Raw material criticality assessment as a complement to environmental life cycle assessment

Examining methods for product-level supply risk assessment

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Summary

The diversity of raw materials used in modern products, compounded by the risk of supply disruptions—due to uneven geological distribution of resources, along with socioeconomic factors like production concentration and political (in)stability of raw material producing countries—has drawn attention to the subject of raw material "criticality." In this article, we review the state of the art regarding the integration of criticality assessment, herein termed "product-level supply risk assessment," as a complement to environmental life cycle assessment. We describe and compare three methods explicitly developed for this purpose—Geopolitical Supply Risk (GeoPolRisk), Economic Scarcity Potential (ESP), and the Integrated Method to Assess Resource Efficiency (ESSENZ)—based on a set of criteria including considerations of data sources, uncertainties, and other contentious methodological aspects. We test the methods on a case study of a European-manufactured electric vehicle, and conclude with guidance for appropriate application and interpretation, along with opportunities for further methodological development. Although the GeoPolRisk, ESP, and ESSENZ methods have several limitations, they can be useful for preliminary assessments of the potential impacts of raw material supply risks on a product system (i.e., "outside-in" impacts) alongside the impacts of a product system on the environment (i.e., "inside-out" impacts). Care is needed to not overlook critical raw materials used in small amounts but nonetheless important to product functionality. Further methodological development could address regional and firm-level supply risks, multiple supply-chain stages, and material recycling, while improving coverage of supply risk characterization factors.

KEYWORDS

critical raw materials, industrial ecology, life cycle assessment, life cycle sustainability assessment, raw material criticality assessment, supply risk

1 | INTRODUCTION

Though not explicitly required by the international standards (ISO, 2006a,b) on life cycle assessment (LCA), there is general agreement in the LCA community regarding three "areas of protection" (AoPs) to support sustainable development: "human health," "ecosystem quality," and "natural resources." While the first two AoPs are addressed via relatively well-developed life cycle impact assessment (LCIA) methods, LCIA methods for the "natural resources" AoP—particularly regarding mineral resources—have long been controversially debated in the LCA community (Dewulf et al., 2015; Drielsma et al., 2016a,b; Finnveden, 2005; Stewart & Weidema, 2005). Some have even argued that the "natural resources" AoP, at least with respect to mineral resources, does not belong in *environmental* LCA at all (Drielsma et al., 2016a,b), as common notions of "resources" (e.g., CRIRSCO, 2006; OECD, 2017; USGS, 1980) have a fundamentally anthropocentric perspective concerned with the instrumental value of resources for human uses. Nonetheless, a wide range of LCIA methods are available for the "natural (mineral) resources" AoP—each having different problem definitions, assumptions, and modeling approaches (Sonderegger et al., 2017).

Most existing LCIA methods for the "natural (mineral) resources" AoP, like the Abiotic Depletion Potential method (Guinée & Heijungs, 1995; van Oers, de Koning, Guinée, & Huppes, 2002; van Oers & Guinée, 2016), along with "future efforts" methods like ReCiPe (Goedkoop et al., 2009), EcoIndicator 99 (Goedkoop, Hofstetter, Müller-Wenk, & Spriemsma, 1998), IMPACT 2002+ (Jolliet et al., 2003), and Surplus Cost Potential (Vieira, Ponsioen, Goedkoop, & Huijbregts, 2016), have a relatively long-term time horizon (i.e., decades, centuries, or longer) for assessing potential impacts of present consumption on future accessibility of mineral resources. These conventional approaches overlook the importance of resource accessibility over shorter timeframes. The diversity of raw materials used in modern products, compounded by the risks of supply disruptions—due to uneven geological distribution of resources, along with socioeconomic factors like production concentration and political (in)stability of raw material producing countries—has drawn attention to the subject of raw material "criticality." Methods for criticality assessment have been developed outside the LCA community (e.g., European Commission, 2010, 2014, 2017; Graedel et al., 2012; Graedel, Harper, Nassar, Nuss, & Reck, 2015a; National Research Council, 2008). While these assessments have been conducted on a national, regional, or global level, raw material criticality is also relevant on a product-level—to inform product design, material selection, and supply-chain management. There is a growing interest in adapting criticality assessment to a product-level analysis as a complement to (environmental) LCA (Bach et al., 2016; Cimprich, Karim, & Young, 2017a; Cimprich et al., 2017b; Gemechu, Helbig, Sonnemann, Thorenz, & Tuma, 2015; Helbig et al., 2016a; Henßler, Bach, Berger, Finkbeiner, & Ruhland, 2016; Mancini, Benini, & Sala, 2016; Schneider et al., 2014; Sonnemann, Gemechu, Adibi, De Bruille, & Bulle, 2015).

Given that LCA has traditionally addressed environmental aspects with biophysical impact mechanisms—in contrast to the more socioeconomic nature of "criticality"—the idea of connecting criticality assessment to LCA has been controversially debated. Nonetheless, product-level criticality assessment is a valuable *complement to* environmental LCA that could be considered part of a broader life cycle sustainability assessment (LCSA) framework (Schneider, 2014; Sonnemann, Gemechu, Adibi, De Bruille, & Bulle, 2015). There are several motivations for this approach. First, as explained by Cimprich et al. (2017a,b) and Schneider (2014), connecting criticality assessment to a *functional unit*—a central concept in LCA—helps inform product-level design and management decisions. Another useful characteristic of LCA is the capacity to highlight "hotspots" in a product system—that is, specific activities and processes that make large contributions to potential environmental impacts and therefore offer important areas for improving a product's environmental "profile." In a similar way, product-level criticality assessment could highlight "critical raw materials" in terms of the likelihood of supply disruptions and the potential (socioeconomic) impact of these disruptions. Finally, the life cycle inventory (LCI) phase of LCA typically involves constructing a product bill of materials (BOM) that identifies raw material inputs to the product system. Therefore, as Mancini et al. (2016) suggest, raw material criticality—despite being a largely socioeconomic construct—can be linked to physical flows and processes addressed within environmental LCA.

In this article, we review the state of the art regarding product-level criticality assessment as a complement to environmental LCA. The next section briefly describes three existing methods explicitly developed for this purpose: Geopolitical Supply Risk (GeoPolRisk), first developed by Gemechu et al. (2015) and subsequently extended by Helbig et al. (2016a) and Cimprich et al. (2017a,b); the Economic Scarcity Potential (ESP) method developed by Schneider et al. (2014), and the Integrated Method to Assess Resource Efficiency (ESSENZ), which is effectively an extension and update of the ESP method (Bach et al., 2016). We compare the methods in terms of their purpose, key assumptions, and modeling of impact mechanisms. In Section 3, we examine the methods based on a set of criteria, with an emphasis on data sources, uncertainties, value choices, and other contentious methodological aspects. In Section 4, we test the methods on a case study of a European-manufactured electric vehicle. Finally, we conclude with guidance for appropriate application and interpretation, along with opportunities for further methodological development.

2 | DESCRIPTION OF METHODS

The GeoPolRisk, ESP, and ESSENZ methods aim to provide information on raw material "criticality" as a complement to environmental LCA. The concept of criticality is often framed in terms of "risk" of supply disruption (or "supply risk") along with some measure of potential (socioeconomic) impacts of supply disruption—often termed "vulnerability to supply disruption" (Erdmann & Graedel, 2011; Graedel & Reck, 2016). Some criticality assessments include other dimensions such as environmental implications of primary resource extraction and raw material processing (Bach et al., 2016; Graedel et al., 2012; Kolotzek, Helbig, Thorenz, Reller, & Tuma, 2018; Schneider, 2014), thermodynamic constraints on resource accessibility (Calvo, Valero, & Valero, 2017), or social aspects of raw material use (Bach et al., 2016; Kolotzek et al., 2018; Schneider, 2014). In this article, however, we focus on "supply risk" and "vulnerability," as these are the most common notions of "criticality," and the main ones operationalized in the GeoPolRisk, ESP, and ESSENZ methods.

According to a review by Achzet and Helbig (2013), commonly applied notions of "supply risk" in criticality assessment include, but are not limited to, production concentration on a country- or company-level; "country risk" (e.g., in terms of political stability, governance quality, and level of development); and by-product dependency (i.e., some metals, like indium, are "co-produced" with "host" metals, like zinc). In a subsequent review, Helbig, Wietschel, Thorenz, and Tuma (2016b) identified substitution potential (or "substitutability") as the most frequently applied notion of vulnerability in criticality assessment, followed by several "importance" calculations like value of products, value of materials, and strategic importance. As argued by Glöser, Tercero Espinoza, Gandenberger, and Faulstich (2015) and Frenzel, Kullik, Reuter, and Gutzmer (2017), what is commonly termed "supply risk" in criticality assessment arguably represents *probability* of supply disruption. Therefore, in accordance with classical risk theory, we define "supply risk" as a function of supply disruption probability *and* vulnerability. From this point forward, we use the term "product-level supply risk assessment" to encompass the GeoPolRisk, ESP, and ESSENZ methods.

There are fundamental differences between product-level supply risk assessment and conventional LCIA methods. First, in the words of business strategy scholars (Porter & Kramer, 2006), conventional LCIA methods concern potential "inside-out" impacts *of a product system* on the environment (e.g., contributions to climate change, acidification, and particulate matter formation). In contrast, product-level supply risk assessment concerns potential "outside-in" impacts (Porter & Kramer, 2006) of raw material supply disruptions *on a product system* (or, perhaps more accurately, the manufacturer of the product system) —for example, impaired product performance, increased production costs, and/or lost revenue due to production shutdowns. The "outside-in" impact mechanism of supply risk is the main reason why we consider supply risk as a *complement to* environmental LCA. Second, there is a key difference in the type of flows to be assessed. In conventional LCIA methodology per the international LCA standards (ISO, 2006a,b), characterization factors (CFs) are applied only to "elementary flows" from the LCI. ISO (2006a) defines an "elementary flow" as "material or energy entering the system being studied that has been drawn from the environment *without previous human transformation*, or material or energy leaving the system being studied that is released into the environment *without subsequent human transformation*" (3.12, emphasis added). This definition implies that "elementary" flows, like ores and emissions, cross the boundary between the product system and the environment.

However, the total supply risk associated with a product system is a function of its *entire supply chain*, for example, as qualitatively described by Sprecher et al. (2015) in a supply-chain resilience analysis for rare earth elements. Therefore, many of the relevant flows for supply risk assessment occur *within* the product system. Consequently, product-level supply risk assessment cannot be done solely on the basis of "elementary flows." Rather, CFs need to be applied to *intermediate* flows as well. "Intermediate flows" are defined by ISO (2006a) as "product, material or energy flows occurring *between unit processes* of the product system being studied" (3.22, emphasis added). Much like the "inherent toxicity" of intermediates in each stage of chemical synthesis (Eckelman, 2016), supply disruption risks are incurred in each stage of a product's supply-chain. We collectively refer to elementary and intermediate flows as "inventory flows."

The following subsections explain how the GeoPolRisk, ESP, and ESSENZ methods assess product-level supply risk using proxy indicators for supply disruption probability and vulnerability. We describe and compare the modeling of impact mechanisms, while highlighting key assumptions.

2.1 | Supply disruption probability

Figure 1 illustrates impact mechanisms linking political (in)stability of upstream raw material producing countries to supply disruption risks (equivalent to an LCIA midpoint) and ultimately to potential socioeconomic impacts on downstream countries or companies manufacturing a given product (equivalent to an LCIA endpoint). Although the ESP and ESSENZ methods, unlike the GeoPolRisk method, also consider a wider range of factors relevant to supply disruption probability, including mining capacity, recycling, price volatility, demand growth, and others (as detailed in the supporting information Table S1-1 available on the journal's website), the modeled impact mechanisms for those factors are conceptually similar to the mechanisms illustrated for political (in)stability in Figure 1. As a country-level measure of political stability, all three methods use some form of the Worldwide Governance Indicators (WGIs) published by the World Bank (2018). In the GeoPolRisk method, only the indicator "political stability and absence of violence and terrorism" is used. The ESP method combines three WGIs (voice and accountability, political stability and absence of violence and terrorism, and government effectiveness) into an equally weighted index. Along with the WGIs considered in the ESP method, the ESSENZ method also considers regulatory quality, rule of law, and control of corruption.

As illustrated in Figure 1, supply disruption probability is also a function of mediating factors that influence the likelihood and severity of supply disruptions arising from political (in)stability of raw material producing countries. The GeoPolRisk method weights the WGI values of upstream raw material producing countries by their import shares to downstream product manufacturing countries. The ESP and ESSENZ methods, in contrast, calculate a global average WGI index using country production shares of raw materials. Whereas the ESP and ESSENZ methods aim to provide global-level CFs that can be applied by multinational companies having operations all over the world, the GeoPolRisk method aims to express supply risk for a particular downstream product manufacturing country as a function of its trading relationships with upstream raw material producing countries. Another methodological difference is that, whereas the ESP and ESSENZ methods model production concentration, measured by the Herfindahl–Hirschman Index (HHI) (Herfindahl, 1950; Hirschman, 1945), separately from political stability, the GeoPolRisk method incorporates the HHI as a mediating factor in supply disruption probability arising from political (in)stability of trade partner countries. The HHI is calculated as the sum of the squared production shares of all producers (which can be countries or companies), and ranges from 0 (indicating a perfectly competitive market) to 1 (indicating a pure monopoly). In the logic of the GeoPolRisk method, highly concentrated production of raw materials limits the ability of importing countries to restructure trade flows in the event of a disturbance (such as political unrest) that may lead to supply disruption. The HHI and import shares thus measure the tendency toward "having all your eggs in one basket," while the WGI value of each trade partner represents a "source" of risk (or at least a proxy thereof). Helbig et al. (2016a) modified the GeoPolRisk method to account for domestic production, which is assumed to be "risk-free" from a geopolitical perspective.

The ESP and ESSENZ methods also differ from the GeoPolRisk method by applying a "distance-to-target" approach based on Müller-Wenk and Ahbe (1990) and Frischknecht, Steiner, and Jungbluth (2009). A calculated WGI index that exceeds the "target" value for political (in)stability

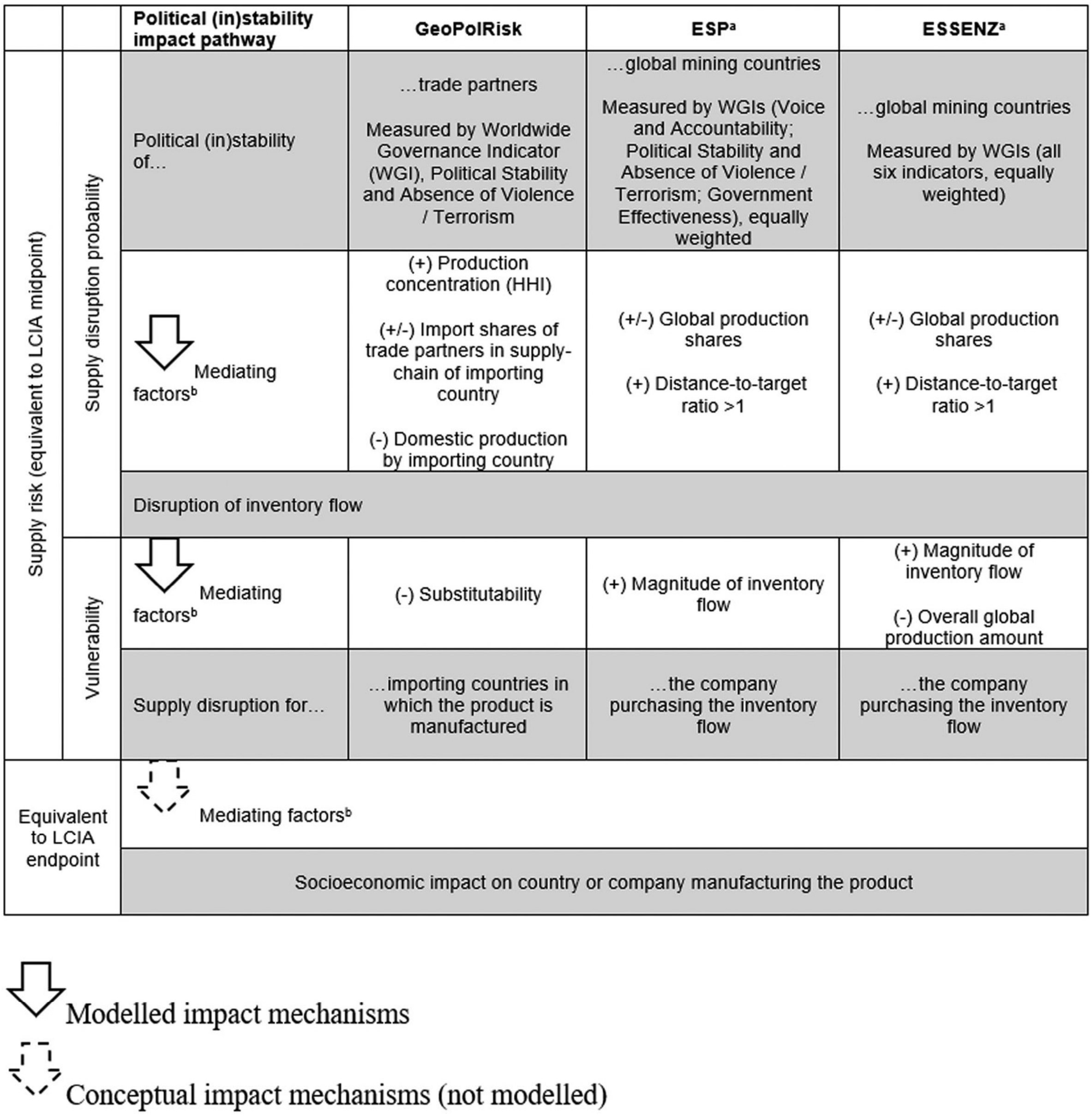

FIGURE 1 Impact mechanisms from political (in)stability of raw material producing countries to potential socioeconomic impacts on downstream countries or companies manufacturing a product

Note. [a]Whereas the GeoPolRisk method focuses only on political (in)stability as one factor in supply disruption probability, the ESP and ESSENZ methods also consider other factors (such as mining capacity, recycling, price volatility, demand growth, and others) that are not shown in this figure. Modeled impact mechanisms for these other factors, as detailed in Supporting Information S1 available on the Web, are conceptually similar to those for political (in)stability illustrated in this figure.

[b]Mediating factors are those that explain cause–effect relationships. Factors with a (+) are positively related to supply risk, while factors with a (−) are negatively related to supply risk. Factors that can positively or negatively influence supply risk are indicated with a (+/−).

indicates high probability of supply disruption. Similar logic applies to the other supply disruption probability factors considered within the ESP and ESSENZ methods, as detailed in Table S1-1 available on the Web. Although the ESP and ESSENZ methods are similar in their approach for calculating CFs, they differ in considered supply disruption probability factors, indicators used to measure these factors, and target values for the indicators (details in Table S1-1 available on the Web). Though it is possible to aggregate CFs for all supply disruption probability factors into an "overall" supply disruption probability CF (e.g., by applying equal weighting as suggested by Schneider et al. (2014), such aggregation is not recommended for the ESSENZ method due to uncertainty regarding the relative importance of the various factors (Bach et al., 2016).

2.2 | Supply disruption vulnerability

The GeoPolRisk, ESP, and ESSENZ methods also differ in their approach to supply disruption vulnerability. With respect to the GeoPolRisk method, Cimprich et al. (2017b) developed a "product-level importance" factor that effectively "cancels out" the magnitude of inventory flows. The basic

TABLE 1 Parameter uncertainty for GeoPolRisk, ESP, and ESSENZ methods

Supply risk factor	GeoPolRisk	ESP	ESSENZ
Political stability	Worldwide Governance Indicators (WGIs): 90% confidence intervals (World Bank 2018)	Worldwide Governance Indicators (WGIs): 90% confidence intervals (World Bank 2018)	Worldwide Governance Indicators (WGIs): 90% confidence intervals (World Bank 2018)
Production (primary)	USGS mineral commodity summaries (USGS 2016) or similar: no uncertainty information	USGS mineral commodity summaries (USGS 2016) or similar: no uncertainty information	USGS mineral commodity summaries (USGS 2016) or similar: no uncertainty information
Commodity trading	UN Comtrade (United Nations 2018): no uncertainty information	Not applicable	Not applicable
Inventory flows	Case specific; depends on data sources	Case specific; depends on data sources	Case specific; depends on data sources
Substitutability	Ordinal ranking of "closest substitute" performance (Graedel et al., 2015b): qualitative discussion of uncertainty	Not applicable	Not applicable

rationale behind this idea is that, like ingredients in food (Peck, 2016), every input to a product system is assumed to be equally necessary for product performance (as defined by the functional unit in LCA), regardless of the *amounts* of the inputs. "Cancelling out" the magnitude of inventory flows further implies that GeoPolRisk CFs are not only specific to a given importing country, but to a particular product system as well. In contrast, the ESP and ESSENZ methods assume that, all else being equal, inventory flows of larger magnitude imply higher vulnerability to supply disruption. The ESSENZ method builds upon the ESP method by normalizing the magnitude of an inventory flow for the product system by the corresponding global production amount. All else being equal, a higher global production amount is assumed to mitigate supply disruption. Along with their "product-level importance" factor, Cimprich et al. (2017a) further extended the GeoPolRisk method to incorporate "substitutability" of inventory flows as a risk mitigation factor, using semiquantitative indicator values from a study by Graedel, Harper, Nassar, and Reck (2015b).

3 | EXAMINATION OF METHODS

In this section, we examine the GeoPolRisk, ESP, and ESSENZ methods based on a set of criteria described in Table S1-2 available on the Web. Some of the criteria, such as those pertaining to the modeling of impact mechanisms, are mainly descriptive, and have already been addressed in the previous section. The following subsections focus on data sources and uncertainties (including parameter uncertainty and model uncertainty), along with value choices and other contentious methodological aspects.

3.1 | Parameter uncertainty

As summarized in Table 1, parameter uncertainty is attached to all supply disruption probability and vulnerability factors addressed within the GeoPolRisk, ESP, and ESSENZ methods, as well as the inventory flows to which CFs are applied. First, all three methods require data on raw material production quantities and political stability of producing countries. While the World Bank (2018) provides confidence intervals for its WGI indicator values, uncertainty information is not typically provided for raw material production data such as those from the USGS (2016). Uncertainty information is also typically missing for commodity trade data, such as those from the UN Comtrade database (United Nations, 2018), needed for the GeoPolRisk method. Trade data can be particularly difficult to obtain for very specific commodities, which often lack an appropriate commodity code (e.g., the rare earth metals neodymium and gadolinium), or are aggregated into a single commodity code (e.g., HS 26 15 90 for "niobium, tantalum, vanadium ores and concentrates").

Identification and quantification of inventory flows contributes another source of parameter uncertainty. While obtaining high-quality inventory data is a common challenge in LCA, it is especially problematic for supply risk assessment. Inventory flows of small magnitude may be "cut-off" due to (presumably) minimal importance to environmental impact categories and (long-term) impacts on resource accessibility, yet these small inventory flows could be some of the most important ones for supply risk assessment. Critical raw materials, like indium, antimony, and selenium, are often used in small amounts but nonetheless play important roles in product functionality and may have limited substitution potential (Graedel et al., 2015a). Consequently, product-level supply risk assessment requires a fully comprehensive accounting of *all* inventory flows, no matter how small they may be. The problem of small flows with large impacts can also occur in some environmental LCA impact categories, like human toxicity and ecotoxicity.

Other important inventory considerations in product-level supply risk assessment pertain to the boundaries of the studied product system. "Background" inventory flows not directly incorporated into the BOM of the end-use product, but nonetheless necessary for production processes (e.g., production of manufacturing equipment, process chemicals, supplies, and energy flows), may be subject to supply risks that could impact the product system. The background system is also interesting for considerations of substitutability. For example, a producer of solar photovoltaic (PV) panels could face supply risks for materials used in these products, but a company using solar energy in a manufacturing process could substitute another energy source in the event of a supply disruption impacting producers of PV panels. Ideally, product-level supply risk assessment should consider the product BOM along with production losses and background inventory flows. Regarding the background system, however, it is important to distinguish between "consumable" inventory flows purchased on a continuous basis (e.g., fuels, lubricants, and process chemicals) and capital assets (e.g., machinery and infrastructure) that are amortized over a period of time. The former category is more relevant to short-term supply risk. Due to limitations of data availability and/or methodological aspects, production losses and background inventory flows are not presently accounted for in the GeoPolRisk, ESP, and ESSENZ methods.

Finally, uncertainty is attached to material substitutability indicator values such as those from the aforementioned study by Graedel et al. (2015b). Their indicator values are derived from opinions of interviewees, each of whom evaluated the performance of the "closest substitute" for a given metal in a particular application (e.g., tungsten in cemented carbides used in high-performance cutting tools). Substitute performance was rated on an ordinal scale from "exemplary" to "poor." Although this approach is somewhat subjective, as Cimprich et al. (2017a) argue, its validity is supported by interviewing key informants (e.g., product designers and material scientists) who are likely to have relevant knowledge and expertise, and may even be making decisions about actual material substitutions. Moreover, the Graedel et al. (2015b) study covers a wide variety of raw materials (62 metals were assessed) across a broad spectrum of applications. An alternative approach, as employed in the 2017 update of the European Commission's criticality assessment (Blengini et al., 2017; European Commission, 2017), uses the term "substitution" (to reflect the *present* availability of known substitutes) instead of "substitutability" (i.e., the potential for *future* substitutions). Even where substitutes are presently available, substitution does not provide an immediate response to supply disruptions (Blengini et al., 2017; European Commission, 2017; Sprecher et al., 2017); there can be a significant time lag (which can be years or decades) for implementation (e.g., to make necessary adjustments to product design and manufacturing processes). The less "substitutable" a commodity is (e.g., due to differences in chemical and material properties), the longer this time lag is likely to be.

Aside from a Monte Carlo analysis conducted by Gemechu et al. (2015) for GeoPolRisk (supply disruption probability only) of beryllium imported to the EU-28, no further quantitative assessment of parameter uncertainty has been conducted for the GeoPolRisk, ESP, or ESSENZ methods.

3.2 | Model uncertainty

While parameter uncertainty is important, the most fundamental sources of uncertainty attached to the GeoPolRisk, ESP, and ESSENZ methods stem from their simplified modeling of supply risk impact mechanisms. As Frenzel et al. (2017) point out, "supply disruption" is a rather nebulous term. In reality, there could be a whole range of supply disruption events of varying magnitude, scope, and duration—each with a different probability of occurrence (Frenzel et al., 2017; Hatayama & Tahara, 2015). These nuances are not well represented in the GeoPolRisk, ESP, and ESSENZ methods. Moreover, while the GeoPolRisk, ESP, and ESSENZ methods assume that proxy indicators, like the HHI for production concentration and the WGI for political stability, are related to supply disruption probability, the form of this relationship may not be linear as the methods implicitly assume. Similarly, substitution of inventory flows could mitigate supply risk, but this complex multidimensional issue is greatly simplified by assigning each inventory flow an ordinal ranking of "substitutability." Further, indicators like the WGI and the Human Development Index (HDI; used as an indicator of "socioeconomic stability" in the ESP method) may not be independent of each other. Analysis by Graedel et al. (2015a) for 62 metals found few significant correlations between indicators used within their methodology, though there were some moderate correlations—particularly between the WGI and HDI. This is another reason why aggregation of supply risk factors is not recommended in the ESSENZ method. The role of material recycling, which could mitigate supply risk, is not explicitly addressed in the GeoPolRisk method, though the ESP and ESSENZ methods do consider recycled material content (separately from the impact mechanism of political stability illustrated in Figure 1) as a factor for mitigating supply disruption probability (see Table S1-1 available on the Web).

Further modeling complications are related to levels of analysis. While the ESP and ESSENZ methods aim to provide global-level supply risk CFs that can be applied by multinational companies having operations all over the world, this approach may not reflect country-level differences in supply risk based on trading relationships and domestic production. A country-level supply risk assessment, as in the GeoPolRisk method, may not reflect regional and firm-level supply risk factors. Country-level measures of political stability and governance quality, like the WGIs (which are widely used in criticality assessments) do not necessarily reflect variations in governance and stability within countries or industries. Further, while the GeoPolRisk method treats domestic production as "risk-free," a case study of dental X-ray equipment by Cimprich et al. (2017a) brings reason to challenge this assumption. In their study, gadolinium (a rare earth element used in dental X-ray scintillators) was found to have minimal supply risk for a dental X-ray system manufactured in the United States, as the 2015 dataset (USGS, 2016) indicated significant domestic production of rare earth elements within the United States (Cimprich et al., 2017a). However, this domestic production was sourced entirely from one company that went bankrupt in 2017—subsequent to the 2015 dataset (Cimprich et al., 2017a). For some forms of supply risks, such as earthquake-related risks (Nakatani et al., 2017), a *facility-level* analysis may be most appropriate. Nonetheless, import tariffs imposed by the United States in June 2018, and the resulting prospects of a global trade war, underscore the relevance of country-level supply risk factors. As further discussed by Cimprich et al. (2017a), assessment of material substitutability is also complicated by levels of analysis, as materials serve different functional roles from one product to another and even between components of a given product.

Another modeling challenge is the complex multistage structure of globalized product supply chains. The ESSENZ method addresses this issue by incorporating supply risk factors in each of four generic supply-chain stages: ore stocks, mining of ores, raw materials, and (intermediate) product (details in Table S1-1 available on the Web). Political stability—a supply disruption probability factor highlighted in this article—is considered in the ore mining stage. Except for a case study of polyacrylonitrile-based carbon fibers by Helbig et al. (2016a), the limited applications of the GeoPolRisk method thus far implicitly assume a single-stage supply chain from upstream raw materials (such as minerals and metals) to final product manufacturing and assembly. Although Helbig et al. (2016a) developed an extension of the GeoPolRisk method to improve modeling of supply disruption probability in multistage global supply chains, the extended method is not explicitly connected to the functional unit of a product, and does not incorporate vulnerability factors like substitutability. In principle, however, different supply disruption probability and vulnerability factors would be needed for each inventory flow input to each unit process—an enormous exercise in data collection and computation. The simplified modeling of product supply chains in existing supply risk assessment methods is analogous to the tendency of environmental LCA to "lump together" emissions from different unit processes without regard for spatial and temporal variability in environmental impact mechanisms.

Finally, while the GeoPolRisk, ESP, and ESSENZ methods provide a static snapshot of estimated supply risk at a given point in time, product supply chains—and the "outside-in" influences of socioeconomic and other risk factors—are all highly dynamic and complex. This complexity creates data-related challenges (i.e., data need very frequent updates) and modeling challenges (i.e., interactions and feedback loops), which have not yet been addressed.

3.3 | Value choices and other contentious methodological aspects

Along with parameter uncertainty and model uncertainty, the GeoPolRisk, ESP, and ESSENZ methods incorporate several value choices, including the selection and aggregation of political stability indicators—which differs between all three methods—and the "target" indicator values in the ESP and ESSENZ methods. Uncertainty stemming from indicator selection and aggregation could be addressed by looking for associations between indicators and/or by conducting sensitivity analyses. The selection and aggregation of indicators may also depend on the awareness, tolerance, and readiness that decision-makers (i.e., downstream product manufacturers) have for different forms of risk.

Despite the rationale articulated in detail by Cimprich et al. (2017a,b), the idea of "cancelling out" the magnitude of inventory flows—a unique feature of the GeoPolRisk method—remains somewhat counterintuitive. This aspect of the GeoPolRisk method does not reflect the notion of resource efficiency (i.e., minimizing the *amounts* of critical raw materials used)—which is often seen as a supply risk mitigation strategy (e.g., European Commission (2010, 2014, 2017). However, the fact that the GeoPolRisk method "cancels out" the magnitude of inventory flows is *not* meant to imply that the amounts of inventory flows are completely irrelevant to product-level supply risk; rather, the reasoning is that the amounts are irrelevant to the *functionality* of the product. If supply of any number of inventory flows is disrupted, regardless of the amounts in which they are needed, a completed product cannot be produced. The magnitude of inventory flows may nonetheless be relevant to supply risk in other ways. For example, one approach could be to incorporate the risk-mitigating effect of inventory stockpiles or "safety stocks," though this would require further methodological development.

4 | CASE STUDY

To provide a tangible product for discussion, we tested the GeoPolRisk, ESP, and ESSENZ methods on a case study of a European-manufactured electric vehicle—a complex, high-tech product of strategic importance to a low-carbon economy. This case study is based on LCI data compiled by Stolz, Messmer, and Frischknecht (2016), which we "cleaned" to aggregate similar inventory flows (e.g., four entries for copper were merged into one) and to omit some types of inventory flows (e.g., in relation to land occupation and water use) that are not presently addressed by the GeoPolRisk, ESP, and ESSENZ methods. The functional unit is defined as one vehicle kilometer travelled, and the system boundary includes production, operation, and end-of-life of the vehicle, along with construction, maintenance, and end-of-life of roads on which the vehicle is driven. Data are assumed to be representative of Switzerland for the time period of 2014–2016. The original and "cleaned" versions of the LCI are provided in Supporting Information S2.

Figure 2 compares results of the GeoPolRisk, ESP, and ESSENZ methods when considering only inventory flows covered by CFs in all three methods. While this "partial LCI" is not representative of the full product system under study, it helps highlight similarities and differences between the GeoPolRisk, ESP, and ESSENZ methods that can otherwise be difficult to discern given data gaps. All three methods are missing CFs for many inventory flows, and coverage of inventory flows varies between methods (e.g., while cobalt has high supply risk calculated per the ESSENZ method, the GeoPolRisk method does not have a CF for cobalt). Results for all inventory flows (except those without CFs in *any* of the methods, which are omitted for readability) are provided in Figure S1-1 available on the Web. These results must be carefully interpreted to avoid confusing a zero value with a missing CF. It should also be noted that the GeoPolRisk, ESP, and ESSENZ methods each apply a single CF value to all rare earth elements as a group, rather than distinguishing between individual rare earth elements. This is an important limitation, as the supply risks are unlikely to be the same for all rare earth elements. Cerium, for example, is presently overproduced from rare earth deposits, and this overproduction could affect supply risk calculations (e.g., in the "mining capacity" category of the ESSENZ method).

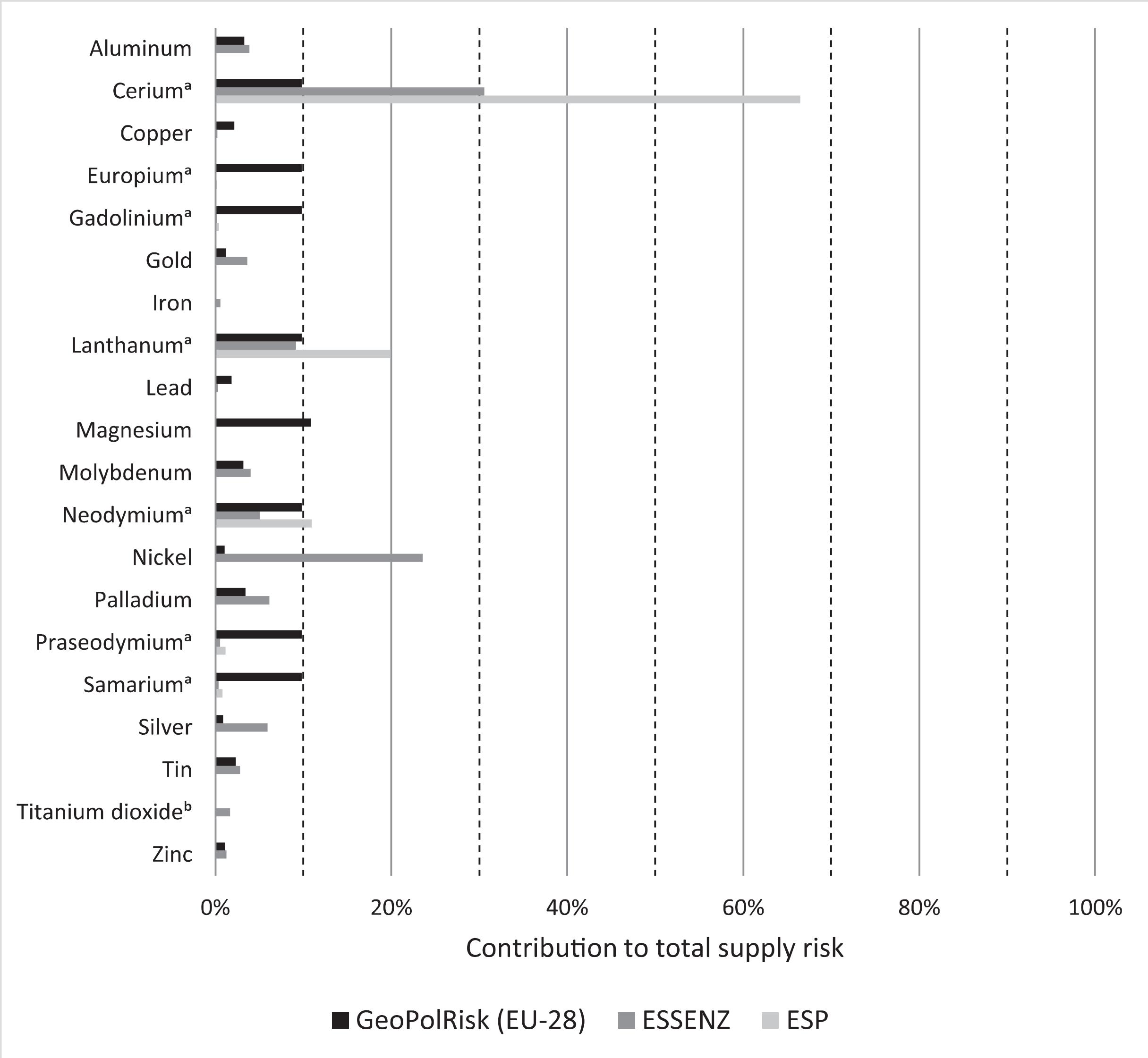

FIGURE 2 Supply risks of raw materials used in a European-manufactured electric vehicle. To avoid confusion between a zero value and a missing supply risk characterization factor, this figure includes only raw materials that are covered by CFs in all three of the GeoPolRisk, ESP, and ESSENZ methods

Note. [a]The GeoPolRisk, ESP, and ESSENZ methods each apply a single CF value to all rare earth elements (cerium, europium, gadolinium, lanthanum, neodymium, praseodymium, and samarium).

[b]The CF value of titanium is used as a proxy for titanium dioxide in the ESP and ESSENZ methods.

Given that a single CF value is applied to all rare earth elements, the GeoPolRisk method's unique approach of "cancelling out" the magnitude of inventory flows results in all rare earth elements being assessed with equivalent supply risk regardless of the amounts in which they are used. The ESP and ESSENZ methods, in contrast, assess rare earth elements used in larger amounts (like cerium) with higher risk than those used in smaller amounts (like europium and gadolinium). Magnesium, which has relatively high country-level production concentration, is assessed with higher supply risk per the GeoPolRisk method than per the ESP and ESSENZ methods. Nickel is used in a relatively large amount, which contributes to its higher supply risk per the ESSENZ method compared to the ESP and GeoPolRisk methods. The higher supply risk of nickel per the ESSENZ method compared to the ESP method could be attributed to data updates and differences in considered supply risk factors and calculation of CFs. It is also important to recognize that the ESP and ESSENZ methods calculate global average supply risk CFs, whereas GeoPolRisk CFs are specific to a given geographical area (the EU-28 in this case). Finally, whereas the GeoPolRisk method only assesses supply risk arising from political (in)stability of trade partners, the ESP and ESSENZ methods consider a wider range of supply risk factors—such as demand growth, mining capacity, trade barriers, feasibility of exploration projects, price volatility, and co-production (see Table S1-1 available on the Web)—alongside political stability of raw material producing countries. These factors are not intended to be aggregated into an overall CF; aggregation was performed in this case study for illustrative purposes only (disaggregated results are presented in Figure S1-2 available on the Web. Finally, given data gaps, the GeoPolRisk results presented in Figure 2 do not include substitutability of inventory flows, which could mitigate supply risks to some extent.

5 | CONCLUSIONS AND RECOMMENDATIONS

In this article, we have reviewed the state of the art regarding product-level supply risk assessment as a complement to environmental LCA. We described and compared three methods explicitly developed for this purpose—GeoPolRisk, ESP, and ESSENZ—in terms of their purpose, key assumptions, and modeling of impact mechanisms. We examined the methods based on a set of criteria, with an emphasis on data sources, uncertainties, value choices, and other contentious methodological aspects. We then tested the methods on a case study of a European-manufactured electric vehicle. Ultimately, we aim to provide guidance for appropriate application and interpretation, while highlighting opportunities for further methodological development. Despite their limitations, the GeoPolRisk, ESP, and ESSENZ methods can be useful for preliminary assessments of "outside-in" product-level supply risk as a complement to "inside-out" environmental LCA. The ESSENZ method, which is more comprehensive and current than the preceding ESP method, is suitable for calculating global average supply risk CFs that can be applied by multinational companies having operations all over the world. This method also incorporates a wide range of supply risk factors. The GeoPolRisk method is suitable for country-level supply risk assessment, though it is more narrowly focused on supply risks arising from political (in)stability of trade partners from which inventory flows are imported. In any case, care is needed with respect to "cut-offs" in the LCI, so as to not overlook critical raw materials used in small amounts but nonetheless important to product functionality. Opportunities for future methodological development include, but are not limited to, increased spatial resolution of CFs (e.g., by assessing regional and firm-level supply risk factors not captured by existing global or country-level assessments), improved modeling of multiple supply-chain stages (e.g., mining, smelting, and refining of metals, and perhaps even downstream product fabrication and manufacturing stages), and assessment of the risk-mitigating potential of material recycling. Further, there is a need to broaden the coverage of supply risk CFs, while increasing the granularity of inventory flows covered (e.g., by disaggregating the category of rare earth elements). CFs also need regular updates to reflect ongoing changes in raw material production, commodity trading, and geopolitical conditions. Finally, greater computational power and/or integration into LCA software could facilitate practical application of product-level supply risk assessment.

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CONFLICT OF INTEREST

The authors have no conflict to declare.

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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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