CRITICALITY AND LIFE CYCLE ASSESSMENT OF LITHIUM-ION BATTERY RAW MATERI

Auteur : Almansour, Sana
Promoteur(s) : Pirard, Eric
Faculté : Faculté des Sciences appliquées
Diplôme : Cours supplémentaires destinés aux étudiants d'échange (Erasmus, ...)
Année académique : 2021-2022
URI/URL : http://hdl.handle.net/2268.2/14172

CRITICALITY AND LIFE CYCLE ASSESSMENT OF LITHIUM-ION BATTERY RAW MATERIALS

Supervised by

Dieuwertje SCHRIJVERS (WeLOOP)

Eric PIRARD (Uliège)

Naeem ADIBI (WeLOOP)

MASTER THESIS

Sana ALMANSOUR

AMIR master

Abstract

WeLOOP is developing a web tool to help companies assess the criticality risks associated with raw materials in their supply chain by evaluating three sources of risk: accessibility, price, and reputation. At the same time, WeLOOP works on several Life Cycle Assessment projects linked to batteries and storage systems. There is a significant gap in available LCA data for batteries. In this thesis, we have conducted an inclusive criticality assessment for lithium-ion battery raw materials based on the methodology suggested by the IRTC (International Round Table on Materials Criticality). The data collection and the criticality indicators calculated in this thesis will be incorporated into the WeLOOP web tool. The second part of the thesis was to conduct a life cycle assessment of lithium-ion battery recycling processes. The results of the criticality assessment highlighted the criticality risks of cobalt, lithium, natural graphite, and bauxite/aluminum (all four are on the EU criticality list 2020). We also raised the question of potential criticality risk associated with nickel due to the recent price fluctuations and provided several recommendations for future criticality studies. The LCA study has shown that the avoided impacts thanks to recycling are very important compared to the environmental impacts of battery production (NMC111 cell). This is due to recycling processes' recovery of valuable and critical battery metals/ metals' salts. Those recovered materials can be used in producing new lithium-ion batteries, which will play an important role in the circularity and sustainability of lithium-ion batteries. However, more research is needed to enhance the efficiency/recovery rates and lower the environmental impacts of recycling.

List of definitions

Lithium-ion battery: is a rechargeable battery technology composed of cells in which lithium ions move from the anode through an electrolyte to the cathode during discharge and the opposite way when charging.
Raw material criticality: "the field of study that evaluates the economic and technical dependency on a certain material and the probability of supply disruption, for a defined stakeholders group within a certain time frame."
Life Cycle Assessment: "A technique for assessing the environmental aspects and potential impacts associated with a product."

The refining/processing stage: also called the post-mining stage, is a series of operations that transform raw materials into substances; these substances are used to make products.
By-product: is a mineral or metal whose supply is dependent on the production of the main carrier metal.
Reserves: "that part of the reserve base that could be economically extracted or produced at the time of determination.
Emerging technologies: are new technologies that could change the economic structures, and some aspects of social life and even could affect the environment in the long term.
Emerging economy: is a term that describes the economy of countries with low income and rapid growth, the growth engine of these countries is economic liberalization (lessening the economic regulations and restrictions imposed by governments).
Export restrictions: there are many forms of export restrictions such as export prohibition, export taxes, export quotas, and licensing requirements.
Child labor: forms of work and employment that children are too young to perform. Where the circumstances/nature of these labor activities, can have harmful effects on the children's health, safety, or morals.

Hydrometallurgy: the use of aqueous solutions to leach the desired metal from the cathode material, the most common combination of leaching reagents is H_2SO_4/H_2O_2. The leaching step is followed by precipitation reactions to recover the metals by manipulating the pH of the solution.
Pyrometallurgy: the use of a high-temperature furnace to reduce the component metal oxides to an alloy of Co, Cu, Fe, and Ni. This process is already established commercially for consumer LIBs
Resource nationalism: The state's efforts to acquire a larger share of important downstream industries.
Black mass preparation: Lithium batteries are mechanically treated by disassembling, shredding, electrolyte evaporation, and Separation and sorting to obtain the "black mass", which contains the electrode components such as lithium metal oxides (LMOs) and graphite.

List of abbreviations

LIB: Lithium-ion Battery
EV: Electric Vehicles
CRM: Critical Raw Materials
NMC: Lithium Manganese Cobalt Oxide battery
LFP: Lithium iron phosphate battery
LCO: Lithium cobalt battery
LMO: Lithium-ion manganese oxide battery
PVDF: polyvinylidene difluoride used as basic binder material
BM: Black mass
LCA: Life Cycle Assessment
LCI: Life-Cycle Inventory
LCIA: Life Cycle Impact Assessment
IRTC: International Round Table on Materials Criticality in Business Practice
PEF/OEF (Product Environmental Footprint/ Organization Environmental Footprint)
USGS: United States Geological Survey
RMIS: Raw Materials Information System
OECD: Organization for Economic Co-operation and Development
ISO: International Standards Organization
ETI: Enabling Trade Index
PPI: Policy Perception Index
HHI: Herfindahl–Hirschman Index
ETI: Enabling trade index
FSI: Failed States Index
EI: Environnemental implication
EPI: Environnemental Performance Index
HDI: Human Development index
GPI: Global Peace Index
CPI: Corruption Perception Index
WGI: World Governance Indicator
WGI - (CC) Control of corruption
WGI - (RL) Rule of law
WGI - (PV) Political stability & absence of Violence/terrorism
WGI - (GE) Government effectiveness
WGI - (RQ) Regulatory Quality
WGI – (VA) Voice and Accountability

Contents

Abstract 1

List of definitions 2

List of abbreviations 3

Introduction 10

State of the art 13

Batteries technologies and their raw materials 13

Criticality assessments 16

Life cycle assessment of lithium battery recycling processes 20

Available Life Cycle Inventories LCI for lithium batteries recycling processes 22

Methods 24

Criticality assessment methodology 24

Selection of criticality indicators and data sources based on the web-tool model 24

Data collection for lithium battery raw materials criticality assessment 26

Calculating the criticality indicators 29

Data gaps 30

Introduction of the criticality model that is implemented in the webtool 31

Life Cycle Assessment LCA methodology 35

Data Quality Rating (DQR) for available inventories and databases for lithium batteries recycling processes 35

Methodology of LCA study of LIB production and recycling processes 36

Results 38

Results of the criticality assessment 38

Results of the criticality assessment for each lithium battery raw material individually 38

The results of the criticality assessment based on the webtool model 55

Results of the life cycle assessment LCA 58

Results for the DQR for available inventories and databases for lithium batteries recycling processes 58

Result of LCA of lithium batteries recycling processes 58

Discussion 64

EIT Chapter 66

Conclusion 68

References 70

Annexes..77
Annex 1 / Overview of Lithium-ion Batteries recycling processes 77
Annex 2 / Life Cycle Assessment..90
Annex 3 / Available Life Cycle Inventories LCI for lithium batteries recycling processes.......................92
Annex 4 / Detailed description of criticality aspects and indicators 95
Annex 5 / Data gaps for Lithium battery raw materials criticality assessment 114
Annex 6 / Criticality assessment results based on the webtool model 119

List of Figures

Figure 1 Lithium-ion battery working principle (Chawla, Bharti and Singh, 2019) 13
Figure 2 Historical evolution and advances of lithium battery technologies (Kim et al., 2019) 14
Figure 3 Supplying countries (mining) for Lithium battery raw materials (WeLOOP, 2022) 15
Figure 4 Representation of the criticality concept (Buijs, Sievers, and Espinoza, 2012) 16
Figure 5 Indicators for the probability of supply disruption and/or the vulnerability to a supply disruption, their frequency of use, and the scope in which they are used. (Schrijvers et al. 2020) 17
Figure 6 Possible Lithium battery recycling routes (WeLOOP 2021) 20
Figure 7 Breaking down the 1st risk, company may not have access to the product (WeLOOP, 2022) 32
Figure 8 Breaking down the 2nd risk, the product may suddenly change substantially in price (WeLOOP, 2022) 33
Figure 9 Breaking down the 3rd risk, company's reputation might be affected by the use of a product (WeLOOP, 2022) 34
Figure 10 Results of the criticality assessment of Cobalt (WeLOOP, 2022) 38
Figure 11 Cobalt mining countries (WeLOOP, 2022) 39
Figure 12 Cobalt refining countries (WeLOOP, 2022) 39
Figure 13 Cobalt reserves countries (WeLOOP, 2022) 40
Figure 14 Cobalt main uses and applications (WeLOOP, 2022) 41
Figure 15 Results of the criticality assessment of Natural graphite (WeLOOP, 2022) 42
Figure 16 Results of the criticality assessment of Lithium (WeLOOP, 2022) 44
Figure 17 Lithium mining countries (WeLOOP, 2022) 45
Figure 18 Lithium refinery exporters (WeLOOP, 2022) 45
Figure 19 Results of the criticality assessment of Bauxite/Aluminum (WeLOOP, 2022) 46
Figure 20 Bauxite mining countries (WeLOOP, 2022) 47
Figure 21 Aluminum refining countries (WeLOOP, 2022) 47
Figure 22 Results of the criticality assessment of Nickel (WeLOOP, 2022) 48
Figure 23 EU sourcing of refined nickel (WeLOOP, 2022) 49
Figure 24 Nickel price changes in the last year (2021-2022) (USD/ton) (Trading Economics 17th May 2022) 49
Figure 25 Results of the criticality assessment of Manganese (WeLOOP, 2022) 51
Figure 26 Results of the criticality assessment of Iron/Steel (WeLOOP, 2022) 52
Figure 27 Results of the criticality assessment of Phosphate rock (WeLOOP, 2022) 53
Figure 28 Results of the criticality assessment of Copper (WeLOOP, 2022) 54
Figure 29 Schematic of the second problematic "There is a mismatch between supply and demand of lithium battery raw materials in the market" (problematics/criticality aspects/criticality indicators) (WeLOOP, 2022) 55
Figure 30 Supply is dominated by a few countries, and the supplying countries are subjected to trade restrictions (WeLOOP, 2022) 56
Figure 31 Criticality assessment results for " supplying countries is subjected to export restrictions", which might cause a mismatch between supply and demand in the market, which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022). 57
Figure 32 LCA results of the production of NMC 111 cell (BATTER project WeLOOP, 2022) 59
Figure 33 LCA results (Single score) of the production of NMC 111 Cathode (BATTER project WeLOOP, 2022) 59

Figure 34 LCA results (Climate change) of the production of NMC 111 Cathode (BATTER project WeLOOP, 2022) 60
Figure 35 LCA results, Comparison between LIB recycling processes (SCORELCA? WeLOOP, 2022) 61
Figure 36 LCA results, NMC111 cell production impact verses the avoided impacts thanks to LIB recycling processes (SCORELCA WeLOOP, 2022) 62
Figure 37 PESTLE analysis by using the criticality indicators 66
Figure 38 MTB black mass preparation process (WeLOOP 2021) 79
Figure 39 Pyrometallurgical treatment of Lithium batteries (WeLOOP 2021) 81
Figure 40 Valibat recycling process schematic TES in France, (WeLOOP 2021) 83
Figure 41 Lithium batteries direct recycling process schematic (WeLOOP 2021) 85
Figure 42 The structure of an LCA study according to ISO14040/44 (WeLOOP, 2022) 90
Figure 43 LCA study (WeLOOP training, 2022) 91
Figure 44 Tracking data sources of Ciez's inventory (WeLOOP 2021) 92
Figure 45 Tracking data sources of Mohr's inventory (WeLOOP 2021) 93
Figure 46 Tracking data sources of Rajaeifar's inventory (WeLOOP 2021) 94
Figure 47 Proportion of the primary global supply of Lithium battery raw materials potentially subject to export restrictions between 2017 and 2021. 98
Figure 48 Periodic tables of criticality for 62 metals, for environmental implications (Graedel et al. 2015) 107
Figure 49 The 2020 EPI Framework (Wendling et al., 2020) 108
Figure 50 Overview of considered categories, subcategories, and indicators to determine compliance with social standards (Bach et al., 2017) 109
Figure 51 The most peaceful countries in 2022, based on the peace index score. (World Population Review, 2022) 111
Figure 52 Measurement framework for the global estimation of child labor (Intranational Labor Organization ILO)(UNICEF, 2021) 113
Figure 53 Global criticality assessment of lithium battery raw materials (WeLOOP, 2022). 119
Figure 54 Schematic of Supply is not compliant with (future) policy regulations (problematics/criticality aspects/criticality indicators) (WeLOOP, 2022) 120
Figure 55 Criticality assessment results of: Supply is not compliant with (future) policy regulations which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022) 121
Figure 56 Schematic of the second problematic “There is a mismatch between supply and demand of lithium battery raw materials in the market” (problematics/criticality aspects/criticality indicators) (WeLOOP, 2022) 123
Figure 57 Global criticality assessment results of a mismatch between supply and demand of lithium battery raw materials in the market, which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022) 124
Figure 58 Criticality assessment results for "an expected a strong demand increase while the supply might not be able to catch up", which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022). 125
Figure 59 Criticality assessment results for "Supplying country is subjected to an unstable investment climate and social unrest", which might cause a mismatch between supply and demand in the market,

which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022). 127
Figure 60 Criticality assessment results for " Supply is dominated by a few countries, and/or a few companies, and the supplying countries is subjected to trade restrictions", which might cause a mismatch between supply and demand in the market, which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022). 129
Figure 61 Criticality assessment results for " supplying countries is subjected to export restrictions", which might cause a mismatch between supply and demand in the market, which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022). 130
Figure 62 Criticality assessment results for " supplying countries is subjected to trade restrictions/ETI", which might cause a mismatch between supply and demand in the market, which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022). 131
Figure 63 Criticality assessment results for "Supply is dominated by a few companies", which might cause a mismatch between supply and demand in the market, which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022). 132
Figure 64 Schematic of the risk, price fluctuations for lithium battery raw materials, and its problematics (WeLOOP, 2022) 133
Figure 65 Schematic of "Additional costs may be expected due to environmental/social reporting requirements or taxes", which might cause a risk of price fluctuations for lithium battery raw materials (WeLOOP, 2022). 134
Figure 66 Schematic of "Supply is dominated by a few companies, which may misuse their pricing power", which might cause a risk of price fluctuations for lithium battery raw materials (WeLOOP, 2022). 135
Figure 67 Schematic of the risk that the company's reputation may be affected by the use of LIB raw materials (WeLOOP, 2022) 136

List of tables

Table 1 General composition of lithium-ion battery 14
Table 2 Previous criticality assessments (Criticality aspects and indicators) 18
Table 3 Criticality aspects, criticality indicators, and the data sources used in our criticality assessment based on IRTC recommendations. 24
Table 4 Country performance indicators, Score range, Meaning of the score 26
Table 5 The conversion of the indicators values to a scale from 0 to 100 28
Table 6 Available databases of lithium batteries recycling processes (WeLOOP, 2022) 35
Table 7 Data quality rating (DQR) according to the PEF method for available LCIs for lithium batteries recycling processes **(for a European scope)** (WeLOOP, 2022) 58
Table 8 Comparison between pyro, hydro, and direct recycling processes 87
Table 9 Continuation of the comparison between pyro, hydro, and direct recycling processes 87
Table 10 LIBs recycling facilities details in Europe (WeLOOP 2021) 88
Table 11 LIBs recycling facilities details worldwide (WeLOOP 2021) 89
Table 12 By-products with their carrier metal 101
Table 13 Human development groups 110
Table 14 Child labor index considerations (United Nations Development Program, 2022) 113
Table 15 Data gaps for Lithium battery raw materials criticality assessment 114

Introduction

Rechargeable Lithium batteries have been on the market for about three decades. They have powered portable electronic devices such as mobile phones, laptops, and other small electronic devices. Since 2008, lithium batteries have been used in electric and hybrid vehicles due to their attractive characteristics, high energy density, low memory effect, and significant charge cycles. With the electrification movement of the transportation system, the production and the use of lithium batteries are expected to keep increasing in the future. The EU Green Deal predicted that the demand for lithium-ion batteries will increase 14-fold by 2030. The EU Green Deal is working towards having more sustainable batteries placed in the EU market, with high-performance and safe all along their life cycle (*European Commission-Press release Green Deal: Sustainable batteries for a circular and climate neutral economy*, 2020).

However, lithium-ion battery sustainability faces several challenges over the supply chain, from raw materials extraction to cell production to end-of-life treatment. For example, the raw materials used in the batteries must be extracted and used in a responsible, sustainable manner, in full respect of human rights, social, and ecological standards. Alongside with minimizing the environmental impacts of the production of lithium-ion batteries and increasing the lifespan of the batteries. Moreover, batteries should be repurposed, remanufactured, or recycled at the end of life. Recycling will help feed back valuable and critical raw materials from spent lithium-ion batteries to the economy.

Lithium-ion batteries contain critical raw materials CRMs for the EU; those CRMs are cobalt, lithium, natural graphite, and Bauxite/Aluminum. CRMs have high importance to the EU economy, with supply risks associated with geopolitical, environmental, and/or social issues in the supplying countries. Bearing in mind that most of the raw materials used in lithium-ion batteries are extracted and refined outside the EU. Criticality assessments can be done to identify what materials are at risk of the full deployment of the transportation electrification plan in the EU. It also determines what materials should be prioritized for mitigation measures such as recycling and substitution.

Since a considerable number of lithium-ion batteries will reach their end-of-life stage in the coming years, recycling Lithium batteries presents a mitigation measure for battery CRMs, since recovering materials by recycling decreases resource extraction. Although, lithium-ion battery recycling processes still have considerable environmental impacts. However, when sustainable recycling is done, it could reduce the energy consumption and the environmental impacts associated with the resource extraction to produce lithium batteries. However, one major challenge of recycling lithium-ion batteries is that the batteries' design and chemistries are still evolving, resulting in unstable output recycling flows.

Today there is no clear, comprehensive overview of the challenges facing the deployment of lithium-ion battery technology from a sustainability point of view. In this thesis, we worked on assessing the sustainability of lithium-ion batteries. By conducting an inclusive criticality assessment of the most used raw materials in lithium-ion batteries. Alongside a life cycle assessment (LCA) of lithium-ion batteries with a focus on recycling processes. Previous criticality studies had included materials and metals of lithium-ion batteries. Nonetheless, those criticality studies had different objectives and scopes, which resulted in using different criticality aspects and indicators (see (Schrijvers *et al.*, 2020)).

In this thesis, the criticality assessment was based on the methodology suggested by the IRTC (International Round Table on Materials Criticality). The work started with a list of 14 criticality aspects and problematics, with suggested criticality indicators and data sources. The first step was to conduct research for each criticality aspect/problematic on the list, find an indicator to quantify the problem, then find available data sources that will be used to calculate the criticality indicators. Finding the indicators were either based on checking criticality indicators used by previous criticality studies or on suggested indicators by the IRTC. Numerous data sources have been investigated for the current assessment, such as Geological surveys, World Bank, Raw Material Information System RIMS, World Economic Forum & Global Alliance for Trade Facilitation, etc. During the investigation of the data sources, documentation of each aspect, problem, indicator, and data source of criticality was done. The second step was the data collection for nine featured raw materials that are used in the two most common types of lithium-ion batteries (Lithium Nickel Manganese Cobalt Oxide NMC and Lithium Iron Phosphate LFP). In the Methods chapter, we discuss in detail the data collection process. The third step of the criticality assessment was to calculate the criticality indicators and get the criticality assessment results.

The criticality assessment is part of a project between the IRTC and WeLOOP, where the collected data will be used in a web tool that is still under development. This Web tool will help companies evaluate criticality in their supply chain based on three sources of risk: accessibility, price, and reputation.

The second part of the work is the life cycle assessment of lithium-ion batteries production (NMC111) with a focus on recycling processes. As a preamble for the LCA study, we worked on a state-of-the-art lithium-ion battery recycling process, available LCA studies for battery recycling processes, and their available inventory and databases. Source tracking and Data Quality Rating was also done to evaluate the quality of the available inventories and databases. Then we conducted our own criticality assessment for lithium-ion battery production, the recycling process, and the avoided environmental impacts thanks to the recycling processes. That showed recycling is one of the most important criticality mitigation measures.

This thesis is composed of six chapters: State-of-the-art, Methods, Results, Discussion, EIT chapter, and Conclusion. The state-of-the-art chapter is to give an overview of lithium-ion battery technologies, criticality assessments, and life cycle assessments of lithium-ion batteries.

State-of-the-art

Lithium-ion battery technologies, criticality assessment, and life cycle assessment

State of the art

Batteries technologies and their raw materials

Lithium-ion battery is mainly composed of cathode, anode, electrolyte, and separator (see Table 1). Lithium-ion battery is a general term, refer to wide variety of battery chemistries, the battery is usually named after its cathode material. However, lithium-ion batteries have one concept in common, which is the charge and the discharge reactions from the cathode (lithiated metal oxide) to the graphite anode. During the charge reaction, lithium ions travel from the cathode to anode passing through the separator. The discharge reaction happens the other way around. As shown in Figure 1.

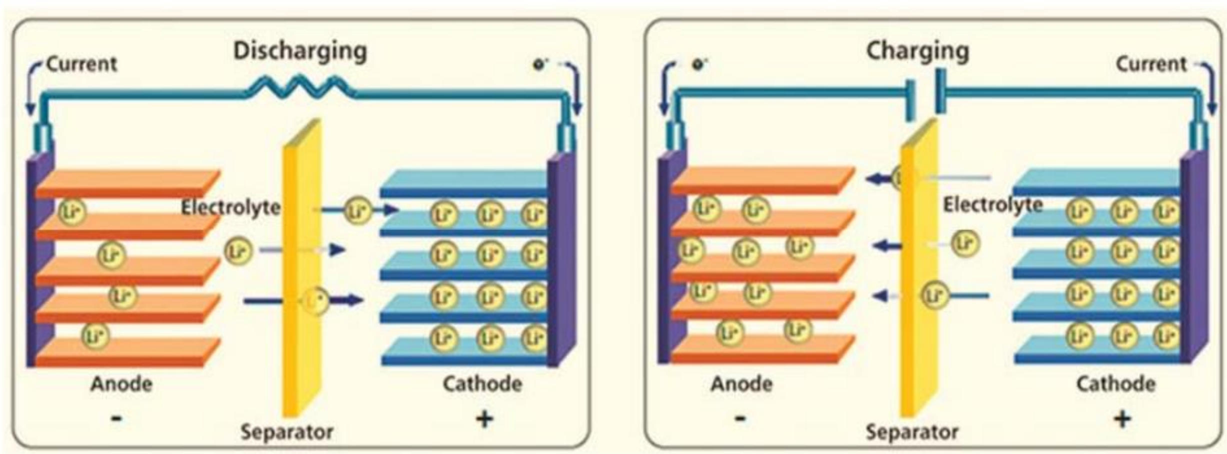

Figure 1 Lithium-ion battery working principle (Chawla, Bharti and Singh, 2019)

There are many varieties of lithium-ion batteries: Lithium Nickel Manganese Cobalt Oxide NMC ($LiNi_xMn_yCo_zO_2$), Lithium Iron Phosphate LFP ($LiFePO_4$), Lithium Cobalt Oxide LCO ($LiCoO_2$), Lithium Nickel Cobalt Aluminum Oxide NCA ($LiNi_xCo_yAl_{1xy}O_2$), and Lithium Manganese Oxide LMO ($LiMn_2O_4$).

The most used types of lithium-ion batteries are Nickel Manganese Cobalt Oxide NMC and Lithium Iron Phosphate LFP. NMC cathode chemistry is $LiNi_xMn_yCo_zO_2$, it is one of the most successful lithium-ion cathodes. NMC have several attractive features, such as quality uniformity, high-energy density, high power rating, due to its high lithium diffusion rate and electron mobility. It is mainly composed of cobalt, nickel, and manganese. There are several NMC varieties depending on the metal content, for example NMC 333 consists of 33% nickel, 33% manganese, and 33% cobalt. It is also called NMC 111. Other NMC variations are NMC 532, NMC 622, and NMC 811.

Lithium Iron Phosphate LFP with a cathode chemistry $LiFePO_4$, the advantage of using LFP is that the cathode materials are iron and phosphate. Which are more abundant and cheaper than some of the metals used in NMC cathode (such as cobalt)(Catherine Lane, 2022).

Figure 2 shows the historical evaluation of lithium-ion batteries.

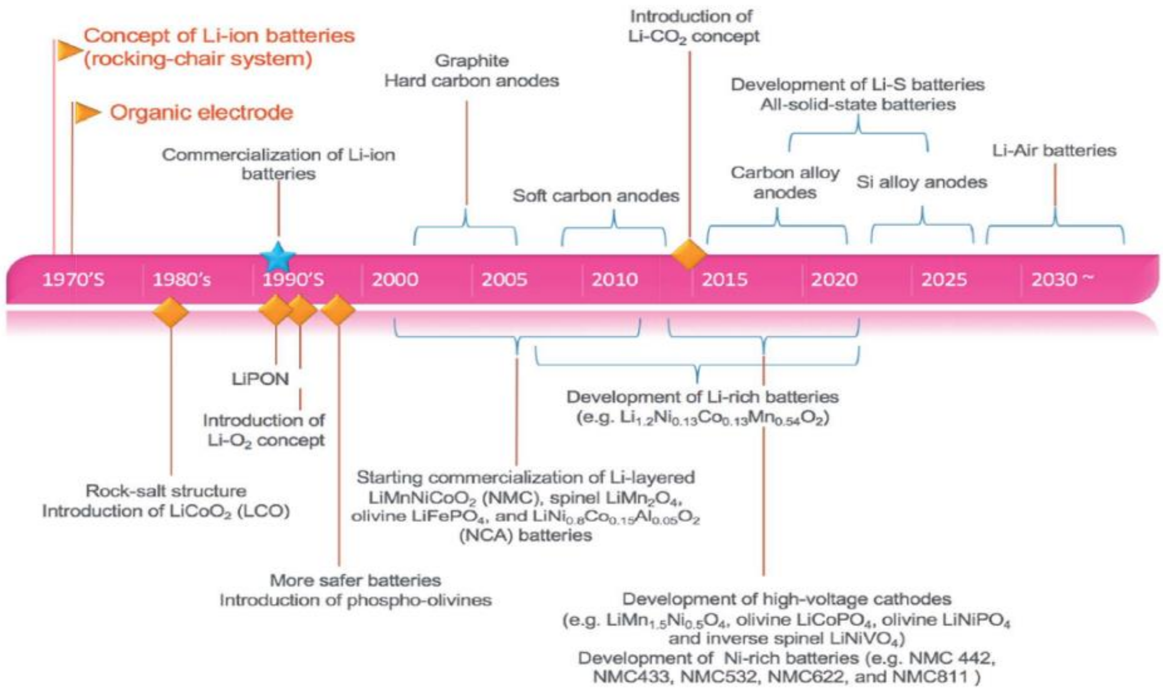

Figure 2 Historical evolution and advances of lithium battery technologies (Kim et al., 2019)

A general overview of lithium-ion battery components and most used materials are shown in *Table 1*

Table 1 General composition of lithium-ion battery

Battery component	**Weight (%)**	**Most used materials**
Casing	25%	Steel/ Plastics
Cathode	27%	$LiCoO_2$, $LiNi_xMn_yCo_zO_2$, $LiMn_2O_4$, $LiNiO_2$, or $LiFePO_4$
Anode	17%	Graphite/$Li_4Ti_5O_{12}$
Current collectors and Cu and Al foils	13%	Cu, Al
Electrolyte	10%	Solution of $LiPF_6$, $LiBF_4$, $LiClO_4$, and $LiSO_2$ dissolved in propylene carbonate, ethylene carbonate, or dimethyl sulfoxide
Binder	4%	Polivinylidene Difluoride (PVDF)
Separator	4%	Microporous polypropylene

As we can see all lithium-ion battery chemistries use Critical raw materials CRMs (from the EU criticality list in 2020). Graphite for the anode, Lithium for the cathode salts, electrolyte, and in the anode. Cobalt in cobalt-containing battery types such as NMC, NCA, and LCO. The EU criticality list highlights raw materials that represent high importance to the EU economy, with supply risks associated with geopolitical, environmental, and/or social issues in the supplying countries. Most of the raw materials used in lithium-ion batteries (critical and non-critical) are extracted and refined outside the EU (see Figure 3).

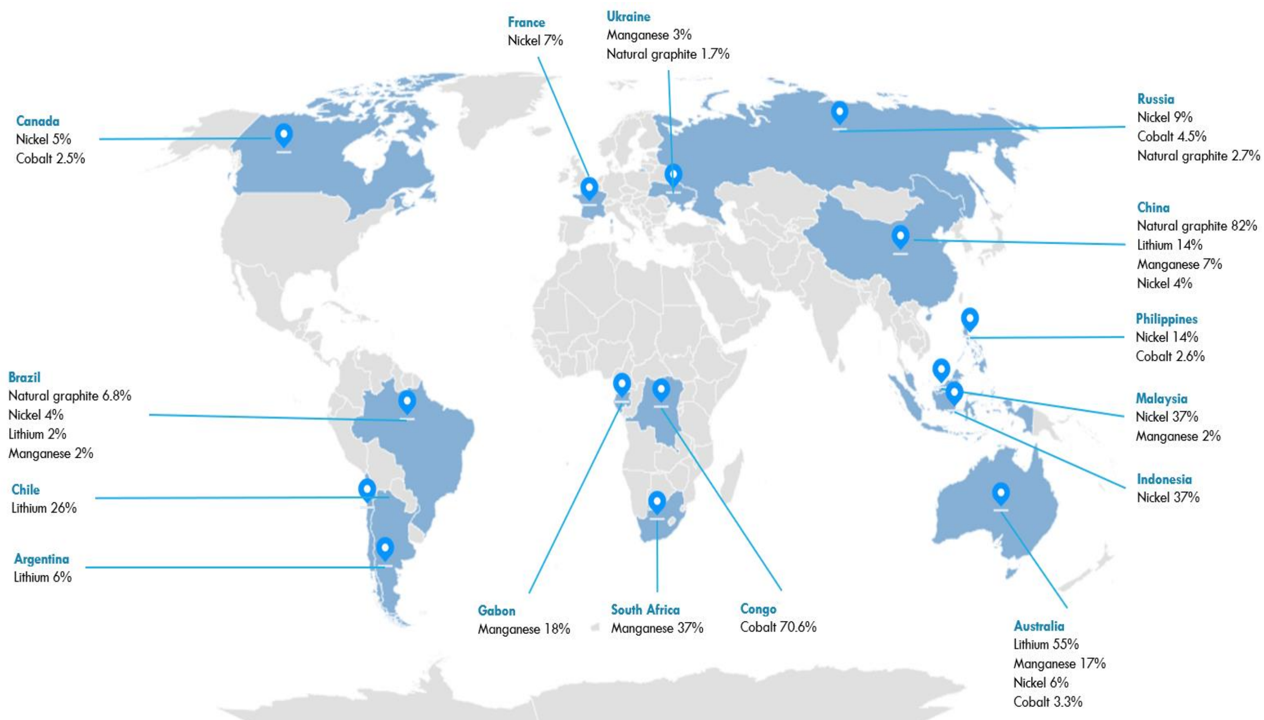

Figure 3 Supplying countries (mining) for Lithium battery raw materials (WeLOOP, 2022)

Criticality assessments can be done to identify what materials are at risk of the full deployment of the transportation electrification plan in the EU (using Lithium-ion battery technologies). It also identifies what materials should be prioritize for mitigation measures such as recycling and substitution. The following part is an overview of criticality assessment studies.

Criticality assessments

Criticality assessment estimates the economic dependency as well as the technical dependency on certain raw materials. It also evaluates the probability of supply disruption for raw materials, for a specific group of stakeholders during a given period of time. Criticality assessment is requisite in the industry for informative materials selection, product design, process design, and investment decisions. Criticality assessment is also essential for policymakers when setting policy agendas and trade agreements (Schrijvers et al. 2020).

In 2012, Buijs et al., Have defined critical raw materials as “mineral, non-energy raw materials that combine a comparatively high economic importance with a comparatively high risk of supply disruptions.” Where the criticality concept has two dimensions, one dimension measures the economic importance or the expected impact of shortage (negative impact). The second dimension measures the risk of supply shortage. To distinguish between critical and non-critical raw materials (see Figure 4), thresholds may be defined in both dimensions (Buijs, Sievers and Espinoza, 2012).

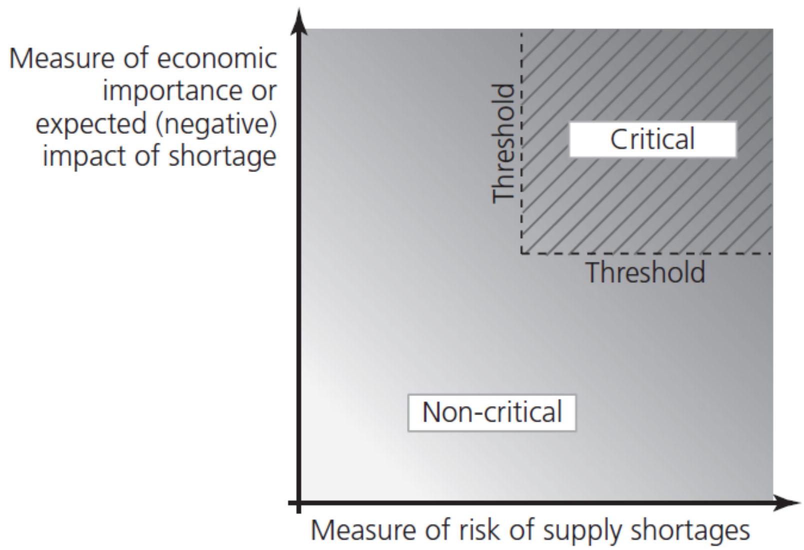

Figure 4 Representation of the criticality concept (Buijs, Sievers, and Espinoza, 2012)

Graedel et al., have defined the criticality of metals as” imbalances between metal supply and demand, actual or anticipated.” However, Greadel et al. have considered a criticality concept with three dimensions supply risk, environmental implications, and vulnerability to supply restrictions (Graedel, Harper, Nassar, Nuss, Reck, *et al.*, 2015).

Schrijvers et al., have defined raw material criticality as “the field of study that evaluates the economic and technical dependency on a certain material and the probability of supply disruption, for a defined stakeholders group within a certain time frame.” (Schrijvers *et al.*, 2020)

The European Commission has defined critical raw materials as “raw materials with high economic importance for the EU and high supply risk.” The European Commission has established a critical raw materials list at the EU level every three years since 2011, 2014, 2017, and 2020 (“Study on the EU’s list of Critical Raw Materials (2020) Final Report,” no date).

Criticality assessment studies are performed to evaluate the criticality of raw materials in a specific product or technology. At different levels: company level, country level, region level, or even at a global level in a short-term or long-term. Criticality assessments use a wide range of criticality indicators to quantify and evaluate various criticality aspects and factors. The evaluated criticality aspects vary between geological, geopolitical, technological, social, and environmental aspects. Due to the diversity of goals and scopes of criticality assessment studies, there is no one standard methodology to carry out a criticality assessment study. This has led to various criticality assessment studies with varying criticality indicators, and therefore it is not feasible to compare the results of different criticality studies (Schrijvers et al. 2020).

Figure 5 gives a complete overview of typical criticality indicators including indicators that represent criticality mitigation efforts (which can decrease supply risks, such as recycling, substitution, and stockpiles).

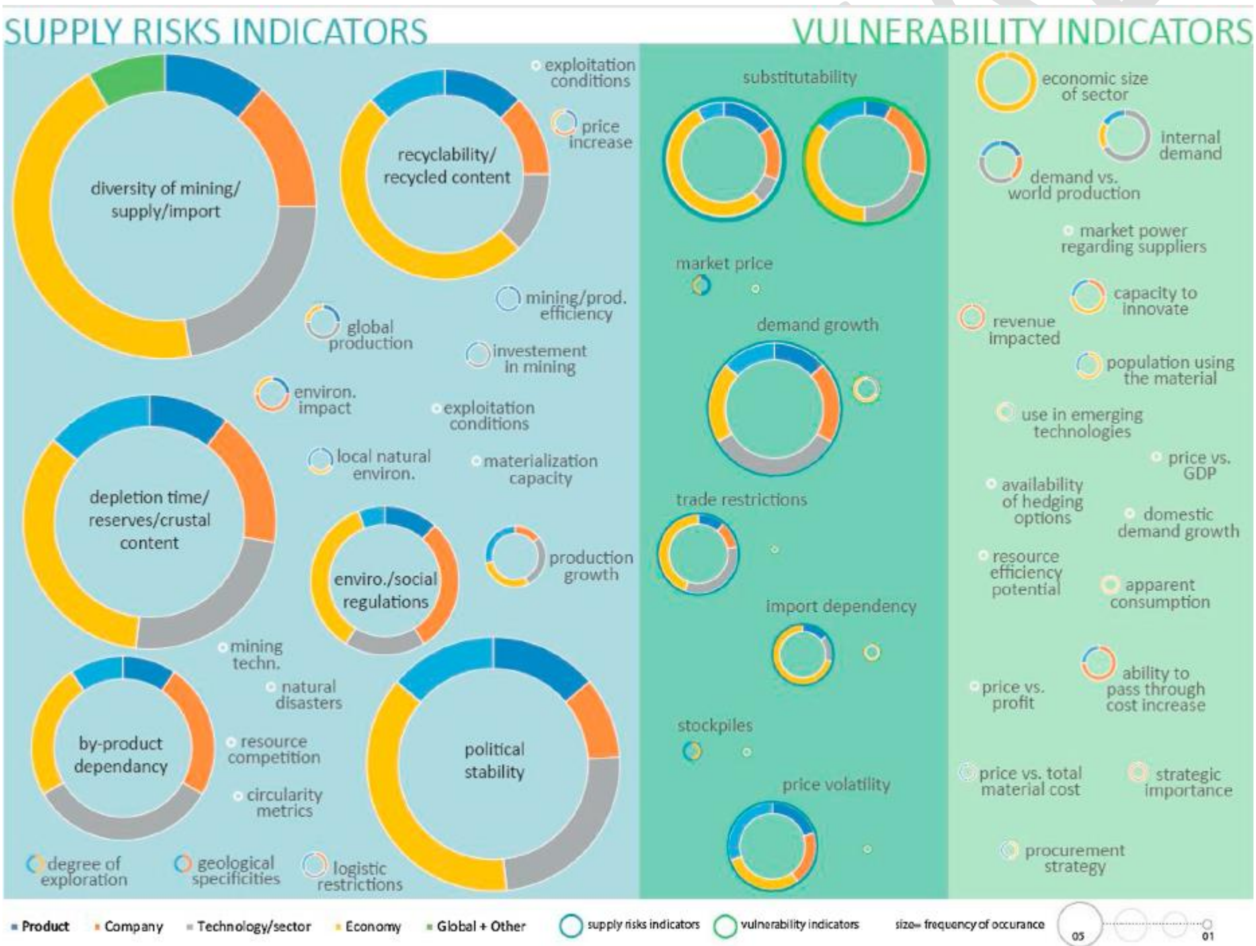

Figure 5 Indicators for the probability of supply disruption and/or the vulnerability to a supply disruption, their frequency of use, and the scope in which they are used. (Schrijvers et al. 2020)

from Figure 5, the most used supply risk indicator is the diversity of supply (mining/refining/reserves). This indicator is calculated using the Herfindahl-Hirschmann-Index, it is often combined with political stability indicators of the supplying countries. The most common used political stability indicators are the worldwide governance indicators. The aim of using those indicators (diversity of supply and political stability) is to estimate the probability of supply disruption. The other most frequent used indicators are

Depletion time/reserves/crustal content, Recyclability/recycled content, By-product dependency, and Environmental/social regulations. Figure 5 also presents vulnerability indicators, the most used vulnerability indicators are substitutability, demand growth, price volatility, trade restrictions, and import dependency.

Table 2 sets a few examples of previous criticality assessment studies and the different indicators used in these studies.

Table 2 Previous criticality assessments (Criticality aspects and indicators)

Criticality assessment	Criticality aspects/Category	Criticality indicators
(Moss *et al.*, no date)	Likelihood of rapid global demand growth	Demand structure and forecasts.
	Limitations to expanding global production capacity in the short to medium term	Reserve estimates, supply forecasts, and byproduct dependency.
	Concentration of supply	Production statistics.
	Political risk related to major supplying countries	Failed States Index, Worldwide Governance Index, and expert assessment.
(Graedel, Harper, Nassar, Nuss, Reck, *et al.*, 2015)	Supply risk related to geological, technological, and economic factors	Depletion time, and companion metal fraction.
	Supply risk related to social and regulatory factors	Policy potential index, and Human development index.
	Supply risk related to geopolitical factors	Worldwide governance indicators (Political Stability & Absence of Violence/Terrorism), and global supply concentration.
	Environmental Implications	Cradle to gate LCA.
	Vulnerability to Supply Restriction	Importance (Material assets, National economic importance), Substitutability (Substitute performance, substitute availability, Environmental impact ratio, Net import reliance ratio), and Susceptibility (Global innovation index, and net import reliance).
SCARCE **(Bach *et al.*, 2017)**	Demand growth	Percentage of annual growth based on past developments.
	Concentration of reserves	Herfindahl-Hirschmann-Index.
	Price fluctuation	Price Volatility.
	Physical availability	Abiotic resource depletion.
	Occurrence of co-production	Percentage of production as a companion metal.
	Primary material use	Percentage of new material content.
	Company concentration	Herfindahl-Hirschmann-Index.
	Feasibility of exploration projects	Policy Potential Index.
	Trade barriers	Enabling Trade Index.
	Political stability	Worldwide Governance Indicators.

	Concentration of production	Herfindahl-Hirschmann-Index.
	Economic importance	Value added of sectors which utilize the raw material in production.
	Share of global production	Imported amounts in relation to global production.
	Domestically required demand	Imported amount.
	Dependency on imports	Domestic production compared to imported amounts.
	Availability of purchasing strategies	Share of the raw material imported from countries, for which purchasing strategies are established.
	Substitutability	Share of raw material, which can be substituted.
	Utilization in future technologies	Share of raw material, which will be significant for future technologies.
	Compliance with social standards	Global peace index, Worldwide governance indicators, social hotspot database risk indicators, Cingranelli-Richards human rights physical integrity rights index, and share of materials extracted within a small scale as well as artisanal small scale mining operations.
	Environmental indicators	Sensitivity of local biodiversity, Water scarcity, and Climate change.
(European commission criticality assessment, 2020)	Supply risk/disruption	Diversity of supply, Political stability, Depletion, Recyclability
	Supply vulnerability	Substitutability, demand growth and price volatility

In this criticality assessment, 14 criticality aspects were studied, such as supply is dominated by a few countries/companies; supplying countries is subjected to trade restrictions, unstable investment climate, and/or social unrest; Expected demand increase due to use in emerging technologies and/or emerging economies; environmental impacts associated with the product; and social circumstances associated with the product. The selection of the indicators is presented in the next chapter 'Methods'.

It is important to emphasize that the criticality indicators used in our study were used to assess three sources of risk: accessibility, price, and reputation. No indicators that represent criticality mitigation efforts was included in our assessment. Mitigation efforts can decrease the supply risks, such as recycling, substitution, and stockpiles.

As recycling presents a mitigation measure for raw materials criticality (by recovering materials and decreasing resource extraction). Furthermore, recycling is an important factor to reach the sustainability objectives of lithium-ion batteries. And since a considerable number of lithium-ion batteries will reach their end-of-life stage in the coming years. It is important to assess the environmental impacts associated with lithium-ion batteries recycling processes. We included in our study a life cycle assessment of lithium-ion battery recycling processes. The following paragraph is an overview of available life cycle assessment studies and inventories for lithium batteries recycling processes.

Life cycle assessment of lithium battery recycling processes

There are different commercial recycling processes for treating lithium batteries at the End of Life; pyrometallurgical, hydrometallurgical, and mixed processes. Usually, recycling processes of lithium batteries are either a combination of pyrometallurgical and hydrometallurgical techniques with pre-treatment or post-treatment processes (Bai *et al.*, 2020a), as shown in Figure 6 Possible Lithium battery recycling routes (WeLOOP 2021). Pyrometallurgical recycling processes are the dominant processes for recycling lithium batteries due to their flexibility (Mossali *et al.*, 2020a), (Lv *et al.*, 2018).

The primary focus of current lithium batteries recycling processes is to recover high-value metals such as Co and Ni. Current recycling processes of Lithium batteries only recover Co, Ni, Cu, Al, and steel. Plastic fractions are mostly burned for energy recovery, and graphite, Mn, and Li are rarely recovered (Dewulf *et al.*, 2010a). Nevertheless, lithium's prices are continually increasing, making it inevitable for Lithium battery recyclers to improve the recovery rate of lithium. Lithium battery industrial recycling processes mainly focus on batteries with high cobalt content, such as LCO (Lithium cobalt battery $LiCoO_2$) and NMC (Lithium Manganese Cobalt Oxide). In comparison, other lower-value battery chemistries are not a primary focus of industrial recycling processes, such as LMO (lithium-ion manganese oxide) and LFP (lithium iron phosphate battery) (Winslow, Laux and Townsend, 2018). . (Check Annex 1 / Overview of Lithium-ion Batteries recycling processes).

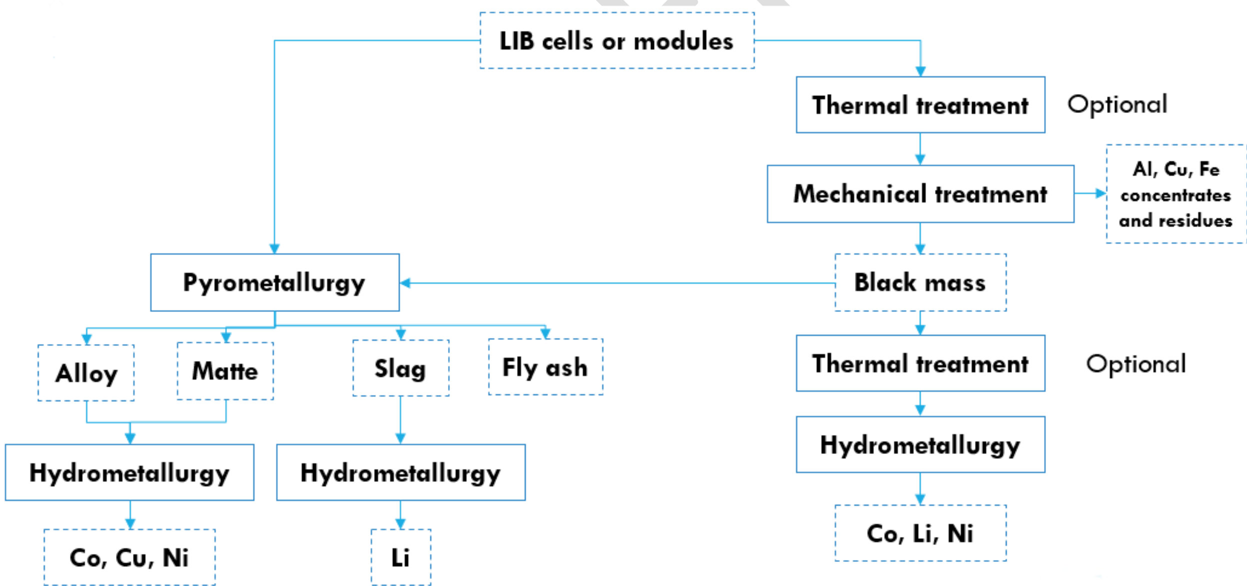

Figure 6 Possible Lithium battery recycling routes (WeLOOP 2021)

Life cycle assessment studies on lithium-ion battery recycling processes are limited since it is considered an emerging technology. Per consequence, it is challenging to obtain good quality data from real processes, leading to nonreliable life cycle inventories LCI (Dunn *et al.*, 2015a). In addition, there is a lack of LCA studies related to the collection, transportation, sorting, dismantling, and preparation of black mass from spent lithium batteries. These processing steps could have considerable impacts (Boyden, Soo and Doolan, 2016).

As a result, LCA studies on lithium battery recycling processes have focused on assessing the impacts associated with the recovery of valuable metals (Yang *et al.*, 2021). There are only a limited number of LCA studies on lithium battery recycling processes. These LCA studies differ in their goal and scope, the recycling processes, the types and chemistries of the lithium batteries, and the assessment method used in the study.

For example, (Dunn *et al.*, 2012) have conducted a cradle to grave LCA study to assess the environmental burdens (energy consumption and emissions) of automobiles that use LMO batteries (cathode material LiMn2O4). Their study calculated the energy consumption and air emissions when recovering LiMn2O4, Al, and Cu through three recycling processes; (hydrometallurgical, intermediate physical, and direct physical recycling) by studying how closed-loop recycling affects the environmental impacts of battery production. However, it is noteworthy that the authors have used theoretical estimations, which could lead to a large uncertainty margin on their results.

(Elwert *et al.*, 2016) have conducted an LCA study to assess the environmental impact of the hydrometallurgical recycling process (Lithorec recycling process) of NMC (LiNiMnCoO2) batteries. They found that the impacts of the emissions generated when recovering Cu and Al electrode plates 'overweight' the credits of recovering these metals. They have also found that the recovery of the outer steel casing and Co and Ni from the active cathode material accounts for most environmental benefits.

(Ciez and Whitacre, 2019) have done an attributional LCA study to examine the GHG emissions and the energy inputs associated with producing and recycling NMC-622, NCA, and LFP lithium batteries. They compared three recycling processes: pyrometallurgical, hydrometallurgical, and direct cathode recycling. This study showed that pyrometallurgical and hydrometallurgical processes do not remarkably reduce the GHG emissions during the life cycle. On the other hand, direct cathode recycling can reduce emissions.

(Mohr *et al.*, 2020)have conducted an LCA study to compare pyrometallurgical and hydrometallurgical recycling processes for different cell chemistries NCA, NMC, LFP, and SIB (Sodium-ion batteries). These processes were used as a benchmark to evaluate an advanced hydrometallurgical recycling process modeled based on primary data obtained from a German recycling company called Duesenfeld GmbH. The goal was to quantify the potential reduction of environmental impacts that recycling different cell chemistries can achieve. They stated that recycling lithium batteries could significantly reduce their product's environmental impacts, depending on cell chemistry. They have found that recycling NMC and NCA by the advanced hydrometallurgical process have the lowest impact due to the recovery of Co and Ni, especially under resource depletion aspects.

On the other hand, for cells made of abundant and cheap materials, such as LFP (lithium iron phosphate), recycling can cause other environmental impacts. They concluded that maximum materials recovery might not always be favorable under environmental aspects. Therefore, hydrometallurgical processes need to be adapted to the specific cell chemistry to reach the maximum environmental benefits.

(Rajaeifar *et al.*, 2021) have done an LCA study to compare three pyrometallurgical recycling processes regarding global warming potential and cumulative energy demand. These pyrometallurgical processes are direct current DC plasma smelting technology, the same DC plasma smelting technology preceded by pre-treatment, and ultra-high temperature UHT furnace. The lithium battery cathode type is NMC111. Their results showed that DC plasma smelting technology preceded by pre-treatment reduces the global warming potential by up to 5 times compared to using the ultra-high temperature furnace.

The most critical challenge for LCA studies on lithium battery recycling processes is the scarcity of reliable data for LCIs, fixed impact models, and allocation standards (Zhang *et al.*, 2018). To overcome these challenges, many resources and support are needed from Lithium batteries producers, recyclers, and governments (Yang et al., 2021). (See Annex 2 / Life Cycle Assessment, for an overview about LCA)

Available Life Cycle Inventories LCI for lithium batteries recycling processes

Building the life cycle inventory is a crucial step in any LCA study. Data availability and quality define the reliability of the LCI. Unfortunately, LCIs of the lithium batteries recycling process lack the availability of reliable data. Primary data collected from lithium batteries recyclers are subjected to confidentiality agreements; therefore, they cannot be used easily. Secondary data are data obtained from the literatures, and the databases of LCA software tools. Although building the LCI based on primary data is preferable and reliable, secondary data can be a valid substitute based on solid models and assumptions. Most LCA studies use primary and secondary data, and very few studies use only primary data or secondary data. Ecoinvent database is used to perform the LCI phase in most of the LCA available in around 66% of the studies, BatPac database is mentioned in 17% (Tolomeo et al., 2020).

We have made an overview about three recent LCIs for lithium-ion batteries recycling process. We tracked down the sources of the data used in these inventories. (See Annex 3 / Available Life Cycle Inventories LCI for lithium batteries recycling processes). Then we conducted a data quality rating (DQR) for the available LCIs for lithium batteries recycling processes, and the available databases (See Life cycle assessment is an effective tool for a comprehensive assessment of the environmental impacts of products and services in the context of sustainable development. An LCA study has three main steps: Compiling an inventory (Life Cycle Inventory LCI), which is composed of relevant inputs and outputs of a product system. Evaluating the potential environmental impacts associated to the product system. And finally, interpreting the results of the inventory analysis/ Impact assessment step based on the objective of the LCA study. the challenges for the battery sector.

LCA studies on lithium-ion battery recycling processes are limited since it is considered an emerging technology. As a consequence, it is challenging to obtain good quality data from real processes, leading to nonreliable life cycle inventories LCI (Dunn *et al.*, 2015a). In addition, there is a lack of LCA studies related to the collection, transportation, sorting, dismantling, and preparation of black mass from spent lithium batteries. These processing steps could have considerable impacts (Boyden, Soo and Doolan, 2016). As a result, LCA studies on lithium battery recycling processes have focused on assessing the impacts associated with the recovery of valuable metals (Yang *et al.*, 2021). There are only a limited number of LCA studies on lithium battery recycling processes. These LCA studies differ in their goal and scope, the recycling processes, the types and chemistries of the lithium batteries, and the assessment method used in the study. This is why there is a need to investigate and evaluate the quality of the available LCIs and databases of LIB recycling processes.

Data Quality Rating (DQR) for available inventories and databases for lithium batteries recycling processes). The DQR showed that most of the available databases and LCIs have just fair quality. However, none of the available databases and LCIs scored excellent or very good quality (see Results for the DQR for available inventories and databases for lithium batteries recycling processes). According to the PEF/OEF (Product Environmental Footprint/ Organization Environmental Footprint) method, these data cannot be used for the most relevant processes of a company. For example, the data cannot be used to assess EV cars or EV bikes as the end of life is among the most relevant processes for these products.

Methods

Criticality assessment method, Life cycle assessment method

Methods

Criticality assessment methodology

Criticality can be demonstrated in several problematics/criticality aspects each criticality aspect is reflected by one or multiple indicators. Criticality indicators are used to measure and quantify criticality aspects. The current criticality assessment was based on the methodology suggested by the IRTC. The work started with a list of 14 criticality aspects and problematics, with suggested criticality indicators and data sources. The first step was to conduct research for each criticality aspect/problematic on the list. Followed by finding one or several indicators to quantify the problematic, and then find available data sources that will be used to calculate the criticality indicators. Finding the criticality indicators was either based on checking criticality indicators that have been used by previous criticality studies or based on suggested indicators by the IRTC. Numerous data sources have been investigated for the current assessment such as Geological surveys, World Bank, Raw Material Information System RIMS, World Economic Forum & Global Alliance for Trade Facilitation, etc. During the investigation of the data sources, a documentation of each criticality aspects, problematic, indicator and data sources was done (see Annex 4 / Detailed description of criticality aspects and indicators).

Selection of criticality indicators and data sources based on the web-tool model

Table 3 presents an overview of all the criticality aspects used in our criticality assessment, the indicators used to quantify the criticality aspects/ problematics, and the data sources used to quantify those indicators. Two criticality aspects are presented in the table but not included in the assessment "The supplying country is subject to natural disasters" and "Competing use in high-margin or high-priority products". At the moment, there are no criticality indicators and data sources to measure and quantify these two problematics. In this study we used 23 indicators.

Table 3 Criticality aspects, criticality indicators, and the data sources used in our criticality assessment based on IRTC recommendations.

Criticality problematics/ Criticality aspects	**Indicator (quantifying the criticality aspects)**	**Data source**	**Year**
Supply is dominated in a few countries	HHI – Mining countries	USGS	2021
		RMIS	2022
	HHI – refining countries	RMIS	2022
The supplying country is subject to natural disasters	<u>No available measuring indicators</u>		
The supplying country is subject to trade restrictions/resource nationalism	Export restrictions between 2017-2020	(OECD 2021)	2017-2020
	Enabling trade index	World Economic Forum & Global Alliance for Trade Facilitation	2016
The supplying country is subject to societal unrest	WGI – Rule of law	World bank	2020
The supplying country is subject to an unstable investment climate	WGI – Political stability & absence of Violence/terrorism	World bank	2020
	WGI - Government effectiveness	World bank	2020

<table>
<tr><td rowspan="3"></td><td colspan="2"></td><td></td><td></td></tr>
<tr><td colspan="2">WGI - Regulatory Quality</td><td>World bank</td><td>2020</td></tr>
<tr><td colspan="2">Failed States Index</td><td>World Population Review</td><td>2022</td></tr>
<tr><td>Supply is dominated by a few companies</td><td colspan="2">HHI-dominant companies</td><td></td><td>2022/
2021</td></tr>
<tr><td>(Competing) use in high-margin or high-priority products (e.g. health care, strategic sectors)</td><td colspan="2"><u>No available measuring indicators</u></td><td></td><td></td></tr>
<tr><td>By-product dependency of mining</td><td colspan="2">% Supply as by-product</td><td>USGS
Cobalt institute</td><td>2022</td></tr>
<tr><td>Expected demand increases due to use in emerging technologies</td><td colspan="2" rowspan="2">% Expected demand increase Compound Annual Growth Rate between 2020-2050 for sustainable development scenario</td><td rowspan="2">(Metals for Clean Energy, 2022)
By KU Leuven and Eurometaux</td><td rowspan="2">2022</td></tr>
<tr><td>Expected demand increases due to use in emerging economies</td></tr>
<tr><td rowspan="2">Potential to increase supply from mines</td><td colspan="2">HHI - reserves</td><td>USGS</td><td>2021</td></tr>
<tr><td colspan="2">Policy Perception Index</td><td>Annual Survey of Mining Companies of the Fraser Institute</td><td>2021</td></tr>
<tr><td>Share of (current) production capacity used in mining and refining</td><td colspan="2">Production to reserves ration</td><td>USGS</td><td>2021</td></tr>
<tr><td rowspan="2">Environmental impacts associated with the product</td><td colspan="2">Environmental implication EI score (Cradle to gate LCA)</td><td>(Graedel et al. 2015)</td><td>2015</td></tr>
<tr><td colspan="2">Environmental Performance Index</td><td>(Wendling et al., 2020)</td><td>2020</td></tr>
<tr><td rowspan="6">Social circumstances associated with the product</td><td rowspan="2">Human rights</td><td>Human Development index</td><td>United Nations Development Program</td><td>2019</td></tr>
<tr><td>Environmental Performance Index</td><td>World bank</td><td>2020</td></tr>
<tr><td colspan="2">Conflict: Global Peace Index</td><td>World population review</td><td>2022</td></tr>
<tr><td rowspan="2">Governance/ Corruption</td><td>Corruption Perception Index</td><td>Transparency International</td><td>2021</td></tr>
<tr><td>WGI – Control of corruption</td><td>World bank</td><td>2020</td></tr>
<tr><td colspan="2">Child labor (% ages 5-17)</td><td>United nation development program</td><td>2010-
2019</td></tr>
</table>

(See the documentation in Annex 4 / Detailed description of criticality aspects and indicators)

Data collection for lithium battery raw materials criticality assessment

The second step was the data collection, for nine raw materials which are used in the two most common types of lithium-ion battery (Lithium Nickel Manganese Cobalt Oxide NMC and Lithium Iron Phosphate LFP). These raw materials are cobalt, nickel, lithium, manganese, natural graphite, copper, phosphate rock, iron/steel, and Bauxite/Aluminum. For each raw material we collected:

The shares of the mining countries (USGS, 2022).

The shares of refining countries (RMIS, 2022).

The shares of reserves countries (USGS, 2022).

The market share of the major mining companies (Investing News Network, no date).

The main uses and applications (RMIS, 2022).

For the expected demand increase in emerging technologies, emerging economies we used the Compound Annual Growth Rate between 2020-2050 (for sustainable development scenario) from the report “Metal for clean energy” by KU Leuven (Leuven and Gregoir -Principal Author, no date).

The Environmental implication EI score which is a Cradle to gate LCA from (Graedel, Harper, Nassar, Nuss, Reck, *et al.*, 2015).

The share of supply as by-product (“Study on the EU’s list of Critical Raw Materials (2020) Final Report,” no date), (Cobalt Institute, 2022), (Graedel, Harper, Nassar, Nuss, Reck, *et al.*, 2015).

The second set of data collection was for indicators and indexes that evaluate the performance of the supplying countries. Such as governance level, human rights, conflict, corruption level, investment climate, mining polices, trade policies, and environmental performance. The country performance indicators were collected for 214 countries. In is assessment we used 14 country performance indicators; Table 4 shows a brief description of the indicators that we have used.

Table 4 Country performance indicators, Score range, Meaning of the score

Indicator (the year of evaluation)	**Score range**	**Description**	**Source**
WGI - Political stability & absence of Violence (2020)	[0-100] From weak to strong	Indicates the likelihood of destabilization or overthrowing the government by unconstitutional or violent means, including politically motivated violence and terrorism	World Bank
WGI - Government effectiveness (2020)	[0-100] From weak to strong	Gives information about the quality of public services, civil service, the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government’s commitment to such policies	World Bank

WGI - Regulatory Quality (2020)	[0-100] From weak to strong	Gives information on the ability of the government to formulate and implement sound policies and regulations that permit and promote the private sector development	World Bank
WGI - Rule of law (2020)	[0-100] From weak to strong	Indicates the extent to which agents have confidence in and abide by the rules of society, especially the quality of contract enforcement, property rights, the police, and the courts, and the likelihood of crime and violence	World Bank
WGI - Control of corruption (2020)	[0-100] From weak to strong	Indicates to which extent public power benefits from private gain, covering all forms of corruption and the control of the state by elites and special interests	World Bank
WGI - Voice and Accountability (2020)	[0-100] From weak to strong	Indicates to which extent a country's citizens can participate in selecting their government. It also shows the freedom of expression and association and free media	World Bank
Failed State Index (2022)	[0-120] The higher the index, the worse the situation	Provides information about the political stability of countries. It is established by the World Bank as an indicator of the Fund for Peace and the World Governance	World Population Review
Policy Perception Index (2021)	[0-100] The higher the PPI, the more attractive the country's mining policies	Indicates the overall investment attractiveness of mining policies of governments	Annual Survey of Mining Companies of the Fraser Institute
Enabling trade index (2016)	[1-7] The higher the better trade facilitation	Evaluates to which extent economies facilitate the free flow of goods over borders (and to their destination)	World Economic Forum & Global Alliance for Trade Facilitation
Environmental Performance Index (2020)	[0-100] The higher the EPI, the better the country's environmental performance	Assesses and ranks the environmental health and the ecosystem vitality in 180 countries. EPI provides the state of sustainability in these countries by evaluating how close those countries are to established environmental policy targets.	(Wendling *et al.*, 2020)
Child labor (% ages 5-17) (2010-2019)	Percentage % The higher the worse	Percentage of children ages (5-17) involved in child labor	United Nations Development Program

Global Peace Index (2022)	[1-5] The lower the score the more peaceful the country	Analyzes and quantifies which nations are the most peaceful, and which nations are the most dangerous by evaluating three distinct categories (militarization, safety and security, and domestic and international conflict)	World population review
Corruption Perceptions Index CPI (2021)	[0-100] From highly corrupted to very clean (the lower the more corrupted)	Evaluates the levels of public sector corruption in 180 countries worldwide	Transparency International
Human Development Index HDI (2019)	[0-1] The higher the HDI, the better	Measure the average achievement in three basic dimensions of human development (long and healthy life, knowledge, and a decent standard of living)	United Nations Development Program

For this criticality assessment, the country performance indicators' values were converted to a scale of 0-100, with the higher the score, the worse the country performance, the higher the associated risk. The conversions of these values are shown in Table 5.

Table 5 The conversion of the indicators values to a scale from 0 to 100

Indicator	**Conversion equation**
WGI - Political stability & absence of Violence/terrorism	$100\text{-}WGI_{\text{percentile score}}$
WGI - Government effectiveness	$100\text{-}WGI_{\text{percentile score}}$
WGI - Regulatory Quality	$100\text{-}WGI_{\text{percentile score}}$
WGI - Rule of law	$100\text{-}WGI_{\text{percentile score}}$
WGI - Control of corruption	$100\text{-}WGI_{\text{percentile score}}$
WGI - Voice and Accountability	$100\text{-}WGI_{\text{percentile score}}$
Failed State Index	100 x (FSI value/120)
Policy Perception Index	100-PPI value
Enabling trade index	100 x (1-(ETI value-1)/6)
Environmental Performance Index	100-EPI value
Child labor (% ages 5-17)	No conversion needed
Global Peace Index	100 x (GPI value -1)/4
Corruption Perceptions Index CPI	100 - CPI value
Human Development Index HDI	(1- HDI value) x 100

Calculating the criticality indicators

The third step of the criticality assessment was to calculate the criticality indicators in order to get the raw materials' scores and the results for the criticality assessment.

Calculating the supply concentration risk:

As we have mentioned earlier, the Herfindahl–Hirschman Index (HHI) is usually used to quantify the market concentration. The concentration of supply (mining, refining, reserves) was calculated by the Herfindahl–Hirschman Index (HHI), using the following equation:

$HHI(a) = \sum_{i=1}^{N}(a_i^2)$, where:

N is the number of the countries,

a_i is the share of the country.

To evaluate the risk of supply being dominated by a few countries/companies, the global supply concentration equation of (Graedel, Harper, Nassar, Nuss, Reck, *et al.*, 2015) was used, by the transformation of the HHI using the natural logarithm function (ln), as shown in the following equation: GSC=17.5 x ln (HHI) – 61.18

HHI-supplying countries (mining & refining) and the converted/transformed country-performance indicators where aggregated (by multiplying HHI to the relevant country-performance indicator). And that were done to evaluate the probability of supply disruption related to supply risks in the supplying countries (such as geopolitical, social, environmental and investment risks). The final score was the maximum between the mining and the refining stage.

Expected demand increase and Cradle-to-gate LCA were transformed via a "distance to target method" (Bach et al. 2017). This transformation is to scale the values in this range [0-100]. It is calculated as shown in the following equation:

$$Indicator\ result_{i,c} = \frac{DtT - value_{i,c} - DtT - value_{min,c}}{DtTvalue_{max,c} - DtT - value_{min,c}}$$

For each raw material the total share of supply subjected to export restrictions was calculated. By the sum of the shares of supplying countries which were subjected to trade restrictions between 2017-2020 (OECD 2021).

The potential to increase supply from mines is calculated by aggregating the HHI-reserves with PPI (Policy Perception Index.

Data gaps

In this criticality assessment, we have faced several issues related to the scarcity of well-documented data for mining, refining, reserves, companies' share in the market, etc. For example, no data were found for lithium refining market share. And since the refining stage was the reason behind adding lithium to the EU 2020 criticality list ("Study on the EU's list of Critical Raw Materials (2020) Final Report," no date), we had to include the lithium refining stage in our criticality assessment. To solve this issue, the market share of lithium refining countries was estimated using the refinery exporter monetary values from the (RMIS, 2022) .

On the other hand, refining countries' share of Natural graphite and phosphate rock was missing but no estimations were made to tackle this issue.

Cradle-to-gate LCA (Environmental implication (EI) score) was missing for natural graphite and phosphate rock.

Share of expected demand increase was missing for Iron/steel, natural graphite, phosphate rock, and manganese.

Market shares of supplying companies were missing for natural graphite.

For country-performance indicators, the most common data gaps we faced were missing Policy Perception Index PPI scores and Enabling Trade Index ETI scores for several countries. To solve this issue, PPI and ETI were set to zero for these countries. The share of the market which was not represented because of these data gaps was calculated and documented. Data gaps are presented and discussed in detail in (Annex 5 / Data gaps for Lithium battery raw materials criticality assessment).

Introduction of the criticality model that is implemented in the webtool

The criticality part of this current thesis will be integrated into a webtool (under development) (IRTC Business & WeLOOP, 2022). This tool will evaluate the criticality of raw material based on three sources of risk: accessibility, price, and reputation. These three sources of risks are formulated as specific problems that users of raw materials (e.g., companies) can experience. The last part of the work was to connect the three sources of risks (and their problematics and sub-problematics) with the criticality aspects and indicators. Figure 7, Figure 8, and Figure 9 present the storyline that connects criticality indicators with these three sources of risks (IRTC Business & WeLOOP, 2022).

To dive into the three evaluated risks in the webtool; we have the first risk "The company may not have access to product": because one of the company's suppliers is not able to deliver their product and there are few. This situation could happen because the supply of a product is dominated by a few countries or a few companies, which might be affected by natural disasters, trade policies, regulations, societal distortions.

The second risk evaluated by the webtool is "A product may suddenly change substantially in price" because the supply is dominated by a few companies, which may misuse their pricing power. Additional costs may be expected due to environmental/social reporting requirements or taxes. Or finally, a mismatch between supply and demand in the market. This situation could happen due to several problematics such as the material being mainly produced as a by-product of another product (If the demand for the main product decreases, the supply of the by-product decreases as well). Demand is expected to strongly increase due to its use in emerging technologies and/or emerging economies, while supply might not be able to catch up. One supplier is not able to deliver their product and there are few alternative suppliers.

The third risk is 'The company's reputation may be affected by the use of a product" due to the product's environmental impacts or social circumstances that are deemed unacceptable by social norms (IRTC Business & WeLOOP, 2022).

For more info a full cause-and-effect chain for criticality can be found on (IRTC & WeLOOP, 2022).

Figure 7, Figure 8, and Figure 9 present the source of risk, the problematics that could lead to the situation, the linked criticality aspects, and the indicators used to quantify these criticality aspects. For example, the company's reputation may be affected by the use of a product" due to the product's environmental impacts or social circumstances that are deemed unacceptable by social norms. This problematic is linked to two criticality aspects; environmental impacts associated with the product and social circumstances associated with the product. The environmental impacts associated with the product can be evaluated by Life Cycle Assessment (LCA) and Environmental Performance Index (EPI). The second criticality aspect which is social circumstances associated with the product, for example, child labor, human right violation in one of the supplying countries. This criticality aspect can be quantified by several indicators such as the Human Development index, WGI – Voice and accountability, and Child labor indicator (% ages 5-17) by the United nation development program.

This current criticality assessment did not include mitigation measures (such as substitution, recycling, diversifying the supply, etc.). However, the webtool (under development) will provide advised action to prevent or mitigate these risks that may face a company. For example, one way to prevent accessibility risk is by diversifying the company suppliers.

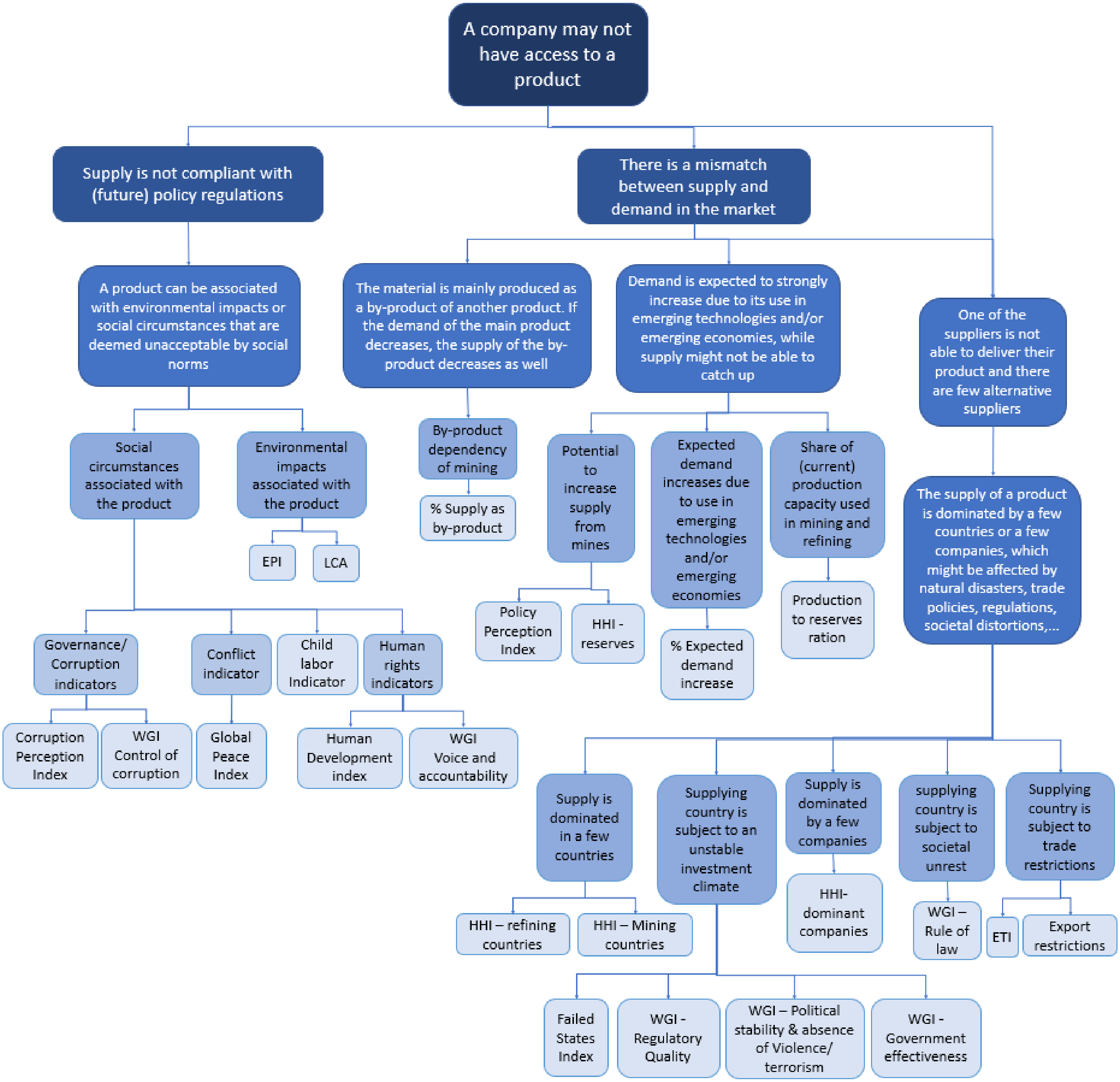

Figure 7 Breaking down the 1st risk, company may not have access to the product (WeLOOP, 2022)

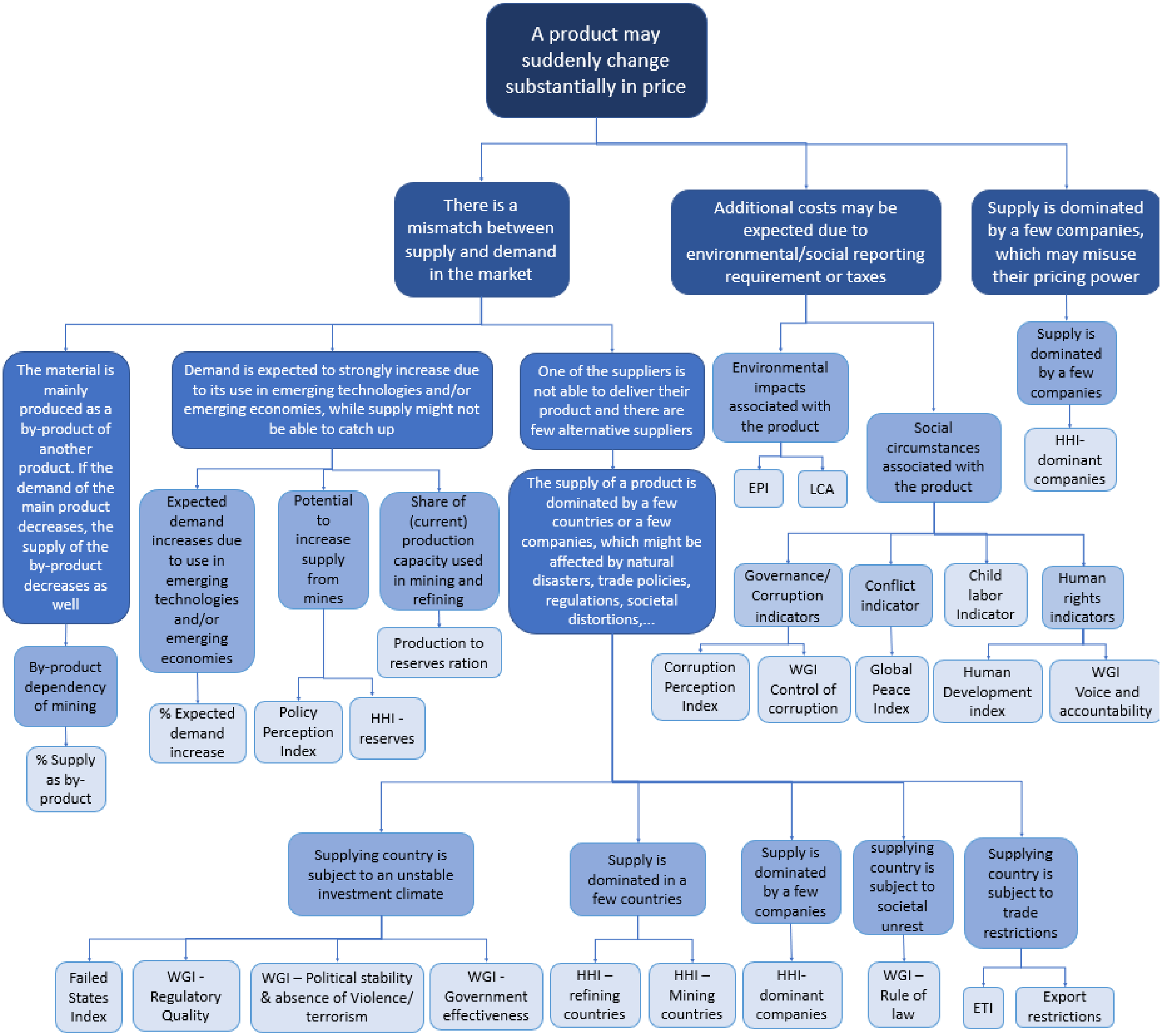

Figure 8 Breaking down the 2nd risk, the product may suddenly change substantially in price (WeLOOP, 2022)

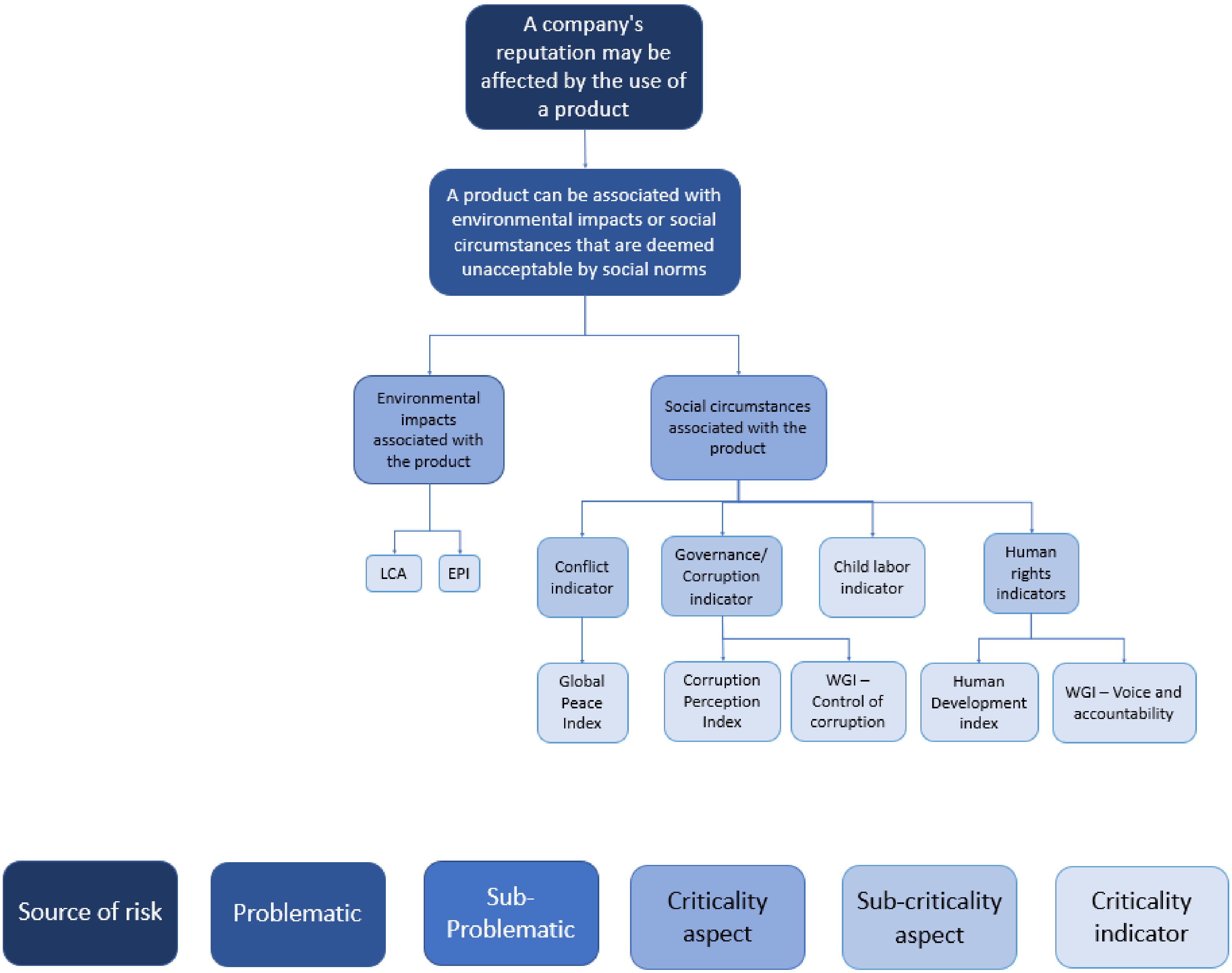

Figure 9 Breaking down the 3rd risk, company's reputation might be affected by the use of a product (WeLOOP, 2022)

Life Cycle Assessment LCA methodology

Life cycle assessment is an effective tool for a comprehensive assessment of the environmental impacts of products and services in the context of sustainable development. An LCA study has three main steps: Compiling an inventory (Life Cycle Inventory LCI), which is composed of relevant inputs and outputs of a product system. Evaluating the potential environmental impacts associated to the product system. And finally, interpreting the results of the inventory analysis/ Impact assessment step based on the objective of the LCA study. the challenges for the battery sector.

LCA studies on lithium-ion battery recycling processes are limited since it is considered an emerging technology. As a consequence, it is challenging to obtain good quality data from real processes, leading to nonreliable life cycle inventories LCI (Dunn *et al.*, 2015a). In addition, there is a lack of LCA studies related to the collection, transportation, sorting, dismantling, and preparation of black mass from spent lithium batteries. These processing steps could have considerable impacts (Boyden, Soo and Doolan, 2016). As a result, LCA studies on lithium battery recycling processes have focused on assessing the impacts associated with the recovery of valuable metals (Yang *et al.*, 2021). There are only a limited number of LCA studies on lithium battery recycling processes. These LCA studies differ in their goal and scope, the recycling processes, the types and chemistries of the lithium batteries, and the assessment method used in the study. This is why there is a need to investigate and evaluate the quality of the available LCIs and databases of LIB recycling processes.

Data Quality Rating (DQR) for available inventories and databases for lithium batteries recycling processes

Available databases for lithium battery recycling processes are listed in Table 6. Ecoinvent has two processes pyrometallurgical process and the hydrometallurgical process. The data were taken from old references (Fisher *et al.*, 2006), and the data has been extrapolated from 2005 to 2021. GaBi has a pyrometallurgical process, taking data from the German project LitthoRec. The EcoSystem has developed a French database for WEEE LCI; this database does not include batteries/cells/accumulators in their LCIs at the end of life of WEEE. Also, there are no projects to extend their LCIs to lithium battery recycling processes. The DQR evaluates the databases listed in Table 6 and three recent life cycle inventories for LIBs recycling processes from (Rajaeifar *et al.*, 2021), (Mohr *et al.*, 2020), and (Ciez and Whitacre, 2019). The results of the DQR will be presented in the following chapter.

Table 6 Available databases of lithium batteries recycling processes (WeLOOP, 2022)

Data-base	Process	Date	Reference	Technology	Geographical representation
Ecoinvent	Pyro	2021-2024	(Fisher *et al.*, 2006)	This dataset represents the treatment of Li-Ion batteries from electric and electronic devices by a pyrometallurgical process. It includes energy & auxiliary consumption, waste production, emission (to air/to water) production and rough estimations of the efforts for infrastructure & transportation. Treatment of used Lithium-ion battery. Crushing the batteries, followed by a neutralization and processing step.	Global
	Hydro		(Fisher *et al.*, 2006)	This dataset represents the treatment of Li-Ion batteries from electric and electronic devices by a hydrometallurgical process. It includes energy & auxiliary consumption, waste production,	Global

				emission (to air/to water) production and rough estimations of the efforts for infrastructure & transportation. Treatment of used Lithium-ion battery. Shredder, followed by chemical treatment to separate the various fractions produced.	
GaBi	Pyro	2021-2024	(LithoRec project, 2009)	The process consists of mechanical treatment, pyrometallurgical, and hydrometallurgical processes. The mechanical process includes dismantling the battery (e.g., removing aluminum housing and copper cables). In the pyrometallurgical process, the material is heated in a furnace so that metals such as copper, aluminum, cobalt, and nickel are separated by melting. The separated active materials are treated with caustic soda to dissolve the lithium in the hydrometallurgical process. Finally, plastic waste from the battery is incinerated with energy credit.	Germany
EIME	No available data				
EcoSystem	This database has not included batteries/cells/accumulators in their LCIs on the end of life of WEEE.				
PEF/OEF	Mixed Pyro-Hydro	2021	(Xu *et al.*, 2008; Dewulf *et al.*, 2010b)	E-mobility Dismantling process of the battery Pyrometallurgical treatment process for the cell Then, Hydrometallurgical treatment process for the cell.	Europe

Methodology of LCA study of LIB production and recycling processes

First, we conduct an LCA study to evaluate the environmental impacts of the production of NMC111 cells. With a focus on the production of the electrodes (the anode and the cathode). The LCA software we used in this assessment is SimaPro; the inventory data of the NMC111 cell production was taken from the Ecoinvent database. This LCA was part of Batter project by WeLOOP, this project focus on the circular economy of mobility batteries.

Then, we conducted an LCA study to compare LIB recycling processes (hydrometallurgical versus pyrometallurgical processes). This LCA study was part of SCORELCA project by WeLOOP, in partnership with TND. TND is a French company expert in metallurgy, building a pilot plant for recycling Lithium-ion batteries in the North of France. TND developed the Life Cycle Inventories (LCI) for the LIB recycling processes. Their LCI is truly representative of the current technologies and market, based on real data, and will allow evaluating the environmental impacts of LIB recycling processes. The data were built based on data collected by TND from the industrial LIB recycling process in France and Belgium. The LCA modeling of the pyrometallurgical process was done by me. The cell production and the hydrometallurgical processes were modeled by other colleagues in WeLOOP, to which I contributed directly. In this thesis, we used both LCA models to present the impacts of production and compare LIB recycling processes.

Results

Criticality assessment results, Life cycle assessment results

Results

Results of the criticality assessment

The main purpose of the criticality assessment for this current thesis was to conduct research for the data sources suggested by the IRTC project. To do the data collection for lithium battery raw material, and to quantify the criticality aspects by calculating the criticality indicators. Weighting and aggregation of the indicators to reach to one final criticality score for each raw material was outside the scope of this thesis. Therefore, the results are presented as a comparison between the indicators 'scores for each raw material. The second part of the results is presented based on the evaluation of the supply risk by the webtool model. The later presentation gives a comparison between lithium battery raw material.

Results of the criticality assessment for each lithium battery raw material individually

Before start discussing the results, it is important to emphasize that one indicator does not indicate if the material is critical or not. One should capture the whole picture by analyzing all the relevant indicators.

Cobalt

Cobalt is on the EU criticality list of 2020; this current assessment shows that cobalt has high potential supply risks arising from almost all the criticality indicators. Figure 10 shows the results of the criticality assessment of cobalt,

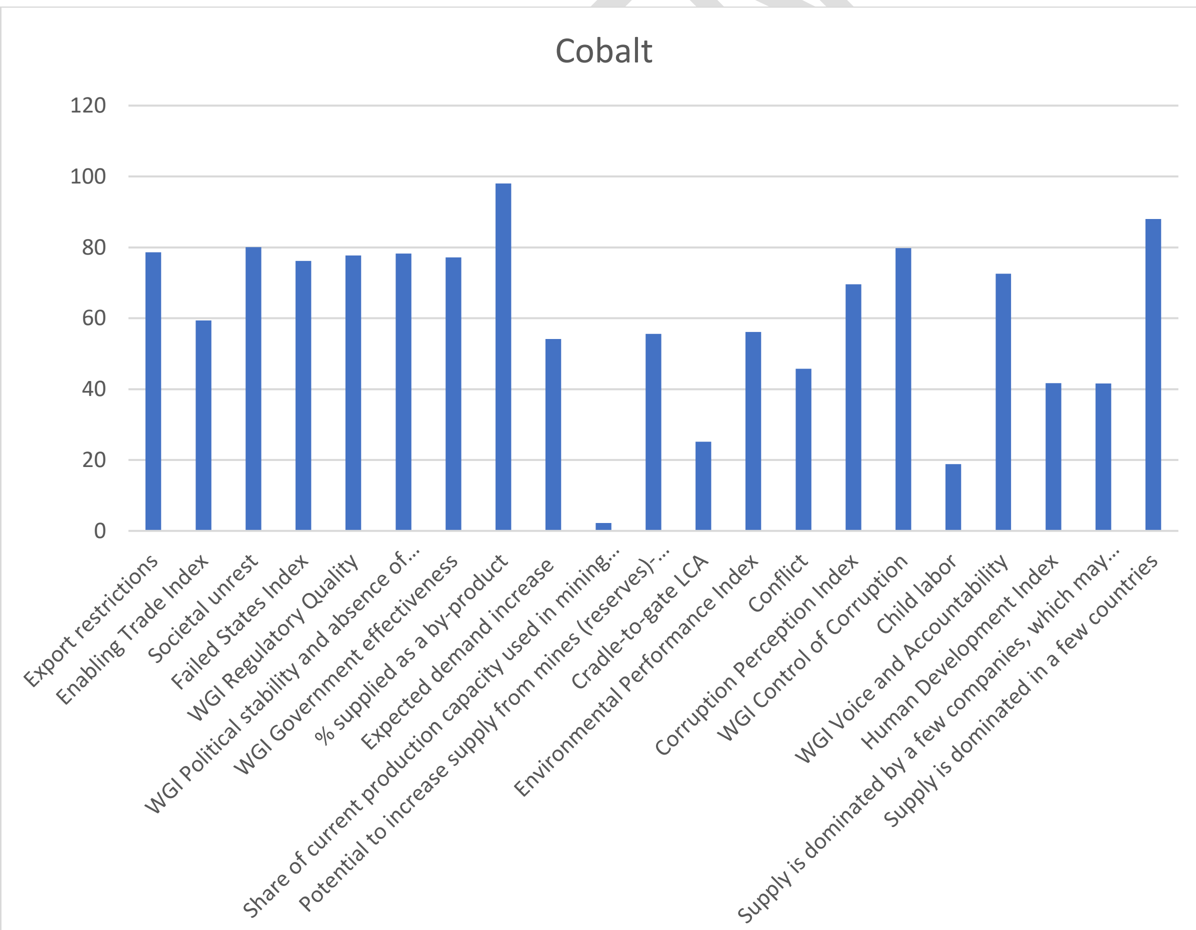

Figure 10 Results of the criticality assessment of Cobalt (WeLOOP, 2022)

From Figure 10, we can see that cobalt has high scores in almost all the criticality indicators used in this current assessment. By-product dependency is the first hotspot, 98% of cobalt is supplied as a by-product of copper and nickel mining operations. The artisanal-mined cobalt in Congo and cobalt production in Morocco were excluded from the previous statement.

The second hotspot for cobalt is that the supply is dominated by few countries. Congo is the world's leader in supplying mined cobalt with a share of about 70% of global mine production, followed by Russia with 4.5%, and Australia with 3.3% (see Figure 11).

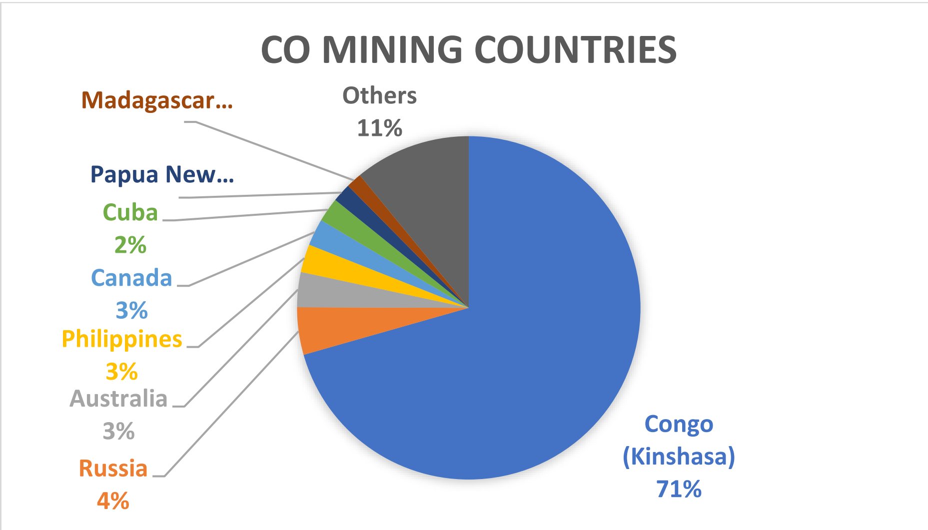

Figure 11 Cobalt mining countries (WeLOOP, 2022)

Congo exports partially refined cobalt to be further processed in other refining countries. China is the world's leader in refined cobalt production. Also, the world's biggest consumer of cobalt is China, with more than 80% going to the production of rechargeable batteries (see Figure 12).

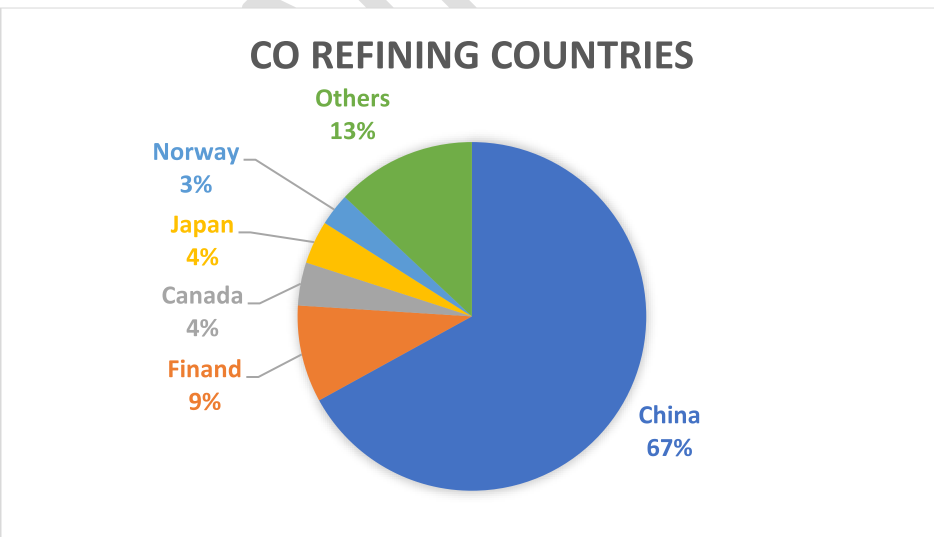

Figure 12 Cobalt refining countries (WeLOOP, 2022)

From Figure 10, we can see that the third hotspot for cobalt is that the supplying country is subjected to an unstable investment climate and social unrest. Which is represented by WGI - Regulatory Quality, WGI - Government effectiveness, and WGI – Political stability & absence of Violence/ terrorism, WGI-Rule of law, and Failed States Index. With scores' range between [76-80]. As we have discussed earlier the major mining producer of cobalt is Congo DRC (70.6% of cobalt are mined in Congo DRC), that has very poor governance and unstable investment climate.

The fourth hotspot for cobalt is trade restrictions, where 78.6% of the cobalt global supply (mining stage) has been subjected to export restrictions between 2017 and 2020. Cobalt is mainly mined in Congo DRC with low ETI score of about 3.03. The Enabling Trade Index ETI scores between 1 and 7, the higher score the better trade flow over the border of the supplying country.

The fifth hotspot for cobalt is social circumstances and environmental impacts associated with the mining and/or refining of cobalt. Which is represented by these criticality indicators: Environmental Performance Index, Cradle-to-gate LCA, WGI- Voice and Accountability, Human Development Index, Global Peace Index, Corruption Perception Index, WGI-control of corruption, and child labor indicator.

The mining stage of cobalt is the one with the higher risk due to social circumstances. Cobalt is mainly mined in Congo DRC which is known for a high risk of investment climate, and very poor governance according to the World Bank. Congo DRC has a low Human Development Index HDI (Congo DRC) = 0.48. Cobalt is a hotspot for child labor, whereas mentioned before it is mainly mined in Congo DRC where 26.7% of children ages (5-17) are involved in child labor. Also, small scale mining of cobalt takes place in the southern province of Katanga. This region of Congo is affected by human rights abuses such as child labor and unacceptable working conditions.

Cobalt has also a potential risk of low probability of increasing supply from mines. Presented by the indicator "Potential to increase supply from mines ((HHI-reserves)-Policy Perception Index)". Where PPI Indicates the overall investment attractiveness of mining policies of governments. Congo DRC has the biggest share of reserves 45% of global reserves (see Figure 13). The PPI score of Congo DRC is low PPI=29.

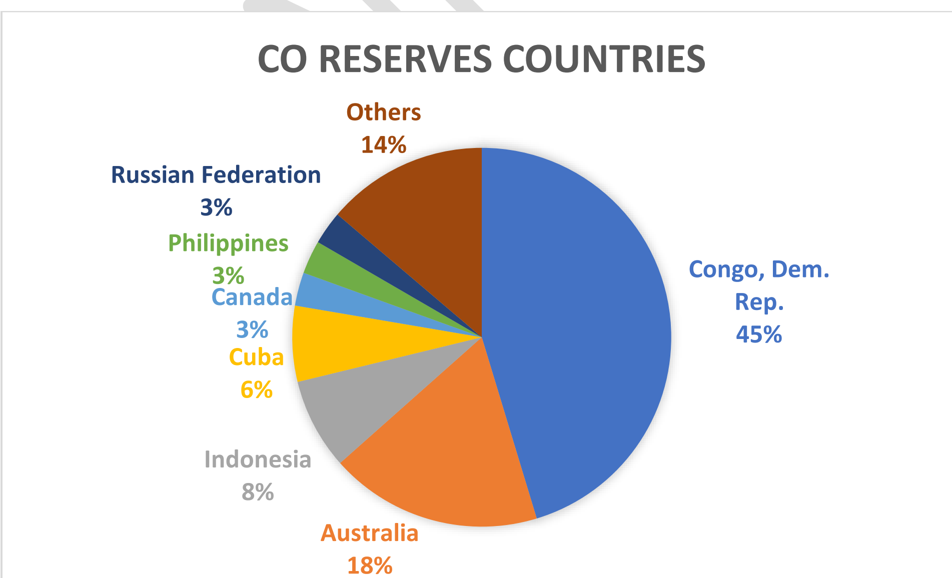

Figure 13 Cobalt reserves countries (WeLOOP, 2022)

Cobalt is an essential metal to implement the long-term EU climate-neutral economy strategy due to its use in rechargeable batteries for energy storage and electric vehicles. Cobalt major use is in rechargeable batteries (see Figure 14). Rechargeable batteries are crucial for the transportation electrification plan and energy storage for of low carbon technologies. And this explains the relatively high score of cobalt of the indictor "expected demand increase due to the use in emerging technologies".

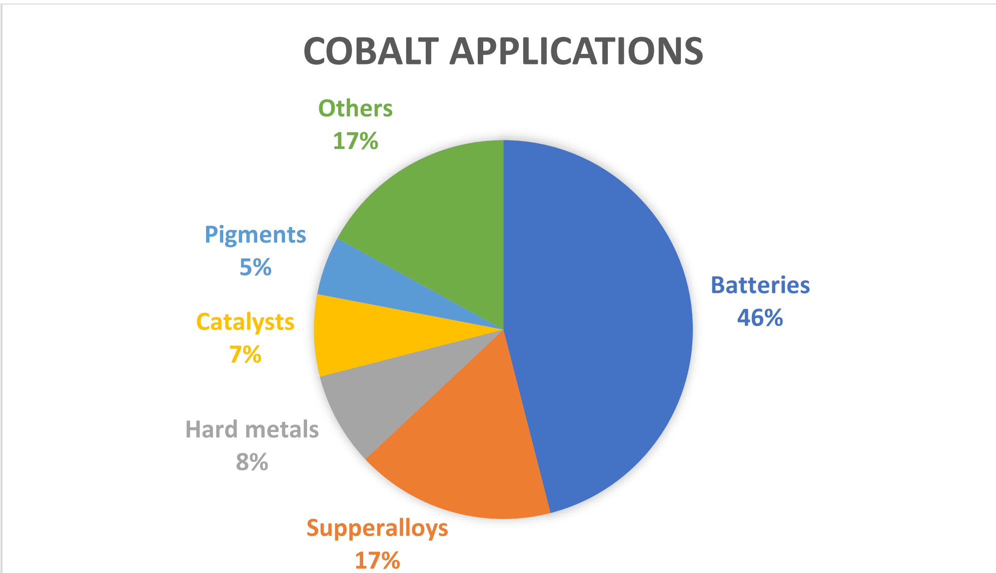

Figure 14 Cobalt main uses and applications (WeLOOP, 2022)

Natural graphite

Natural graphite is on the criticality list of the EU 2020. Results of the criticality assessment of Natural graphite are shown Figure 15.

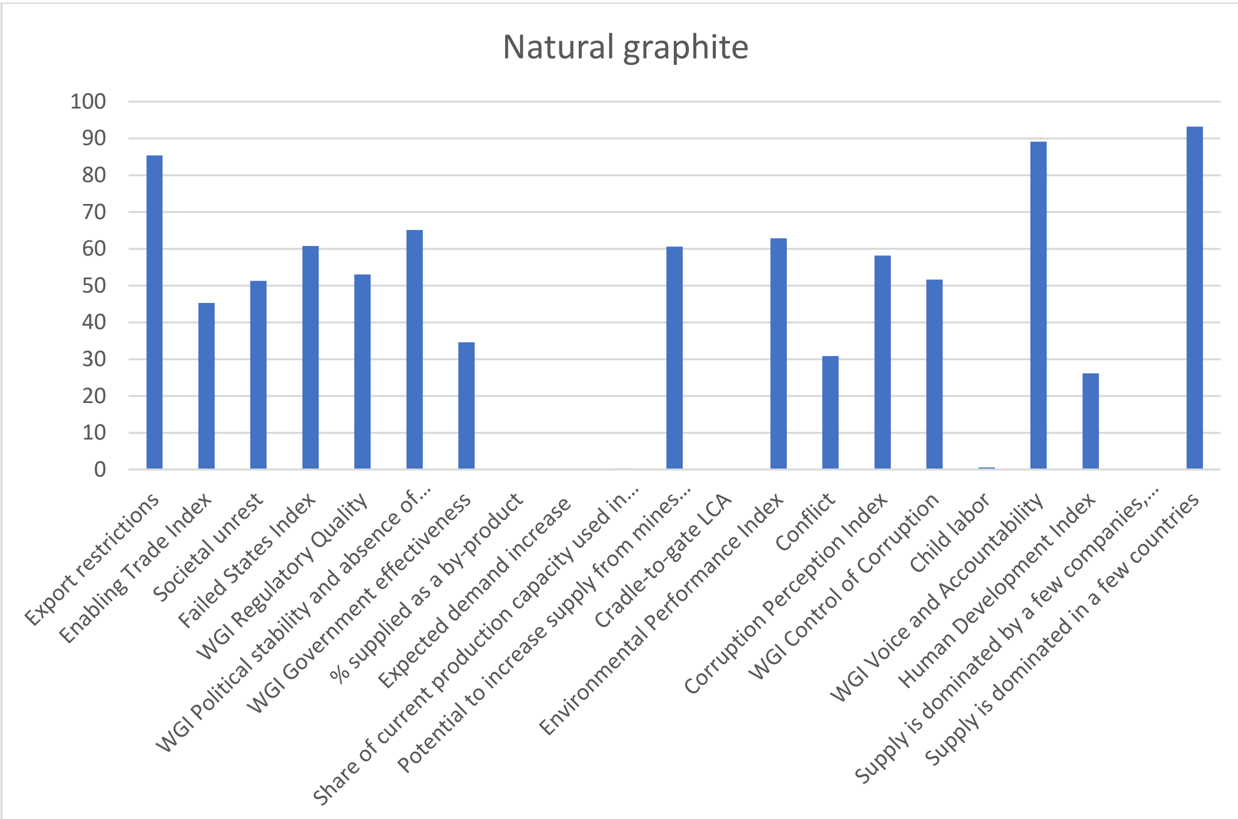

Figure 15 Results of the criticality assessment of Natural graphite (WeLOOP, 2022)

The first hotspot is "Supply is dominated by a few countries", natural graphite has high risk with China dominating 82% of the global mining production.

The second hotspot is the social circumstances related to human rights represented by "(HHI-mining)-(WGI-Voice and accountability)". Due to the domination of China with 82% of global mining production of natural graphite. The risk is due to the very high supply concentration and the level of governance in China which is between on average and low.

Same reasoning goes to the social unrest, unstable investment climate, and other social circumstances associated indicators (failed state index, WGI-Regulatory Quality, and WGI-Political stability and absence of violence/terrorism, corruption indicators).

The third hotspot is "Export restrictions" with 85.4% of the total global supply (mining stage) has been subjected to export restrictions between 2017 and 2020.

Reserves accessibility could be limited due to unattractive mining policies in the reserves countries. This was estimated by the indicator "(HHI-reserves)-Policy Perception Index)". Turkey, China, and Brazil have the major shares of natural graphite reserves, with shares of 28%, 23%, and 22% respectively. The mining policy attractiveness in Turkey, China, and Brazil is on average, with a PPI score of 55.4, 44.5, and 47.6 respectively.

The results of this criticality assessment show risks of supply concentrations, trade restrictions, social circumstances, social unrest, unstable investment climate, and reserves accessibility associated with natural graphite. All these risks combined result in the criticality of natural graphite.

One of the limitations of this current criticality assessment is that the "Expected demand increase due to use in emerging technologies" is missing for natural graphite. Also, the shares of dominating companies and the EI score (Cradle-to-gate LCA) are missing.

The reason behind the data gaps in this assessment is that the data source for the expected demand increase (Leuven and Gregoir -Principal Author, no date) just includes metals.

However, natural graphite is important for several emerging technologies. Such as the production of the anode in lithium-ion batteries. It is also used as the primary filter material in bipolar plates for fuel cells ("Study on the EU's list of Critical Raw Materials (2020) Final Report," no date).

Lithium

Lithium is on the EU criticality list of 2020; the results of lithium criticality assessment are shown in Figure 16.

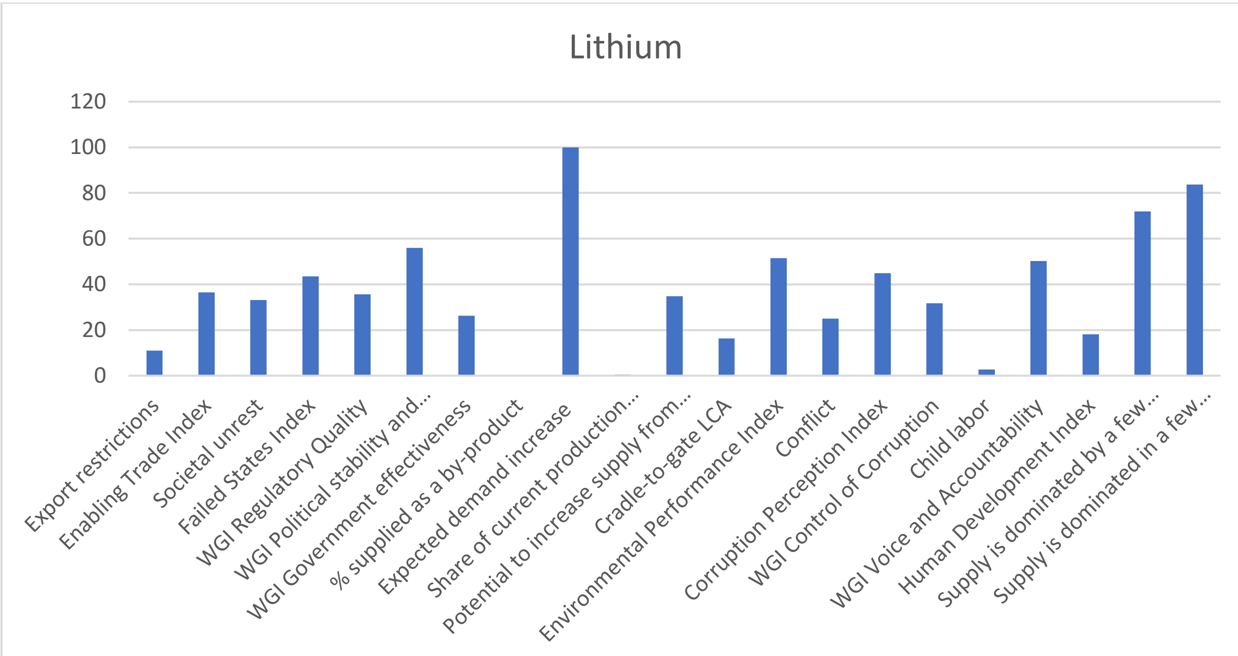

Figure 16 Results of the criticality assessment of Lithium (WeLOOP, 2022)

The main hotspot for lithium is the expected demand increase due to demand increase in emerging technologies and/or emerging economies (with a 100% expected demand increase).

Lithium has a big contribution to low-carbon technologies, it is essential for the electrification of the transportation system (Lithium-ion batteries) for hybrid and electric vehicles. Lithium-ion batteries are also used to store energy for renewable energy (Solar, wind, etc.). Moreover, lithium is used in novel low-density Al-Li alloys which is used in the production of aircrafts, to reduce their weight and improve the fuel economy ("Study on the EU's list of Critical Raw Materials (2020) Final Report," no date). The demand of lithium is expected to increase to a 21-fold times of the current demand of lithium (Leuven and Gregoir -Principal Author, no date).

The second hotspot for lithium is the "Supply is dominated by a few countries" with Australia, Chile, China dominating 55%, 26%, and 14% of global mining production, respectively (See Figure 17).

The third hotspot is "Supply is dominated by a few companies" the top four major mining companies of lithium are: Jiangxi Ganfeng Lithium, Tianqi Lithium, Albemarle, and SQM with market shares of 29%, 21%, 20%, 18% respectively.

Lithium has high importance the EU economy due to its big contribution to low-carbon technologies. With high supply concentration in a few countries for refining and mining stages. With some social and environmental circumstances associated to the supplying countries. Moreover, supply is dominated by a few companies, which results in it considered critical to the EU economy.

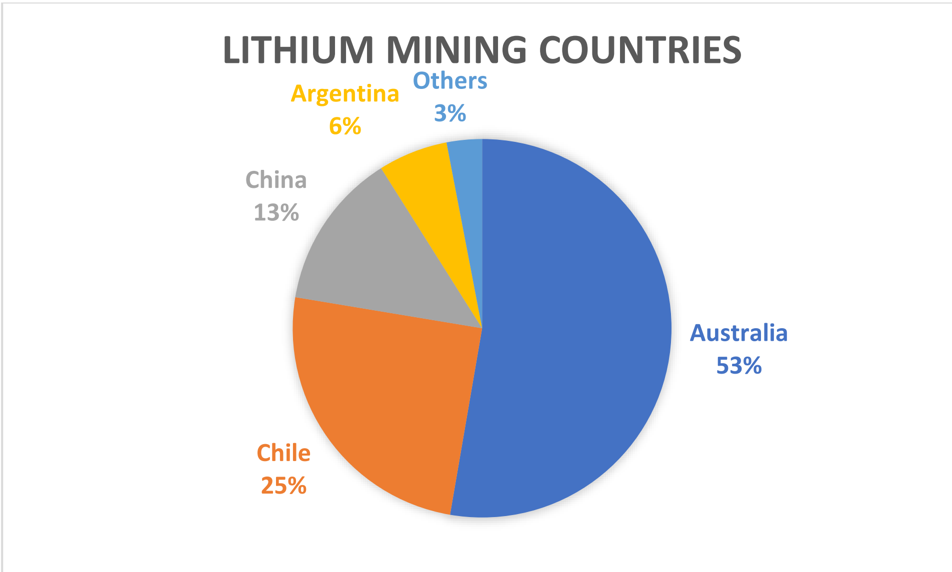

Figure 17 Lithium mining countries (WeLOOP, 2022)

Regarding the rest of indicators (trade restrictions, societal unrest, unstable investment climate, and environmental and social circumstances), for lithium the refining stage is the one that is more susceptible for supply risks. Which is different from the rest of battery raw materials where the mining stage is usually more susceptible for supply risks. The top lithium refinery exporters are Chile, China, and Argentina (Figure 18). This is in accordance with the results of the EU criticality assessment in 2020.

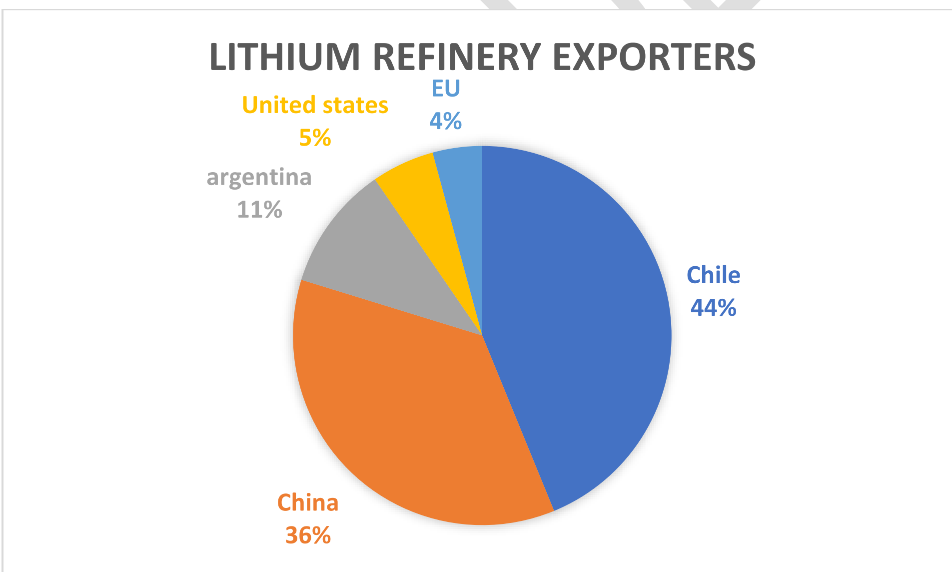

Figure 18 Lithium refinery exporters (WeLOOP, 2022)

Lithium was not considered as critical in the EU criticality study in 2017, it was added to the criticality list in 2020. Due to the processing (refining stage). The EU criticality study in 2017 did not include the processing/refining stage (the lithium compounds considered were lithium carbonate and lithium hydroxide). In 2020 the processing/refining stage was evaluated, the study showed that processing/refining is the stage with the higher supply risk.

Bauxite/Aluminum

Bauxite is on the EU criticality list 2020; the results of our criticality assessment are shown in Figure 19.

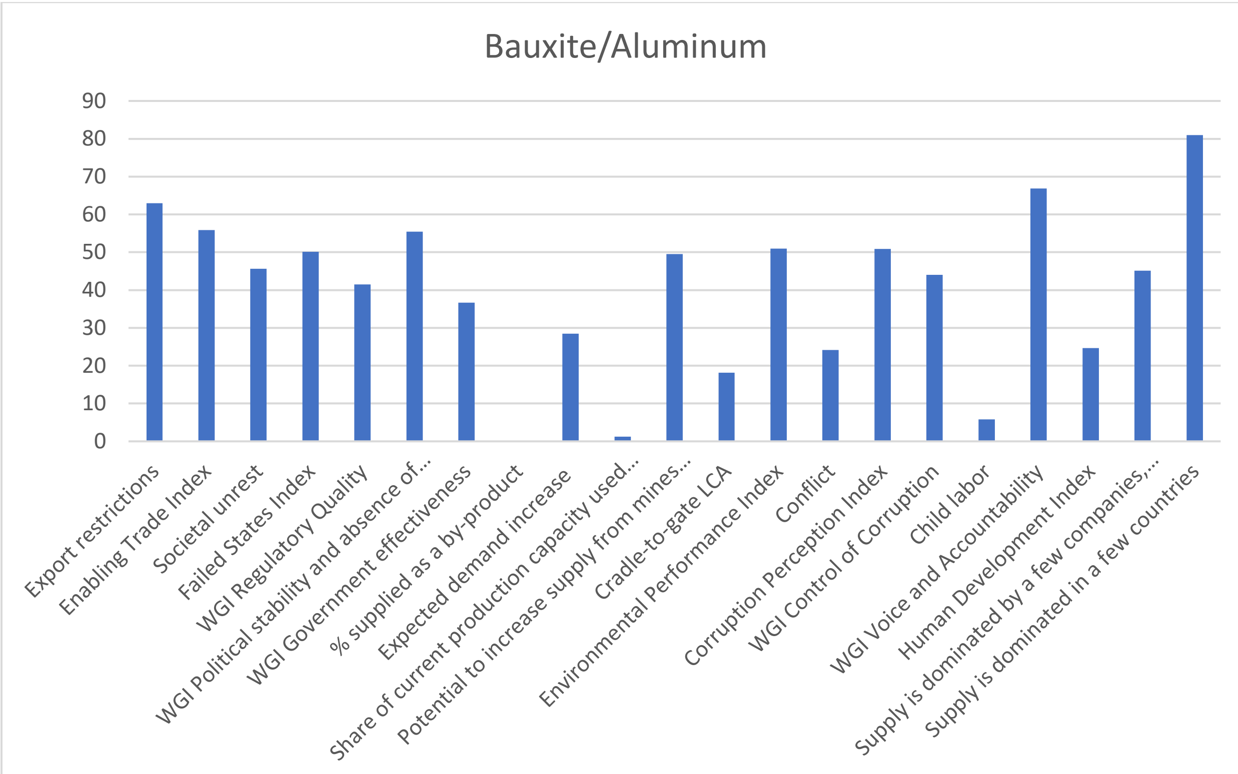

Figure 19 Results of the criticality assessment of Bauxite/Aluminum (WeLOOP, 2022)

The main hotspot for Bauxite/Aluminum is "The supply is dominated in a few countries", the result here is associated with the refining stage. With China dominates 56% of the Aluminum global refining production (see Figure 21). "The supply is dominated in a few countries" is also high for the mining stage. With Australia, China, and Guinea dominating the bauxite mining production with shares of the global supply of 28%, 22%, 22%, respectively (see Figure 20).

The second hotspot is the social circumstances associated with human rights (measured by WGI-Voice and Accountability). The score here associated to the Aluminum refining stage.

The third hotspot is trade restrictions, due to export restrictions in the Aluminum refining countries. The second trade restrictions indicator is ETI (Enabling Trade Index), for this indicator the risk comes from the mining stage. Bauxite is mainly mined in Australia, China, and Guinea with ETI scores of 5.1, 4.49, 0 respectively. Due to data gapes the ETI for Guinea was set to zero, which might influence this score since Guinea supply 22% of global bauxite mine production. (22% of the market is not represented because of data gaps for Guinea).

Other risks related to social unrest, unstable investment climate, social and environmental circumstances is playing a role in causing the supply risk in both mining and refining stages.

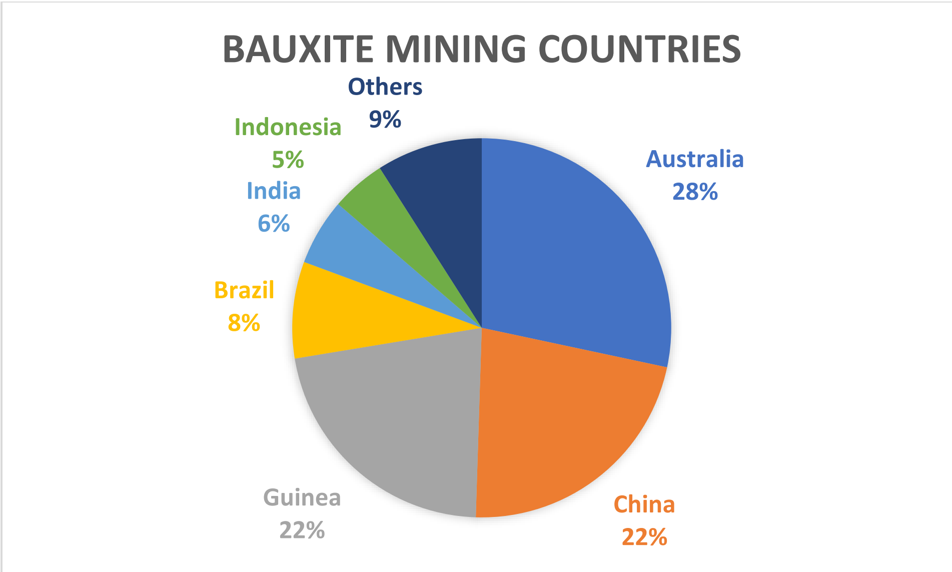

Figure 20 Bauxite mining countries (WeLOOP, 2022)

The Aluminum refining countries are shown in the following figure.

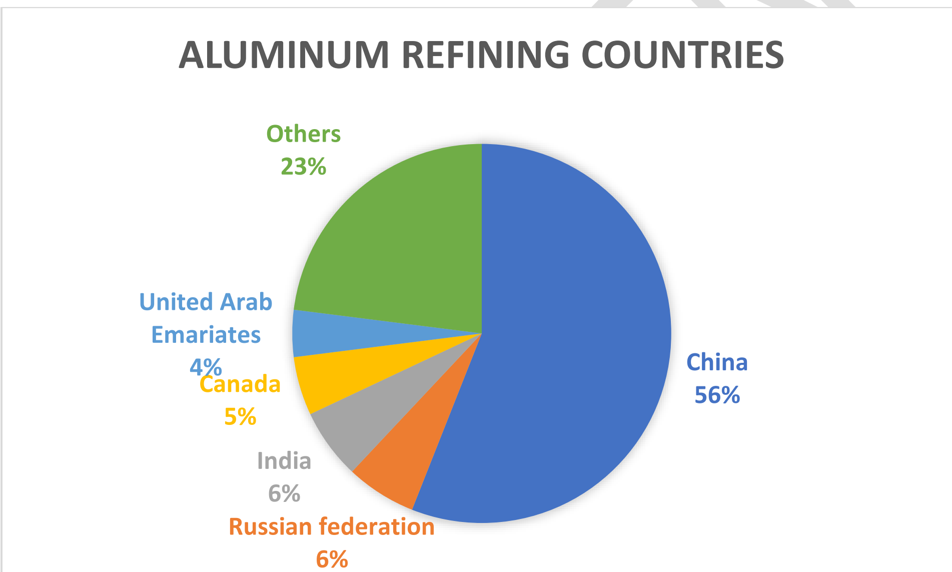

Figure 21 Aluminum refining countries (WeLOOP, 2022)

Bauxite/Aluminum was not on the EU criticality list in 2017, it was added to the EU criticality list in 2020 due to the supply risks associated with the extraction stage (mining stage). Aluminum is critical due to its importance in the EU manufacturing sector and the competing demand from other global regions/ countries (for example China is the major Importer of Aluminum). It is also due to the EU import reliance which is substantial. The EU import reliance of bauxite is 87%, the EU import reliance of refined aluminum is 59% (RMIS,2022). In the is current criticality assessment the import reliance was not assessed, which may consider as a limitation that should be discussed in future assessments.

Nickel

The results of the criticality assessment of Nickel are shown in Figure 22

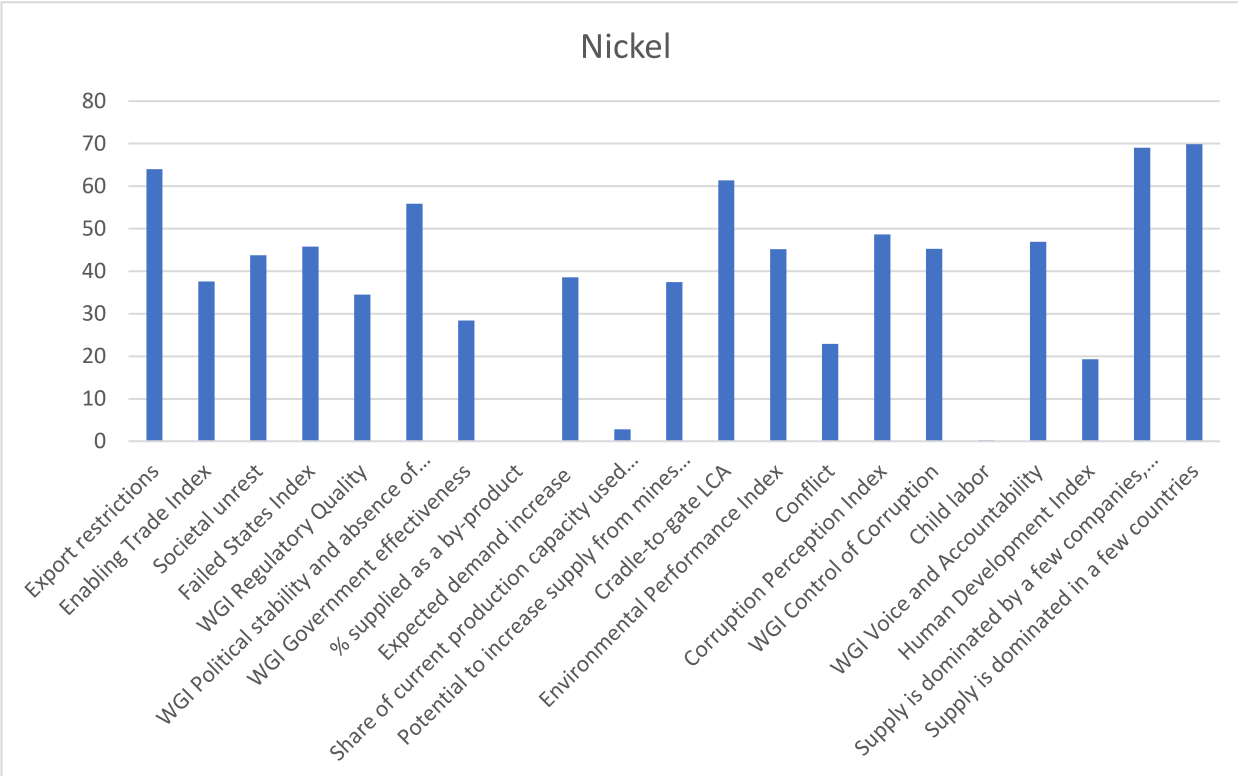

Figure 22 Results of the criticality assessment of Nickel (WeLOOP, 2022)

The main hotspot for nickel is "Supply is dominated in a few countries", the risk here is associated with the mining stage. The top three nickel mining producers are Indonesia, Philippine, and Russia with shares of 37%, 14%, 9%, respectively.

The second hotspot of nickel is" supply is dominated by a few companies", the top three nickel mining companies are Nornickel, Vale, and Glencore with market shares of 28%, 25%, and 13% respectively.

The third hotspot is export restrictions from the top three mining countries Indonesia, Philippine, and Russia. Nickel has environmental impacts because of its relatively considerable LCA score.

The other risks of societal unrest, unstable investment climate, and social and environmental circumstances are relatively low. Except for WGI political stability and absence of violence/terrorism, this score is associated with the mining stage (Indonesia, Philippine, and Russia).

Nickel was not on the EU criticality list 2020, however recently lithium market has faced price fluctuations due to the Russian-Ukraine war. This political conflict did not reflect in this current assessment because most of the country performance indicators were evaluated in 2020, 2021, 2019, and some in 2016. However Global Peace Index, and Failed Sates Index were marked that they represent the year 2022.

The conflict situation in Russia could cause a supply risk for nickel in the EU. Because the major EU sourcing comes from Russia with a share of 26%. EU sourcing of refined nickel is shown in Figure 23.

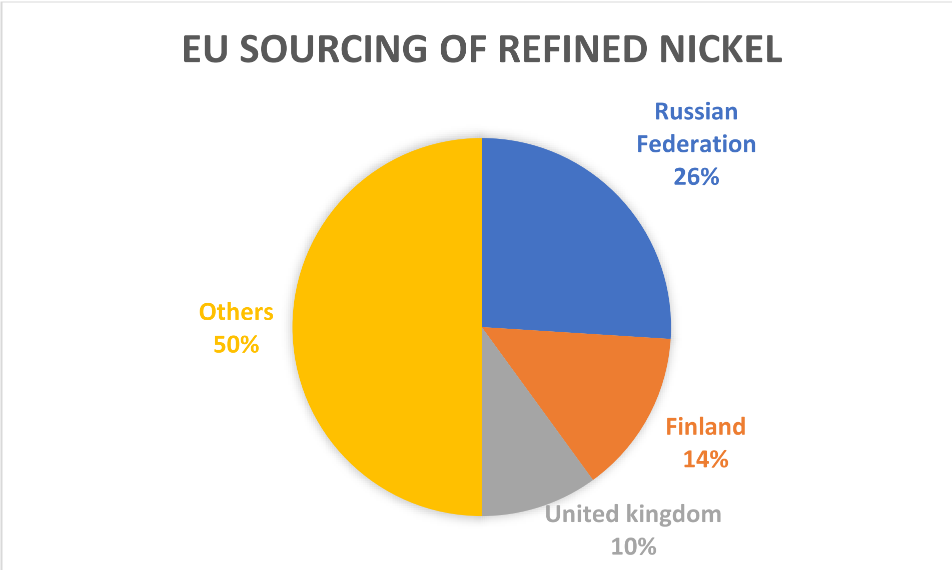

Figure 23 EU sourcing of refined nickel (WeLOOP, 2022)

Nickel prices have faced a considerable increase due to the Russian/Ukraine war (20th of February 2022). Where the price of nickel was 23300 USD/ton on February 1st, and it reached 48508 USD/ton between March 7th-15th. The nickel market faced strong price fluctuations between March and May 2022, a s shown in Figure 24. In April 2022, nickel prices started decreasing until they reached 26450 USD/ton at the time of writing this report on May 17th, 2022.

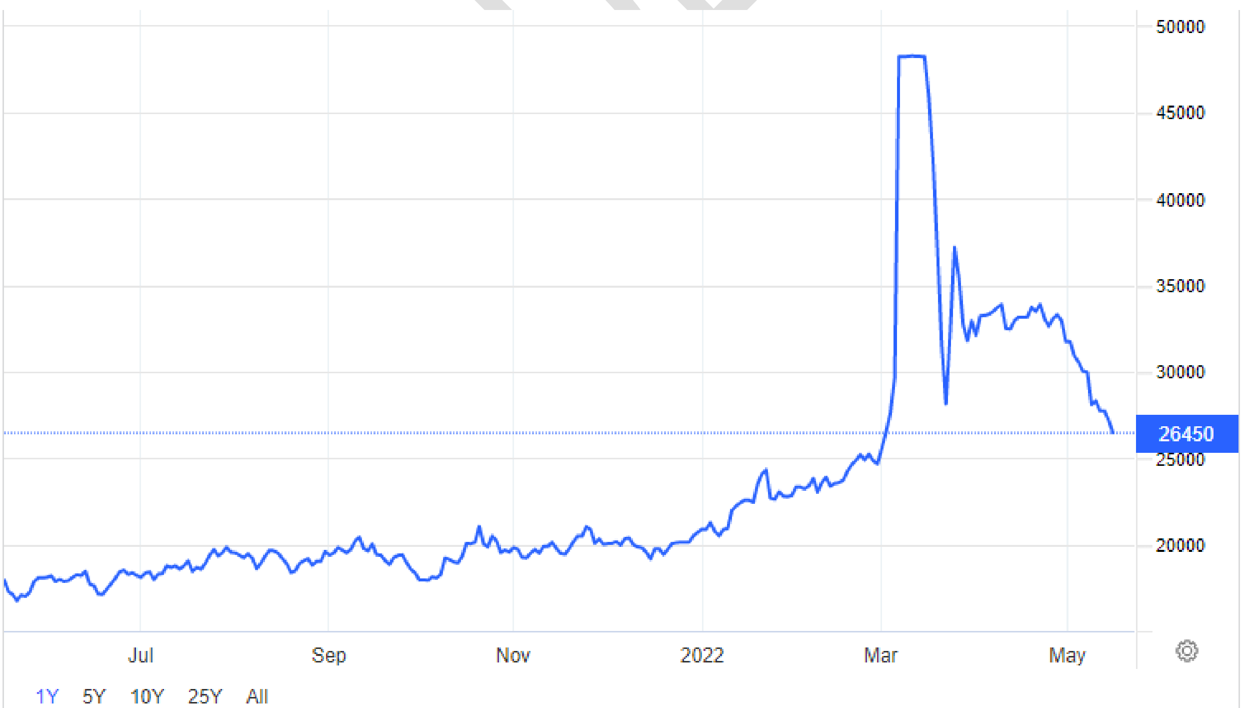

Figure 24 Nickel price changes in the last year (2021-2022) (USD/ton) (Trading Economics 17th May 2022) https://tradingeconomics.com/commodity/nickel

Other concerns have been arising lately is the potential criticality risk of high-quality nickel class. Depending on the application of nickel it can be divided into two classes nickel class 1 and nickel class 2. Nickel class 1 is used in rechargeable batteries and is mined from nickel sulfide. Where nickel class 2 is used in the steel industry and mined from nickel laterite. Nickel class1 sulfide ores are mainly mined in Russia, Canada, and Australia. Nickel class2 laterite ores are mainly mined in Australia, Indonesia, the Philippines, and New Caledonia.

To answer this question there is a need that future criticality studies differentiate between the different deposits, grades, classes of the same metal. This will not be easy due to the lack of well documented data of mining and refining operations.

Manganese

The results of the criticality assessment of Manganese are shown in Figure 25

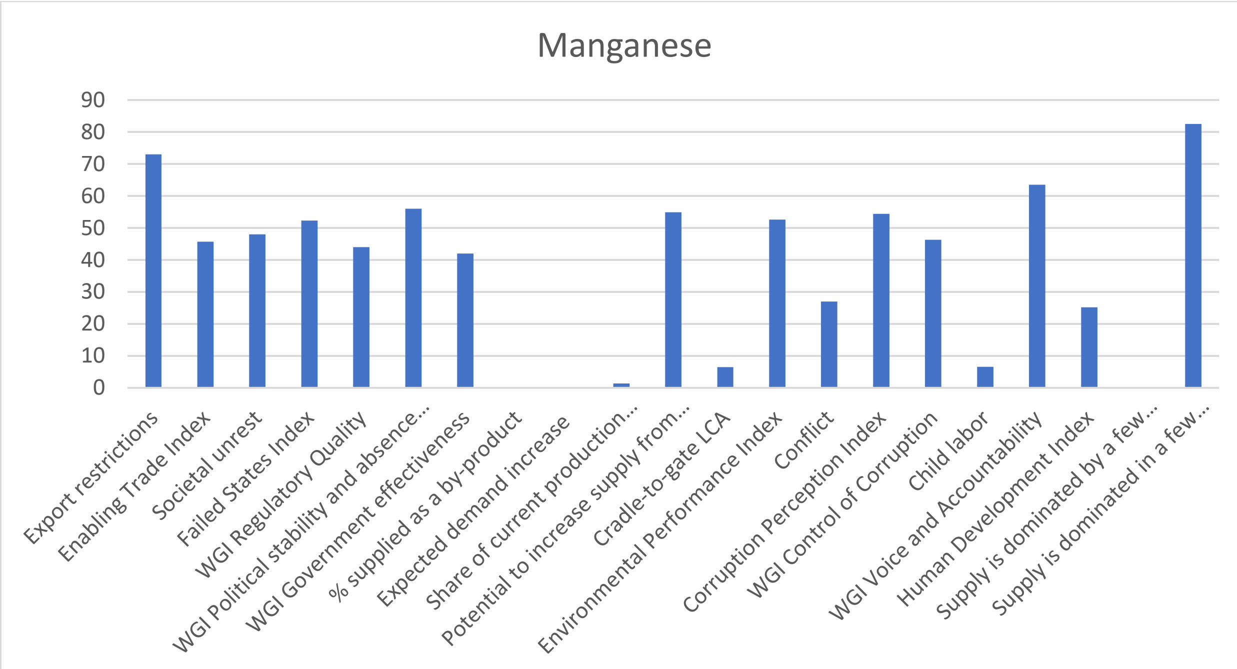

Figure 25 Results of the criticality assessment of Manganese (WeLOOP, 2022)

The main hotspot of manganese is "Supply is dominated by a few countries" the score here is associated to the refining stage where China dominates the global manganese refining production with a 60% share.

The second hotspot is the export restrictions, the score is associated with the mining stage with export restrictions from the two main mining producers South Africa (37%), and Gabon (18%). The other risks associated to societal unrest, unstable investment climate, and social and environmental circumstances are relatively low.

For this current assessment, taking in account all the indicators manganese is not to be consider critical. Manganese was not on the EU criticality list in 2020.

Also, for there is arising concerns that high-quality grade manganese might be critical. Manganese is abundant, but the high-quality grade used for batteries might be critical. To answer this question there is a need that future criticality studies differentiate between the different deposits, grades, classes of the same metal. This will not be easy due to the lack of well documented data of mining and refining operations.

Iron/Steel

The results of the criticality assessment of Iron/Steel are shown in Figure 26

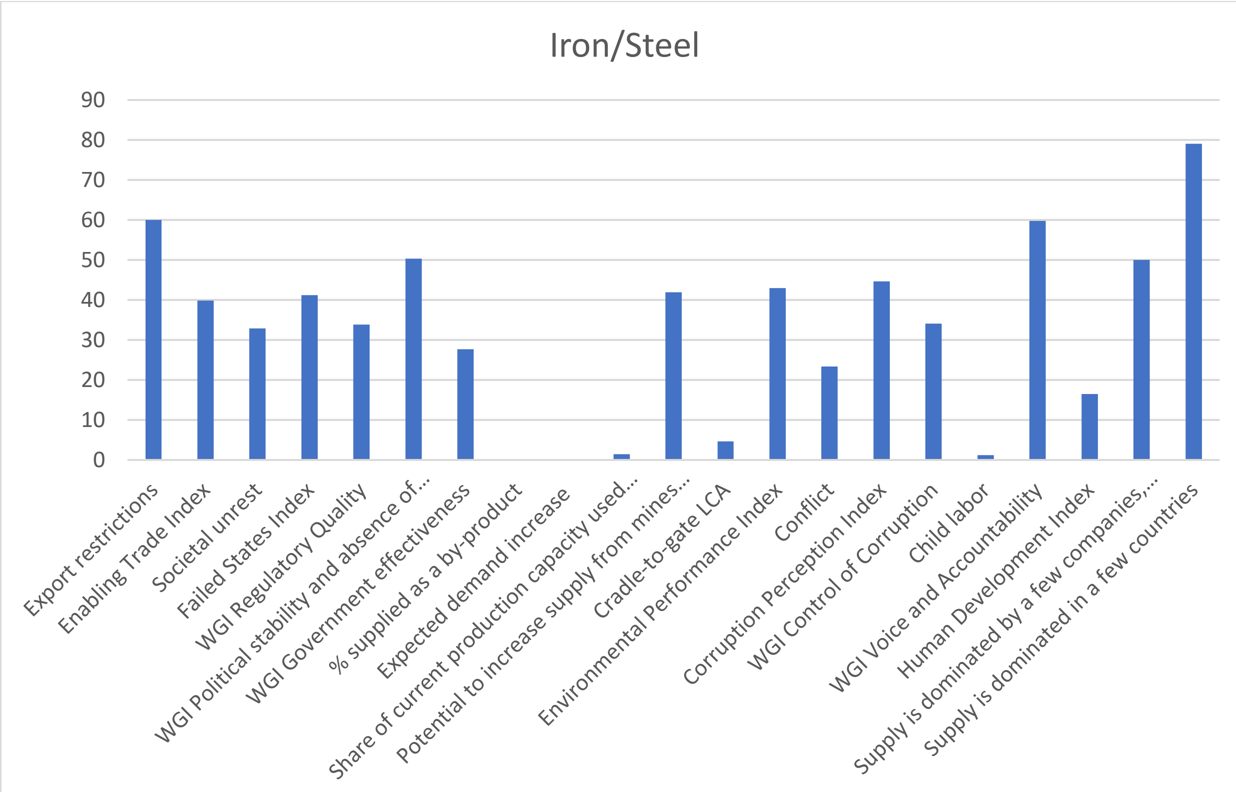

Figure 26 Results of the criticality assessment of Iron/Steel (WeLOOP, 2022)

The main hotspot is “supply is dominated by a few countries” which is associated to the refining stage. Where China dominates the global supply with a share of 54%. The second hotspot is the export restrictions from the refining stage.

The other risks associated to societal unrest, unstable investment climate, trade restrictions, and social and environmental circumstances are relatively low. For this current assessment, taking in account all the indicators Iron/Steel is not to be consider critical. Iron/Steel was not on the EU criticality list in 2020.

Phosphate rock

The results of the criticality assessment of Phosphate rock are shown in Figure 27

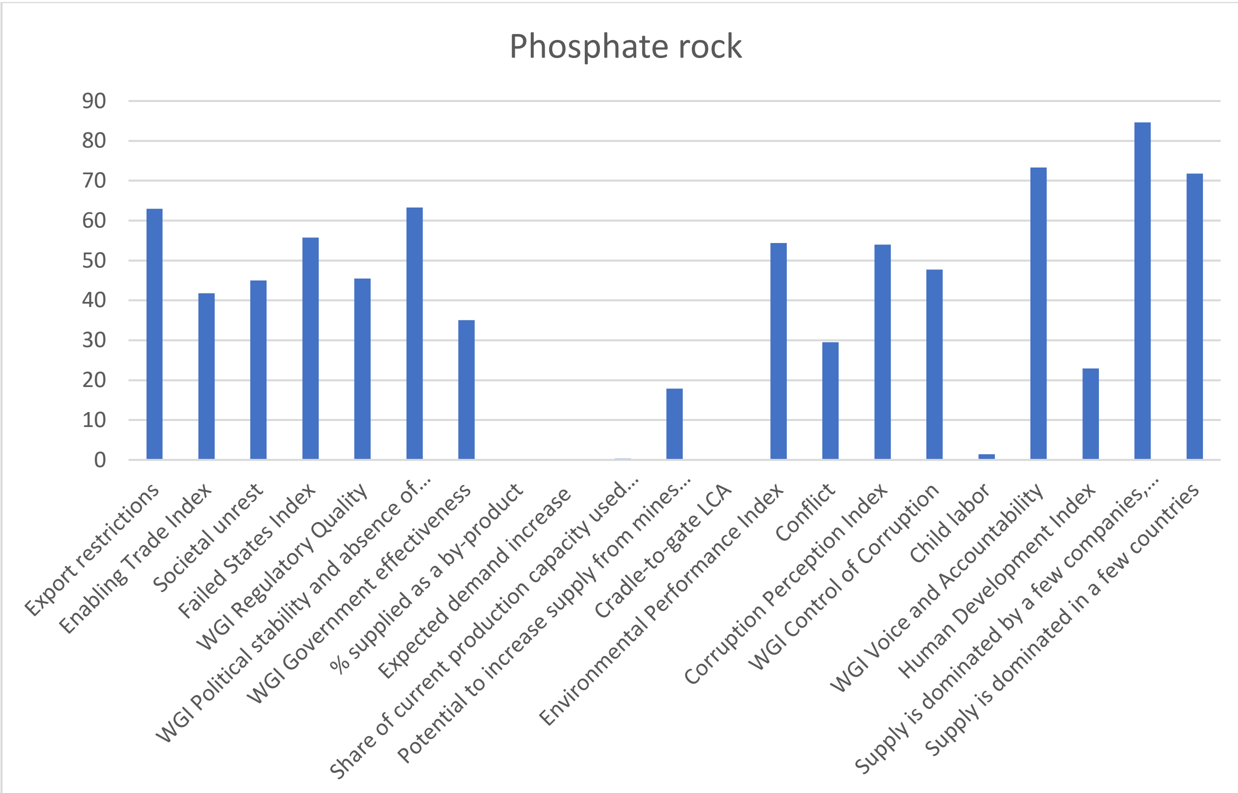

Figure 27 Results of the criticality assessment of Phosphate rock (WeLOOP, 2022)

The main hotspot here is “Supply is dominated by a few companies”, the top three Phosphate rock mining companies are Vale, Nutrien, and Mosaic with market shares of 53%, 35%, and 11% respectively. Uncertainties of this score are possible due to lack of well documented data of the market shares of mining companies.

The second hotspot is “Supply is dominated by a few countries” which is associated to the mining stage. Phosphate rock mining production supply is dominated by China, Morocco, and United States with 39%, 17%, 10% of global supply, respectively.

The third hotspot is the social circumstances related to human rights in the supplying countries WGI-Voice and accountability (WGI-VA). Since Phosphate rock is mainly mined in in China and Morocco where the governance level is between on average and low in both countries.

For this current assessment, taking in account all the indicators Phosphate rock is not to be consider critical. Phosphate rock was not on the EU criticality list in 2020.

Copper

The results of the criticality assessment of copper are shown in Figure 28.

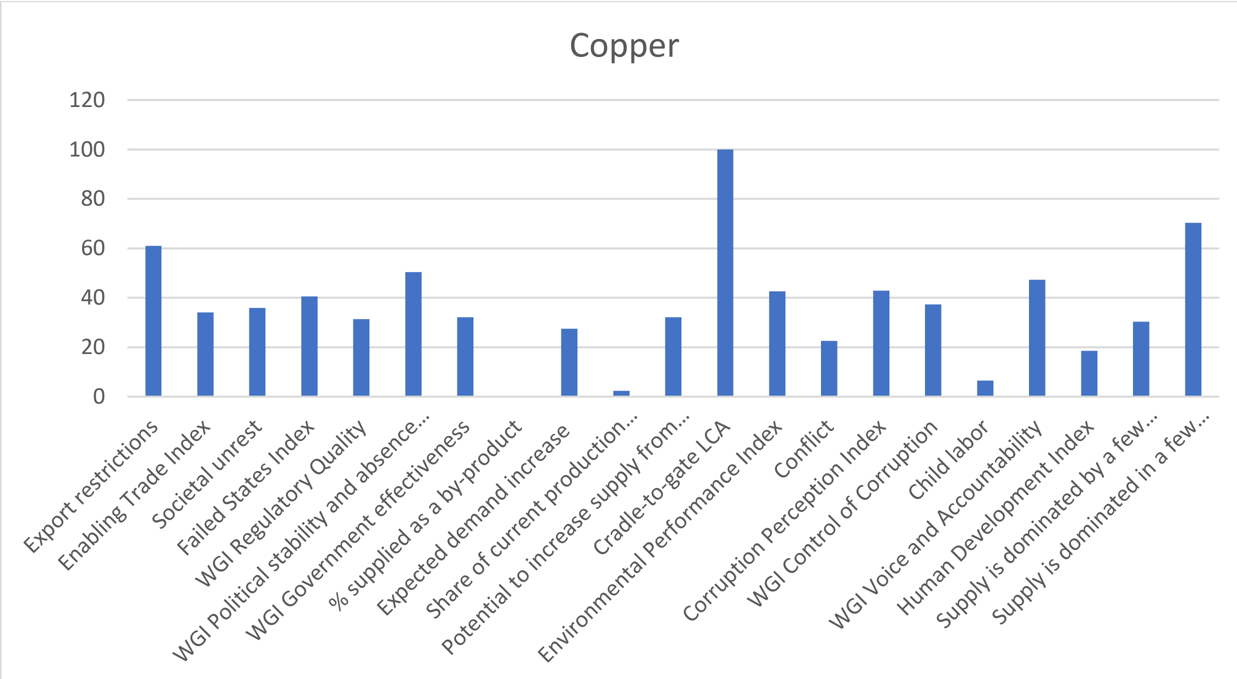

Figure 28 Results of the criticality assessment of Copper (WeLOOP, 2022)

The main hotspot for copper is its environmental impacts associated with the extraction and the refining stages. The second hotspot is "Supply is dominated by a few countries" which is associated with the refining stage.

Copper has low scores in almost all of the criticality indicators in our assessment. Hence, copper is not to be consider critical in this current assessment. Copper was not on the EU criticality list in 2020.

The results of the criticality assessment based on the webtool model

The results of the criticality assessment are discussed for each of the three risks individually. The results' discussion is simplified by dividing each risk into its problematics, criticality aspects, and indicators. Then we discuss the hotspots for each indicator, and the reasons behind these hotspots. (Check Annex 6 / Criticality assessment results based on the webtool model, for the full results discussion). Here we only present an example of the risk "the company not having access to lithium battery raw materials". The first problematic that may cause this risk "mismatch between supply and demand", one of its sub-problematics "one of the suppliers is not able to deliver their product", which could be caused by ten criticality indicators. Here we chose only to analysis three indicators: supply is dominated by a few countries (mining and/or refining), and supplying countries is subjected to trade restrictions.

Analyzing the risk of the company not having access to lithium battery raw materials

The supply risk of not having access to lithium battery raw materials, this potential risk might take place due to two main problematics:

- There is a mismatch between supply and demand of lithium battery raw materials in the market.
- The supply of lithium battery raw materials is not compliant with (future) policy regulations.

There is a mismatch between supply and demand in the market

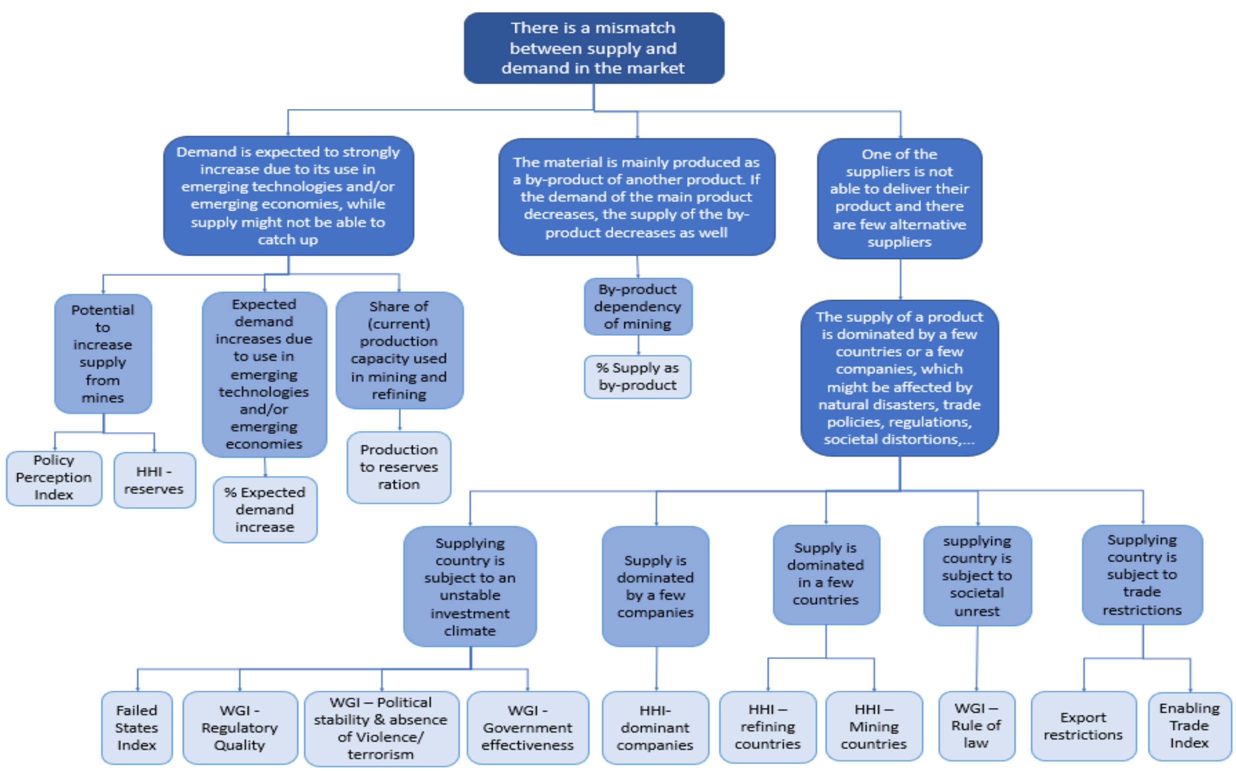

Figure 29 Schematic of the second problematic "There is a mismatch between supply and demand of lithium battery raw materials in the market" (problematics/criticality aspects/criticality indicators) (WeLOOP, 2022)

A mismatch between supply and demand of lithium battery raw materials in the market, may be caused by three sub-problematics: a strong demand increase while the supply might not be able to catch up, the material is mainly produced as a by-product of another product, and one of the suppliers is not able to deliver their product (with few alternative suppliers) (see Figure 29).

One of the suppliers is not able to deliver their product could happen due to several reasons: the supply of a product is dominated by a few countries or a few companies, which might be affected by natural disasters, trade policies, regulations, and societal distortions etc. Which was categorized by five criticality aspects (see Figure 29). Here we will just discuss three indicators, supply is dominated by a few countries (mining and/or refining), and supplying countries is subjected to trade restrictions.

Supply is dominated by a few countries

Supply is dominated by few countries, this indicator evaluates if a few countries have a dominant share of the supply (for mining production and refining production), and then it chose the stage with the higher risk. All lithium battery raw materials have scores between 70 and 93 (see Figure 30).

Figure 30 Supply is dominated by a few countries, and the supplying countries are subjected to trade restrictions (WeLOOP, 2022)

Natural graphite has the highest risk with China dominating 82% of the global supply (mining stage). Cobalt comes in second with Congo DRC dominating 70.6% of the global supply (mining stage). Lithium comes in third with Australia, Chile, China dominating 55%, 26%, and 14% of global supply, respectively (mining stage). For manganese China dominates 60% of global supply (refining stage). Aluminum smelter production supply is dominated by China with 57% of global supply (refining stage). Steel supply is also dominated by China with 54% of global supply (refining stage). Phosphate rock supply is dominated by China, Morocco, and United States with 39%, 17%, 10% of global supply, respectively (mining stage).

Copper supply is dominated by China and Chile with 41% and 9% respectively (refining stage). And lastly, nickel supply is dominated by Indonesia, The Philippine, and Russia 37%, 14%, 9% of global supply, respectively (mining stage).

Regarding the supply is dominated by a few countries, we found that the mining stage is the hotspot of Natural graphite, phosphate rock, cobalt, nickel, and lithium. Where the refining stage is a hotspot for manganese, Aluminum, copper, and steel.

Supplying countries are subjected to export restrictions

The second indicator with high risk of almost all lithium battery raw materials is export restrictions. Posing export restrictions by major supplying countries can lead to a volatile market due to price increases, which results in supply disruptions. There are many forms of raw materials export restrictions, however, the most common are export prohibition, export taxes, export quotas, and licensing requirements. This indicator was applied to the mining and refining stages to estimates the total supply share that is subjected to export restrictions between 2017-2020. Then the stage with the highest score (higher risk) was chosen as the final score.

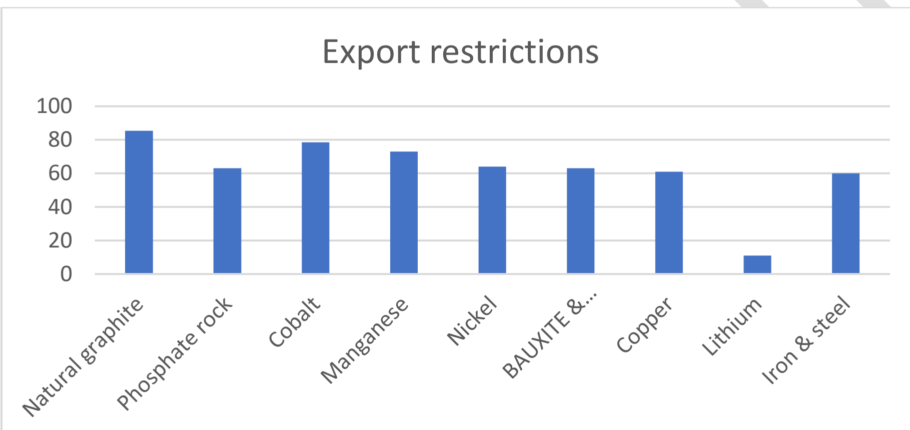

Figure 31 Criticality assessment results for " supplying countries is subjected to export restrictions", which might cause a mismatch between supply and demand in the market, which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022).

From Figure 31, one can see that natural graphite is the main hotspot, where 85.4% of the total global supply (mining stage) has been subjected to export restrictions between 2017 and 2020. For cobalt 78.6% of the total global supply (mining stage) has been subjected to export restrictions between 2017 and 2020. 73% of manganese global supply (mining stage) has been subjected to export restrictions between 2017 and 2020. 64% of nickel's total global supply (mining stage) has been subjected to export restrictions between 2017 and 2020. 63% of phosphate rock's total global supply (mining stage) has been subjected to export restrictions between 2017 and 2020. 61% of copper's total global supply (mining stage) has been subjected to export restrictions between 2017 and 2020.

For Aluminum 63% of the total global supply (refining stage) has been subjected to export restrictions between 2017 and 2020. For steel too, the refining stage is the one with most export restrictions, where 60% of the total global supply has been subjected to export restrictions between 2017 and 2020. Lithium was the only raw material with very low export restrictions risk, where only 11% of the total global supply (refining stage) has been subjected to export restrictions between 2017 and 2020.

Results of the life cycle assessment LCA

Results for the DQR for available inventories and databases for lithium batteries recycling processes

We have conducted a data quality rating (DQR) for the available LCIs for lithium batteries recycling processes, see Table 7. This recalculated DQR is according to the PEF method applied to the use of data in the European context for the year 2022.

Table 7 Data quality rating (DQR) according to the PEF method for available LCIs for lithium batteries recycling processes ***(for a European scope)*** *(WeLOOP, 2022)*

LCI	Process	Source	TiR	TeR	GR	Average	Overall DQR
(Mohammad Ali Rajaeifar, 2021) UK	DC plasma smelting	Tetronics company, UK, 2019	3	3	2	2.6	Good quality
	UHT Furnace	Umicore patent, Belgium,2007	5	5	2	4	Fair quality
	Hydro	GREET model, lab experiment, US, 2014	5	5	5	5	Poor quality
(Marit Mohr, 2020) Germany	Hydro	Recupyl, France, 2004 (Fisher, 2006)	5	4	2	3.6	Fair quality
	Pyro	Batrec, Switzerland, 2004 (Fisher, 2006)	5	4	2	3.6	Fair quality
	Advanced hydro	Duesenfeld, Germany, 2014	5	3	2	3.3	Fair quality
(Rebecca E. Ciez, 2019) Germany	Pyro	Umicore patent, Belgium,2007	5	5	2	4	Fair quality
	Hydro	GREET model, lab experiment, US, 2014	5	5	5	5	Fair quality
	Direct	Lab-scale experiment, Germany, 2015	5	4 or 3	2	3.6 or 3.3	Fair quality
Ecoinvent	Pyro	Batrec, Switzerland, 2004 (Fisher, 2006)	5	4	2	3.6	Fair quality
	Hydro	Recupyl, France, 2004 (Fisher, 2006)	5	4	2	3.6	Fair quality
GaBi	Pyro	Project LithoRec, Germany, 2018	3	2	2	2.3	Good quality
PEF/OEF	Mixed Pyro-Hydro	Dewulf J, et al. 2009 J. Xua et al. 2008 Umicore 2009	5	5	2	4	Fair quality

Based on this DQR, one can see that most of the available databases and LCIs have just fair quality (score: >3 to ≤ 4.0). However, none of the available databases and LCIs scored excellent or very good quality.

According to the PEF method, these data cannot be used for the most relevant processes of a company. For example, the data cannot be used to assess EV cars or EV bikes as the end of life is among the most relevant processes for these products.

The DQR results emphasize the importance of building a more reliable LCI that is truly representative of the current LIB recycling technologies and market. Hence the importance of the SCORELCA project by WeLOOP and TND, the LCA results (with the new representative inventory of the LIB recycling process) are shown in the following paragraph.

Result of LCA of lithium batteries recycling processes

The results of the LCA study of the production of NMC111 cell is presented in Figure 32,

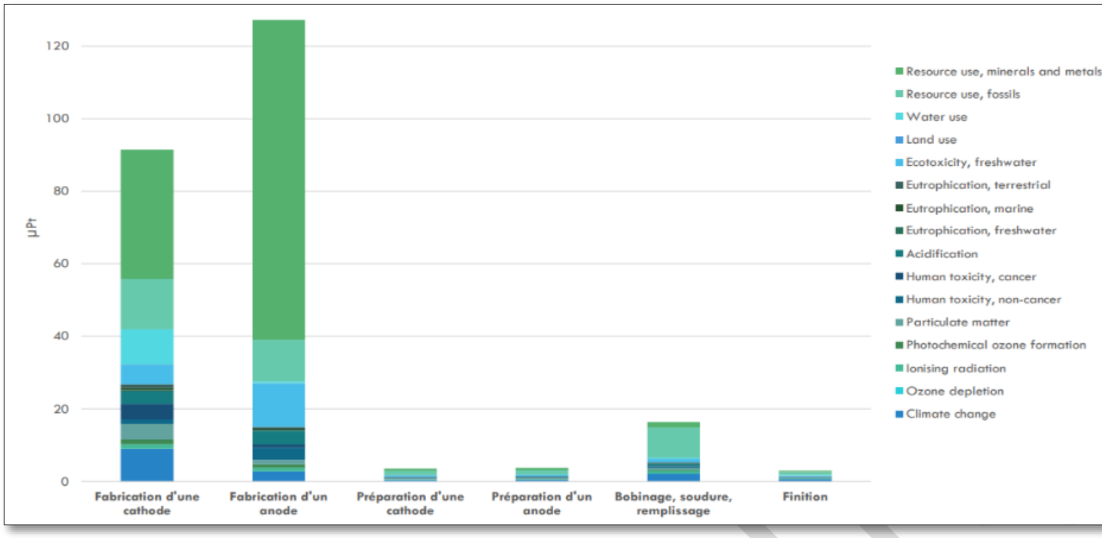

Figure 32 LCA results of the production of NMC 111 cell (BATTER project WeLOOP, 2022)

As one can see, the production of the cathode and the anode have the highest environmental impacts, mainly in resource use (minerals and metals) and fossil resource use. To dive more into the impacts of the NMC111 cathode and anode production. An LCA was conducted to check the impacts of the production of the cathode and the anode and the contributions of its main components (Figure 33). To do so, the European commission PEF method was used the results were extracted using the EF3.0 LCIA method. The characterized results from the LCA model are then normalized and weighted to obtain a 'unitless' single score indicator. EF3.0 aggregates all the impacts (resource use, climate change, Ozone depletion, etc.) into one single score, allowing to easily compare the environmental impact of different products, processes, or scenarios.

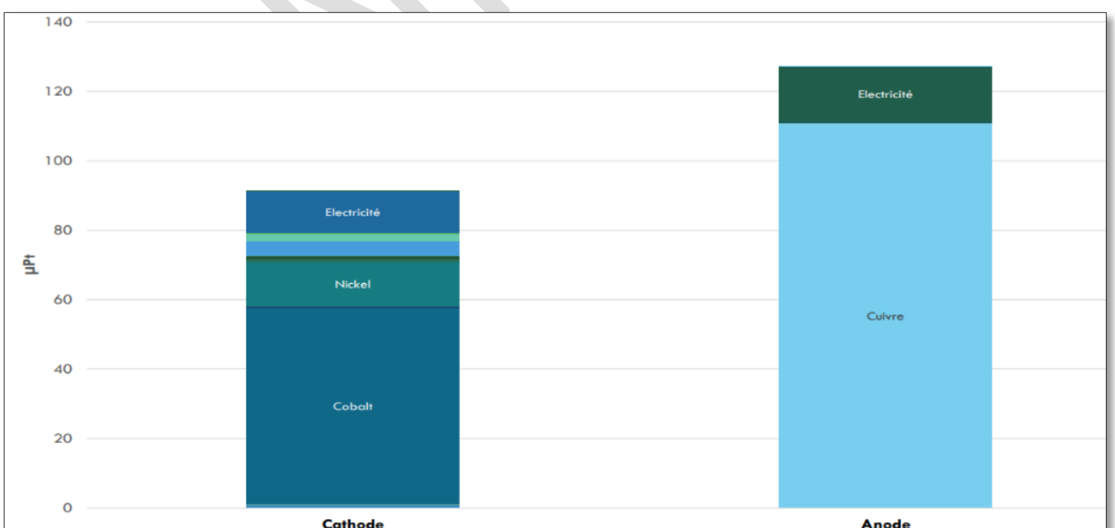

Figure 33 LCA results (Single score) of the production of NMC 111 Cathode (BATTER project WeLOOP, 2022)

From Figure 33, we can see that cobalt extraction/processing is one of the major factors behind the environmental impacts of cathode production, followed by nickel and the electricity consumption (French electricity mix). On the other hand, copper extraction/processing is the most impactful in anode production. We can see that the production of the anode has a higher impact that the production of the cathode.

Because climate change is a hot topic, we have conducted a complimentary analysis to investigate the contribution of the cathode and the anode production to climate change. The results are shown in Figure 34,

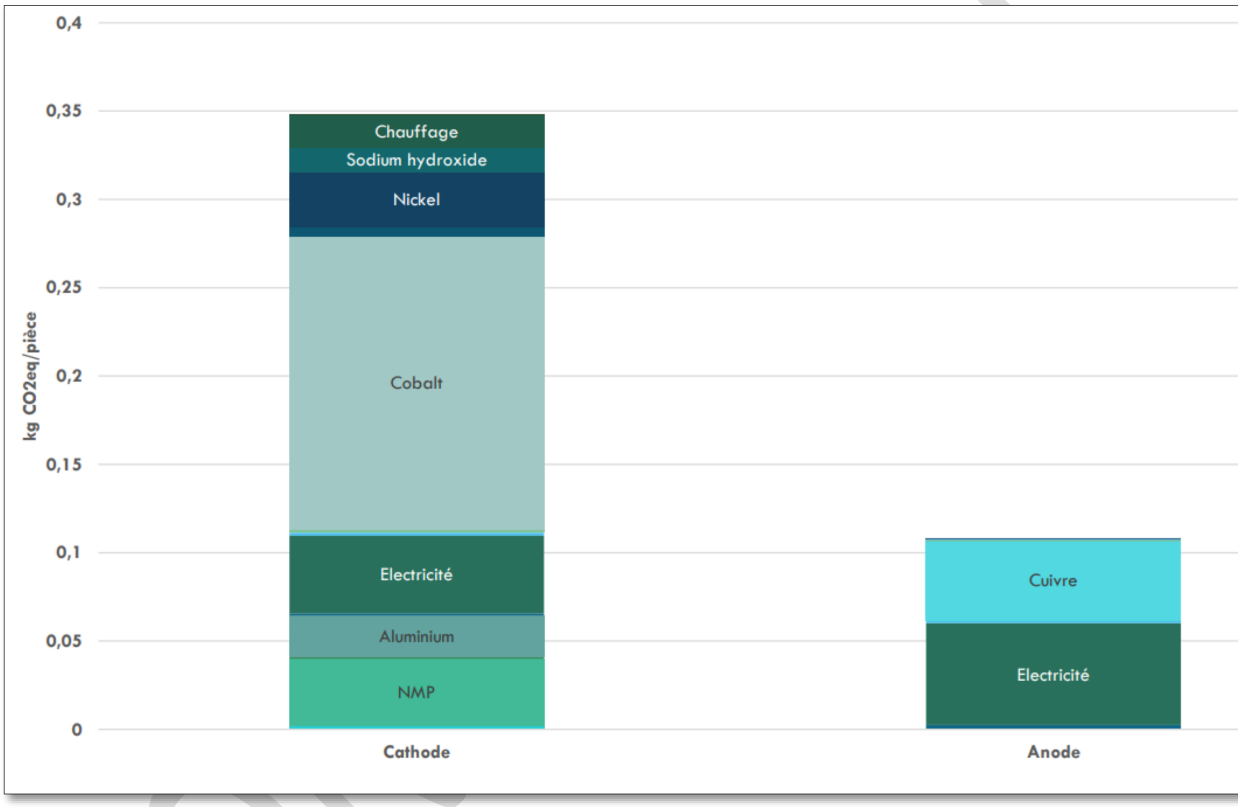

Figure 34 LCA results (Climate change) of the production of NMC 111 Cathode (BATTER project WeLOOP, 2022)

From Figure 34, we can see that the production of the cathode contributes significantly more to climate change than the production of the anode. With cobalt as a major hotspot, it means that the extraction and the processing of cobalt in NMC11 cell production are the main responsible for climate change.

To compare LIB recycling processes, we have conducted an LCA using the LCI inventory developed by TND for different industrial LIB recycling processes. The results of the LCA are shown in Figure 35

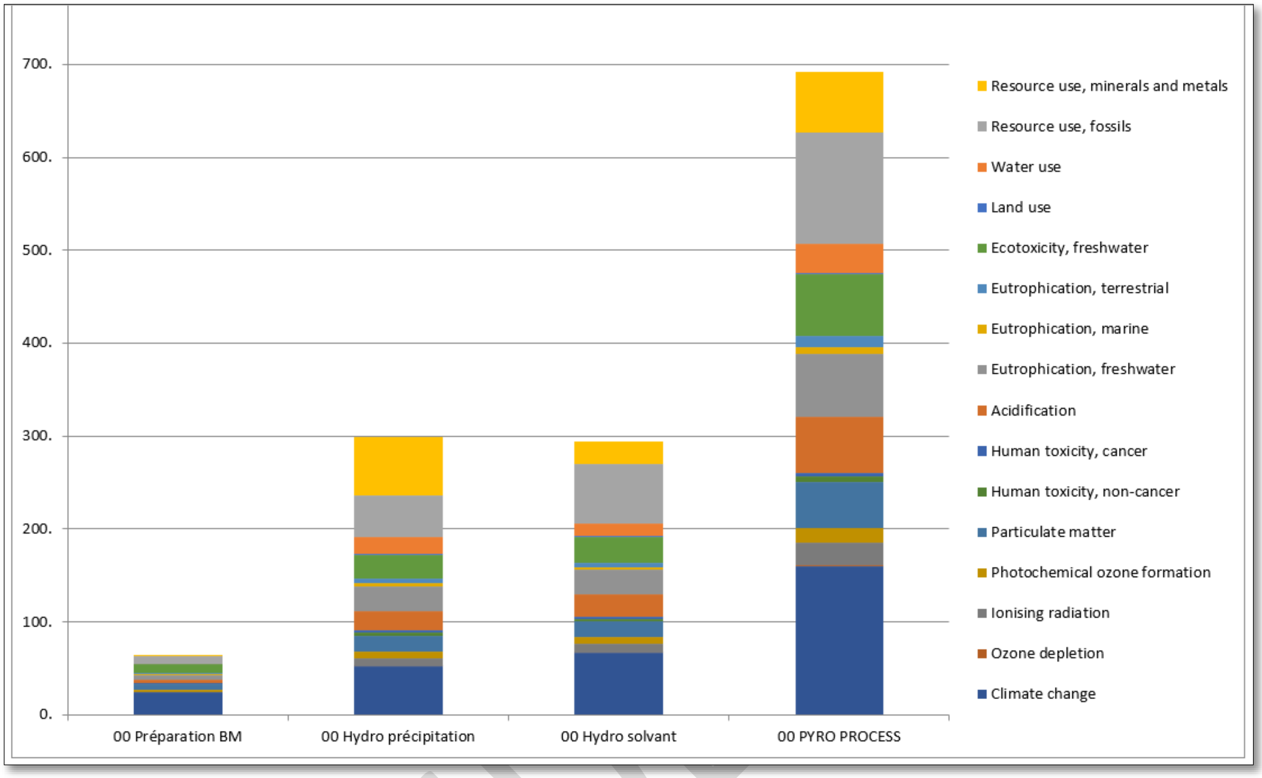

Figure 35 LCA results, Comparison between LIB recycling processes (SCORELCA? WeLOOP, 2022)

From Figure 35, we can see that pyrometallurgical processes' impacts are double that of hydrometallurgical processes, especially in the contribution to climate change and fossil resource use. It is important to mention that the pyrometallurgical processes were followed by some hydrometallurgical processes to recover the targeted metals. We also notice that black mass preparation has the lowest impact. For the hydrometallurgical processes, precipitation and solvent extraction have almost the same global impact. However, solvent extraction has more impact in the climate change category. Where precipitation has more impact on resource use (minerals and metals).

To see the whole picture, the avoided impacts thanks to recycling LIB was compared with the impacts of NMC111 cell production. The results are shown in Figure 36

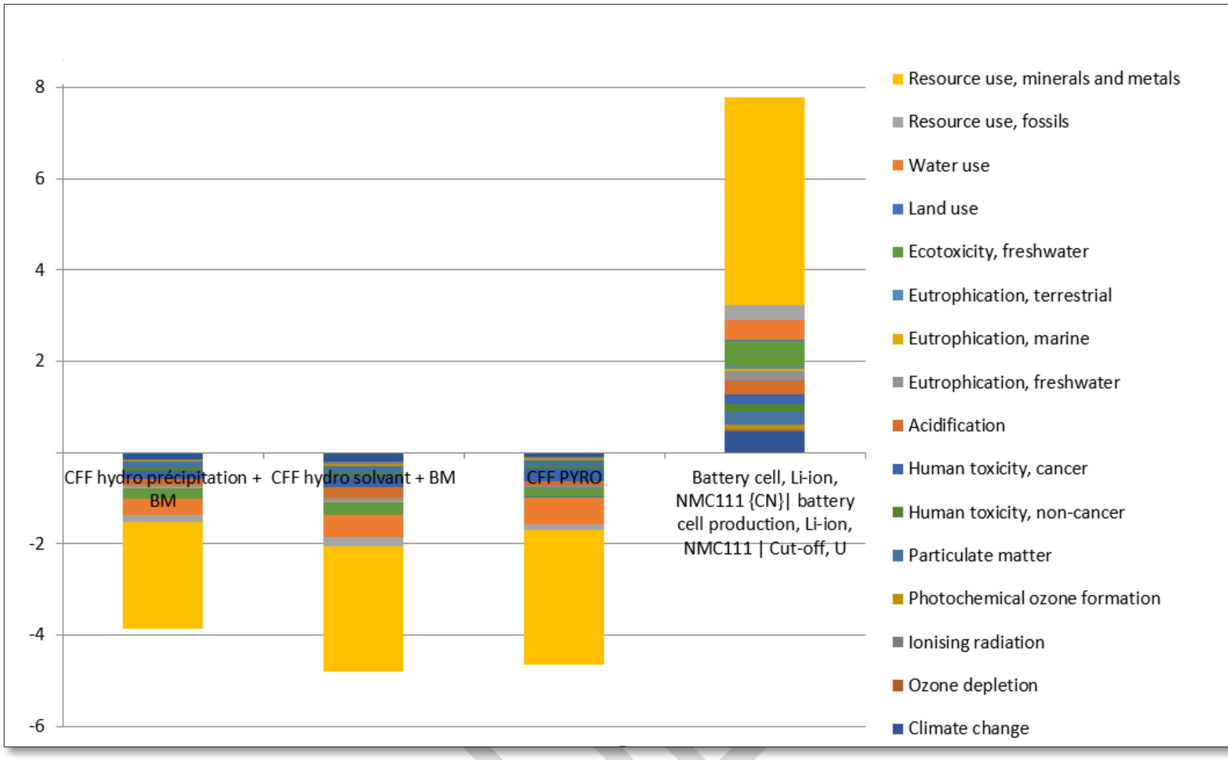

Figure 36 LCA results, NMC111 cell production impact verses the avoided impacts thanks to LIB recycling processes (SCORELCA WeLOOP, 2022)

From Figure 36, we can see that the avoided impacts (in negative) thanks to recycling are very important compared to the environmental impacts of the battery production (here NMC111 cell). And this is due to the recovery of valuable and critical battery metals/ metals' salts by recycling processes. Those recovered metals/metals' can be used in producing new lithium-ion batteries, which will play an important role in the circularity and sustainability of lithium-ion batteries.

We can also notice that the highest avoided impacts go to the hydrometallurgical treatment by solvent extraction preceded by black mass preparation. Followed by pyrometallurgical processes, and the hydrometallurgical treatment by precipitation comes in last.

Batteries Europe 2020 by the European Commission set targets for increasing the recycling efficiencies of LIB by 2030. An overall recovery by the average weight of waste battery of more than 60%. The target recycling efficiencies of the most targeted metals are Cobalt > 95%, Nickel > 95%, Lithium > 70%, and Copper > 95%.

Discussion

Discussion, and recommendations

Discussion

Due to the time frame of the study, aggregation and weighting of the criticality indicators to get a final criticality score per raw materials was out of the scope of this assessment. This is why the discussion of the results was based on assessing the hotspot indicators for each raw material. One criticality indicator does not show whether the material is critical or not. We should consider all the indicators to see the whole picture.

To get more realistic results of criticality assessments, evaluation of different grades/classes of some metals should be included. For example, the case on nickel with two grades/classes coming from two different deposits. Nickel class 1, with primary applications in lithium-ion batteries, has the potential to be critical. On the other hand, nickel class 2, mainly used for stainless steel, might not have the same concerns. Nevertheless, this would be complicated to be included in criticality assessments due to the lack of well-documented mining data. Another example is the case of lithium; future criticality studies should differentiate between lithium coming from brines and lithium coming from pegmatite deposits. The same goes for manganese, where manganese is abundant, but the high-quality grade used for batteries might be critical.

Short-term or sudden supply disruption, for example, a sudden conflict in a major supplying country, can lead to supply disruption. At the moment, there is no way to tackle this issue. Nickel was not on the EU criticality list in 2020. However, the nickel market has recently faced strong price fluctuations between March and May 2022 due to the war between Russia and Ukraine. Since Russia provides 26% of the EU sourcing of refined nickel, EU criticality studies are done every three years, which means the supply disruption of nickel in 2022 will not be included until 2023.

One other issue is country performance indicators are most of the time a year or two older, at least when they are used to conduct a criticality study. This might lead to an unrepresentativeness of some issues in some of the supplying countries (current and/or sudden issues cannot easily be reflected).

One of the indicators used in this study is the production to reserves ratio, which scored very low values for all the metals. It might be irrelevant and could be overlooked in future assessments. Or we need to find a way to calculate it differently or transform it to a different scale.

Criticality assessment results help with more informed decision-making; for example, when a company has in its supply chain a critical raw material, that does not mean that this CRM should be replaced or avoided. Of course, substitution is a criticality mitigation measure. However, it is not the only solution. Several mitigation actions could be done, such as reasonable use, diversifying the supply, increasing the recycling rates of that CRM, increasing mine capacity (in sustainable manners), and starting new resource explorations.

As a mitigation measure, one suggestion was to increase the capacity of mines and/or start new resource explorations. This mitigation measure has not been considered in previous criticality assessments. Here in this criticality assessment, we have discussed the potential to increase supply from mines calculated by HHI – reserves. And the share of (current) production capacity used in mining and refining was calculated by the Production to reserves ratio. However, having huge reserves will not help increase the supply when the mining operations do not have the optimal capacity.

EIT Chapter

EIT Raw Materials Chapter

EIT Chapter

The work in this thesis is part of developing a web tool that will help companies evaluate criticality in their supply chain based on three sources of risk: accessibility, price, and reputation. In other words, the web tool will help assess criticality risks in the raw materials value chain. The criticality assessment done in this thesis will help with the more sustainable management of lithium-ion battery raw materials. Assessing the criticality of lithium-ion battery raw materials is crucial to achieving sustainability goals. Knowing what materials are at risk of potential supply disruption is a warning sign for policymakers, governments, and industries to take mitigation actions. Criticality assessments help companies make more informed material selections, sustainable products, and process designs (eco-design), and more informed investment decisions. Criticality assessments also help governments and policymakers set policy agendas and trade agreements. In this criticality assessment we assessed economical (price fluctuations), social (human rights and child labor aspects), and environmental (LCA and environmental performance) circumstances associated with lithium-ion battery raw materials.

We have worked on a PESTLE analysis by using the criticality indicators used in this thesis to assess the criticality of raw materials of lithium-ion batteries. We present it in the following figure:

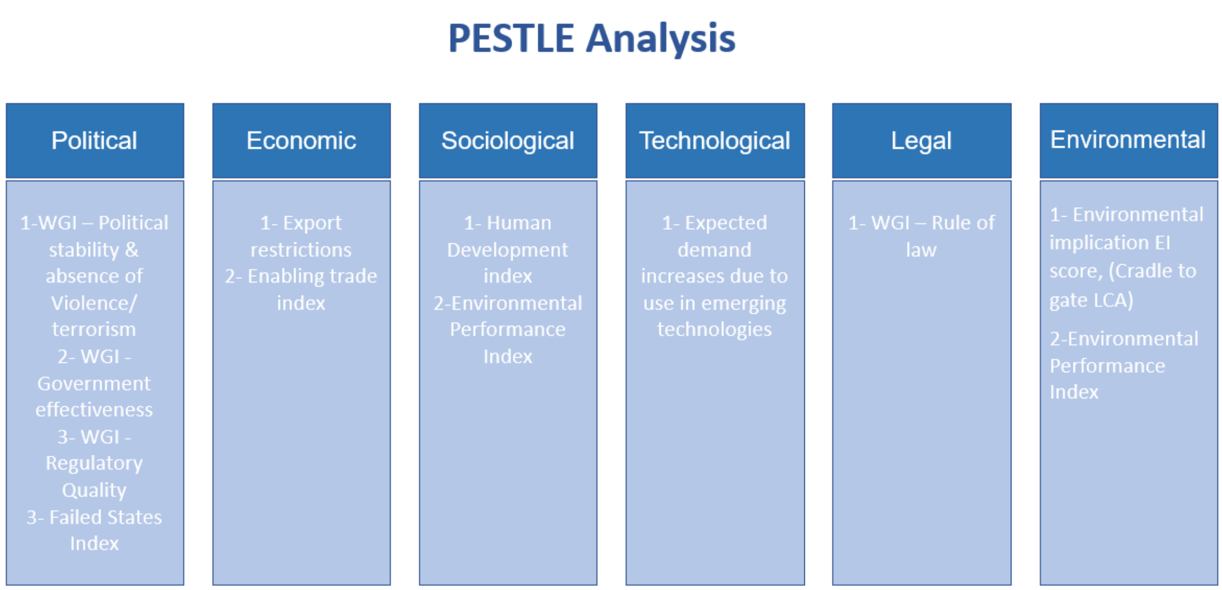

Figure 37 PESTLE analysis by using the criticality indicators

The PESTLE analysis is a framework to analyze the key factors (Political, Economic, Sociological, Technological, Legal, and Environmental) influencing a project from the outside. Since the PESTLE analysis cannot be applied in our case. We used the criticality indicators to show that our assessment covers all the key factors influencing a project from the outside.

We have performed an LCA study to assess the environmental impacts associated with the production and the recycling processes of lithium-ion. We found that the production of the anode has a higher impact than the production of the cathode. Also, we found that cobalt's extraction/processing is the major factor behind the environmental impacts of cathode production. And that copper's extraction/processing is the major factor the environmental impacts of the anode production. When comparing the LIB recycling processes, we found that the pyrometallurgical processes' impacts are double that of the hydrometallurgical processes. The avoided impacts thanks to recycling are very important compared to the environmental impacts of the battery production (NMC111 cell). And this is due to the recovery of valuable and critical battery metals/ metals' salts by recycling processes. Those recovered metals/metals' salts can be used in producing new lithium-ion batteries, which will play an important role in the circularity and sustainability of lithium-ion batteries. Which will result in less resource extraction and avoid the environmental impacts and the resource depletion associated with resource extraction. However, in the future more work research need to be done to enhance the efficiency and the recovery rates of recycling as well as to lower the environmental impacts associated to recycling, and to lower the energy consumption of recycling (especially pyrometallurgical processes).

A lot of the requisites of the EIT chapter do not apply to the work behind the thesis. Since the work was mainly a criticality and life cycle assessment of lithium-ion batteries, we cannot conduct an LCA for our assessment. We cannot conduct a TEA (techno-economic analysis) because we did not work on a physical product/process. The whole work of the thesis assessed the criticality and sustainability of raw materials.

And the work is already based on a business idea: the web tool that will help companies assess the criticality risks in their supply chain. The success of the web tool will increase the visibility of WeLOOP services by signing new contracts and agreements with companies interested in assessing criticality in their supply chain since the criticality field is still new and yet to reach maturity and with the IRTC project's efforts to build standards of inclusive and reliable criticality assessments. The web tool is intended to evolve into something that most companies would use and benefit from.

Conclusion

Rechargeable Lithium-ion batteries are essential for the EU-low carbon economy plan. Due to their applications in electric vehicles (electrification of the transportation system) and energy storage system for renewable energies. Assessing the criticality of lithium-ion battery raw materials is crucial to achieving sustainability goals. Knowing what materials are at risk of potential supply disruption is a warning sign for policymakers, governments, and industries to take mitigation actions. Criticality assessments help companies make more informative materials selections, more sustainable products, and processes designs (eco-design), and more informed investment decisions. Criticality assessments also help governments and policymakers set policy agendas and trade agreements.

Lithium-ion batteries need four critical raw materials, cobalt, natural graphite, lithium, and bauxite/aluminum (EU criticality list 2020). In this thesis, a comprehensive criticality assessment has been done to assess the criticality of lithium-ion battery raw materials. This current criticality assessment included all the criticality aspects and problematics suggested by the IRTC (International Round Table on Materials Criticality). The assessment results have emphasized the criticality problematics and risks associated with four battery CRMs. The possibility of criticality risk associated with nickel due to the political conflict between Russia and Ukraine was discussed too (since 26% of the EU nickel sourcing comes from Russia), and recent price fluctuations in the nickel market were taken as a sign to support the hypothesis. We have also discussed the criticality concerns of nickel class1 (battery-grade nickel) and high-quality manganese (battery-grade manganese). As a suggestion to assess their criticality risk, we have proposed that future studies should evaluate different grades/quality/classes of the same element. Applying this inclusive methodology will give more reliable and relevant criticality studies; however, finding well-documented data will be more challenging.

We have faced several issues while conducting this criticality assessment. For example, data gaps such as refining countries' shares of some raw materials and missing country-performance indicators for several supplying countries. Lack of well-documented data such as market shares for supplying companies. Due to the time frame of the study, aggregation and weighting of the criticality indicators to get a final criticality score per raw materials was out of the scope of this assessment.

"Closing the loop" of lithium-ion batteries is one of the sustainability goals; this could be achieved by remanufacturing, refurbishing, reuse (second-life application), and recycling. Recycling is essential to bring lithium battery critical raw materials back to the loop to close it. Therefore, it is important to ensure that recycling processes will be as sustainable as they could be with lower environmental impacts, less energy consumption, more efficiency, and more recovery rates. Life cycle assessment studies help assess the environmental impacts associated with the recycling processes, know the hotspots, and work to reduce their impacts. We have conducted and LCA study to analysis the environmental impacts associated with NMC111 cell production, and to compare between lithium-ion battery recycling process. We found that the production of the anode has a higher impact than the production of the cathode. Also, we found that cobalt's extraction/processing is the major factor behind the environmental impacts of cathode production. And that copper's extraction/processing is the major factor the environmental impacts of the anode production. When comparing the LIB recycling processes, we found that the pyrometallurgical processes' impacts are double that of the hydrometallurgical processes. The avoided impacts thanks to recycling are very important compared to the environmental impacts of the battery production (NMC111 cell). And this is due to the recovery of valuable and critical battery metals/ metals' salts by recycling processes. Those recovered metals/metals' salts can be used in producing new lithium-ion batteries, which will play an important role in the circularity and sustainability of lithium-ion batteries. However, in the future more work research need to be done to enhance the efficiency and the recovery rates of recycling as well as to lower the environmental impacts associated to recycling, and to lower the energy consumption of recycling (especially pyrometallurgical processes).

We have also conducted a data quality rating DQR of life cycle inventories LCIs and databases of available lithium battery recycling processes. The DQR revealed that most of the available LCIs and databases are old and not relevant to the new recycling processes and the new lithium-ion battery's chemistries, which raises the need for collaboration between the whole lithium battery supply chain actors (raw materials producers, manufacturer, recyclers, governments, etc.) to build more reliable inventories.

References

12, M.L. (2019) *HARVEST USED ELECTRODE*.

(12) United States Patent (2007).

Achzet, B. and Helbig, C. (2013) “How to evaluate raw material supply risks-an overview,” *Resources Policy*, 38(4), pp. 435–447. doi:10.1016/j.resourpol.2013.06.003.

Angerer, G. and Fraunhofer-Institut für System- und Innovationsforschung (no date) *Rohstoffe für Zukunftstechnologien Einfluss des branchenspezifischen Rohstoffbedarfs in rohstoffintensiven Zukunftstechnologien auf die zukünftige Rohstoffnachfrage*.

Bach, V. *et al.* (2017) “Enhancing the assessment of critical resource use at the country level with the SCARCE method – Case study of Germany,” *Resources Policy*, 53, pp. 283–299. doi:10.1016/j.resourpol.2017.07.003.

Bai, Y. *et al.* (2020a) “Energy and environmental aspects in recycling lithium-ion batteries: Concept of Battery Identity Global Passport,” *Materials Today*. Elsevier B.V., pp. 304–315. doi:10.1016/j.mattod.2020.09.001.

Balica, S. (2012) “Approaches of understanding developments of vulnerability indices for natural disasters,” *Environmental Engineering and Management Journal*, 11(5), pp. 963–974. doi:10.30638/eemj.2012.120.

Blengini, G.A. *et al.* (2017) “EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements,” *Resources Policy*, 53, pp. 12–19. doi:10.1016/j.resourpol.2017.05.008.

Bobba, S. *et al.* (no date) *Critical raw materials for strategic technologies and sectors in the EU : a foresight study.*

Botzen, W.J.W., Deschenes, O. and Sanders, M. (2019) “The economic impacts of natural disasters: A review of models and empirical studies,” *Review of Environmental Economics and Policy*. Oxford University Press, pp. 167–188. doi:10.1093/reep/rez004.

Boyden, A., Soo, V.K. and Doolan, M. (2016) “The Environmental Impacts of Recycling Portable Lithium-Ion Batteries,” in *Procedia CIRP*. Elsevier B.V., pp. 188–193. doi:10.1016/j.procir.2016.03.100.

Buijs, B., Sievers, H. and Espinoza, L.A.T. (2012) “Limits to the critical raw materials approach,” *Proceedings of Institution of Civil Engineers: Waste and Resource Management*, 165(4), pp. 201–208. doi:10.1680/warm.12.00010.

Catherine Lane (2022) *Battle of the batteries: NMC vs LFP. Which lithium ion option is best?*, *SolarReviews*. Available at: https://www.solarreviews.com/blog/lithium-ion-solar-batteries-compared (Accessed: June 5, 2022).

Chawla, N., Bharti, N. and Singh, S. (2019) “Recent advances in non-flammable electrolytes for safer lithium-ion batteries,” *Batteries*. MDPI Multidisciplinary Digital Publishing Institute. doi:10.3390/batteries5010019.

Chen, Q. (no date) *II 2020 epi report*.

Ciez, R.E. and Whitacre, J.F. (2019) "Examining different recycling processes for lithium-ion batteries," *Nature Sustainability*, 2(2), pp. 148–156. doi:10.1038/s41893-019-0222-5.

Cobalt Institute (2022) *Cobalt Institute* . Available at: https://www.cobaltinstitute.org/ (Accessed: June 6, 2022).

Dai, Q. *et al.* (2017) *Update of Life Cycle Analysis of Lithium-ion Batteries in the GREET ® Model*.

Danino-Perraud, R. (2020) *The Recycling of liThium-ion BaTTeRies A Strategic Pillar for the European Battery Alliance études de l'Ifri Raphaël Danino-PeRRauD Center for Energy*.

Dewulf, J. *et al.* (2010a) "Recycling rechargeable lithium ion batteries: Critical analysis of natural resource savings," *Resources, Conservation and Recycling*, 54(4), pp. 229–234. doi:10.1016/j.resconrec.2009.08.004.

Dunn, J.B. *et al.* (2012) "Impact of recycling on cradle-to-gate energy consumption and greenhouse gas emissions of automotive lithium-ion batteries," *Environmental Science and Technology*, 46(22), pp. 12704–12710. doi:10.1021/es302420z.

Dunn, J.B. *et al.* (2015a) "The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction," *Energy and Environmental Science*, 8(1), pp. 158–168. doi:10.1039/c4ee03029j.

Elwert, T. *et al.* (2016) "Current developments and challenges in the recycling of key components of (Hybrid) electric vehicles," *Recycling*. MDPI AG, pp. 25–60. doi:10.3390/recycling1010025.

Erdmann, L. and Graedel, T.E. (2011) "Criticality of non-fuel minerals: A review of major approaches and analyses," *Environmental Science and Technology*, pp. 7620–7630. doi:10.1021/es200563g.

European Commission-Press release Green Deal: Sustainable batteries for a circular and climate neutral economy (2020).

EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model Energy Systems Division (no date). Available at: www.anl.gov.

Eynard, U. *et al.* (no date) "Non-Critical Raw Materials Factsheets LEGAL NOTICE EUROPEAN COMMISSION." doi:10.2873/867993.

Fisher, K. *et al.* (2006) *Delivering sustainable solutions in a more competitive world Battery Waste Management Life Cycle Assessment Final Report for Publication Battery Waste Management Life Cycle Assessment Final Report for Publication*.

Geological Survey, U. (no date) *MINERAL COMMODITY SUMMARIES 2021*.

Graedel, T.E., Harper, E.M., Nassar, N.T., Nuss, P., Reck, B.K., *et al.* (2015) "Criticality of metals and metalloids," *Proceedings of the National Academy of Sciences of the United States of America*, 112(14), pp. 4257–4262. doi:10.1073/pnas.1500415112.

Grützke, M. *et al.* (2015) "Extraction of lithium-ion battery electrolytes with liquid and supercritical carbon dioxide and additional solvents," *RSC Advances*, 5(54), pp. 43209–43217. doi:10.1039/c5ra04451k.

Harper, G. *et al.* (2019) "Recycling lithium-ion batteries from electric vehicles," *Nature*. Nature Publishing Group, pp. 75–86. doi:10.1038/s41586-019-1682-5.

Hischier, R. *et al.* (2007a) *Modules*.

International Labor Organization (ILO) (2022) *Database description: Child labour statistics (CHILD)*. Available at: https://ilostat.ilo.org/resources/concepts-and-definitions/description-child-labour-statistics/ (Accessed: June 6, 2022).

IRTC & WeLOOP (2022) *Publication for cause-and-effect chain for criticality* . Available at: https://miro.com/app/board/o9J_lskuPg0=/ (Accessed: May 27, 2022).

IRTC Business & WeLOOP (2022) *IRTC Decision Tool exploration*. Available at: https://weloop-irtc.web.app/ (Accessed: May 27, 2022).

Johnson (2019) *Faraday battery challenge plasma smelting: Techno-economic assessment study report, ReLiB project*.

Kaufmann, D. *et al.* (2010) *Electronic copy available*.

Kim, T. *et al.* (2019) "Lithium-ion batteries: outlook on present, future, and hybridized technologies," *Journal of Materials Chemistry A*. Royal Society of Chemistry, pp. 2942–2964. doi:10.1039/C8TA10513H.

Larouche, F. *et al.* (2020) "Progress and status of hydrometallurgical and direct recycling of Li-Ion batteries and beyond," *Materials*. MDPI AG. doi:10.3390/ma13030801.

Latunussa, C. el *et al.* (no date a) "LEGAL NOTICE EUROPEAN COMMISSION." doi:10.2873/631546.

Leuven, K.U. and Gregoir -Principal Author, L. (no date) *Metals for Clean Energy*.

Li, L. *et al.* (2013) "Recovery of metals from spent lithium-ion batteries with organic acids as leaching reagents and environmental assessment," *Journal of Power Sources*, 233, pp. 180–189. doi:10.1016/j.jpowsour.2012.12.089.

LithoRec project (2009) *LithoRec and LithoRec II*, *The Technische Universität Braunschweig*.

Lv, W. *et al.* (2018) "A Critical Review and Analysis on the Recycling of Spent Lithium-Ion Batteries," *ACS Sustainable Chemistry and Engineering*. American Chemical Society, pp. 1504–1521. doi:10.1021/acssuschemeng.7b03811.

Makuza, B. *et al.* (2021) "Pyrometallurgical options for recycling spent lithium-ion batteries: A comprehensive review," *Journal of Power Sources*. Elsevier B.V. doi:10.1016/j.jpowsour.2021.229622.

Manhart, A. *et al.* (2019) "The environmental criticality of primary raw materials – A new methodology to assess global environmental hazard potentials of minerals and metals from mining," *Mineral Economics*, 32(1), pp. 91–107. doi:10.1007/s13563-018-0160-0.

Methodological note to the Inventory of Export Restrictions on Industrial Raw Materials Table of contents (no date).

Mohr, M. *et al.* (2020) "Toward a cell-chemistry specific life cycle assessment of lithium-ion battery recycling processes," *Journal of Industrial Ecology*, 24(6), pp. 1310–1322. doi:10.1111/jiec.13021.

Moss, R.L. *et al.* (2011) *Critical Metals in Strategic Energy Technologies*, *JRC-scientific and strategic reports, European Commission Joint Research Centre Institute for Energy and Transport*. doi:10.2790/35600.

Moss, R.L. *et al.* (no date) "Critical Metals in Strategic Energy Technologies Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies The Hague Centre for Strategic Studies," pp. 24884–2011. doi:10.2790/35600.

Mossali, E. *et al.* (2020a) "Lithium-ion batteries towards circular economy: A literature review of opportunities and issues of recycling treatments," *Journal of Environmental Management*, 264. doi:10.1016/j.jenvman.2020.110500.

Mudd, G. and Mudd, G.M. (2008) *Environmental Sustainability Metrics for Nickel Sulphide Versus Nickel Laterite Critical Minerals Assessment View project CSIRO's Wealth from Waste Flagship Research Custer View project NICKEL SULFIDE VERSUS LATERITE : THE HARD SUSTAINABILITY CHALLENGE REMAINS*. Available at: https://www.researchgate.net/publication/237440102.

National Research Council (U.S.). Committee on Critical Mineral Impacts on the U.S. Economy. *et al.* (2008) *Minerals, critical minerals, and the U.S. economy*. National Academies Press.

Nuss, P. and Eckelman, Matthew J (2014) "Life Cycle Assessment of Metals : A Scientific Synthesis," *Metals Environmental Impacts*, 9(7), pp. 1–12. doi:10.1371/journal.pone.0101298.

OECD (2017) *Export restrictions on Industrial Raw Materials*. Available at: https://qdd.oecd.org/subject.aspx?Subject=ExportRestrictions_IndustrialRawMaterials (Accessed: October 31, 2020).

Patent Application Publication (2016).

Rajaeifar, M.A. *et al.* (2021) "Life cycle assessment of lithium-ion battery recycling using pyrometallurgical technologies," *Journal of Industrial Ecology*, 25(6), pp. 1560–1571. doi:10.1111/jiec.13157.

"Relithiation in oxidizing conditions_US20170200989A1_" (no date).

RMIS (2022) "Raw Materials Information System, JRC, European Commission." Available at: https://rmis.jrc.ec.europa.eu/ (Accessed: June 6, 2022).

Robert E. Hoskisson, L.E.C.M.L. and M.W. (2017) "Strategy in Emerging Economies," *Academy of Management Journal*, 43(3).

Rollat, A. *et al.* (2016) "Prospective analysis of the flows of certain rare earths in Europe at the 2020 horizon," *Waste Management*, 49, pp. 427–436. doi:10.1016/j.wasman.2016.01.011.

Rosenau-Tornow, D. *et al.* (2009) "Assessing the long-term supply risks for mineral raw materials-a combined evaluation of past and future trends," *Resources Policy*, 34(4), pp. 161–175. doi:10.1016/j.resourpol.2009.07.001.

Schrijvers, D. *et al.* (2020) "A review of methods and data to determine raw material criticality," *Resources, Conservation and Recycling*. Elsevier B.V. doi:10.1016/j.resconrec.2019.104617.

Smith (2014) *2) United States Patent45) Date of Patent: (54) PROCESS FOR RECOVERING AND REGENERATING LITHIUM CATHODE MATERAL FROM LITHIUM-ON BATTERIES (71) Applicant: Retriev Technologies Incorporated, Anaheim, CA (US*.

Sommerville, R. *et al.* (2021) “A qualitative assessment of lithium ion battery recycling processes,” *Resources, Conservation and Recycling*, 165. doi:10.1016/j.resconrec.2020.105219.

Song, J. *et al.* (2019) “Material flow analysis on critical raw materials of lithium-ion batteries in China,” *Journal of Cleaner Production*, 215, pp. 570–581. doi:10.1016/j.jclepro.2019.01.081.

Strategic Research Agenda for batteries 2020 (no date).

“Study on the EU’s list of Critical Raw Materials (2020) Final Report” (no date). doi:10.2873/904613.

The Global Enabling Trade Report 2016 A joint publication of the World Economic Forum and the Global Alliance for Trade Facilitation Insight Report (no date). Available at: http://wef.ch/getr16.

Tolomeo, R. *et al.* (2020) “Application of life cycle assessment to lithium ion batteries in the automotive sector,” *Sustainability (Switzerland)*. MDPI. doi:10.3390/su12114628.

UNICEF (2021) *Child Labour: Global estimates 2020, trends and the road forward*. Available at: https://data.unicef.org/resources/child-labour-2020-global-estimates-trends-and-the-road-forward/ (Accessed: June 6, 2022).

USGS (2022) *United States Geological Survey*.

Velázquez-Martínez, O. *et al.* (2019) “A critical review of lithium-ion battery recycling processes from a circular economy perspective,” *Batteries*. MDPI Multidisciplinary Digital Publishing Institute. doi:10.3390/batteries5040068.

Wendling, Z.A. *et al.* (2020) *Environmental Performance Index*. New Haven.

Winslow, K.M., Laux, S.J. and Townsend, T.G. (2018) “A review on the growing concern and potential management strategies of waste lithium-ion batteries,” *Resources, Conservation and Recycling*. Elsevier B.V., pp. 263–277. doi:10.1016/j.resconrec.2017.11.001.

World Population Review (2022) *Most Peaceful Countries 2022*. Available at: https://worldpopulationreview.com/country-rankings/most-peaceful-countries (Accessed: June 6, 2022).

Xu, J. *et al.* (2008) “A review of processes and technologies for the recycling of lithium-ion secondary batteries,” *Journal of Power Sources*, pp. 512–527. doi:10.1016/j.jpowsour.2007.11.074.

Xu, P. *et al.* (2020) “Efficient Direct Recycling of Lithium-Ion Battery Cathodes by Targeted Healing,” *Joule*, 4(12), pp. 2609–2626. doi:10.1016/j.joule.2020.10.008.

Yang, Y. *et al.* (2021) “On the sustainability of lithium ion battery industry – A review and perspective,” *Energy Storage Materials*. Elsevier B.V., pp. 186–212. doi:10.1016/j.ensm.2020.12.019.

Yun, L. *et al.* (2018) “Metallurgical and mechanical methods for recycling of lithium-ion battery pack for electric vehicles,” *Resources, Conservation and Recycling*, 136, pp. 198–208. doi:10.1016/j.resconrec.2018.04.025.

Yunis, J. and Aliakbari, E. (2021) *Fraser Institute Annual Survey of Mining Companies 2021*.

Zhang, X. *et al.* (2018) "Toward sustainable and systematic recycling of spent rechargeable batteries," *Chemical Society Reviews*. Royal Society of Chemistry, pp. 7239–7302. doi:10.1039/c8cs00297e.

Annex

Annexes

Annex 1 / Overview of Lithium-ion Batteries recycling processes

The primary focus of current lithium batteries recycling processes is to recover high-value metals such as Co and Ni. Current recycling processes of Lithium batteries only recover Co, Ni, Cu, Al, and steel. Plastic fractions are mostly burned for energy recovery, and graphite, Mn, and Li are rarely recovered (Dewulf *et al.*, 2010a). Nevertheless, lithium's prices are continually increasing, making it inevitable for Lithium battery recyclers to improve the recovery rate of lithium. Lithium battery industrial recycling processes mainly focus on batteries with high cobalt content, such as LCO (Lithium cobalt battery $LiCoO2$) and NMC (Lithium Manganese Cobalt Oxide). In comparison, other lower-value battery chemistries are not a primary focus of industrial recycling processes, such as LMO (lithium-ion manganese oxide) and LFP (lithium iron phosphate battery) (Winslow, Laux and Townsend, 2018).

There are different commercial recycling processes for treating lithium batteries at the End of Life; pyrometallurgical, hydrometallurgical, and mixed processes. Usually, recycling processes of lithium batteries are either a combination of pyrometallurgical and hydrometallurgical techniques with pre-treatment or post-treatment processes (Bai *et al.*, 2020a). Pyrometallurgical recycling processes are the dominant processes for recycling lithium batteries due to their flexibility (Mossali *et al.*, 2020a), (Lv *et al.*, 2018).

Pre-treatment

Used lithium batteries are processed depending on their size, chemistry, format, and electric power. There are two categories of spent lithium batteries loads introduced to the recycling plants. The first category is small-size batteries, including batteries from portable devices, small electronic equipment, and E-bikes. This category includes various types, sizes, and chemistries. Sorting is required before starting the treatment process.

The second category is end-of-life battery packs from electric and hybrid vehicles and stationary energy storage devices. This category includes battery modules composed of individual cells, frames made of steel or aluminum, electric cables, printed circuit boards, plastic components, and thermal insulation materials. Generally, these battery packs are manually dismantled into modules or individual cells before starting the recycling process. This dismantling step must be done under precautions, as the workers could be exposed to severe electrical risks (Larouche *et al.*, 2020).

Pre-treatment is a crucial step before hydrometallurgical and direct recycling processes. Pre-treatment help to: maximize the recovery of valuable materials, safe handling, and disposal of hazardous components, reduce the safety risks, and reduce the amount of feed entering the recycling process. If the pre-treatment processes are done locally, that could reduce transportation costs, which represent an essential share of the overall cost of lithium battery recycling processes (Larouche et al., 2020). Pre-treatment processes could include physical pre-treatment, chemical pre-treatment, and thermal pre-treatment, with these distinguished steps: battery pack dismantling, sorting, discharging, size reduction (crushing and shredding), separation, electrolyte recovery, binder separation, thermal treatment, and washing.

Pre-treatment could give different forms of active materials:

- A mix of cathode and anode materials is composed of Cu, Al, graphite, carbon, PVDF, and cathode active materials.

- Cathode material only, composed of Al, carbon, PVDF, and cathode active material.

- Active material, where the binder (mostly PVDF) is dissolved using a solvent, or thermal treatment is conducted to degrade the binder and the carbon.

- Black mass BM contains high amounts of valuable metals such as Co, Ni, and Mn; Al and Cu are removed mechanically or manually or dissolved in an alkaline solution. On the other hand, the black mass contains PVDF and carbon. In general, when preparing the black mass, the anode is separated from the cathode at the beginning. Therefore, the black mass could still have some Al and Cu due to contamination from entering current collectors to prepare the black mass.

- Calcined black mass BM, where the thermal treatment is performed by subjecting the active material to high temperature in an oxidizing atmosphere, which results in oxidizing the inorganic compounds and burning the binder and the carbon (Larouche *et al.*, 2020).

The following steps summarize a black mass preparation:

- Mechanical and physical pre-treatment: this step aims to remove the outer case, segregate valuable materials, reduce scrap volume, and increase the surface area. It proceeds with the following steps: first crushing step, magnetic separation (to remove steel fractions), second fine grinding (to segregate the current collectors and the organic fractions), sieving and air-jet separation, Eddy current separation (to separate and remove Al, Cu), densimetric table separation (to remove plastic fractions), ending the process by washing and floatation.
- Thermal pre-treatment: this step aims to decompose the binder, remove the carbon, and improve the efficiency of lithium recovery. Several processes could be used for the pre-thermal treatment: calcination, oxygen-free roasting in an N_2 atmosphere, enclosed-vacuum environment, vacuum pyrolysis
- Chemical and mechano-chemical pre-treatment: the use of organic solvents and supercritical fluids to extract the electrolyte or dissolve the binder; and particle size reduction to increase the surface area, which enhances the leaching (in the case of subsequent hydrometallurgical treatment). Several chemical and mechano-chemical pre-treatment processes include electrolyte dissolution with the supercritical CO_2, an anhydrous solvent with boiling $T<80°C$, binder dissolution (with NMP, DMF, Citrus Fruit Juice, or DMAC), and mechano-chemical pre-treatment with CEDTA chelate agent in a grinding mill (Mossali *et al.*, 2020b).

MTB is a French company specializing in Black mass preparation; Figure 38 highlights the main steps in their processes.

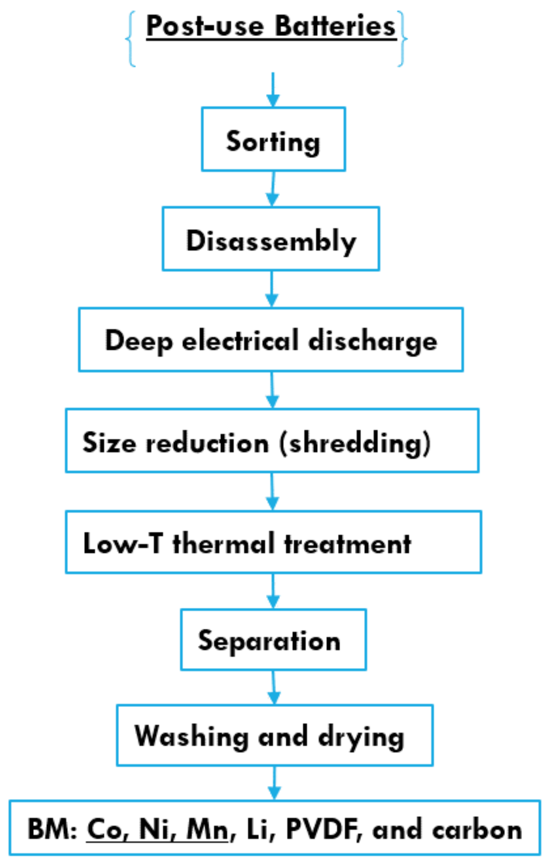

Figure 38 MTB black mass preparation process (WeLOOP 2021)

Pyrometallurgical recycling processes

Pyrometallurgical processes are based on high-temperature treatment to reduce the metal oxides found in the spent lithium batteries to obtain metal alloys of Co, Cu, Fe, and Ni, as shown in Figure 39 High-temperature furnaces are used for smelting the batteries. Pyrometallurgical processes are already well-established for recycling spent Lithium batteries coming from portable electronic devices, where lithium batteries can be treated with other types of waste, which helps with improving the process thermodynamics. This can be adapted to lithium batteries coming from electric vehicles. In addition, pyrometallurgical processes can be used for whole battery pack or modules as the metal current collector help with the smelting process; this gives the advantage that no prior passivation step is required (Harper *et al.*, 2019). Pyrometallurgical processes produce metallic alloys, slag, and gaseous products. The gases are comprised of volatile organics from burning the electrolyte and the binder components at a lower temperature (less than 150°C), and the polymer fractions are decomposed at higher temperatures. The slag contains metals such as Al, Mn, and Li, which can either be sent to be used in other industries (e.g., the cement industry) or these metals can be reclaimed by further hydrometallurgical processes. Hydrometallurgical processes can also process the metallic alloy to reclaim the component metals (Harper *et al.*, 2019).

The principle behind pyrometallurgical processes is using high temperatures to recover and purify metals, where the metals go through a series of physical and chemical transformations. The phase transitions and structural changes happen at a lower temperature, while the chemical reactions occur at higher temperatures. Pyrometallurgical processes depend on various parameters: temperature, time, flux addition, and purge gas types.

The thermal treatment methods used in the pyrometallurgical recycling processes for Lithium batteries are roasting/calcination and smelting. In general, roasting is composed of exothermic gas-solid reactions at high temperatures. For recycling Lithium batteries, a pre-treatment step is required before the roasting process to get the cathode materials. The active cathode material can be recovered by carbothermic reduction roasting, which is heated with a reducing agent (carbon, charcoal, or coke). This method produces carbon residue and a mixture of impure metals and oxides that need further refining (Makuza et al., 2021).

Smelting is heating the material above its melting point. For Lithium battery recycling process, smelting eases the separation of the metals in the liquid phase because of the reduction reactions and the formation of molten immiscible layers. During recycling Lithium batteries by smelting, the battery modules or battery packs can be fed directly into the high-temperature furnace without a prior passivation step. Smelting has two phases; the first phase is heating the material at a lower temperature to evaporate the electrolyte. This step must be done carefully because intensive heating would cause sudden evaporation of the electrolyte, which leads to overpressure that would cause the battery to explode. The second phase is heating the material at a high temperature to melt the feeds; during this phase, all the organic material is burnt out through an exothermic reaction which provides energy for the process. Carbon and Aluminum act as reductants for the smelting process. Smelting is conducted in a blast or electric furnace, and flux is added to produce molten metal (alloy), slag, and gases. The unwanted impurities react with the flux, which leads to slag formation(Makuza *et al.*, 2021).

The advantages of pyrometallurgical processes are:

- Straightforward techniques to extract high-value transition metals (e.g., Co & Ni).
- Flexible and easy process.
- Long-term profitability.
- Immediate commercial feasibility.
- Optimal technology readiness.
- Little safety risk, no prior passivation step is required because the process is on the battery pack or the modules level; the hazards are contained within the process.
- Although the aluminum from the foils and the packaging cannot be recovered since it is slagged as Al2O3, this reaction produces a large amount of energy, decreasing the energy requirements and contributing to the reduction process for metal reclamation.
- As burning the electrolytes and the plastic fractions is an exothermic reaction, reducing the energy required for the process.

The disadvantages of the pyrometallurgical processes are:

- High energy consumption.
- A limited number of materials are reclaimed.
- High capital and operating costs.
- No reclamation of the electrolyte and plastic fractions which account for 40-50% of the total weight of the battery.

- No reclamation of lithium salts.
- Requirement for pre-sorting step for batteries containing Co.
- Environmental impacts resulting from the generation of gaseous pollutants (these toxic gases must be captured and treated). (Bai *et al.*, 2020b) (Harper *et al.*, 2019)

Pyrometallurgical processes can be preceded by a pre-treatment process composed of; discharging, dismantling step to separate the electrodes and recover the electrolyte, size reduction, screening step to separate the metallic fractions (Al, Cu, Fe, etc.) from the graphite and the plastic fractions. This pre-treatment step is followed by the smelting step to recover the high-value transition metals (Ni, Co, and Cu). Black mass can be used as a feed for pyrometallurgical recycling process.

One of the challenges in pyrometallurgical processes is the loss of lithium to the slag; several pieces of research have been done to tackle this challenge, for example, the recovery of lithium by a combination of pyrometallurgical and hydrometallurgical processes. Some of these pieces of research are lithium incorporation in slag, vacuum evaporation, and inert atmosphere roasting (Bai *et al.*, 2020b). To some extent, these methods prevent losing lithium; by collecting lithium compounds and then recovering them through additional hydrometallurgical steps.

Due to their commercial feasibility, long-term profitability, and flexible, straightforward processing steps, several companies have employed pyrometallurgical processes to recycle spent lithium batteries: Accurec (Germany), Umicore (Belgium), and Sumitomo-Sony (Japan).

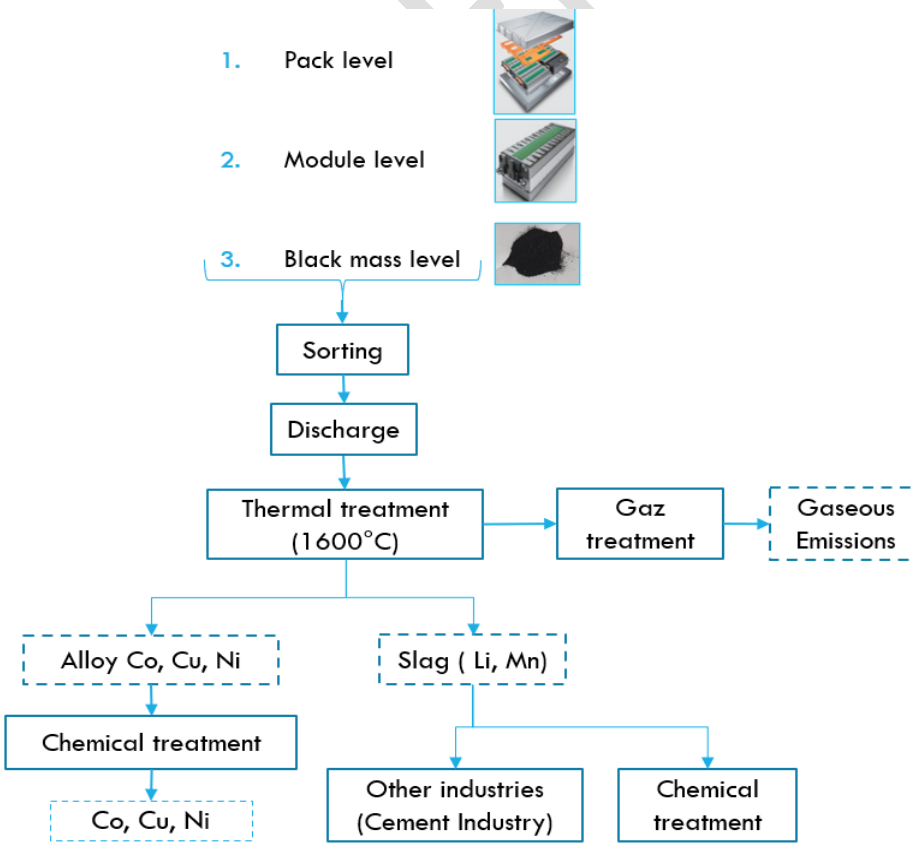

Figure 39 Pyrometallurgical treatment of Lithium batteries (WeLOOP 2021)

Hydrometallurgical recycling processes

Hydrometallurgical recycling processes are defined as the use of aqueous solutions to leach the targeted metals, followed by the separation/purification stage, and lastly, recovery of the targeted metals by precipitation; hydrometallurgy processes are preceded by pre-treatment, black mass preparation, or pyrometallurgical processes (Larouche et al., 2020).

1.3.1- Leaching

Leaching is a technique to bring the targeted metals into the solution. The valuable metals from the lithium batteries cathode are leached out using leaching agents (inorganic acids are the most common). The leaching agent is often used with a reducing agent such as H_2O_2 and Na_2SO_3, the reducing agent helps with easily dissolving the metal-forms in the acidic leaching solutions (this by oxidizing the metal-forms to a higher oxidation state) (Yun *et al.*, 2018). However, using inorganic acids as leaching agents has some drawbacks; it is not economically beneficial compared to organic acids. Plus, leaching with inorganic acids releases toxic gases such as SO_3 and Cl_2, which impact the environment and human health; as a result, those emissions must be treated. Using organic acids as leaching agents could be an alternative to inorganic acids; several pieces of research have been done to investigate this topic; nonetheless, it is still in the research and development phase, and it is yet to prove its efficiency (Yun *et al.*, 2018). The most common industrial leaching type is the inorganic acids leaching using inorganic acids such as H_2SO_4, HNO_3, or HCl. The most commonly used reagent is a combination of sulfuric acid and hydrogen peroxide H_2SO_4/H_2O_2. Other types of leaching exist, such as organic acid leaching, alkaline acid leaching, bio-based leaching, intensified leaching, and selective leaching. Nevertheless, these processes are not commercialized yet (Larouche et al., 2020).

1.3.2- Separation and purification

Leaching is followed by the precipitation and purification stage to selectively separate the valuable metals dissolved into the solution by manipulating the pH of the solution to recover the metals. In the industry, solvent extraction and chemical precipitation processes are used, electrochemical deposition can be used too (Yun *et al.*, 2018). Solvent extraction is a hydrometallurgical method used to extract and separate metal ions from filtrates by using extractants such as D2EHPA, ACORGA, DEHPA, etc. Chemical precipitation is a hydrometallurgical method used to precipitate targeted metals; for example, when recycling spent lithium batteries, Co, Ni, and Mn are often precipitated using NaOH, NH_4OH, and $KMnO_4$; Where Li is precipitated using Na_2CO_3, H_3PO_4, and $H_2C_2O_4$. Usually, solvent extraction and chemical precipitation ensure highly efficient separation (Yun et al., 2018).

1.3.3- Metal recovery/Metal precipitation

The last stage of hydrometallurgical treatment is the metal recovery or metal precipitation to recover the targeted metals, metal salts, and metal compounds from the solution. The industrial processes use recrystallization, Ionic precipitation, and electrolytic reduction; other processes can be used to recover the metals, such as reduction with gas and electrochemical reduction (Larouche et al., 2020).

Several recycling companies use hydrometallurgical processes to recycle Lithium batteries, such as: Batrec in Switzerland and Lithorec in Germany, where they recover CoO and Li salts. TES in France has developed the VALIBAT process. TES uses acid leaching and hydrolysis to recover $Co(OH)_2$ and Li_2CO_3. Retriev in Canada and the USA has developed the Toxco process(Mossali *et al.*, 2020b). As an example of the hydrometallurgical recycling process of lithium batteries, Figure 40 presents the Valibat recycling process schematic by TES company in France.

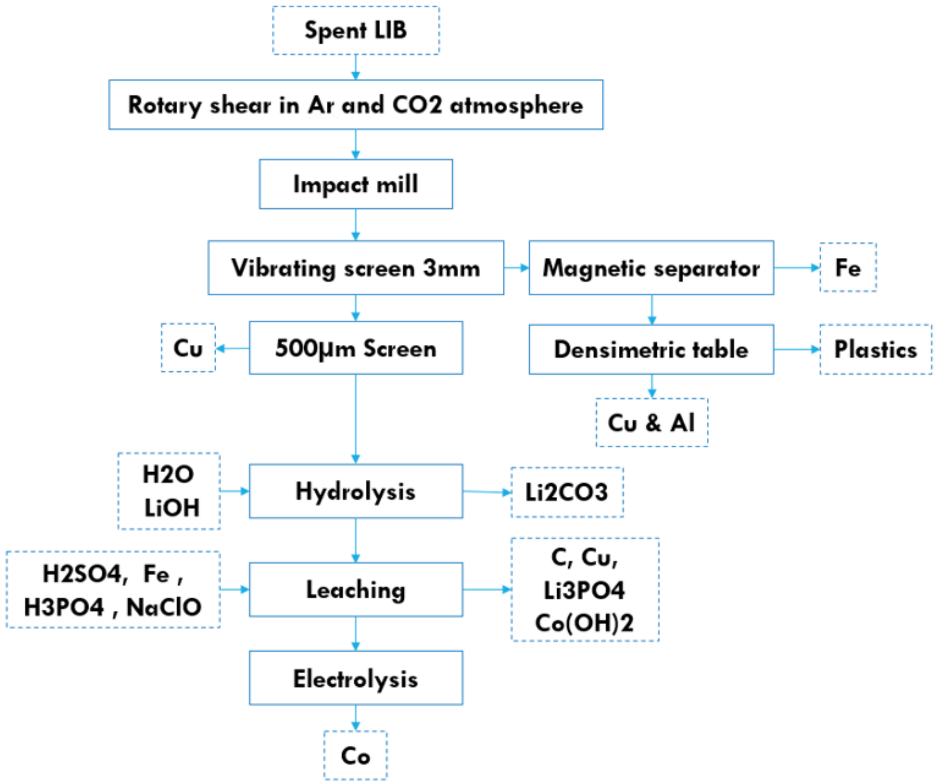

Figure 40 Valibat recycling process schematic TES in France, (WeLOOP 2021)

Advantages of Hydrometallurgical recycling processes

- High recovery efficiency,
- High-quality outputs,
- Good technology readiness,
- Moderated energy consumption,
- No gaseous emissions,
- Recovery of all LIBs cathodic metals,
- Mild reaction conditions.

Disadvantages of Hydrometallurgical recycling processes

- Wastewater productions,
- Incomplete binder/electrolyte recycling,
- The complexity of the procedure,
- Need for pre-treatments,
- Selectivity of reagents,
- Use of harmful solvents
- Mixing the anode and cathode materials at the start of the recycling process complicates downstream processing,
- Highly resource-intensive, (Velázquez-Martínez et al., 2019).

Direct recycling processes

Direct recycling can be defined as separating the cathode or the anode followed by reconditioning for the active material to be directly used in a new cell (see Figure 41). Here the active material of the cathode or the anode is directly reused without extracting the primary metals or salts (Harper *et al.*, 2019). In direct recycling, the active material does not get dissolved entirely. Instead, the idea is to reactivate the active material and recover its lost properties during its lifetime. Different direct recycling methods have been reported. In general, these methods might involve physical separation of the electrodes' active material, removing the binder by washing, thermal treatment, re-lithiation of the active material (which means replenishing the lithium of the active material), and ending with thermal treatment (Larouche et al., 2020).

Direct recycling is not commercialized yet. Nevertheless, some companies claim to incorporate direct recycling processes into their recycling activities. For example, OnTo Technology in the USA and Canada uses direct recycling processes to recover active materials from Lithium batteries. The supercritical CO2 accesses the active material and disassembly/cutting, and the valuable components are recovered by heating at 400-900°C with LiOH alkaline solution (Larouche *et al.*, 2020). In 2014, Retriev (a recycling company in the USA and Canada) patented a direct recycling process with a 95% recovery capacity. Their process is comprised of steps of crushing and screening, thermal treatment (to remove the binder and modify the carbon surface), selective flotation (to remove the carbon), re-lithiation of the active material in a solution of lithium hydroxide, calcination at 500–800 °C (Smith, 2014).

On the other hand, numerous R&D projects are experimenting with direct recycling processes. For example, Panpan Xu et al. have reported a direct regeneration of spent LiFePO4 (LFP) cathodes. Their method is based on defect-targeted healing, combining physical separation and re-lithiation in a low-temperature aqueous solution followed by rapid post-annealing. Their process recovers active cathode material (Xu *et al.*, 2020). In 2016, Steven E. Sloop patented methods to recycle cathode material of a lithium-ion battery, where the harvest used electrode material is heated under pressure in a concentrated lithium hydroxide solution. Next, the positive-electrode material is separated from the lithium hydroxide solution and rinsed in basic liquid. Lastly, the positive-electrode material is dried and sintered (Steven E. Sloop, 2016). In 2017, Steven E. Sloop patented a new method to recycle the cathode material of a lithium-ion battery. The new process has similar steps as the previous one. The latest addition is that the re-lithiation of the positive-electrode material happens in a solution compromising lithium-ion and an oxidizing agent ("Relithiation in oxidizing conditions_US20170200989A1_," 2017). Again in 2019, Steven E. Sloop patented another method to recycle coated cathode material of a lithium-ion battery, similar steps to previous patents. The new addition is the re-lithiation of the coated positive-electrode material in a solution compromising Lithium-ion and an oxidizing agent. As a result, coted positive-electrode material may be reinstated using lower process temperatures than Uncoated positive-electrode material (Steven E. Sloop, 2019).

Advantages of direct recycling:

- Direct recycling allows the processing of lithium battery chemistries with low value (e.g., LFP).
- Direct recycling has fewer steps and a shorter chemical process path.
- Direct recycling is claimed to have economic advantages over leaching because it requires fewer steps. But on the other hand, there are arguments claiming that to fully re-functionalize the active

material, direct recycling might need at least the same number of steps as recovering the metals by leaching and then resynthesis of the active material (Larouche *et al.*, 2020).
- Direct recycling significantly reduces energy usage and greenhouse gas emissions.

Disadvantages of direct recycling:

- Direct recycling has not yet proven complete restoration of the cathode capacity.
- Direct recycling is designed for specific batteries; hence it is susceptible to market variation and the introduction of battery chemistries.
- Direct recycling requires a homogenous input flow, which means an accurate separation of batteries,
- Direct recycling has not yet proven its industrial feasibility.

(Velázquez-Martínez et al., 2019 ; Larouche et al., 2020)

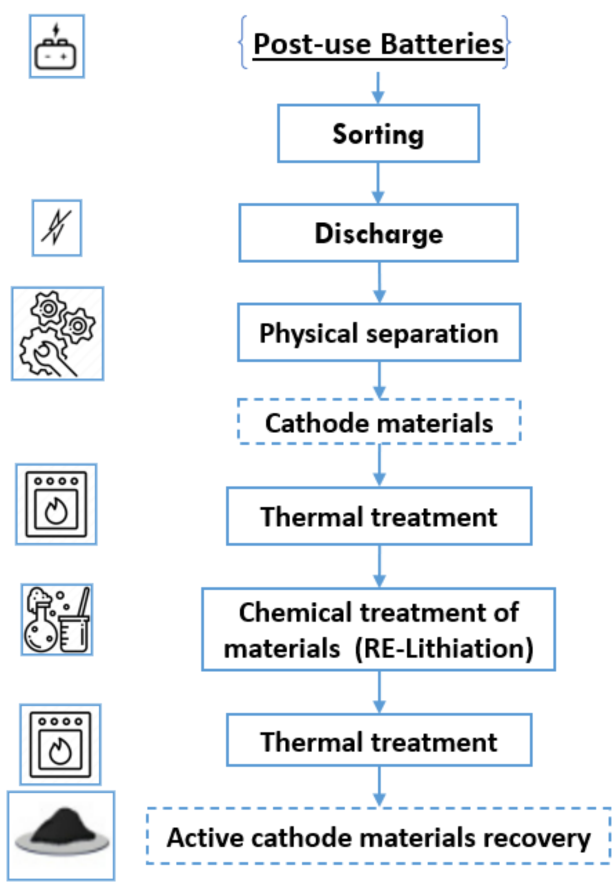

Figure 41 Lithium batteries direct recycling process schematic (WeLOOP 2021)

Sub-scenarios of Lithium battery recycling processes

Plastic incineration vs recycling

Plastics are very low value and make up a very low mass percentage of the total cell, therefore it is unlikely to make economic sense to recycle plastic fractions when recycling spent Lithium batteries. In pyrometallurgical processes, the initial pyrolysis of electrolyte and plastic could be used to supply energy for metals recovery, Accurec (Battery recycling company in Germany) utilizes vacuum pyrolysis at 250 ◦C to remove the electrolyte and plastics, which are condensed and destined for "thermal use", which is not considered recycling according to EU/493/2012 (Mossali et al., 2020b).

Many lithium batteries recycling companies separate plastics. However, it is unclear if any send them for recycling rather than disposal. Duesenfeld (Battery recycling company in Germany) is one of the few companies to explicitly describe the fate of plastics as disposal, or repurposing in construction (Sommerville *et al.*, 2021).

The recovery of Graphite, Lithium, and the Electrolyte

Graphite is presently not of major interest for the battery recycling industry and in most cases, it is lost during high temperature treatment, some industrial recycling processes use it as reducing agent in furnace (Umicore in Belgium, Accurec in Germany, and OnTo technologies in the USA and Canada), or it is filtered off in leaching step (TES in France), or it remains as fraction of the black mass (Akkuser in Finland) (Velázquez-Martínez *et al.*, 2019).

Lithium is not recovered in most industrial processes. Some industrial recycling processes recover lithium compounds Li_2CO_3, Li_3PO_4, and/or LiOH. For example: Accurec (in Germany), OnTo technology (in the USA and Canada) recover Li_2CO_3 with high purity (>99%), the recovered lithium carbonate can be used in Cathode powder synthesis (Velázquez-Martínez *et al.*, 2019).

Electrolyte is generally lost in most industrial recycling processes. However, some emerging technologies recover the electrolyte with supercritical CO_2, which can remove reactive functional groups from the graphite surface, on the other hand this step may damage the crystalline structure of the graphite (process by OnTo technology in the USA and Canada) (Velázquez-Martínez *et al.*, 2019).

Lithium battery recycling Challenges

Several challenges face the recycling of lithium batteries to name a few:
The collection of spent lithium batteries is costly and requires involvement of all members of the supply chain (producers, sellers, governments, waste managers and recyclers, and users).

The diversity in lithium battery chemistries and the rapid evolution of technologies make it more complicated to recycle lithium batteries.

The rapid change of commodities market prices restricts profit margins for recyclers, which weaken the viability of the industry (Larouche *et al.*, 2020).

Comparing the different lithium battery recycling processes

Recycling spent lithium batteries from electric vehicles is essential to avoid landfilling and secure secondary supply for strategic and critical elements. When comparing the different recycling processes for spent Lithium batteries from the technology readiness perspective, pyrometallurgical processes take the lead as the best technology, whereas hydrometallurgical processes come in second. The same goes for complexity, where the pyrometallurgical process is less complex than hydrometallurgical processes. On the other hand, the quantity and the quality of recovered materials are better when using hydrometallurgical processes, as shown in Table 8 and Table 9, representing a comparative scoring for the three main recycling processes. Where 5 is the best score and 1 is the worst score.

Table 8 Comparison between pyro, hydro, and direct recycling processes

	Technology readiness	Complexity	Quality of recovered material	Quantity of recovered material	Waste generation	Energy usage	Capital cost	Production cost	Presorting of batteries required
Pyro	5	5	1	3	2	1	1	5	5
Hydro	4	3	3	4	3	3	3	3	4
Direct recycling	2	1	2	5	4	3	3	1	1

Table 9 Continuation of the comparison between pyro, hydro, and direct recycling processes

	Cobalt recovered	Nickel recovered	Copper recovered	Manganese recovered	Lithium recovered	Aluminum recovered	Cathode morphology preserved	Material suitable for direct reuse
Pyro	5	5	5	3	1	No	No	No
Hydro	5	5	4	3	3	5	No	No
Direct recycling	5	5	5	5	5	5	5	4

Other end-of-life scenarios of Lithium-ion batteries

Landfilling is not a good choice for spent lithium batteries due to possible contamination of soil and groundwater from the electrolyte and metal leaching. Also, when spent lithium batteries come in contact with moisture, they release toxic

Lithium battery packs from electric vehicles retain about 80% of their performance at their end-of-life stage. Therefore, it allows the lithium battery packs to be employed in second-life applications, such as stationary storage systems. However, repurposing the lithium battery pack for the second-life application requires first disassembly and testing for degradation and failure. Then, if the battery pack is in good condition, some adjustments are made, adding electrical hardware, control and safety systems, and packaging for the second use (Ahmadi et al., 2017). Several challenges may face the second-life application of Lithium batteries, such as their durability and performance and the safety risks associated with aging batteries. In addition, giving a second life to lithium batteries reduces their carbon footprint (Strategic Research Agenda for batteries 2020, 2020).

In Lansink's ladder, reuse (second-life or second-use application) is the preferable option since it minimizes the environmental impacts and maximizes the economic value. Several companies worldwide have started projects to improve the testing and monitoring of Lithium batteries at the end-of-life stage to check the batteries' characteristics for a second-life application in stationary energy storage. These projects include the ReLiB project in the UK, the ReCell project in the USA, and ReLieVe project, the Lithorec project, and the Amplifll project in Europe (Harper *et al.*, 2019).

Industrial recycling processes and facilities for Lithium batteries

In 2018, 97000 tons of Lithium batteries were recycled worldwide. From this amount, 67000 tons had been recycled in China, representing about 69% of the global capacity of lithium batteries recycling. South Korea came in second with 18000 tons (18.5%), with the rest recycled mainly by the EU and North America (Danino-Perraud, 2020). In China, it has been estimated that less than 40% of lithium battery materials are recovered by recycling processes (Song *et al.*, 2019).

The most distinguished European players in the Lithium battery recycling market; are Accurec (Germany), AkkuSer (Finland), Duesenfeld (Germany), Redux (Germany), Umicore (Belgium), SNAM (France), and Eurodieuze (France). Several future European *lithium battery* recycling facilities are under construction, such as Northvolt and STENA recycling in Sweden, Fortum in Finland, and Orano, Mecaware, and Sanou Koura in France.

In the Global Lithium battery recycling market, Asian facilities are the lead, such as GEM, Brunp, Huayou Cobalt, and Ganxhou in China. SungEel HiTech in South Korea, Dowa and Kyoei Sriko in Japan. There are several important players in the US and Canada, such as Li-Cycle, RETRIEV, and On To Technology.

We have set the recycling facilities in Europe with the annual capacity, process details and recovered products in Table 10,

Table 10 LIBs recycling facilities details in Europe (WeLOOP 2021)

Company	Location	Capacity (tons/year)	Process details	Recovered products
Umicore	Belgium	7000	**Pyro-hydro** Combined Pyro and hydro: Dismantling, Shaft furnace (pre-heating, pyrolysis, UTH smelting), Then, the alloy is leached in H2SO4 and polished to extract and crystallize CoSO4 and NiSO4.	CoCl2, LiCoO2, Ni (OH)2, Cu, Fe, and Slag (Al, Si, Ca, Fe, Li,Mn, REE)
Accurec GmBH	Germany	4000	**Pre-treatment - Pyro-Hydro** Pre-treatment (Sorting Dismantling, Milling, separation, agglomeration, filtration, ambient), Pyro (Vacuum thermal treatment, smelting in an arc furnace), Hydro (treating slag with H2SO4 leaching)	Li2CO3, Co-Alloy, and Metallic alloy
Akkuser Ltd	Finland	4000	**Pre-treatment** (High airflow comminution, size separation, second comminution, size separation, magnetic separation)	Co, Cu powder, Fe, Non-ferrous metals
SNAM	*France*	300	**Pre-treatment** Sorting, pyrolysis to remove the electrolyte, crushing, sieving to isolate the valuable electrode powder.	Active material
Batrec Industrie AG	Switzerland	200	**Hydro** Crushing in inert CO2 atmosphere. Leaching and washing in acidifies aqueous solutions. Li is neutralized. Process details were not available in the literature.	Valuable metals
TES Valibat process	France	110	**Pre-treatment-hydro** Pre-treatment (crushing, vibrating screen, secondary screen, magnetic separator, densimetric table) and hydro (Hydrolysis leaching)	Co(OH)2, Li2CO3, LiCO2, Li3PO4, Steel, Cu, Al, C
Duesenfeld LithoRec process	Germany	Unknown	**Pre-treatment - Pyro- Hydro** Pre-treatment (Discharge and disassembly, Gas blanket comminution, mixing, density separation, second comminution, size separation, density separation) Pyro (vacuum drying, calcination), Hydro treatment(Leaching)	High-grade cathode materials Li2CO3, metal oxides (CoO), Al, Cu, plastics

In Table 11 we have set the recycling facilities worldwide with the annual capacity, process details and recovered products

Table 11 LIBs recycling facilities details worldwide (WeLOOP 2021)

Company	Location	Capacity (tons/year)	Process details	Recovered products
Glencore	Canada	7000	**Pyro-hydro** Pyrometallurgy combined with hydrometallurgical leaching.	Alloy of Cu, Ni and Co
Inmetco	USA	6000	**Pyro** Treatment in a rotary furnace (to remove organic components), refining in an electric arc furnace.	Co, Ni, and Fe alloy
Retriev Technology (Toxco)	USA/Canada	4500	**Hydro** Wet grinding in a brine solution (to dissolve Li salts and recover Li2CO3), floatation (to remove steel case and plastic), hydrometallurgical processes to recover metals	CoO, Li2CO3
Dowa Eco-System	Japan	6500	**Pyro**	
JX Nippon	Japan	5000	**Pyro**	
Sony SUMIMOTO	Japan	150	**Pyro-hydro** Calcination (to remove plastics and the electrolyte). Pyrometallurgical process (Co–Ni–Fe alloy), leaching to recover Co.	CoO, Cu, stainless steel, Li is slagged
GEM	China	300000	**Hydrometallurgical processes**	Unknown
Huayou Cobalt	China	60000		
Brunp	China	100000	**Pyro-hydro**	
SungEel HiTech	South Korea	8000	**Hydro**	

(Mossali *et al.*, 2020b; Sommerville *et al.*, 2021), (Velázquez-Martínez *et al.*, 2019)

Annex 2 / Life Cycle Assessment

Life cycle assessment is an effective tool for a comprehensive assessment of the environmental impacts of products and services in the context of sustainable development. The international Standards Organization (ISO) definition of LCA is "A technique for assessing the environmental aspects and potential impacts associated with a product" (ISO 14040, 2006). An LCA study has three main steps: Compiling an inventory (Life Cycle Inventory LCI), which is composed of relevant inputs and outputs of a product system. Evaluating the potential environmental impacts associated to the product system. And finally, interpreting the results of the inventory analysis/ Impact assessment step based on the objective of the LCA study (Guido Sonnemann, 2020).

Steps to conduct an LCA study, Figure 42 shows the structure of an LCA study according to ISO14040/44,

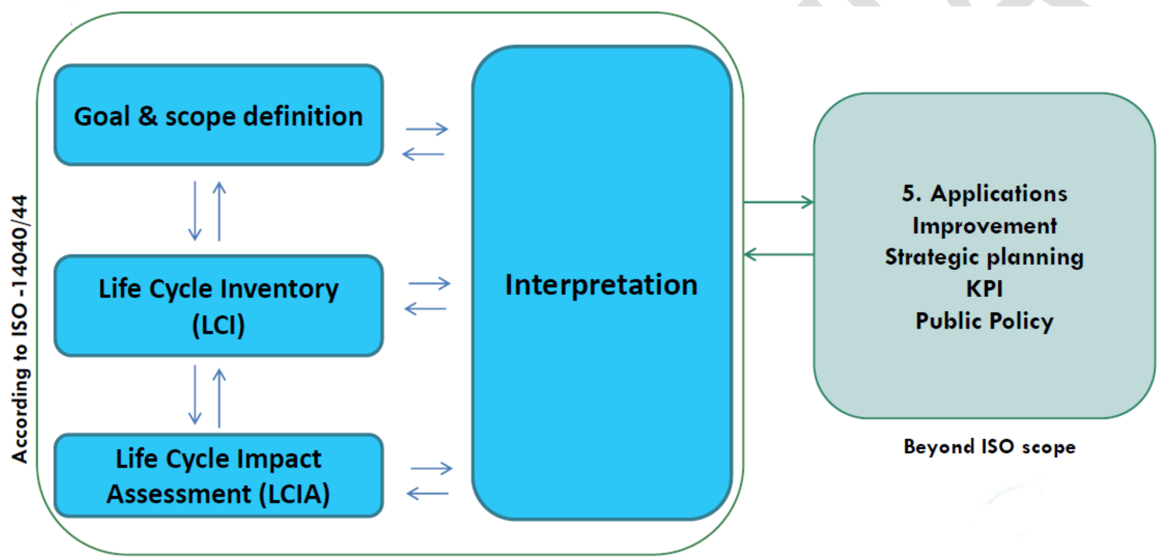

Figure 42 The structure of an LCA study according to ISO14040/44 (WeLOOP, 2022)

- Goal and scope definition (defining a functional unit, reference flow, and system boundaries).
- Life Cycle Inventory LCI (unit processes and the inputs and outputs of each process).
- Life Cycle Impact Assessment LCIA, the LCI results gives the impacts as midpoint categories (human toxicity, Ionizing radiation, Ozone layer depletion, Global warming, Mineral extractions) those midpoint categories then classified into Damage categories (Human Health, Ecosystem Quality, Climate Change, and Resources).
- Interpretation which means the identification of significant issues or what we call hotspots. Running different checks such as sensitivity and consistency analysis. And finally, finishing with conclusions, recommendations, limits, and reporting.

Life Cycle Assessment modeling has some limitations, first the assessed impact is a potential impact. Which results in no real impacts, thresholds, margin of safety or risks. The expression of the results is relative because it is linked to the functional unit. The inherent uncertainty in environmental models and the concern for the impact categories representing the future. Other limitations related to the Life Cycle Inventory LCI, such as missing data, data gaps, and the data quality. Other limitations to an LCA study can be related to the impact categories chosen, the models/Characterization factors available, and the relevant inventory data (WeLOOP training, 2022). Figure 43, shows how an LCA study looks like,

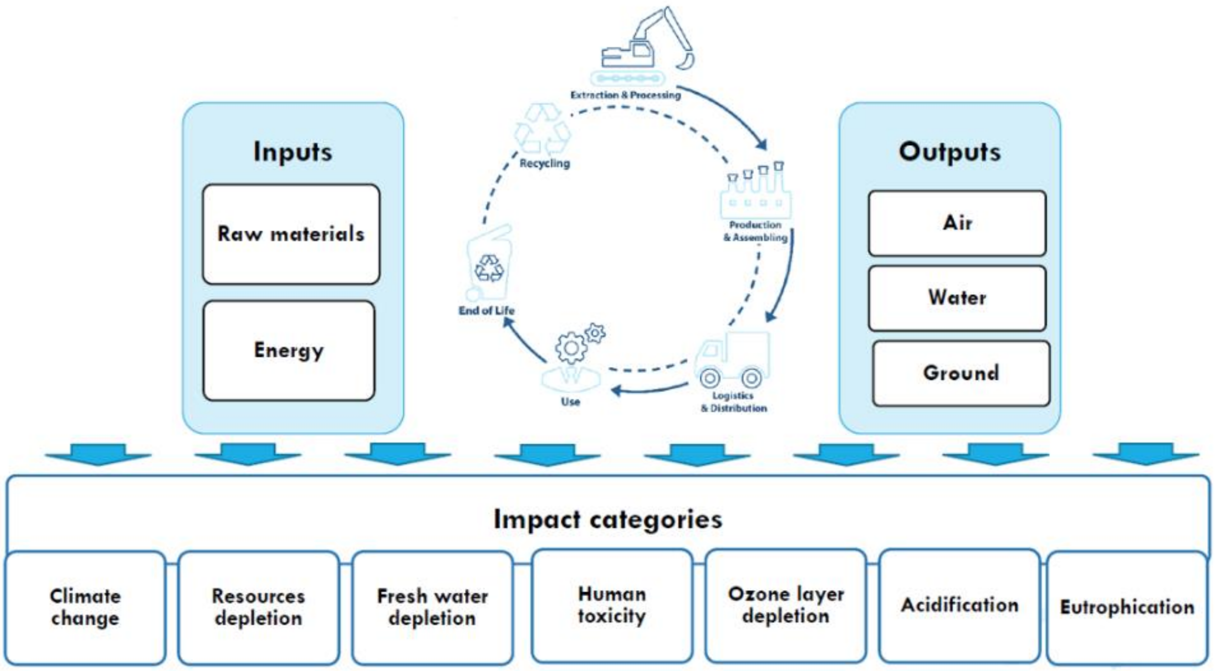

Figure 43 LCA study (WeLOOP training, 2022)

Data sources for an LCA study can be divided into two types: primary data and secondary data. Primary data are specifically collected for the LCA study, it can be data collection from manufacturers (inputs and outputs needed for a process), data collection on product's use profile, and data on key parameters. Secondary data are not specifically collected for LCA studies, it can be data from literature on processes (theoretical or empirical model, standard design criteria), or average data on input and outputs of a unit process from LCA databases.

There are several LCA databases ELCD, Ecoinvent, Gabi databases, and inies. Ecoinvent database was developed by the EcoinventCenter in Switzerland. It contains more than 3000 LCIs about raw materials, energy, waste treatment, transports, manufacturing processes etc.

The data quality can be rated by five dimensions: temporal correlation, geographical correlation, technological correlation, accuracy, and completeness. Temporal correlation is assessed by the year of data collection and update. The geographical correlation is assessed by the geographical area (local, regional, national, continental, and global). The technological correlation is assessed by the technological mix (weighted average) or best available technology. The accuracy is assessed by variability measurements. The completeness is assessed by the data coverage.

There are several LCA modeling software, the expert softwares are GaBi software, OpenLCA, Umberto, and SimaPro.

Annex 3 / Available Life Cycle Inventories LCI for lithium batteries recycling processes

Building the life cycle inventory is a crucial step in any LCA study. Data availability and quality define the reliability of the LCI. Unfortunately, LCIs of the lithium batteries recycling process lack the availability of reliable data. Primary data collected from lithium batteries recyclers are subjected to confidentiality agreements; therefore, they cannot be used easily. Secondary data are data obtained from the literatures, and the databases of LCA software tools. Although building the LCI based on primary data is preferable and reliable, secondary data can be a valid substitute based on solid models and assumptions. Most LCA studies use primary and secondary data, and very few studies use only primary data or secondary data. Ecoinvent database is used to perform the LCI phase in most of the LCA available in around 66% of the studies, BatPac database is mentioned in 17% (Tolomeo et al., 2020).

We have collected three recent life cycle inventories for LIBs recycling processes from (Rajaeifar *et al.*, 2021), (Mohr *et al.*, 2020), and (Ciez and Whitacre, 2019).

1- (Ciez and Whitacre, 2019) inventory for modeling pyrometallurgical, hydrometallurgical, and direct cathode recycling processes for treating NMC-622, NCA, and LFP battery chemistries.

Ciez obtained the data for the pyrometallurgical process from the Umicore patent (*(12) United States Patent*, 2007). the hydrometallurgical process was modeled from peer-reviewed literature (GREET model) (Dunn *et al.*, 2015b), the assumptions for emissions and the embodied energy were sourced from Ecoinvent and GREET model 2016. Direct cathode recycling was modeled based on experimental work done by (Grützke *et al.*, 2015) at the University of Munster, Germany.

We have worked on tracking the data sources used in the inventory of (Rebecca E. Ciez, 2019), presented in Figure 44.

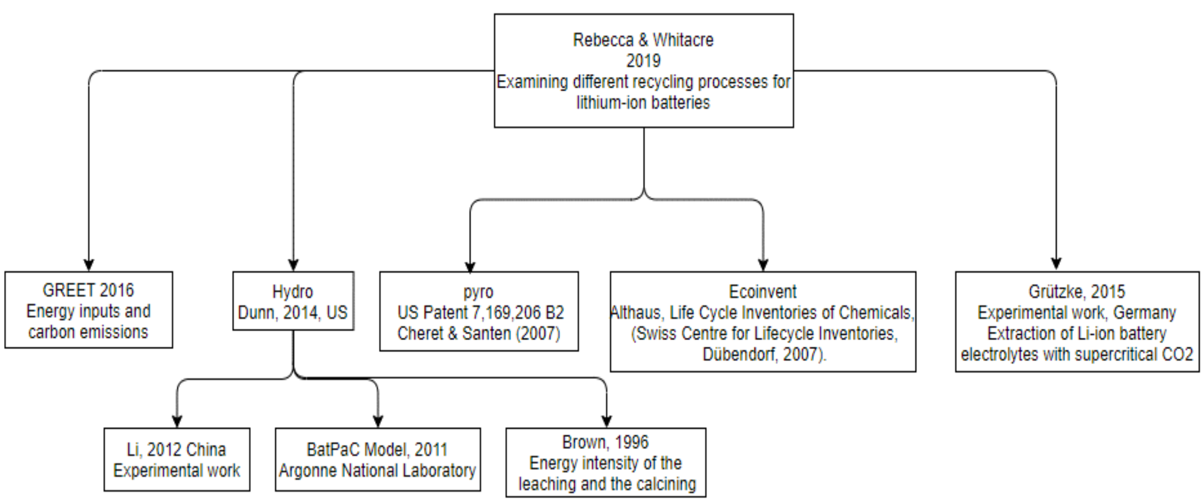

Figure 44 Tracking data sources of Ciez's inventory (WeLOOP 2021)

1- (Mohr *et al.*, 2020)inventory for modeling pyrometallurgical, hydrometallurgical, and advanced hydrometallurgical processes for treating NCA, NMC, LFP, and SIB battery chemistries

Mohr obtained the data for current pyrometallurgical and hydrometallurgical recycling processes from (Fisher *et al.*, 2006). Fisher's report covered different types of batteries [ZnO, ZnC, AlMn], [LiMn, Li, Li-ion], [AgO] [NiCd, NiMH] [PbA]. Fisher's inventory was based on mix of primary and secondary data, the primary data were obtained from batteries recyclers, where Lithium batteries recycling processes happened in the EU.

The hydrometallurgical process was modeled based on Recupyl's Valibat process from 2004, Recupyl is a recycling company in France now goes under the name TES. [In Recupyl's Valibat process, waste batteries are first shredded under inert gas and then chemically treated, resulting process outputs are the metal constituents contained in the cathode material (lithium salts and respective other metals) as well as separated parts of the cell housing (aluminum, copper, and plastic)]. The pyrometallurgical process was modeled based on Batrec recycling process (Switzerland, 2004). [The precise process flow is not disclosed, it is only known that the process involves a crushing step before neutralization and further processing].

The inventory provided by Fisher is relatively old, has inconsistencies and several ambiguities, and uses secondary data to quantify the avoided burdens of primary material production through recycling. (Mohr *et al.*, 2020)Also, took the database from the basis for respective processes in Ecoinvent (Hischier *et al.*, 2007a), this database doesn't differentiate between cell chemistries and only provides generic outcomes. (Mohr *et al.*, 2020)adapted the data to distinct cell chemistries NCA, NMC, LFP, and SIB. Lastly, the advanced hydrometallurgical recycling process was modeled based on primary data obtained from a German recycling company called Duesenfeld GmbH from the year 2014.

We have worked on tracking the data sources used in the inventory of (Mohr *et al.*, 2020), it is presented in Figure 45.

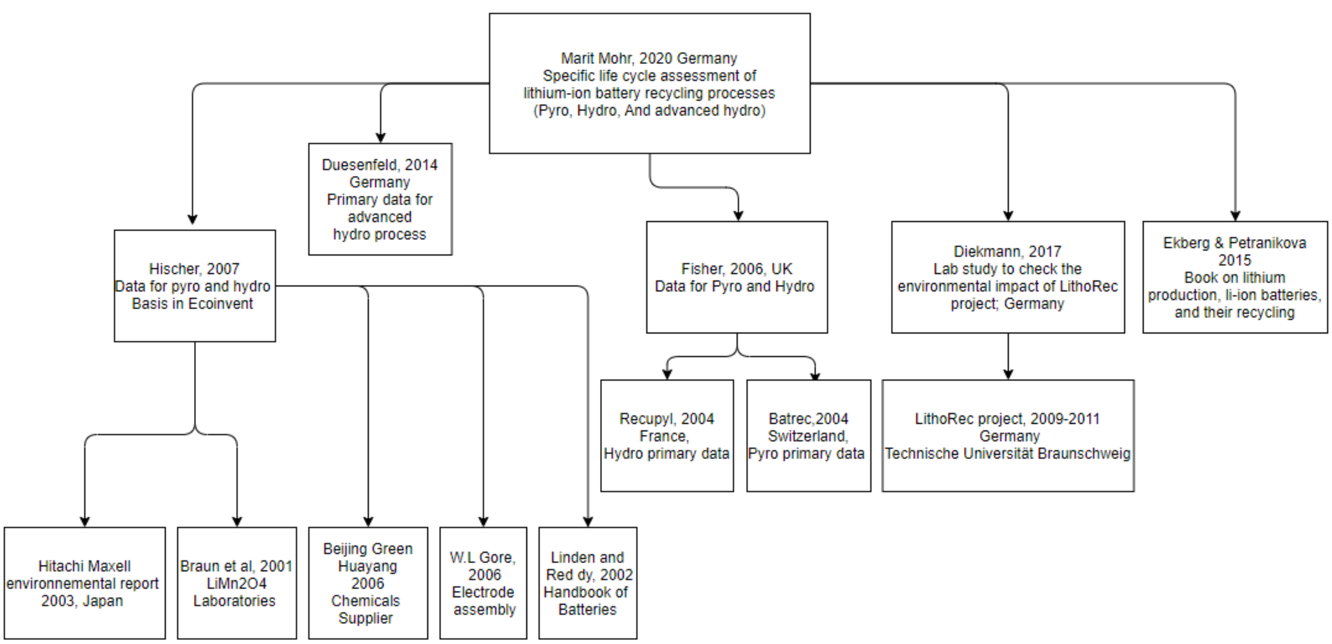

Figure 45 Tracking data sources of Mohr's inventory (WeLOOP 2021)

2- (Rajaeifar *et al.*, 2021) Inventory for modeling different pyrometallurgical processes to treat NMC111 lithium batteries.

Rajaeifar et al. obtained the data for the direct current plasma smelting from Tetronics company, and these data were quantified and modeled by action facilities are in place and operative. Reserves include only recoverable materials." (Geological Survey, no date)(Johnson, 2019). The second scenario studied in this assessment was DC plasma smelting preceded by pre-treatment, the pre-treatment (shredding) for this was adopted From the Ecoinvent database 2019 and (Hischier et al., 2007). The removal of volatile components was modeled and adapted from the calcination process described by the GREET model developed by Argonne National Laboratory (Dai *et al.*, 2017). The third scenario was to model an industrial pyro-hydrometallurgical process. The UHT furnace data were adapted from peer-reviewed literature (Dunn et al., 2015), the Umicore patent (*(12) United States Patent*, 2007), Umicore is a commercial recycling facility in Belgium, and the EverBatt model (*EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model Energy Systems Division*, no date; Dunn *et al.*, 2015b). The generated alloy is subjected to a series of hydrometallurgical treatments in the three scenarios. However, since the focus of this study is to assess the pyrometallurgical processes, the authors used the pre-existing GREET model and complementary data from the literature for the hydrometallurgical treatment part (Li *et al.*, 2013) and (Dunn *et al.*, 2015b) .

We have worked on tracking the data sources used in the inventory (Rajaeifar *et al.*, 2021), presented in Figure 46.

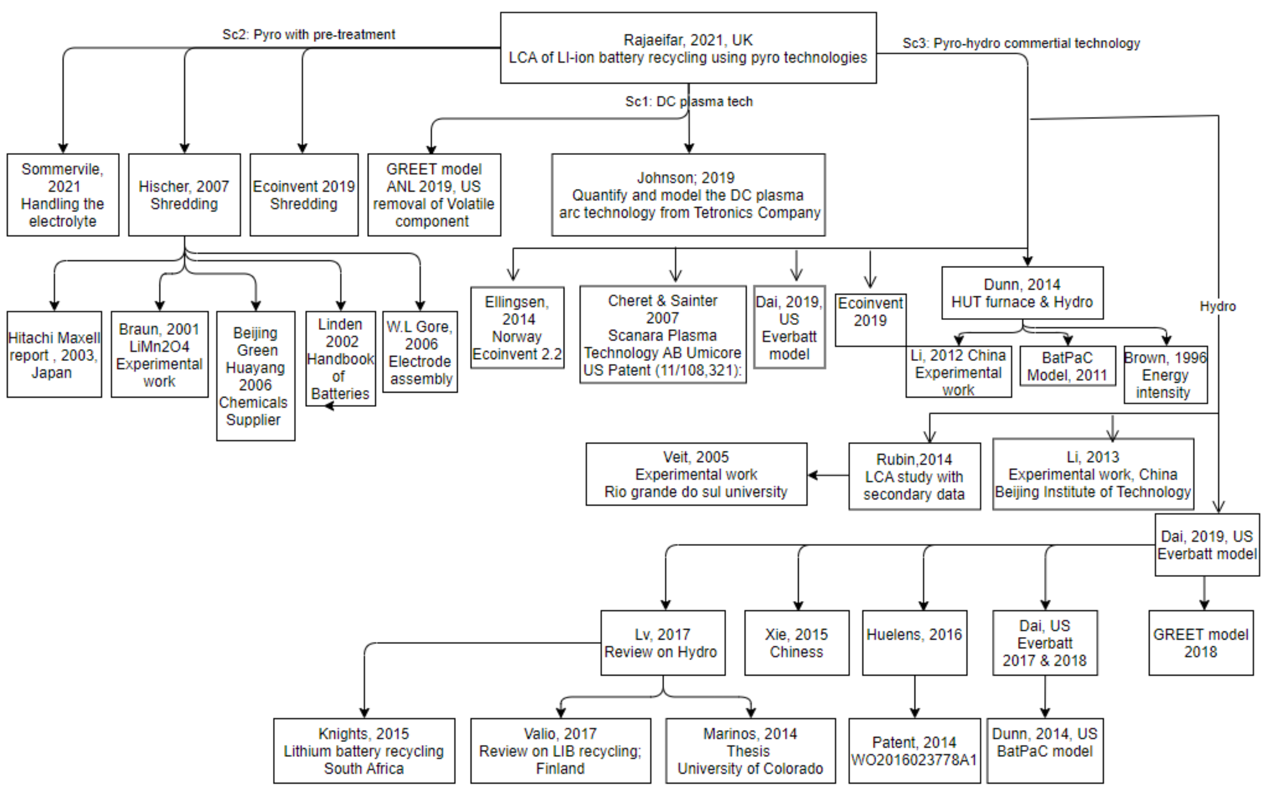

Figure 46 Tracking data sources of Rajaeifar's inventory (WeLOOP 2021)

Annex 4 / Detailed description of criticality aspects and indicators

For the selection of the criticality indicators, we have conducted a search on all the possible data sources suggested by the IRTC. And here we present in detail all the criticality aspects with a brief description of each aspect. Also, we present a description for all the criticality indicators that have been used to quantify the criticality aspects, as well as all the data sources:

1- Supply is dominated by a few countries; when one or only a few players dominate the supply, those players have the power to aff (Moss et al., 2011). Theoretically, there could be a bottleneck anywhere in the supply chain. For example, in distribution or manufacturing. But as we don't have the data to quantify all possible bottleneck, we only focus on mining and refining. Supply is dominated by a few countries can be quantified by two criticality indicators:

1.1- HHI Mining countries raw materials

The share of mining countries is a supply risk indicator used to check the diversity of supplying or producing countries; it is also known as country production concentration. It is considered one of the most used indicators by criticality studies(Achzet and Helbig, 2013). In this study, for measuring this value (quantifying the indicator), a country risk-weighted Herfindahl–Hirschman Index HHI is applied. Another way of measuring the share of supplying countries is to use the sum of the one to three largest producers. The HHI is calculated as shown in the following formula:

$HHI(a) = \sum_{i=1}^{N}(a_i^2)$, where:

N is the number of producing/mining countries,

a_i is the share of a country of the annual production.

An example of supplying dominated by one country is the case of rare earth elements (REEs); where China controls about 90% of the global production of rare earth minerals—keeping in mind that China has about only one-third of identified REEs global resources (Rollat *et al.*, 2016).

1.2-HHI refining countries

The refining/processing stage, also called the post-mining stage, is a series of operations that transform raw materials into substances; these substances are used to make products.

Supply disruption could be increased because few countries dominate the refining of numerous metals. In the 2020 EU criticality list, the supply risk of raw materials was assessed by two critical stages mining/extraction and processing/refining. In some cases, the refining stage can be more critical than the mining/extraction stage. For example, in the 2020 EU criticality list, the refining stage was the most critical stage for the following elements: Tungsten, Titanium, Silicon metal, Scandium, Phosphorus, PGMs, Niobium, Magnesium, Lithium, Indium, Hafnium, Germanium, Gallium, and Bismuth (European Commission, 2020).

For measuring this indicator, the Herfindahl–Hirschman Index HHI is applied, too. The HHI for refining countries is calculated as shown in the following formula:

$HHI(a) = \sum_{i=1}^{N}(a_i^2)$, where:

N is the number of refining/processing countries,

a_i is the share of a country of the annual refining/processing.

2- The supplying country is subject to natural disasters

Natural disasters such as flooding, tsunami, landslides, earthquakes, and storms might lead to supply disruption. When a supplying country suffers from natural disasters, this can cause damages to mines, refining facilities, etc., which can lead to the closure of these facilities for some time—causing a supply shortage that will be reflected in the supply/demand balance which causes supply disruption. (Eynard et al., 2020).

To date, criticality studies have not considered the natural disasters criticality aspect, because there are no current methods to quantify the risk of natural disasters due to their complexity. However, to have a comprehensive criticality assessment, it is important to include the natural disasters aspect, which leaves it an area for future research. During our literature review, we found two studies that have a potential strategy to quantify the aspect of "natural disasters".

In 2012, Stefania Balica, worked on approaches to understand the developments of vulnerability indexes for natural disasters. Where Balica defined vulnerability as "the degree of fragility of a (natural or socio-economic) community or system toward natural hazards.". Balica also defined an indicator as an inherent characteristic that quantifies and estimates the condition of a system. Balica's work described different approaches to vulnerability indices based on natural disasters. These indices are environmental vulnerability index, climate vulnerability index, economic vulnerability indices, social vulnerability indices, coastal vulnerability indices, drought vulnerability indices, vulnerability assessment to aquifers, water poverty index, and composite vulnerability index for small island states (Balica, 2012).

Recently, Botzen et al, did a review of models and empirical studies to quantify the economic impacts of natural disasters. Although the main focus of the study was quantifying the economic impacts of natural disasters, the authors presented computational models for simulating the direct impacts of natural disasters using catastrophe models. Catastrophe models give detailed results on damages or property losses caused by the natural disaster by simulating hypothetical disaster characteristics with different intensities and probabilities at a particular location. For example, in the case of a flood disaster, the model indicates areas that are susceptible to flood risk, inundation depths, and flow velocity. The model also gives the probability of occurrence. The authors also introduced the CGE model, which simulates the impacts of natural disasters on economic activities and supply disruptions, where the model includes the equilibrium of demand and supply in various markets (Botzen, Deschenes, and Sanders, 2019).

There are several limitations to quantifying the "impact of natural disasters on supplying countries". Since natural disasters are real-complex life phenomena and predicting future disasters requires using computational simulations. Not to forget that historic natural disasters don't necessarily predict future disasters, plus, if a disaster takes place, it does not necessarily lead to supply disruption. This could lead to a considerable range of uncertainties related to these models. More research is needed to find feasible ways to address and quantify this criticality aspect.

3- The supplying country is subject to trade restrictions/resource nationalism.

Political factors can play a role in aggravating the supply risks, mainly when a few countries dominate the supply. A few examples of political factors can be political instability, internal conflicts, and resource nationalism, which refers to the state's efforts to acquire a larger share of important downstream industries. Another political factor is when the supply-dominant country tries to increase revenue over time. This gives the state the power to intervene in decisions related to global production and pricing; such activities can take the form of trade restrictions. Trade restrictions affect the exports of certain raw materials, such as limiting the exports or taxing exports. All this can exacerbate supply disruption(Moss et al., 2011). Therefore, it is essential to assess the political risks of the dominant supplying countries. Two indicators quantify this criticality aspect

3.1- Trade restrictions (OECD, 2020)

Trade barriers such as export restrictions highly influence the market of raw materials. Recently, export restrictions have become more frequent, especially on raw materials. Posing export restrictions by major supplying countries can lead to a volatile market due to price increases, which results in supply disruptions. There are many forms of raw materials export restrictions, however, the most common are export prohibition, export taxes, export quotas, and licensing requirements. Export restrictions would have stronger effects when the country imposing these restrictions is a major supplier. Trade agreements with the supplying countries can reduce the supply disruption risk anticipated by the export ban.

One famous example of export restrictions affecting the raw materials market is when China imposed an export ban on several raw materials (rare earth elements REEs, tungsten, and molybdenum). These restrictions drove the European Union, the United States, and Japan to bring a case to the World Trade Organization's (WTO) Dispute Settlement Body in 2012. This resulted in China lifting its export restrictions in 2015, following the WTO's ruling (Blengini *et al.*, 2017).

Figure 47 presents the proportion of the primary global supply of Lithium battery raw materials potentially subject to export restrictions between 2017 and 2021. Data were taken from OECD inventory and USGS.

OECD is Organization for Economic Co-operation and Development. Data on raw materials export restrictions were taken from the OECD (Methodological note to the Inventory of Export Restrictions on Industrial Raw Materials Table of contents, 2021), the OECD inventory covered the period between 2009 and 2020. Some extrapolations have been done during collecting data for this assessment. For example, when a country has no export restrictions on any raw materials supplied by this country for the last 12 years. And this country supplies a raw material not mentioned in the OECD inventory, it has been considered that this raw material has no export restrictions too (This was the case for some LIB raw materials supplied by France, Norway, and Peru).

On the other hand, when a country has export restrictions on every raw material supplied by this country for the last 12 years. And this country supplies a raw material not mentioned in the OECD inventory. It has been considered that this raw material has export restrictions too (This was the case for some LIB raw materials supplied by Vietnam, India, and Madagascar).

For Natural Graphite supplied by China, in 2017 China imposed export restrictions on Natural Graphite, but these export restrictions were lifted from 2018 to 2020. However, in this assessment, the supply from China was considered to be potentially subjected to export restrictions between 2017-2020.

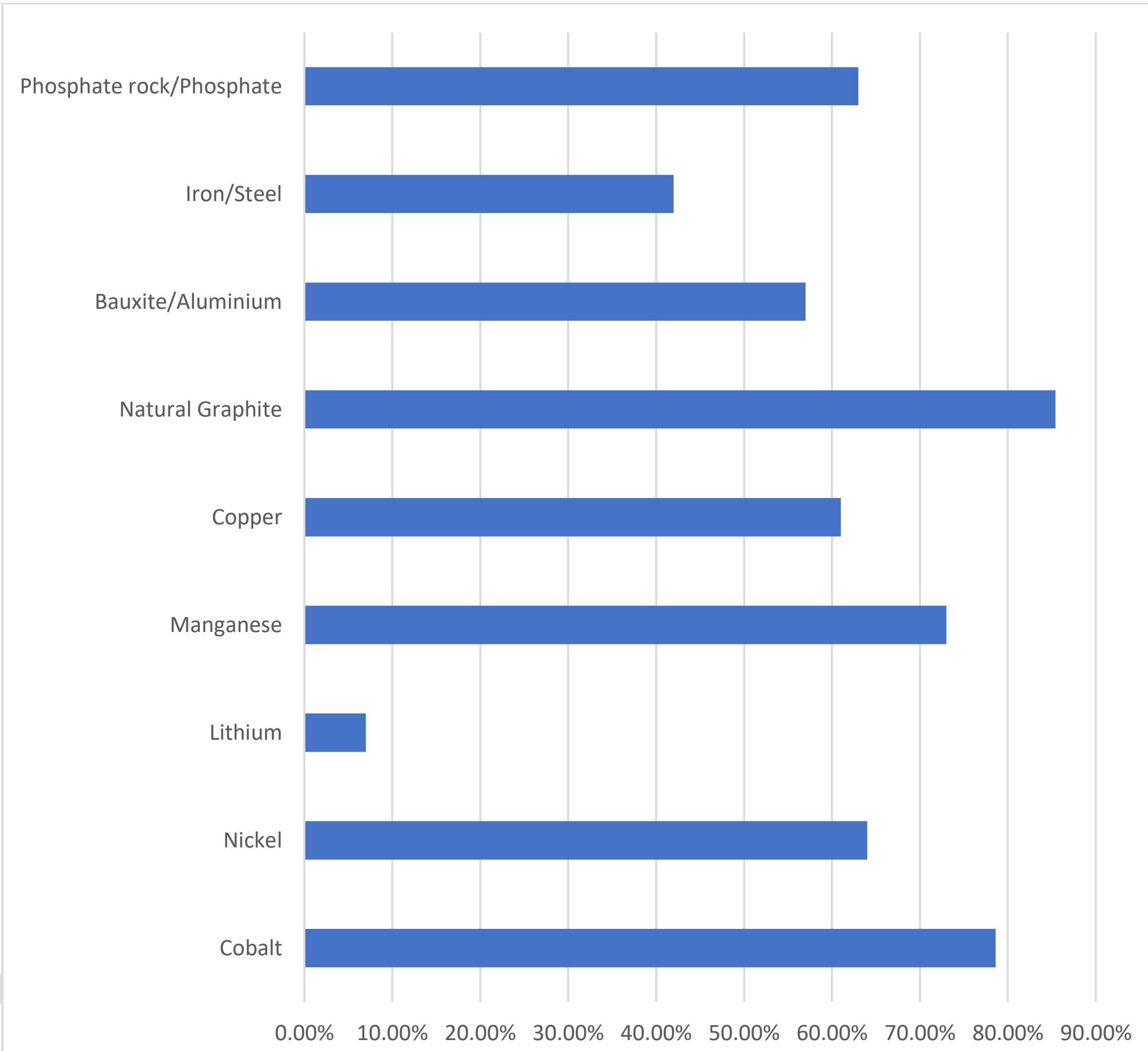

Figure 47 Proportion of the primary global supply of Lithium battery raw materials potentially subject to export restrictions between 2017 and 2021.

3.2-Enabling trade index (ETI).

Enabling trade index was co-produced by the World Economic Forum and the Global Alliance for Trade Facilitation, it was launched in 2008. to provide insights about trade costs (The Global Enabling Trade Report 2016 A joint publication of the World Economic Forum and the Global Alliance for Trade Facilitation Insight Report, 2016) ETI evaluates to which extent economies facilitate the free flow of goods over borders (and to their destination). This is done by having policies, infrastructures, and services to facilitate trade activities. ETI is composed of four subindexes, each subindex is composed of one or several pillars, where there are seven pillars in total. The first subindex is market access which has two pillars foreign market access and domestic market access. The second subindex is border administration which has one pillar the efficiency and transparency of border administrations. The third subindex represents the infrastructure, it is consisting of three pillars: availability and quality of transport infrastructure, availability and quality of transport services, and availability and use of ICTs. The last subindex is the operating environment which is represented by one pillar operating environment(The Global Enabling Trade Report 2016 A joint publication of the World Economic Forum and the Global Alliance for Trade Facilitation Insight Report, 2016). The following figure represents the framework of the ETI.

This indicator is considered a trade barrier, where trade barrier is measured by multiplying the share of the raw materials supplying country with the Enabling Trade Index. Enabling Trade Index is a country-specific indicator, it is a well-established indicator which means it has lower uncertainties since it has been improved over time (Bach et al., 2017)ell-established indicator which means it has lower unceThe Global Enabling Trade Report 2016 A joint publication of the World Economic Forum and the Global Alliance for Trade Facilitation Insight Report, 2016).

4- supplying country is subject to societal unrest: This aspect is quantified by WGI-rule of law. WGI-Rule of law (RL) indicates the extent to which agents have confidence in and abide by the rules of society, especially the quality of contract enforcement, property rights, the police, and the courts, and the likelihood of crime and violence.

5- The supplying country is subject to an unstable investment climate; this criticality aspect can be quantified by four indicators

5.1- WGI – Political stability & absence of Violence/terrorism (PV). This indicator gives information about the likelihood of destabilization or overthrowing the government by unconstitutional or violent means, including politically motivated violence and terrorism(Kaufmann *et al.*, 2010). Criticality indicators can be interrelated, where some indicators might fit other aspects for example WGI – Political stability & absence of Violence/terrorism (PV) which is used here for the aspect 'supplying country is subject to an unstable investment climate', it might also be used for the societal unrest aspect.

5.2- WGI - Government effectiveness (GE), this indicator gives information about the quality of public services, civil service, the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies.

5.3- WGI - Regulatory Quality

Regulatory quality (RQ) this indicator gives information on the ability of the government to formulate and implement sound policies and regulations that permit and promote the private sector development

5.4- Failed State Index

Failed state index provides information about the political stability of countries. It is established by the World Bank as an indicator of the Fund for Peace and the World Governance.

It is recognized that Failed state index or WGI indicators serve as totally rough – proxies to measure the political stability and societal unrest of the dominant supplying countries. Also, these indicators assess the potential for intervention in the market processes by major supplying countries (Moss et al. 2011).

6- A few companies dominate the supply

When one or few companies gain a dominant position in the market, they have the power to control the pricing of the raw materials. This might lead to market imbalances and price volatility, resulting in a tense market situation and developing into a resources monopoly or oligopoly form. Therefore, it is important to evaluate to which extent the domination of a few companies could be an indicator of short-term supply risk. The indicator "few companies dominate the supply" was used as a supply risk indicator by several criticality studies. Most of these previous criticality studies considered raw materials producing companies and some studies also included companies that process raw materials. The indicator "few companies dominate the supply" was also referred to as "concentration of raw materials producing companies" (Achzet and Helbig, 2013). This indicator can be measured by the Herfindahl-Hirschman Index HHI (Rosenau-Tornow *et al.*, 2009) or with the top-3-approach:

($Dominant\ supplying\ companies_{Top-3}(a) = \sum_{i=1}^{3}(\alpha_i . a_i)$) (Erdmann and Graedel, 2011).

One example of a company dominating the raw materials supply, is the case of the lithium mining company SQM in Chile. In the 1990s, SQM suppressed other Li-producing companies and gained a dominant position in the market. Due to their low production cost and high production capacity, which led to a tensed-market situation.

7- Competing use in high-margin or high-priority products

High-margin products give a high profit in comparison with how much money is spent on the production of these products, such as jewelry, cosmetics, and watches. High-priority products have big importance, such as products and materials used in the health care sector, or products that are important for strategic sectors such as the energy, national security, and defense sectors. For example, when evaluating one raw material that is used for television screens, and also in the health care sector. In times of market scarcity, television screen manufacturers might have more problems obtaining access to the raw material. Because the health care sector is prioritized.

Another example is when evaluating a raw material used simultaneously in the electricity sector (sector with low-profit margins) and in mobile phones (sector with high-profit margins). Price increases might have more impact on the electricity sector because if one technology (becomes more expensive, alternative technologies will be invested in). On the other hand, in the mobile phone sector, the margins are high enough to absorb some price volatility.

8- By-product dependency of mining

A by-product is a mineral or metal whose supply is dependent on the production of the main carrier metal. For example, In and Cd are by-products of zinc mining, zinc here is considered the carrier metal. The extraction of by-products directly depends on the extraction and the processing of the carrier metal. Therefore, the availability of the by-products in the market is not dependent on the demand for the specific material, but rather on the demand for the carrier metal. This could lead to strong price fluctuations. From there, the concept of by-product dependency emerged. By-product dependency is an indicator to assess supply elasticity and the temporal availability of resources. There are some uncertainties related to the by-production of mining, such as the lack of explicit data about production and reserves capacities. One aspect of assessing the by-product dependency is allocating the exploration cost, which means assigning the production cost of extraction between the carrier metals and by-products. Wherefrom the cost calculations, one can derive important information for resource availability in the short-term and long-term. One issue is data availability, where these data are partially accessible(Achzet and Helbig, 2013). The by-product dependency is measured by the following equation:

By-product= $\frac{by-production}{Total\ production}$

The following table shows some examples of by-products and their carrier metal.

Table 12 By-products with their carrier metal

Carrier metal	By-products
Cu	Mo, As, Bi, Ag, Au, Co, Se, Te, PGM
Sn	In, Ta, Nb
Pt	Au, Pd, Rh, Ru, Ir
Al	Ga
Zn	Ge, In, Te, Se, Cd
Pb	Bi, Te, Se, Ag, In
Ni	PGM, Cu, Co, Au
Mo	Re

(Graedel et al. 2015) have used the Companion Metal Fraction CF indicator to quantify the by-product dependency criticality aspect, CF gives the percentage of the metal which was mined as a by-product.

For Lithium battery raw materials, the most important metal mined as a byproduct is Cobalt, with 98% of cobalt production mined as a by-product (Cobalt Institute, 2022). Most cobalt is mined as a byproduct of copper or nickel mining processes, except for Cobalt production in Morocco and some Canadian arsenide ores. As a result, the recovery rates of Cobalt are tied to the by-production dependency, where in some cases cobalt is left as a waste of the mining processes of the carrier metal, this varies between less than 10% up to more than 80% (Supporting Information for Graedel et al. 2015).

9- Expected demand increases due to use in emerging technologies
Emerging technologies could change the economic structures, and some aspects of social life and even could affect the environment in the long term. Emerging technologies lead to sudden demand increase of a few or several raw materials which might lead to shortages in the market, these shortages in the market can be gradual and foreseeable. The consequences of possible shortages in the market are strong price increases (Angerer and Fraunhofer- 2009).
Use in emerging technologies is used as an indicator of the risk of supply disruption (Schrijvers *et al.*, 2020). For example, Lithium-ion batteries are emerging as important technologies due to their

increasing use in electric vehicles (the electrification movement of the transportation system), their use in small electrical and electronic appliances, and their stationary energy storage applications. Where the demand for Lithium-ion batteries is anticipated to have a rapid yearly increase of above 30% for the next ten years. As a result, the demand for metals used in the production of Lithium-ion batteries is increasing, leading to potential increases in prices or market shortages. Therefore, metals such as Lithium and Cobalt are among the critical metals for the EU economy (Bobba *et al.*, no date).

Robotics is also an emerging technology; robotics uses 44 raw materials of which 19 raw materials are critical for the EU economy (such as chromium, cobalt, molybdenum, natural graphite, nickel, magnesium, vanadium, copper, tin, antimony, and bismuth). Where the major suppliers of the critical raw materials of robotics are China, South Africa, and Russia with the respective shares of 40%, 10%, and 9%. It is difficult to forecast the growth rate of materials demand in the robotics sector due to the variety of sectors that which robotics is involved.

In the long-term, Platinum demand is expected to increase due to its use in fuel cell electric vehicles (emerging technology). Palladium is also expected to have a demand increase (about a fivefold increase) due to its use in emerging technologies such as micro-electric capacitors and seawater desalination (Latunussa *et al.*, no date a)ts use in emerging technologies such as micro-electric capacitors and seawater desalination (Latunussa *et al.*, no date a).

It is very important to secure stable and diverse acc(Bobba *et al.*, no date).

“Metals for Clean Energy” report done by KU Leuven and commissioned by Eurometaux (Europe’s metals association) in 2022. The goal behind their analysis is to lay out reliable scenarios for the evolution of European and global metals markets concerning the energy transition and the Green Deal. Using the IEA energy pathway scenarios.

“IEA is the International Energy Agency that was founded after the energy crisis of the ‘70s and analyses current energy trends and long-term outlooks, lately with a strong focus on climate aspects. IEA has developed three energy pathway scenarios, and evaluated the use of critical raw materials in these scenarios:

- Net-zero emissions by 2050 (NZE): Global energy pathway to achieve net-zero emissions by 2050, which is consistent with limiting the global temperature rise by 1.5 degrees Celsius, in line with COP26. This scenario also covers the ambitions of energy-related SDGs (e.g., achieving universal energy access by 2030).
- Stated policies scenario (STEPS): Exploration of energy pathways without additional policy implementation. A granular and sector-by-sector look is applied to include existing policies.
- Sustainable development scenario (SDS): Scenario consistent with limiting the global temperature rise by 2 degrees (Paris agreement), and it assumes that all energy-related SDGs are met. It requires increased effort to realize near-time emission reductions.” (Leuven and Gregoir, 2022).

In the data collection sheet for our criticality assessment of lithium battery raw materials, we have used the Compound Annual Growth Rate between 2020-2050 for the SDS. which reflects total demand increase, both for emerging technologies and emerging economies as well as other industrial development.

10- Expected demand increases due to use in emerging economies

The emerging economy term describes the economy of countries with low income and rapid growth, the growth engine of these countries is economic liberalization (lessening the economic regulations and restrictions imposed by governments). Emerging economies can be divided into two categories: transition economies (China and the former Soviet Union) and developing countries (In the middle east, Latin America, Africa, and Asia) (Robert E. Hoskisson, 2017). The rapid growth of emerging economies has led sometimes to supply disruption. Due to the increasing demand for several metals and minerals due to the dynamic technological changes in these emerging technologies. From this arises the need to secure access to a stable supply of critical raw materials used in emerging economies("Study on the EU's list of Critical Raw Materials (2020) Final Report," 2020).

One example of increasing demand for material due to its growing demand from emerging economies in the case of coking coal. Where for a long period of time coking coal has had stable and low prices, in 2003 the prices of coking coal had a sharp increase due to the strong demand for coking coal for steel making in China (the increased demand for steel is due to large infrastructure projects in China)(Latunussa et al., 2020).

11- Potential to increase supply from mines,

The potential to increase supply from mines is related to reserves concentration as well as the policy climate in the countries that hold these reserves. Where policy climate is an important factor that should be taken into consideration in mineral exploration investments. This criticality aspect can be quantified by three indicators HHI – reserves, Reserves-to-production ratio, and Policy Perception Index PPI.

11.1- HHI – reserves.

Before discussing the reserves-related indicators, it is important to fully understand the difference between resources, reserves, and reserves base.

In the USGS the term 'Resource' is defined as a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible. 'Original Resource' is defined as the amount of a resource before production. And the term 'Identified Resources' is defined as resources for which location, grade, quality, and quantity are known or estimated from specific geologic evidence. Identified resources include economic, marginally economic, and subeconomic components. To reflect varying degrees of geologic certainty, these economic divisions can be subdivided into measured, indicated, and inferred.

The term 'Reserve Base' is defined as **"**That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the in-place demonstrated (measured plus indicated) resource from which reserves are estimated. It may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources).".

The term 'reserves' is defined as "that part of the reserve base that could be economically extracted or produced at the time of determination.

In previous criticality studies the indicator "reserves' concentration" was used for evaluating supply risk. Herfindahl–Hirschman Index (HHI) was used to quantify the country's concentration of reserves. The HHI for reserves countries is calculated as shown in the following formula:

$HHI(a) = \sum_{i=1}^{N}(a_i^2)$, where:

N is the number of reserves countries, a_i is the share of a country's reserves.

However, there is no one defined limit to identifying critical minerals. For example, in 2006 the US Federal Ministry of Economics and Technology considered HHI values that are equal to or more than 0.15 as critical. Where the US Federal Institute for Geosciences and Natural Resources considered HHI values that are equal to or more than 0.2 as critical. (Achzet, 2013)

Other criticality studies have used the sum of one to three largest reserves countries. They have considered that it is critical to have a reserve concentration of about 50% in one country or more than 65% in two countries.

11.2- Reserves-to-production ratio,

The ratio of reserves to the current annual production gives an estimation of the potential increase in supply from mines. It is simply calculated by dividing the volume of reserves by the volume of the annual production,

Reserves-to-production ratio=$\frac{Reserves}{Production}$ (static reach reserves), when this ratio is less than 25a, the mineral is considered critical. (Achzet, 2013)

this ratio measures how long the mineral reserves will last with the current annual production rates. However, this indicator should be used carefully to avoid misinterpretation. Mineral deposits are not fully explored because developing reserves is costly and time-consuming, and reserves development and mineral exploration (for mineral deposits that were not previously known) are ongoing activities at mines. Moreover, technological innovations could convert mineral resources into reserves by making it economically and technologically feasible to extract the mineral rocks that are known to be geologically interesting but uneconomic. Another factor affecting the mineral reserves' definition is the economic conditions (Changing in prices and extraction costs).

There is another related ratio, which is the minerals' reserves base to production ratio this measure gives a "longer-term" view of mineral availability (NRC (U.S.), 2008).

It is calculated as following Reserves base-to-production ratio=$\frac{Reserves\ base}{Production}$ (static reach reserves base), when this ratio is less than 50a, the mineral is considered critical (Achzet, 2013). Since "reserves" is a dynamic concept, this indicator does not reflect absolute scarcity, but rather highlights the need for further exploration and perhaps technological development in the mining sector.

11.3- Policy Perception Index

The policy perception index (PPI) indicates the overall investment attractiveness of mining policies of governments. PPI quantifies and measures how government policies affect investments, where 40% of investment decisions are determined by policy factors (Yunis and Aliakbari, 2021). PPI is a composite index that examines policy factors of a government, there factors are “uncertainty concerning the administration of current regulations, environmental regulations, regulatory duplication, the legal system and taxation regime, uncertainty concerning protected areas and disputed land claims, infrastructure, socioeconomic and community development conditions, trade barriers, political stability, labor regulations, quality of the geological database, security, and labor and skills availability.

In the 2021 report of the survey of mining companies, a number of jurisdictions have not been included, such as Afghanistan, Albania, Angola, Argentina: Neuquen, Armenia, Belarus, Bulgaria, Burundi, Cambodia, Central African Republic, Cyprus, Dominican Republic, Egypt, Eritrea, Estonia, Ethiopia, Fiji, France, French Guiana, Gabon, Greece, Guatemala, Honduras, Hungary, India, Iraq, Israel, Ivory Coast, Japan, Jordan, Kenya, Laos, Lesotho, Madagascar, Malawi, Malaysia, Mozambique, Myanmar, New Caledonia, Nigeria, Oman, Pakistan, Poland, Portugal, Republic of the Congo (Brazzaville), Romania, Saudi Arabia, Serbia, Sierra Leone, Slovakia, Solomon Islands, South Dakota, South Korea, South Sudan, Sudan, Suriname, Swaziland, Tajikistan, Thailand, Tunisia, Uganda, Uruguay, Vietnam, and Zambia.”(Yunis and Aliakbari,2021).

In some cases the same country has several PPI values depending on the state, region or city (the case of the USA, Canada, and Australia), in our project we took the least favorable value. “Nevertheless,

12- Share of (current) production capacity used in mining and refining

The current market dynamics are important factors to consider when assessing future supply disruption and supply-chain bottlenecks. The most studied factors are resource availability, supply concentration, political risks related to dominant supplying countries, potential demand increase, potential substitution, and recycling. Although these factors are essential for understanding and assessing the supply-demand balance. Nonetheless, it is insufficient to only consider them when assessing potential supply disruptions in the short to medium-term evaluation (Moss *et al.*, 2011). Therefore, it is important to consider the current production capacity used in mining and refining and understand the limitations to expanding the global production capacity in the short to medium term. The supply disruption risk associated with the limitations of current production capacity is caused by the low-price elasticity in the short to medium-term. This supply disruption risk could be caused by several factors, such as full capacity production of existing projects while new projects still need many years to start the production. Another factor could be that the investors are unwilling to take the risk and be involved in large long-term investments in a volatile market. This risk is also related to by-production dependency where the production is rather driven by the economic value of the carrier metal (Moss *et al.*, 2011).

Forecasts from mining and refining industry sources can be used as data sources when assessing the potential supply risk associated with the share of current production capacity. Such industry forecasts usually estimate the capacity of existing mining and refining projects, and potential secondary sources (e.g., recycling) and examine future exploration and investments. The interactions of the two indicators (potential supply increase and the limitations to production capacity) should be taken into account. For example, even if there was a rapid increase in demand if the production capacity is steady and can keep pace with the demand, it is unlikely for the demand increase to cause a supply disruption (Moss *et al.*, 2011).

In this study the share of current production capacity was quantified by the production to reserves ratio, measured by the following equation:

$$Production\ to\ reserves\ ratio = \frac{Global\ production\ in\ 2021}{Global\ reserves}$$

This indicator overlaps with the "Reserves-to-production ratio" indicator which was used to quantify the "potential to increase supply from mines" aspect.

In our criticality assessment for lithium battery raw materials, we have used the production-to-reserves ratio to quantify the share of the current production capacity used.

13- Environmental impacts associated with the Product; this aspect can be quantified by two indicators:

Environmental impacts could represent a source of supply risk, where environmental impacts could impose low to high probable supply disruption of a certain raw material. The probable supply disruption is due to a few factors; the possible environmental impact associated with the use of the raw material, potential environmental regulations, and the probable environmental risk caused by the disruptive availability of the raw material. Also, the use of raw materials with high environmental impact can affect the reputation of a company. Previous criticality assessment studies have considered environmental factors (Graedel et al. 2015) (Nuss and Matthew J. Eckelman, 2014) (Manhart *et al.*, 2019). However, criticality indicators used to quantify the environmental impacts overlap with the criticality indicators related to the social factors. For example, the indicators are assessed by life cycle assessment methods such as ecosystem quality biodiversity, and human health could be related to environmental and social factors. Anyway, these indicators represent different possible risks, those risks could or could not be correlated. It is recommended to present environmental factors indicators separated from the social factors indicators since there is not a clear cause-and-effect mechanism of social and environmental associations on criticality (Schrijvers *et al.*, 2020).

13.1- Life Cycle Assessment

LCA Life Cycle Assessment is a tool used to quantify the environmental burdens associated with raw materials, products, technologies, and services. Life cycle assessment studies can be performed for cradle-to-gate systems or cradle-to-grave systems. Cradle-to-gate LCA study for a product usually includes the resource extraction stage (the extraction of raw materials), the manufacturing stage, and the distribution stage. Where cradle-to-grave LCA studies include all stages from resource extraction (cradle), manufacturing stage, distribution stage, use phase, to last the disposal phase which is the end-of-life stage (grave) (Nuss and Eckelman 2014).

(Graedel et al. 2015) used environmental life cycle assessment to quantify the environmental implications associated with the production of 1 kg of metal with a cradle-to-gate approach.

For example, platinum and gold have high cradle-to-gate environmental impacts, these impacts are related to the extraction and processing of the metal from its ore deposits, normally environmental impacts are calculated for one kilogram of metal (Graedel et al. 2015).

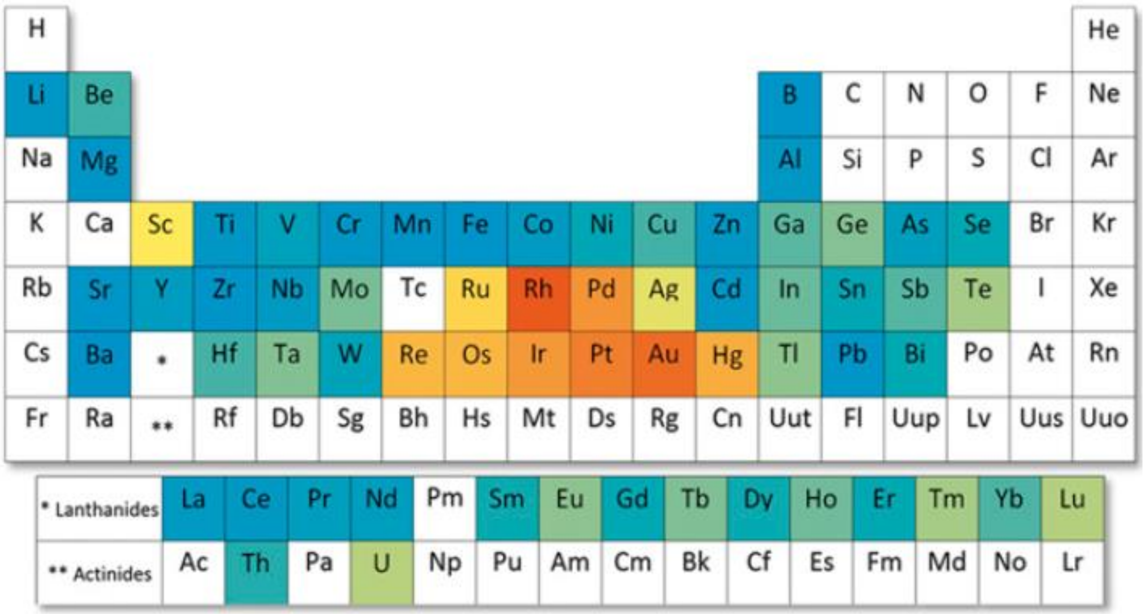

Figure 48 Periodic tables of criticality for 62 metals, for environmental implications (Graedel et al. 2015)

A significant number of LCA studies have been conducted to assess the energy use and the environmental impacts of metals. Life cycle inventory LCI databases are used as data sources; the most common data source is the Ecoinvent database. Nevertheless, many available LCIs have the data in an aggregated form which means the data are already pre-allocated or even are at the level of the system process. This makes conducting a robust comparison challenging, moreover, makes it difficult to include co-production issues in the assessment. Furthermore, data from LCI databases do not always represent the global routes of the production of metals, they also do not include the chemical forms of the element (metallic form or mineral form) (Nuss and Eckelman 2014).

Environmental implications (EI) are taken from (Graedel et al. 2015),.Their data are based on the Ecoinvent 2.2 database for 1 kg of the material, using SimaPro8.0.3 software. Using ReCiPe v1.10 as the impact assessment method, where the end-point results were transformed to a [0-100] scale. The EI criticality indicator consisted of potential damages to human health and ecosystems per kilogram of the metal mix at the factory gate.

Due to the economic allocation of mining impacts among the co-products, by-products have a relatively low environmental footprint. However, their mining can still be associated with high overall environmental impacts, which are not well reflected by the LCA results. This could result in the underestimation of potential reputational risks or regulatory risks related to the mining of these elements. Therefore, it is useful to include another indicator which is the Environmental Performance Index EPI.

13.2- Environmental Performance Index (Wendling *et al.*, 2020)

The Environmental Performance Index EPI assesses and ranks the environmental health and the ecosystem vitality in a significant number of countries (180 countries). EPI provides the state of sustainability in these countries by evaluating how close those countries are to established environmental policy targets.

The framework of the Environmental Performance Index EPI (2020) is organized into two policies which are environmental health (with 40% weight) and ecosystem vitality (with 60% weight). These two policies are organized into 11 issue categories, four issue-categories in the environmental health policy, and seven issue-categories in the Ecosystem vitality policy. The issue categories in the environmental health policy are air quality 20%, sanitation and drinking water 16%, heavy metals 2%, and waste management 2%. The issue categories in the Ecosystem vitality policy are Biodiversity and habitat 15%, Ecosystem services 6%, Fisheries 6%, climate change 24%, water resources 3%, pollution emissions 3%, and agriculture 3%. These policies and issue categories are finally organized into 32 performance indicators (solid waste, drinking water, sanitation, household solid fuels, PM exposure, wastewater, Black C, CH4, N2O, CO2, GHGs, NOx, SO2, Lead, etc.).

The overall EIP provides indications and evaluations of countries which have best practices in addressing environmental challenges. EPI uses data analyze performance, this is achieved by issue category, policy objective, peer group, and country. To understand the environmental progress and refine the policy choices.

Figure 49 shows the EPI framework, policies, issue categories, and indicators (Wendling *et al.*, 2020)

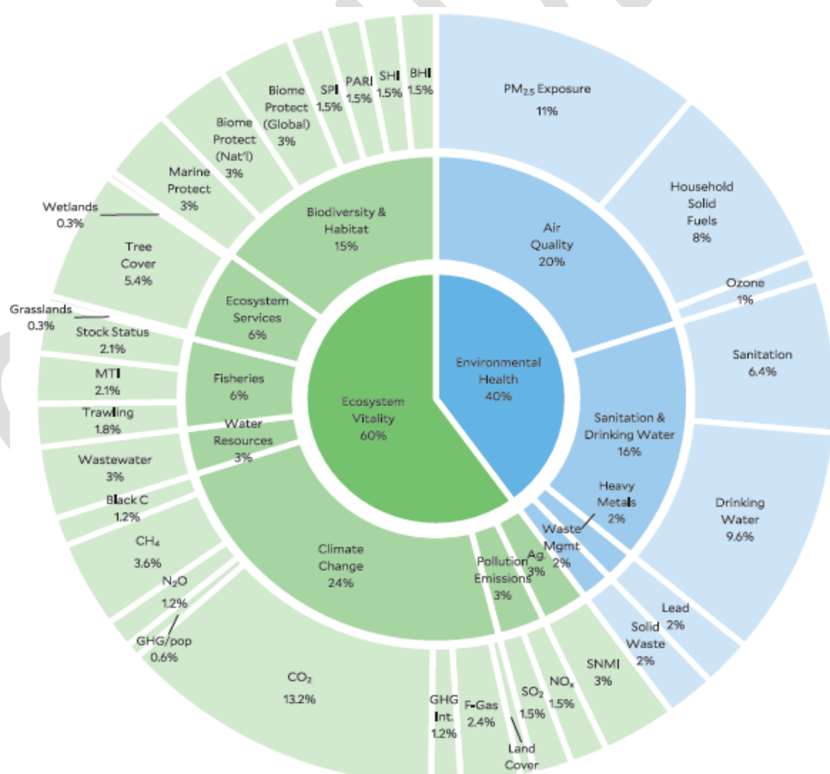

Figure 49 The 2020 EPI Framework (Wendling et al., 2020)

In parallel with LCA and EPI, another source of environmental indicators that can be interesting to consider is the Environmental Sustainability dimension of the International Human Development Indicators of the United Nations Development Program. Where this Environmental Sustainability dimension has 15 indicators to name a few; CO_2 emissions (kg per 2010 US$ of GDP, CO_2 emissions (production emissions per capita in tons), Fossil fuel energy consumption (% of total energy consumption), and Natural resource depletion (% of GNI).

14- Social circumstances associated with the product

Nowadays, Consumers are more concerned about the social circumstances associated with the products they purchase. These social impacts can be related to the mining or refining of raw materials such as minerals and metals that are mined in conflict zones. Another concern is artisanal mining which requires intense physical labor and poor work conditions. Also, artisanal mining or small-scale mining operations are often subjected to violent conflicts and wars (Bach *et al.*, 2017). Governments and companies must follow certain standards and norms, when a company uses raw materials with a high social impact, this can affect the reputation of the company (Schrijvers *et al.*, 2020).

Other essential social aspects are ensuring that human rights are not violated, also no child labor or forced labor is associated with the supply of raw materials. Geopolitical risks such as conflicts, wars, poor governance, and corruption must be assessed for the supplying countries.

Some previous criticality studies have included the social circumstances associated with the products, for example (Bach *et al.*, 2017) considered the societal acceptance as a criticality dimension, this dimension is composed of two sub-dimensions compliance with social standards and compliance with environmental standards. Bach et al., measured the social aspects by introducing the following categories: small scale mining (Share of small scale and artisanal mining), geopolitical risk (armed conflicts and poor governance), and human right (Child labor, forced labor, and torture). The following figure shows the categories and indicators used by (Bach *et al.*, 2017).

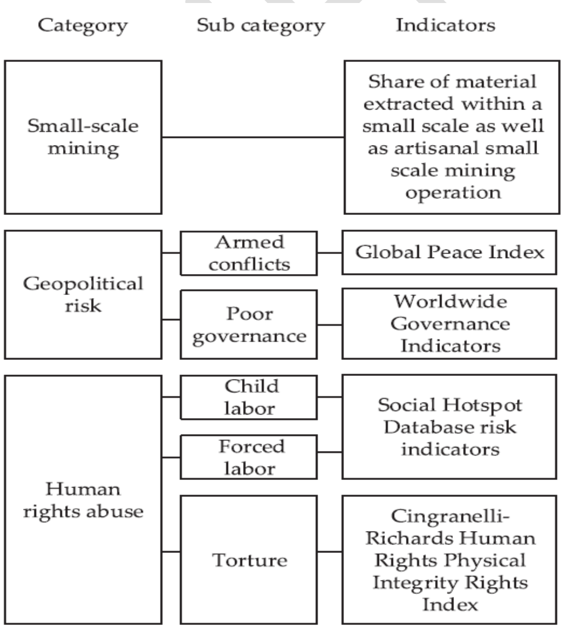

Figure 50 Overview of considered categories, subcategories, and indicators to determine compliance with social standards (Bach et al.*, 2017)*

One example of social circumstances associated with the product is the conflict minerals and metals such as tin, tantalum, tungsten, and gold. Conflict minerals are mined in politically unstable areas by armed groups. These armed groups often use forced labor to extract these minerals, then and sell them and use the money to fund their armed activities (European Commission, Conflict Minerals Regulation).
Another example is the high social risks associated with the cobalt supply chain. Where small-scale mining of cobalt takes place in the Sothern province of Katanga of Congo DRC, this region is subjected to human rights abuses such as unacceptable working conditions and child labor. (European Commission Critical Raw Materials Factsheets, 2020)
In this criticality assessment, the social aspect is quantified by four main indicators Human Rights, Conflict, Governance/Corruption, and Child labor/Forced labor.

14.1- Human rights

The Human Development Index (HDI) is an indicator provided by the United Nations Development Program and its International Human Development Indicators. HDI is a composite index to measure the average achievement in three basic dimensions of human development. These dimensions are long and healthy life, knowledge, and a decent standard of living. Previous criticality studies have used the Human Development Index (HDI) to calculate supply risk since it reflects the quality of life and health issues.

Graedel et al., have used HDI to evaluate the supply risk, by weighting the HDI by each metal's production. Graedel et al., have considered the mining production as well as the refining production, to then select the highest risk production weighting to identify the "bottleneck" (Graedel, Harper, Nassar, Nuss, Reck, *et al.*, 2015). Achzet et al., have used the HDI to evaluate the political risk in the supplying countries. They stated that HDI measures the life expectancy of the population, its education, and income (Achzet and Helbig, 2013). However, it is not clear what is the link between the political risk and the life expectancy of the population, its education, and income.

In our criticality assessment, we have used the Human Development Index (HDI) as a Human Rights indicator. Since the quality of life (long and healthy life) and a decent standard of living is correlated to Human Rights. Based on HDI countries are classified into four groups, as shown in Table 13:

Table 13 Human development groups

Very high human development	0.898
High human development	0.753
Medium human development	0.631
Low human development	0.513

Also, we have used the world governance indicator Voice and accountability to represent Human Rights. Where WGI-VA indicates to which extent a country's citizens can participate in selecting their government. It also shows the freedom of expression and association and free media.

The United nation development program provides numerous indicators, these indicators are divided into 14 dimensions: Human Development Index (HDI), Demography, Education, Environmental Sustainability, Gender, Health, Human Security, Income/composition of resources, Inequality, Mobility, and communication, Poverty, Socio-economic sustainability, Trade, and financial flows, and Work employment and vulnerability. further details about these indicators can be found in annex1. For human rights indicators, we have investigated several other sources such as the United Nations Security Council Resolutions, United Nations Human Rights Council, Office of the United Nations High Commissioner for Human Rights, Amnesty International, Global witness, Human Rights Watch, and Mines and communities. There were no quantified data from these sources to be used for our criticality assessment.

14.2- Conflict

For conflict indicators, we have investigated several sources such as:

a) The Global Peace Index is provided by the Institute for Economics and Peace. Their evaluation covers 163 independent nations and territories worldwide. The Global Peace Index analyzes and quantifies which nations are the most peaceful, and which nations are the most dangerous by evaluating three distinct categories: militarization, safety and security, and domestic and international conflict. The Global Peace Index is a complex indicator comprised of 23 indicators; these indicators are then combined into a single Peace Index Score between [1-4]. In our criticality assessment, we have used the Global Peace Index to represent and quantify the conflict indicator. Figure 51shows the most peaceful countries in 2022, based on the peace index score.

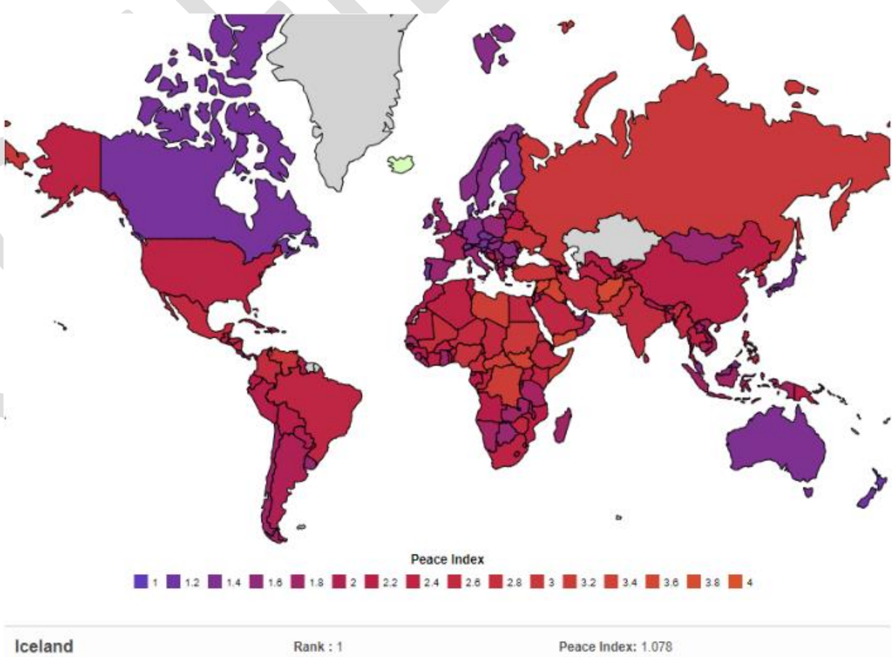

Figure 51 The most peaceful countries in 2022, based on the peace index score. (World Population Review, 2022)

b) Heidelberg Conflict Barometer evaluates and documents the political conflicts worldwide. It presents the Conflict's name, parties, items, start date, and the Levels of intensity (Int). The level of intensity is quantified as follow: Int= 5 (war); Int= 4 (limited war); Int= 3 (violent crisis); Int= 2 (non-violent crisis); and Int= 1 (dispute). It was not feasible to incorporate Heidelberg Conflict Barometer in our criticality assessment since one country can be a part of several conflicts.
c) Assessment Capacities Project/Global Emergency Overview (Full severity index). The INFORM Severity Index summarizes a wide range of quantitative information about crisis severity. It presents detailed data and information about numerous types of crises worldwide such as conflict, violence, political and economic crises, multiple crises country, regional crises, international displacement, Flood, Drought, earthquakes, food security, tropical cyclone, and complex crisis. Due to the complexity of this indicator, it was not feasible to incorporate it in our criticality assessment.

We have also investigated the Geneva Academy Rule of Law in Armed Conflicts, Crisis Watch, and the Uppsala Conflict Data Program (Georeferenced Event Dataset and Major Episodes of Political Violence). However, there were no quantified data from these sources to be used for our criticality assessment.

14.3- Governance/Corruption

For measuring the Governance/Corruption indicators we have used two indexes the Corruption Perception Index and the WGI – Control of corruption (CC).

The WGI – Control of corruption (CC) indicates to which extent public power benefits from private gain, covering all forms of corruption and the control of the state by elites and special interests.

The corruption Perception Index issued by Transparency International evaluates the levels of public sector corruption in 180 countries worldwide. The corruption Perception Index is presented as a score from 0 (highly corrupted) to 100 (very clean).

We have also investigated the National Resource Governance Institute. However, there were no quantified data to be used for our criticality assessment.

14.4- Child labor / forced labor

Child labor includes forms of work and employment that children are too young to perform. Where the circumstances/nature of these labor activities, can have harmful effects on the children's health, safety, or morals. The definition of child labor might also include hazardous unpaid household services/chores.

Child labor is a complex phenomenon since not all work performed by children can be considered child labor. There must be a distinction between child labor and children's activities which are part of the normal socialization processes (International Labor Organization (ILO), 2022).

The united nation development program built an indicator that quantified child labor (% ages 5-17). The child labor (% ages 5-17) indicator is part of the work, employment, and vulnerability dimension of the International Human Development Indicators. This indicator gives the percentage of children engaged in economic activities or/and in unpaid household

services, hazardous working conditions, or any worst forms of child labor. The indicator involves four age categories (5-11), (12-14), (15-17), and (5-17).
The evaluation of child labor consideration for each age group is listed in Table 14.

Table 14 Child labor index considerations (United Nations Development Program, 2022)

Age range	Child labor during the reference week
Ages 5-11	Children engaged in at least one hour of economic activity and/or involved in unpaid household services for more than 21 hours.
Ages 12-14	Children engaged in at least 14 hours of economic activity and/or involved in unpaid household services for more than 21 hours.
Ages 15-17	Children engaged in at least 43 hours of economic activity
Ages 5-17	Children engaged in hazardous working conditions or any worst forms of child labor other than hazardous.

Data source: (UNICEF, 2021)
In our criticality assessment, we have used this indicator (% ages 5-17) to quantify child labor.
The framework to measure the global estimation of child labor is presented in Figure 52,

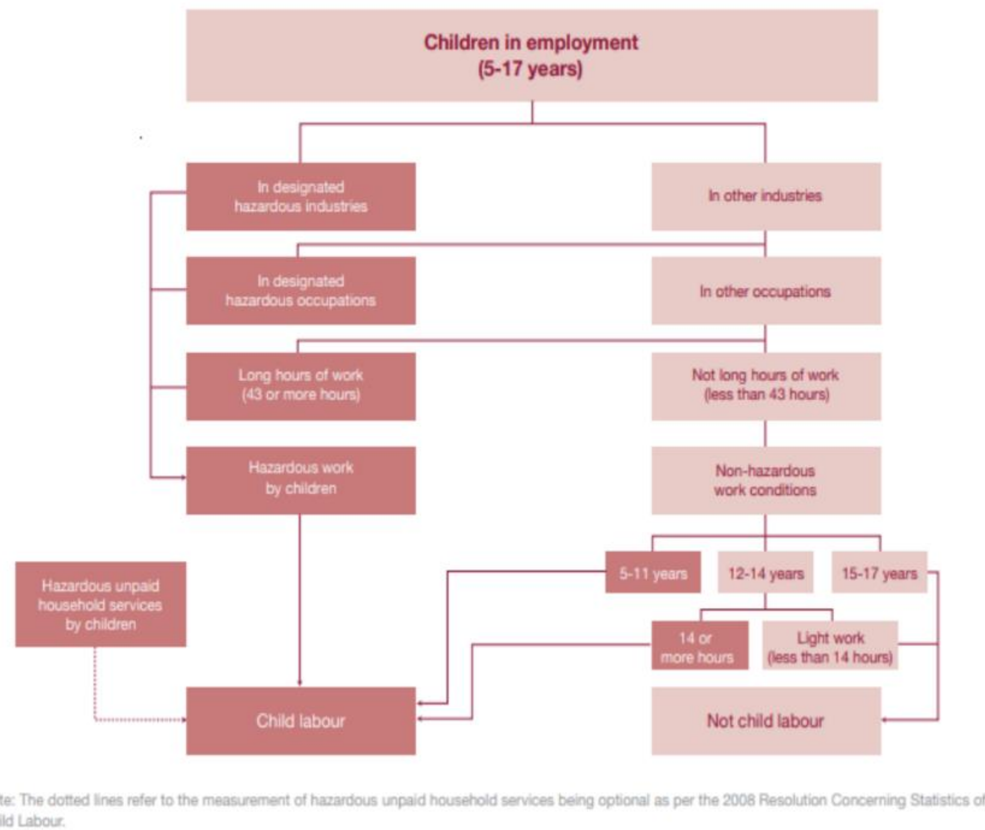

Figure 52 Measurement framework for the global estimation of child labor (Intranational Labor Organization ILO)(UNICEF, 2021) .

Annex 5 / Data gaps for Lithium battery raw materials criticality assessment

Table 15 Data gaps for Lithium battery raw materials criticality assessment

Material	Indicator	Stage	Countries	Share	Comment	Action
Cobalt	PPI	Mining	Cuba, Madagascar	2.3%+1.5%	3.8 % of the market is not represented because of data gaps for Cuba and Madagascar	**PPI is set to 0 in Cuba, Madagascar, and Japan**
		Refining	Japan	4%	4 % of the market is not represented because of data gaps for Japan	
		Reserves	Cuba, Madagascar	7% + 1%	8 % of the market is not represented because of data gaps for Cuba and Madagascar	
	ETI	Mining	Cuba, Papua New Guinea	2.3%+1.8	4.1 % of the market is not represented because of data gaps for Cuba, Papua New Guinea	**ETI is set to 0 in Cuba and Papua New Guinea**
		Reserves	Cuba, Papua New Guinea	7%+ 1%	8 % of the market is not represented because of data gaps for Cuba and Papua New Guinea	
Nickel	PPI	Mining	France	7%	7% of the market is not represented because of data gaps for France	**PPI is set to 0 in France**
		Refining	Japan	7%	7% of the market is not represented because of data gaps for Japan	
Lithium	PPI	Mining	Portugal	1%	1% of the market is not represented because of data gaps for Portugal	**PPI is set to 0 in Portugal**
Manganese	PPI	Mining	Gabon, Ukraine, India, Cote Ivoire, Malaysia, Myanmar, Georgia, Vietnam	18% + 3% + 3%+ 3%+ 2%+ 1%+ 1%+ 1%	32% of the market is not represented because of data gaps for Gabon, Ukraine, India, Cote Ivoire, Malaysia, Myanmar, Georgia, Vietnam	**PPI is set to 0 in Gabon, Ukraine, India, Cote Ivoire, Malaysia, Myanmar,**

						Georgia, Vietnam
		Refining	Ukraine, India	6% + 5%	11% of the market is not represented because of data gaps for Ukraine, India	
		Reserves	Ukraine, Gabon, India	9.3%+ 4.1%+ 2.3%	15.7% of the market is not represented because of data gaps for Ukraine, Gabon, India	
	ETI	Mining	Myanmar	1%	1% of the market is not represented because of data gaps for Myanmar	**ETI is set to 0 in Myanmar**
	GPI	Mining	Kazakhstan	1%	1% of the market is not represented because of data gaps for Kazakhstan	**GPI is set to 0 in Kazakhstan**
Copper	GPI	Mining	Kazakhstan	2%	2% of the market is not represented because of data gaps for Kazakhstan	
		Reserves	Kazakhstan	2%	2% of the market is not represented because of data gaps for Kazakhstan	
	PPI	Mining	Zambia, Poland	4%+2%	6% of the market is not represented because of data gaps for Zambia, Poland	**PPI is set to 0 in Zambia, Poland**
		Refining	Japan	6%	6% of the market is not represented because of data gaps for Japan	
		Reserves	Zambia, Poland	4%+2%	6% of the market is not represented because of data gaps for Zambia, Poland	
Natural Graphite	PPI	Mining	Madagascar, Ukraine, India, Vietnam, Mozambique,	2.2%+ 1.7%+ 0.7%+ 0.5%+ 3%+ 0.9%	9% of the market is not represented because of data gaps for	**PPI is set to 0 in Mozambique,**

			Korea, Dem. Rep.		Madagascar, Ukraine, India, Vietnam, Mozambique, Korea, Dem. Rep.	**Korea, Dem. Rep.**
		Reserves	Madagascar, Mozambique, India, Uzbekistan,	8.1%+ 7.8%+ 2.5%+2.4%	20.8% of the market is not represented because of data gaps for Madagascar, Mozambique, India, Uzbekistan,	**PPI is set to 0 in Uzbekistan**
	ETI	Mining	Korea, Dem. Rep.	0.9%	0.9% of the market is not represented because of data gaps for Korea, Dem. Rep.	**ETI is set to 0 in Korea, Dem. Rep.**
		Reserves	Uzbekistan	2.4%	2.4% of the market is not represented because of data gaps for Uzbekistan	**ETI is set to 0 in Uzbekistan**
	EPI	Mining	Korea, Dem. Rep.	0.9%	0.9% of the market is not represented because of data gaps for Korea, Dem. Rep.	**EPI is set to 0 in Korea, Dem. Rep.**
	HDI	Mining	Korea, Dem. Rep.	0.9%	0.9% of the market is not represented because of data gaps for Korea, Dem. Rep.	**HDI is set to 0 in Korea, Dem. Rep.**
Aluminum	PPI	Mining	India, Vietnam, Jamaica, Saudi Arabia	6%+1%+1%+1%	9% of the market is not represented because of data gaps for India, Vietnam, Jamaica, Saudi Arabia	**PPI is set to 0 in Jamaica, Saudi Arabia, United Arab Emirates, Bahrain; Iceland**
		Refining	India, United Arab Emirates, Bahrain; Iceland	6%+4%+2%+1%	13% of the market is not represented because of data gaps for India, United Arab Emirates, Bahrain; Iceland	
		Reserves	Vietnam, Jamaica, India	18.1%+6.3%+2.1%	26.5% of the market is not	

					represented because of data gaps for Vietnam, Jamaica, India	
	ETI	Mining	Guinea	22%	22% of the market is not represented because of data gaps for Guinea	**ETI is set to 0 in Guinea**
		Reserves	Guinea	23.1%	23.1% of the market is not represented because of data gaps for Guinea	
Iron & steel	PPI	Mining	India, Ukraine, Iran, Islamic Rep.	9%+ 3%+ 2%	14% of the market is not represented because of data gaps for India, Ukraine, Iran, Islamic Rep.	**PPI is set to 0 in Iran, Islamic Rep.**
		Refining	India, Japan	6%+5%	11% of the market is not represented because of data gaps for India, Japan	
		Reserves	Ukraine, India, Iran, Islamic Rep.	3.6% +3.1%+1.5%	8.2% of the market is not represented because of data gaps for Ukraine, India, Iran, Islamic Rep.	
	GPI	Mining	Kazakhstan	2%	2% of the market is not represented because of data gaps for Kazakhstan	
		Reserves	Kazakhstan	1.4%	1.4% of the market is not represented because of data gaps for Kazakhstan	
Phosphate rock	PPI	Mining	Jordan, Egypt, Tunisia, Israel, Algeria, Togo, India, Vietnam, Saudi Arabia	4%+ 2% +1% +1% +1% +1% +1%+ 2% +4%	17% of the market is not represented because of data gaps for Jordan, Egypt, Tunisia, Israel, Algeria, Togo, India, Vietnam, Saudi Arabia	**PPI is set to 0 in Jordan, Egypt, Tunisia, Israel, Algeria, Togo**,

		Reserves	Egypt, Algeria, Saudi Arabia, Jordan	3.9% +3.1%+ 2%+1.4%	10.4% of the market is not represented because of data gaps for Egypt, Algeria, Saudi Arabia, Jordan	
	ETI	Mining	Togo	1%	1% of the market is not represented because of data gaps for Togo	**ETI is set to 0 in Togo**
	GPI	Mining	Kazakhstan	1%	1% of the market is not represented because of data gaps for Kazakhstan	

Annex 6 / Criticality assessment results based on the webtool model

The main purpose of the criticality assessment for this current thesis is to conduct research for the data sources suggested by the IRTC project. To quantify the criticality aspects and measure the criticality indicators followed by the data collection for lithium battery raw material. Weighting and aggregation of the results to reach to on criticality score for each element is outside the scope of this study. Therefore, the results are presented as shown in Figure 53. The results are presented as a comparison between the scores for all lithium battery raw materials for each criticality indicator.

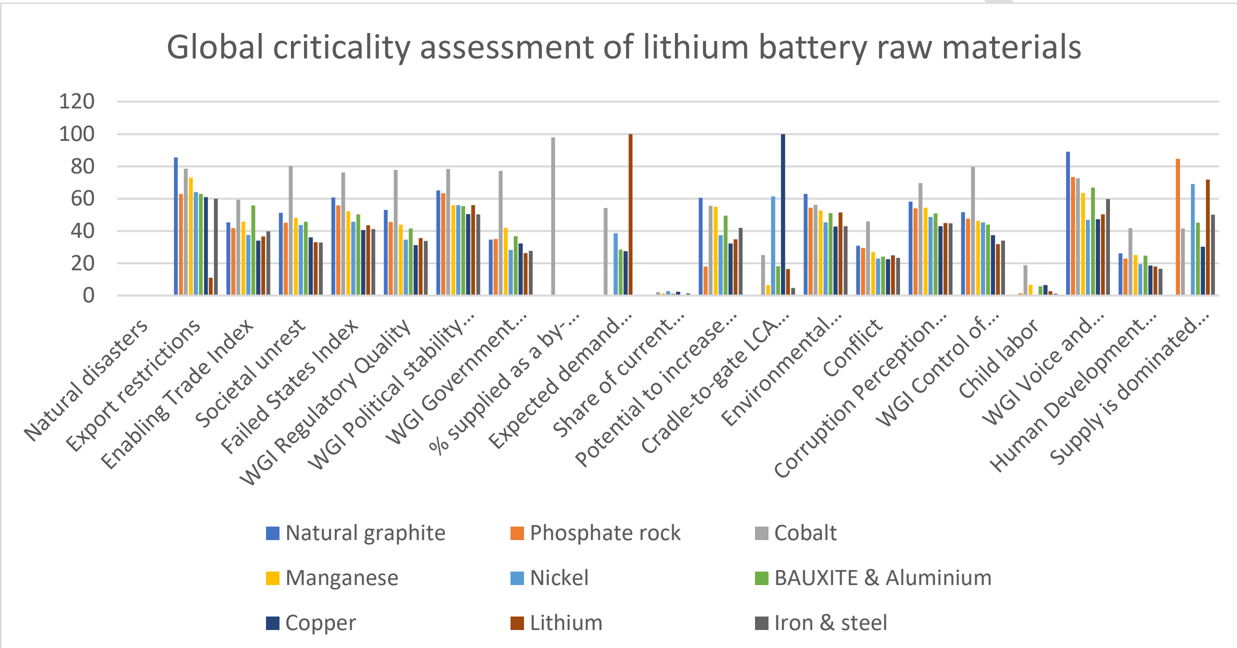

Figure 53 Global criticality assessment of lithium battery raw materials (WeLOOP, 2022).

The results of the criticality assessment are discussed for each of the three risks individually. The results' discussion is simplified by dividing each risk into its problematics, criticality aspects, and indicators. Then we discuss the hotspots for each indicator, and the reasons behind these hotspots.

Analyzing the risk of the company not having access to lithium battery raw materials

The supply risk of not having access to lithium battery raw materials, this potential risk might take place due to two main problematics:

- The supply of lithium battery raw materials is not compliant with (future) policy regulations.
- There is a mismatch between supply and demand of lithium battery raw materials in the market.

Each of these problematics will be discussed in detail, as well as the results of the assessments for each of them.

Supply is not compliant with (future) policy regulations

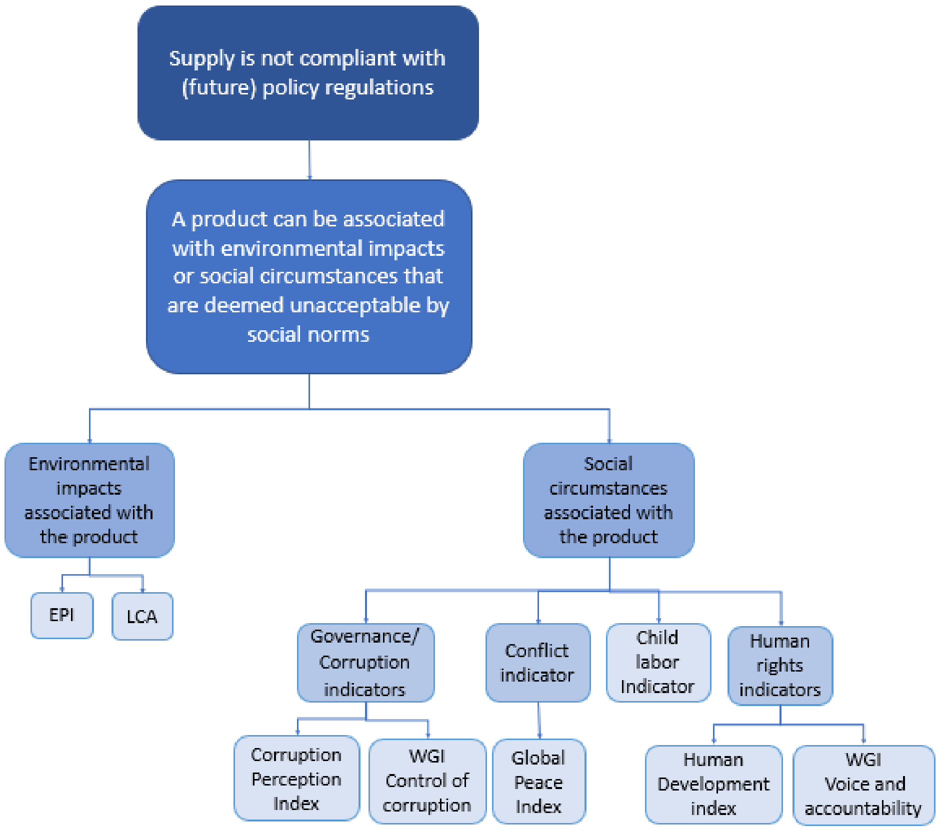

Figure 54 Schematic of Supply is not compliant with (future) policy regulations (problematics/criticality aspects/criticality indicators) (WeLOOP, 2022)

The first problematic (supply of lithium battery raw materials is not compliant with (future) policy regulations), can be caused by environmental impacts associated with the production of lithium battery raw materials. This criticality aspect was quantified by two criticality indicators: the Environmental Performance Index for lithium battery raw materials supplying countries (Chen, no date), and Cradle-to-gate LCA for lithium battery raw material. LCA score is also called Environmental implication (EI) score(Graedel, Harper, Nassar, Nuss, Reck, *et al.*, 2015).

It is also can be caused by social circumstances associated with lithium battery raw materials. Which can be related to human rights, conflicts, governance/corruption, and/or child labor in the supplying countries of lithium battery raw materials. The indicators used to quantify these aspects are WGI- Voice and Accountability, Human Development Index, Global Peace Index, Corruption Perception Index, WGI-control of corruption, and child labor indicator.

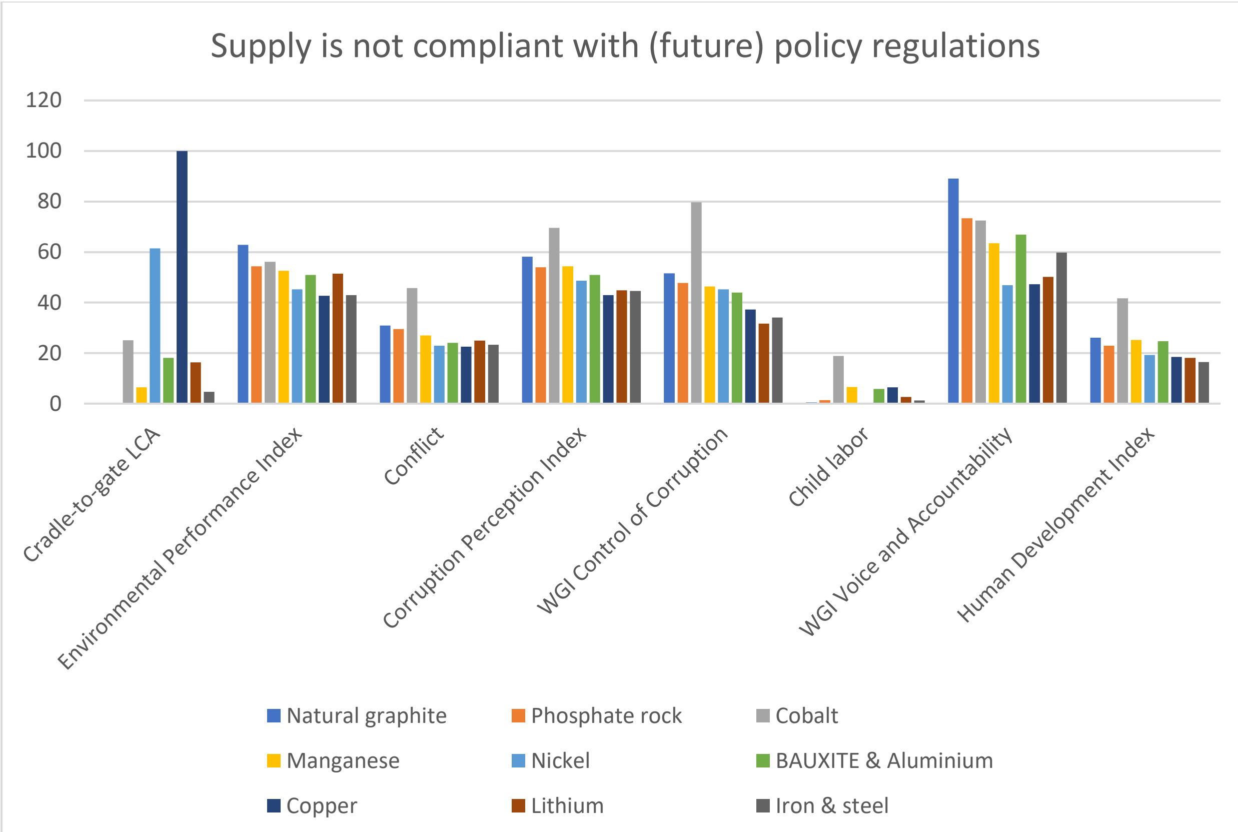

Figure 55 Criticality assessment results of: Supply is not compliant with (future) policy regulations which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022)

From Figure 55, we start with the environmental circumstances associated with the extraction/production of lithium battery raw materials. For the cradle-to-gate LCA indicator (EI score), the highest environmental impacts go to copper with a very high environmental implication score EI=17.1. This is due to the environmental impacts associated with the mining and refining of copper. The second highest EI score goes to Nickel with EI= 10.5, and the third higher EI score goes to Cobalt with EI = 4.3. Keeping in mind that the EI scores of natural graphite and phosphate rock were missing.

The rest social and environmental indicators evaluate the supply risk, are measured by multiplying the country performance Indicator by the share of the supplying country (for mining and refining stages). In this assessment the maximum score between mining and refining countries was taking as the final score.

For the Environmental Performance Index (EPI), as one can see, all the supplying countries of lithium battery raw materials seem to have relatively close EPI scores in the range between [43-63]. This range of EPI scores could be interpreted that lithium battery raw materials have important environmental impacts associated with the supplying countries (mining and/or refining countries).

For the social circumstances associated with the mining/refining of lithium battery raw materials, we start with the indicator of conflicts in the supplying countries (measured by the Global Pace Index (GPI)). The main hotspot here is Cobalt with a score of (GPI=46), where the lead supplier for cobalt (mining) is Congo DRC with a share of about 70.6% of global mine production. Congo DRC is known for a high risk of investment climate, and very poor governance according to the World Bank (as we will see when discussing the WGIs later). The second hotspot in the conflict aspect is Natural graphite (GPI=31) and Phosphate rock (GPI= 29.5).

The second set of indicators of social circumstances associated with the mining/refining of lithium battery raw materials are the corruption indicators Corruption Perception Index (CPI) and WGI-control of corruption (WGI-CC). Cobalt here also stands as the main hotspot for both indexes with CPI=70, WGI-CC=80. This is also owing to the mining stage of cobalt, with the Congo DRC the lead supplier with poor governance. Natural graphite comes in second as hotspot, with scores more than 50 in both indicators. The major producer of Natural graphite is China with 82% of global mine production, where the level of governance is between on average and low. The rest of the lithium battery raw materials have noticeable CPI scores that varies between 43 and 55. They have a slightly lower range of WGI-CC scores between 30 and 47.

The Child labor indicator gives the percentage of children ages (5-17) involved in child labor (by the United Nation Development Program). The results shows if the raw materials of lithium batteries are supplied from countries that have child labor. Cobalt here is a hotspot, whereas mentioned before it is mainly mined in Congo DRC where 26.7% of children ages (5-17) are involved in child labor. Also, small scale mining of cobalt takes place in the southern province of Katanga. This region of Congo is affected by human rights abuses such as child labor and unacceptable working conditions. Manganese comes in second, 18% of global mine production comes from Gabon 19.6% where 26.7% of children ages (5-17) are involved in child labor. Copper comes in third where 9% global mine production is in Congo DRC. The fourth mention-worthy score goes to Bauxite/Aluminum. 22% of global bauxite mine production happens in Guinea where 24.2% % of children ages (5-17) are involved in child labor.

For the social circumstances related to human rights in the supplying countries of lithium battery raw materials we start with WGI-Voice and accountability (WGI-VA). The main hotspot here is natural graphite, 82% of natural graphite is mined in China where the level of governance is between on average and low. The second hotspot is phosphate rock (39% mined in China, 17% in Morocco). The third hotspot is Cobalt with 70.6% is mined in Congo DRC with very poor governance and working conditions. Manganese, Aluminum, and Iron/Steel have considerable WGI-VA scores.

Lastly the Human Development Index (HDI) for evaluating the social circumstances related to human rights in the supplying countries of lithium battery raw materials. One can notice that Cobalt is a hotspot for this indicator (70.6% of cobalt are mined in Congo DRC). Congo DRC has a low Human Development Index HDI (Congo DRC) = 0.48. The rest of lithium battery raw materials have relatively close and acceptable HDI scores.

We can notice that Cobalt is a hotspot in almost all the social aspects (conflict, corruption, child labor, and HDI), and this is due to the fact that cobalt is mainly mined in Congo DRC (70.6%), and mainly refined in China (67%).

There is a mismatch between supply and demand in the market

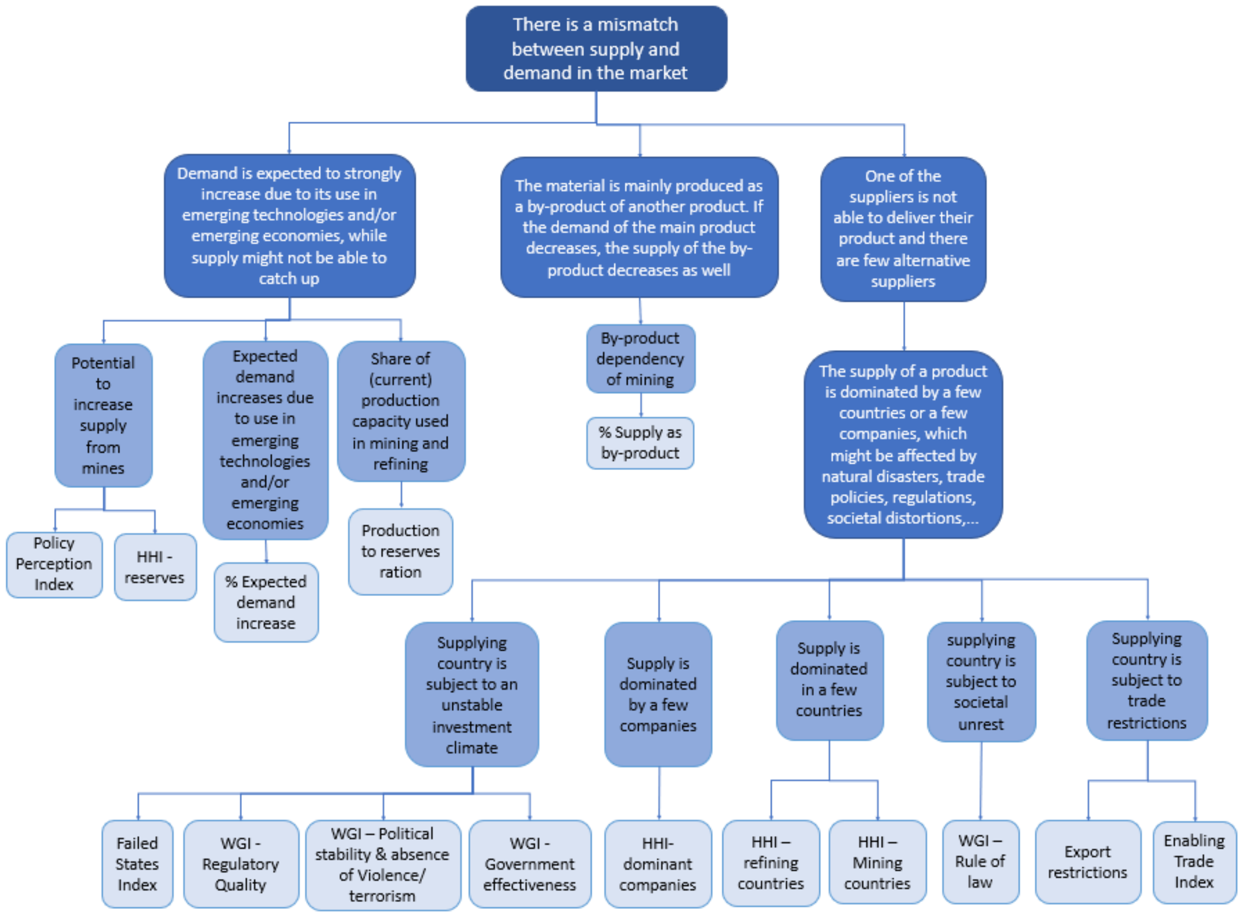

Figure 56 Schematic of the second problematic "There is a mismatch between supply and demand of lithium battery raw materials in the market" (problematics/criticality aspects/criticality indicators) (WeLOOP, 2022)

The second problematic "There is a mismatch between supply and demand of lithium battery raw materials in the market". This can be caused by three sub-problematics: a strong demand increase while the supply might not be able to catch up, the material is mainly produced as a by-product of another product, and one of the suppliers is not able to deliver their product (with few alternative suppliers). Fifteen criticality aspects have been used here to measure this problematic (see Figure 56).

The global criticality assessment results to assess this problematic is shown in Figure 57. Due to the complexity of this problematic, we will focus on each of the sub-problematic, its criticality aspects, indicators, and its assessment results.

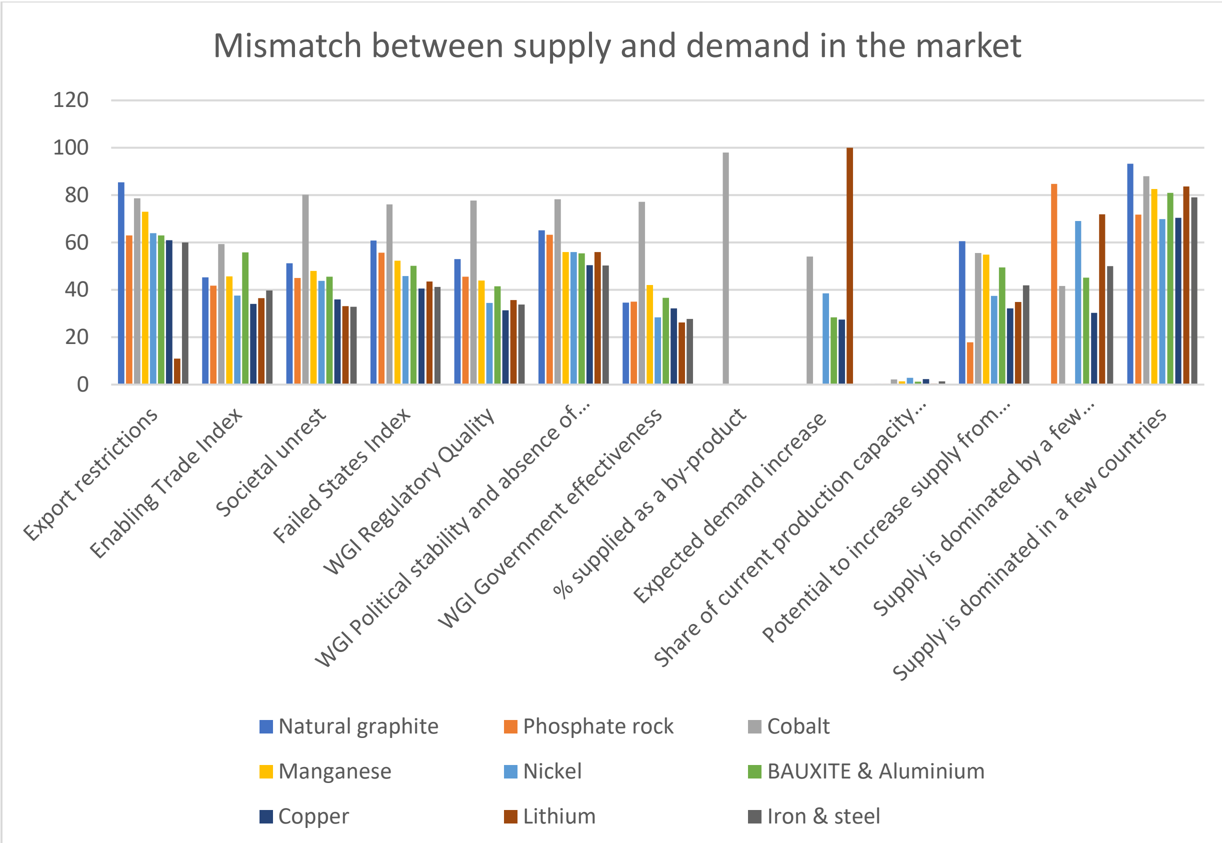

Figure 57 Global criticality assessment results of a mismatch between supply and demand of lithium battery raw materials in the market, which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022)

By-product dependency

The first sub-problematic that might cause mismatch between supply and demand in the market is the by-product dependency. When the material is mainly produced as a by-product of another product, if the demand of the main product decreases, the supply of the by-product decreases (this is what we call by-product dependency). This was measured by the share of supply as by-product (see Figure 56). From Figure 57, we can see that for lithium battery raw materials the only one that is supplied as a by-product is cobalt. 98% of total cobalt mine production is a by-product of copper and nickel mining operations (Cobalt Institute, 2022).

Strong demand increase while the supply is not able to catch up

The second sub-problematic is strong demand increase while the supply is not able to catch up. Three of criticality aspects in this study were used for breaking down this sub-problematic, the first one is: expected demand increase due to use in emerging technologies and/or emerging economies. This aspect is quantified by % of demand increase, the data are taken from the Compound Annual Growth Rate between 2020-2050 for a sustainable development scenario (Leuven and Gregoir -Principal Author, no date)). Which estimates the demand increase in emerging technologies, emerging economies, and other industry development.

The share of (current) production capacity used in mining and refining was used to estimate the ability of the supply to catch up with the strong demand increase. This aspect was evaluated by production to reserves ratio indicator. The ability of the supply to catch up with the strong demand increase, was also estimated by measuring the potential to increase supply from mines. This aspect was calculated by using two indicators, HHI-reserves, and Policy Perception Index (PPI) the later indicates the overall investment attractiveness of mining policies of governments (used on reserves' countries of lithium battery raw materials). The potential to increase supply from mines was calculated as the product of these two indicators.

The assessment results for the first sub-problematic are shown in following chart Figure 58.

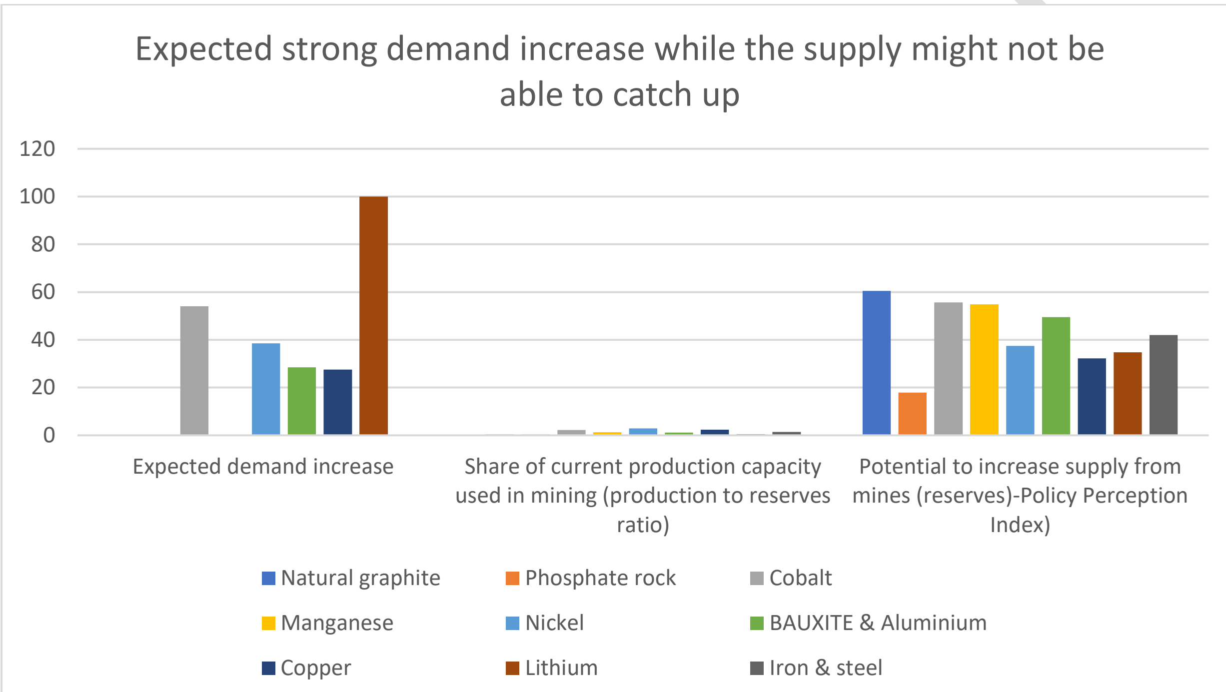

Figure 58 Criticality assessment results for "an expected a strong demand increase while the supply might not be able to catch up", which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022).

In our assessment the expected demand increase in emerging technologies and/or economies the main hotspot is Lithium (with a 100% expected demand increase). Lithium has a big contribution to low-carbon technologies, it is essential for the electrification of the transportation system (Lithium-ion batteries) for hybrid and electric vehicles. Lithium-ion batteries are also used to store energy for renewable energy (Solar, wind, etc.). Moreover, lithium is used in novel low-density Al-Li alloys which is used in the production of aircrafts, to reduce their weight and improve the fuel economy ("Study on the EU's list of Critical Raw Materials (2020) Final Report," no date). The demand of lithium is expected to increase to a 21-fold times of the current demand of lithium (Leuven and Gregoir -Principal Author, no date).

Cobalt comes in second as a hotspot (with about 54% expected demand increase), Cobalt also has a significant importance in the low-carbon technologies. It is used in the production of several chemistries of lithium-ion batteries such as Lithium Nickel Manganese Cobalt Oxide NMC, Lithium Nickel Cobalt Aluminum Oxide NCA, and Lithium Cobalt Oxide LCO. Which are used in the electrification of the transportation system and the energy storage systems for renewable energies.

Nickel comes in third as a hotspot (with about 38.5 % expected demand increase) this is due to its use in the energy transition, too. However, nickel was not on the EU criticality list of 2020. Expecting the demand growth of nickel is complicated because there are two class of nickels nickel class 1 and nickel class 2. Nickel class 1 is the one used in lithium-ion batteries, and it requires more intense processing than nickel class 2 that is used in lower purity nickel products. Recently there are raising concerns that nickel class 1 might be critical. This will require more in-depth criticality assessments that distinguish between different classes of metals which might come from different deposits or need different degrees of processing.

One of the limitations of this current criticality assessment is the data source for the expected demand increase (Leuven and Gregoir -Principal Author, no date) just includes metals. Natural graphite which is critical was not included, which makes our assessment limited regarding this criticality indicator. Natural graphite is used in the production of the anode in lithium-ion batteries. It is also used as the primary filter material in bipolar plates for fuel cells ("Study on the EU's list of Critical Raw Materials (2020) Final Report," no date).

From Figure 58, one can see that base metal such as Copper and Aluminum are also expected to experience acceleration in demand growth due to their use in energy transition (with less than 30% expected demand increase).

From Figure 58, the share of current production used in mining, which was calculated by the production to reserves ratio is very low for all lithium battery raw materials. Which could be considered as a good sign for the potential to increase supply from mines. However, it is a theoretical indicator, because other factors can affect the accessibility to the raw materials, such as the mining policies in the reserves countries, also geopolitical and social factors could also have an impact.

As said earlier, reserves accessibility could be limited due to unattractive mining policies in the reserves countries. This was estimated by the indicator "(reserves)-Policy Perception Index)" (see Figure 58). The main hotspot is natural graphite (score of 60.5), with Turkey, China, and Brazil having the major shares of global reserves, with shares of 28%, 23%, and 22% respectively. The mining policy attractiveness in Turkey, China, and Brazil is average, with a PPI of 55.4, 44.5, and 47.6 respectively. Cobalt comes in second as a hotspot (with 55.6 score), with 46% of global reserves located in Congo DRC. Where the mining policy attractiveness in Congo DRC is low, PPI score= 29. Manganese comes in third as a hotspot (with 55 score), with 47% of global reserves located in South Africa. South Africa's mining policy attractiveness is average, PPI score= 49.7.

One of the suppliers is not able to deliver their product and there are few alternative suppliers

The third sub-problematic that might cause mismatch between supply and demand in the market, when one of the suppliers is not able to deliver their product and there are few alternative suppliers. This could happen due to several reasons: the supply of a product is dominated by a few countries or a few companies, which might be affected by natural disasters, trade policies, regulations, and societal distortions etc. Which was categorized by four criticality aspects (see Figure 56).

Supplying country is subjected to an unstable investment climate and social unrest

Supplying country is subjected to an unstable investment climate, this criticality aspect was quantified by three world Governance Indexes (WGI - Regulatory Quality, WGI - Government effectiveness, and WGI – Political stability & absence of Violence/ terrorism) and failed state index. By first multiplying the share of the mining and refining countries by each of the countries' indexes, then the maximum score between mining and refining was chosen as the final score. Another criticality aspect is the supplying country is subjected to social unrest. Which was measured by multiplying the share of supplying countries (mining and refining) by WGI-Rule of law. The results are shown in Figure 59,

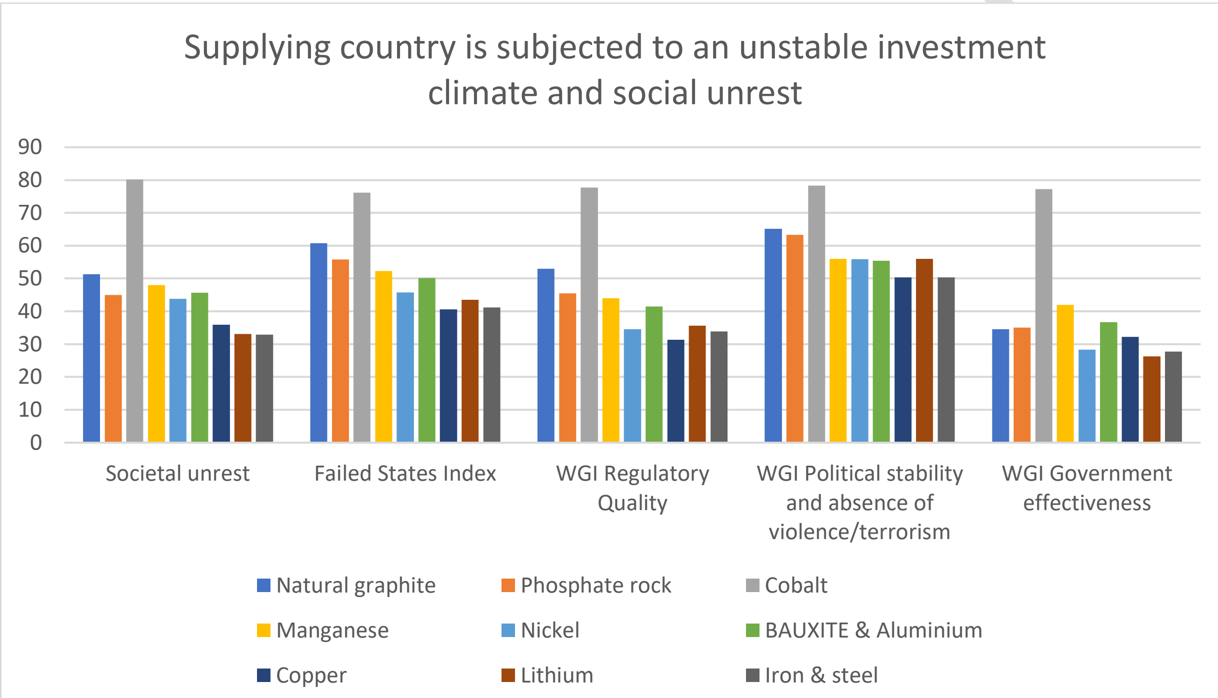

Figure 59 Criticality assessment results for "Supplying country is subjected to an unstable investment climate and social unrest", which might cause a mismatch between supply and demand in the market, which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022).

From our criticality assessment, we found that almost for all the lithium battery raw materials the mining is the stage with the higher supply risk. Except for lithium the refining stage is the one that is more susceptible for supply risk. This is in accordance with the results of the EU criticality assessment in 2020. Also, for iron/steel, for both Failed States Index, and WGI-Regulatory Quality, the refining stage was the most impactful.

As one can notice, cobalt stands out as the main hotspot in all the indicators of unstable investment climate and social unrest. As we have discussed earlier the major mining producer of cobalt is Congo DRC (70.6% of cobalt are mined in Congo DRC), that has very poor governance and unstable investment climate.

Natural graphite comes in second as a hotspot for social unrest, failed state index, WGI-Regulatory Quality, and WGI-Political stability and absence of violence/terrorism. With score range in between [50-

65]. Where natural graphite is mainly mined in China with (82% of global mining production), where the level of governance is between on average and low.

Phosphate rock come in third as hotspot from a point of view of Failed States Index, and WGI-Regularity Quality, WGI-Political stability and absence of violence/terrorism. Phosphate rock is mainly mined in in China with 39% of global production, and Morocco with 17% of global mine production. Which makes sense because governance level in China is between on average and low, and governance level in Morocco is between low and on average, too.

Manganese comes in fourth as a hotspot to be supplied from countries with unstable investment climate and societal unrest. Where it scores between [42-63] in all indicators. Mn is mainly mined in South Africa and Gabon with 37% and 18% of global mining production, respectively. The level of governance in South Africa is on average and in Gabon is low.

WGI-Political stability and absence of violence/terrorism indicator is one on the indicators where all of battery raw materials score at least 50 and more. The second hotspot indicator is Failed States Index, with all the lithium battery raw materials scoring at least 40 and more. Societal unrest comes in third as a hotspot indicator with six of the battery raw materials scoring 40 and above.

Supply is dominated by a few countries

The third sub-problematic that might cause mismatch between supply and demand in the market, this could happen due to several reasons: the supply of a product is dominated by a few countries or a few companies, which might be affected by natural disasters, trade policies, regulations, and societal distortions etc. Which was categorized by four criticality aspects (see Figure 56).

As mentioned earlier there are other criticality indicators to measure the possibility that one of the suppliers is not able to deliver their product and there are few alternative suppliers. We have discussed so far unstable investment climate and societal unrest. Now we will discuss, supply is dominated by a few countries (mining and/or refining), supply is dominated by a few companies, and supplying countries is subjected to trade restrictions. The results of our criticality assessment are shown in the following figure.

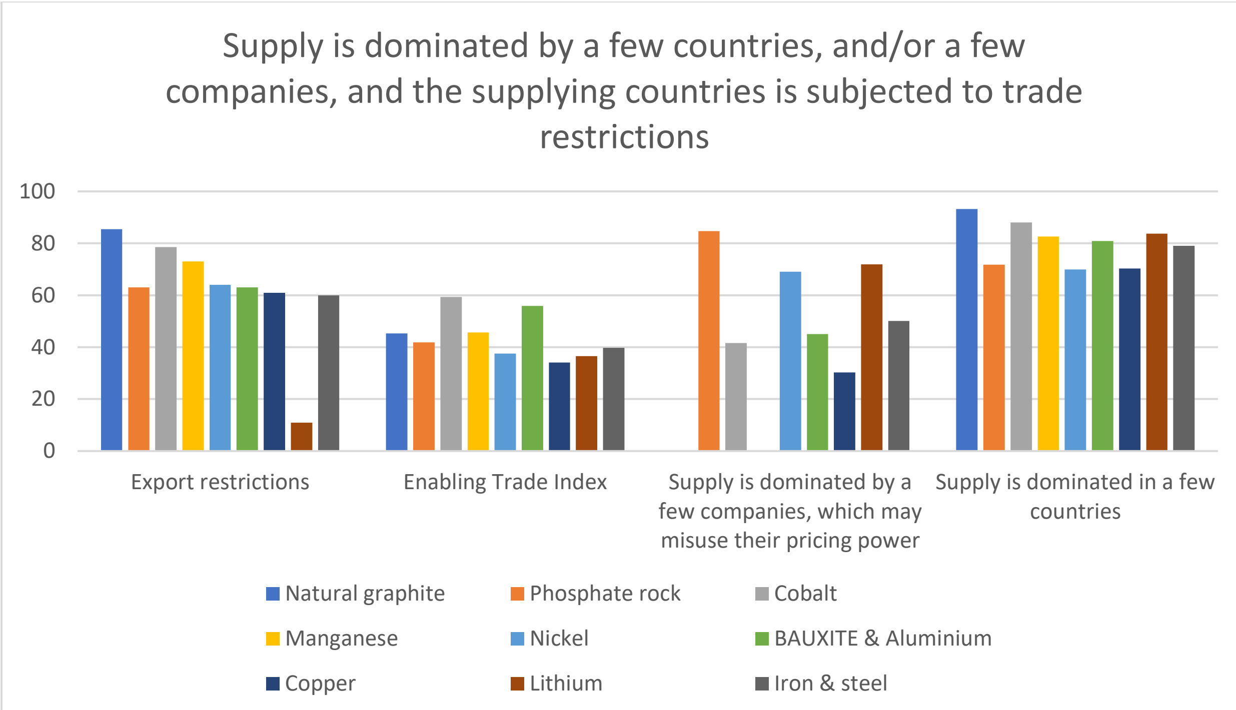

Figure 60 Criticality assessment results for " Supply is dominated by a few countries, and/or a few companies, and the supplying countries is subjected to trade restrictions", which might cause a mismatch between supply and demand in the market, which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022).

In this category one can notice that the indicator with the highest risks for all lithium battery raw materials, is supply is dominated by few countries. This indicator shows when few countries having a big share of the supply (mining production and refining production), and then it chose the stage with the high risk. All lithium battery raw materials have scores between 70 and 93 (see Figure 60).

Natural graphite has the highest risk with China dominating 82% of the global supply (mining stage). Cobalt comes in second with Congo DRC dominating 70.6% of the global supply (mining stage). Lithium comes in third with Australia, Chile, China dominating 55%, 26%, and 14% of global supply, respectively (mining stage). For manganese China dominates 60% of global supply (refining stage). Aluminum smelter production supply is dominated by China with 57% of global supply (refining stage). Steel supply is also dominated by China with 54% of global supply (refining stage). Phosphate rock supply is dominated by China, Morocco, and United States with 39%, 17%, 10% of global supply, respectively (mining stage). Copper supply is dominated by China and Chile with 41% and 9% respectively (refining stage). And lastly, nickel supply is dominated by Indonesia, The Philippine, and Russia 37%, 14%, 9% of global supply, respectively (mining stage).

Regarding the supply is dominated by a few countries, we found that the mining stage is the hotspot of Natural graphite, phosphate rock, cobalt, nickel, and lithium. Where the refining stage is a hotspot for manganese, Aluminum, copper, and steel.

Supplying countries are subjected to trade restrictions

The second indicator with high risk of almost all lithium battery raw materials is export restrictions. Posing export restrictions by major supplying countries can lead to a volatile market due to price increases, which results in supply disruptions. There are many forms of raw materials export restrictions, however, the most common are export prohibition, export taxes, export quotas, and licensing requirements. This indicator was applied to the mining and refining stages to estimates the total supply share that is subjected to export restrictions between 2017-2020. Then the stage with the highest score (higher risk) was chosen as the final score.

Figure 61 Criticality assessment results for " supplying countries is subjected to export restrictions", which might cause a mismatch between supply and demand in the market, which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022).

From Figure 61, one can see that natural graphite is the main hotspot, where 85.4% of the total global supply (mining stage) has been subjected to export restrictions between 2017 and 2020. For cobalt 78.6% of the total global supply (mining stage) has been subjected to export restrictions between 2017 and 2020. 73% of manganese global supply (mining stage) has been subjected to export restrictions between 2017 and 2020. 64% of nickel's total global supply (mining stage) has been subjected to export restrictions between 2017 and 2020. 63% of phosphate rock's total global supply (mining stage) has been subjected to export restrictions between 2017 and 2020. 61% of copper's total global supply (mining stage) has been subjected to export restrictions between 2017 and 2020.

For Aluminum 63% of the total global supply (refining stage) has been subjected to export restrictions between 2017 and 2020. For steel too, the refining stage is the one with most export restrictions, where 60% of the total global supply has been subjected to export restrictions between 2017 and 2020. Lithium was the only raw material with very low export restrictions risk, where only 11% of the total global supply (refining stage) has been subjected to export restrictions between 2017 and 2020.

The second indicator that has been used in this assessment to evaluate the trade restrictions in the supplying countries, was the Enabling Trade Index ETI. ETI evaluates to which extent economies facilitate the free flow of goods over borders (and to their destination). This indicator was also applied for both mining and refining stages, then the stage with the highest score (higher risk) was chosen as the final score.

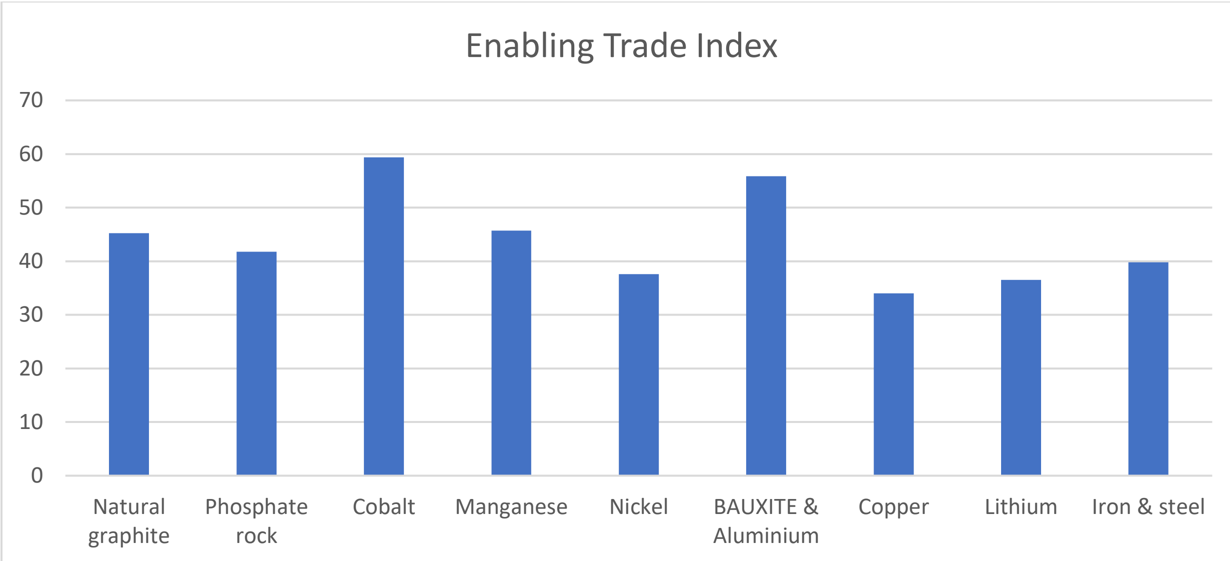

Figure 62 Criticality assessment results for " supplying countries is subjected to trade restrictions/ETI", which might cause a mismatch between supply and demand in the market, which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022).

Cobalt was the main hotspot for the ETI indicator with a score of 59.5 (see Figure 62) the risk comes from the trade restrictions in the supplying countries in the mining stage. Cobalt is mainly mined in Congo DRC with ETI score of 3.03. The Enabling Trade Index ETI scores between 1 and 7, the higher score the better trade flow over the border of the supplying country. 4.1 % of the market is not represented because of data gaps for Cuba, Papua New Guinea.

Bauxite/Aluminum comes in second with a score of 55.8, where also the risk comes from the trade restrictions in the supplying countries in the mining stage. Bauxite is mainly mined in Australia, China, and Guinea with ETI scores of 5.1, 4.49, 0 respectively. Due to data gapes the ETI for Guinea was set to zero, which might influence this score since Guinea supply 22% of global bauxite mine production. 22% of the market is not represented because of data gaps for Guinea.

Followed by manganese with trade restriction risk coming from the mining stage, too. Manganese is mainly mined in South Africa, Gabon, and Australia, with ETI scores of 4.52, 3.24, 5.1 respectively. Here, only 1% of the market is not represented because of data gaps for Myanmar.

For natural graphite trade restriction risk is also coming from the mining stage. Natural graphite is mainly mined in China with ETI scores of 4.49. For this score only 0.9% of the market is not represented because of data gaps for Korea, Dem. Rep.

Phosphate rock's trade restriction risk comes from the mining stage. Phosphate rock is mainly mined in China, Morocco, and the United States with ETI scores of 4.49, 4.6, 5.24 respectively. For this score only 1% of the market is not represented because of data gaps for Togo.

In our assessment we have found that trade restrictions (measured by ETI) are mainly linked to the mining stage of most of lithium battery raw materials. Except for Lithium where the trade restrictions (measured by ETI) are linked to the refining stage.

The supply is dominated by a few companies

The last indicator to be discussed here is the supply is dominated by a few companies. This indicator was evaluated by checking market shares of the mining companies for each lithium battery raw material, then calculating the HHI-supplying companies. Natural graphite and manganese were excluded from this evaluation due to data gaps related to the supplying companies' market share (see Figure 63).

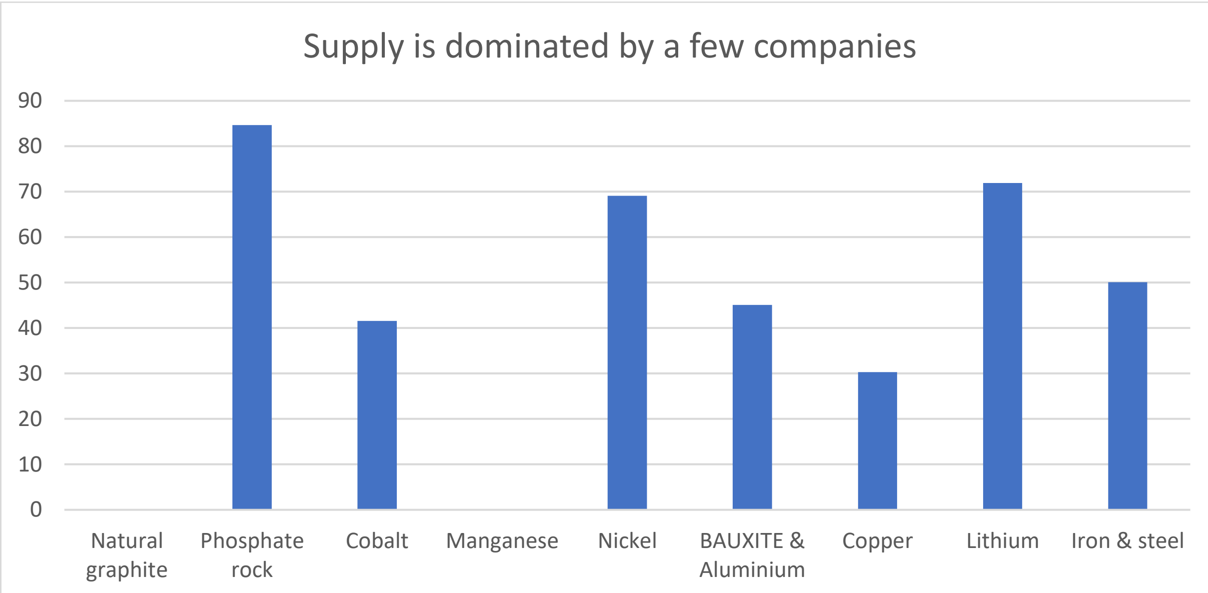

Figure 63 Criticality assessment results for "Supply is dominated by a few companies", which might cause a mismatch between supply and demand in the market, which might lead to the risk that the company does not have access to lithium battery raw materials (WeLOOP, 2022).

Phosphate rock is the main hotspot for the HHI-supplying companies indicator, the three major phosphate rock mining companies are Vale, Nutrien, and Mosaic with market shares of 53.5%, 35%, and 11% respectively. The market cap (million USD) for each company was used to calculate the market share here. Since there were missing data for their production capacity. Lithium comes in second as a hotspot, the top four major mining companies of lithium are: Jiangxi Ganfeng Lithium, Tianqi Lithium, Albemarle, and SQM with market shares of 29%, 21%, 20%, 18% respectively. The market cap was also used here to calculate the market share. Nickel was the third hotspot, the top four major mining companies of nickel are: Nornickel, Vale, Glencore, BHP with market shares of 28%, 25%, 13%, and 9% respectively. The total nickel production capacity for each company was used to calculate the market share here.

The fourth hotspot was iron, the top four major mining companies of iron are Vale, Rio Tinto, BHP, and Fortescue Metals Group with market shares of 14%, 13%, 11%, 9% respectively. The total iron mining production was used to calculate the market share.

The limitations of this indicators are the data gapes regarding market shares of supplying companies (also some estimations have been made to calculate the market share for some raw materials). And only the mining companies were considered in this evaluation since it was not feasible to find reliable data sources.

Analyzing the risk of price fluctuations for lithium battery raw materials

The risk of price fluctuations for lithium battery raw materials means that the price of one or several lithium battery raw materials may suddenly change substantially. A company may face this risk due to three main problematics: When there is a mismatch between supply and demand. Additional costs may be expected due to environmental/social reporting requirement or taxes related to the production/ use of lithium battery raw materials. And when the supply of lithium battery raw materials is dominated by a few companies.

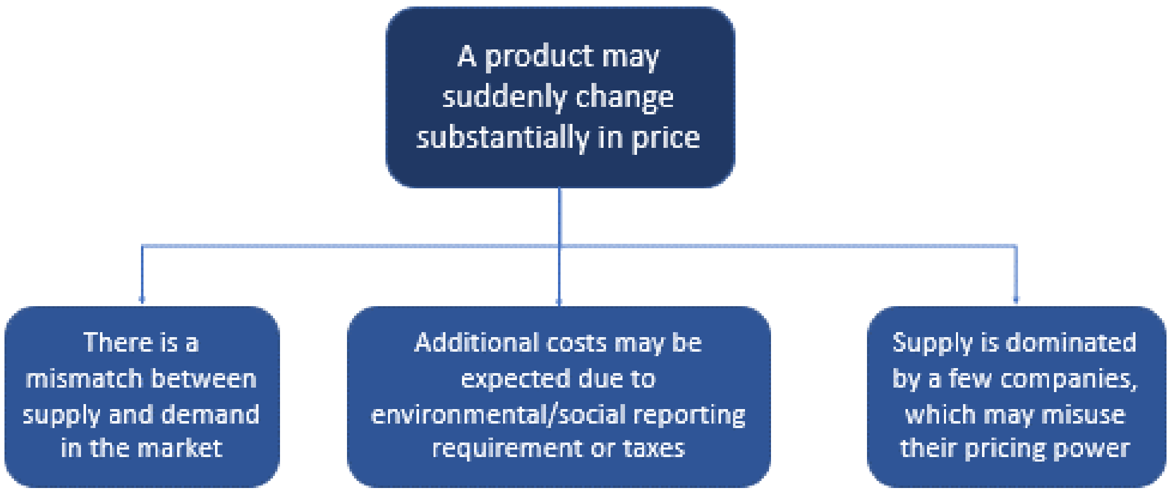

Figure 64 Schematic of the risk, price fluctuations for lithium battery raw materials, and its problematics (WeLOOP, 2022)

There is a mismatch between supply and demand in the market

The price of one or several lithium battery raw materials may suddenly change substantially to a mismatch between supply and demand. This can be caused by three sub-problematics: a strong demand increase while the supply might not be able to catch up, the material is mainly produced as a by-product of another product, and one of the suppliers is not able to deliver their product (with few alternative suppliers).

The results of this problematic on lithium battery raw materials were discussed in detail in the previous paragraph (see There is a mismatch between supply and demand in the market).

Additional costs may be expected due to environmental/social reporting requirement or taxes

Additional costs may be expected due to environmental/social reporting requirement or taxes related to the production/ use of lithium battery raw materials. This problematic may be caused due to environmental impacts and/or social concomitances associated with the lithium battery raw materials (See Figure 64).

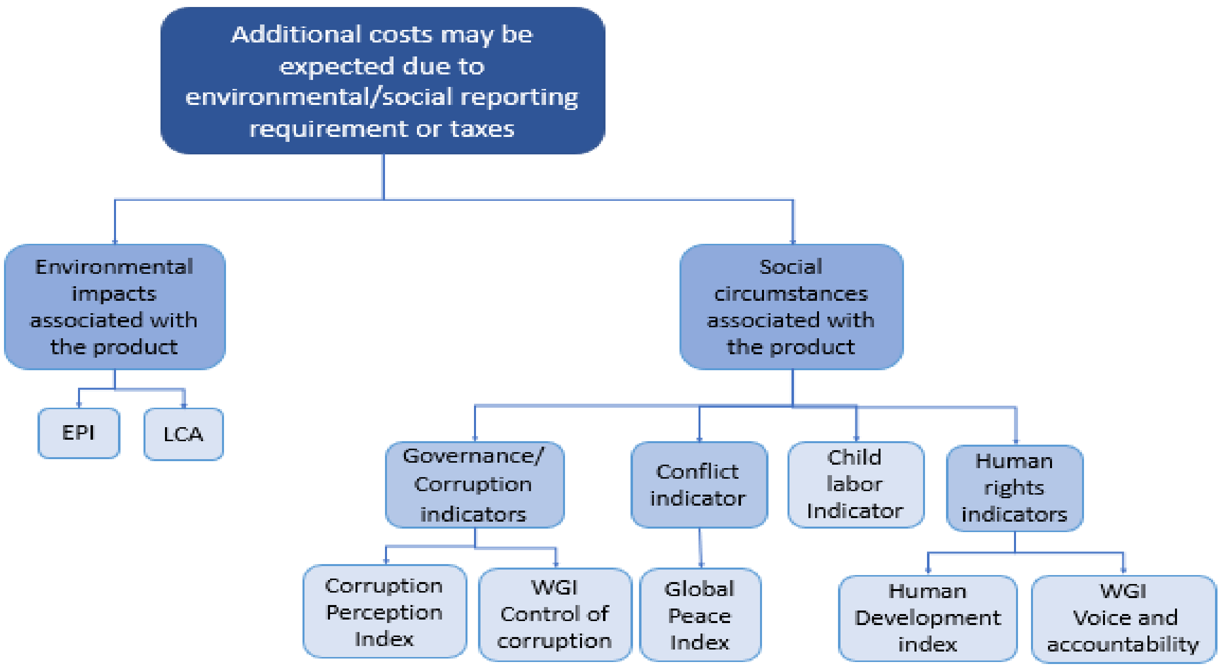

Figure 65 Schematic of "Additional costs may be expected due to environmental/social reporting requirements or taxes", which might cause a risk of price fluctuations for lithium battery raw materials (WeLOOP, 2022).

The results of our criticality assessment of environmental impacts and/or social concomitances associated with the lithium battery raw materials, were discussed in detail in previous paragraph (see **Error! Reference source not found.**).

Supply is dominated by a few companies, which may misuse their pricing power

When one or few supplying companies dominate the supply of lithium battery raw materials, they might misuse their pricing power. Which might lead to the risk of price fluctuations for lithium battery raw materials. The results of our criticality assessment of supply of lithium battery raw materials are dominated by a few companies is discussed in detail in previous paragraph (see **Error! Reference source not found.**).

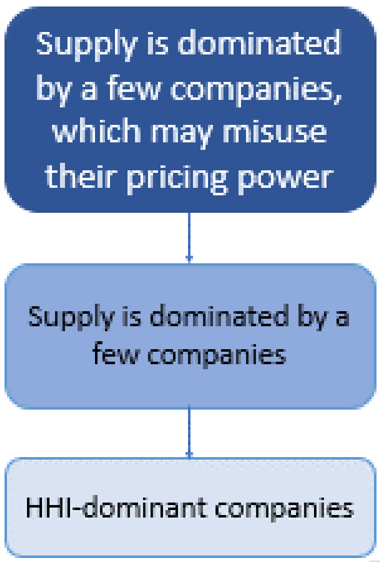

Figure 66 Schematic of "Supply is dominated by a few companies, which may misuse their pricing power", which might cause a risk of price fluctuations for lithium battery raw materials (WeLOOP, 2022).

Analyzing the risk of jeopardizing the company's reputation by the use of lithium battery raw materials

The third risk is that reputation of accompany may be affected by the use of one or several lithium battery raw materials. This could happen if the lithium battery raw materials are associated with environmental impacts or social circumstances that are deemed unacceptable by social norms (see Figure 67). The results of our criticality assessment of environmental impacts and/or social concomitances associated with the lithium battery raw materials, were discussed in detail in previous paragraph (see **Error! Reference source not found.**).

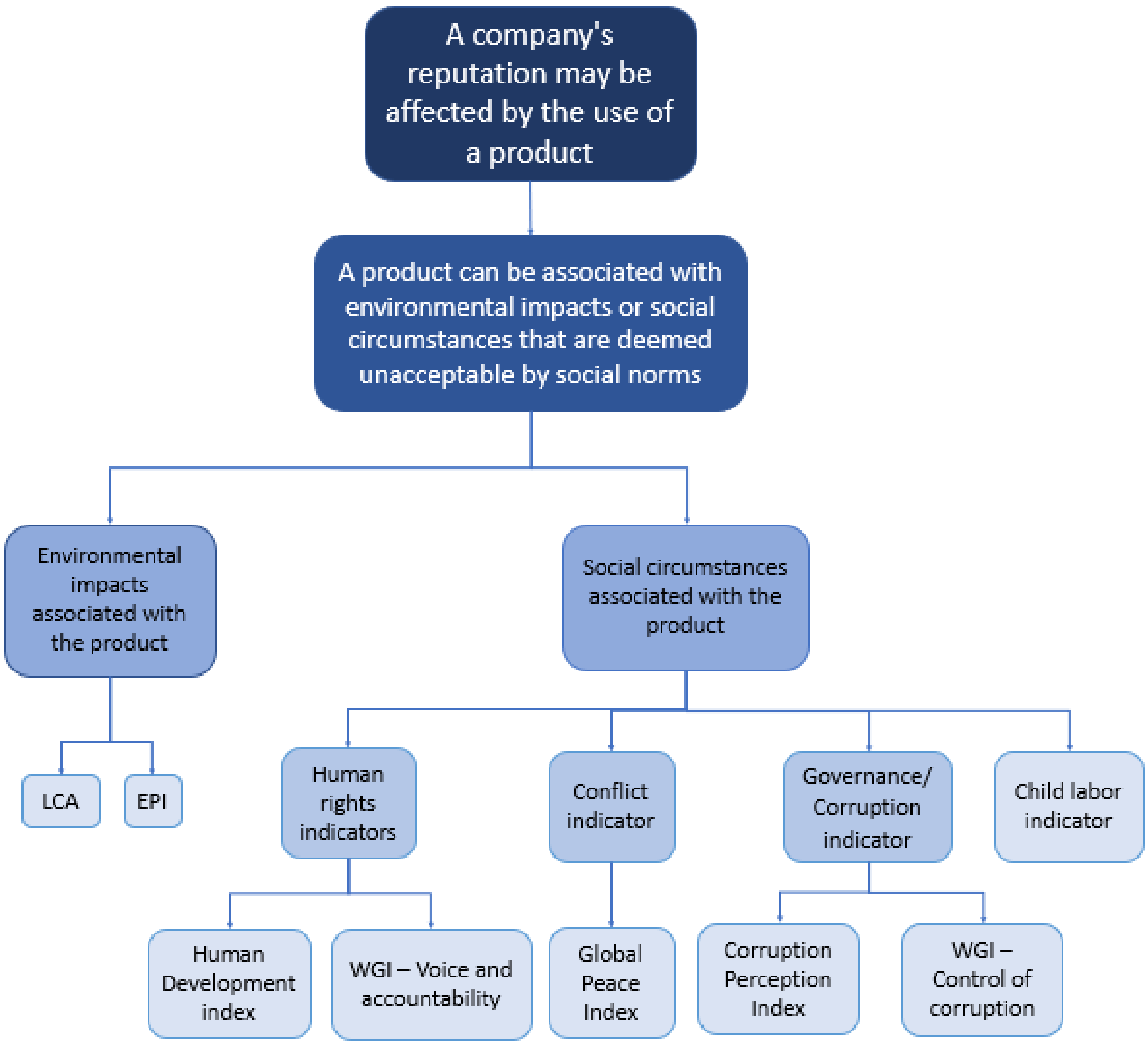

Figure 67 Schematic of the risk that the company's reputation may be affected by the use of LIB raw materials (WeLOOP, 2022)