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Title: The role of raw materials to achieve the Sustainable Development Goals: tracing the risks and positive contributions of cobalt along the lithium-ion battery supply chain

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Abstract:

Given the fast-growing demand for electric mobility, the European Union (EU) has invested in responsible sourcing of battery raw materials, but the sustainability of their value chains is not fully addressed. Life cycle sustainability assessment (LCSA) is a tool to identify social, economic and environmental aspects of raw materials, but it is mostly used for negative impacts, whereas the supply and use of raw materials may also lead to benefits. The Sustainable Development Goals

(SDGs) can help to determine how raw materials boost or hinder the achievement of a sustainable society. In this study, the SDGs were used as a reference to assess contributions and risks of cobalt supply for electric mobility in the EU and whether this technology supports the achievement of the SDGs. The risks were determined using eight indicators focused on social risks, but environmental aspects like water quality and usage, and greenhouse gas emissions were also considered. Literature and databases were consulted to identify which SDGs receive contributions or burdens. Global and European cobalt supply scenarios were defined, considering the most representative countries. Results indicate that, although some SDGs receive positive contributions, like SDG 8 (Decent work and economic growth) and SDG 13 (Climate action), most of the identified correlations are negative, especially for SDG 3 (Good health and well-being) and SDG 16 (Peace, justice and strong institutions). The European scenario has a low risk towards socio-environmental issues in 53% of the assessed aspects, whereas the Global scenario presents a high risk in 47% of them.

1. INTRODUCTION

Sustainability is a topic often used in combination with development. A well-accepted definition of sustainable development *"is that it meets the needs of the present without compromising the ability of future generations to meet their own needs"* (Brundtland 1987). The European Union (EU) has invested in actions towards a sustainable society and supply of raw materials, the most prominent being the transition to low-carbon energy sources and decarbonization of the mobility systems. This is the case of the European Green Deal initiative, whose main objectives focus on reducing the greenhouse gases (GHG) emissions within the EU by at least 55% by 2030 compared to 1990 levels, and making Europe the first climate-neutral continent by 2050 (European

Commission 2019; EUCO 2020). However, sustainable production and supply of raw materials for battery technologies should not only focus on the environmental impacts but also on social and economic aspects, as they are also pillars of sustainability. Besides, some researchers have indicated that the technical factor should not be forgotten, as it may bring a better understanding of the decreasing availability of certain raw materials in nature, the required energy to produce them and their lack of substitutability (Dewulf et al. 2015).

The current vehicle use accounts for 12% of the total GHG emissions within the EU, and car manufacturers are expected to reduce the GHG emissions of their fleets by 37.5% between 2021 and 2030 to help to achieve the Green Deal goals (Haas and Sander 2020). The electrification of the mobility systems (e-mobility) will be crucial to achieving these goals, with electric vehicles (EVs) being the type of transport with the highest expected demand in terms of resources. Compared to the current levels, the demand for cobalt and graphite for e-mobility is projected to increase tenfold by 2050, while the demand for lithium is likely to be 40 times higher (European Commission 2020a). Both raw materials are essential to produce lithium-ion batteries (LIBs), which are today the preferred energy storage systems for EVs (Olivetti et al. 2017; Pelegov and Pontes 2018). New battery chemistries are being investigated for EVs, such as lithium-sulfur and lithium-air batteries, which could reduce the demand for these metals (Xu et al. 2020). However, it is not clear when these new chemistries will be available on the market, the reason why LIBs are still relevant to be analyzed. The EU is committed to ensuring sustainable battery production and development within Europe, with initiatives such as the European Battery Alliance, the strategic Battery Action Plan, the EU Battery Regulation Proposal, and the Important Projects of Common European Interest (IPCEI).

Some of the positive aspects of LIBs that made them so successful in EVs are their high energy density, long cycle life, lightweight and deep discharges, although some manufacturers of hybrid electric vehicles prefer nickel-metal hydride batteries (Olivetti et al. 2017). LIBs are available in different compositions, depending on their anode and cathode chemistry. The lithium-nickel-manganese-cobalt oxide (NMC) is the most widely used chemistry for EVs, along with the lithium-iron-phosphate (LFP) (Tsiropoulos et al. 2018). The NMC chemistry can also vary depending on the content of the metals. The cathode can have different ratios between the metals, which is indicated by the numbers following the NMC abbreviation and refer to the mass ratio between nickel, manganese and cobalt, respectively. The currently most widely used chemistries are $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ (NMC 111), $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ (NMC 622) and $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC 811). The LIBs industry is transitioning to NMC chemistries with lower cobalt content and more nickel, as a way to reduce supply risks on critical raw materials, but also for economic reasons and to improve battery performance, for instance, higher capacity and energy density (Tsiropoulos et al. 2018). It is expected that NMC 811 will become the preferred chemistry after 2025 (Tsiropoulos et al. 2018), as up to 70% less cobalt is used in this type of cathode compared to NMC 111 (Bechberger et al. 2021). However, this chemistry is reported to result in higher environmental impacts compared to NMC 111, as a result of the high nickel content (Sun et al. 2020; da Silva Lima et al. 2021). NMC 622 chemistry could be a good alternative, as it has less cobalt than the initial chemistry (NMC 111) but has a better balance between the content of the different metals.

Although battery manufacturers point to a lower content of cobalt in LIBs, this is an essential metal in NMC-based batteries. One of the main reasons for reducing cobalt content is that this metal is considered a critical raw material for the EU, due to its economic importance and risk of supply disruption (European Commission 2020b, 2020c). In addition, cobalt sourcing, which is mainly supplied by the Democratic Republic of the Congo (DRC), is reported to be linked to human rights violations and environmental burdens. Forced labor, child labor, poverty, unsafe working conditions, and political instability are examples of social issues, while emissions of GHG, nitrogen dioxide and sulfur oxides, extensive use of water, acidification and global warming potential have been reported as environmental impacts (Mancini et al. 2020; van den Brink et al. 2020; Schmidt et al. 2016; Dai et al. 2019; Peters and Weil 2018; Farjana et al. 2019; Keersemaker 2020; Thies et al. 2019; Tsurukawa et al. 2011; Ellingsen et al. 2013). Even though many negative socio-environmental impacts have been identified in the supply of cobalt for LIBs, there are also positive contributions, such as the creation of jobs and infrastructure development for the local community (Mancini et al. 2019). Both positive and negative aspects along the cobalt supply chain can be related to the sustainability pillars (i.e. social, environmental and economic), which in turn can be linked to the Sustainable Development Goals (SDGs) defined by the United Nations (United Nations 2015). Linking SDGs to sustainable development implies multiple possible correlations, both from a positive and negative perspective. The seventeen SDGs encompass the action plan for environmentally sustainable economic development and can be used to evaluate whether the society will achieve sustainable development by 2030 (United Nations 2015).

Although the SDGs consist of important targets for achieving a sustainable society, the use of these goals to assess the performance of raw materials, such as LIBs production, has not yet been fully explored. A recent study described the positive and negative impacts of several biotic and abiotic raw materials value chains on the SDGs (Mancini et al. 2019); however, this study described the potential burdens and benefits to the SDGs in a general way, without focusing on one raw material or a specific sector and country. The authors considered the manufacturing in a more aggregated format, with raw materials assessed as a whole. The representation of the SDGs along the raw materials supply chain is done qualitatively, by allocating direct and indirect negative impacts or positive contributions, but it is not clear if one SDG presents more positive or negative impacts than the other in a specific value chain stage.

A more recent work focused on the cobalt supply for LIBs identifies the socio-environmental risks in metal production in the DRC (Mancini et al. 2020). This study delivers important qualitative and quantitative results, indicating risk levels according to well-defined indicators. Although this study is more specific regarding the raw material (cobalt), sector (mining) and country (DRC and others), the results are focused only on the extraction stage and are country-specific. Furthermore, no link between the socio-environmental risks and the SDGs is mentioned, although several social implications and environmental risks are identified. A third study has been identified, which focuses on the sustainability of battery cell production within Europe and how this affects seven SDGs (Bechberger et al. 2021). This work has important recommendations for improvements regarding environmental hotspots, raw materials governance, industrial policy, circular economy, economic efficiency, employment, and the achievement of the SDGs more directly related to these aspects. However, once more a general approach is taken, looking into different raw materials (cobalt, lithium and graphite) in a European context. Although the internal European supply of raw materials and LIBs has developed significantly in recent years, it still does not represent the largest share of raw materials and LIBs supply to the EU.

Therefore, there is a lack of a study addressing the risks of a representative cobalt supply chain for LIB used in a European context, as well as the correlation of these impacts with the SDGs. This correlation between social and environmental risks and contributions to the SDGs allows evaluating if the use of LIBs with cobalt in its composition helps to achieve the SDGs. The objectives of this study are: i) the development of a hotspot analysis to identify which SDGs are affected positively or negatively along the cobalt supply chain for LIBs, assessed qualitatively and quantitatively; ii) the identification of significant social risks and some environmental hotspots that some countries and sectors may face along the supply chain of cobalt for LIBs, through the extension of the framework developed by Mancini et al. (2020) to the downstream stages.

2. METHODS

2.1. Selection of representative stages and countries in the cobalt supply for lithium-ion batteries

The cobalt supply chain for LIBs was divided into four stages: i) mining of cobalt; ii) refining of material; iii) cathode material production; and iv) battery cell and battery pack production. This division is based on the information found in the literature about the different operating plants along the supply chain. The mining stage includes the extraction, as well as the concentration of the cobalt ores to crude cobalt hydroxide ($Co(OH)_2$) since these hydrometallurgical plants are often located in the proximity of the mining activities and therefore affect the same local communities (Dai et al. 2018). The second stage comprises refining the crude hydroxide to cobalt sulfate ($CoSO_4$). Concerning the cathode material production, the manufacture of NMC 622 was considered. This choice is because NMC 622 has less cobalt compared to NMC 111, and NMC 811 was not considered as this chemistry has been reported to result in higher environmental impacts than NMC 111 (Sun et al. 2020; da Silva Lima et al. 2021). The manufacturing plants generally produce other cathode materials besides the NMC, such as lithium cobalt oxide (LCO) and nickel-cobalt-aluminum oxide (NCA), these are also intended for battery applications, but only NMC 622 is considered. Finally, regarding the last stage of the cobalt supply chain for LIBs (i.e.

battery cell and pack production), it consists of mixing, coating, and drying processes for the battery cell production and the effective assembly of the battery pack (Sun et al. 2020).

In this study, two scenarios for the LIBs supply in the EU were considered, one representing the current global supply chain and an expected future scenario representing a European supply (Figure 1), the latter is based on the different EU initiatives to develop the production of LIBs within Europe. Apart from the goals to secure access to raw materials and reduction of environmental hotspots, the initiatives focus on the creation of a full competitive battery value chain in Europe, with incentives to research, innovation, and a highly skilled workforce (European Commission 2018, 2020d, 2017). Considering the battery supply and the targets defined in the European Green Deal, a comparative study between European and Global LIBs supply scenarios was carried out.

For the Global scenario, the selected countries represent the largest flows per each stage (Figure 1). The DRC accounted for 61% of the worldwide production of cobalt ores in 2017 (European Commission 2020e), while East Asia is nowadays the market leader in EVs batteries with the largest share of LIBs produced worldwide (Beuse et al. 2018). Currently, more than 90% of the global LIBs production takes place in China, Korea, and Japan, with China being the largest producer (Batteries Europe ETIP - European Commission 2020). In addition to the production of battery cells and battery packs, China is also the leading country in the refinery of cobalt-based battery materials and production of cathode materials (Lebedeva et al. 2016).

For the European scenario (Figure 1), the countries were selected based on a potential future local supply within Europe, not necessarily depicting the currently largest streams imported into the European market, except for the mining stage, which was considered to take place in the DRC, similarly to the Global scenario. This is because the European supply of cobalt ores and concentrates is highly dependent on this country, which accounts for 68% of the EU sourcing of cobalt ores and concentrates and is, therefore, the largest supplier of cobalt ores and concentrates in Europe (European Commission 2020e). Europe's largest cobalt supplier is Finland, a country responsible for 14% of the EU sourcing of cobalt ores and intermediates and 54% of refined cobalt (European Commission 2020e). Although Finland holds a significant share of the primary cobalt supply to the EU, the current values would not meet the European demand, especially considering that a significant increase in demand is foreseen for EVs in the upcoming years. Since only one country was considered per stage of the supply chain, the DRC was selected for mining in both scenarios. The following stage, consisting of the NMC cathode material production is considered to occur in Poland, as Umicore has recently reported activities in the country (Umicore 2019a; Bechberger et al. 2021), and little information on other manufacturers of the specific cathode material within Europe was found in the literature. Regarding the manufacturing of the LIBs itself, East Asia is the main supplier and European carmakers have struggled to secure sufficient battery supply from the Asian market (Eddy et al. 2019). With the prospect of exponential growth of EVs in the upcoming years, high-level policymakers in Europe have indicated the importance of the battery industry to ensure Europe's competitiveness in the automotive sector by focusing on local battery production (Beuse et al. 2018). While the production of LIBs in Europe today represents only 6% of the current global battery capacity (450 GWh), it is estimated that by 2029 the European share of the total battery capacity produced (2550 GWh) will increase to 16% of the global battery market. Therefore, the current manufacturing capacity is increasing, and new plants are being built all over Europe (Batteries Europe ETIP - European Commission 2020; Bechberger et al. 2021). In this study, Germany was selected as a representative European country for battery cell and battery pack production, as a significant share of the factories currently in operation, as well as prospective plants, are concentrated in the country (Batteries Europe ETIP - European Commission 2020). The two scenarios were used to identify the most noticeable positive contributions and risks to the SDGs originating from different production stages and countries, which is further described in Section 2.2. As mentioned before, the scenarios will also be used to compare the risk levels along the supply chain and to identify the stages that fail to achieve a responsible and sustainable supply chain, as described in Section 2.3.

2.2. Sustainable Development Goals along the cobalt supply chain for lithium-ion batteries

The assessment of the risks along the cobalt value chain for LIB that affect positively or negatively the achievement of the SDGs started from the methodology and findings of Mancini et al. (2019), who listed the relationship between several SDGs and the supply of different raw materials, using a broad materials scope (i.e. biotic and abiotic raw materials). From their findings, the issues and contributions to different SDGs that were related to the cobalt supply chain were selected. To advance this initial selection, the monitoring frameworks used by Mancini et al. (2019) were consulted, to include potential negative impacts and benefits to SDGs not listed in their study, as it was not cobalt-specific. These frameworks were the UN monitoring framework on SDGs (United Nations General Assembly 2020) and the Eurostat indicators set for monitoring the SDGs (European Union, Eurostat 2019). The authors of this study used the documents available at the time of the study, which were similar versions to the 2017 documents used by Mancini et al. (2019). The most relevant positive and negative correlations and their respective SDGs were selected, considering the cobalt supply chain for EVs. Additional information regarding potential risks and contributions to the SDGs in the supply stages was collected from the literature and databases, as listed in Table S5 in the Supporting Information (SI). Different types of sources have been consulted, including life cycle assessment (LCA) and social LCA studies, scientific peer-reviewed literature, international organization reports (International Labour Organization; The World Bank), and reports from European institutions (European Commission - Joint Research Centre). The selection of SDGs relies on the direct burdens and benefits identified from the work of Mancini et al. (2019) and its related monitoring frameworks, as well as information available in the literature. The SDGs selection presents some elements of subjectivity, as social risks can be directly or indirectly linked to a wide range of goals and targets. The selection, therefore, implies attributing degrees of relevance and significance in the relationship between different phenomena, which is described in the SI (Sections 1.1 to 1.4 and Section 2.2). The main outcome is a quantitative and qualitative assessment of the positive contributions (handprint) and risks (footprint) identified per relevant SDG, at each stage of the supply chain. The SDGs as defined by the United Nations are illustrated in Figure S1 in the SI.

2.3. Indicators for social and environmental risks along the cobalt supply chain for lithium-ion batteries

The assessment of the potential socio-environmental risks along the cobalt supply chain for LIB was performed by adapting the framework of Mancini et al. (2020), where the authors selected ten indicators to evaluate the degree of responsible and sustainable sourcing in the extraction phase of raw materials. The ten indicators are listed in Table S1 (SI), next to the risks assessed by them, their respective data sources and the year of the data. As one of the goals of this study was to extend the indicators to the downstream stages of the cobalt supply chain for LIB, the relevance of these indicators was evaluated considering the stages following the mining of cobalt. The Resource Governance Index (RGI) describes the management of natural resources and is only applicable to the extraction stage, therefore no data was useful for countries at the downstream stages of the LIBs supply, such as Finland, Poland and Germany. Moreover, a comparison between the RGI and the Worldwide Governance Indicator (WGI) for the same countries and years resulted in a direct relation between these two indicators, meaning they report similar issues. The WGI has been reported as the most robust indicator to capture the level of governance in a country and is applicable to different life cycle stages of a material (Blengini et al. 2017). Therefore, the RGI was considered irrelevant for this study, as well as the Global Peace Index (GPI). In the case of the GPI, it was observed that the indicator had overlapping information with the INFORM Human Hazard in terms of ongoing conflicts and with the Fragile States Index (FSI) regarding safety and militarization. Thus, a total of eight indicators were selected for this study, as listed in Table 1. Each indicator has a different unit for assessing the potential risks and ranges of values that result in low- or high-risk levels. Following the framework of Mancini et al. (2020), the different risk levels by indicator were assigned a semi-quantitative score between 1 and 4, with the lowest values representing the lowest risks, as further described in Table 1. In this way, it was possible to use the same risk levels for all indicators, despite the difference in their units or how they are quantified. A relevant difference between the work of Mancini et al. (2020) and this study is that in the former, the authors used country-based data whereas this study relied on local or region-specific data whenever this was available. For instance, regarding the Water Risk Index (WRI) indicator at the cobalt mining stage, Mancini et al. (2020) consider the values reported for the DRC, meaning the country as a whole, whereas this study considers the specific region of Katanga, where 45% of the current world's known reserves of mineable cobalt are located (Decrée et al.

2015). For each of the indicators, the most suitable SDGs representing potential burdens and benefits were assigned, as a way to identify which SDGs have the lowest or highest risks in terms of achievement. As an example, the WGI is widely used to assess countries' governance and consists of six dimensions of governance: voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law, and control of corruption (Mancini et al. 2020). These six dimensions are strongly related to SDG 16 (Peace, justice and strong institutions), the reason why this SDG was selected as a correlation to the indicator. The complete reasoning to link one or more SDGs per indicator is further described in the SI (Section 2.2). The indicators were applied to the Global and European scenarios and the risks scores were calculated by country and/or supply stage. The result of this assessment was a qualitative and quantitative mapping of the affected SDGs along the cobalt supply chain.

3. RESULTS AND DISCUSSION

3.1. Risks and contributions to the Sustainable Development Goals along the cobalt supply chain for lithium-ion batteries

The positive (handprint) and negative (footprint) effects of the cobalt supply chain on the SDGs were identified as described in Section 2.2 and are listed in Table 2. The SDGs listed are the ones for which contributions and risks have been identified based on the findings of Mancini et al. (2019), but looking specifically at the cobalt supply for LIBs. For some SDGs, the direct correlation was not identified, therefore not all the 17 SDGs are covered. The handprint and footprint of the cobalt supply chain for LIB on the SDGs are illustrated in Figure 2, where it is possible to visualize the stages in which more SDGs are affected and how positive/negative are these correlations. The mapping of the affected SDGs in the cobalt supply chain consists of a qualitative and quantitative assessment of the contributions and risks to the SDGs per stage of the supply chain. This is somehow similar to what has been done by Mancini et al. (2019), although the authors used a more qualitative approach, separating into direct or indirect positive contributions and adverse impacts. Another difference is related to the fact that the authors did not describe the impacts for one raw material in specific, but for the overall raw materials used nowadays (biotic and abiotic). Moreover, it is not clear what criteria were used by the authors to position the SDGs in their graphical representation within the same impact category (e.g. direct positive contribution), as some SDGs are positioned higher than others. This could be related to how many impacts were identified, similarly to what was done in this study, but they could also have been positioned depending on the relevance of the impact using some prioritization rule. From Table 2 and Figure 2, it is clear that the extraction stage is the one affecting more SDGs, mostly in a negative manner, although positive contributions have been identified. A more detailed description of the contributions and risks to the SDGs per stage of the supply chain is available in the SI (Section 1).

3.2. Hotspot analysis for Global and European supply chains of cobalt for lithium-ion batteries

The risk levels by indicator (Table 1) and stage/country (Figure 1) were calculated for both the Global and the European scenarios. The results for each scenario and the differences between them are depicted in Figure 3 and the values are listed in the SI (Table S2). Higher risk levels are present in the Global scenario of cobalt supply. The European scenario results mainly in low to medium risks, whereas the Global scenario has mostly medium to high risks. Most indicators show higher risk levels for all stages in the Global scenario compared to the European one, except for Fair salary, which seems to be at equal risk in Finland and higher risk in Poland (European scenario). There is no difference in the mining stage, which is the same in both scenarios. The difference between the overall risk levels of the Global and European scenarios becomes clear looking at the results represented in Table 3, which shows a distribution of the risk levels assessed for both of them. For each scenario, 32 scores were assigned considering the eight indicators and the four supply chain stages. For the Global scenario, almost half of the risks along the supply chain were considered high risk (15 out of 32 or 47%), whereas, for the European scenario, more than half of the assessed risks resulted in low risk (17 out of 32 or 53%).

A comparison between the risk levels for mining of cobalt in the DRC and Finland is provided in the SI (Table S3). A fully European supply chain would result in much lower risks. However, since Finland is the main cobalt supplier within the EU and is responsible for only 14% of the EU demand, this hypothetical scenario is currently unfeasible. Looking at the downstream stages of the supply chain, other representative countries were only identified for the Global scenario, being Japan and South Korea (see Table S4 of SI). Compared to China, these two other countries would also result in lower risks for the three downstream stages (refining up to battery manufacturing). Japan would be the best-performing country, with low risks in all indicators, except for FSI, which has a medium risk. South Korea has slightly higher risks for some indicators, but overall, it results in low risk, only WGI, FSI and EPI show a medium level.

The results for cobalt mining in the DRC are mostly in line with the results obtained by Mancini et al. (2020), except for WRI, which resulted in low risk in their work in contrast to a high risk identified in this study. This difference can be due to the specific type of data used in the assessment. For instance, Mancini et al. (2020) do not specify which geographical scope was considered for the WRI, which may have been the entire country, while in this study, the specific mining region Katanga was considered. Moreover, the WRI value by the Aqueduct Water Risk Atlas indicates a national low risk for mining regarding the physical water quantity. Possibly, Mancini et al. (2020) used this value to determine the overall water risk level. However, the water quantity only represents one aspect of the water risk, which is additionally composed of the physical water quality and the regulatory control. For the two latter, the DRC poses a very high risk. This results in overall high risk, as obtained in this study.

Looking in more detail at the risk indicators individually per country, the DRC has the lowest levels of governance and the highest risk of conflict, child labor and forced labor. The lowest risk this cobalt-supplying country receives is for fair salary, which is still within the medium-risk range. China also scores badly for most indicators, the worst ones are in the range of high-risk levels, being WGI, FSI, child labor, Environmental Performance Index (EPI) and WRI. A relevant observation is that the largest players of each stage, i.e. the countries in the Global scenario, are also the ones with the highest risks in all indicators, whereas the European countries receive low to medium risks. An exception is the cathode production in Poland, which is linked with a high-risk level regarding forced labor. Scrutinizing the overall supply chains (bottom bars in Figure 3), the Global scenario indicates very high risks for WGI, FSI and child labor, followed by high risks for conflicts (INFORM Human Hazard), forced labor and EPI. The only medium risk was identified for WRI and low risk was found for fair salary.

Considering all the supply stages (Figure 3 and Table S2), an average high-risk level (2.7) is obtained for the Global supply chain, whereas the European one has an average medium risk (1.8). A low risk (1.1) could be assigned to the European scenario if the risks of the mining stage could be reduced, for instance, by increasing the supply from Finland (Table S3). However, the DRC is currently the most important supplier of cobalt ores and concentrates for Europe; although the EU is currently promoting the local supply of raw materials, it is not yet realistic to consider a European country as the main cobalt supplier to the EU. Although assigning an average risk level per scenario may be seen as a "weak sustainability" approach (Ziemba 2019), detailed explanation on why this was done and how aspects of "strong sustainability" were considered is provided in the SI (Section 2 after Table S2).

Some SDGs describe goals and targets aiming at the society as a whole and are not specifically related to industrial activities, such as cobalt production for LIBs. An example is SDG 7 (Affordable and clean energy), which aims at "*affordable, reliable, sustainable and modern energy for all"* with targets of increasing the share of renewable energy in the global energy mix and improvements in energy efficiency (United Nations 2015). However, to provide clean and sustainable energy to the society, for instance by storing renewable energy in LIBs, the whole supply chain of the technologies should also make use of clean and sustainable energy, which is not always the case in the cobalt sector. Some stages of cobalt production are very energy-intensive and make use of coal-based energy, which is a fossil-based and inefficient type of energy, with a reported average thermal efficiency of 33% (Farjana et al. 2019; Buskies 1996; Bugge et al. 2006; Goto et al. 2013). Therefore, although the use of LIBs contributes positively to SDG 7, the supply chain has some negative impacts, which were also considered.

An alternative to lower the risks at the beginning of the cobalt supply chain would be the increase of cobalt recycling and higher input of recycled cobalt in LIBs manufacturing as a way to minimize the mining of the metal in countries with a high risk. This would also support Europe towards a circular economy, which in turn has been reported to contribute to the achievement of several SDGs, such as SDG 6 (Clean water and sanitation), SDG 7 (Affordable and clean energy), SDG 8 (Decent work and economic growth), SDG 12 (Responsible consumption and production), and

SDG 15 (Life on land) (Schroeder et al. 2018). Nevertheless, significant improvements would have to be made in the proper collection and recycling of end-of-life batteries containing cobalt. A recent study has determined that although portable batteries are the main application of cobalt nowadays (41.2%), in a 7 years period (battery lifetime and hoarding time), only 1% of the initial cobalt remains in this application due to low collection-to-recycling rates (Godoy León et al. 2020). Moreover, the currently available recycling technologies do not result in recycled metals with the best quality required in the manufacturing of NMC active material and are still highly costly (pyro and hydrometallurgy) or require manual disassembly methods, which makes it challenging to upscale economically (Harper et al. 2019; Roy et al. 2021; Kim et al. 2021). Another possibility would be that the EU reinforces policies and guidelines to ensure responsible sourcing of cobalt. Currently, different initiatives focused on the responsible and sustainable supply of raw materials are available. Some to be mentioned are the OECD due diligence guidance for responsible mineral supply chains (OECD 2016), International Finance Corporation's performance standards on environmental and social sustainability (International Finance Corporation 2012), China Chamber of Commerce of Metals, Minerals & Chemicals Importers and Exporters (CCCMC) Guidance (CCCMC 2015) and Social LCA (UNEP 2020), but these are focused on different raw materials and mostly LSM. Other initiatives focused on cobalt are the Cobalt Industry Responsible Assessment Framework (CIRAF) (Cobalt Institute 2019), Umicore sustainable procurement framework for Cobalt (Umicore 2019b), Responsible Cobalt Initiative of the CCCMC (CCCMC and OECD 2016), Responsible Minerals Initiative cobalt due diligence standard (RCI and RMI 2021) and reporting template (RMI 2021), Eurasian Resources Group Clean Cobalt & Copper Framework (ERG 2021) and projects on cobalt artisanal mining in the DRC (Mancini et al. 2020). However, these initiatives must be properly implemented and followed to guarantee lower risk levels than nowadays. Another remark is the need for accurate and recent data that reflect the current situation of the mining areas. In this study, the PSILCA 3 database (PSILCA 2020) was used to assess child labor and fair salary, as this is one of the most reliable databases for social risks assessment. However, the data for these two indicators refer to periods between 2006 and 2018, which might differ from the current situation. It is reasonable to consider that data availability regarding these issues is scarce, but this could be another point of attention to the EU, in order to identify the priorities in terms of policies to reduce social pressures. Recently, the Global Battery Alliance announced the Battery Passport, which intends to align the battery-related industries and energy suppliers with the objectives defined in the Paris Agreement (Global Battery Alliance and World Economic Forum 2020). This initiative aims at important outcomes for the battery value chain, such as transparency regarding the practices along the battery life cycle, the definition of standards for sustainable and responsible battery supply, and validation and progress assessment towards stainable, responsible and resource-efficient batteries (Global Battery Alliance and World Economic Forum 2020). The Battery Passport is expected to be launched in 2022 and to support the achievement of the Paris Agreement goals, which are aligned with some of the SDGs.

The most representative SDGs for which risks were identified through the indicators are listed in Figure 3 (below each indicator), with SDG 1, SDG 3, SDG 4, SDG 8 and SDG 16 being good representations of the social-related issues assessed. Regarding indicators for environmental risks, SDG 6, SDG 13, SDG 14 and SDG 15 were identified as the most representative ones. In general, water consumption, water quality and GHGs emissions negatively affect SDG 6, SDG 13, SDG 14 and SDG 15 in all stages, whereas expected increased employment due to elevated demand of EVs positively contributes to SDG 8, in all stages. Conflicts related to SDG 16 are more pronounced in the mining sector but are also present to a certain extent in the other stages. Problems regarding human rights violations are mostly reported in the extraction phase, which takes place in the DRC. Although health issues and employment opportunities are distinguished in all the sectors, other social risks such as child labor and working conditions are mainly of concern in the mining sector. These most representative SDGs have been identified for the specific case of cobalt supply, however, a more sustainable and socio-environmentally production chain is required for several sectors to achieve the SDG targets by 2030. Recent initiatives and research related to clean technologies that provide contributions to achieve the SDGs have been explored (Giannetti et al. 2020), but there are still significant challenges to accomplish the SDGs by 2030.

3.3. Limitation of the study

This study may have limitations due to different system boundaries than those used to gather information to identify and classify the risks, which required some adaptations and assumptions. Moreover, some of the information collected was not sector-specific and similar activity was used to estimate the potential risks. The scope of this assessment included the supply of cobalt up to the battery manufacturing, but it is important to investigate the following stages, which include the use and end-of-life of the LIB. An assessment of a complete value chain would provide a more complete overview of the role of cobalt in the achievement of the SDGs, as most of the benefits are expected at the use phase. In addition, it is relevant to mention that the findings of this study rely on the values and background knowledge of the authors about the aspects studied, especially the assessment of social impacts and their correlation of impacts and risks to specific SDGs. The methodology developed and used in this study depends, to some extent, on the opinion and interpretation of the authors, which may vary from person to person depending on their country or region and their social values. For instance, people may have different perceptions of what is considered a positive or negative aspect of the cobalt supply chain, as well as which of the SDGs and their targets best represent the positive contributions, negative impacts or potential socio-environmental risks. Therefore, it is important to consider that if this methodology is used by other researchers, the outcomes of their assessment may be different depending on the information they have access to during the execution of the study, but also their opinions and background experience with socio-environmental aspects may lead to different results and conclusions than the ones presented in this study.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

In this study, a quantitative and qualitative assessment of the risks and contributions to the SDGs along the cobalt supply chain for NMC 622 LIBs was performed. Two supply scenarios, at the Global and European levels, were analyzed, focusing on the social aspects but also including some environmental risks. Although the economic aspects of the cobalt supply for LIBs were not taken into account in this study, this is an important pillar of sustainability and the achievement of the SDGs will require economic investments and development, as it has been estimated that USD 6.9 trillion a year will be needed to achieve the climate and development objectives by 2030, investments mostly related to the reduction of carbon emissions (OECD et al. 2018). Therefore, research on the economic aspects of the cobalt value chain for LIBs is recommended.

A hotspot analysis was conducted to identify the risks per sector and country within a defined Global and European supply chain scenarios. From the results, it is clear that the cobalt supply chain for LIB affects several SDGs, both positively and negatively. The water consumption, water quality and emissions of GHGs result in risks to SDG 6 (Clean water and sanitation), SDG 14 (Life below water), SDG 15 (Life on land) and SDG 13 (Climate action) in all stages, whereas expected increased employment in all sectors due to elevated demand of EVs positively contributes to SDG 1 (No poverty) and SDG 8 (Decent work and economic growth). Conflicts related to SDG 16 (Peace, justice and strong institutions) are more pronounced in the mining sector but through the risk analysis, it was identified that issues affecting this SDG are also present in the downstream stages. Issues regarding human rights violations are mainly reported in the extraction phase, taking place in the DRC, but medium to high risks related to governance, fragile state and human hazard were found for China and Poland.

The social risks of the supply chain at downstream stages of cobalt mining are currently less studied than the global environmental impacts, which are abundantly described in several LCAs and other studies. The findings of this study indicate that there are social issues at these stages. Thus, more research and up-to-date information are recommended to better assess the social risks at the downstream stages. The hotspot analysis highlighted the potential risks for all sectors and countries of both Global and European supply scenarios. For the Global scenario, this evaluation confirmed that the extraction of cobalt in the DRC poses a very high social risk, especially for what concerns conflict risk, child labor, forced labor and governance, as well as high environmental risks. China, where the downstream sectors of the global cobalt supply for LIB are concentrated, is identified as a country at high risk in most categories, with exceptions for conflicts, fair salary and human labor that had low to medium risks. In contrast, the downstream stages of the European cobalt supply for LIBs (which includes Finland, Poland and Germany) pose a low risk for most of the indicators. The fight against climate change must also allow a fair and inclusive transition, with opportunities for all society members and minimizing inequalities (OECD et al. 2018).

Several challenges are to be faced to achieve the SDGs in the next decade, which will demand measures from policymakers but more importantly, the implementation and execution of defined strategies towards a sustainable society. First, the EU should provide well-defined guidelines on responsible sourcing of cobalt and other (critical) raw materials required for the energy transition and ensure these are followed by the countries supplying these metals. This will help to reduce the social and environmental risks, especially at the mining stage, as is the case for cobalt from the DRC. Next to that, an information network may be needed to provide accurate evidence of the current situation in those countries. Moreover, the EU should set targets for recycling and recovery of metals from end-of-life LIBs, as the use of recycled metals will reduce the demand for primary metals. This raises an additional point of improvement, which is the advances required in recycling technologies since nowadays the quantity and quality of the recovered materials still need improvements and some technologies, such as direct recycling, are currently only applicable on a small scale.

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SUPPORTING INFORMATION

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1 (word file): This supporting information provides the definition of SDGs according to the United Nations, a detailed description of how the SDGs are positively or negatively affected along the cobalt supply chain for lithium-ion batteries, the initial indicators considered to assess the socio-environmental risks, tables containing the risk levels for each country considered in the study, explanation on how SDGs were selected per risk indicator, consulted data sources and literature, and additional information.

Supporting Information S2 (csv file): This supporting information provides the risk values identified for each of the indicators and countries as well as the data sources used.

Tables

Table 1: *Risk levels and scores (1 to 4) applied to the selected indicators according to their range of values (Mancini et al. 2020)*

		Governance	Conflicts		Human and social rights			Environment	
Assigned score	**Risk level**	Worldwide Governance Indicator	INFORM Human Hazard	Fragile States Index	Child labor[1]	Fair salary[2]	Forced labor[3]	Environmental Performance Index	Water Risk Index
1	Low risk	1.25 to 2.5	0 to 2.49	< 30	0 to 4.9	≥ 2	0.3 to 2.2	75 to 100	0 to 2
2	Medium risk	0 to 1.24	2.50 to 4.99	30 to 60	5 to 9.9	1.5 to 1.99	2.3 to 4.1	50 to 74	2 to 3
3	High risk	-1.24 to 0	5 to 6.99	61 to 90	10 to 19.9	1 to 1.49	4.2 to 6.9	25 to 49	3 to 4
4	Very high risk	-1.25 to -2.50	7 to 10	> 90	> 20	0 to 0.99	7.0 to 104.6	0 to 24	4 to 5

[1]Percentage of all children aged 7–14.
[2]Ratio between sector average wage (USD/month) and the living average wage (USD/month).
[3]Prevalence (victims per 1000 inhabitants).

Table 2: *Identified Sustainable Development Goals (SDG) affected by cobalt supply chain stage (no specified scenario) and the respective number of positive contributions and negative impacts or risks identified considering artisanal and small-scale mining (ASM) and large-scale mining (LSM). A detailed description of the handprint and footprint identified per supply chain stage and SDG is available in the Supporting Information (Sections 1.1 to 1.4)*

Supply chain stage	SDG	Positive contribution(s) - handprint	Negative impact(s) / risk(s) - footprint
Mining of cobalt	1 NO POVERTY	1. Employment and increasing population income	1. “Resource course”, leading to poverty and (potential) land competition 2. Displacement of the local population (e.g. indigenous), who may experience poverty and land competition
	3 GOOD HEALTH AND WELL-BEING	1. The cobalt in batteries contributes to lower noise pollution as electric vehicles have reduced noise 2. The cobalt in batteries contributes to improvements in health conditions of the local population as a result of lower emissions of particulate matter (PM), nitrogen oxides (NOx), volatile organic compounds (VOCs), NH_3 and SO_2, also leading to lower mortality rates due to respiratory and cardiovascular issues	1. Particulate matter formation 2. Toxic and potentially carcinogenic exposure 3. Improper working conditions
	4 QUALITY EDUCATION	Not identified	1. Child labor results in low quality (or absence of) education for the children who are forced to work
	5 GENDER EQUALITY	Not identified	1. Gender unbalance for work rights in favor of men 2. Social vulnerability and sexual abuse of women
	6 CLEAN WATER AND SANITATION	1. Lower acidification with ASM than LSM 2. Surface water quantity and quality (potentially) increased as a result of groundwater dewatering (to allow machinery operation)	1. Potential water acidification as a result of future depletion of surface minerals and mining of sulfide ores 2. Contamination of water bodies due to metals in particulate matter (lower water quality) 3. Groundwater levels need to be reduced for LSM 4. Lack of sanitation and hygiene in some mining areas

7 AFFORDABLE AND CLEAN ENERGY	1. Beneficiation less energy-intensive in LSM compared to ASM 2. Mining industries can share their energy infrastructure with the local community 3. Mining of cobalt is (currently) essential for low-carbon and renewable energy	1. Onsite operations and transport of cobalt is highly energy-intensive, with a big share being coal-based, a non-renewable energy source (thermal efficiency up to 50%) 2. Although needed for the energy transition, cobalt production is reported to use fossil-based energy (coal) 3. The decrease in ore grade results in higher energy demand to produce the same amount of cobalt, resulting in additional use of coal-based energy (inefficient and fossil-based)
8 DECENT WORK AND ECONOMIC GROWTH	1. Increased population income and business opportunities	1. Improper work conditions - child labor (e.g. DRC) 2. Improper work conditions - forced labor or modern slavery (e.g. DRC)
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	1. Development of infrastructure (e.g. roads, power and water networks) 2. New technologies such as sea mining could reduce the pressure from mining	1. Potential adverse environmental impacts in new mining technologies (e.g. sea mining)
11 SUSTAINABLE CITIES AND COMMUNITIES	1. The cobalt in batteries contributes to improved air quality as a result of more electric vehicles and fewer emissions 2. The cobalt in batteries contributes to sustainable transport with (potential) expansion of electric mobility to public transport	Not identified
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Not identified	1. Decrease in recovery rate of cobalt compared to mined ore
13 CLIMATE ACTION	1. The cobalt in batteries contributes to low-carbon energy and climate action once the battery is ready for use	1. Emissions of GHGs from fuel and electricity 2. GHGs emissions at the ore leaching stage 3. Shift towards cobalt sulfide ores and more GHGs due to pyrometallurgical processes

	14 LIFE BELOW WATER	Not identified	1. Impact on biodiversity as a result of water pollution and (potential) water scarcity resulting from mining activities
	15 LIFE ON LAND	Not identified	1. Improper water for animals (e.g. in the Katanga region) 2. Improper water for farming (e.g. in the Katanga region) 3. Concessions for mining in natural reserve areas 4. Reduction of carbon capture capacity and biomass provision in the area
	16 PEACE, JUSTICE AND STRONG INSTITUTIONS	1. Opposite from gold mining, cobalt mining is not linked to the funding of conflicts	1. Fraud, corruption and bribery in the mining sector 2. Conflicts between ASM and LSM 3. China ownership in the DRC may threaten the western cobalt market
Refining of material	1 NO POVERTY	1. Employment and increasing population income	Not identified
	3 GOOD HEALTH AND WELL-BEING	1. The refined material in batteries contributes to lower noise pollution as electric vehicles have reduced noise 2. The refined material in batteries contributes to improvements in health conditions of the local population as a result of lower emissions of particulate matter (PM), nitrogen oxides (NOx), volatile organic compounds (VOCs), NH_3 and SO_2, also leading to lower mortality rates due to respiratory and cardiovascular issues	1. Chronic inhalation of cobalt sulfate may cause cancer 2. Potential radiation exposure to uranium 3. Lack of protective equipment in some countries

4 QUALITY EDUCATION	Not identified	1. Child labor results in low quality (or absence of) education for the children who are forced to work
6 CLEAN WATER AND SANITATION	Not identified	1. Improper treatment of wastewater with toxic compounds may lead to water pollution
7 AFFORDABLE AND CLEAN ENERGY	1. Refining of cobalt is (currently) essential for low-carbon and renewable energy	1. Crystallization process to produce cobalt sulfate is highly energy-intensive, in some cases with most energy being fossil-based (e.g. coal in China)
8 DECENT WORK AND ECONOMIC GROWTH	1. Creation of jobs	1. Improper work conditions - child labor (e.g. China)
11 SUSTAINABLE CITIES AND COMMUNITIES	1. The refined material in batteries contributes to improved air quality as a result of more electric vehicles and fewer emissions 2. The refined material in batteries contributes to sustainable transport with (potential) expansion of electric mobility to public transport	Not identified
13 CLIMATE ACTION	1. The refined material in batteries contributes to low-carbon energy and climate action once the battery is ready for use	1. Emissions of GHGs from fuel, steam and kerosene required in the refining
14 LIFE BELOW WATER	Not identified	1. Potential impact on biodiversity as a result of improper wastewater treatment and water pollution (e.g. toxic compounds)
15 LIFE ON LAND	Not identified	1. Potential improper water quality for animals if wastewater is not properly treated 2. Potential improper water quality for farming if wastewater is not properly treated

	16 PEACE, JUSTICE AND STRONG INSTITUTIONS	1. Development and strengthening of Chinese institutions through cobalt refining	1. Conflicts related to waste disposal in refineries in China 2. Risk of supply disruption of refined cobalt as China holds 80% of the market 3. Potential risks regarding governance (e.g. China) 4. Potential risks regarding fragile state (e.g. China)
Cathode material production	1 NO POVERTY	1. Employment and increasing population income	1. Unfair salary conditions in some countries (e.g. Poland)
	3 GOOD HEALTH AND WELL-BEING	1. Improved hygiene and protection measures reduced overall airborne workplace levels of cobalt 2. The cathode in batteries contributes to lower noise pollution as electric vehicles have reduced noise 3. The cathode in batteries contributes to improvements in health conditions of the local population as a result of lower emissions of particulate matter (PM), nitrogen oxides (NOx), volatile organic compounds (VOCs), NH_3 and SO_2, also leading to lower mortality rates due to respiratory and cardiovascular issues	1. High levels of airborne occupational cobalt and dust exposure
	4 QUALITY EDUCATION	Not identified	1. Child labor results in low quality (or absence of) education for the children who are forced to work
	6 CLEAN WATER AND SANITATION	Not identified	1. Potential water contamination with toxic compounds if wastewater is not properly treated
	7 AFFORDABLE AND CLEAN ENERGY	1. Cathode production is (currently) essential for low-carbon and renewable energy	1. High energy demand for the Kiln process (650-950°C), with most energy being fossil-based (e.g. coal in China and Poland)

8 DECENT WORK AND ECONOMIC GROWTH	1. Higher employment levels as a result of the increase in demand for batteries	1. Improper work conditions - child labor (e.g. China, Poland) 2. Improper work conditions - forced labor (e.g. China, Poland)
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	1. Advances in technology to reduce cobalt content in batteries (NMC 811)	1. Increased environmental impacts as a result of increased nickel content (NMC 811)
11 SUSTAINABLE CITIES AND COMMUNITIES	1. The cathode in batteries contributes to improved air quality as a result of more electric vehicles and fewer emissions 2. The cathode in batteries contributes to sustainable transport with (potential) expansion of electric mobility to public transport	Not identified
13 CLIMATE ACTION	1. The cathode in batteries contributes to low-carbon energy and climate action once the battery is ready for use	1. High energy demand to produce active material
14 LIFE BELOW WATER	Not identified	1. Potential impact on biodiversity as a result of improper wastewater treatment and water pollution (e.g. toxic compounds)
15 LIFE ON LAND	Not identified	1. Potential improper water quality for animals if wastewater is not properly treated 2. Potential improper water quality for farming if wastewater is not properly treated
16 PEACE, JUSTICE AND STRONG INSTITUTIONS	Not identified	1. Potential risks regarding governance (e.g. China and Poland) 2. Potential risks regarding fragile state (e.g. China and Poland) 3. Potential risks regarding human hazard (e.g. China)

Battery cell and battery pack production	1 NO POVERTY	1. Employment and increasing population income	Not identified
	3 GOOD HEALTH AND WELL-BEING	1. The battery in electric vehicles (EVs) contributes to lower noise pollution as EVs have reduced noise 2. The battery in EVs contributes to improvements in health conditions of the local population as a result of lower emissions of particulate matter (PM), nitrogen oxides (NOx), volatile organic compounds (VOCs), NH_3 and SO_2, also leading to lower mortality rates due to respiratory and cardiovascular issues	1. Aggravated asthma, decreased lung function, increased respiratory symptoms, nonfatal heart attacks, and irregular heartbeat due to particulate matter emission
	4 QUALITY EDUCATION	Not identified	1. Child labor results in low quality (or absence of) education for the children who are forced to work
	6 CLEAN WATER AND SANITATION	Not identified	1. High water consumption for battery manufacturing 2. Need for proper wastewater treatment to avoid water pollution
	7 AFFORDABLE AND CLEAN ENERGY	1. Contribution to low-carbon and renewable energy once the battery is ready for use	1. High demand for electricity, with fossil-based energy generation (e.g. coal in China and oil in Germany) 2. High demand for steam, with fossil-based energy generation (e.g. coal in China and oil in Germany)
	8 DECENT WORK AND ECONOMIC GROWTH	1. Higher employment levels as a result of the increase in demand for batteries	1. Improper work conditions - child labor (e.g. China) 2. Improper work conditions - forced labor (e.g. China)
	11 SUSTAINABLE CITIES AND COMMUNITIES	1. The battery in electric vehicles contributes to improved air quality as a result of more electric vehicles and fewer emissions	Not identified

	2. The battery in electric vehicles contributes to sustainable transport with (potential) expansion of electric mobility to public transport	
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	1. Eco-design of batteries under development to improve reuse and recycling of components	Not identified
13 CLIMATE ACTION	1. The battery in electric vehicles contributes to low-carbon energy and climate action once the battery is ready for use	1. Impacts on global warming potential from electricity requirements
14 LIFE BELOW WATER	Not identified	1. Potential impact on biodiversity as a result of water pollution and water scarcity resulting from battery production
15 LIFE ON LAND	Not identified	1. Potential improper water quality for animals if wastewater is not properly treated 2. Potential improper water quality for farming if wastewater is not properly treated 3. Potential water scarcity for animals and farming due to high water consumption for battery manufacturing
16 PEACE, JUSTICE AND STRONG INSTITUTIONS	Not identified	1. Conflict reported in China, as the local population is against the installation of a battery plant 2. Potential risks regarding governance (e.g. China) 3. Potential risks regarding fragile state (e.g. China) 4. Potential risks regarding human hazards (e.g. China)

Table 3: *Distribution of the risk levels assessed for the Global and European scenarios, considering the eight indicators and the four stages of the supply chain of cobalt for lithium-ion batteries*

Scenario	Score 1 (low risk)	Score 2 (medium risk)	Score 3 (high risk)	Score 4 (very high risk)	Total risk levels assessed along the supply chain
Global	4	8	15	5	32
European	17	8	2	5	32

Figure Legends

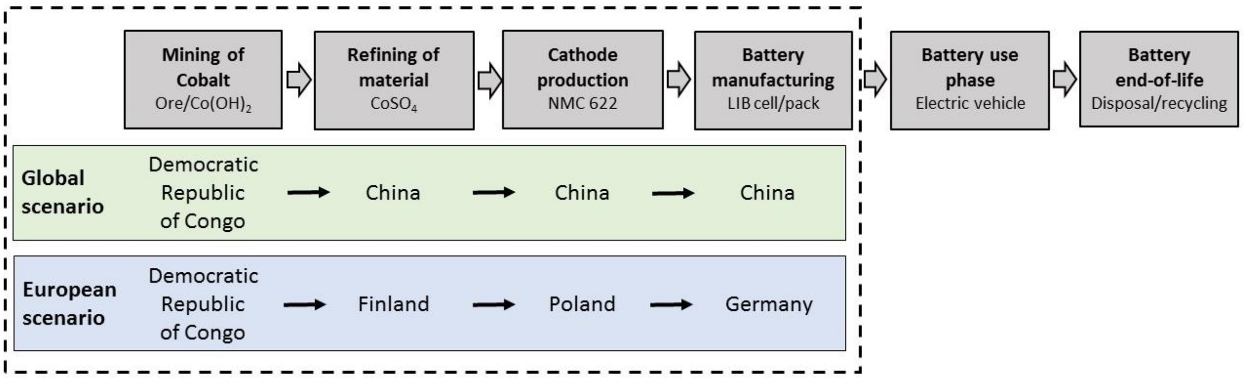

Figure 1: *Cobalt value chain for lithium-ion battery (LIB) applied to mobility. The considered LIB has a nickel-manganese-cobalt 6:2:2 (NMC 622) cathode composition. The grey rectangles represent the stages of cobalt processing and use, whereas the dashed lines represent the boundaries of this study. This assessment focuses on the cobalt supply in a Global scenario (in green) and a hypothetical European scenario (in blue) with their respective most representative countries. Although the Democratic Republic of Congo is not a European country, it supplies about 68% of the metal used in Europe (European Commission 2020e)*

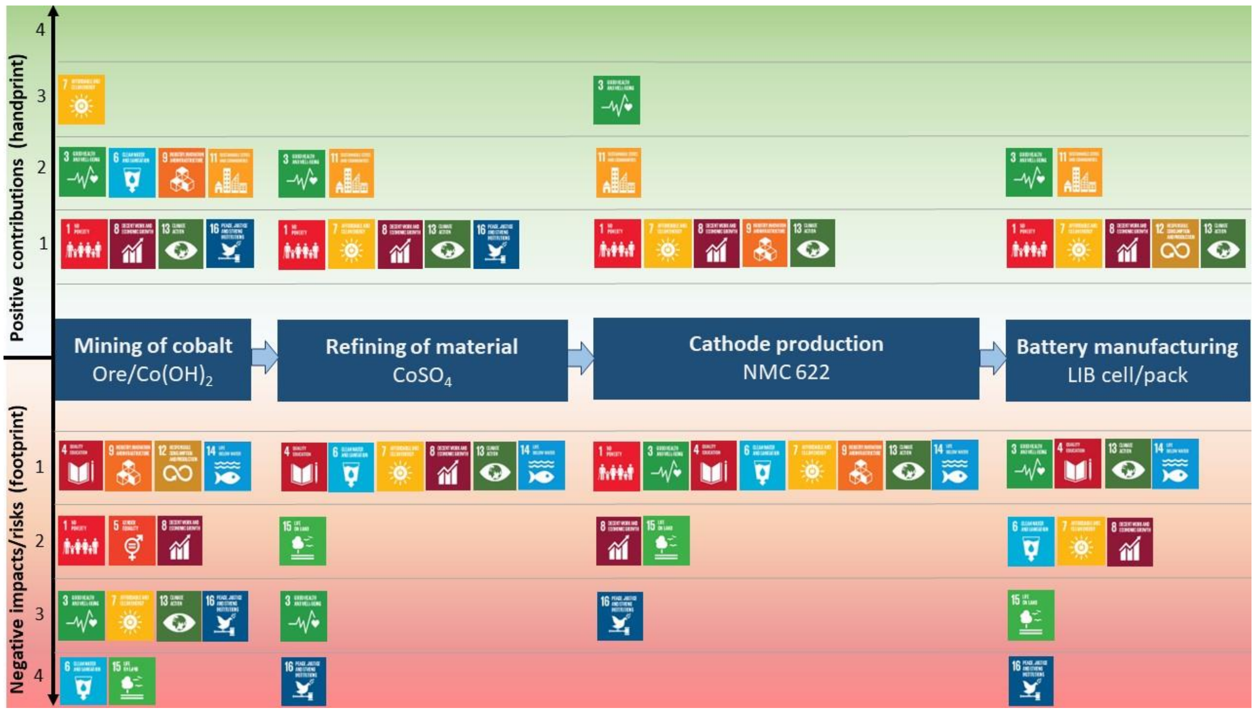

Figure 2: *Mapping of positive contributions and negative impacts or risks to the Sustainable Development Goals (SDGs) identified along the cobalt supply chain for lithium-ion batteries (LIB) with nickel-manganese-cobalt cathode (NMC 622). The SDGs above the supply chain stages (green area) are considered to receive positive contributions whereas the ones below the supply chain stages (red area) are considered to suffer from adverse impacts or risks. The numbers indicated on the vertical axis correspond to the number of positive/negative correlations, as listed in Table 2. The further the SDG is from the supply chain level, the more positive/negative correlations have been identified. The complete list of SDGs can be found in Figure S1 in the Supporting Information*

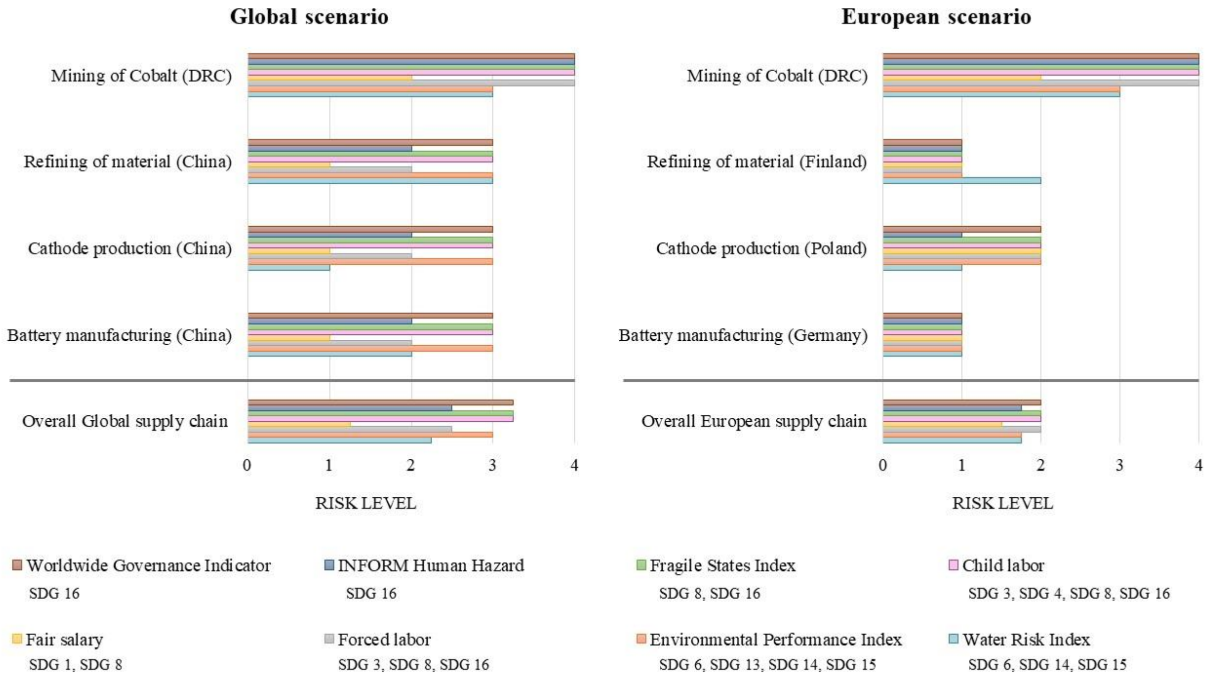

Figure 3: *Risk levels in the Global and European scenarios of the cobalt supply chain for lithium-ion batteries. The risk levels were identified for each of the eight considered indicators with scores ranging from 1 (low) to 4 (very high), risk levels listed in Table 1. For the overall supply chain (below the horizontal grey line), an average of the scores per stage was calculated. The average values are associated with low risk (1.0 - 1.6), medium risk (1.7 - 2.4), high risk (2.5 - 3.2), or very high risk (3.3 - 4.0). Under each indicator, the most representative Sustainable Development Goals (SDGs) are indicated. "DRC" stands for the Democratic Republic of Congo. The risk values can be found in Table S2 of the Supporting Information*