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RESEARCH AND ANALYSIS

Design of an endpoint indicator for mineral resource supply risks in life cycle sustainability assessment The case of Li-ion batteries

Jair Santillán-Saldivar[1,4] | Tobias Gaugler[2] | Christoph Helbig[2,3] | Andreas Rathgeber[2] | Guido Sonnemann[1,4] | Andrea Thorenz[2,3] | Axel Tuma[2,3]

[1] Institut des Sciences Moléculaires, Université de Bordeaux, Talence, France

[2] Institute of Materials Resource Management, University of Augsburg, Augsburg, Germany

[3] Resource Lab, University of Augsburg, Augsburg, Germany

[4] Institut des Sciences Moléculaires, CNRS, Talence, France

Correspondence
Christoph Helbig, University of Augsburg, Universtaetsstr. 16, 86159 Augsburg, Germany.
Email: christoph.helbig@wiwi.uni-augsburg.de

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Abstract

Concerns have risen in recent years about the accessibility of raw materials considered "critical" for technological advancements. The GeoPolRisk indicator was designed as a midpoint indicator in life cycle sustainability assessment to measure geopolitical supply risk with the aim to incorporate raw material criticality as a complement to environmental life cycle assessment (LCA). A recent review of supply risk methods conducted within the Task Force on mineral resources of the Life Cycle Initiative hosted by UN Environment Programme highlighted the opportunity to extend the methodology to an endpoint level. We address this opportunity by presenting GeoPolEndpoint, an indicator that measures the socio-economic damage of the use of mineral resources linked to the area of protection "Natural Resources" in LCA. We build upon previous efforts by introducing price elasticity considerations and modeling potential effects of supply disruptions on commodity markets in the form of a welfare loss and a loss of consumer surplus. The socio-economic damage occurs as geopolitically driven increased costs for raw materials. We test our method on aluminum, cobalt, nickel, and copper, materials relevant for lithium-ion batteries. Results show that nickel and cobalt dominate the contribution to socio-economic damages because of their price and supply risk; we estimate the impact of the use of the four analyzed materials as a potential increased cost ranging from 0.30 to 1.86 USD/kWh depending on the technology and year. We build the steps to assess how the use of certain raw materials could have a substantial economic impact when developing technologies, possibly identifying the shifting of burden due to certain materials not usually deemed important from an environmental perspective. This article met the requirements for a gold-gold JIE data openness badge described at http://jie.click/badges.

KEYWORDS
criticality assessment, industrial ecology, life cycle sustainability assessment (LCSA), price elasticity, supply risk

1 INTRODUCTION

Addressing concerns of limited accessibility, raw material criticality assessments are a complement to environmental life cycle assessments (LCAs) (Cimprich et al., 2019). Traditionally, LCA focuses on the analysis of inputs and outputs and their potential environmental impacts associated to a product system (ISO, 2006). Criticality considerations (Schrijvers et al., 2020) were identified and included in LCA under the Life Cycle Sustainability Assessment (LCSA) framework to provide a socio-economic pathway to analyze resource utilization beyond classical environmental impact (Sonnemann, Gemechu, Adibi, De Bruille, & Bulle, 2015).

Criticality approaches can be used next to other covering life cycle impacts of mineral resource use, namely depletion perspectives, future effort, or thermodynamic approaches (Sonderegger et al., 2020). Product-level supply risk assessments provide this complementary perspective by assessing "outside-in" impacts: increased production costs or lost revenue due to production shutdowns, caused by a lack of mineral resource accessibility (Cimprich et al., 2019; Frischknecht et al., 2019). ESSENZ (Bach, Berger, Finogenova, & Finkbeiner, 2019) and GeoPolRisk (Gemechu, Helbig, Sonnemann, Thorenz, & Tuma, 2016) are interim recommended or suggested methods for quantifying potential accessibility issues to raw materials related to short-term (typically up to 10 years) geopolitical and socio-economic aspects by the Task Force on Mineral Resources of the Life Cycle Initiative hosted by UN Environment (Berger et al., 2020, p. 805; Frischknecht et al., 2019). However, these accessibility issues belong to the so-called midpoint level in LCA terminology, measuring an impact at an early stage of the cause–effect chain (Bare, Hofstetter, Pennington, & de Haes, 2000). So far, there has been no applicable method to link midpoint-level supply disruptions (in equivalency units) to the endpoint-level socio-economic damage (in monetary units). Assessing the socio-economic damage on the endpoint level would allow a better comparison or aggregation of different midpoint impact categories. Therefore, our goal here is to estimate the socio-economic damage through the cause–effect chain of potential geopolitical supply disruptions for a better understanding the final tangible impacts of raw materials use.

As suggested by the ISO standard on LCA, the damage should be associated to a functional unit of any service-providing product (ISO, 2006). Among current efforts related to the area of protection (AoP) "Natural Resources," the abiotic depletion potential (ADP) method explores the contribution of a product system to the depletion of mineral resources (Guinée & Heijungs, 1995; Van Oers, de Koning, Guinée, & Huppes, 2002; Van Oers & Guinée, 2016), the LIME2 method quantifies future externalities of mineral resource use (Itsubo & Inaba, 2012), and the surplus cost potential (SCP) explores cost increases of future resource extractions (Ponsioen, Vieira, & Goedkoop, 2014; Vieira, Ponsioen, Goedkoop, & Huijbregts, 2016). However, these methods explore long-term scenarios and do not address resource accessibility considerations (Frischknecht et al., 2019).

Reaching the endpoint level, or damage to the AoP "Natural Resources," requires the inclusion of a factor linking the endpoint category with the midpoint impacts. Such a linking factor is so far not modeled in any of the recommended supply risk methods (Cimprich et al., 2019). Previous attempts to include economic importance, mass share, and substitutability into such a damage factor for mineral resources already incorporated the concept of vulnerability to supply disruptions (Helbig, Wietschel, Thorenz, & Tuma, 2016b), but did not manage to quantify the economic damage of a supply disruption (Cimprich et al., 2017, 2018).

We argue that supply disruption events are linked to monetary socio-economic damage through the following cause–effect chain: In the case of a geopolitical tension causing a supply disruption, the supply curve shifts, meaning that the commodity price increases and, at the same time, less material is traded on this partial market (Baumol & Blinder, 2015; McEachern, 2011; Varian, 2014). Such a supply disruption is more likely for critical raw materials and it causes economic damage (Graedel & Reck, 2016). In contrast, the demand curve does not move due to a supply disruption event, assuming that substitution options are not immediately available. Therefore, the new equilibrium after the event will be at a higher price. The price will remain on a higher level for as long as the disruption persists. All companies using the raw material for production purposes will be directly affected by these higher commodity prices. The details of managing the increased raw material costs lie outside the scope of this article, but the options include cost cutting for other expenses, selection of hedging measures, and, importantly, increasing sales prices and therefore consumer price increases (Fridgen, König, Mette, & Rathgeber, 2013).

Despite this cause–effect chain being plausible in theory, its empirical evidence is difficult. Long-term price data series for commodity markets often do not help, because supply and demand curves usually cannot be observed directly as only the equilibrium price is determined on the stock exchange (Varian, 2014). Supply curves change, for example, due to new exploration, depletion of mines, and new technologies. In normal circumstances, the supply is relatively stable, whereas the demand is strongly influenced by factors like global economic activity, monetary policy, technological changes, or trade policies. This yields to the fact that most equilibrium price changes are determined by changes in the demand and only allow to derive the slope of the supply curve. Nevertheless, Fu, Polli, and Olivetti (2019) quantified long-run elasticities for three by-product metals. In contrast, here we examine events at which the raw material supply changes unexpectedly. The events we investigated are unexpected and, therefore, the risk of damage is not included in the market prices (Koch & Fenili, 2013). By looking on specific events of supply disruptions, we estimate the slope of the demand curve. These events are natural catastrophes with documented effects on mining or processing activities; their risk on mineral production has been confirmed on the case of copper (Schnebele, Jaiswal, Luco, & Nassar, 2019). The slope of the demand curve implies the economic damage: given a low slope, a reduction of the supply would only yield to a small increase in price and consequently a low reduction of welfare. In contrast, a high slope would imply sharply rising prices. This would result in a high wealth reduction on the demand side driven by a large consumer price increase.

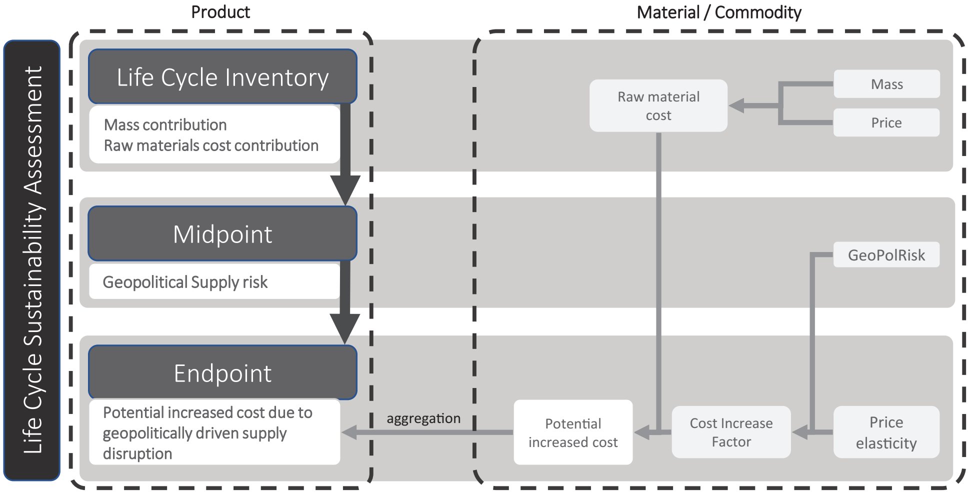

FIGURE 1 Methodological pathway for the development of an endpoint indicator based on geopolitical supply risk considerations

In this article, we quantify the potential socio-economic damage of geopolitical supply risks of four metals relevant to LIBs. LIB demand has increased in the past two decades primarily due to mobile consumer electronic devices. By now, LIB demand growth is determined by the growing market share of electric vehicles (Pillot, 2017). Aluminum, cobalt, nickel, and copper are all required in LIB, as either current collectors or typical metals in cathode materials (Peters & Weil, 2016). Cobalt, next to lithium, is a main contributor to supply risks of LIB materials (Helbig, Bradshaw, Wietschel, Thorenz, & Tuma, 2018). The geopolitically driven increased costs are modeled as potential short-term increased costs on the product system of LIB due to unexpected supply disruptions for its raw materials. The GeoPolRisk method serves as the impact factor on the midpoint level and the slope of the demand curve (price elasticity) as the damage factor on the endpoint level. The GeoPolRisk method takes up the geopolitical risks addressed by criticality assessments and was originally developed and applied for a European case of critical metals (Gemechu et al., 2016). In a later extension, the differentiation between the most often used dimensions of criticality assessments *likelihood of supply disruption* and *vulnerability* has been clarified (Cimprich et al., 2017).

In the methods section, we first show the steps toward the calculations of midpoint GeoPolRisk factors. Furthermore, as part of our proposed methodological development, we provide the basis for the obtention of metal price elasticities of supply based on natural catastrophes and the corresponding endpoint calculations. With the aim to assess the contribution of four materials to the socio-economic damage attributed to the production of LIB, we later on present our results for Al, Co, Ni, and Cu from the perspective of a LIB producer within the Organization for Economic Co-operation and Development (OECD) country group. At last, we discuss the limitations and future perspectives of the novel methodology as an endpoint indicator to model the implications of resources supply risk in the AoP Natural Resources within the LCSA framework.

2 | METHODS

The proposed indicator is a function of the supply risk of a material at a global scale and its potential price variation facing a supply disruption. Figure 1 illustrates the path we follow to build the endpoint indicator for one resource in 1 year. In LCA, the functional unit represents the service provided by the product over its lifetime. Given the assumption that production is still possible despite the event, the damage of a geopolitical supply shortage is equivalent to the geopolitically driven increased costs for the production due to higher raw material costs. The result provides a damage value in monetary units related to specific raw materials and applicable for the assessed year. In this section, we present the application of the previously developed GeoPolRisk midpoint method to the case of LIB, the development of the new method components that will be integrated on the final endpoint calculation, and the required life cycle inventory data for two types of LIBs.

2.1 | Midpoint indicator for geopolitical supply risk

Our proposal takes on previous work on the integration of criticality considerations into LCSA (Sonnemann et al., 2015). For a given material, year, and region, the GeoPolRisk method provides an indicator of the proportion of mass at risk in a life cycle taking into account the production concentration at global level and the import mix of the analyzed country or region (Cimprich et al., 2017). The GeoPolRisk value is the product of the global production concentration and the weighted average of the political stability of trade partner countries and domestic production (Gemechu et al., 2016). The production concentration is given with the Herfindahl–Hirschman index (HHI), which is calculated as the sum of the squared production shares of each country. The weighted average of political stability is calculated as the sum of country-specific rescaled values of the Worldwide Governance Indicators in the dimension of political stability and absence of violence (WGI-PV) multiplied by the share of imports from that country of total imports and domestic production (Kaufmann, Kraay, & Mastruzzi, 2010). Domestic production is considered free of risk in geopolitical terms (Helbig et al., 2016a).

In order to develop an endpoint indicator based on the GeoPolRisk method, it becomes necessary to apply it at a larger scale because metals are traded in a global market. We apply the GeoPolRisk methodology to the group formed by the members of the OECD. The decision on the use of the OECD members as reference group is based on its design as a global network with high impact on economic, environmental, and social policies around the globe (OECD 2019a); and for its focus on stimulating economic development and global trade (OECD, 2019b). The adjusted formula for the global fraction at risk of a commodity for a given year to be further used and referenced in this article is determined by:

$$GeoPol_{\mathrm{OECD}}\,(a,t) = HHI\,(a,t) \cdot \overline{\mathrm{WGI}_{\mathrm{OECD}}\,(a,t)} = \frac{\sum_c p_c^2(a,t)}{P^2(a,t)} \cdot \frac{\sum_c g_c(a,t) \cdot f_{c,\mathrm{OECD}}(a,t)}{p_{\mathrm{OECD}}(a,t) + F_{\mathrm{OECD}}(a,t)},$$

where p_c is the production of a commodity in a country c and $P = \sum_c p_c$ is the global production; g_c is the score of the country in the WGI-PV transformed to a 0–1 scale; $f_{c,OECD}$ is the trade flow of a commodity from country c to the group of OECD countries and F_{OECD} is the total import volume of OECD countries for the commodity; p_{OECD} is the production of a commodity in the group of the OECD countries; a is the resource; and t is the year.

The resulting indicator has no dimension and can be described as a weighted average of all export flows from producing countries in the world. The possible obtainable values range from 0 to 1: 0 meaning the non-existence of geopolitical risk and 1 representing that a 100% of the supply is at imminent disruption risk.

A set of three public databases is used to obtain the $\mathrm{GeoPol}_{\mathrm{OECD}}$ values in this study: The United States Geological Survey (USGS) database for production data (USGS, 2018), the World Bank database for the World Governance Indicators (Kaufmann & Kraay, 2015) and the UN Comtrade database for trade data of commodities around the globe (United Nations, 2019).

2.2 | Modeling of supply disruption impacts

The potential price variation due to sudden supply disruption events is modeled based on the calculation of price elasticity values. The "price elasticity of demand" indicates the effect of a (marginal) price change of a commodity on the requested quantity. For this calculation, the quantity and world market price changes (in percentages) are set in relation to each other (Varian, 2014, p. 274):

$$\textit{Price elasticity of demand} = \frac{\%\text{ change in quantity } q}{\%\text{ change in price } p}.$$

To clarify this connection, the supply curve and the demand curve of a commodity are exemplarily sketched as straight lines in Figure 2a.

In case of a supply shortage, (A) the supply curve (1) shifts to supply curve (2) and as a result, (B) the price increases from p (1) to p (2). This leads to (C) a decline in demand from q (1) to q (2). The extent of the price increase—which corresponds to the slope of the (dotted) demand curve—results from the ratio between the change in quantity and the change in price. In our paper, proxies for price elasticity values are obtained from the study of the effect of short-term supply shortages on global commodity prices caused by natural disasters. Our central goal is to measure the price variation which results from a supply disruption. As a reduced offer leads to an increased price, buyers have to bear this increase in material costs. A price

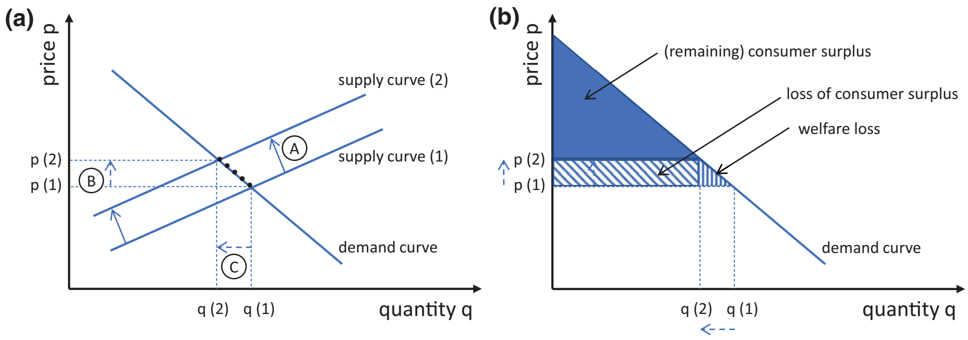

FIGURE 2 (a) Supply and demand curves and the consequences of a supply reduction. (b) Reduction of the consumer surplus and welfare loss as a result of an increased commodity price

increase leads to the situation that some processors of the metals are not willing or able to buy the metal at that higher price. As a consequence, their profit is lost (cf. "welfare loss" in Figure 2b). In addition, the remaining processors have to pay a higher price ("p (2)" instead of former price "p (1)" in Figure 2b), which results in a loss of consumer surplus.

The higher the slope of the demand curve, the larger the price jump and the more material processors are affected. Graphically spoken, a higher slope leads to a larger hypothenusis and consequently to a larger area of the triangle. In addition, remaining processors face higher factor costs and consequently also lose consumer surplus (Samuelson & Nordhaus, 2004).

Therefore, we interpret this price change as a measure for economic damage on the raw material consuming industry. Hence, our model coincides with a change on the demand curve in the Walrasian equilibrium model (Varian, 2014). For the purpose of LCSA, the slope of the demand curve serves as a mediating factor which can later on be integrated into the damage factor applied on the inventory.

To estimate the slope of the demand curve and therefore the impact of a supply shock, we focus on situations at which the supply changes due to external shocks. Natural disasters are situations where producers are forced to reduce their capacity, because the mines or the transportation infrastructure are destroyed (Benson & Clay, 2004). For our study, it is irrelevant whether the infrastructure—which includes transport, power, and communications networks—is completely or only partially destroyed. In any case, the supply of the raw material is impaired. As a first step, we look at natural disasters during which mines were affected. For this purpose, the "NatCat" database of Munich Re (2019) was used for identifying the dates and the type of each disaster (e.g., earthquake and tsunami, tropical cyclone, flood, and flash flood) as well as the affected country and the geographical coordinate of each natural disaster. On the other hand, the location of the mine as well as the prices of the commodities concerned are of interest. Mining data was taken from the annual Minerals Yearbook (USGS, 2018). We use commodity prices from the London Metal Exchange (LME), which were obtained from the data provider Thomson Reuters (2019). Both the spot price and the 3-month future contract were available as possible commodity prices, whereby we used the price with the higher liquidity for each commodity. Only events in which more than 1% of the global mining volume was affected are considered. For lower affected mining volumes, it can be assumed that their possible influence on the global price is negligible. In addition, the distance between the disaster and the affected mine should not be greater than 100 km measured by the great circle (longitude and latitude of event and mine). Furthermore, we focus on events that are followed by a price increase of the commodity affected. In the case of natural disasters whose occurrence can be predicted relatively well meteorologically (such as tropical cyclone), we also considered events where the related commodity's price increase can be observed even before the event itself. On the basis of these criteria, the natural disaster best fitting our criteria for each commodity is identified and the associated price changes are examined. On the one hand, the type of an event might play a role: For some event types (e.g., cyclones), their occurrence and location can already be predicted a few days in advance. In contrast, for example, the accurate future spread of a wildfire is more difficult to predict. The liquidity of the various commodity markets might also be relevant. If liquidity in a partial market is low, a price change could be delayed. For reference, price changes are analyzed from the five trading days before the event's occurrence until five trading days at the LME after the event has passed. The choice of these three points in time is based on the fact that an event might not only induce a price change on the day of its occurrence, but also a few days before or afterward.

In this paper, the question arises of how the commodity price changes when the supply changes. We use the natural catastrophes as past events with observed price changes and utilize the same elasticities for potential geopolitically driven supply disruptions resulting in geopolitically driven increased costs. Therefore, we define ε as the quotient of the change in price and the change in quantity. Hence, our ε is the inverse of the elasticity defined in formula (2). With our approach, it is possible to identify commodity-specific disasters and the associated short-term impact measured by the inverse price elasticity of demand specific to one material (ε_a), which is defined as the percentage price change of the concerned metal divided by the percentage of global mining volume affected (Varian, 2014).

2.3 | Design of the GeoPolEndpoint indicator

With the presented concepts, a formula that provides a measure of the socio-economic damage factor on the AoP Natural Resources under a Life Cycle perspective was designed:

$$\mathrm{GeoPolEndpoint}_{\mathrm{OECD}}\ (a,t) = \mathrm{GeoPol}_{\mathrm{OECD}}\ (a,t) \times \varepsilon_a \times \bar{p}\,(a,t) = \ \mathit{Cost\ increase\ factor}\,(a,t) \times \bar{p}\,(a,t)\,,$$

where ε_a is the inverse price elasticity of resource a, which we assume to be constant on the entire curve (isoelasticity; Sah & Wada, 2003) and $\bar{p}$ is the average price of a resource a in year t. The product of ε_a and $\mathrm{GeoPol}_{\mathrm{OECD}}$ will be further referred as cost increase factor.

For resource a and year t, the result of this calculation is interpreted as an average cost increase of facing a sudden geopolitically driven supply disruption per unit of mass of the material under analysis. The measure implies the material flow at risk multiplied by the elasticity and the price. If the supply disruption occurs, the material flow is reduced by this amount, leading to a price increase defined by the elasticity. Hence, our indicator consists of the price increase times the volume leading to measure for the reduced consumer surplus (see Figure 2b). Consequently, our measure approximates the potential loss in economic welfare of the material processing companies in OECD countries, if a supply disruption occurs. These damage factors are intended to be multiplied by the mass flows in an LCA inventory and provide a measure of the damage

TABLE 1 Mass contribution of selected chemical elements to the LCA inventory of LIB (Peters & Weil, 2016)

Element	Mass share NCA-C (%)	Mass share NMC-C (%)
Al	5.8	3.5
Co	2.0	5.4
Ni	10.7	5.4
Cu	11.2	16.5

TABLE 2 $\text{GeoPol}_{\text{OECD}}$ values for the four analyzed raw materials

Raw material	$\text{GeoPol}_{\text{OECD}}$ 2015	$\text{GeoPol}_{\text{OECD}}$ 2016	$\text{GeoPol}_{\text{OECD}}$ 2017
Bauxite (Al)	0.023	0.020	0.019
Cobalt (Co)	0.080	0.081	0.097
Nickel (Ni)	0.015	0.012	0.014
Copper (Cu)	0.008	0.014	0.012

caused by the use of the individual resource as part of LCSA. The geopolitically driven increased costs from all considered resources are summed at the end.

2.4 | Life cycle inventory for Li-ion battery case study

Based on the inventory provided by Peters and Weil (2016), Table 1 shows the mass contribution of aluminum, cobalt, nickel, and copper to the cells of LIB with nickel–cobalt–aluminum (NCA-C) or nickel–manganese–cobalt (NMC-C) cathode active material, both with graphite anode material. NCA-C battery cells are calculated with an energy density of 133.1 Wh/kg, NMC-C of 130.4 Wh/kg (Peters & Weil, 2016). For a more general discussion of supply risks associated with LIB materials, see Helbig et al. (2018).

The average prices of 2017 for the four metals range in between 1.97 USD/kg for aluminum and 55.6 USD/kg for Cobalt. Nickel and copper have been traded in 2017 at 10.5 USD/kg and 6.17 USD/kg, respectively. Prices refer to LME market prices (Thomson Reuters, 2019). The same prices are used for the calculation of price elasticity proxies. Cobalt prices doubled from 25.5 USD/kg in 2016. Calculated price averages for Al, Co, Ni, and Cu, for the years 2015–2017 can be found as part of the Supporting Information.

3 | RESULTS

The proposed endpoint indicator is applied to four materials in the supply chain of LIB from an OECD perspective. Subsequently, the obtained results at midpoint and endpoint levels will be compared with the inventory in order to assess the overall contribution of the four focus materials to the supply risk and to the socio-economic damage attributable to LIB.

3.1 | Geopolitical supply risk

Based on the GeoPolRisk methodology, the $\text{GeoPol}_{\text{OECD}}$ values of the four selected raw materials are calculated for the years 2015, 2016, and 2017. The overall results can be identified in Table 2.

In the case of aluminum, $\text{GeoPol}_{\text{OECD}}$ values obtained for 2015, 2016, and 2017 are 0.023, 0.020, and 0.019, respectively. The contribution to the supply risk is attributed to the increasing participation of Russia, the Middle East, and China in the import shares for OECD members. Bauxite is used for the calculation of the GeoPolRisk indicator to guarantee a consistency with the elasticity values, which was calculated for an event that affected bauxite production. GeoPol values could, of course, also be calculated for aluminum smelting countries, or as aggregated values for multi-stage supply chains as shown at the example of petrochemical supply chains by Helbig et al. (2016a). Results for cobalt (0.080, 0.081, and 0.097) are explained by a highly concentrated production in countries outside of the OECD, with DR Congo being the main producer with a strong and increasing participation in the global market. Additionally, the contribution from countries included in the OECD decreased in the last analyzed

TABLE 3 Specification of events and affected mines

Type of event	Country affected	Commodity affected	Distance between event and mine (km)
Cyclone, storm surge	India	Aluminum	67
Hurricane, storm surge	Cuba	Cobalt	57
Typhoon, landslide	Philippines	Nickel	36
Flood	Romania	Copper	41

TABLE 4 Effect of events on the proxied price elasticity of demand of the four analyzed commodities

Commodity	5 days before ($t = -5$)	At event day ($t = 0$)	5 days after ($t = +5$)
Aluminum	0.01	0.04	0.03
Cobalt	0.00	0.81	0.24
Nickel	0.11	0.37	0.34
Copper	−0.29	0.21	0.24

year. The production of nickel and copper is relatively well distributed around the globe with strong participation of members from the OECD. Therefore, the supply risk of these materials is substantially lower in comparison to the first two (0.015, 0.012, and 0.014 for nickel; 0.008, 0.014, and 0.012 for copper).

3.2 | Price elasticity

Following the modus operandi described in the method section we identified events that led to a supply shortage of the four commodities investigated. These events are specified in Table 3 and introduced in more detail below. For disasters that are moving events, such as tropical cyclones, we define that the location of the event is the place where the storm hits land. This approach is reasonable since a tropical cyclone has the greatest destructive power at this point before it then quickly weakens inland.

For aluminum, we determine the effects of cyclone Hudhud and the associated storm surge. The event occurred in India on October 13, 2014 and impacted 16.94% of global bauxite mining volume (USGS, 2018). A natural catastrophe impacting aluminum smelting was not found. The effects of the Hudhud disruption can, however, be seen even in the next supply chain level for aluminum, for which the proxy for the price elasticity of demand within the five trading days before the event was 0.01, the estimated elasticity on the day of the event was 0.04. In the five trading days after the event, it was 0.03.

Hurricane Matthew and the subsequent storm surge had an impact on the production of cobalt in Cuba (global mining volume affected: 2.23%). This event, which started on October 4, 2016, only had an estimated impact on the day of the event itself, at 0.81. In the subsequent five trading days, a proxy of 0.24 was determined. This may be because the extent of the damage only becomes evident after the event. Another explanation is that the information about the production decline only reached the market participants with a delay.

Typhoon Parma (Pepeng) crossed the Philippines on October 5, 2009, leading to a decline in nickel ore production (global mining volume affected: 4.12%). Already in the analyzed timeframe before the event, a 0.11 increase in the price elasticity was proxied. The event day was characterized by an increase in price elasticity of 0.37. The increase during the five trading days after the event was 0.34.

A flood on July 4, 2005 had an impact on copper mining in Romania, accounting for 4.66% of global mining volume. The fact that a negative value (−0.29) was calculated for the period of five trading days prior to this event indicates that the impact of this storm had not been anticipated. It can be assumed that there has been an expansion in supply or that demand has decreased before the event. On the day of the event itself, the proxy for the price elasticity of demand was 0.21. We additionally observed an increase of 0.24 on the five following trading days.

Table 4 summarizes the commodity-specific proxy for elasticity.

3.3 | Overall results

After integrating $\text{GeoPol}_{\text{OECD}}$ values and proxies for price elasticities for the metals, cobalt shows the highest socio-economic risks for OECD countries due to geopolitical supply disruptions. Not only is cobalt most exposed to geopolitical supply disruptions because of its high production concentration and low mining volume inside OECD countries; it is also most vulnerable to supply disruptions, showing the highest positive price elasticity

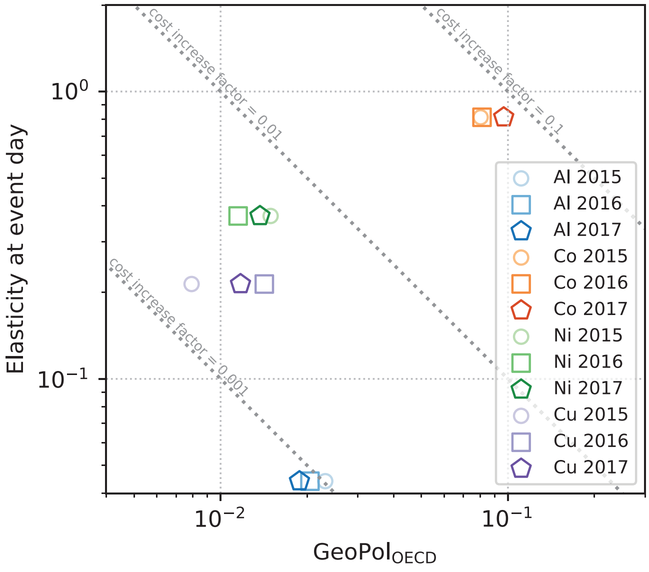

FIGURE 3 Cost increase factors for Al, Co, Ni, and Cu in 2015, 2016, and 2017. Plot is in a double logarithmic scale. Underlying data used to create this figure can be found in the Supporting Information

to a short-term event. Figure 3 gives a graphical representation of these patterns, using the elasticity at the event day from Table 4. Note that the proxy for price elasticity is calculated as a general factor for each metal and is assumed not to be dependent on the year of analysis.

We interpret the product of the $\mathrm{GeoPol}_{\mathrm{OECD}}$ and the elasticity at event day as the relative cost increase caused by the geopolitical supply risk of the metal. If price elasticities 5 days before the event date are also considered, it appears that these proxies are substantially lower than on the event day itself. It can be assumed that the importance of this time window is of lower priority. The proxy elasticities 5 days after the event day are, in general, lower than on the event day itself. We assume that these elasticity values tend to be relatively higher if the negative effects of the event turn out to be greater than expected on the day of the event itself.

Aluminum and copper share cost increase factors with values that range from 0.0008 to 0.001 and 0.0017 to 0.003, respectively, followed by nickel with a range from 0.0042 to 0.0055. However, the value for cobalt ranges from 0.065 in 2015 to 0.079 in 2017. This difference in the values is further extended with the calculation of the GeoPolEndpoint factor, which results from the product of the cost increase factor and the average price of the materials.

The smallest GeoPolEndpoint value is attributed to aluminum with a relative damage at the endpoint level of 1.69, 1.45, and 1.63 USD/t-Al (for 2015, 2016, and 2017 respectively; 1 t = 1,000 kg), followed by copper with corresponding values of 9.33, 14.8, and 15.5 USD/t-Cu. Increased endpoint factors are obtained for nickel and cobalt, with 65.4, 41.0, and 53.0 USD/t-Ni for nickel and 1860, 1690, 4370 USD/t-Co for cobalt. The overall socio-economic damage at endpoint level attributable to the supply risk of Al, Co, Ni, and Cu in NCA is equivalent to 1.78%, 1.83%, and 3.13% of the total costs of these materials in the battery inventory for the years 2015, 2016, and 2017, respectively. For the case of NMC, this overall contribution to the damage is higher, comparable to 3.37%, 3.48%, and 5.20% of their cost.

Figure 4 shows the relative contribution of aluminum, cobalt, nickel, and copper to the raw material costs in the battery cell and the socio-economic damage at endpoint level, obtained as the product of the GeoPolEndpoint value, the mass share, and energy density.

From an inventory perspective, the mass share of copper and nickel is superior to aluminum and cobalt in the case of NCA. While the mass share of copper is even higher in the case of NMC, cobalt and nickel have a similar contribution in the latter case (see Table 1). In terms of raw materials cost, the relevance of cobalt and nickel becomes evident, especially in the year 2017 when an increase on the price of cobalt makes its cost share more dominant in the LIB inventory.

The relative contribution of the raw materials to the supply risk assessment has remained stable over the analyzed period. However, the $\mathrm{GeoPol}_{\mathrm{OECD}}$ indicator for cobalt emerges as a reflection of the supply chain of this material, for which a large percentage of its production is located in high risk countries. Results at endpoint-level rank cobalt as of even greater importance in the assessment of socio-economic damages, representing between 82% and 92% of the total damage associated with Al, Co, Ni, and Cu in NCA (values for 2015 and 2017), nickel also plays a role in this case with a smaller share, attributable to a high contribution in mass and having a relevant $\mathrm{GeoPol}_{\mathrm{OECD}}$ value. For the case of NMC, however, the effect of cobalt displaces the contribution of the other materials, making them negligible in comparison for the case of NMC. In absolute terms, we can model the economic impact of the use of Al, Co, Ni, and Cu as a potential increased cost of materials for the production of LIBs: in the case of NCA, this cost is calculated as 0.34, 0.30, and 0.72 USD/kWh for the years 2015, 2016, and 2017 respectively; contrastingly, the increased cost for NMC is 0.81, 0.74, and 1.86 USD/kWh.

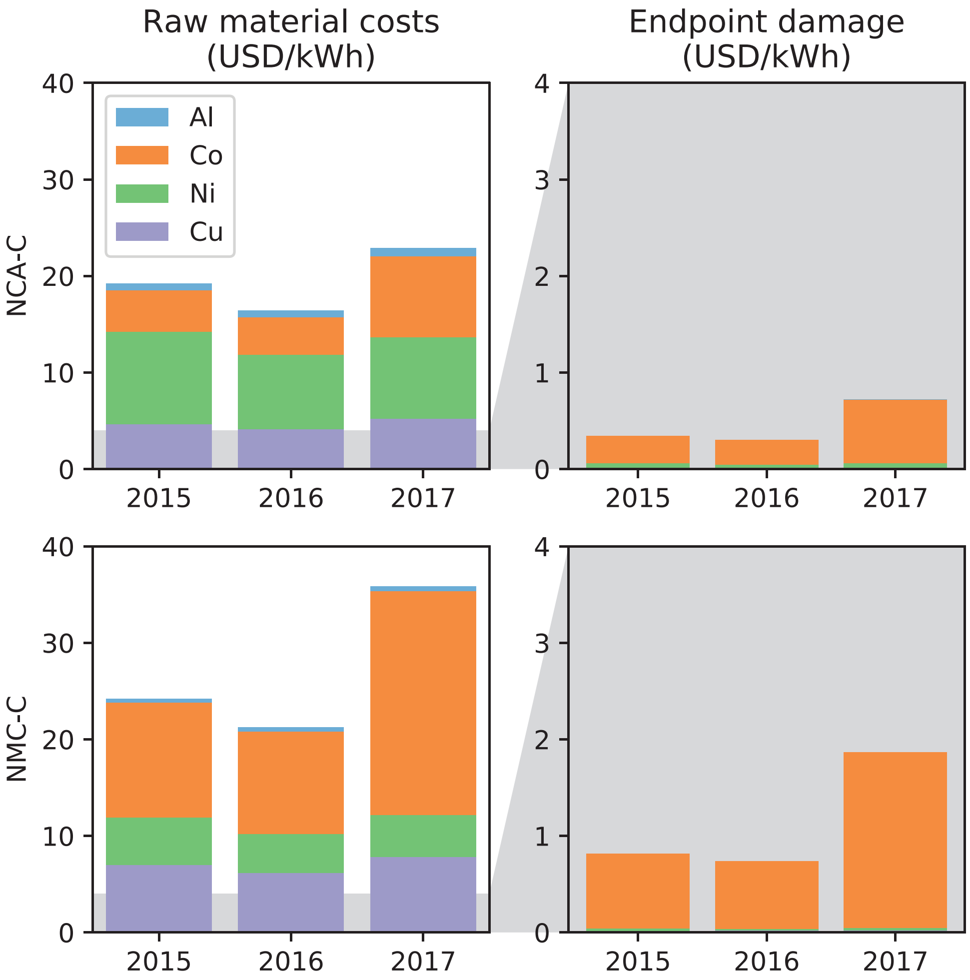

FIGURE 4 Contribution of Al, Co, Ni, and Cu to raw material costs and endpoint damage. Underlying data used to create this figure can be found in the Supporting Information. NCA-C: Nickel-cobalt-aluminium cathode with graphite anode; NMC-C: Nickel-manganese-cobalt cathode with graphite anode

4 | DISCUSSION

The GeoPolRisk method is designed as a regionally differentiated tool to complement LCAs for decision-making processes based on accessibility to Natural Resources, specifically mineral resources. The extension of the method to an endpoint indicator represents a challenge because price considerations for minerals are usually given at a global scale. Therefore, for this first application of the GeoPolEndpoint method, the selection of the OECD country members as a reference group was based on their active participation in the global economy. This decision opens an opportunity to assess the GeoPolEndpoint results from different perspectives; taking advantage of the versatility provided by the regional approach of the GeoPolRisk method, future applications could also focus on other country groups given that these could be considered to have a relevant role in global economy and trade market. The perspective of non-OECD countries could also include the possibility of actually profiting from increased commodity prices, in particular for exporting countries. In this article, however, we follow the argument that higher commodity prices lead to higher consumer prices and therefore a welfare loss.

This first application of the GeoPolEndpoint methodology focuses on LIB. This case study was selected given the availability of information related to the estimation of price elasticity for a large portion of the materials present in the used inventories: 29.7% wt in the case of NCA and 30.9% wt for NMC. Based on the inventories, a main future challenge is the obtention of elasticity values for lithium and manganese; these, despite not being great contributors in mass, could become relevant sources of socio-economic damage when assessing supply risk or subsequent potential increased cost, similar to cobalt.

The main challenge when designing the method is the obtention of elasticity values as these are calculated based on event studies; therefore, these results are not yet statistically significant. The use of a small set of datapoints forces us to assume isoelasticity of the demand function in order to apply the obtained values in the presented endpoint method (Sah & Wada, 2003). The analysis of other types of events like earthquakes, volcanic activity, and wildfire, that also cause supply disruption is encouraged to study effects on the prices of commodities. From the analyzed events, it is relevant to consider the timeframe in which their effects are visible in the global market. Sudden price variations were explored from the five trading days before the event's occurrence until five after the event has passed to capture all possible outcomes. Some predictable events could produce price variations before occurrence, and sudden disruptions could only take effect on the price at later dates. Future assessment of events that cause supply disruption should be studied considering this approach.

Some efforts have been made to develop resource scarcity indicators in LCA. Among these, some examples include the ADP method for resource depletion (Guinée & Heijungs, 1995; Van Oers et al., 2002; Van Oers & Guinée, 2016), the LIME2 method to quantify future externalities of resource use (Itsubo & Inaba, 2012), and the SCP method for future mineral extraction costs (Ponsioen et al., 2014; Vieira et al., 2016), all focused on a long-term perspective. Unlike other methods designed to assess the increase in scarcity of resources, the GeoPolRisk method (midpoint) and the GeoPolEndpoint method (endpoint) are based on the integration of criticality considerations in LCA through the LCSA framework (Sonnemann et al., 2015). The causes and effects of criticality considerations are analyzed in the short term; a continuous assessment of the geopolitical supply risk of raw materials is required to provide up to date information. Data for the midpoint factor from production and trade data can be updated annually. Data on elasticities can be updated once relevant natural disasters are added to the respective databases, which cannot be regular due to the stochastic nature of disasters.

Our method provides results based on resource supply risk and with a focus on primary production of the analyzed materials. In a recent publication by Santillán-Saldivar et al. (2021), the effect of recycling as a risk mitigation strategy is explored and a method is provided to better estimate the geopolitical supply risk taking into consideration the domestic recycling activities. A further integration of these proposed methods could serve to estimate the potential economic benefits or costs of implementing risk mitigation strategies such as recycling or substitution.

In absolute terms and based on the GeoPolEndpoint method, the potential geopolitically driven increased cost for the use of Al, Co, Ni, and Cu in LIB represents between 1.7% and 3.1% of the materials cost in the original inventory for NCA and between 3.3% and 5.2% for NMC. As part of this substantial percentage, it is possible to identify the increasing relevance of cobalt and nickel when moving from the original mass and cost contribution in the life cycle inventory, through the geopolitical supply risk and to the GeoPolEndpoint values. In contrast, the contribution of copper and aluminum to the potential geopolitically driven increased cost becomes negligible, despite their mass contribution to the inventory. These results are mainly caused by the prices and geopolitical supply risk which are assumed independent for purposes of the method.

5 | CONCLUSION

In this article, we designed an endpoint indicator for studying the implications of mineral resources supply risk in the AoP Natural Resources based on the GeoPolRisk method within the LCSA framework. With this enhancement, we address an area of methodological development identified in the work of the Life Cycle Initiative Task Force on Mineral Resources: linking the midpoint-level supply risk indicators to endpoint-level socio-economic damages in LCSA due to the geopolitically driven increased costs (Berger et al., 2020; Sonderegger et al., 2020). We tested our method on aluminum, cobalt, nickel, and copper, four raw materials relevant to the inventory of LIBs. We used the inventory information from NCA and NMC batteries and applied the novel methodology for the years 2015 to 2017 from the perspective of battery producers in the OECD country members. With the developed method, we build steps to assess how the use of certain raw materials could have a substantial economic impact when developing new technologies. We identify the possible shifting of burden from environmental damages, in particular in relation to climate change impacts for low carbon solutions, to new economic costs due to supply constraints.

Similar to other assessments of material criticality, our method faces data limitations, particularly in terms of price elasticity, primary production, and commodity trading (e.g., as reflected in the focus on four key materials that represent about 30% of the mass in the inventory of LIB). Subsequent efforts should be focused on obtaining more comprehensive data on supply disruption produced by different events forming the base to obtain proxy price elasticity values for other relevant materials. Further applications of the methodology could also analyze results from different perspectives and study a procedure to better aggregate countries. Application of the GeoPolEndpoint method is encouraged for the assessment of socio-economic impacts from the point of view of the European Union, the Asia-Pacific Cooperation, or non-OECD countries, among others.

Our designed endpoint methodology aims to quantify the effect of the use of mineral resources in the AoP Natural Resources by providing geopolitically driven increased costs, a socio-economic indicator measured in monetary units proposed as complement to LCA and within the LCSA framework. With the newly introduced method, we build the steps to assess how the use of certain raw materials could have a significant economic impact when developing new technologies, therefore providing a new decision-making tool based on the integration of criticality considerations to life cycle sustainability assessment.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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ORCID

Christoph Helbig https://orcid.org/0000-0001-6709-373X
Guido Sonnemann https://orcid.org/0000-0003-2581-1910

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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