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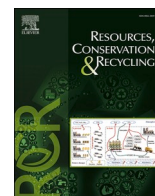
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Full length article

Spatially and temporally differentiated characterization factors for supply risk of abiotic resources in life cycle assessment

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ABSTRACT

Life cycle assessment, a comprehensive tool to evaluate environmental impacts across a product's life cycle, traditionally focuses on "inside-out" impacts caused by the product on the environment, emphasizing resource use, global warming, and other environmental impacts. In contrast, the "outside-in" perspective considers resource availability and accessibility to industry. This second perspective was developed as a way to integrate raw material criticality assessment into LCA. The GeoPolRisk method assesses the supply risk based on global production concentration, import shares, political stability scores, and the average price of the commodity. This article introduces a characterization model for the GeoPolRisk method and calculates the Geopolitical Supply Risk Potential of using 46 raw materials across different countries in multiple years. The characterization factors show the highest values for precious metals, like platinum group metals (PGMs), reflecting their high market prices and concentrated production in geopolitically unstable regions. The results emphasize the significance of spatial and temporal variations in characterization factors, providing a nuanced assessment of supply risk of raw materials associated with the product system. Despite data limitations, the characterization factors offer a good estimate of the supply risk of raw materials available for use in product systems. A case study on photovoltaic laminate production highlights gallium, copper, and tin as significant contributors to supply risk. From an "outside-in" perspective, the case study demonstrates how the GeoPolRisk method complements traditional environmental indicators such as global warming, making it a valuable tool for assessing mineral resource supply risk in Life Cycle Assessment.

1. Introduction

Assessing the impacts of abiotic resource use has been a topic of discussion in the field of life cycle assessment (LCA) for a decade (Dewulf et al., 2015; Drielsma et al., 2016). LCA is a comprehensive tool that assesses the environmental impacts throughout the life cycle of a product or process. The general impact pathways, which encompass all exchanges between the product system and the environment, relate to three areas of protection (AoP) used in LCA (Finnveden et al., 2009; Guinée et al., 2011). Existing methods that quantify the impacts of abiotic resource use address issues like resource depletion, scarcity, or dissipation (Drielsma et al., 2016; Udo de Haes and Lindeijer, 2002), and describe the impacts on the AoP resulting from the product system's use of resources, often referred to as "inside-out" impacts (Udo de Haes and Lindeijer, 2002). From another perspective, several articles have highlighted the significance of resource availability and accessibility when

addressing the impacts of resource use on the AoP, especially regarding natural resources (Charpentier Poncelet et al., 2022; Dewulf et al., 2015; Drielsma et al., 2016; Sonnemann et al., 2015). These impacts that influence the product system are referred to as "outside-in" impacts, which sparked interest in integrating raw material criticality assessment into LCA (Cimprich et al., 2019; Sonnemann et al., 2015).

Raw material criticality refers to the evaluation of the economic and technical dependence on a specific raw material, as well as the probability of potential disruptions in its supply within a defined timeframe, for a particular stakeholder group (Graedel et al., 2015; National Research Council, 2008). This definition aligns closely with the conventional risk theory, where criticality can be defined in terms of "risk" and "vulnerability to supply risk" (Achzet and Helbig, 2013; Cox, 2009). Commonly used indicators for supply risk include mineral production concentration, import risk, depletion potential, recyclability, and by-product dependency (Achzet and Helbig, 2013; Schrijvers et al.,

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2020). On the other hand, direct material substitutability remains a prominent indicator for assessing vulnerability (Achzet and Helbig, 2013; Schrijvers et al., 2020). Most of the criticality assessment methods address the supply risk of a raw material with the goal to inform relevant stakeholders or policymakers on the issues with its supply and demand (Schrijvers et al., 2020). The supply risk of a raw material varies relative to different economies; for example, raw materials like helium, boron, and gallium pose a higher supply risk to the EU compared to the US, and this risk can vary across different years (IRENA, 2024; Siddhantakar et al., 2023).

The third dimension of criticality, “environmental implications” was introduced by Graedel et al., referring to the environmental impacts of the use of the critical raw material (Graedel et al., 2012). While LCA traditionally evaluates the environmental impacts from an “inside-out” perspective, various product-level criticality methods were developed to complement LCA from an “outside-in” perspective. A review of criticality assessment methods (Schrijvers et al., 2020), considering their goals and scope, has identified product-level assessment methods such as ESSENZ methods, the integrated method to assess resource efficiency (Bach et al., 2016), and the GeoPolRisk method, a life cycle criticality assessment method (Gemechu et al., 2015). Their compatibility with LCA has been assessed by different projects, such as the United Nations Environment Programme Life Cycle Initiative (UNEP-LC INITIATIVE) (Berger et al., 2020; Sonderegger et al., 2020) and the ORIENTING project (Operational Life Cycle Sustainability Assessment Methodology Supporting Decisions Towards a Circular Economy) (Bachmann et al., 2021; Hackenhaar et al., 2024) which specifically assesses their compatibility with the Life Cycle Sustainability Assessment (LCSA) (UNEP, 2011). UNEP-LC INITIATIVE has recognized the ESSENZ method and GeoPolRisk methods as relevant for addressing potential accessibility issues in a product system (Berger et al., 2020). On the other hand, the ORIENTING project recommends the GeoPolRisk method, as it evaluates the supply risk of raw material to a specific country, region, or company within a defined period, while ESSENZ is a comprehensive resource efficiency method providing global values for supply risk and other indicators (Hackenhaar et al., 2022).

The GeoPolRisk method, originally developed by Gemechu as a midpoint characterization factor (CF) in LCA (Gemechu et al., 2015), quantifies supply risk by considering the global production concentration of raw materials and the import shares of trade partners, weighted by the country’s political stability score. It evaluates the supply risk for a country/group of countries/region for a given time period. Over time, this method has seen several enhancements, including incorporating domestic production (Helbig et al., 2016) and recycling of resources as risk mitigation factors (Santillán-Saldivar et al., 2021a). The above-mentioned projects (ORIENTING and UNEP-LC INITIATIVE) have reviewed this method and provided recommendations to enhance its compatibility with LCA.

Previous studies on the GeoPolRisk method have implemented most of these recommendations, such as extending the method from the midpoint to the endpoint, which directly relates to the AoP natural resources (Santillán-Saldivar et al., 2021b). Another recommendation was associating the method with the mass flow in life cycle inventories. This was achieved by introducing a new factor at the midpoint level, the yearly average market price of the raw material. This modification allowed the method to associate with the mass flow to measure the geopolitically related supply risk for a product system, representing the amount of resources at risk of supply disruption measured in monetary units (Santillán-Saldivar et al., 2022) and was tested through a case study involving four raw materials used in the cathode of a lithium-ion battery. However, the main limitation of the studies is that they have applied the CFs to a limited number of raw materials and years, primarily due to the complexity of the calculation and data availability, which is also highlighted in the ORIENTING project report. Another limitation was recognized in the characterization model: the comparability of supply risk with other environmental indicators. Expressing risk

in monetary units could indirectly imply economic damage, which is not intended at the midpoint level but is typically calculated at the endpoint (Santillán-Saldivar et al., 2021b).

This article aims to introduce a characterization model with an equivalence factor for the GeoPolRisk method, using a calculation library and new data sources, to compute spatially and temporally differentiated CFs for direct application in LCA studies which could potentially be used in an LCA software. The goal is to broaden the coverage of the GeoPolRisk method to include 46 abiotic resources, both energetic and non-energetic using updated and reliable data sources for 38 countries and six different years. One set of CFs are then applied to a case study of manufacturing a photovoltaic laminate whose inventory was extracted from the ecoinvent database version 3.9.1. The results are then analyzed and compared to other resource indicators, the Abiotic Depletion (van Oers et al., 2002), and Mineral Resource Scarcity (Vieira et al., 2017), and the discussion emphasizes the unique attributes of the GeoPolRisk method. Finally, the article presents the limitations of the GeoPolRisk method and provides an outlook for future developments to address them.

2. Materials and methods

This section presents a brief overview of the GeoPolRisk method and the modified characterization model, the new data sources used in the computation of the CFs, and then presents the case study on the manufacturing of a photovoltaic laminate using the computed CFs for the US, France, and China.

2.1. The GeoPolRisk characterization model

The GeoPolRisk method was developed to quantify the supply risk of raw materials within a product system to a country, region, or group of countries. It was originally conceived to complement LCA (Gemechu et al., 2015) as a midpoint CF for LCSA. The production concentration is evaluated with the normalized Herfindahl–Hirschman Index (HHI) (from 0 to 1) for raw material extraction or processing, and the political instability is estimated with the Worldwide Governance Indicators (WGI) (Kaufmann et al., 2010). Further developments of the method have incorporated supply risk mitigation factors such as local production and domestic recycling of the raw material (Helbig et al., 2016; Santillán-Saldivar et al., 2021a). The method was then improved to align the GeoPolRisk method with other indicators used in LCA by associating it with mass flows in LCA (Santillán-Saldivar et al., 2022). This article builds upon their characterization model.

The GeoPolRisk method can evaluate the supply risk not only from the perspective of a country but also from the perspective of a region, group of countries, or a company. In this article, they are referred to as an economic unit. The complete equation for calculation of the GeoPolRisk Midpoint of a raw material “A” from the perspective of an economic unit “c” in a given year is as shown in Equation 1:

Equation 1: Equation to calculate the value for the GeoPolRisk midpoint (Santillán-Saldivar et al., 2022)

$$\text{GeoPolRisk Midpoint } CF_{Ac} = HHI_A * \sum_i \left(\frac{g_i * f_{Aic}}{p_{Ac} + F_{Ac}} \right) * \bar{p}$$

HHI_A is the Herfindahl–Hirschman index for raw material “A” calculated as the sum of the squared production shares of all the countries producing raw material “A”. The GeoPolRisk method weights the import (“ f_{Aic} ”) of raw material A to economic unit “c” from “i” with the political (in) stability indicator of the exporting country (“ g_i ”). “ F_{Ac} ” is the total imports to the entity in assessment, and p_{Ac} is the domestic production of raw material A in entity c. The trade data, f_{Aic} , is reduced and redistributed using the end-of-life recycling input rate (“ $EoLR_{iR}$ ”). $EoLR_{iR}$ is an indicator of the contribution of recycling to meet the demand (European Commission, 2018), which is used in the GeoPolRisk method

as a proxy for domestic recycling to evaluate potential supply risk mitigation scenarios. The redistribution of the trade data leads to two different scenarios with values ranging from a best-case scenario (BCS) to a worst-case scenario (WCS). A BCS is where the imports of a country with a high political instability score are reduced, and a WCS is where imports of a country with a low political instability score are reduced (Santillán-Saldivar et al., 2021a). \bar{p} represents the yearly average market price of the raw material in US dollars/ kilogram of raw material. The value, without the price, represents the probability of supply disruption of raw material “A” to economic unit “c”. This value, also known as the *GeoPolRisk score*, is non-dimensional and can primarily be used in comparative risk assessment.

$GeoPolRisk\ Midpoint_{Act}$ has units as US dollars per kilogram of raw material “A” consumed (USD/kg_A). This value indicates “the amount of resources that are at risk of supply disruption and is expressed in monetary units” by multiplying the *GeoPolRisk score* with the yearly average market price of the raw material (Santillán-Saldivar et al., 2022). However, in LCA, a CF represents the contribution per quantity of an elementary flow to a specific environmental impact (here, the geopolitically related supply risk). The unit of a CF is the same for all elementary flows within an impact category. For midpoint categories, it typically relates them to the impact of a reference elementary flow. With the ongoing energy transition, there is a projected increase in demand for metals, notably copper and aluminum. Copper, widely traded and used in numerous applications (K.E.K et al., 2022; Valenta et al., 2019), especially in electricity-related technologies, is expected to maintain high demand despite efforts to increase recycling rates (Harpprecht et al., 2024; IEA, 2021; Watari et al., 2022). Given its significance, copper is often considered a suitable reference for risk assessment. This article presents the midpoint CFs of the *GeoPolRisk* method to an equivalent using copper as a reference as done in the Surplus Ore Potential method (Vieira et al., 2017).

The CF is called Geopolitical Supply Risk Potential (GSP) to evaluate the Geopolitical Supply Risk (GSR) of raw materials consumed in a product/product system. The values for the GSP are obtained by dividing $GeoPolRisk\ midpoint_{Act}$ with the average $GeoPolRisk\ midpoint$ of copper for the countries and over 5 years (2017 to 2020) as shown in Equation 2 where “A” represents the raw material, “c” represents an economic unit, “t” refers to the time period (year). At the midpoint level, the indicator seeks to quantify “the risk of relative potential accessibility

issues for a product system related to short-term geopolitical and socio-economic aspects?” (Berger et al., 2020). As an import-based indicator, using the characterization model, the CFs represent the supply risk of a raw material equivalent to the supply risk of importing one kilogram of copper to an economic unit at a given time period. This provides a way to compare the GSR for different processes or product systems using a common reference. An overview of the framework is presented in Fig. 1.

Equation 2: The *GeoPolRisk* characterization model to calculate the Geopolitical Supply Risk Potential

$$Geopolitical\ Supply\ Risk\ Potential\ (GSP_{Act}) = \frac{GeoPolRisk\ midpoint_{Act}}{GeoPolRisk\ midpoint_{copper}}$$

2.2. Data to calculate the geopolitical supply risk potential

The calculation of the GSP is done by a python library, *geopolrisk-py* (Koyamparambath et al., 2023), developed to automate the calculation. The characterization model uses trade data from a comprehensive disaggregated database for bilateral trade flows known as the Database for International Trade Analysis (French acronym, BACI). The traded price is calculated using the “cost, insurance, and freight (CIF) value,” a mechanism commonly used in international trade that considers the cost, insurance, and freight of a product being transported from the seller to the buyer (United Nations, 2023). Global mine production data were obtained from the World Mining Data - 2021 report published by the Austrian Federal Ministry of Finance (FMRA, 2023). Recycling data for all the countries is not publicly available; hence, to maintain consistency in applying CFs, the model used in this article excludes considerations for metal recycling rates. For certain raw materials such as gallium, indium, and rhenium, the trade data is aggregated with other raw materials, and disaggregated datasets for each raw material are not available. To overcome the limitation, the exporting countries are matched with the producing countries to extract the trade data for each of these raw materials. However, in the case of rare earth elements (REE), production data is also aggregated. Consequently, all REEs are grouped together. A supplementary material lists raw materials, trade data, and HS commodity codes, including an explanation of data sources.

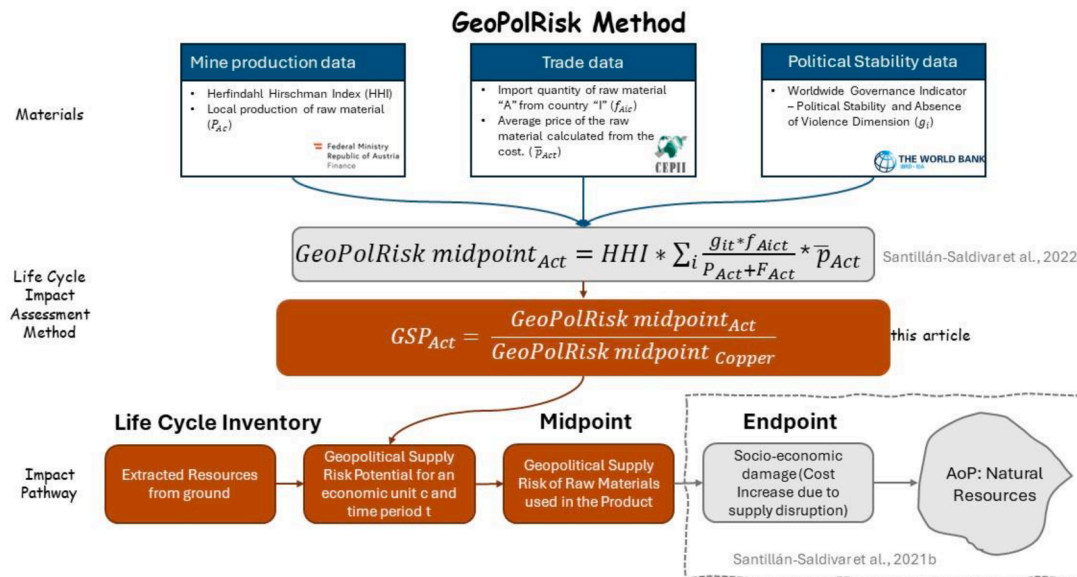


Fig. 1. Overview of the methodological framework, new data sources, and the data required for calculating the GSP using the *GeoPolRisk* method, along with advancements based on previous studies (Santillán-Saldivar et al., 2022). Other references: the *GeoPolRisk* endpoint model by (Santillán-Saldivar et al., 2021b).

2.3. Application of the geopolitical supply risk potential

To demonstrate the application of the GeoPolRisk method in analyzing raw material supply risks, the case of photovoltaic (PV) laminate production using Copper Indium Gallium Selenide (CIGS) technology was examined. The analysis utilized inventory data from the ecoinvent 3.9.1 database, with the selected functional unit being the production of 1m² of PV laminate using CIGS technology.

Amidst the transition to renewable energy sources to reduce greenhouse gas emissions and combat climate change, PV laminates play a crucial role in solar energy systems (IEA, 2023). CIGS is a thin-film PV material with high energy conversion efficiency. It offers monolithically interconnected modules, simplifying the manufacturing process and reducing costs (Eldada, 2011). CIGS also uses significantly fewer raw materials compared to other PV laminate technologies. To assess supply risks for the raw materials in different geographic locations, we assumed production in three distinct regions: the United States (USA), France, and China. We applied spatially differentiated CFs using the GeoPolRisk method to these four countries and analyzed the results.

Mapping the CFs of the GeoPolRisk method to LCI elementary flows presents a challenge primarily arising from the inherent nature of supply risk associated with the traded commodity. Within the context of LCA, the traded commodity refers to the intermediate flow obtained from a mining activity. LCA characterizes the impacts associated with elementary flows, encompassing inputs and outputs. Consequently, applying CFs directly to intermediate flows becomes impractical, as they cannot be automatically traced unless unit processes are considered.

To address this limitation, we assume that, in mining activities in ecoinvent, the elementary input flow of the mineral extracted from the ground is in the same range as the intermediate output flow of the mineral being produced. This assumption is true for most of the mining activities in ecoinvent, except for activities where mineral processing waste is high and mining activities where elementary flows are allocated to co-products having different economic values. This assumption enables the application of CFs to elementary rather than intermediate flows, rendering the GeoPolRisk method feasible in this context.

The GeoPolRisk method takes on the perspective of an economic unit and time period while calculating the CFs for raw materials. Ideally, the geographic location of the elementary flow where the activity occurs is utilized to apply the corresponding CF and calculate the GSR of the product system. However, within the ecoinvent processes, activities involve a combination of flows originating from various geographical locations, and to address this challenge, a potential solution is to assume that all activities occur within a specific geographic location, except for mining activities, and apply the specific CFs to all elementary flows. Nevertheless, the supply risk associated with the primary product is inherently linked to the location of its manufacturing. This is because there's an assumption that the supply risk linked to intermediate products is at least equal to, if not greater than, the supply risk of the raw materials required for producing the intermediate product in the same location where the primary product is made. From an 'outside-in' perspective, the indicator's goal is to quantify the supply risk of raw materials due to 'economic' and 'geopolitical' factors. Using the modified characterization model, it becomes feasible to link the CFs to mass flow, thereby providing a quantitative value for the supply risk of the product through aggregation.

This study applies the GSP for the USA, France and China during the year 2021 to the elementary flows, and the results are compared with other resource indicators in LCA: the Abiotic Depletion which evaluates the depletion of mineral resources based on cumulative production in 2015 (van Oers and Guinée, 2016), and the Mineral Resource Scarcity indicator which evaluates the extra amount of ore mined per unit of resource extracted (Vieira et al., 2017) which is included in ReCiPe 2016 impact assessment method (Huijbregts et al., 2017). The UNEP-LC INITIATIVE also recommends the Abiotic Depletion and Mineral Resource Scarcity indicators to address the impacts of mineral resource

use (Berger et al., 2020). The carbon footprint is evaluated using the IPCC method to assess the burden shift between carbon footprint and supply risk (IPCC, 2013).

3. Results and discussions

The findings are divided into three sections for presentation and discussion. First, the CFs for the USA, China, and France are introduced and analyzed. Subsequently, the outcomes of applying the method to the case study are outlined and discussed. Lastly, a subsection explores how the GeoPolRisk method complements environmental indicators.

3.1. Geopolitical supply risk potential - The CFs for the geopolitical supply risk

Fig. 2 illustrates these CFs for 46 raw materials on a logarithmic scale computed for the USA, France, and China, computed for 2021. A full list of CFs for all the Organization for Economic Co-operation and Development (OECD) countries (38 member countries) from 2017 to 2021 is in the supplementary material.

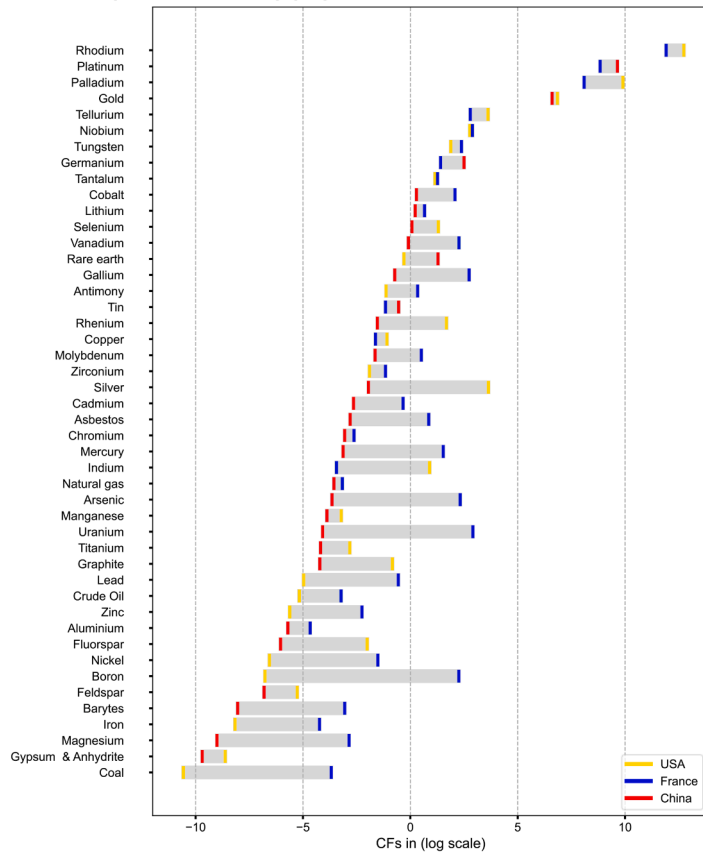
From Fig. 2, Section A, it is evident that platinum group metals (PGMs), specifically rhodium, platinum, and palladium, demonstrate considerably higher CFs compared to other resources. Precious metals like gold and silver also exhibit relatively elevated CFs. Tellurium ranks next highest among specialty metals after PGMs and gold, followed by niobium, tungsten, germanium, and tantalum. Regarding energetic raw materials, uranium displays one of the highest CFs, followed by natural gas, crude oil, and coal. Section A arranges data based on the lowest values among the three countries in 2021, with the bar indicating the extent of difference in CFs between countries, highlighting the highest values at the right edge of the bar. France registers the highest CFs for over 50 % of the 46 raw materials among the three countries. For raw materials such as boron, coal, magnesium, uranium, arsenic, and gallium, among others, France's CFs are significantly higher than those of other countries, especially China. However, for the top CFs (PGMs), France records the lowest values. This analysis underscores the significance of geographical variation in CFs.

One major reason some raw materials exhibit high CFs is due to their production concentration in a few countries. Over 80 % of the world's rhodium production comes from South Africa, and platinum and palladium are produced in South Africa and Russia (USGS, 2023a). China is the dominant producer of gallium, tungsten, vanadium, REE, and graphite (USGS, 2022). Global niobium production is primarily concentrated in Brazil, which also holds 94 % of the world's reserves (USGS, 2023b). Geographical specificity is also important due to the risk of imports, which is influenced by the geopolitical situation of the exporting country. Combined with the high concentration of raw material production, low political stability in the exporting country increases the supply risk of raw materials, particularly evident in the case of raw materials with the top CFs.

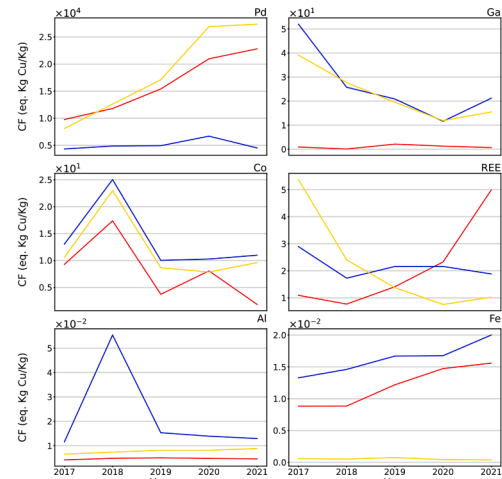
The variation observed within the CFs is due to trade choices made by the importing country and the availability of domestic production. For instance, France's lack of production for raw materials like REE, gallium, magnesium, and iron increases reliance on imports for these resources. On the other hand, the USA and China mitigate their supply risk for these raw materials with their local production. For PGMs, their high CFs are primarily due to the concentrated production and the low political stability of the exporting country. However, when compared to other raw materials, it is the price that plays the most significant role, particularly by orders of magnitude.

The introduction of price into the GeoPolRisk midpoint by Santillan Saldívar et al. in 2022 allows these values CFs to associate supply risk with mass flows (Santillán-Saldívar et al., 2022). However, the price of the raw material is not merely a means to translate mass into supply risk; it also adds inherent value to the indicator. The traded price in this context varies based on bilateral trade deals and policies established between

A. Geopolitical Supply Risk Potential - 2021



B. Metals



C. Energetic Raw Materials

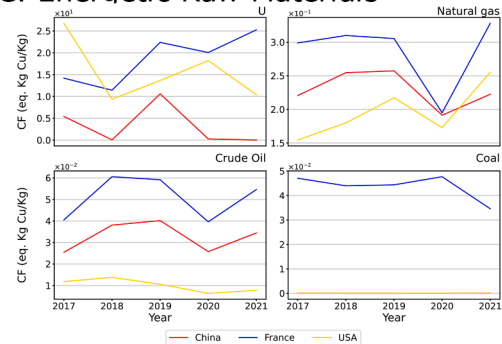


Fig. 2. Geopolitical Supply Risk Potential of 46 raw materials (including energy resources) for the USA, France, and China in 2021. A. illustrates the GSPs in eq. Kg Cu/Kg on a logarithmic scale (base 10), highlighting the country with the highest and lowest values among the USA, France, and China in 2021. B. and C. depict the GSP trends for selected metals and energy resources (in absolute scale), respectively, across the 5-year period from 2017 to 2021 for the USA, France, and China.

importing and exporting countries. While the supply risk score is sensitive to the economic unit under study, the price adds an additional layer of sensitivity. This means that even if the quantity of PGMs used in products is relatively low, their cost and the high supply risk score contribute to a significant risk of supply disruption.

The evolution of supply risk, influenced by factors such as production capacity, trade, political stability scores, and fluctuating prices, impacts CFs from year to year. In Fig. 2, sections B and C, a comparison of CFs for the USA, China, and France from 2017 to 2021 for selected metals and energetic raw materials is presented. For instance, palladium shows an increase in GSP, primarily due to rising prices, as production concentration has remained stable over multiple years with South Africa and Russia dominating. On the other hand, there is a notable decrease in the supply risk of gallium, driven by a price decrease of up to 50 % over the five-year period, although it remains unchanged for China due to it being the largest producer globally. There has been an increase in the GSP of REE for China. This can be attributed to the suspension of operations in Heavy REE mining within China and dependence on countries like Myanmar, where the political situation is unstable, influencing higher CFs. CFs for aluminum and iron have generally remained stable, with occasional peaks, notably in France; however, they remain comparatively lower than other materials. Similar observations are found for energetic raw materials, where energy-producing countries like the USA and China exhibit relative stability, while France shows a higher GSP. Among energy raw materials, uranium stands out with the highest CFs, driven once again by the three factors, particularly price. Other studies have also shown that temporal differences can influence raw material supply risk for an economic unit (Koyampambath et al., 2021). The CFs presented in this article are both spatially and temporally

differentiated, providing a unique aspect to the GeoPolRisk method and setting it apart from other methods in LCA. This differentiation allows for comparative analysis and a more precise calculation of supply risk for the product system.

3.2. Results: the geopolitical supply risk of PV laminate production

The inventory analysis reveals that iron accounts for 50 % of the contribution to raw material consumption. Iron holds a crucial role in the economy, especially in this case study, where it is primarily employed in the construction of structures. Following iron, zinc emerges as the next highest contributor, as it is utilized in the construction of PV laminate. In addition to zinc, metals like copper, cadmium, selenium, tin, gallium, and indium are used in construction when using CIGS technology. Meanwhile, other metals such as barium, lead, aluminum, and magnesium appear in the inventory contribution, though not directly consumed in the construction.

The GeoPolRisk results show that gallium contributes the most to the supply risk, as indicated by the GSR indicator in Fig. 3. Gallium production is primarily concentrated in China, responsible for over 80 % of global production (USGS, 2023a). It is found in trace amounts in bauxite ore (McCullough and Nassar, 2017) and is typically obtained as a by-product of processing other metals like zinc and copper. In July 2023, China introduced export restrictions on gallium and gallium-containing products, consistent with a pattern of past trade restrictions on critical raw materials (Reuters, 2023). To produce 1 m² of PV laminate, 13 g of gallium is required, underscoring its crucial role (Dimmler and Wächter, 2007). The results also show a notable contribution from copper, primarily due to its mass in various processes, followed by tin. Since the CFs

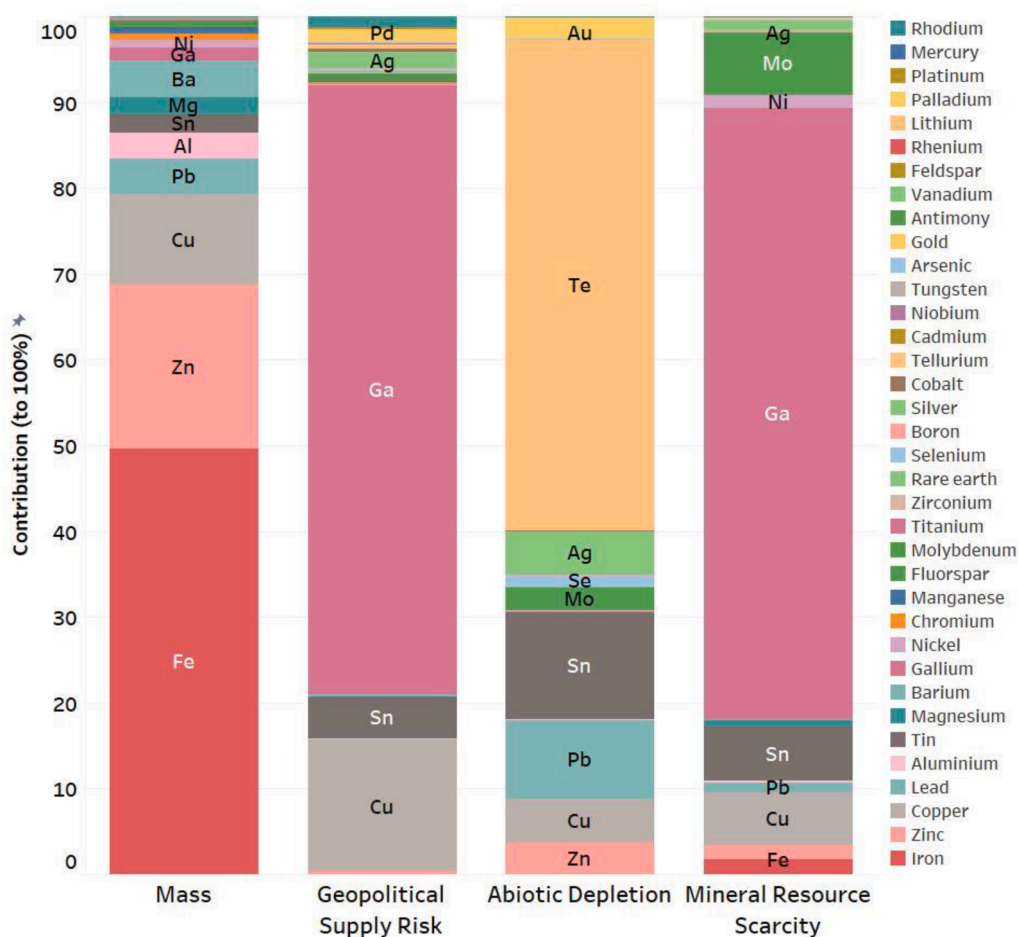


Fig. 3. Contribution of various non-energetic raw materials to the mass of the inventory in producing PV laminates and their Geopolitical Supply Risk, the Abiotic Depletion using ultimate reserves, and Mineral Resource Scarcity (Scarcity).

are also applied to all background processes, including enclosures and oil extraction, barium and zinc also emerge as contributors to the impacts. Fig. 3 displays the results of applying the GSP to the dataset of photovoltaic laminate production in the USA.

Concerning abiotic depletion, Tellurium tends to dominate the results due to its high extraction-to-reserve ratio and therefore its high ADP. Tellurium is not directly used as material for the PV but it is often part of the background processes elementary flows since it is a by-product of copper and gold extraction. Tin makes the second most significant contribution to abiotic depletion, arising from the production of tin concentrate. Lead, zinc, and silver also play a notable role in these results and are extracted during the production of zinc concentrate. In case of gallium, it does not appear in the results of abiotic depletion due to its low extraction rate.

Mineral resource scarcity of gallium was highlighted the most in the ReCiPe2016 method. This indicator focuses on the concept of diminishing ore grades and the additional effort needed to extract the same amount of metal due to the declining quality of ores. (Huijbregts et al., 2017). However, in the case of gallium, it's not simple to calculate the scarcity. The methodology uses ultimate reserves, such as the ADP method which does not reflect the future availability and factors like annual production potential and installed production capacity should be considered. However, the CFs of mineral resource scarcity calculated based on the defined methodology were possible only for 18 mineral resources, which include elements like molybdenum, tin, and copper (Vieira et al., 2017), and remaining values for other mineral resources, such as gallium, are extrapolated based on the price (Huijbregts et al.,

2017). It was studied that there is no equilibrium between the production of gallium and its price, which has an influence on the mineral resource scarcity results and the GeoPolRisk results as well.

3.3. Geopolitical supply risk indicator as a complement to environmental LCA

Fig. 4 compares GSR results to global warming (GW) results on an absolute scale. The results contrast resource-rich countries like China with resource-dependent nations like France and compare the corresponding potential environmental impact such as the GW indicator. The GW with varying electricity mix for the respective country. For China, raw materials used in the production of PV contribute significantly, accounting for over 50 % of the supply risk, while other countries show relatively even higher contributions. The supply risk for producing PV laminates in France is the highest, with contributions coming from raw materials such as zinc, lead, and copper, in addition to gallium.

The results underscore the fact that China produces over 80 % of the world's gallium supply, and its control over several other raw materials has led to a lower supply risk in producing PV laminates. However, it has the highest carbon footprint in this production. In contrast, France has the highest supply risk while maintaining the lowest carbon footprint for PV laminate production. Despite having a relatively decarbonized energy production, France's reliance on raw materials from other countries potentially increases its supply risk. China serves as the primary exporter of raw materials used in PV laminates (IEA, 2022). Germany specializes in silicon PV modules, and the United States produces

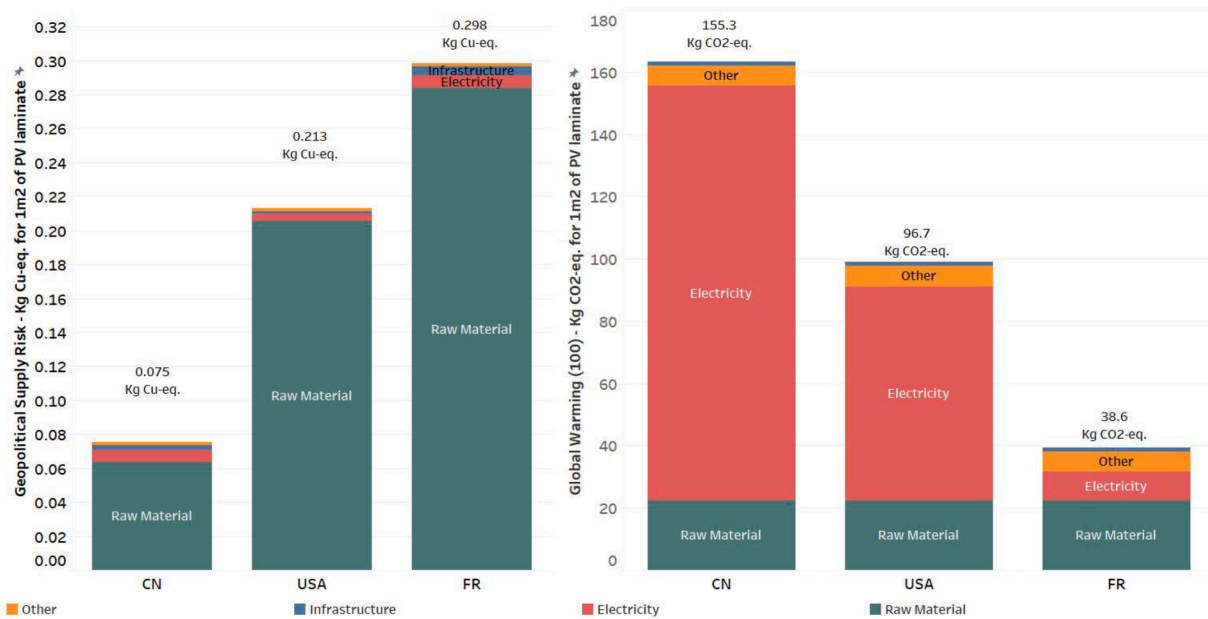


Fig. 4. Contribution of different processes for the Geopolitical Supply Risk (non-energetic) for different countries (China - CN, the USA, and France - FR) compared with their respective global warming impact.

semiconductor-grade products. However, their reliance on raw materials still exposes them to potential supply chain risks. The spatially and temporally differentiated CFs offer practitioners the flexibility to choose the most suitable CF for estimating the supply risk of the product and with this case study, the ease of applicability of the GeoPolRisk method in LCA is demonstrated.

4. Limitations

The GeoPolRisk method is broadly applicable to the extracted metals and minerals. However, calculating the CFs has limitations due to data availability. The same HS code is used for gallium, indium, and rhenium in CF calculation, aggregating their trade data. Extracting trade data based on producing countries in this study introduces uncertainty into CF values. Additionally, CFs for precious metals are calculated at the refinery level due to a lack of mine-level trade data.

Reliable data availability is crucial for CF computation. Despite newer data on trade and governance, detailed and disaggregated datasets for raw material production are lacking. Previous applications of GeoPolRisk method used USGS as a primary source, but their datasets often aggregate minor producers (Cimprich et al., 2017; Helbig et al., 2016; Koyamparambath et al., 2021; Santillán-Saldivar et al., 2022). However, with the data changes made in this article, calculation of the CFs for 46 raw materials were possible. The geopolrisk-py library can also facilitate the calculation of more CFs and also be used as a comparative risk assessment tool.

The CFs applied in the case study are pragmatic and based on what is feasible with publicly available data. Although our data offer an overview of supply risk to the USA, China and France, evaluating the supply risk of the product system requires the application of CFs specific to the actual geographic location. This limitation could promote another area for potential improvement in the database, the accurate attribution of the geographical location where the activity is conducted to the corresponding elementary flow.

This study applies CFs based on the assumption that all activities, except mining, are conducted within a selected country, which often does not reflect reality. This issue can be addressed by tracing intermediate flows in LCA that contain information about the geographic location, enabling the computation of material flows in each process. Current efforts are made to create an automation within the geopolrisk-

py library to associate the computation of CFs based on technosphere flows by integrating it with an LCA software. Such integration could be beneficial to be able to estimate the precise supply risk of a product system considering multiple stages. Moreover, the study acknowledges a lack of precision in CFs, attributed to the exclusion of raw material recycling. This limitation is primarily due to data unavailability, as indicated in the methods section.

When applying the CFs to an LCA database such as ecoinvent there are other limitations. Mining activities with co-products can introduce discrepancies in resource impacts. This is mainly because of the issues in the mass balance introduced by economic allocation in the database. Discussions regarding the drawbacks of pre-allocated databases extending to other impacts are already underway (Howard, 2017). The use of an unallocated database could simplify resource-oriented studies, at least to some extent.

5. Outlook

The ongoing development of the methodology aims to address the current limitations highlighted in the GeoPolRisk method. While applying the CFs to intermediate flows may not follow the conventional LCA guidelines, it can still be pursued to achieve desired outcomes. In the context of life cycle criticality assessment, there is ongoing debate regarding which flow must be considered, with a common agreement being the necessity to apply the CFs to intermediate flows (Helbig et al., 2016), as raw material criticality becomes a concern after it enters the economy. However, this task is not straightforward, especially with the GeoPolRisk method, whose CFs differ geographically. Ongoing studies aim to apply CFs to intermediate flows, interpret the results, and analyze the feasibility of application.

The choice of data source significantly impacts the results of the GeoPolRisk method and, as mentioned as a limitation, introduces considerable uncertainty. The next research direction focuses on evaluating the uncertainty of the GeoPolRisk method and analyzing the sensitivity of data choices, as well as the discrepancies arising from selecting different HS codes.

6. Conclusions

This article presents a modified characterization model for the

GeoPolRisk method to calculate the Geopolitical Supply Risk. The Geopolitical Supply Risk Potential is equated to copper, providing a basis for comparison with other resource and environmental indicators which aims to quantify "the risk of relative potential accessibility issues for a product system related to short-term geopolitical and socio-economic aspects.". This article presents a list of CFs for 46 raw materials for three countries (the USA, China and France) and an extensive list of CFs (for all the OECD countries) are provided in the supplementary material calculated using the geopolrisk-py library. The library also facilitates the calculation of supply risk of 46 raw materials for more countries and for different time periods.

The CFs presented in this article reveal the highest values for precious metals, particularly PGMs, attributed to their high market prices. PGMs exhibit a high supply risk score due to their concentrated production and the geopolitical instability of their producing countries. Specialty metals follow with the next highest CFs. The results highlight variations in CFs for the same raw material across different time periods and economic units. This differentiation, both spatially and temporally, enables a more precise and comparative analysis of the supply risk associated with the product system.

Despite limitations due to data availability and the background database used in LCA, the CFs offer a good estimate of the supply risk potential of raw materials for the product system. To enhance accuracy and achieve a more precise quantification of supply risk, integrating the CFs into existing LCA software would be advantageous.

The case study underscores that the GeoPolRisk method provides a distinctive perspective compared to other resource assessment methods in LCA. Adopting an "outside-in" perspective, the GSR identifies and quantifies the supply risk associated with the raw materials used in the PV laminate, emphasizing significant contributions from materials such as gallium and copper. Gallium, which is a critical raw material obtained as a byproduct of bauxite refining, has a high scarcity and geopolitical supply risk impact. Also, the case study reveals how the GSR impact assessed by the GeoPolRisk method can complement environmental indicators such as carbon footprint and facilitate the analysis of burden shifts. Therefore, with a wide list of CFs provided in the supplementary material for multiple time period, the GeoPolRisk method stands out as a valuable tool for evaluating the supply risk of mineral resources in the context of LCA.

Declaration of generative AI in scientific writing

During the preparation of this work the author(s) used AI in order to refine the language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRedit authorship contribution statement

Anish Koyamparambath: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft. **Philippe Loubet:** Conceptualization, Formal analysis, Supervision, Visualization, Validation, Writing – review & editing. **Steven B. Young:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. **Guido Sonnemann:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.resconrec.2024.107801](https://doi.org/10.1016/j.resconrec.2024.107801).

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