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Quantifying the life-cycle health impacts of a cobalt-containing lithium-ion battery

Rickard Arvidsson¹ · Mudit Chordia¹ · Anders Nordelöf¹

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Abstract

Purpose Lithium-ion batteries (LIBs) have been criticized for contributing to negative social impacts along their life cycles, especially child labor and harsh working conditions during cobalt extraction. This study focuses on human health impacts — arguably the most fundamental of all social impacts. The aim is to quantify the potential life-cycle health impacts of an LIB cell of the type nickel-manganese-cobalt (NMC 811) in terms of disability-adjusted life years (DALY), as well as to identify hotspots and ways to reduce the health impacts.

Methods A cradle-to-gate attributional life-cycle assessment study is conducted with the functional unit of one LIB cell and human health as the sole endpoint considered. The studied LIB is produced in a large-scale “gigafactory” in Sweden, the cobalt sulfate for the cathode is produced in China, and the cobalt raw material is sourced from the Democratic Republic of the Congo (DRC). Potential health impacts from both emissions and occupational accidents are quantified in terms of DALY, making this an impact pathway (or type II) study with regard to social impact assessment. Two scenarios for fatality rates in the artisanal cobalt mining in the DRC are considered: a high scenario at 2000 fatalities/year and a low scenario at 65 fatalities/year.

Results Applying the high fatality rate, occupational accidents in the artisanal cobalt mining in the DRC contribute notably to the total life-cycle health impacts of the LIB cell (13%). However, emissions from production of nickel sulfate (used in the cathode) and of copper foil (the anode current collector) contribute even more (30% and 20%, respectively). These contributions are sensitive to the selected time horizon of the life-cycle assessment, with longer or shorter time horizons leading to considerably increased or decreased health impacts, respectively.

Conclusions In order to reduce the health impacts of the studied LIB, it is recommended to (i) investigate the feasibility of replacing the copper foil with another material able to provide anode current collector functionality, (ii) reduce emissions from metal extraction (particularly nickel and copper), (iii) increase the recycled content of metals supplied to the LIB manufacturing, and (iv) improve the occupational standards in artisanal mining in the DRC, in particular by reducing fatal accidents.

Keywords Life cycle assessment · Disability-adjusted life years · Occupational accidents · Cobalt mining · Nickel-manganese-cobalt (NMC) · Human health · Social risks

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1 Introduction

Like diamonds of certain origins, cobalt mined from the Democratic Republic of the Congo (DRC) has been associated with the noun “blood” in news media (Kennedy 2017; Lindberg and Andersson 2019). The DRC currently provides around 70% of the global cobalt supply, partly through artisanal mining, which provides livelihood for almost 200,000 people (BGR 2019; OECD 2019). Although not counted among of the traditional 3TG conflict minerals (i.e., tantalum, tin, tungsten, and

gold), cobalt mined in the DRC has been associated with numerous health and social impacts, including high exposure to cobalt and other toxicants from mining (including dust), occupational accidents, long working hours, child labor, corruption, and displacement of indigenous people (Banza et al. 2009; Elenge et al. 2011; Elenge and De Brouwer 2011; Tsurukawa et al. 2011; Amnesty International 2013; Elenge 2013; Amnesty International and Afrewatch 2016; Faber et al. 2017; Banza Lubaba Nkulu et al. 2018; BGR 2019; Lindberg and Andersson 2019; Sovacool 2019; Bamana et al. 2021). These impacts are particularly prevalent in artisanal, small-scale cobalt mining, which currently accounts for approximately 20% of the cobalt extracted in the DRC (Al Barazi et al. 2017), while the industrial, more mechanized extraction generally has a considerably lower occurrence of, e.g., child labor. At the same time, positive social externalities of artisanal mining have also been reported, including reduced poverty, increased state revenue, increased services, and collective occupational identity (Tsurukawa et al. 2011; de Haan and Geenen 2016; Sovacool 2019). For example, while many Congolese struggle to earn 1 US\$/day, artisanal miners generally earn more than 3 US\$/day (Tsurukawa et al. 2011; de Haan and Geenen 2016). There are also some social impacts occurring in other low-income countries which are seemingly absent in artisanal cobalt mining in the DRC, an example being forced labor (Tsurukawa et al. 2011; OECD 2019). This means that despite harsh conditions, the work is not undertaken without consent or under the threat of a penalty, such as violence or retention of identity papers (International Labour Office 2016).

The current main use of cobalt is in lithium-ion batteries (LIBs), which have become the dominant technology for rechargeable energy storage (OECD 2019). Commercialized by Sony Co. and others in the early 1990s, LIBs have enabled many products of high significance in contemporary societies, such as mobile phones, laptops, and electric vehicles (Li et al. 2018). Different LIB chemistries exist in the market today based on the type of application, such as lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA), lithium cobalt oxide (LCO), lithium iron phosphate (LFP), and lithium manganese oxide (LMO), of which the NMC, NCA, and LCO chemistries contain cobalt in varying proportions (Porzio and Scown 2021). Most of the currently used LIBs in electric vehicles are NMC 111 (sometimes called NMC 333), NMC 532, or NMC 622, where the numbers represent the relative shares of nickel, manganese, and cobalt in the cathode, respectively (Harper et al. 2019). However, there is a strive towards further reducing the cobalt content of NMC batteries, as in the more recently developed NMC 811 cathode material (Fan et al. 2020).

This study focuses on the contribution of LIBs to human health impacts — arguably the most fundamental of all social impacts. The question that the study aims to answer is as follows: How large are the potential negative health impacts from an LIB along its life cycle, which are the hotspots and how can the health impacts be reduced? In particular, the study seeks to investigate the relative contribution to potential health impacts from cobalt in a modern low-cobalt LIB. To answer this question, an LCA of an LIB of the type NMC 811 is performed from cradle to gate, with human health as the endpoint. Specifically, potential health impacts from emissions and occupational accidents are assessed using the quantitative disability-adjusted life years (DALY) indicator. Since there is a causal link from the release of emissions and accidents to DALY, this study applies a so-called impact pathway approach (Benoît Norris et al. 2020) to social impact assessment. The authors are not aware of any previous quantitative assessments of potential health impacts for LIBs, although there exist a few qualitative health assessments of LIBs and/or cobalt where a so-called reference scale approach (Benoît Norris et al. 2020) to social impact assessment is applied. Mancini et al. (2021) assessed “occupational health and safety” impacts of artisanal mining of cobalt together with 13 other social impacts, using a five-point ordinal scale going from “no noted risks” to “systematic and grave abuse.” The latter category was assigned to the occupational health and safety of artisanal cobalt mining. Thies et al. (2019) also assessed a range of social impacts of an LIB pack (NMC type), including “risks of occupational toxics and hazards,” using the ordinal-scale system from the Social Hotspots Database, which is a widely used database in social LCA. That scale contains “no risk” (which translates to 0.0), “low risk” (0.1), “medium risk” (1), “high risk” (5), and “very high risk” (10). They concluded that Chinese production of the LIBs yielded higher risks of occupational toxics and hazards than German production, even if the raw materials (including cobalt) were sourced responsibly. Similarly, Sharma and Manthiram (2020) conducted a qualitative social assessment of an NMC 811 and an LFP battery based on publications from human rights organizations, newspapers, academics, and community members. They concluded that producing the cobalt required for 26 million electric vehicles by 2030 would result in 25,000 children needing to work by hand for 10 h per day in the DRC, as well as to toxic pollution of the local community from cobalt mining. Consequently, they recommend that the use of cobalt in LIBs must be eliminated entirely.

2 Method and materials

In order to assess the magnitude of the potential health impacts of an LIB cell containing cobalt, as well as the relative contribution of cobalt, a process-based or

attributional LCA was conducted (Yang 2019), with a cradle to gate scope (Fig. 1). The system boundary largely follows that of Chordia et al. (2021), who studied the environmental impacts of the same battery, with the notable exception of the cobalt sulfate production, as described in Sect. 2.4. The functional unit of that study was 1 kWh of theoretical energy storage capacity for a 21,700-type cylindrical LIB cell of the NMC 811 chemistry after the formation step, with the composition described in Table 1. The cell is intended for automobile applications, weighing 68 g and having a specific energy density value within the range of 210–240 Wh/kg (Chordia et al. 2021). In this study, the functional unit of one such battery cell is chosen as it is a more tangible functional unit for interpretation. However, it can be translated into kWh of energy storage approximately, for comparisons with other battery cells, by applying a factor of 65 cells/kWh.

The applied impact pathway (or type II) method for assessing potential health impacts in the context of social LCA was first conceptualized by Baumann et al. (2013) and then formalized by Arvidsson et al. (2018). It entails a quantification and relative comparison of health impacts along product life cycles, as well as a quantification of the potential net health impact of products:

Table 1 Approximate composition of the functional unit of the study — one cylindrical NMC 811 battery cell weighting about 68 g (Chordia et al. 2021)

Cell component	Share of weight
Positive current collector and tab (aluminum)	3%
Active cathode material (nickel, cobalt, and manganese)	37%
Negative current collector and tab (copper)	7%
Active anode material (synthetic graphite)	23%
Electrolyte (lithium hexafluorophosphate and organics)	10%
Separator (polyethylene)	2%
Cylindrical container (nickel-plated steel)	12%
Lid (nickel-plated steel)	3%
Fastening tape (polyethylene)	1%
Insulation ring (polyethylene)	2%

$$DALY_{net} = \sum_{positive} DALY + \sum_{negative} DALY \quad (1)$$

DALY stands for disability-adjusted life years (unit: years). Since DALY is a measure of years lost due to death

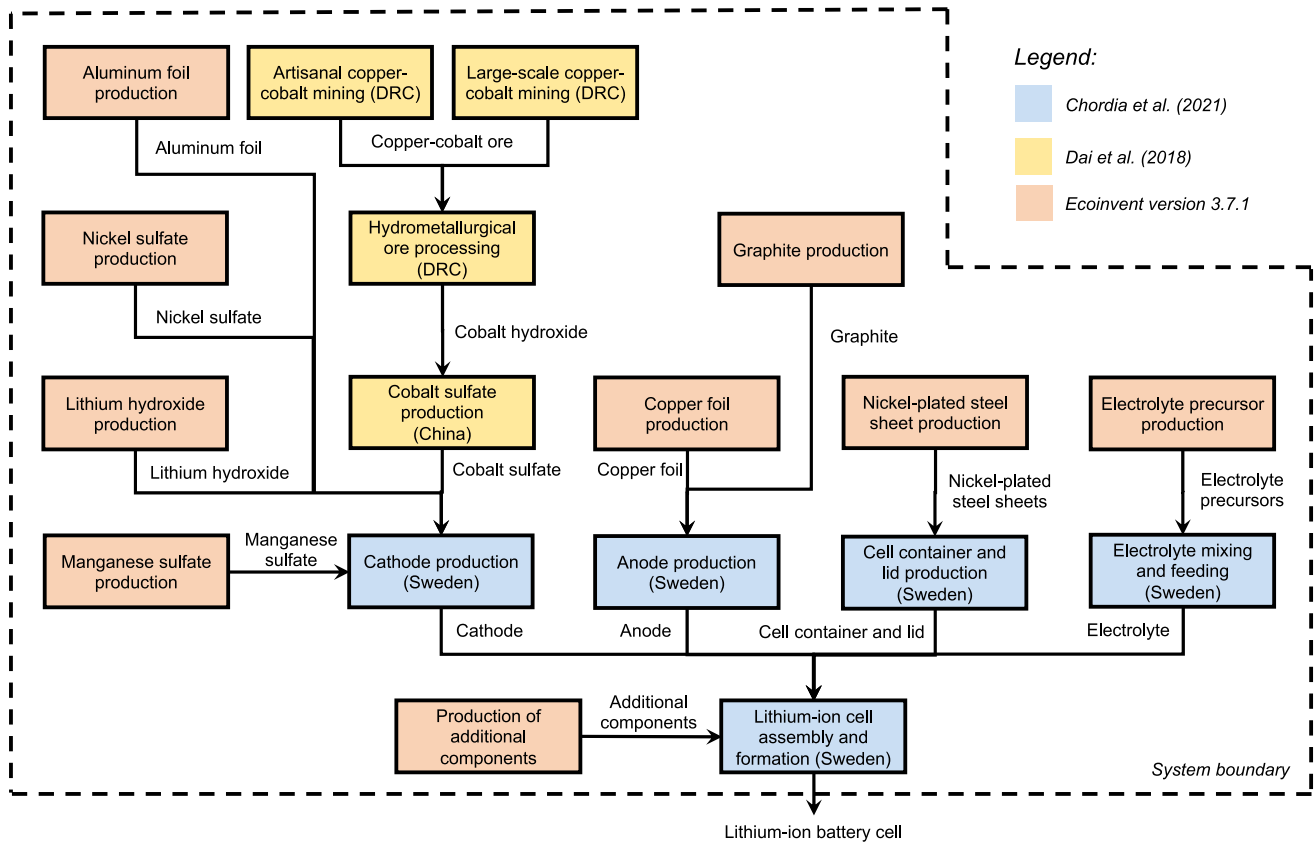


Fig. 1 Flow chart describing the main processes of the cradle-to-gate product system studied and main inventory data sources. The system boundary is shown as a dashed line. The cobalt sulfate supply chain is shown in higher resolution

or disability, DALY values with a positive sign imply a negative impact on human life and health, whereas negative DALY values imply a positive impact. Many different potential health impacts can occur along product life cycles and the analyst must *a priori* select those believed to be of significance for quantification. In the case of LIBs, based on existing reports of health impacts (Sect. 1), contributions from (i) emissions and (ii) occupational accidents are considered:

$$DALY_{net} = DALY_{emissions} + DALY_{accidents} \quad (2)$$

The quantification of potential health impacts from emissions ($DALY_{emissions}$) and occupational accidents ($DALY_{accidents}$) are described in Sects. 2.1 and 2.2, respectively. No positive potential health impacts are considered in this assessment, but some potentially positive contributions are discussed in Sect. 3.4. Health impacts from conflicts have been included in some previous studies of cobalt and gold from the DRC (Arvidsson et al. 2018; Furberg et al. 2018). However, the Katanga region of the DRC, where most cobalt is mined, has recently been reported to be the most stable part of the entire country, since the mineral wealth has created a middle class and provided political stability (Sovacool 2019). While the presence of valuable minerals in poor countries can spur conflict, this does not seem to be the case in the Katanga region. Reports suggest that the two Katangese provinces Haut-Katanga and Luabala “are not considered conflict zones” (OECD 2019), and that “cobalt has, opposite to gold, tin and coltan [a tantalum-containing mineral], not yet started any war in the DRC” (Lindberg and Andersson 2019). Therefore, health impacts from conflict are not included in this study.

The product system was modeled using OpenLCA (version 1.10.3) with most inventory data coming from the Ecoinvent database, version 3.7.1 with cutoff allocation of recycled materials (Wernet et al. 2016). However, two processes were modeled using other sources: (i) lithium-ion cell production and (ii) battery-grade cobalt sulfate production (Fig. 1). The modeling of these processes is described in more detail in Sects. 2.3 and 2.4, respectively.

2.1 Emission health impacts

Like previous studies on health impacts of products (Arvidsson et al. 2018; Furberg et al. 2018; Debaveye et al. 2020), this study relies on the impact assessment method ReCiPe (Huijbregts et al. 2017). ReCiPe considers health impacts related to the following emission-related midpoint impact categories: particulate matter, tropospheric ozone formation, ionizing radiation, stratospheric ozone depletion, human toxicity, and global warming (Huijbregts et al. 2017). In addition, ReCiPe also considers health impacts from water scarcity, which is included here as

well. These potential health impacts from emissions and water use affect the general population. Potential health impacts of emissions ($DALY_{emissions}$) are quantified according to:

$$DALY_{emissions} = \sum_{i,m} Q_{i,m} \times CF_{i,m} \times CF_{m,e} \quad (3)$$

where $Q_{i,m}$ is a quantity of elementary flow i contributing to the midpoint impact category m , $CF_{i,m}$ is a characterization factor describing the contribution of i to m , and $CF_{m,e}$ is an endpoint characterization factor describing the contribution of m to the endpoint impact category e . Only the endpoint human health is considered in this study. The endpoint characterization factors are derived based on how much the midpoint impact categories contribute to potential health impacts as described in the ReCiPe 2016 report (Huijbregts et al. 2016). For example, in the case of stratospheric ozone depletion, it is based on the increase of UV light and subsequent diseases caused by ozone depletion. A hierarchist value perspective is chosen as main perspective in this study, reflecting the current scientific consensus on time frames and impact mechanisms (Huijbregts et al. 2016), although the implications of choosing other value perspectives (individualist or egalitarian) are also discussed. The emission and water use data for $Q_{i,m}$ come from Chordia et al. (2021), Dai et al. (2018), and the Ecoinvent database as shown in Fig. 1.

2.2 Occupational accidents

Potential health impacts from occupational accidents ($DALY_{accidents}$) were quantified using the approach by Scanlon et al. (2015), where work environment characterization factors (CF_{WE}) for industry sectors j are calculated according to:

$$CF_{WE,j} = \frac{DALY_j}{Q_j} \quad (4)$$

where $DALY_j$ is the total number of years lost due to injuries or premature death in industry sector j , and Q_j is the total output of the same sector. Such outputs can be in terms of units (e.g., number of cars), mass (e.g., kg of steel), energy (e.g., MJ of electricity), or some other measure reflecting the industry sector’s output. The accidents included are based on reported occupational accident data from industries in the USA, and include both fatal and non-fatal accidents, such as bruises, wounds, and traumatic injuries. The industry sectors are often more aggregated than the typical unit process in an LCA, for example aggregating many types of metal mining into the category “All other metal ore mining.” Scanlon et al. (2015) provide 127 CF_{WE} , often in the orders of 10^{-7} to 10^{-10} year/kg for sectors where the output is quantified in terms of mass, which is the most common case. Such occupational health impacts affect workers along the life cycle.

The CF_{WE} provided by Scanlon et al. (2015) were deemed acceptable proxies for occupational accidents in the whole product system, except for one process: artisanal cobalt mining. Here, a specific CF_{WE} for artisanal cobalt mining in the DRC was instead calculated using Eq. (4), updating the value previously calculated by Furberg et al. (2018). The amount of cobalt extracted in artisanal mining in the DRC (Q_j in Eq. 4) was calculated using the reported cobalt production and artisanal share in the DRC, averaged over the years 2009–2015 (Al Barazi et al. 2017), resulting in about 26,000 ton/year. The DALY in Eq. (4) was calculated as the sum of the years of life disabled (YLD) and years of life lost (YLL):

$$DALY = YLD + YLL \quad (5)$$

The YLD is, in turn, calculated as:

$$YLD = I \times DW \times L \quad (6)$$

where I is the number of incidents, DW is a disability weight, and L is the duration of the disability. The number of incidents was estimated assuming 175,000 artisanal cobalt miners in the DRC, which is an average of ranges reported (BGR 2019; OECD 2019). The frequency of occupational accidents in artisanal cobalt mining in the Katanga region was obtained from the study by Elenge et al. (2013), who reported the frequency of wounds as well as fractures on upper and lower limbs. These are common injuries in artisanal mining, frequently reported also in, e.g., artisanal gold mining in Ghana (Kyeremateng-Amoah and Clarke 2015). The frequency of wounds is paired with DW and L values for open wounds provided by Haagsma et al. (2016). The frequency of fractures on upper and lower limbs are paired with average values of DW and L for different fractures: humerus, hand, radius, and ulna bones for upper limbs, as well as foot, femur, patella, tibia, fibula, and ankle bones for lower limbs (Haagsma et al. 2016). The resulting YLD obtained was about 370 years, or $1.4 \cdot 10^{-5}$ year/kg cobalt.

The YLL is calculated as:

$$YLL = N \times (LEX - L) \quad (7)$$

where N is the number of fatalities, LEX is the life expectancy at birth, and L is the age of death. The number of fatalities in artisanal cobalt mining the DRC has been estimated at up to 2000 per year based on a questionnaire administered in cobalt-producing provinces by Siddharath Kara (MacDonald and Pokharel 2020), who is a researcher and expert on modern slavery. A much lower estimate of 65 fatalities per year have been published by the World Bank (2020), based on cases reported in media. However, due to limited access and coverage by media on these matters, this value is presumed to be a clear underestimation. In fact, Kara claims to have personally witnessed the collapse of a

single mining tunnel in the DRC, alone leading to more than 60 deaths (MacDonald and Pokharel 2020). Given the workforce estimated above, a rate of 2000 fatalities means that almost 1% of the workforce die every year. Approximately 1% fatality rate per year was similarly reported for small-scale tin mining cooperatives in Bolivia (ILO 1999). The median age of artisanal cobalt miners in the DRC is 25 years (Elenge et al. 2013), and the life expectancy in the DRC is 61 years in 2021. The resulting YLL becomes 72,000 years, corresponding to $2.8 \cdot 10^{-3}$ year/kg cobalt. The lower estimate of fatal accidents in artisanal cobalt mining in the DRC of 65 per years gives a YLL at $1.0 \cdot 10^{-4}$ year/kg cobalt. Even though this lower estimate is considered unreasonably low, results based on this estimate are still presented in this study for comparison.

When adding the YLD and YLL (high estimate) per kg cobalt, the CF_{WE} for artisanal cobalt mining in the DRC can be obtained at $2.8 \cdot 10^{-3}$ year/kg cobalt. Given a 0.47% cobalt content of the extracted ore (Dai et al. 2018), this becomes $1.3 \cdot 10^{-5}$ year/kg copper-cobalt ore. This can be compared to the several orders of magnitude lower CF_{WE} for (industrial) copper ore and nickel ore mining in Scanlon et al. (2015) at $8.4 \cdot 10^{-9}$ year/kg.

Since the CF_{WE} are not implemented in the Ecoinvent database, they need to be added manually. Unfortunately, manually adding CF_{WE} to all linked upstream processes in the Ecoinvent database is not feasible. Thus, the CF_{WE} are added for all processes in the cobalt production system and the battery cell production, as well as for all direct inputs to these (which might also be present in other places upstream in the system). Table S1 in the Supporting Information (SI) lists all processes for which the CF_{WE} are implemented. Although this means that a number of upstream processes are not accounted for regarding their work environment impacts, this approach is judged to account for a significant share of the total work environment impacts since all major inputs to the studied system are included.

2.3 Lithium-ion cell production

The LIB cell production is modeled according to Chordia et al. (2021), since that study considers a presumably benign scenario regarding potential health impacts of cobalt-containing LIBs. First, they assess a cylindrical NMC 811 cell, which contains cobalt but in lower amounts than, e.g., the currently more common NMC 111 cell. Second, they model a large-scale “gigafactory,” which has lower impacts compared to smaller-scale cell production. Third, the location of the gigafactory in Sweden means an electricity mix based mainly on hydropower and nuclear, which leads to lower potential health impacts compared to more fossil-based electricity mixes. Using this context for the study,

which represents an estimate of potential health impacts from upcoming LIB cell production in northern Europe, the focus is intentionally set on the mineral extraction and cell precursor materials production life-cycle stages, in line with the overall aim of investigating the role of cobalt, rather than health impacts of the energy supply to later production steps.

The gigafactory model is based on data from environmental permit applications and technical reports published by the company Northvolt AB for a facility currently being put into operation in Northern Sweden, representing an annual production of 16 GWh of battery cell storage capacity (Chordia et al. 2021). The factory will produce both cylindrical and prismatic cells, but only cylindrical cells were considered by Chordia et al. (2021), as well as in this study. The model includes the complete cell production and assembly from input chemicals and materials, ending with the formation of the cells, which is the finishing process where the cells are charged and discharged a number of times. For this study, one significant change was made to the model: the battery-grade cobalt-sulfate supply was changed, as described in Sect. 2.4.

2.4 Battery-grade cobalt sulfate production

The Ecoinvent database contains a dataset for cobalt sulfate production provided by the cobalt development institute, which was applied in the study by Chordia et al. (2021). This dataset reportedly covers 30% of the global production of refined cobalt products in 2012 and includes cobalt ore mining in Canada, Cuba, the DRC, New Caledonia, and the Philippines (Environmental Resource Management 2016). However, this dataset does not distinguish cobalt extraction from its refining and is therefore considered too aggregated for this study with a focus on health impacts along the cobalt supply chain. In addition, the dataset does not include refined cobalt production in China, even though China is currently the largest producer of refined cobalt products. Consequently, less aggregated inventory data on battery-grade cobalt sulfate production from Dai et al. (2018) are used instead. They provide datasets for three main processes: (i) large-scale copper-cobalt ore mining in the DRC, (ii) crude cobalt hydroxide production in the DRC, and (iii) battery-grade cobalt sulfate in China. In addition, we added a fourth dataset for artisanal copper-cobalt ore mining. However, since this artisanal mining occurs without any modern mining equipment, using basic tools for digging and sometimes only hands (Sovacool 2019), the dataset does not have any inputs except for the cobalt, copper, and rock mined (Table S3). Together, these four processes cover the main route of cobalt sulfate production, since most (70%) of the cobalt is mined in the DRC (Table S2) and most (80%) refined cobalt products are produced in China after import from the DRC in the form of crude cobalt hydroxide

(OECD 2019; Sovacool 2019). A process for copper-cobalt ore production in the DRC is created, consisting of 20% artisanal ore input as reported by Al Barazi et al. (2017) and the remaining 80% ore input from industrial-scale extraction. For all upstream processes linked to material and energy inputs, datasets from the Ecoinvent database were used. Congolese or Chinese datasets were used if available, otherwise global or rest-of-the-world datasets were used. An exception to this is the sodium metabisulfite, as described below.

For the large-scale copper-cobalt ore mining in the DRC, the data in Dai et al. (2018) is based on the Tenke Fungurume Mine, where both oxide and sulfide ores are mined. The unit-process dataset was scaled from 1 ton copper-cobalt ore to 1 kg copper-cobalt ore. The diesel input reported is mainly for large mining vehicles like caterpillars according to the report and was therefore approximated using the Ecoinvent process “diesel, burned in agricultural machinery.” The water input was assumed to come from “natural unspecified origin,” since it is unknown if the water comes from, e.g., rivers or lakes. The ore reportedly contains 2.44% copper and 0.47% cobalt, while the rest of the ore was assumed to consist of inert rock. No losses during the mining are reported in the source. The resulting unit process for large-scale copper-cobalt ore mining in the DRC is shown in Table S4.

The production of crude cobalt hydroxide from the copper-cobalt ore occurs through hydrometallurgical ore processing, again modeled based on the operation at the Tenke Fungurume Mine in the DRC. However, the data in Dai et al. (2018) had to be reworked into a unit process dataset for the purpose of this study. The cobalt output is first calculated based on a 0.47% cobalt content in the ore and an 80% cobalt yield. The copper output was calculated in the same way. Economic allocation between copper and cobalt is then conducted based on 10-year average prices as described in Dai et al. (2018). Finally, the cobalt output is recalculated into a crude cobalt hydroxide output based on a 35% cobalt content and all flows are scaled to 1 kg crude cobalt hydroxide. Electricity is assumed to be medium voltage. The limestone input is assumed to be crushed when purchased. Transport of the crude cobalt hydroxide to China (about 16,000 km, 17% truck and 83% ocean tanker) is included in the dataset. While not reported in Dai et al. (2018), tailings are formed during refining of copper ores in the DRC (Adrianto et al. 2022). The difference in mass between the ore input and the crude cobalt hydroxide output is therefore assumed to become tailings. Both oxidic and sulfidic copper-cobalt ores are mined in the DRC (Dai et al. 2018; Shengo et al. 2020), but since the shares are unknown, 50% of oxidic and sulfidic tailings each are assumed. Treatment processes from the Ecoinvent database are applied for these tailings, with a global geographical scope for the oxidic tailings and a

dataset representing tailings treatment in the neighboring country of Zambia for the sulfidic tailings. The resulting unit process for the hydrometallurgical ore processing in the DRC is shown in Table S5.

The production of battery-grade cobalt sulfate is modeled specifically based on the Tongxiang plant run by Huayou Cobalt and the data are considered “conservative” estimates. The unit-process data provided by in Dai et al. (2018) are scaled from per ton cobalt equivalent to per kg battery-grade cobalt sulfate. The resulting unit process for the battery-grade cobalt sulfate in China is shown in Table S6. One of the inputs to the battery-grade cobalt sulfate production — sodium metabisulfite — does currently not have a dataset in the Ecoinvent database. Therefore, its production was approximated as an input of sodium hydroxide based on Dai et al. (2018), see Table S7.

3 Results and discussion

Figure 1a shows the potential health impacts of the assessed LIB cell divided into four contributions. The first two are accidents in artisanal cobalt mining in the DRC based on the two different fatality estimates used in the study — the higher estimate at 2000 fatalities/year and the more conservative media reporting of 65 fatalities/year. The third is the contribution from emissions and water use throughout the product system, as calculated using the ReCiPe impact assessment method. The fourth is accidents in other parts of the product system based on the accident data from Scanlon et al. (2015). A main observation is that emissions and water use constitute the highest contribution by approximately one order of magnitude. The second largest contribution is

from occupational accidents in artisanal cobalt mining in the DRC, when the high fatality estimate is used. The contribution from occupational accidents in other parts of the product system is notably lower — about 30 times lower than the high estimate for accidents in artisanal cobalt mining and about 200 times lower than the contribution from emission and water use. The low estimate of the accidents in artisanal cobalt mining in the DRC is about 30 times lower than the high estimate, making the contribution comparable to accidents in other parts of the product system.

Figure 2b shows a more detailed contribution analysis for the higher and presumably more relevant estimate of fatalities in artisanal cobalt mining in the DRC. It shows that these accidents contribute with about 13% of the potential health impacts of the LIB cell. Other accidents, i.e., meaning accidents in the product system other than the artisanal cobalt mining, contribute with < 1%. The majority of the contributions (87%) make up the various green bars, which represent emissions and water use in different parts of the product system. Here, there are four distinct inputs to the gigafactory for which the production contribute with > 5% of the potential health impacts: (i) production of the nickel sulfate used for making the nickel-containing cathode (30%), (ii) production of the copper foil used in the current collector of the anode (20%), (iii) production of the cell container and lid made from nickel-plated steel (8%), and (iv) production of the cobalt sulfate, which is also part of the cathode (6%). In addition, several smaller contributions, each contributing less than 5%, together amount to 23% of the potential health impacts. The vast majority of these contributions are from impacts occurring upstream of the gigafactory. Considering that the nickel sulfate and copper foil productions constitute the two main contributors — even in this case with the high

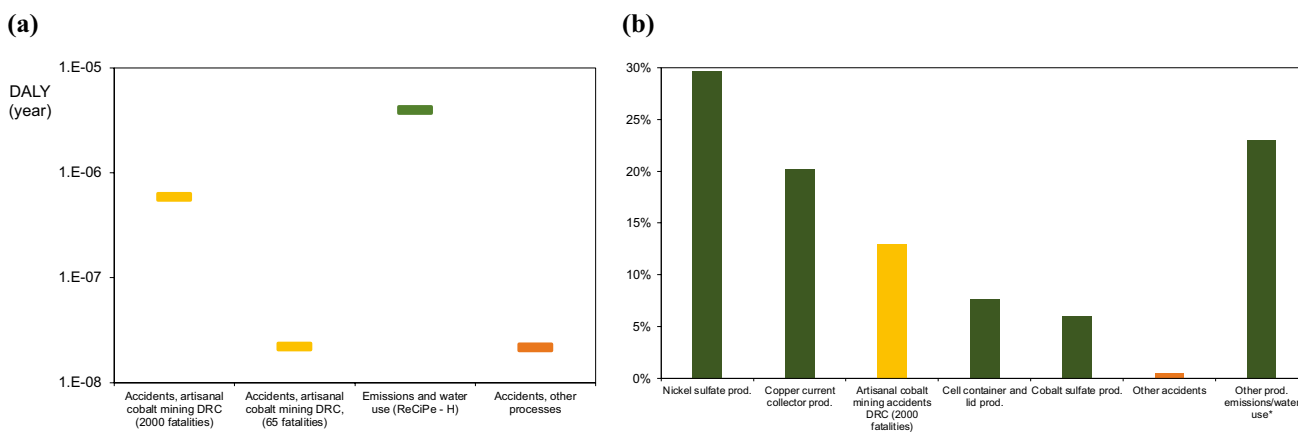


Fig. 2 Potential health impacts from the lithium-ion battery cell. **a** Contributions from the main types of health impacts are shown as absolute results on a logarithmic scale. **b** Relative contributions given the high estimate for fatalities in artisanal cobalt mining in the DRC. Green bars represent emission and water use impacts from ReCiPe,

the yellow bar represents accidents in artisanal cobalt mining in the DRC (high estimate), and the orange bar represents other occupational accidents. *The contributions to this category are all < 5% each and mostly upstream to the gigafactory

estimate of fatalities in artisanal cobalt mining in the DRC — these two input materials are analyzed in more detail in Sects. 3.1 and 3.2, respectively.

3.1 Nickel sulfate production

The inventory data for nickel sulfate production was taken from the Ecoinvent database, specifically the global dataset “market for nickel sulfate.” About 92% of the nickel sulfate in that process is produced jointly with cobalt during extraction of ores containing both the metals and the data originates from LCA work commissioned by the Cobalt Development Institute (Environmental Resource Management 2016). A final 8% is produced by reacting nickel (class 1) with sulfuric acid. The nickel supply to this Ecoinvent process comes mainly from cobalt–nickel ores, nickel–copper ores, and as a byproduct from platinum group metal mining and refining. The two midpoint impact categories that contribute the most to the potential health impacts of the nickel sulfate market process are fine particulate matter formation (51%) and human non-carcinogenic toxicity (21%). For the fine particulate matter formation, the dominating elementary flow is sulfur dioxide, mainly occurring during the production of nickel from platinum group metal mining and cobalt–nickel ore mining. Here, it can be noted that sulfur dioxide is considered differently between the three value perspectives of the ReCiPe method (Huijbregts et al. 2016). Direct emissions of fine particulate matter obviously contribute to fine particulate matter formation. Sulfur dioxide, however, only contributes indirectly by constituting condensation nuclei that leads to the formation of secondary particulate matter. In the individualist, short-term value

perspective in ReCiPe, only primary particulate matter is considered. In the hierarchist, medium-term perspective, the main perspective selected for this study, indirect particulate matter from sulfur dioxide is included. In addition, in the egalitarian, long-term perspective, indirect particulate matter from other emissions besides sulfur dioxide is also considered (i.e., nitrogen oxides and ammonia). Figure 3a shows that the potential health impacts from nickel sulfate go down by 80% from the hierarchist to the individualist perspective. Reduction in fine particulate matter formation due to the omission of indirect particulate matter from sulfur dioxide is the biggest reason for this decrease in potential health impacts. An egalitarian value perspective (not shown in Fig. 3a), on the other hand, increases potential health impacts of nickel sulfate by a factor of 40 compared to the hierarchist perspective.

For the human non-carcinogenic toxicity, the main contributing elementary flows are arsenic and zinc ions originating from the treatment of sulfidic tailings. Again, as shown in Fig. 3a, these potential health impacts depend considerably on the selected value perspective and become notably reduced if a more short-term perspective is chosen. For example, a limited number of exposure routes (drinking water and air) is considered in ReCiPe’s individualist perspective (Huijbregts et al. 2016). Also, the time horizon in the individualist perspective is only 20 years, versus 100 years in the hierarchist perspective, which means that the toxic substances have less time to cause harm.

In terms of data representativeness, it can be noted that the unit process dataset for treatment of sulfidic tailings in the Ecoinvent database, which includes the leaching of several toxic metals, is generic and applied to many

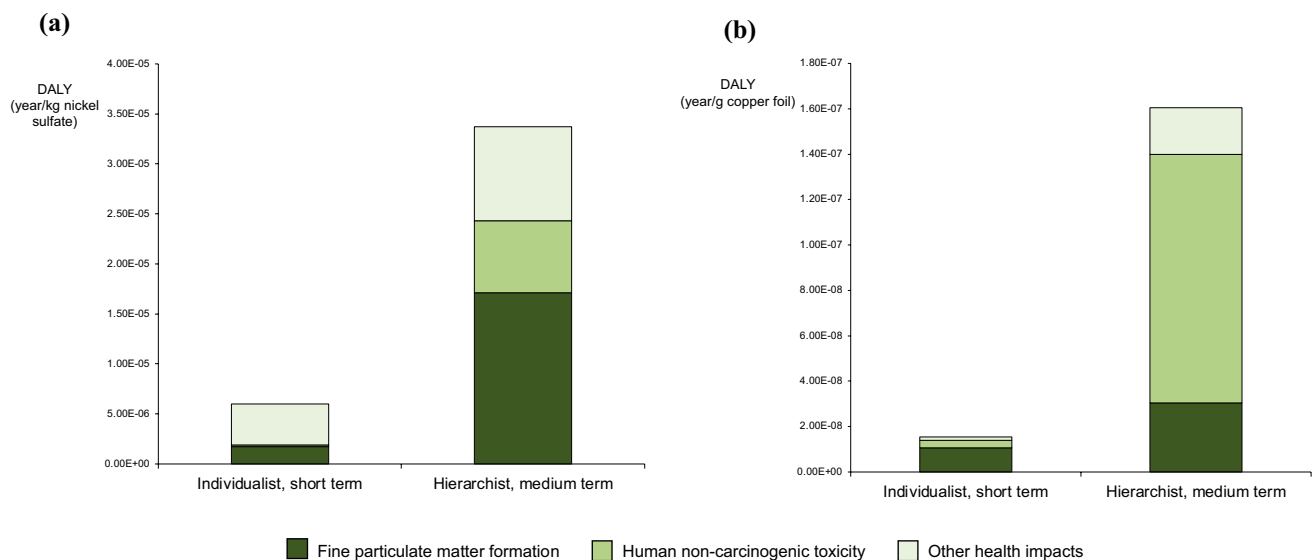


Fig. 3 Potential health impacts from two main contributors to the health impacts of the studied LIB cell, **a** nickel sulfate production and **b** copper foil production, given two different value perspectives. The hierarchist perspective is the chosen main perspective of this study

non-ferrous metal extraction processes in the database. As a result, sulfidic tailings are identified as a large contributor to toxicity impacts in many product systems (Reinhard et al. 2019). Hence, collection of more data with higher specificity regarding the treatment of tailings from different extractions could influence the results of this study.

3.2 Copper foil production

The production of copper foil, which serves as the current collector for the graphite anode, is modeled as sheet rolling of so-called cathode copper. The two midpoint impact categories that contribute the most to the potential health impacts of the copper foil production are the same as for nickel sulfate production, but in reversed order: human non-carcinogenic toxicity (68%) and fine particulate matter formation (19%). For the human non-carcinogenic toxicity, the main contributing processes are treatment of sulfidic tailings due to zinc ion emissions and treatment of copper slag due to arsenic ion emissions. For the fine particulate matter formation, the main contribution comes from the mining of platinum group metals, from which copper is a byproduct, specifically from sulfur dioxide emissions. Nickel sulfate and copper foil production thus mostly have the same main contributing midpoint impact categories, processes, and elementary flows. Unsurprisingly, there are large differences in potential health impacts depending on the value perspective for the copper foil production as well. As shown in Fig. 3b, the individualist perspective gives approximately a factor of 10 lower health impact compared to the hierarchist perspective, mainly due to reductions in human non-carcinogenic toxicity and fine particulate matter formation. Again, the individualist perspective gives lower potential health impacts due to shorter time horizons, fewer exposure routes, and exclusion of indirect particulate matter formation. The egalitarian perspective (not shown in Fig. 3b), on the other hand, gives more than 100 times higher potential health impacts compared to the hierarchist perspective. This is due to longer time horizons and inclusion of additional types of indirect particulate formation.

3.3 Potential improvements

Considering first the design of the studied LIB cell, one option for health improvements could be to lower the cobalt content further, i.e., in line with the generally ongoing efforts for LIBs by moving away from the cobalt-rich NMC 333 chemistry (Fan et al. 2020). However, as shown in Fig. 1b, if nickel is used instead, as in the studied NMC 811 chemistry, that also brings considerable potential health impacts. If the reduction of cobalt is done at the expense of increased nickel content, a net reduction in potential health impacts might not occur. Possibly, the copper current collector foil

could be replaced by some other conductive material. Any such changes must, however, not compromise the technical performance of the LIB cell significantly, in relation to its prerequisites for use. Materials that might be investigated as potential alternatives include aluminum, nickel, titanium, stainless steel, and possibly also carbon-based nanomaterials such as carbon nanotubes and graphene (Zhu et al. 2021).

Moving upstream in the product system, the analyses in Sects. 3.1 and 3.2 showed that much of the potential health impacts along the life cycle of the studied LIB cell are related to mining of metals and the treatment of tailings. Emission reductions in metal mining and tailings treatment would thus reduce the potential health impacts of the studied LIB cell. For example, in the dataset where nickel is produced as a by-product during platinum group metal mining, each kg of nickel produced causes about 7 kg of sulfur dioxide emissions. The sulfur originates from sulfidic ores and is emitted as sulfur dioxide during several refining steps, such as roasting (Classen et al. 2009). Recovering that sulfur dioxide would reduce potential health impacts from the nickel sulfate production process. In addition, increased recycled content of metals such as nickel and copper would also reduce upstream impacts. The current recycled contents in the Ecoinvent datasets for cathode copper and nickel (class 1) datasets are approximately 20% and < 1%, respectively. Battery manufacturers could investigate the possibility of sourcing metal supplies with higher recycled contents.

Accidents during artisanal cobalt mining in the DRC also contribute notably to the potential health impacts of the studied LIB cell. Sovacool (2019) proposed seven policy recommendations for better governing of cobalt mining in the DRC. These include to: (i) enforce better occupational standards for artisanal and small-scale mining operations, (ii) form joint ventures with artisanal and small-scale mining and large-scale and industrial mining interests, (iii) implement better dust and tailings management at large-scale and industrial mining, (iv) pursue broader and more robust community benefit sharing agreements, (v) support training for alternative livelihoods, (vi) recognize the limitations of traceability schemes and formalization, and (vii) do not ban artisanal and small-scale cobalt mining. Some of these recommendations, such as enforcing better occupational standards, might directly lead to reductions in potential health impacts. For example, Elenge (2013) suggested that it would be possible to introduce some degree of mechanization in artisanal cobalt mining, since the costs would be offset by a more or less guaranteed production level over time, which would reduce the physical strain of the artisanal miners. For other recommendations, an indirect effect might occur, e.g., if training for alternative livelihoods reduces the need for wounded or tired miners to return to mining where they are at higher risk of suffering

from fatal accidents. Other publications generally provide similar recommendations, albeit formulated differently and at a different level of detail (Tsurukawa et al. 2011; BGR 2019; OECD 2019; Sovacool et al. 2020). The seventh recommendation by Sovacool (2019) — to not ban artisanal mining of cobalt — reflects that there are also benefits from artisanal cobalt mining in the DRC, which, given a ban, would disappear (see Sect. 1). Instead, Sovacool (2019) advocates efforts to improve the mining practices. This recommendation is also echoed in other sources, e.g., Tsurukawa et al. (2011). Notably, this is opposite to the recommendation by Sharma and Manthiram (2020), who recommended a complete elimination of cobalt in LIB cathodes.

3.4 Potential positive health impacts

The aim of this study has been to quantify the potential negative health impacts caused by the supply chain activities of a selected LIB cell. However, there might also be potential positive health impacts related to the life cycle of this LIB cell. These could occur during the use of the cell, in particular if it enables the replacement of fossil fuel-based vehicles (through electromobility) or fossil fuel-based electricity (through stationary storage of electricity from renewable energy sources). Investigating such health benefits would require studies with wider cradle-to-grave scopes. However, there might also be potential positive health impacts within the LIB cell production system studied here. For example, the income generated by artisanal cobalt miners in the DRC — and possibly income elsewhere in the product system as well — might lead to health benefits. Previous work by Feschet et al. (2013) has started to outline an impact pathway for positive health impacts from earning an income based on the so-called Preston curve, which shows how the life expectancy in low-income countries increases with higher income rates in general. However, this approach calculates changes in life expectancy rather than DALYs and it requires certain criteria to be fulfilled. For example, the added value of the activity must be distributed relatively equally among the population for this approach to apply. This is currently not fulfilled in the DRC, which has among the world's highest corruption levels. Therefore, this approach to quantifying positive health impacts from income can currently not be included in Eq. (2). However, there might be local and more direct health benefits from earning an income, which do not affect the general population of a region as per the Preston curve, but nevertheless affect, e.g., specific miners and their families. We recommend further studies to investigate this relationship between incomes and health status in more detail.

3.5 Limitations and uncertainties

The aim of assessing a wide range of potential health impacts inevitably bring sources of uncertainty. The main inventory data sources of this study are Chordia et al. (2021), Dai et al. (2018), and the Ecoinvent database, version 3.7.1. The data from Chordia et al. (2021) represent a modern gigafactory and is considered fit for the aim of this study. As explained in Sect. 2.4, Dai et al. (2018) is the only known source with cobalt supply data presented at the unit process level, which is considered valuable in a study with a particular interest in the contribution from cobalt. Still, the data from Dai et al. (2018) is limited, e.g., in terms of emissions reported and treatment of tailings, which are therefore important areas for further data gathering to reduce the uncertainty in potential health impacts from emissions. The Ecoinvent database has the explicit aim of providing background data to LCA studies (Wernet et al. 2016), and as such it is considered fit for the aim of this study. However, considering the large contribution from nickel sulfate and copper foil production to the potential health impacts of the studied battery cell (Fig. 2b), further detailed investigations of emissions and treatment of tailings from nickel and copper mining would be useful to reduce the uncertainty of this study and identify improvement opportunities.

The three main data sources when it comes to characterization factors for social impact assessment are ReCiPe for emissions and water use (Huijbregts et al. 2017), Scanlon et al. (2015) for occupational accidents for most processes and our own calculations for occupational accidents from artisanal cobalt mining. ReCiPe is widely used to assess potential health impacts from emissions and water use in LCA studies. The three value perspectives — individualist, hierarchist and egalitarian — represent different views on time perspective and inclusiveness when it comes to environmental and health impacts, with the individualist/short term and egalitarian/long term perspectives being the two extremes. While these perspectives can provide a wide range of potential health impacts (Fig. 3), they also illustrate how differences in fundamental values influence the results. The characterization factors from Scanlon et al. (2015) cover the most relevant industry sectors, but are aggregated, as in “copper ore and nickel ore mining.” Here, a further disaggregation and differentiation between different locations, e.g., industrial copper-cobalt ore mining in the DRC and nickel mining in Russia in that case, would reduce the uncertainty in the estimation of potential health impacts from occupational accidents. Regarding our calculations of work environment characterization factors for artisanal cobalt mining, the largest source of uncertainty is likely the 65–2000 fatalities/year range. Further investigations to reduce uncertainty in that value are strongly recommended.

4 Conclusions

This study has shown that the cobalt input to the NMC-type LIB production (in the form of cobalt sulfate) contributes notably to the battery's potential health impact, both through occupational accidents during artisanal cobalt mining in the DRC (13%) and through emissions and water use during the production of cobalt sulfate (6%). The occupational accidents impact artisanal miners in the Katanga region of the DRC specifically. However, cobalt is not the only contributor to the potential health impacts, nor necessarily the largest. Potential health impacts from the production of two other input materials to the production of the LIB contribute even more: nickel sulfate (30%) and copper foil (20%). The reason for these high potential health impacts are emissions of sulfur dioxide, zinc, and arsenic. However, the magnitudes of these impacts depend on the time horizon applied in the assessment — a long time horizon indicate even higher potential health impacts from nickel sulfate and copper production, whereas when using a shorter time horizon, these health impacts are notably reduced. Contrary to the occupational accidents in artisanal cobalt mining, these emissions impact the general population. In order to reduce potential health impacts of NMC batteries, a number of recommendations are proposed to LIB cell manufacturers: (i) investigate the feasibility of replacing the copper foil with another conductive material able to provide anode current collector functionality; (ii) reduce emissions from metals extraction; and (iii) increase the recycled content of sourced metals. Finally, improved occupational standards in artisanal mining in the DRC are recommended to reduce accident rates, in particular fatal accidents.

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Data availability The data that supports the findings of this study are cited in Sect. 2 or available in the Supporting Information (SI), specifically Tables S1–S7. Access to some upstream data requires access to the Ecoinvent database.

Declarations

Conflict of interest The authors declare no competing interests.

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