0.17	0.39	569	101.145
Greece	188	288	0.16	0.25	476	114.166
Bulgaria	293	70	0.87	0.21	363	33.509
Malta	205	48	2.68	0.63	253	7.659
Croatia	155	81	0.25	0.13	236	62.052
Lithuania	158	58	0.35	0.13	216	44.81
Estonia	77	26	0.28	0.1	103	27.219
Latvia	87	9	0.52	0.05	96	16.596
Switzerland	13197	22513	4.22	7.19	35710	312902

Source: Extracted from European Environment Agency, 2020.

Appendix III – Indicators, reference points, basis for evaluation, and rating criteria

Workers					
Risk category	**Indicator**	**Reference points**	**Basis for reference**	**Basis for evaluation**	**Rating scale**
Fair salary	Living wage in relation to minimum wage	The wages should guarantee the basic needs	ILO standards, UNEP methodology sheets	Combining information on average, minimal, and living wages	Coverage of family (2 adults and 2 children with 1 income) living wage: 1: > 90% 2: 90 -75% 3: 74 -50% 4: 49- 25% 5: < 25 %
	Description of payment performance	Payments should not delay and must be paid as planned	ILO standards, UNEP methodology sheets	Evaluated based on narrative reports	1: no risks reported 2: some generic risks reported 3: presence of risks reported 4: high risks reported as common practice 5: very high risk reported by multiple sources
Hours of work	Average weekly working hours per employee	Employee cannot work more than an average 48 hours a week	ILO standards, UNEP methodology sheets	Based on narrative reports and ILO country statistics	1: < 38h per week 2: 38-43 h per week 3: 44-48h per week 4: 49-53 h per week 5: > 53 h per week
	Description of working (over-) time practices	At least one day off per week, working more than 48 hours must be considered exceptional, be remunerated and can not be more than 12 hours.	ILO standards, UNEP methodology sheets	Evaluated based on narrative reports	1: compliance with regulation reported 2: some generic risks reported 3: presence of risks reported 4: high risks reported as common practice 5: very high risk reported by multiples sources
Health and safety	Description of potential dangers to health and safety & wheter appropriate safety measures are taken	Risks must be avoided, and general safety conditions must be followed.	ILO standards, ISO 26000, UNEP methodology sheets	Evaluated based on narrative reports	1: no risks reported 2: some generic risk reported 3: presence of risks reported 4: presence of high risk reported due to lack of appropriate safety measures 5: very high risk reported due to gross negligence and failure to provide basic safety measures
Freedom of association and collective bargaining	Workers Rights Index by ITUC	Workers rights must be guaranteed, they should be allowed to engage in collective baragaining and organize themselves to protest for their rights.	ILO standards, OECD Guidelines for Multinational Enterprises, UN Global Compact	International Trade Union Confederation, Global Rights Index	1: Rating 1: “Sporadic violations of rights” 2: Rating 2: “Repeated violations of rights” 3: Rating 3: “Regular violations of rights” 4: Rating 4: “Systematic violations of rights” 5: Rating 5: “No guarantee of rights”
	Description of the situation of trade unions & their members	Workers should be ablte to organize themselves without interference and sanctions	ILO standards, UNEP methodology sheets, OECD Guidelines for Multinational Enterprises, UN Global Compact	Evaluated based on narrative reports	1: provision of worker’s rights is largely reported as given 2: some generic risks reported 3: clear presence of risks reported 4: high risks reported as common practice 5: very high risk reported by multiple sources

Extracted from Rupp (2020)

Workers					
Risk category	**Indicator**	**Reference points**	**Basis for reference**	**Basis for evaluation**	**Rating scale**
Social benefits/social security	Presence of social protection for workers	Medical insurance, pensions and social security should be provided to workers	ILO standards, UNEP methodology sheets	Combination of various social security coverage indicators provided in ILO country statistics	According to availability, indicators are combined to a rough estimation: 1: > 90 % coverage in most categories 2: 90- 75 % coverage in most categories 3: 74-50 % coverage in most categories 4: 49-25% coverage in most categories 5: < 25% coverage in most categories
Child labor	Occurrence of child labor	Child labor should not occur. According to the ILO, children are allowed to work with some economic activities and household chores as long as it does not affects their studies or poise any harms to them	ILO standards, UNEP methodology sheets, OECD Guidelines for Multinational Enterprises, UN Global Compact	ILO country statistics & U.S. Department of Labor's List of Goods Produces by Child Labor or Forced Labor	1: No risks for child labour reported 2: < 5% 3: 5-10 % and/or listed 4: 11-15% and/or listed 5: > 15% and/or listed
	Description of occurrence and kind of child labor		ILO standards, UNEP methodology sheets, OECD Guidelines for Multinational Enterprises, UN Global Compact	Evaluated based on narrative reports	1: no risks reported 2: some generic risks reported 3: clear presence of risks reported 4: high risks reported as common practice 5: very high risk reported by multiple sources
Forced labor	Description of occurrence and kind of forced labor	According to the ILO, fored labor should not occur.	ILO standards, UNEP methodology sheets, OECD Guidelines for Multinational Enterprises, UN Global Compact	Evaluated based on narrative reports	1: no risks reported 2: some generic risks reported 3: clear presence of risks reported 4: high risks reported as common practice 5: very high risk reported by multiple sources
Equal opportunities/ discriminatiion	Description of discrimination	Workers should not be discrimated based on sex, age, race, religion, political opinion, national or ethnic origin, or any other individual or group characteristic unrelated to ability	ILO standards, UN Declaration on Human Rights, OECD Guidelines for Multinational Enterprises, UN Global Compact, UNEP methodology sheets	Evaluated based on narrative reports	1: anti-discrimination regulations generally enforced 2: some risks reported 3: clear presence of risks reported 4: high risks reported of structural discrimination as common practices 5: very high risk reported of structural discrimination with tangible adverse effects on workers, reported by multiple sources
	Gender Inequality Index	Women should not be discriminated based on gender	ILO standards, UN Declaration on Human Rights, OECD Guidelines for Multinational Enterprises, UN Global Compact, UNEP methodology sheets	Social Institutions & Gender Index (SIGI); developed by the OECD; (100% = very high discrimination & countries are classified in 5 categories)	1: SIGI rating < 20 %: very low 2: SIGI rating 20-30%: low 3: SIGI rating 31-40%: medium 4: SIGI rating 41-50%: high 5: SIGI rating > 50%: very high
	Description of Gender Discrimination	Women should not be discriminated based on gender	ILO standards, UN Declaration on Human Rights, OECD Guidelines for Multinational Enterprises, UN Global Compact, UNEP methodology sheets	Evaluated based on narrative reports	1: no risks reported 2: some risks reported 3: clear presence of risks reported 4: high risks reported of structural discrimination as common practices 5: very high risk reported of structural discrimination with tangible adverse effects on workers, reported by multiple sources

Extracted from Rupp (2020)

Workers

Risk category	Indicator	Reference points	Basis for reference	Basis for evaluation	Rating scale
Informality	Rate of Informality	Higher informality indicates higher social risks. This status generally affects negatively social benefits, job and income security.	The ILO Department of statistics see this indicator as a crucial addition to evaluate employment quality	ILO country statistics	1: < 10% 2: 10-25% 3: 26-50 % 4: 51-75% 5: > 75%

Local Community

Risk category	Indicator	Reference points	Basis for reference	Basis for evaluation	Rating scale
Cultural heritage & discrimination	Description of potential infrigement or adverse risks vis-à-vis cultural heritage	All practices, knowledge, traditional craftsmanship, cultural spaces and objects should be respected	UN Declaration on Human Rights, ILO conventions, Universal Declaration on Cultural Diversity, UNEP methodology sheets	Evaluated based on narrative reports	1: no risks reported 2: some generic risks reported 3: clear presence of risks reported 4: high risks reported clearly 5: very high risk reported by multiple sources
Local employment	Description of dynamics of local and migrants	Economic activies should support local employment	ISO 26000, ILO conventions, OECD Guidelines for Multinational Enterprises, UNEP methodology sheets	Evaluated based on narrative reports	1: no risks reported 2: some generic risks reported 3: clear presence of risks reported, e.g. with regards to high levels of migrant workers 4: high risks reported clearly 5: very high risk reported by multiple sources
Safe and healthy living conditions	Description of pollution dynamics	The health of the local community shoult not be affected by the activities. Environmental pollution should be mitigated and avoided	UN Declaration on Human Rights, ISO 26000, UNEP methodology sheets	Evaluated based on narrative reports that considers pollution levels (water, air and soil)	1: no pollution reported 2: pollution reported as elevated 3: elevated pollution levels reported 4: high risk for pollution reported as in already high polluted areas 5: very high risk for pollution reported by multiple sources in already high polluted areas
	Burden of disease in the country	The health of the local community shoult not be affected by the activities. Environmental pollution should be mitigated and avoided	UN Declaration on Human Rights, ISO 26000, UNEP methodology sheets	Disability-Adjusted Life Years (DALY); expresses overall disease burden, in number of years lost due to ill, health, disability or early death	1: DALY < 15 2: DALY 15 - 25 3: DALY 26 - 35 4: DALY 36- 45 5: DALY > 45
Acess to material resources	Description of dynamics of resource depletion and environmental burden	Natural resources should not be overexploited	UN Declaration on Human Rights, ISO 26000, ISO 14000, OECD Guidelines for Multinational Enterprises, UN Global Compact, UNEP methodology sheets	Evaluated based on narrative reports	1: no connection to resource decline reported 2: generic risk of contribution to declining access to resources 3: clear substantial risk of contribution to declining access to resources 4: high risk for resource scarcity reported 5: very high risk for resource scarcity reported by multiple sources
	Description of potential material resource conflicts	The access to material resources from the local communities should be respected and protected. In the case of depletion, risk assessments should be carried	UN Declaration on Human Rights, ISO 26000, ISO 14000, OECD Guidelines for Multinational Enterprises, UN Global Compact, UNEP methodology sheets	Evaluated based on narrative reports	1: no risks reported 2: some generic risks reported 3: clear presence of risks reported 4: high risks reported 5: very high risk reported by multiple sources

Extracted from Rupp (2020)

Local Community

Risk category	Indicator	Reference points	Basis for reference	Basis for evaluation	Rating scale
Delocalization & migration	Description of migration or displacement	Dislocation or migration movement should not occur. In case of siplacemente, compensation needs to be provided	UNEP methodology sheets	Evaluated based on narrative reports	1: no risks reported 2: some generic risks reported 3: clear presence of risks reported 4: high risks reported 5: very high risk reported by multiple sources
Access to immaterial resources	Human Freedom Index	Access and rights to immaterial resources should be respected and ensured, such as freedom of expression, protest and acess to information	UNEP methodology sheets	Human Freedom Index, includes freedom of expression, press and the rights to protest (scale of 0 - 10; with 10 = more freedom)	1: Index rating >9 2: Index rating 9-8 3: Index rating 7-6 4: Index rating 5-4 5: Index rating < 4
	Description of issues regarding rights to free expression, press or right to protest	Access and rights to immaterial resources should be respected and ensured, such as freedom of expression, protest and acess to information	UNEP methodology sheets	Evaluated based on narrative reports	1: no risks reported 2: some generic risks reported 3: clear presence of risks reported 4: high risks reported of systematic violation rights 5: very high risk reported of systematic violation of rights by multiple sources
Respecting indigenous rights	Description of rights violation and discrimination faced by indigenous	Indigenous rights should be respected and protected	UN Declaration on Human Rights, Indigenous Rights, ILO conventions, UN Declaration on the Rights of Indigenous People	Evaluated based on narrative reports	1: no risks reported 2: some generic risks reported 3: clear presence of risks reported 4: high risks reported of systematic violation rights 5: very high risk reported of systematic violation of rights by multiple sources

Business owners

Risk category	Indicator	Reference points	Basis for reference	Basis for evaluation	Rating scale
Supplier relationships	Description of dynamics of supplier relationships	Supplier relationships should include fair procurement practices	UNEP methodology sheets	Evaluated based on narrative reports	1: fair relationships reported 2: some generic risks reported 3: clear presence of risks reported due to power asymmetries 4: high risks reported 5: very high risk reported with tangible adverse impacts, reported by multiple sources
Due diligence/social responsibility	Description of due diligence/social responsibility practices (towards the actor by downstream)	Compliance with social standards should be ensured. Investigations shoud be carried to assess potential negative social impacts	OECD Guidelines for Multinational Enterprises, ISO 26000, UNEP methodology sheets	Evaluated based on narrative reports & availability of sustainability reports, codes of conduct, etc	1: due diligence systematically and effectively fulfilled 2: some shortcomings reported 3: clearly insufficient due diligence practices reported 4: high risks that due diligence obligations are not fulfilled 5: very high risk reported by multiple sources

Extracted from Rupp (2020)

Consumer

Risk category	Indicator	Reference points	Basis for reference	Basis for evaluation	Rating scale
Transparency	Description of sustainability transparency	Products and social responsibility of products should be provided to support a conscious consumer choice	ISO 26000, OECD Guidelines for Multinational Enterprises, UNEP Methodology sheets	Evaluated based on narrative reports	1: transparency largely given 2: generic risks for lack of transparency 3: specific clear risk for lack of transparency 4: high risk for lack of transparency 5: very high risk reported of systematic misinformation by multiple sources
End-of-life responsibility	Description of end of life responsibility practices	Consumers should be provided with information about appropriate end-of-life options	UNEP methodology sheets	Evaluated based on narrative reports	1: end-of-life responsibilities are reportedly fulfilled 2: end-of-life responsibility is largely fulfilled with minor shortcomings 3: end of life-cycle responsibilities are clearly insufficiently fulfilled 4: end-of-life responsibility is not given 5: end-of-life responsibilities are grossly ignored with dangerous tangible effect

Society

Risk category	Indicator	Reference points	Basis for reference	Basis for evaluation	Rating scale
Prevention and mitigation of conflicts	Description of risk of conflicts	Risks for conflicts or conflict involvement (e.g. due to resource depletion, pollution or poor working standards) should be minimised and prevented	UNEP methodology sheets	Evaluated based on narrative reports	1: no risks reported 2: some risks reported for minor conflicts 3: clear presence of risks for conflicts reported 4: recurring conflicts reported 5: recurring grave conflicts reported by multiple sources
	Presence of conflict in the country	Risks for conflicts or conflict involvement (e.g. due to resource depletion, pollution or poor working standards) should be minimised and prevented	UNEP methodology sheets	Global Peace Index (GPI), & score for domestic and internal conflict; scale from 0-5 (5 = less peaceful)	1: Index rating: < 1,5 2: Index rating: 1,5-2 3: Index rating: 3 4: Index rating: 4 5: Index rating > 4
Contribution to sustainable development	Description of risks to sustainable development	Companies should contribute to sustainable development, meaning foster productive and inclusive economic relations and minimizing the environmental burden	Framework of sustainable development e.g. United Nations Sustainable Development Goals	Evaluated based on narrative reports	1: no risks reported 2: some risks reported of adverse effects on sustainable development 3: substantial risks reported that inclusive sustainable development 4: high risks reported of clear adverse effects on sustainable development 5: very high risks reported of grossenvironmental and social drawbacks to sustainable development
Corruption	Corruption Index	Corruption should not occur and be prevented	ISO 26000, OECD Guidelines for Multinational Enterprises, UN Global Compact	Transparency international: Corruption Perceptions Index (100% = no corruption)	1: Index rating > 90 2: Index rating 90-75 3: Index rating 74-50 4: Index rating 49-25 5: Index rating < 25
	Description of corruption risks	Corruption should not occur and be prevented	ISO 26000, OECD Guidelines for Multinational Enterprises, UN Global Compact	Evaluated based on narrative reports	1: no risks reported 2: general risks for corruption reported 3: direct reports about corruption 4: recurring reports about corruption 5: recurring reports about large scale corruption

Extracted from Rupp (2020)

Appendix IV - Inputs and outputs to produce lithium and cobalt

INPUTS - COBALT PRODUCTION

Flow	Flow property	Unit	Amount	Description
aluminium hydroxide factory	Number of items	Item(s)	9E-10	EcoSpold01Location=RER
blasting	Mass	kg	0.166	EcoSpold01Location=RER
carbon monoxide	Mass	kg	0.072902166	EcoSpold01Location=RER
carbon monoxide	Mass	kg	0.219097834	EcoSpold01Location=RER
cement, alternative constituents 21-35%	Mass	kg	3.241020079	Proxy: approximation with data from nickel mining
cement, alternative constituents 21-35%	Mass	kg	0.002859776	Proxy: approximation with data from nickel mining
cement, alternative constituents 21-35%	Mass	kg	0.376120145	Proxy: approximation with data from nickel mining
chemical, inorganic	Mass	kg	0.085	EcoSpold01Location=GLO
chemical, organic	Mass	kg	0.025	Proxy: approximation with data from nickel mining
Cobalt, in ground	Mass	kg	1.32	Proxy: approximation with data from nickel mining
conveyor belt	Length	m	0.0000042	Proxy: approximation with data from nickel mining
diesel, burned in building machine	Energy	MJ	12.1	Proxy: approximation with data from nickel mining
electricity, medium voltage	Energy	kWh	4.69	EcoSpold01Location=UCTE
heat, district or industrial, natural gas	Energy	MJ	2	EcoSpold01Location=RER
hydrogen cyanide	Mass	kg	0.00393	EcoSpold01Location=RER
hydrogen, liquid	Mass	kg	0.003744178	Stoechiometric calculation: for further treatment it is assumed a reduction with 50% carbon monoxide and 50% hydrogen.
hydrogen, liquid	Mass	kg	0.017055822	
lime, packed	Mass	kg	0.049579156	Proxy: approximation with data from nickel mining
lime, packed	Mass	kg	0.000420844	Proxy: approximation with data from nickel mining
mine infrastructure, underground, non-ferrous metal	Number of items	Item(s)	5.5E-09	Proxy: approximation with data from nickel mining
non-sulfidic overburden, off-site	Mass	kg	-34.9	EcoSpold01Location=GLO
non-sulfidic tailing, off-site	Mass	kg	-65	EcoSpold01Location=GLO
sand	Mass	kg	45.6	Proxy: approximation with data from nickel mining
Water, river, GLO	Volume	m3	0.038	Proxy: approximation with data from nickel mining
Water, well, GLO	Volume	m3	0.22	Proxy: approximation with data from nickel mining

OUTPUTS - COBALT PRODUCTION

Flow	Flow property	Unit	Amount	Description
Aluminium	Mass	kg	0.000019	Proxy: approximation with data from nickel mining
Arsenic, ion	Mass	kg	0.000000649	Proxy: approximation with data from nickel mining
BOD5, Biological Oxygen Demand	Mass	kg	0.0046	Calculated value: calculated as 0.5*COD.
Cadmium, ion	Mass	kg	6.96E-08	Proxy: approximation with data from nickel mining
Calcium, ion	Mass	kg	0.151	Proxy: approximation with data from nickel mining
Carbon disulfide	Mass	kg	0.011	Proxy: approximation with data from nickel mining
Chromium, ion	Mass	kg	0.000000121	Proxy: approximation with data from nickel mining
cobalt	Mass	kg	1	EcoSpold01Location=GLO
Cobalt	Mass	kg	0.000000172	Proxy: approximation with data from nickel mining
COD, Chemical Oxygen Demand	Mass	kg	0.0023	Proxy: approximation with data from nickel mining
Copper, ion	Mass	kg	0.00000175	Proxy: approximation with data from nickel mining
Cyanide	Mass	kg	0.000412	Proxy: approximation with data from nickel mining
Dissolved solids	Mass	kg	0.00114	Proxy: approximation with data from nickel mining
DOC, Dissolved Organic Carbon	Mass	kg	0.000851852	Calculated value: Calculated by default as DOC (gC) = COD/2.7 (COD measured in g O2).
Iron, ion	Mass	kg	0.000064	Proxy: approximation with data from nickel mining
Lead	Mass	kg	0.000000616	Proxy: approximation with data from nickel mining
Manganese	Mass	kg	0.00000544	Proxy: approximation with data from nickel mining
Mercury	Mass	kg	8.3E-09	Proxy: approximation with data from nickel mining
Nickel, ion	Mass	kg	0.00000536	Proxy: approximation with data from nickel mining
Nitrogen	Mass	kg	0.00502	Proxy: approximation with data from nickel mining
Particulates, < 2.5 um	Mass	kg	0.00197	Proxy: approximation with data from nickel mining
Particulates, > 10 um	Mass	kg	0.0203	Proxy: approximation with data from nickel mining
Particulates, > 2.5 um, and < 10um	Mass	kg	0.0177	Proxy: approximation with data from nickel mining
Sulfate	Mass	kg	0.519	Proxy: approximation with data from nickel mining
TOC, Total Organic Carbon	Mass	kg	0.000851852	Calculated value: Calculated by default as TOC (gC) = COD/2.7 (COD measured in g O2).
Water	Mass	kg	38.7	Calculated value based on literature values and expert opinion.
Water, GLO	Volume	m3	0.2193	Calculated value based on literature values and expert opinion.
Zinc, ion	Mass	kg	0.0000168	Proxy: approximation with data from nickel mining

INPUTS - LITHIUM PRODUCTION				
Flow	**Flow property**	**Unit**	**Amount**	**Description**
2-methyl-2-butanol	Mass	kg	0.000545	Average value based on 3 reports (according to personal communication, SQM 2010): (Report 1) SQM, 2007: Informe consolidado de la evaluacion de Impacto Ambiental de la declaracion de Impacto Ambiental del Proyecto 'Ampliacion Planta Carbonato de litio a 48'000 ton/año' RCA 164/07 (Report 2) SQM, 1996: Informe consolidado de la evaluacion de Impacto Ambiental de la declaracion de Impacto Ambiental del Proyecto 'Ampliacion Planta Carbonato de litio a 17'500 ton/año' RCA 381/96 (Report 3) SQM, 2001: Informe consolidado de la evaluacion de
activated bentonite	Mass	kg	0.0144	Value based on SQM (2007).
chemical factory, organics	Number of items	Item(s)	4E-10	Calculated based on literature data published by the industry. For this activity, no information was readily available concerning infrastructure and land-use. Therefore, the infrastructure is estimated based on data from two chemical factories, the BASF site of Ludwigshafen and the chemical factory in Gendorf (which are both located in Germany), which produce a wide range of chemical substances. Based on this data, the following assumptions are made: the built area amounts to about 4.2 ha, the plant has an average output of 50'000 t/a and a lifespan of fifty years. The estimated infrastructure amount is therefore 4.00 E-10 units per kg of produced chemical. References: Althaus H.-J., Chudacoff M., Hischier R., Jungbluth N., Osses M. and Primas A. (2007) Life Cycle Inventories of Chemicals. ecoinvent report No. 8, v2.0. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH. Gendorf (2000) Umwelterklärung 2000, Werk Gendorf. Werk Gendorf, Burgkirchen.
decarbonising waste	Mass	kg	-6.41	Value based on SQM (2007).
diesel, burned in building machine	Energy	MJ	1.88	According to personal communication, SQM 2010 (operational data
electricity, medium voltage	Energy	kWh	0.58	According to personal communication, SQM 2010 (operational data
hazardous waste, for underground deposit	Mass	kg	-0.000205	Value based on SQM (2007).
heat, district or industrial, natural gas	Energy	MJ	2.963532477	According to personal communication, SQM 2010 (operational data 2009). The heat from natural gas has two origins. 1.344 MJ are reported to be from natural gas, high pressure. 1.618 MJ are reported to be from natural gas, liquified. Here it is assumed that in the long term, the mix of natural gas related sources corresponds to the market mix.
hydrochloric acid, without water, in 30% solution state	Mass	kg	0.032686932	Average value based on 3 reports (according to personal communication, SQM 2010): (Report 1) SQM, 2007: Informe consolidado de la evaluacion de Impacto Ambiental de la declaracion de Impacto Ambiental del Proyecto 'Ampliacion Planta Carbonato de litio a 48'000 ton/año' RCA 164/07 (Report 2) SQM, 1996: Informe consolidado de la evaluacion de Impacto Ambiental de la declaracion de Impacto Ambiental del Proyecto 'Ampliacion Planta Carbonato de litio a 17'500 ton/año' RCA 381/96 (Report 3) SQM, 2001: Informe consolidado de la evaluacion de Impacto Ambiental de la declaracion de Impacto Ambiental del Proyecto 'Ampliacion Planta Carbonato de litio a 32'000 ton/año' RCA 083/01
hydrochloric acid, without water, in 30% solution state	Mass	kg	0.007313068	
lithium brine, 6.7 % Li	Mass	kg	4.19	
quicklime, milled, loose	Mass	kg	0.071889768	
quicklime, milled, loose	Mass	kg	0.000610233	
soda ash, light, crystalline, heptahydrate	Mass	kg	2.12	
sodium hydroxide, without water, in 50% solution state	Mass	kg	0.0001875	
solvent, organic	Mass	kg	0.0000208	
sulfuric acid	Mass	kg	0.0252	

OUTPUTS - LITHIUM PRODUCTION				
Flow	**Flow property**	**Unit**	**Amount**	**Description**
lithium carbonate	Mass	kg	1	The commercialized form of lithium carbonate is a fine white powder with a bulk density of ca. 0.8 kg/L. It is only slightly soluble in water; its solubility decreases with increasing temperature. Lithium carbonate is the a precursor material for the industrial production of all other lithium compounds while itself is produced heavily. It is also used in glass and ceramics industries. References: Stamp A., Lang D. J., Wäger P. A. (2012) Environmental impacts of a transition toward e-mobility: the present and future role of lithium carbonate production Garrett D. E. (2004) Part 1 – Lithium, in: Handbook of Lithium and Natural Calcium Chloride. Elsevier, Amsterdam. Wietelmann, U. and Steinbild, M. 2014. Lithium and Lithium Compounds. Ullmann's Encyclopedia of Industrial Chemistry. 1–38.