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Supply risk evolution of raw materials for batteries and fossil fuels for selected OECD countries (2000–2018)

Anish Koyamparambath [a,b], Jair Santillán-Saldivar [a,b], Benjamin McLellan [c], Guido Sonnemann [a,b,*]

[a] Université de Bordeaux, ISM, UMR 5255, F-33400, Talence, France
[b] CNRS, ISM, UMR5255, F-33400, Talence, France
[c] Graduate School of Energy Science, Kyoto University, Yoshida-honmachi, Sakyo-ku, Kyoto, 606-8501, Japan

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ABSTRACT

Fossil fuels are the dominant form of storable energy, but their share in the global energy supply is slowly diminishing due to climate mitigation policies. Alternative energy production from variable renewable energy sources for both stationary and mobile use requires some form of energy storage. Batteries are the current frontrunner for this application, particularly with Li-ion batteries that are reliable and highly efficient. However, batteries themselves have evolved to meet current requirements and expectations. These changes in battery chemistry have shifted the dependency on raw materials used to produce them. Raw materials critical for battery production are subject to supply risk due to their availability or trade policies prompting a need for supply risk assessment. Such resource supply risks depend on the perspective of the importing country or region. By analysing the supply risk of raw materials used in the production of batteries in comparison to fossil fuels, it is possible to understand the shift in risk to storable energy that is underway. In this study, we analyse the supply risk of selected raw materials used in batteries and compare it with the supply risk of fossil fuels for the period 2000 to 2018 from the perspective of the European Union, USA, South Korea, Japan, Canada and Australia using the GeoPolRisk method. Our analysis demonstrates a higher risk of supply for raw materials compared to that of fossil fuels for all the selected territories. Rare earth elements, graphite and magnesium, are amongst the raw materials with the highest supply risk due to their concentrated production in one or only a few countries. Countries have recognised the need for raw material security and made specific policies to ensure secure supply. Raw material security is an emerging concern for all the countries, especially in the case of batteries for major manufacturing nations that are heavily import-dependent. Raw materials producing countries like Canada and Australia focused on stockpiling minerals and minerals exploration while importing countries such as Japan and South Korea are looking for alternate sources for their supply. The results from our analysis suggest that the necessary policy reforms taken for energy security have benefited all the countries with a reduced risk of fossil fuel supply, while similar policies to secure raw materials are discussed but not yet fully implemented.

1. Introduction

Fossil fuels are the fundamental drivers of technological and economic development and continue to dominate the global energy sector (Smil, 2016). In 2019, it was estimated that 64% of global electricity came from fossil fuels (coal, natural gas, petroleum) (Hannah and Max, 2019). From a regional perspective, the share of fossil fuels in the European energy mix during 2018 was 70.2%, and 88% in the Japanese energy mix during 2019, while for the United States of America (USA), fossil fuel with 80% in 2019 still accounts for the largest share of its energy mix (EIA, 2021; Eurostat, 2020; IEA, 2021a). Oil and petroleum have the largest share (34.1%) for Europe, representing a 1.6% increase compared to 1990 (Eurostat, 2020). The use of fossil fuels does not come without consequences; the Intergovernmental Panel on Climate Change (IPCC) has reported that around 40 billion tonnes of CO_2 are released every year (IPCC, 2018). The global carbon dioxide levels have increased by 100 ppm over the last six decades (NASA, 2020) and accordingly, Earth's average surface air temperature has increased by

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* Corresponding author. Université de Bordeaux, ISM, UMR 5255, F-33400, Talence, France.
E-mail address: guido.sonnemann@u-bordeaux.fr (G. Sonnemann).

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about 1 °C (1.8 °F) since 1900, with over half of the increase occurring since the mid-1970s (IPCC, 2005).

The share of global CO_2 emissions attributable to the use of fossil fuels in the energy sector in 2018 was around 47%, while emissions in the transportation sector add up to around 25% (IEA, 2020). To tackle this issue directly associated with climate change, multiple organisations propose a shift in the energy sector from fossil fuels to renewable energy (Solar, Wind, Hydroelectric, etc.) (Gielen et al., 2019). It is estimated that by 2030, renewable energy will be the most viable alternative and cheaper than energy from fossil fuels (Borah et al., 2020); optimistic scenarios point to this as a critical component for meeting the global targets stated in the Paris Agreement (UN, 2015). In this transition to renewables in the electricity sector, variability in generation from key technologies such as wind and solar encourages greater electrical energy storage to maintain supply when there is less sunlight or wind. Moreover, there are hopes to use this electricity to decarbonise the electricity sector and transportation through the use of electric vehicles. We can consider this transformation from energy storage as hydrocarbons to an electrochemical form in batteries from a fundamental perspective.

With the development of mobile energy-utilising products of all varieties, the need for efficient energy storage has increased. From their introduction in the market, batteries were the efficient choice to store electrical energy for future use (Borah et al., 2020). Batteries are classified as primary (disposable) or secondary (rechargeable) based on their chemistry and construction (Yoshino, 2012) and are usually made up of five essential components: anode, cathode, collector, electrolyte and separator (Borah et al., 2020). There have been continuous strides in developing low cost, safe and reliable batteries, with engineering strategies focused mainly on selecting appropriate metals and morphology (Borah et al., 2020). The growth of secondary batteries is in line with the increasing trend of population growth and shift in energy production technologies (fossil to renewable energy). Amongst the secondary batteries, the demand for lead-acid batteries (LAB) remains strong due to its application in various sectors and primarily in automobiles for SLI (starting, lighting and ignition) operations (Zhao et al., 2021). From the late 1990s, there has been a shift of battery technology towards lithium-ion (Li-ion) batteries with the decline of other secondary batteries such as nickel-cadmium (NiCD) batteries due to the environmental impacts of cadmium (Avicenne Energy, 2020). Li-ion batteries are more reliable and efficient than LABs, and they are gradually replacing existing nickel-metal-hydride (NiMH) batteries in the application of energy storage systems and electric vehicles (ATIC, 2018). Li-ion battery application is not limited to high energy-intensive use but also in cellular phones, portable computers whose batteries were primarily NiMH during 2000, are now replaced by Li-ion batteries (Avicenne Energy, 2020). Li-ion batteries often use graphite as an anode and lithium paired with one of cobalt, aluminium, nickel, manganese or ferrous oxides in the cathode. At the same time, copper and aluminium are typical metals for current collectors (Olivetti et al., 2017). From these changing market trends, the dependency on abundantly available and easily accessible raw materials such as lead has shifted to those that are less abundant or concentrated in certain regions (lithium, graphite, etc.). Being a crucial part of the supply chain, the supply of such raw materials are subject to risks to availability, trade policies, or other factors (Graedel et al., 2015).

The metals used in the construction of an electric vehicle (one of the most prominent growing uses of batteries) have also been identified as strategic due to the geopolitical situation of source countries (Cimprich et al., 2018). The industry is making efforts to avoid the use of cobalt due to its cost, importance and ethical and humanitarian issues (child labour, corruption, crime, and poverty) associated with its sourcing (Borah et al., 2020). In order to evaluate the importance and risk to supply associated with such raw materials, in recent years, a variety of methods of “criticality assessment” have been developed (Schrijvers et al., 2020). Such assessment typically considers various factors related to supply risk (technological, geopolitical, economic and environmental) and vulnerability to supply risk for a national economy, technology or the world. Among the materials considered critical by several countries/regions, cobalt, lithium, and rare earth elements (REE) are currently used to construct vital components of some batteries (USGS, 2018a) (Department of Industry Innovation and Science (Australia), 2019). Japan, South Korea, and China are global leaders in battery technology and the top manufacturers of Li-ion batteries. While countries like the USA, Germany, Japan and Italy are among the largest manufacturers of non-Li-ion batteries (Thomasnet, 2018). In the case of Li-ion batteries, amongst the raw material used for its construction, China dominates the market of REE. Australia is one of the major producers of lithium minerals, and a majority of cobalt ore sourced globally is from the Democratic Republic of Congo.

Supply risk is not solely an issue of physical reserves. Governments and their trade policies affect the supply risk of a resource. Unlike China, battery producers South Korea and Japan are heavily import dependent. China dominates the supply of critical raw materials such as magnesium, REE, graphite etc. Given the strong development of the REE industry, China introduced export and production quotas in 1999 to tackle REE illegal mining and address environmental and resource sustainability factors. The quotas were furthered in the year 2010 (Shen et al., 2020). China dominated the market by producing 97% of the global supply of REE in 2010 (TSE, 2011). The rise in export quotas increased the price of REE during that period, which affected countries dependent on China for REE. Issues were raised by the USA, Japan and European Union at the World Trade Organization (WTO) against China, whose tech industry was heavily dependent on China for REE (Morrison and Tang, 2012).

Countries are making significant strides to reduce their risk of access to such raw materials. For example, Japan and the USA are promoting research and development on the substitutability of metals, while Europe and Canada have focused on conflict resolution with countries rich in resources (Barteková and Kemp, 2016a). Despite having reserves domestically and being a dominant producer of REE during the 1950s, the USA had to suspend all REE mining activities in compliance with the Environmental Protection Agency (EPA) and its inability to compete with REE market prices of China. USA recognised around 35 raw materials as critical to it economy and security of the country (USGS, 2018b), of which they are 100% import reliant on 14 raw materials and 75% import reliant on an additional 10, as reported by the Congressional Research Service (CRS Report, 2019). Similar to the USA, the EU publishes a list of critical raw materials of significant economic importance that are evaluated as having a high supply risk. In 2020, it published a list of 30 raw materials as critical raw materials, of which it is 75%–100% import reliant on most metals (EC, 2020). Diversifying the supply of raw materials is one of the supply risk mitigation action plans. Most of the countries are looking towards alternate resource giants such as Canada or Australia to supply raw materials. In 2017, it was estimated that Australia produced 14% of the world’s rare earth minerals, which is an increase of 12% compared to production in 2013 (Thomas, 2020). However, due to a lack of funding to support rare earth mining and extraction, Australia is not yet fulfilling its full potential to meet the international market’s demands (Boggs, 2019). Canada is a leading producer of several raw materials such as zinc, nickel, cadmium etc., and has an abundance of cobalt, graphite, lithium, which is yet to be explored to meet the market requirements (Natural Resources Canada, 2021).

From the perspective of batteries, the policies and supply risk of critical raw materials for the European Union (EU) as one of the largest trade blocs in the world, the USA as another major economy to global trade, Japan and South Korea who are the technological leaders in battery production but heavily import dependent, and resource giants Canada and Australia, are of interest. It is scientifically and strategically interesting to analyse the evolution of supply risk of raw materials from the perspective of each of the selected countries/regions. In this study, we consider the supply risk to these representative countries for a period of eighteen years from 2000 to 2018, for which there is sufficient data to examine changing trends. Moreover, given the context of a shift from conventional to renewable energy and the consequent shift in energy storage, it is worth comparing the emerging critical battery metals with the supply risk of fossil fuels during the same period.

From the multiple methods that have recently been developed to assess resource criticality (Schrijvers et al., 2020), the integrated resource efficiency method 'ESSENZ' (Bach et al., 2016) and the Geopolitical Supply Risk (GeoPolRisk) method (Gemechu et al., 2015) are recommended by the "Task Force on Mineral Resources" established by the Life Cycle Initiative of the United Nations Environmental Programme (Berger et al., 2020). While the ESSENZ method quantifies accessibility using a set of indicators on socio-economic constraints at a global scale, the GeoPolRisk method indicates the supply risk at the product level by weighting the resource imports by the political stability of the exporting country. The GeoPolRisk method is developed as a midpoint characterisation factor for Life Cycle Sustainability Assessment (LCSA) (Cimprich et al., 2018). In this paper, for the first time, the GeoPolRisk method will be applied as a comparative supply risk assessment tool independent to LCSA. In this context, our paper aims to evaluate the supply risk evolution of the raw materials used in batteries compared to fossil fuels over eighteen years (2000–2018) for the selected countries by applying the GeoPolRisk method.

The remainder of the paper is structured as follows. In the materials and method section, we explain the reasons for the period chosen and the use of the GeoPolRisk method for this specific application, as well as providing further details on selecting the raw materials and the data sources used as part of this contribution. In the Results and Discussion sections, we show the GeoPolRisk results for the selected raw materials and fossil fuels, and the underlying factors behind the results are further analysed and compared from different countries' perspectives to explore their relevance and relation to country-specific resource policies. An overarching question addressed is to understand the effects of policy changes in supporting the transition to renewable energy sources.

2. Materials and method

2.1. The GeoPolRisk method

Our study compares the geopolitical supply risk of fossil fuels as energy carriers and the raw materials used in batteries and its evolution over time using the GeoPolRisk method. The GeoPolRisk method has been developed to quantify the supply risk of raw materials within a product to a country, region, or group of countries. In the first iteration, it was proposed to complement environmental life cycle assessment (Gemechu et al., 2015) in the form of a midpoint characterisation factor for life cycle sustainability assessment. The method quantifies supply risk as a function of the global production concentration of the raw material and the trade partner's import shares weighted by their political instability. The production concentration is evaluated with the normalised Herfindahl-Hirschman Index (HHI) (from 0 to 1) for raw material extraction or processing, and the political instability is estimated with the Political Stability and Absence of Violence dimension of the Worldwide Governance Indicators (WGI-PV) (Kaufmann et al., 2010). Subsequently (Helbig et al., 2016), introduced domestic production into the GeoPolRisk formula to incorporate local production in supply requirements. The formula to obtain the GeoPolRisk of a material "A" from the perspective of a country "c" in a given year is as follows:

$$GeoPolRisk_{Ac} = HHI_A \times \sum_i \frac{g_i \times f_{Aic}}{p_{Ac} + F_{Ac}}$$

Where.

HHI_A = Herfindahl-Hirschman Index for commodity A
g_i = Geopolitical (in)stability of country i,
f_{Aic} = Imports of commodity A from country i to country c
F_{Ac} = Total imports of commodity A to country c
p_{Ac} = Domestic production of commodity A in country c

In the most recent extension of the approach (Santillán-Saldivar et al., 2021), included end-of-life recycling as a factor in the GeoPolRisk method. However, in the present study, due to the absence of sufficient, detailed historical data, the recycling input into the supply chain is not considered. As recycling of most bulk metals has been established for many years, but for minor metals (most of the critical materials) the recycling rates are very low anyway (Reuter et al., 2013), it is expected that this exclusion will not significantly impact the results.

The values of the GeoPolRisk range from 0 to 1, where 0 represents an ideal situation with the absence of risk and 1 indicates a high risk of supply disruption. The GeoPolRisk method can be used as a comparative risk assessment tool similar to USEtox (Rosenbaum et al., 2011), a life cycle based indicator to quantify toxicity which can also be used in chemical alternatives assessment and chemical substitution, consumer exposure and risk screening as presented by (Fantke et al., 2021). It can be used to compare the supply risk of resources to a country/region/group of countries. Although GeoPolRisk was developed to analyse metals similar to other criticality assessment methods, in this paper we apply it for the first time for fossil fuels.

2.2. Raw materials selected

Ideally, all materials used in the construction of all battery types would be considered to study supply risk evolution, however as there are many minor battery chemistries for which the overall risk implications would be minimal at the country scale due to the low economic importance, only the major types have been considered here. Table 1 represents the major metals used in the different battery types. The columns represent the different battery types that contain the metals marked in the corresponding rows. The list of metals in each battery is obtained from patents and research articles on the construction and recycling of batteries such as chromium (Clough and Wertz, 2001), manganese (Sayilgan et al., 2009) and zinc (Belardi et al., 2011).

We have selected a list of raw materials presented in Table 2 based on their supply chain bottlenecks and data availability. In addition, the primary fossil fuels, coal, petroleum and natural gas, that offer a storable energy comparison are included. In addition to offering a valuable comparison for established stored-energy equivalents with a history of security policy consideration that can give insights into the applicable policies for critical materials, this is the first application of the GeoPolRisk method to fossil fuels.

2.3. Data sources

The main inputs into the GeoPolRisk method are the raw material production data, raw material trade information, and political instability indicators for the countries involved in their supply chain. The sources of the respective inputs are indicated in Table 2. The production data of the metals for our study were obtained from the British Geological Survey (BGS) (British Geological Survey, 2020) predominately, with some supplementation from the United States Geological Survey (USGS) (USGS, 2021) where data was unavailable in the BGS. Fossil fuel production data were obtained from the BP Statistical Review of World Energy (British Petroleum Company, 2021). The trade information for the raw materials and fossil fuels is obtained from UN Comtrade (United Nations, 2021), while the political instability indicator (WGI-PV) is obtained from the World Bank (World bank, 2020). The WGI-PV measures a country's governance using a score of −2.5 to 2.5 (Low to high) (Kaufmann et al., 2010). Since negative values cannot be accommodated in the GeoPolRisk method, the values are normalised mathematically as y = (x - min)/(max – min) (where min is −2.5 in this case) to an absolute scale of 0–1, where 1 represents lowest score for political stability of a country. The data for the WGI-PV are available

Table 1
Metals and natural graphite typically used in different battery types.

Key Materials	Zinc-carbon	Alkaline	Silver oxide	Li-ion	Zn-Air	Ni–Cd	Ni-MH	Pb-Acid
Silver			X					
Cadmium		X				X		
Cobalt				X		X	X	
Copper				X		X		
Lithium				X		X		
Manganese	X	X			X		X	
Nickel				X	X	X	X	
Lead		X	X					X
Zinc	X	X	X		X	X		
Potassium	X	X			X	X		
Aluminium				X			X	
Lanthanum					X		X	
Cerium							X	
Titanium							X	
Vanadium							X	
Zirconium							X	
Magnesium				X			X	
Ferrous	X	X	X	X		X	X	
Chromium							X	
Neodymium							X	
Praseodymium							X	
Samarium							X	
Tin							X	
Mercury		X	X					
Natural Graphite		X		X				
Source of Information	Belardi et al. (2011)	(Belardi et al., 2011; Martha De Souza et al., 2001)	(Aktas, 2010)	(Nan et al., 2005, 2006; Olivetti et al., 2017)	Ma et al. (2014)	(Huang et al., 2009; Rydh and Karlström, 2002)	(Fetcenko et al., 2015; Nan et al., 2006)	Jolly and Rhin (1994)

from 1996, whereas the trade information for the EU is available only from 2000 and from 1998 for the rest of the selected countries. We have chosen the years of the study from 2000 to 2018 to avoid missing data and obtain a more comparable result based on the same data quality. This range allows us to study the evolution of battery technologies since the beginning of 21st century and the resulting shift in supply risk of different metals and understand how the shift in battery technologies affected certain metal's supply risk.

Availability of data is one of the main concerns to conduct a criticality study over a long period. The GeoPolRisk method assesses supply risk as domestic production and imports weighted by the exporting country's governance indicator. The unavailability of information for any of the elements would lead to the inability to assess the supply risk under the proposed methodology. A number of choices in the selection of metals and intermediates were made based on the availability of data, as discussed briefly below.

Metals have significant potential differences in the supply risk associated with each stage of the supply chain - from the raw ore extraction, the production of primary metal and the final refined or manufactured products. Therefore, the highest risk step is typically considered. Magnesium is one of the main choices of metal for anodes due to its electrochemical properties. Worldwide concern over access to magnesium has increased considerably in recent years. Magnesite, a primary magnesium ore, and dolomite and carnalite are found in many places around the world (Pohl, 1989). In 2016, it was reported that around 64% of the magnesite production came from China (British Geological Survey, 2020). Although China is the dominant producer, Europe produces about 10% of world magnesite (British Geological Survey, 2020). In the case of refined magnesium metal, China dominates the world market with an 86% share of its global production (British Geological Survey, 2020; USGS, 2018a), hence making the refining stage the bottleneck in the supply chain, which is why magnesium metal supply risk is evaluated instead of magnesite. Graphite, used as an electrode in Li-ion batteries, is available as synthetic graphite and natural graphite. Our study focuses on natural graphite as a raw material, as it is the current preferred source (Uysal, 2012).

Limited data availability from the COMTRADE database is one of the biggest limitations we faced during our research. Since the trade information of only the organic compounds of potassium and mercury are available, they were excluded from our study. Vanadium and zirconium data were only available as part of a group defined in the HS code 2615 – niobium, tantalum, vanadium or zirconium ores and concentrates, so it was considered appropriate to exclude vanadium and zirconium from our study as well. Chromium and tin were also excluded from our final list of metals, as the available data were insufficient.

REE are used for the anode in NiMH batteries, making up about 30% of the battery's weight (Lucas et al., 2015). NiMH replaced NiCd batteries due to cadmium being toxic to the environment, thus increasing NiMH share in the battery market since 2002 (Zhao et al., 2021). REE have been considered critical by several nations and trade blocs increasingly since 2010 (TSE, 2011; USGS, 2018a). Lanthanum, cerium, praseodymium and neodymium are the REE most-used in NiMH batteries (Gras and Gras, 2018). The production data of the REE are available only as consolidated data (Monazite, Bastnäsite, etc.) rather than individual elemental production information (USGS, 2018a), as is the trade information in the COMTRADE database. For this reason, all REEs are considered as consolidated data in our study.

With the data obtained for the raw materials shown in Table 2 for global production and imports to the selected countries, the GeoPolRisk indicator was calculated for the period of interest.

3. Results and discussion

Fig. 1 represents the comparison of the evolution of the geopolitical risks associated with the supply of materials used in batteries and fossil fuels for Australia, Canada, the EU, Japan, South Korea and the United States of America from 2000 to 2018. It is apparent from the results illustrated in Fig. 1 that metals used in batteries are associated with higher supply risk than fossil fuels. Natural graphite, magnesium metal, cobalt and REE are noted to have higher supply risk in comparison to the rest of the metals. It can be further observed that the supply risk of natural graphite has remained high throughout the period for all the countries/regions in our study, along with REE.

By disaggregating the GeoPolRisk into its two factors (production

Table 2

Data sources for the production and trade of relevant raw materials in the study.

Raw Materials	Production Information	Trade information	HS-CODE
Silver ore	British Geological Survey	UN COMTRADE	261610 – Silver ores and concentrates
Cadmium ore	British Geological Survey	UN COMTRADE	8107 – Cadmium, articles thereof, including waste and scrap
Cobalt matte	British Geological Survey	UN COMTRADE	810520 – Cobalt; Mattes and other intermediate product of cobalt metallurgy, unwrought cobalt, powders
Copper ore	British Geological Survey	UN COMTRADE	2603 – Copper ores and concentrates
Lithium ore	British Geological Survey	UN COMTRADE	283691 – Carbonates; lithium carbonate
Manganese ore	British Geological Survey	UN COMTRADE	2602 – Manganese ores and concentrates, including manganiferous iron ores and concentrates with a manganese content of 20% or more, calculated on the dry weight
Nickel ore	British Geological Survey	UN COMTRADE	2604 – Nickel ores and concentrates
Lead ore	British Geological Survey	UN COMTRADE	2607 – Lead ores and concentrates
Zinc ore	British Geological Survey	UN COMTRADE	2608 – Zinc ores and concentrates
Aluminium (Bauxite)	British Geological Survey	UN COMTRADE	2606 – Aluminium ores and concentrates
Rare Earth Elements (Oxides)	United States Geological Survey	UN COMTRADE	2846 – Compounds, inorganic or organic, of rare-earth metals; of yttrium or of scandium or of mixtures of these metals
Magnesium metal	British Geological Survey	UN COMTRADE	810411 – Magnesium; unwrought, containing at least 99.8% by weight of magnesium
Ferrous ore	British Geological Survey	UN COMTRADE	2601 – Iron ores and concentrates; including roasted iron pyrites
Natural Graphite	British Geological Survey	UN COMTRADE	2504 – Graphite; natural
Coal	BP World Energy Stats	UN COMTRADE	2701 – Coal, briquettes, ovoid etc., made from coal
Petroleum	BP World Energy Stats	UN COMTRADE	2709 – Petroleum oils, crude
Natural Gas	BP World Energy Stats	UN COMTRADE	271111 – Petroleum gases and other gaseous hydrocarbons; liquefied, natural gas

concentration and resource accessibility), it is possible to understand the main contributor to the supply risk in each case. The HHI is an indicator of production concentration. As mentioned earlier, the value of HHI is between 0 and 1, where a value closer to 0 indicates that production is distributed across many countries, and 1 indicates that the production is concentrated in one country. The mix of countries producing these raw materials has not changed significantly in some cases, while shifting in others, as different producing countries have expanded their production at different rates. Fig. 2 presents the evolution of the concentration of the production of fossil fuels and resources (from Table 2).

We can observe a significant increase in the production concentration of REE from 2001. One-third of the world's rare earth minerals reserves are in China, the dominant producer (TSE, 2011). Due to many factors - most importantly, cheap labour and less stringent environmental standards, China has dominated the downstream stages of rare earth processing, in addition to mining (Barteková and Kemp, 2016b). In recent years, the production of REE in other countries such as Australia has decreased China's global production share from 98% in 2009 (USGS, 2011) to 72% in 2018 (Huleatt, 2019). For the same reasons, China dominates the magnesium metals markets, as explained in the Materials and Method section. China is also a prominent producer of natural graphite with more than 80% share in world production. During 2007–2008, natural graphite production in Bosnia and Herzegovina reduced China's global share from 80% to 50%, although China's domestic production remained unchanged during this period (USGS, 2008). Australia and Chile are the major primary lithium producers, with the former producing mineral concentrates from ore and the latter extracting from brine. Carbonates and hydroxides of lithium are used in the manufacture of batteries (Goonan, 2012). From Fig. 2, it is evident that the production concentration of lithium has been on the rise since the beginning of the millennium. This comes at the same time as the increase in demand for lithium batteries, and the rising concentration is likely attributable to factors of natural reserve availability and preparedness for expanded production in the incumbent countries.

The second factor of GeoPolRisk value is associated with resource accessibility to a certain economy. Government policies on trade of commodities directly impact the access of a particular resource that impacts the production of a product using the corresponding raw material. Importing a resource from a country with low WGI-PV score for political stability can be considered to have a higher risk. Most countries will import commodities from more than one supplier country, so the relative volume is used to weight this risk, which is quantified by the value of the second factor of the GeoPolRisk. Fig. 3 represents the trend of GeoPolRisk value compared to the two component factors of Weighted Trade Average (WTA) and production concentration (HHI). Results are shown for cobalt and lithium, two of the key metals used in batteries, for the EU and Japan, two of the six countries in Fig. 3. Complete comparison and analyses are presented in the supplementary material.

It is evident from Fig. 3 that the supply risk of importing cobalt has been higher for the EU than for Japan. From the data it can be shown that this is due to a predominance of imports from the Democratic Republic of Congo (DRC) (previously Zaire), while Japan imports most of its cobalt from Canada or Australia. The influencing factor for the supply risk here is the production being heavily concentrated in one country, the Democratic Republic of Congo (USGS, 2010). The production concentration is a global factor that national or unilateral policies or strategies cannot influence. The second factor, the WTA, acts as a mitigating variable in GeoPolRisk calculation, as it is multiplied by the HHI, thus reducing the overall evaluation of risk. It can be noted that Japan's WTA seems to have been a significant suppressing factor, with a departure from the HHI trend since around 2007, which has not been the case in the EU. On the other hand, the WTA of lithium imports to Europe and its domestic production reduced the risk associated with the HHI value significantly. Similar trends can be observed in individual national and material trends presented in the supplementary material.

By comparing Figs. 2 and 3, it can be understood that for specific raw materials, the two factors of geopolitical influence considered in the GeoPolRisk method are important to provide a more informative indicator to compare supply risk for a specific national context, where the HHI of global production alone does not suffice in most cases. Moreover, the GeoPolRisk can be utilised to analyse trade policy shifts from importing, as well as exporting, nations.

The historical timeline analysis of raw materials used in batteries compared to fossil fuels helps us understand the evolution of supply risks. In this discussion, we will also try to associate this evolution to some resource policies. A general observation from Fig. 1 indicates that

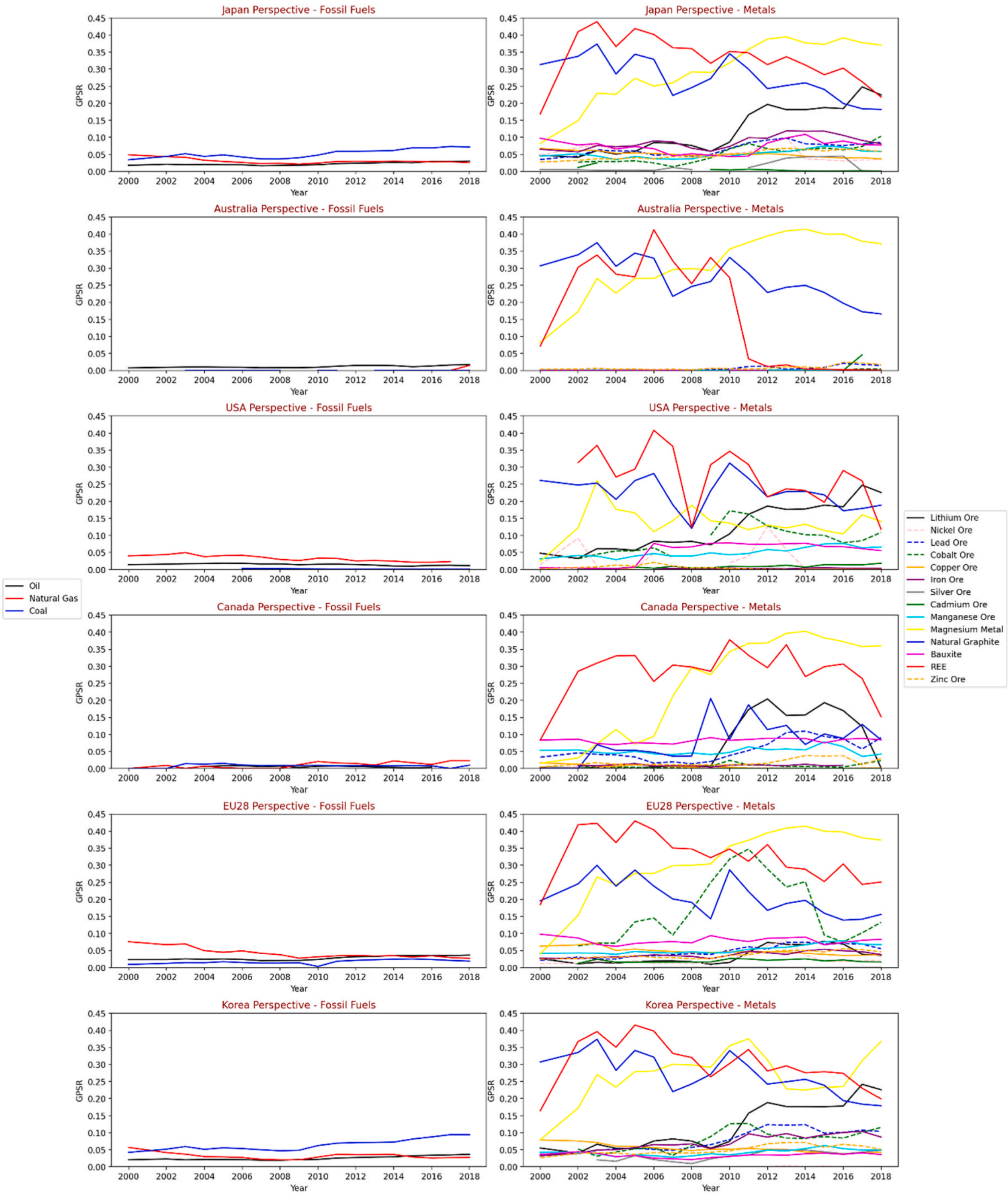

Fig. 1. Evolution of the geopolitically related supply risk of selected metals and fossil fuels from the period of 2000–2018.

the supply risk associated with the metals is much higher than that of fossil fuels. This is in line with the recent report published by the International Energy Agency (IEA, 2021b). While this largely reflects a more even global distribution of production of fossil fuels among various countries, it can be further explained for specific countries based on their energy security policy responses to the oil crises of the 1970s and the relatively recent transition to batteries for electric vehicles, which has not yet seen the same responses to alleviate supply chain risk sufficiently.

Energy security concern was exacerbated by the 1970's oil crisis, during which research was focused on the supply of fossil fuels (Deese, 2014). The security of energy supply is a primary concern for a country that is a net importer of energy, and for particular energy commodities such as oil, which is critical to the current transport sector, most countries are net importers. The majority of the International Energy Agency's member countries are energy importers (IEA, 2014). The United States is the largest importer of energy while also being one of the largest energy producers and has been a net exporter of energy since 2011 (EIA, 2021). As evident from Fig. 1 in comparison with Fig. 2, the USA has mitigated its supply risk of fossil fuels with its policies to some extent, based on its natural resource endowment. The US aims to be energy independent, while the "Shale Revolution" in the mid 2000s has enabled it to be an exporter of gas (EIA, 2018). Unlike the US, the EU, a net importer of energy, focuses its policy on supply diversification of fossil fuels rather than being self-sufficient. The policies of the EU depend on each of its member states and its national policies. The domestic

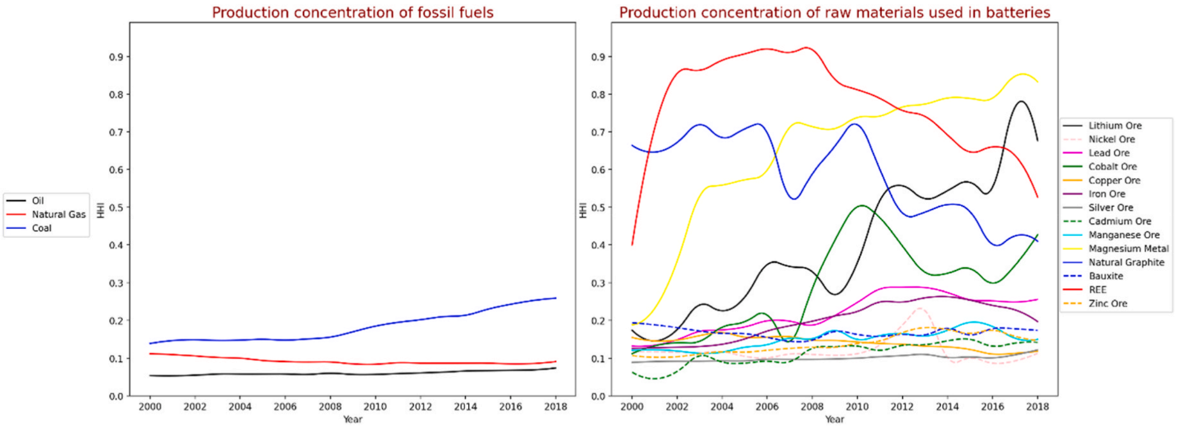

Fig. 2. Comparison of global production concentration (in the form of HHI) of metals and fossil fuels from the period of 2000–2018.

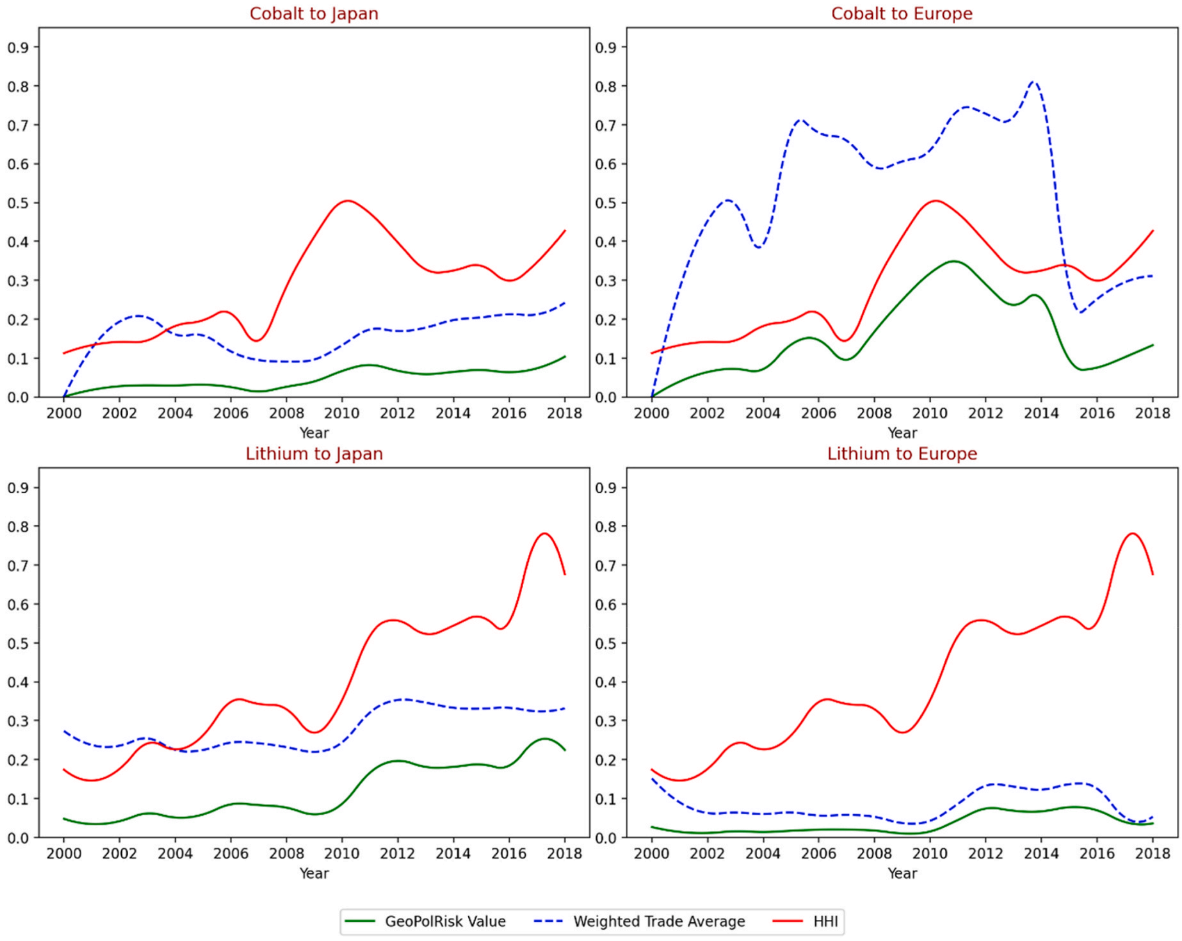

Fig. 3. GeoPolRisk and weighted trade average of cobalt and lithium from the perspective of the European Union and Japan.

production of fossil fuels in the EU has been declining since the late 20th or early 21st century depending on the fuel (British Geological Survey, 2020). As a result, the EU has been relying on imports for energy production. To reduce greenhouse gas emissions, it aims to achieve at least 32% of energy consumption from renewable energy resources by year 2030 (EC, 2021a), which is one way of reducing import dependence.

Energy security is a grave concern for Japan and South Korea, which are both heavily dependent on imports of fossil fuels. Oil embargoes during the second world war and the oil shocks of the 1970's created significant hardship in Japan, and brought energy security to the fore in government policy. More recently, the 2011 Fukushima disaster has again exacerbated concerns over import dependence, particularly with the increased reliance on natural gas and coal for electricity due to the nuclear shutdown that continues to effect most of the nation's nuclear power stations (Financial Times, 2018). The 5th Strategic Energy Plan discusses improving power generation efficiency and output from variable renewable energy which is highly affected by the fluctuating weather conditions (METI, 2018). Similarly, in 2017 (METI, 2018), the South Korean government set goals to increase renewable energy production share to 20% after it was reported as one of the highest contributors of greenhouse gases amongst the OECD countries (OECD. Stat, 2020). Their action plan focuses on a transition to renewable energy sources rather than securing the supply of energy sources.

Though a major exporter of coal and gas, Australia has adopted a different energy security policy to build domestic fuel storage to reduce vulnerability to supply disruptions, since they import most of their liquid fuels. As a part of their due diligence, the "National Energy Security Assessment" has identified liquid fuels as high risk due to heavy reliance on imports (NESA, 2011). Meanwhile, Canada's energy security concerns are very different from what is observed for other countries/regions. Canada has declared itself to be energy secure, yet it has identified some components that could adversely affect them in the future. However, none of these pose a direct risk or threat of supply disruption as Canada is rich in energy resources (Best et al., 2010).

Japan has a long history of resource security measures, including energy and rare metals in the 1980s. Many raw materials have a high supply risk with small domestic production (Ting and Seaman, 2013). The supply risk of REE, which are imported to Japan as intermediate products, has been high throughout the period considered in our study, as observed in Fig. 1. Japan imports them mainly from China. In 2009, the advisory committee on Energy and Natural Resources, Japan, defined metals of high economic importance and difficult to source from other countries, such as rare metals, as strategic (Barteková and Kemp, 2016b), giving priority to national organisations to stockpile them and encourage investment in mining operations overseas. Japan has sought to further address such supply risks through recycling and the development of deep sea mining (Motoori and McLellan, 2021). Refining of REEs and manufacturing of components using them contribute significantly to Japan's economy. The diplomatic standoff between Japan and China in 2010, a supposed reason that led to the Chinese banning the export of REE, forced the Japanese government to craft a long term strategy to address its accessibility (Mancheri et al., 2019).

As a leading manufacturer of Li-ion batteries, all the metals involved in the battery's construction are critical to Japan. They source around 5–8% of lithium from China (British Geological Survey, 2020). The Strategic Energy Plan of 2014 highlights the accumulation and recycling of critical raw materials and sets a goal of at least 50% self-sufficiency of critical raw materials by 2030.

South Korea shares a similar level of supply risk in comparison to Japan. Graphite, magnesium, REE and lithium are noticeable of higher risk. Similar to Japan, South Korea is a heavily import-dependent country. South Korea is a major consumer of graphite, lithium and other metals since it is the largest Li-ion batteries producer. South Korea enacted the Framework Act on Resource Circulation (FARC) in 2018 as one of its strategies to tackle the dependence on raw materials, and South Korea's Renewable Energy 3020 Plan to transition to renewable energy by 2030 (KEI, 2016). According to the act, implementing a circular economy is the suggested viable option for South Korea and developing strategies to establish an infrastructure to stockpile critical raw materials.

Although a producer of several metals, Canada is exposed to supply risks of REE, magnesium, and lithium. Canada reported very low lithium production, leading to the increase in its supply risk in Fig. 1. Canada relies on China to supply REE even though they possess resources, as the low costs of production in China make Canadian resources uncompetitive. Canada's critical minerals list was defined to support the Minerals and Metals Plan (CMMP) to promote its competitiveness in the raw material sector. Responsible minerals development is one of the principles that drive this action plan. It also envisioned supporting the mineral development through significant infrastructure investment and a collaborative strategy for mineral exploration (Natural Resources Canada, 2020).

The "Resource 2030 Taskforce" in 2018 reported that the resource sector played a vital role in Australia's economic growth (Department of Industry Innovation and Science (Australia), 2018). According to the Australian Government, it contributed to around 8% of its GDP in 2018 (Thurtell et al., 2018). Its significant natural resource exports include iron ore, gold, copper, aluminium, nickel, zinc, coal, oil and natural gas. Australia is also the dominant producer of bauxite, lithium and zirconium (British Geological Survey, 2020). For specific critical minerals, Geoscience Australia reported that the nation ranks six in reserves of rare earth minerals (Huleatt, 2019). However, due to a lack of funding to support rare earth mining and extraction, Australia is not yet fulfilling its full potential to meet the international market's demands (Boggs, 2019). Until 2011, the supply risk of REE was high even for Australia, another major resource producer, after which it's domestic production mitigated its REE supply risk. Magnesium and natural graphite are among the three metals whose supply risk is high for Australia. China dominates the production of both of these raw materials. EcoGraf, an Australian firm, is one of the companies planning to open a graphite facility by 2022, potentially mitigating its supply risk (Zakharia, 2020). The global investors are more willing to participate in off-take agreements of such projects (Huleatt, 2019). For example, the Northern Australia Infrastructure Facility encourages start-ups and research and development in REE extraction technology (Boggs, 2019).

The Critical Minerals Strategy developed by the US Department of Energy focuses on diversification of supply chain, research and development in material technology for substitutability and recycling of metals. This strategy was set forth after concerns over disruption in the industry due to China's export restrictions on REE. Until 1998, the US was a major producer and supplier of REE. After a series of incidents led to the temporary closure of the Mountain Pass operation of the mining company Molycorp, they suspended Rare Earths' supply, leading to a dependency on China for REE. The US relies heavily on imports for certain metals such as graphite, manganese, nickel and others, and their designation as critical has led to the promotion of domestic exploration (US Gov, 2017). The current US policy focuses on promoting the local private sector to produce and process the raw materials and secure a supply of raw materials that do not exist in large quantities in the US (CRS Report, 2019). The US – Canada Joint Action Plan was realised in 2020 to ensure a stable supply of critical raw materials and encourage Canada to produce critical raw materials.

In the perspective of the EU, cobalt is among the metals whose supply risk is high. The supply risk of cobalt to the EU peaked around 2011 and decreased, as shown in Fig. 1. The DRC has been the dominant producer since the 1970s, with an increase in production share until 2012 (British Geological Survey, 2020). As observed from the UN COMTRADE data, the EU reduced its imports of cobalt from DRC by 80% in 2015 compared to 2014, increasing imports from countries with a better WGI-PV score such as Australia and Canada; this measure has mitigated the supply risk of cobalt in following years. The European Union (EU) adopted policies to achieve zero-emission mobility. It requires new cars to have zero tail-pipe emission from 2035 and has recognised the importance of batteries in the transition to carbon-free mobility (EC, 2021b, 2019). Horizon 2020, an EU innovation program, has allocated a considerable share of its budget to improvements and innovations in energy storage (Innovation and Networks Executive Agency, 2019). The Strategic Action Plan on Batteries, a milestone in EU policies, is focused on developing and producing batteries (EC, 2018). Like other economies, the European Commission has developed a raw material initiative that aims to tackle the accessibility of raw materials, including those required for batteries. EIT raw materials, the largest consortium in the raw material sector, based out of Europe, has also focused its innovation projects on the sustainable supply of raw materials (EIT R.M, 2020).

It is demonstrated from our study that the supply risk of fossil fuels are lower when compared to that of metals. National policies, diverse supply of fossil fuels, and its distributed production concentration have contributed to mitigating its supply risk. With increased focus on clean energy and climate policies, batteries are growing in importance for storage, particularly for variable renewables. Diversification of supply, an increase of domestic production for the countries with reserves, and recycling are a few methods to increase the supply chain resilience.

These recommendations are also in line with the recommendation from the International Energy Agency (IEA) (IEA, 2021b). In their report, IEA raised concerns for mineral security compared to energy security and recognised the need for international collaboration between producers and consumers (IEA, 2021b).

4. Conclusion

In this paper we have studied the evolution of supply risk of raw materials from the perspective of selected OECD countries with a focus on the ongoing transition from conventional to renewable energy and the consequent shift in energy storage to batteries. We have done this analysis using the GeoPolRisk method, that here is applied for 14 raw materials and for the first time for fossil fuels as a comparative risk assessment for eighteen years (2000–2018). The GeoPolRisk method is characterised by a few limitations coming mainly from uncertainties and variabilities related to the data used.

The share of fossil fuels in the energy mix among the selected OECD countries is slowly declining due to the climate change implications of its use, while renewable energy and other non-carbon technologies are increasing. Batteries are a major choice of electrochemical energy storage for energy produced from renewable energy technology. Batteries have evolved since their creation, constituting raw materials that are not easily accessible. Such raw materials are deemed crucial for the production of batteries arising a need for a so-called criticality assessment.

Our results demonstrate the increase in supply risk for the key raw materials neeeded for Li-ion batteries due to their increasing use and demand in particular for the EU, Japan, South Korea and USA. A general observation is that the supply risk of raw materials is much higher than that of fossil fuels. It becomes evident that REE, natural graphite and magnesium have high supply risk compared to other raw materials because their production is concentrated in only a few countries such as China for REE. It is also observed that countries with domestic production of the raw materials such as Canada and Australia can readily mitigate their supply risk.

Several policies have started to play an important role in reducing the supply risk of the batteries raw materials. In particular, policies to diversify supply, promoting mineral exploration and domestic production are observed to reduce the supply risk. It is expected that policymakers can learn from the energy security measures put in place after the oil crisis in the 1970's to mitigate the currently existing raw material supply risk for the emerging battery technologies.

CRediT authorship contribution statement

Anish Koyamparambath: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **Jair Santillán-Saldivar:** Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – review & editing. **Benjamin McLellan:** Conceptualization, Methodology, Validation, Data curation, Writing – review & editing, Supervision. **Guido Sonnemann:** Conceptualization, Methodology, Validation, Funding acquisition, Resources, Writing – review & editing, Supervision.

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 in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.resourpol.2021.102465.

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