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The role of recycling in alleviating supply chain risk–Insights from a stock-flow perspective using a hybrid input-output database

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ABSTRACT

Metal resources are unevenly distributed throughout the globe but are crucial for the global economy. Many economies are highly dependent and vulnerable to material supply from other parts of the world. This situation can be alleviated by recycling, as regions devoided of important reserves exploit their own urban mine. In this study, we explored an increased domestic recycling scenario utilizing a stock-flow perspective combined with a hybrid input-output database (EXIOBASE). We applied a mass rebalancing procedure on the production and trade flows of ores and metals. We calculated the supply risk with the GeoPolRisk method for single and two-stage supply chains. Results show that recycling reduce the risk associated with trade for most of countries and materials for the metal supply chain, where recycling effectively takes place. In contrast, such risk decrease is not found in the ore supply chain nor in the combined ore and metal supply chain.

1. Introduction

Metals play a crucial role in the global material economy, yet their origin is still heavily tied to primary raw extraction from resources and reserves in the Earth's lithosphere (Graedel et al., 2011). In 2014, the global amount of metal ore extracted from Earth was estimated to be 8.2 billion tonnes (IRP, 2017). Growing populations together with more good consumption per capita is driving a fast growth in the demand of different metals, a trend likely to continue into the near future (IRP, 2017). Primary metal resources are also finite, so metal reutilization within the economy helps alleviate both environmental and scarcity issues. The importance of secondary material production and use has been highlighted in the sustainability agenda with a push towards circular economy and within the framework of the UN Sustainable Development Goals (SDGs). More specifically, SDG 12 (Sustainable Consumption and Production) focuses via the Target 12.5 to substantially reduce waste generation by 2030.

Metal deposits are unevenly distributed through the Earth's crust, leaving countries dependent on, and sometimes vulnerable to others to access the necessary raw materials to build and maintain their own economies. Both social and natural phenomena such as trade disputes (Schmid, 2019) and droughts (Bonnafous et al., 2017) can lead to disruptions in the material supply. Recent examples include the rare earth metal and mineral export restrictions from China, and the Covid-19 pandemic which closed several mines, smelters, and refineries, destabilizing the supply of gold, silver, copper (MacDonald et al., 2020), cobalt, lithium, and others (Akcil et al., 2020).

In order to assess and safeguard against such situations, criticality assessments can be conducted to evaluate raw material accessibility and its strategic importance to the economy. This was a concept established by The National Research Council of the United States of America (NRC), whose criticality matrix captured both the impact and the likelihood of supply restrictions of non-renewable minerals (NRC, 2008). Graedel et al. (2012) contributed to the methodology of assessing criticality by encompassing three dimensions: supply risk, environmental implications, and vulnerability to supply restriction; with each of these dimensions further divided into sub-components. This method has been applied for example by Nassar et al. (2012) who assessed criticality of elements from the copper family at corporate, national and global levels, and Graedel et al. (2015) who focused on the criticality of 62 metals and metalloids in the US and in the world. Similarly, the European Commission (EC) developed its own methodology based on economic importance and supply risk due to poor governance to characterize critical raw materials for the European bloc (EC, 2010, 2017a). Sprecher et al. (2015) focused on material constraint through the lenses of resilience, i.e., when supply chains can cope with possible disturbances to

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meet societal demand. The authors attribute resistance, rapidity and flexibility as factors that allow a system to maintain its functionality. Van den Brink et al. (2020) extended the analysis of supply risk for cobalt in the entire upstream section of the supply chain, including mining and refining. In fact, there is a variety of methods that can be used to evaluate supply risk, depending on the nature of the analysis to be made (Helbig et al., 2016a; Achzet and Helbig, 2013). Achzet and Helbig (2013) categorized these in country concentration, country risk, depletion time, by-product dependency, concentration of raw material producing companies, demand growth, secondary raw material utilization and recycling potential, substitutability, import dependency, commodity prices, and others. Gemechu et al. (2016) developed a method to integrate geopolitical supply risk of raw materials in life cycle sustainability assessment (LCSA). The GeoPolRisk indicator, as coined by the authors, departed from the usual approach of previous developments (EC 2010; Graedel et al., 2012; Nassar et al., 2012; NRC 2008; Schneider et al., 2014) that weighted the World's Bank indicator Worldwide Governance Indicator (WGI) – a proxy for geopolitical stability of countries - by production share. Instead, the authors argued that if the WGI is weighted by import share, it can better represent distinctive supply-chain settings. Later, Helbig et al. (2016b) incorporated more complexity in the GeoPolRisk method, an advancement needed to account for analysis of domestic production and multiple supply-chain stages. The GeoPolRisk indicator has been used to assess supply vulnerability in vehicles (Cimprich et al., 2017), electric vehicles (Gemechu et al., 2017), the material substitutability in electric vehicles and dental X-ray equipment (Cimprich et al., 2018), and to confirm the role of domestic recycling in mitigating supply risk of 13 critical raw materials used in information and communication technologies in the EU (Santillán-Saldivar et al., 2021).

Once such a study is conducted and the supply risk assessed, economies can reduce their vulnerability to external shocks by adopting different strategies such as stockpiling, diversifying supply, substituting materials, reusing products, or extending the lifetime of products. Secondary raw material utilization and recycling can also have a role in reducing geopolitical supply risk of metals (Habib and Wenzel, 2014; Sverdrup et al., 2017; Santillán-Saldivar et al., 2021; Gaustad et al., 2018), as it may decrease import dependency and diversify global production. Tercero Espinoza et al. (2020) explored ways in which circular economy can reduce material criticality, with recycling being the most obvious one. On its own, however, recycling does not necessarily lead to reductions in supply risks, since other factors must be considered. For instance, there is no positive contribution to alleviate external dependency if recycling is conducted overseas or the recycled material is not consumed internally (Santillán-Saldivar et al., 2021). The political stability of the economies from which a country is importing a commodity is also an important factor, as poor governance may culminate in large negative effects on international trade (Marano et al., 2013). Increasing recycling to reduce supply risk is also restricted to the material requirement at a commodity level, but it does not necessarily extend to the material that is embodied within the finished products downstream.

There are hardly any studies on how recycling can mitigate supply risks. A main exception is Santillán-Saldivar et al. (2021) who explored the effect of domestic recycling to alleviate import dependency and supply risk of 13 raw materials used in the ICT sector in the European Union. The authors however did not make the analysis from the available urban mine, i.e., the resources available at the end of products' lifetime (Cossu and Williams, 2015), for their study. Instead, they used statistics of production, trade, and end-of-life recycling input rate (EoL-RIR) of raw materials. In this paper we use the EXIOBASE Multi-Regional Hybrid Supply and Use table (Merciai and Schmidt, 2018). This unique multi-regional stock-flow dataset reconciles and homogenizes several data sources in physical units and allows to account for what is still available to be recycled. By using EXIOBASE, we aim to make a broad analysis of the role of domestic recycling in mitigating supply chain risk. Such analysis involves 1) single and two-stage supply chain, i.e., of ore and metal, 2) 6 commodities: iron and steel (Fe), aluminum (Al), copper (Cu), lead, zinc and tin (Pb, Zn, Sn), platinum group metals (PGM), and other non-ferrous metals (ONFM), 3) 48 regions in the globe: Australia (AU), Austria (AT), Belgium (BE), Brazil (BR), Bulgaria (BG), Canada (CA), China (CN), Croatia (HR), Cyprus (CY), Czech Republic (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Greece (GR), Hungary (HU), India (IN), Indonesia (ID), Ireland (IE), Italy (IT), Japan (JP), Latvia (LV), Lithuania (LT), Luxembourg (LU), Malta (MT), Mexico (MX), the Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Romania (RO), Russia (RU), Slovakia (SK), Slovenia (SI), South Africa (ZA), South Korea (KR), Spain (ES), Sweden (SE), Switzerland (CH), Turkey (TR), the United Kingdom (GB), the United States (US), Rest of the World Africa (WF), Rest of the World America (WL), Rest of the World Asia and Pacific (WA), Rest of the World Europe (WE), and Rest of the World Middle East (WM).

2. Materials and methods

2.1. Data source

Data from the Multi-Regional Hybrid Supply and Use table (MR-HSUT) EXIOBASE v3.3.18 (Exiobase, 2011), year 2011, was utilized to assess the potential of recycling in mitigating supply risk to a set of ores and their corresponding metals (Merciai and Schmidt, 2018). EXIOBASE combines national supply-use tables (SUTs) with international trade and energy, agricultural production, resource extraction data, providing a detailed level of 200 products flows across 164 industries and 6 final demand categories across 48 regions (43 countries plus 5 rest of the world regions, Stadler et al. 2018). Contrary to existing multiregional databases that track flows solely in monetary units, EXIOBASE provides these in hybrid units – physical, energy, and monetary. The waste accounts reconciliation procedure applied in the creation of the database allows for a direct study of physical waste flows and their subsequent treatments. This can be for instance of particular interest for policy targets on circular economy (Merciai and Schmidt, 2018). Fig. 1 gives a simplified representation of the database.

In order to build the database, the system is mass balanced. The balanced system enables the calculation of the embodied materials into products and, therefore, to determine their compositions as waste fractions. A lifetime function is assigned to each product so that, for any good consumed by industries or final consumers, it is possible to disaggregate the waste fractions contained in the product into waste accounts and to additions to stocks. The stock reduction discharged as waste is derived via a time series of physical tables (Aguilar-Hernandez et al., 2019) constructed using as a reference the EXIOBASE monetary input-output tables at constant prices (Wood et al., 2015). As a result, the amount of material waste generated by each country, here described as the potential for urban mining, is an endogenous value in the database. In addition, the waste treatment data is collected by official statistics (Merciai and Schmidt, 2018), and the international trade of waste flows is retrieved from Comtrade (UN, 2019). As a result, the database provides information on the amount of ore and metal products produced, traded and consumed by each of the regions, as well as the possible recoverable waste fractions (from industries, final demand categories, and stocks) that are embodied in the products consumed within national economies.

2.2. GeoPolRisk calculation

The geopolitical risk of the supply chain (extraction and metal production) for the various metal commodities assessed in this paper follows the extended method of GeoPolRisk proposed by Helbig et al. (2016b). GeoPolRisk essentially combines two factors. First, it looks at the diversity of the global supply as represented by the

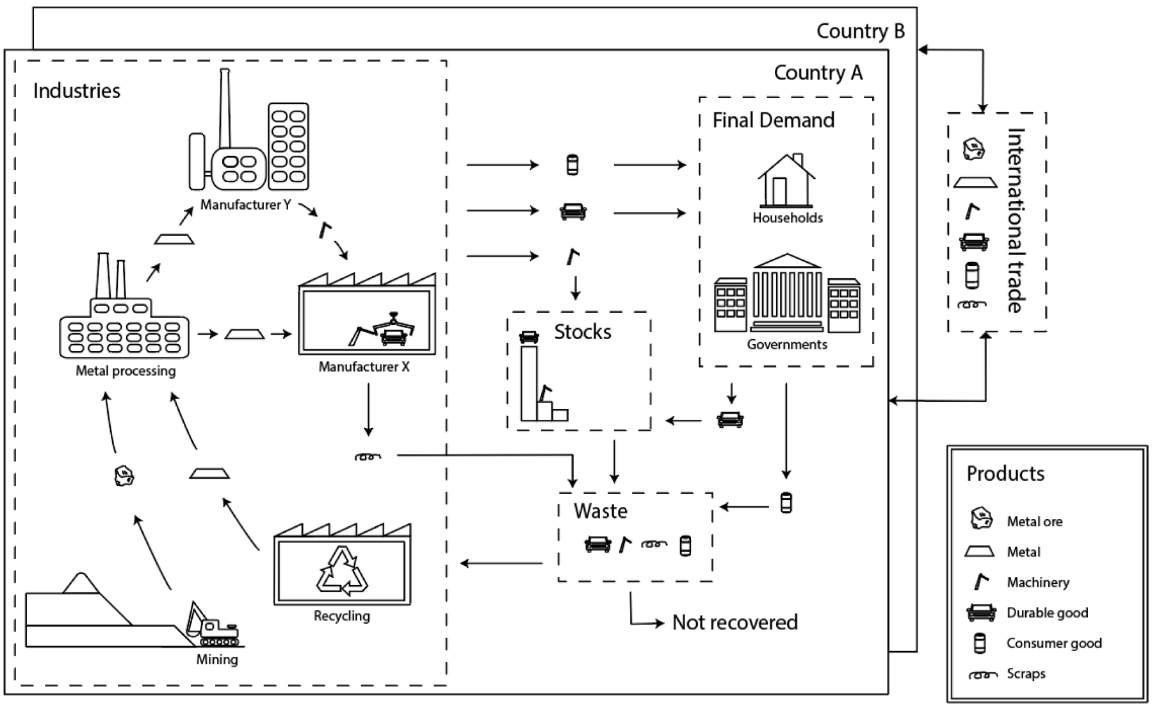

Fig. 1. A simplified representation of EXIOBASE with 6 products, 5 industries, 2 final demand categories in 2 regions. Metal ores are extracted by the mining sectors and used in the manufacture in order to carry out goods. Metal scraps produced in the productive activities are the first source of waste. Goods are then distributed to final consumers (i.e., households and government), accumulated as capital in industries or sold to other countries. In turn, final consumers will either discharge goods as waste or accumulate them. At the same time, some end-of-life goods that were accumulated in previous years become waste. Discharged waste can be then recycled, incinerated or landfilled.

Herfindal-Hirschman Index (see Eq. (1)). The Herfindahl-Hirschman Index (HHI) is a commonly accepted index used to indicate market concentration (U.S. Department of Justice and the Federal Trade Commission, 2010). The World Mining Data (WMD), for example, calculates the HHI of mineral raw materials to evaluate their global market concentration (WMD, 2020). If global markets are dominated by a few countries, there is a higher associated risk for supply chain disruptions.

$$HHI_A = \sum_i \left(\frac{p_{Ai}}{P_A}\right)^2 \tag{1}$$

where p_{Ai} is the production of the commodity A in country i; P_A the global production of commodity A.

Second, it looks at the political and economic stability of the countries supplying materials. For this, the indicator WGI, scaled from 0 to 1, is used. This indicator is sourced from the World Bank and takes into consideration six dimensions. These are: voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law, and control of corruption (World Bank, 2019). EC (2017b) recommends using an average of all six dimensions of the WGI in criticality assessments both to soften the impact of these indicators in the results and due to the high correlation amongst these categories. This proposal is adopted in this paper. To understand how this stability of exporting countries works out for a specific importing country c, the WGI_i of exporting country i is multiplied by the fraction that imports from country i by country c represents from the total domestic production p_{Ac} and total imports F_{Ac} of commodity A in country c (Eq. (2)).

$$\overline{WGI}_{Ac} = \sum_i WGI_i \, \frac{f_{Aic}}{p_{Ac} + F_{Ac}} \tag{2}$$

These two factors are then combined to determine the GeoPolRisk of a given commodity A in country c in a single-stage supply chain (Eq. (3)):

$$GeoPolRisk_{Ac} = HHI_A {}^* \overline{WGI}_{Ac} = \sum_i \left(\frac{p_{Ai}}{P_A}\right)^2 {}^* \sum_i WGI_i \frac{f_{Aic}}{p_{Ac} + F_{Ac}} \tag{3}$$

This paper does not only calculate the GeoPolRisk of a single stage, but the combined stage of ore and metal production. This is done by further factoring the WGI_i of exporting countries by the fraction of imports from total production and imports in each stage (see Eq. (4)).

$$\begin{aligned} GeoPolRisk_{BAc} &= HHI_B {}^* \overline{WGI}_{BAc} \\ &= \sum_i \left(\frac{p_{Bi}}{P_B}\right)^2 {}^* \sum_i \sum_k WGI_i \frac{f_{Bik}}{p_{Bk} + F_{Bk}} \frac{f_{Akc} + \delta_{kc} p_{Ac}}{p_{Ac} + F_{Ac}} \end{aligned} \tag{4}$$

where $GeoPolRisk_{BAc}$ is the geopolitical supply risk factor of commodity B that is transformed to commodity A in a country c; p and P are respectively domestic and global production; f and F are respectively bilateral and total imports; subscript A and B refer respectively to commodity A and B; i is any country that trades commodity B, and k any country that trades commodity A; δ_{kc} is 1 if k is equal to c and 0 in all other cases. Here commodity B refers to ores and commodity A to metals.

The GeoPolRisk in two stages is calculated based on the HHI of the commodity in the first stage. In this work, we also investigate the contribution of the global concentration of the commodity in the second stage in the GeoPolRisk indicator. This is done by replacing the HHI of the ore (when calculating the GeoPolRisk in a two-stage supply chain) by a combination of the HHI of the ore and the HHI of metal. For this, both HHIs are combined via either a weighted arithmetic or geometric mean. The weights were expressed using the mass shares of primary material and either metal or recycled material (see Table A.3 in SI). Here, we explore an increased domestic recycling scenario and its potential in alleviating supply risk of mineral ores and metals in both single and two-stage supply chain systems. With increased recycling, both domestic production and imports of ores and metals change, thus also changing the values of GeoPolRisk. The next section explains how the two factors are affected in the domestic recycling scenario.

2.3. High domestic recycling scenario

The GeoPolRisk in the baseline can be calculated almost directly by using the EXIOBASE data as given in Section 2.1. This paper also has the ambition to show how enhanced recycling rates can reduce the GeoPolRisk, by limiting particularly imports from countries with the highest WGI. For this purpose, EXIOBASE is modified to create a scenario whereby for a given material, the recyclable amount is set to be at least 90% of the top recycling rate achieved by any country or region in EXIOBASE. As a result, economies that recycle less than 90% of the top recycling one will increase their recycling rate, whereas those that have the rate at a minimum of 90% will remain the same. Since the waste accounts in EXIOBASE are represented in waste fractions, i.e. of materials, as opposed to waste of products, these optimized recycling rates are applied directly to the materials themselves. This percentage is set to reflect that not all the supplied waste material can be recycled, as technical factors (product design, separation thermodynamics and recycling technologies) and social factors (social behavior) do impose limitations (Reck and Graedel, 2012).

Once countries start to recycle more materials, more (secondary) materials are made available on the market. Countries thus reduce the demand for virgin metals and may become less dependent on external supplies. In order to reach the equilibrium, a rebalance of the system is performed using an adapted version of the RAS method (Lahr and Mesnard, 2004). The RAS method is a widely known iterative scaling method widely and commonly used for data reconciliation of non-negative matrices. The algorithm was set to consider that all countries would be seeking to reduce their exposure to supply risk simultaneously. Thus, they would: 1) increase self-sufficiency with recycling, 2) prioritize domestic demand by reducing exports, 3) switch imports from less risky economies (better WGI scores). Additionally, the balancing procedure assures that in each country there is enough raw material (either as virgin ore or scraps) to produce metals (see Rebalancing Procedure in SI), and that the total material supply or demand remains the same between the baseline and the recycling scenario. The choice for giving priority of trade to safer countries is built upon the work of Santillán-Saldivar et al. (2021). According to the authors, domestic recycling can reduce supply chain risk via two factors: decreasing external dependency and switching remaining imports towards less risk countries. Thus, the recycling scenario takes into consideration these two factors.

The rebalancing procedure provides added information for the domestic production, imports, and exports for ores and metals for a set of materials. With these, it is possible to calculate the GeoPolRisk in a single and two-stage supply chain for the increased recycling scenario for all 48 economies represented in EXIOBASE.

3. Results and discussion

3.1. Global materials concentration in extraction and metal production

The market concentration of various metals in the extraction and metal production stages is proxied using the HHI indicator for both the baseline and recycling scenarios (Table 1). Here we use the convention of HHI values below 0.15 to be considered a non-concentrated market, whereas values between 0.15 and 0.25 moderately concentrated and above 0.25 highly concentrated (U.S. Department of Justice and the Federal Trade Commission, 2010).

Between the two scenarios, the global market concentration of platinum group metals at the ore stage changed from non-concentrated to moderately concentrated markets, whereas for lead, zinc and tin at the metal stage, the switch was from moderately concentrated to non-concentrated markets. In all other cases, the markets kept their characteristics even in a scenario in which more recycling is supported. The reason behind this is a combination of the limitation on the capacity to upgrade material recycling at a regional scale and the large influence of the big producers (see Fig. 2).

The top recycling rates in EXIOBASE at baseline for iron and steel, platinum group metals, aluminum, lead, zinc and tin, copper, and non-ferrous metals are 65.7%, 67.5%, 67.1%, 65.0%, 67.5%, and 45.9%, respectively. The average additional percentage increase in this scenario is thus 10.3%, 6.5%, 23.3%, 30.4%, 15.7%, and 38.3%, respectively (see Table 1 in SI for a complete overview of recycling rates at baseline). This means that there is a higher potential for recovering other non-ferrous metals and lead, zinc, and tin, than iron and steel or platinum group metals. Here, we note that in this study the total waste produced is calculated endogenously, and thus, the recycling rates can differ from those reported elsewhere (Graedel et al., 2011; EC, 2017c). Looking into the urban mine recycling potential, the waste from stocks plays a bigger role than the final demand categories or industries. In other words, the material accumulation phase in which economies are found constraints the amount of second material available to substitute virgin ones. This is in line with studies conducted by Habib and Wenzel (2014) and Rademaker et al. (2013), where they observed that Chinese market domination of neodymium and dysprosium could be reduced in the future when the urban mine becomes available from obsolete stocks.

On a regional scale, there are countries in which a substantial increase of recycling rates is viable (see Table A.1 in SI), albeit with a minor role in changing the concentration of the global market. Since the global market concentration is heavily affected by the shares of the main producers, we displayed in Fig. 2 the predominance of the top 5 big producers for both ore and metal production for all 6 materials at the baseline and recycling scenarios. The top 5 producers account for at least over half of the global production in all cases, and most of the largest producers kept their respective positions in the ranking. Exceptions between the baseline and recycling scenarios for ores include Russia being replaced in the 5th position by South Africa for iron and the United States for platinum group metals; Rest of Africa in the 5th place by Rest of America for aluminum, Australia taken over the 2nd place

Table 1
Global market concentration represented by HHI for six material groups in the extraction and metal production phase for baseline and recycling scenario. Green, yellow and red represent non-concentrated, moderately concentrated and highly concentrated, respectively.

	Scenario	Fe	PGM	Al	Pb, Zn, Sn	Cu	ONFM
Ore	Baseline	0.199	0.147	0.154	0.184	0.200	0.127
	Recycling	0.204	0.153	0.162	0.174	0.240	0.150
Metal	Baseline	0.277	0.110	0.180	0.177	0.110	0.106
	Recycling	0.265	0.112	0.184	0.142	0.126	0.106

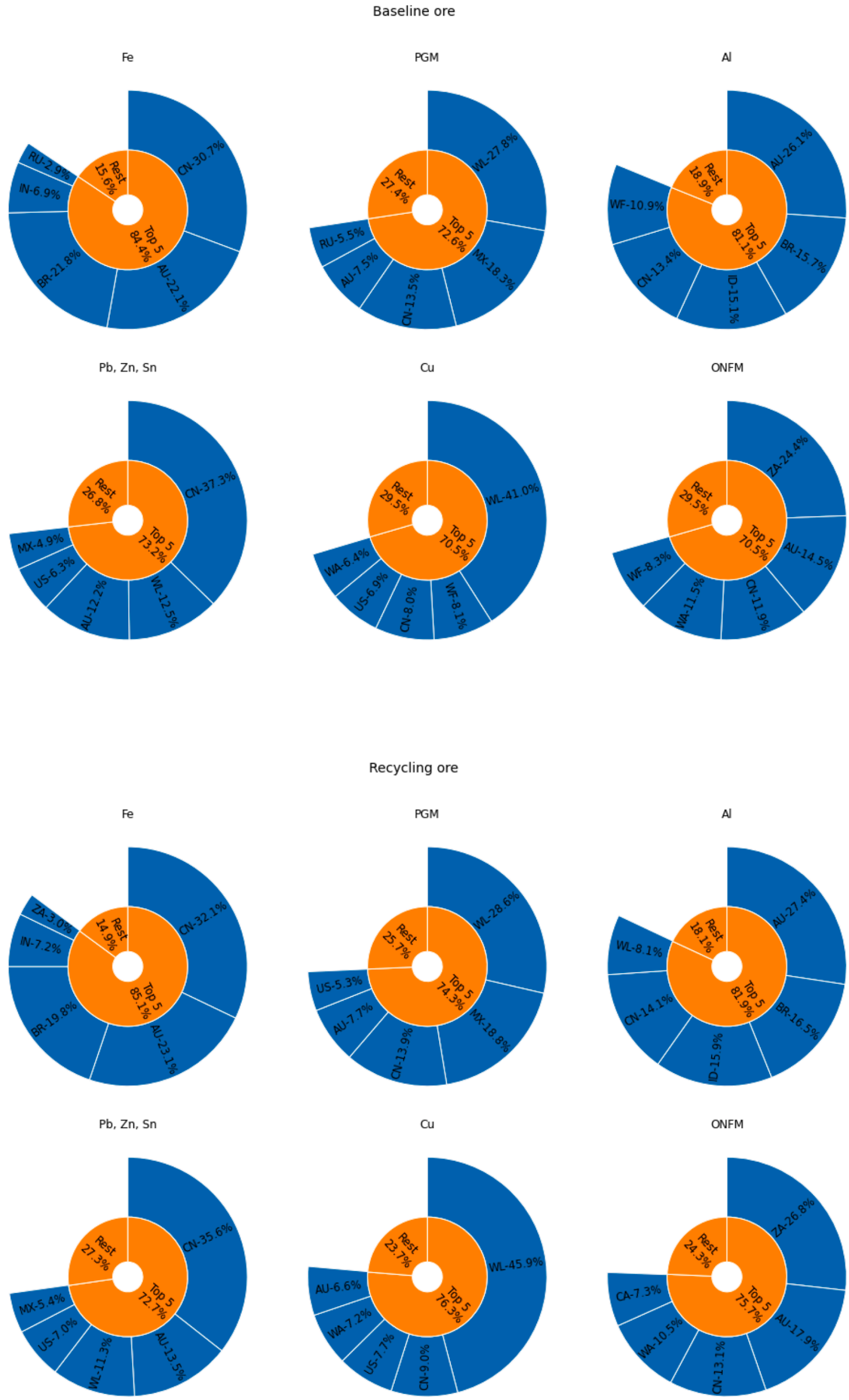

Fig. 2. Global shares of producing countries of ore and metals for six material groups under the baseline and recycling scenarios.

over Rest of America for lead, zinc, and tin; displacement of Rest of Africa from the top producing countries group and promotion of Australia for copper, and replacement of Rest of Africa in the 5th position by Canada for other non-ferrous metals. In the case of metals, Russia was displayed in the 4th position by South Korea, and the United States was included in the 5th position for iron and steel; Canada and Russia swapped places for aluminum; Rest of Asia and Pacific replaced Russia in the 4th position and India entered top producing group for copper; and South Africa and China swapped places, and India replaced Rest of Africa in the 5th position for other non-ferrous metals. Even though the big producers still have the upper hand to keep dominating the market, some of these shifts can change the characteristics of the global market

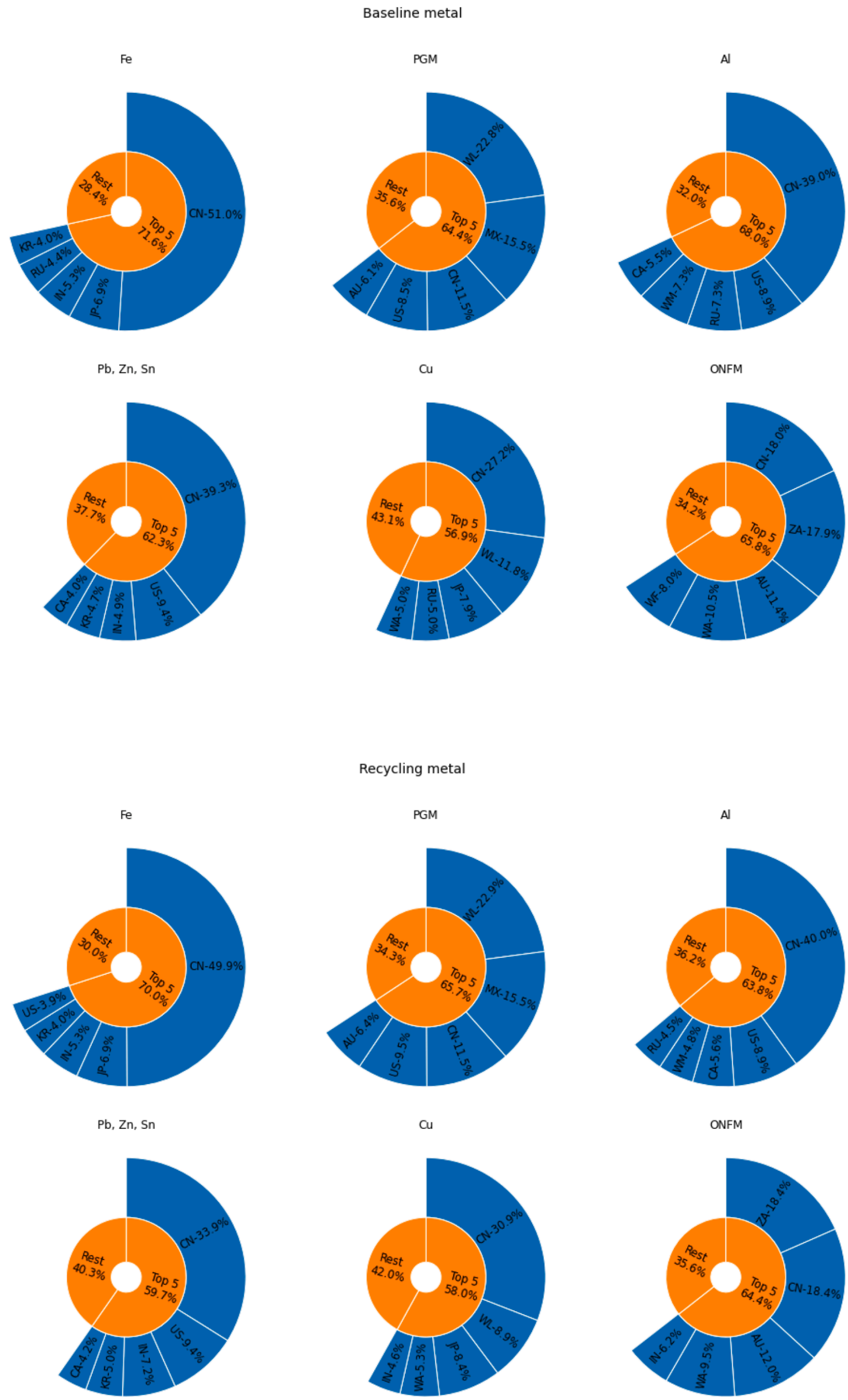

Fig. 2. (*continued*).

concentration. The extraction of platinum group metals ores changes from a non-concentrated to a moderately concentrated global market due to the displacement of Russia – a country with low WGI score - from of one of the top five producing countries. In contrast, the global market production of lead, zinc and tin metals switches from a moderately concentrated to a non-concentrated one, as China, the top producing country, loses participation. Consequently, the global market concentration is dynamically affected by how economies decide to import commodities, either by prioritizing more politically stable countries as illustrated in the recycling scenario or by other factors, such as lower prices or quality and ore grade requirements. There is also a discrepancy of market concentration between ore extraction and metal production stages, which is expected, as economies evolve and specialize in different sectors. As examples, we have the cases for iron and steel and copper. Iron ore (moderate HHI) production is distributed amongst China, Australia, and Brazil, whereas the manufacturing of its counterpart metal (concentrated HHI) is predominated by China (USGS, 2011). In the case of copper, the opposite is observed. For the extraction phase, copper has a higher HHI since mining from the Rest of America (Chile, Peru) is globally dominant. Copper metal production is dominated by China, but it is globally more distributed than mining, leading to a lower HHI for the metal production stage (USGS, 2011). Economies could therefore tailor their supply risk mitigation strategy by prioritizing the imports of a commodity at a specific supply stage. This would depend on how their own economy, and its potential vulnerabilities, is structured. For instance, economies heavily interested in energy transition need to assess whether the demand for copper can be met by their own refineries, in which case a diversification of imports from partners outside of Rest of America could be desirable, or by importing metal copper from different partners whilst boosting their own recycling system.

Enhancing recycling does not have a considerable effect in the global market concentration except for platinum group metals at ore production stage and lead, zinc and tin at metal production stage. However, the amount of virgin material required to be extracted is reduced as circularity increases. At a global level, the mined virgin material for iron, platinum group metals, aluminum, lead, zinc, and tin, copper, and nonferrous metals ores would be reduced under the recycling scenario by 56.0 Mt, 730 t, 5.3 Mt, 1.7 Mt, 1.7 Mt, and 8.2 Mt, respectively. This represents a percentage reduction of 4.3%, 2.7%, 4.9%, 9.5%, 10.6%, and 19.3%, respectively (see Table A.2 in SI). Even under total circularity, i.e., no losses in the system, it would not be possible to eliminate the extraction of virgin materials, as long as the global economy is accumulating materials in stocks. Roughly two-thirds of the global production of metals are added to societal stocks. Whilst aggregated end-of-life recycling rates of metals are high at 71% globally, the degree of circularity is much lower, at 36% due to stock-building (Haas et al., 2015).

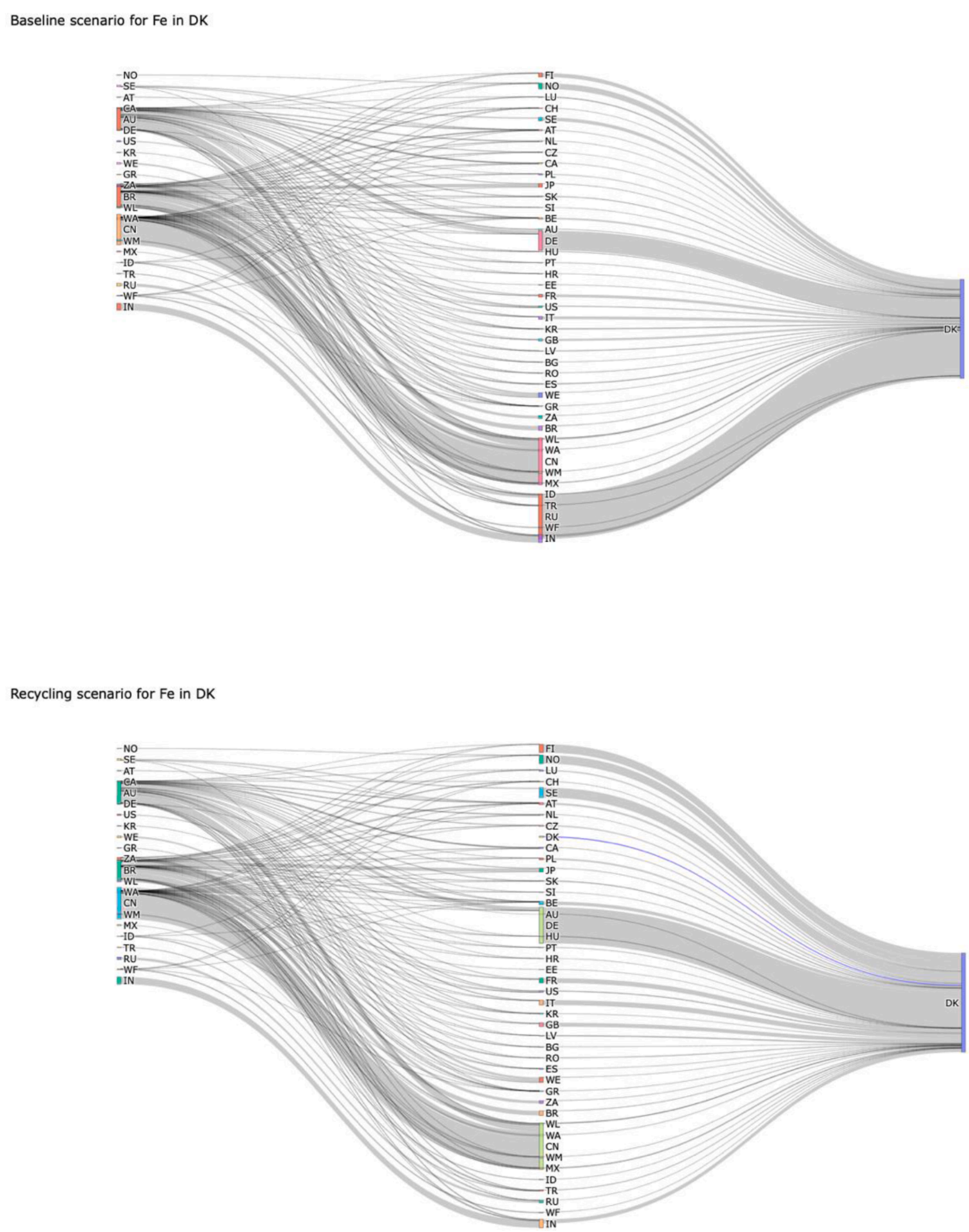

Fig. 3. Supply chain of iron ore and iron and steel in Denmark. Flows in the left represent iron ore flows, and on the right iron and steel. Countries are ordered according to the WGI score, with safest countries on top and riskiest at bottom.

3.2. Country-level GeoPolRisk in single and two-stage supply chain

Whilst the support of recycling and re-introduction of the recovered material to the domestic economy does not largely change the global markets, such measure does affect the HHI of both the ores and the metals, the domestic autonomy and the international trade. All these factors contribute to changes in GeoPolRisk (Eq. (3) and Eq. (4)). In order to better understand how GeoPolRisk is changing, the iron ore and iron and steel supply chain in Denmark is represented in Fig. 3 with flows of each stage of production scaled to a total of 100%. At first, it shows no expressive change on the iron ore supply between both scenarios. Since Denmark does not import iron ore directly in either scenario, recycling does not affect the supply chain risk at the ore stage. However, recycling allows Denmark to produce iron and steel from scraps, lowering its material dependence. Moreover, preference of imports is given to safer countries such as Finland, Norway and Sweden, instead of Russia. As a result, the supply chain risk of iron and steel in Denmark is lowered. The two-stage supply chain however is not so drastically reduced. This is because the GeoPolRisk in two-stages considers the indirect dependency of Denmark of iron ore, i.e., the raw material that is used in countries to produce iron and steel that Denmark imports.

The GeoPolRisk for single stage (ore and metal separately) and two-stage supply chain is represented for 48 economies and 6 different material groups in both baseline and recycling scenarios in Fig. 4. The lowest the GeoPolRisk the safer is the supply chain of the material involved, reaching zero in cases where there is no external dependency. Fig. 4 shows that recycling affects the national material security in different ways depending on the commodity in question and the supply-stage considered. In the first stage of the supply chain, where only mining is considered, there is a prevalence of GeoPolRisk reduction in the national supplies of platinum group metals, aluminum, lead, zinc, and tin, and other non-ferrous metals, whereas the opposite is observed for copper, and no visible distinction is observed for iron. One explanation for this behavior is found on the changes in the HHI. Copper has the highest increase in HHI (see Table 1), which means that the GeoPolRisk for this commodity will have a higher HHI factor in the recycling scenario. Analogically, the opposite is true for lead, zinc, and tin and other non-ferrous metals that have a more pronounced HHI reduction than platinum group metals and aluminum, thus higher potential reductions in GeoPolRisk. Iron, with the lowest change in HHI for ore, also saw a minimal change in supply risk. In the second stage of the supply chain, where metal production takes place and the material recycling effectively occurs, the supply chain risk is reduced for all commodities, and more sharply in the cases of other non-ferrous metals, lead, zinc, and tin, iron and steel and aluminum. Except for aluminum, all four commodities had a reduction in the global HHI, explaining partially why these benefit from a larger alleviation of the GeoPolRisk. Another reason is due to the higher material autonomy that economies can enjoy with recycling, making them less dependent on imports, especially from riskier countries (high WGI). When a two-stage supply chain is analyzed in conjunction, the risk reduction is only noticeable for lead, zinc, and tin, whilst copper becomes increasingly riskier. The origin for an increase in copper is due to a prevalence of the global concentration at the ore stage in countries with high WGI. Consequently, there is a restriction to the pool from which metal-producing countries can source their raw material demand.

Looking more specifically into each material, we see that in the case

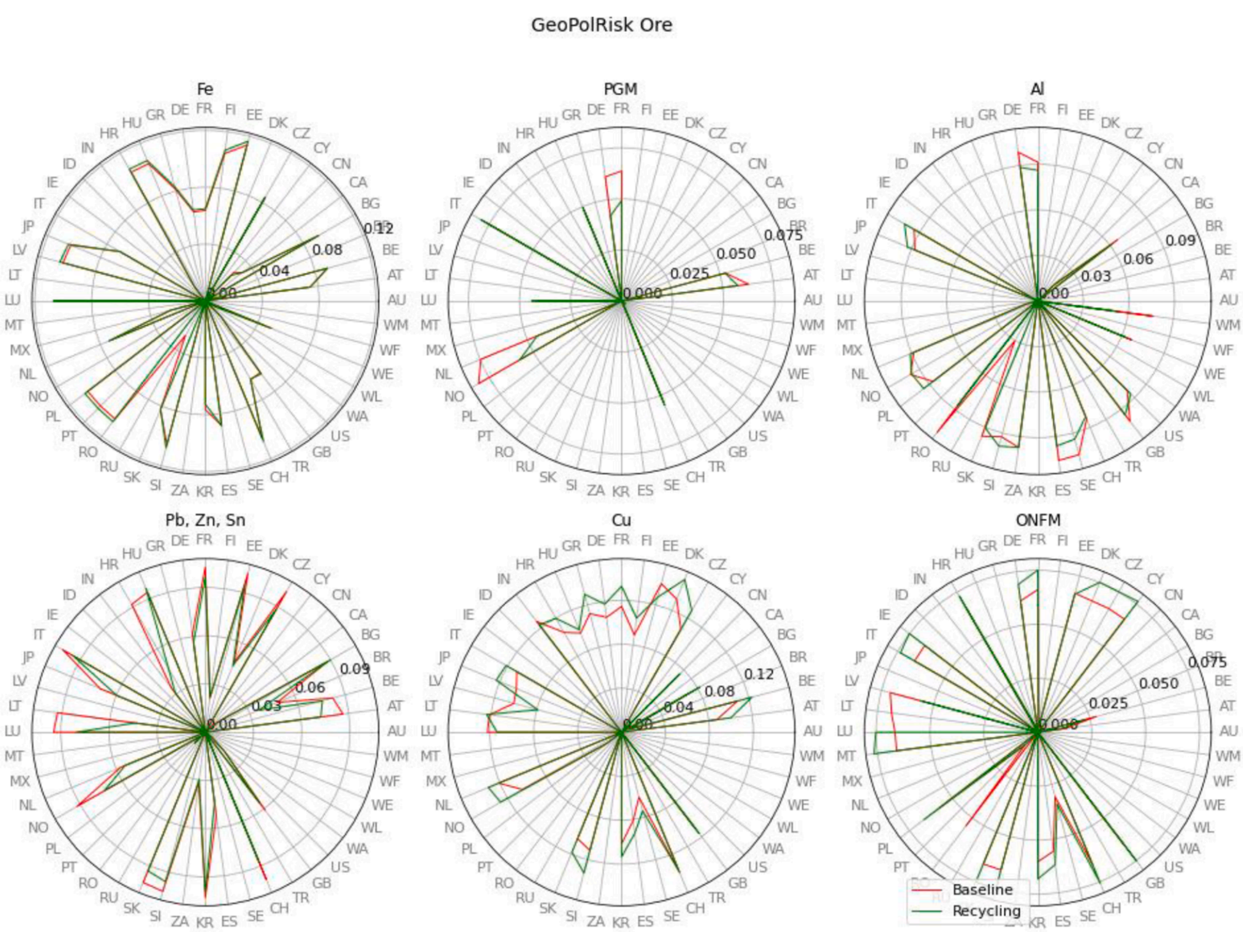

Fig. 4. National GeoPolRisk for six material groups under the baseline and recycling scenarios in single (ore and metal separately) and two-stage (ore and metal) supply chains.

Fig. 4. (*continued*).

of iron, the three countries that most improved their GeoPolRisk at the mining stage include Russia, South Korea, and China. In the recycling scenario, Russia became totally independent from imports. In South Korea and China, a slight movement towards becoming less dependent on trade and prioritizing safer partners contributed to an improvement of the GeoPolRisk. When the metal manufacturing stage is considered, the largest gains in supply risk reduction are found in Malta, Denmark and Rest of Africa region. In fact, Malta was not a metal producing country in the baseline, but with the recycling potential realized, it could rid the country of trade dependency. The higher material autonomy is the defining factor for Rest of Africa's improvement, and the import mix for Denmark. In the two-stage supply chain, Malta, Russia and Norway largely improved the supply chain risk due to a combination of the material independency (Russia for ore and Malta and Norway for metal) and a better import mix along the trade network.

For platinum group metals, the improvements for GeoPolRisk related to ore were more pronounced in the Netherlands, Norway, Germany, France and Austria, all cases due to a better import mix. In contrast, the supply chain of Rest of Asia and Pacific region and Luxembourg became riskier as the import mix shifted towards riskier countries. In the metal refining sector, Cyprus, the Netherlands and Ireland showed the greatest improvements as their material autonomy saw higher gains. In the combined stages risk analysis, Cyprus, Norway, and the Netherlands are examples of countries that take advantage of increased recycling with a more privileged trade network for ores and metals.

Russia, Rest of Middle East, Romania, Sweden and Germany showed the highest GeoPolRisk increase, each with the biggest improvements in prioritizing safest importing partners, although Russia and Rest of Middle East show better material autonomy. In contrast, Poland, Italy, Slovenia, and Japan redirected their imports to riskier countries, which explains why they ended up increasing their GeoPolRisk. Cases with high improvements in the metal sector include Luxembourg, Ireland, Japan and Indonesia, which are also present in the list of the top five countries with highest domestic share gains. Conversely, the supply chain of aluminum metal became riskier in Portugal and Denmark due to the trade with riskier countries. Luxembourg and Russia are the countries that top the GeoPolRisk of the combined stages, each being favored by their position in securing safety at the metal and ore stages, respectively.

In the lead, zinc and tin group, we did not really see clear evidence of the contribution neither from the autonomy nor the import mix to reduce GeoPolRisk at the ore stage, although Lithuania and Croatia both had one of the largest advantages in selecting safer countries to import material from, and thus reduced their GeoPolRisk by larger margins. On the converse side, Bulgaria, Hungary and Finland showed slight increases in supply chain risk increase for the opposite reason. In the metal producing stage, a higher contribution comes from the domestic autonomy with Latvia, Malta and Denmark being good examples. These are also countries with the highest gains in the GeoPolRisk of a two-stage supply chain, suggesting that for these cases there is a higher importance of the trade at the metal stage over ore.

The largest gains in the supply chain safety of copper ore coincides with the those that privileged a safer import mix. This happens for Latvia, Estonia, Luxembourg, and Switzerland. On the metal supply chain, Malta and Romania become safer due to a higher domestic dominance over the copper market. Italy, Austria, Czech Republic and France are examples in which their copper supply risk became less safe, with the first two countries mostly due to the import mix, and the last two due to the national autonomy. For the two-stage supply chain, examples of safer supply chain include Malta, Latvia and Romania, all with better supply chains at either ore or metal stages.

Finally for other non-ferrous metals, we did not notice much correlation on the countries with biggest increase in the ore supply chain safety to either of the two factors. Two exceptions are Belgium and Austria that saw higher material autonomy than most of economies. The metal manufacturing supply chain became safer for all countries, and the degree to the change is more closely related to the domestic autonomy with higher gains for Lithuania, Cyprus and Japan and lower gains for Rest of Africa, Australia and Indonesia. In the combined supply chain case, Lithuania, Rest of Africa and Belgium all had a better network trade, and as such, their supply chain also became safer to a greater degree.

In this work, the GeoPolRisk can be reduced via three different ways: global concentration reduction (HHI), import reduction (reduction effect), i.e., increase domestic material autonomy, and prioritization of safer trading partners (redistribution effect). As a result of the rebalancing algorithm that considers the existing trade routes, the domestic recycling capacity and the ability to reduce imports, and the WGI of economies, the countries ended up either reducing or increasing their supply chain risk. However, for the 6 commodities and two supply chain stages analyzed, we did not find a clear pattern from which of these three mechanisms the main reductions occur. We also noticed that largest gains or reductions might be more observable for certain materials in smaller economies, such as Malta, as opposed to big and developed ones like the United States. This is due to a combination of higher effects of international trade in countries with reduced material demand and the high recycling rates observed in EXIOBASE for more developed countries, with little space for improving recycling, and therefore to change GeoPolRisk.

3.3. Supply risk in two-stage supply chain as a function of global material concentration

The GeoPolRisk for a two-stage supply chain proposed by Helbig et al. (2016b) is a function exclusively of the global concentration of the commodity at the upstream stage (see Eq. (4)). For the ore-metal system, this translates to a dependency only on the HHI of the ore. We further explored the GeoPolRisk indicator for the ore-metal supply chain with different options to characterize the global concentration of the commodities involved in the system. For this, a combination of the HHI of the ore and the HHI of the metal via a weighted arithmetic and geometric mean is considered, with the weights expressed by the mass shares of primary material and either metal or recycled material. Fig. 5 shows the net difference of the GeoPolRisk between the baseline and recycling scenarios when the combined HHIs are used instead of when it depends solely on the HHI of the ore. Overall, the net difference of GeoPolRisk between scenarios is fairly preserved with the different HHIs combinations. This is due to the organization of the trade network of each material between countries. Even though this trade network changes between scenarios, it still remains the same in each scenario for all the different combinations of HHIs. The contrast in the GeoPolRisk net difference is hardly noticeable for platinum group metals and aluminum, but more visible for the other material groups. In the latter case, the GeoPolRisk net difference decreases between scenarios when the approach moves from one that uses solely the HHI of the ore to one that uses a combination of HHIs. This means that the GeoPolRisk decreases between scenarios when combining the HHI of both stages, which for lead, zinc, and tin, copper, and other non-ferrous metals is a directly consequence of having lower global concentration of metal in comparison with their ore counterpart. In the case of iron and steel however, this is due to a decrease in the metal global concentration when recycling is stimulated.

In a previous paper, Santillán-Saldivar et al. (2021) utilized the GeoPolRisk to analyze the contribution of recycling in mitigating supply risk of raw materials in information and communication technologies but limited the study to the European Union and combined the mining and metal sectors into a single-stage supply chain. In this study, we expanded the analysis to a two-stage supply chain system and 48 economies. According to their work, when raw material demand is considered constant, domestic recycling reduce supply chain risk. Here, we argue that in an increased recycling scenario, the raw material demand is constant only for metals, whereas the demand for ores are reduced globally. This helps to explain why the supply risk is reduced for metals, but not necessarily for ores and ores and metals combined. The authors also found out that recycling can both reduce total imports ("reduction effect") and reshuffle the import mix ("redistribution effect"). Although the former has a positive effect in reducing GeoPolRisk, the effect of the latter depends on the constitution of the trading partners. According to Santillán-Saldivar et al. (2021), this redistribution effect can minimize or over compensate for the imports reduction, when the source of imports are directed towards riskier countries, thus stifling the desired decrease in the GeoPolRisk indicator. Apart from these two effects, an additional one is observed in our analysis. This is the effect of changing HHI that results from a shift in domestic productions due to increased recycling. This effect invariably changes the GeoPolRisk to either way, depending on the direction of the global market

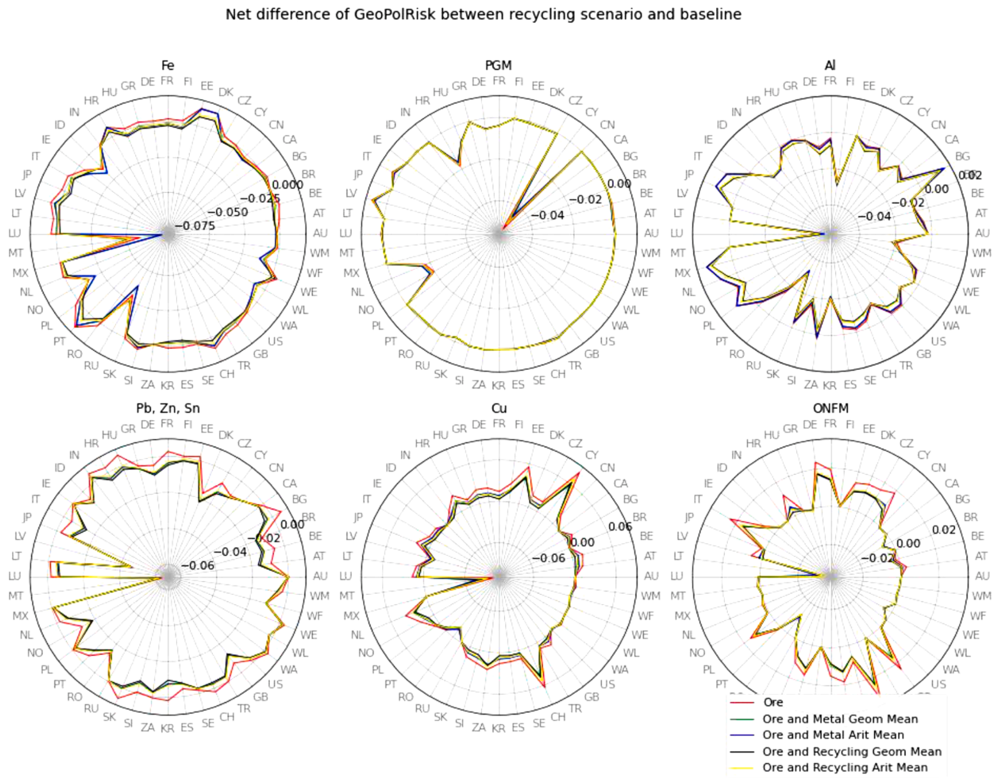

Fig. 5. Net difference of GeoPolRisk between the baseline and recycling scenarios of two-stage supply chain system for 6 materials as a function of ore and metal global concentration.

concentration, and it has not been discussed within the GeoPolRisk framework yet. To evaluate these effects, different approaches to characterize global market concentration in a two-stage supply chain system was utilized. This is represented in Fig. 5, with the HHI of the ore, as intended by Helbig et al. (2016b), and also a combination of the HHI of the ore and the HHI of the metal via a weighted arithmetic and geometric mean. Combining the HHI of the two stages did not produce a considerable effect in the GeoPolRisk. On this matter, Mancini et al. (2018) explored how supply risk factors can influence resource security impact assessments based on how characterization factors in LCA studies are defined, but we did not find this in the HHI factor. As a result, the differences spotted in the GeoPolRisk amongst countries can be attributed to how their own supply and the upstream supply of their partners is organized. For instance, when the domestic autonomy is higher and the import mixes are comprised from safer countries between the recycling and the baseline scenarios, the supply chain becomes less risky.

The novelty of using EXIOBASE and a stock-flow perspective brings new understanding on the capacity of economies to protect themselves against unwanted oscillations in the global market based on policies that support domestic recycling. We see that recycling can increase supply chain resilience at the metal stage, but this does not necessarily reflect in safety at the metal stage nor in the combined stages system. Additionally, EXIOBASE provides further information on the urban mining potential, as this is divided and quantified into three distinct parts in the database. These three distinct parts constitute of the physical waste flows from industries, final demand categories and stocks and are derived from the waste accounts procedure applied to create the database (Merciai and Schmidt, 2018). This allows countries to examine and invest in the most promising sources of secondary material. The EXIOBASE database shows the portion of the domestic waste fractions that are recycled in other countries. We suggest as future work, additional analysis that explores the implications of reducing or eliminating the export of waste for recycling. Such analysis is of great interest as waste bans like the one applied in China takes place (Liu et al., 2021; Dong et al., 2020).

3.4. Limitations

Since a top-down approach and single year is utilized to illustrate the recycling scenario, conclusions should not be overgeneralized. As an example, the EXIOBASE database allows only for the analysis of a set of 6 commodity groups. Aluminum, iron and copper can be analyzed as individual metals, but the other 3 commodity groups are made of a mix of metals which individually can be mined and produced in several different countries. The conclusions for such mixed groups like lead, zinc and tin have to be interpreted cautiously, since current and optimal recycling rates may differ significantly per metal. Additionally, we do not address the quality of the recycled material that is fed back to primary use. As such there can be limitations on the independency degree as industries may require raw materials of a specific composition and quality. Moreover, the analysis has been conducted with the only year available in the EXIOBASE database. Results therefore did not consider possible annual variations. Lastly, even though the method allows for the analysis of the consequences of increased recycling, the database we used to construct the recycling scenario was built by combining a number of very different data sources. Hence, there are uncertainties in the data that should be considered. As an example, results can be affected by poor waste statistics, which can be prevalent in certain economies where informal waste recycling plays a significant role (Forti et al., 2020). Additional uncertainty is present in small economies, where demand is null in the database. For such cases, the results should be interpreted more from a theoretical perspective, as in the possibilities of what the methodology can show.

4. Conclusion

In this article, we explored a scenario where countries increase the domestic recycling of six different material groups up to 90% of benchmark values and its effect on global and regional levels in the supply chain of ores and metals. We adopted a stock flow perspective, which allowed to better understand the possible sources of secondary materials. This proved to be majorly from stocks and not industries or final demand categories. A rebalancing of the system was conducted to determine how countries respond to the surplus of the available second material.

At a global level, the concentration of the markets for ore and metal production and first products thereof did not significantly change due to the influence of the top producers in each category and the limits of the material availability as stocks grows faster than depletes. Increasing recycling therefore would not change the global concentration at least in the short term, as these two factors are maintained. Recycling rates were determined depending on the availability of waste and stock flows in each economy. Countries exhibit a wide range of feasibility to achieve higher recycling rates. Many countries have reached a high plateau based on their current local recycling measures (Table A.1 in SI). Implementing similar measures can help countries with low recycling rates to learn how their rates can be improved, whereas innovation is needed in the high recycling countries to further increase circularity, and thus reduce supply risk at least in the metal production stage.

The adoption of a stock flow perspective and a rebalancing procedure furthered explored the GeoPolRisk method. Even though domestic recycling did not prove to be a good strategy to reduce global market concentration, it would be possible to decrease the supply risk at a national level for most of the countries and materials at the metal stage, as they become less dependent on external sources to meet their internal demand. However, this did not translate into the whole supply chain of ores and the combined supply chain of metals and ores. For these cases, the supply chain risk is not mitigated by all countries and materials, most notably copper, contrary to what has been demonstrated previously.

CRediT authorship contribution statement

Tales Yamamoto: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Stefano Merciai:** Conceptualization, Software, Formal analysis, Writing – review & editing. **José M. Mogollón:** Conceptualization, Formal analysis, Writing – review & editing, Supervision. **Arnold Tukker:** 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.

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Supplementary materials

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