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Global Mining Risk Footprint of Critical Metals Necessary for Low-Carbon Technologies: The Case of Neodymium, Cobalt, and Platinum in Japan

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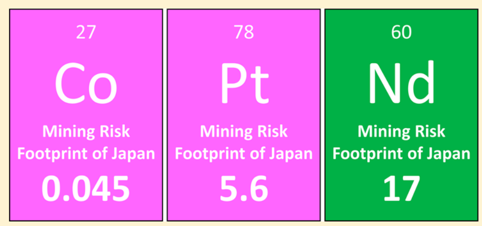
Supporting Information

ABSTRACT: Meeting the 2-degree global warming target requires wide adoption of low-carbon energy technologies. Many such technologies rely on the use of precious metals, however, increasing the dependence of national economies on these resources. Among such metals, those with supply security concerns are referred to as critical metals. Using the Policy Potential Index developed by the Fraser Institute, this study developed a new footprint indicator, the mining risk footprint (MRF), to quantify the mining risk directly and indirectly affecting a national economy through its consumption of critical metals. We formulated the MRF as a product of the material footprint (MF) of the consuming country and the mining risks of the countries where the materials are mined. A case study was conducted for the 2005 Japanese economy to determine the MF and MRF for three critical metals essential for emerging energy technologies: neodymium, cobalt and platinum. The results indicate that in 2005 the MFs generated by Japanese domestic final demand, that is, the consumption-based metal output of Japan, were 1.0×10^3 t for neodymium, 9.4×10^3 t for cobalt, and 2.1×10 t for platinum. Export demand contributes most to the MF, accounting for 3.0×10^3 t, 1.3×10^5 t, and 3.1×10 t, respectively. The MRFs of Japanese total final demand (domestic plus export) were calculated to be 1.7×10 points for neodymium, 4.5×10^{-2} points for cobalt, and 5.6 points for platinum, implying that the Japanese economy is incurring a high mining risk through its use of neodymium. This country's MRFs are all dominated by export demand. The paper concludes by discussing the policy implications and future research directions for measuring the MFs and MRFs of critical metals. For countries poorly endowed with mineral resources, adopting low-carbon energy technologies may imply a shifting of risk from carbon resources to other natural resources, in particular critical metals, and a trade-off between increased mining risk and deployment of such technologies. Our analysis constitutes a first step toward quantifying and managing the risks associated with natural resource mining.



1. INTRODUCTION

The life cycle of a metal resource begins with mining and proceeds through the phases of processing, production, recycling, and then disposal. Today, however, there are virtually no instances in which this entire series of processes occurs within the borders of a single country. In the global supply chains that have been formed through international trade, metal resources move around the world as they go through the various phases of their life cycles. Since many metals are mined in a limited number of countries and numerous other nations are exhibiting a growing demand for products using these metals, understanding the relationship between use of these resources and the global supply chains that begin with the mining process is becoming increasingly important.

One material index for quantitatively understanding the resources used in the economy of a single country via these kinds of global supply chains is the index known as the material footprint (MF) of a nation that was recently proposed by Wiedmann et al.[1] Using the Eora multiregional input−output (MRIO) model developed by Lenzen et al.,[2] the MFs for 186

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countries and regions around the world were measured. The global outputs of resources used directly and indirectly in manufacturing the products ultimately consumed in a particular country are allocated by the MF to that country. In other words, the MF is the amount of resources mined in order to support a nation's final consumption. The concept that views consumers—rather than producers—as the source of environmental and resource problems is generally referred to as "consumption-based accounting" or "environmental footprinting". As Hoekstra and Wiedmann[3] recently reviewed, this concept has been applied to many environmental problems, including climate change,[4−7] air pollutant emissions,[8,9] health impacts of air pollution,[10] water consumption,[11] endangered species,[12] and land use.[13,14]

The MF index reflects a type of consumption-based accounting, but it is also closely related to economy-wide material flow accounts (MFA), which comprehensively ascertain the magnitude of a single country's material consumption by focusing on the weight of materials used. The MF is (strictly inconsistent with, but) approximately equal to the result obtained by adding the raw material equivalent (RME),[15] a well-known indicator of the economy-wide MFA,[16,17] to the domestic extraction (DE) and then subtracting the RME associated with exports. The MF extends the system boundaries of the economy-wide MFA beyond national borders, and supports the idea of recognizing the weight of materials consumed by a single country. In practice, because economy-wide MFA data can be employed to calculate the MF, the MF empirical analyses[1,18,19] conducted to date have been concerned with the materials (used in large amounts) treated by the economy-wide MFA. Specifically, the materials that have been studied in terms of the MF are fossil resources, timber and mineral resources, and base metals such as iron, copper, and aluminum.

On the other hand, exotic metals, in particular those that are essential for future technologies but to which access is limited because of the few countries where they are mined, are recognized as critical metals.[20−22] Discussions are ongoing[20−24] regarding their economic importance as well as the risks involved from a resource-supply perspective. Ascertaining consumption of these metals in particular countries or regions[25−29] and identifying the flow of materials worldwide is key in such discussions.[30−33] By measuring a country's critical metal MF, the mining output triggered by a single economy in each individual mining country can be established. In other words, the MF enables quantitative understanding of the direct and indirect dependence of a country on the countries producing its critical metals. Unlike base metals, however, critical metals generally contribute little to the weight of material inputs to a country,[34] and, to the authors' knowledge, MF calculations have therefore not yet been carried out for critical metals, except for the case of coltan as a "conflict mineral" by Moran et al.[35] Considering the supply risks of critical metals from an MF perspective has also not been reported in the literature.

Against this background, the goal of this study is to measure the MF of critical metals and to develop a methodology for evaluating the risks associated with their mining based on that MF. In this case, the MF is expressed as a quantity of metal. In the empirical analysis, we identify the MF of Japan, globally well-known for its dependence on resource imports, and clarify its structure. Further, we develop a footprint index that incorporates the political risk of the mining countries into the identified MF, with implications for the influence of government policies and actions on metals availability. We refer to this political risk associated with the mining countries simply as the "mining risk" and call the footprint index the mining risk footprint (MRF). The case study is carried out to quantify Japan's MRF with respect to three critical metals. The metals in question are those for which international movements were quantified in a previous study[34] and demand for which is expected to increase as low-carbon technologies come into more widespread use in the future. They are neodymium (Nd, used in motor magnets), cobalt (Co, used in battery electrodes), and platinum (Pt, used in fuel-cell electrolytes).

2. MATERIALS AND METHODS

2.1. Global Flow of Critical Metals. In our previous study,[34] the global flows of Nd, Co and Pt associated with international trade between 231 countries for the year 2005 were estimated. In the present study, these global flow estimates are updated by improving the metal content values of several trade commodities and compiling a data set of the global flows of metals, expressed as $t_{pq}^{(k)}$, the metal movement from country p to country q (p = 1,...,231, q = 1,...,231) embodied in traded commodity k. The number of traded commodities (k) considered to be commodities containing the metals of interest is 153 for Nd, 160 for Co, and 151 for Pt. The commodities selected for each metal are listed in the previous study.[34]

2.2. Material Footprint Calculation Using a Global Link Input−output Model. This study incorporates the international flow of critical metals $t_{\mathrm{pq}}^{(k)}$ described in Section 2.1 into a global link input−output (GLIO)[4,9,36] model to quantify Japan's MF for the metals of interest. The GLIO model is a hybrid (mixed unit) multiregional input−output (MRIO) model that allows us to calculate the metal outputs (t_p^{JPD} and g_p^{JPX}) of country p that are directly and indirectly generated by Japanese domestic final demand (JPD) and export (JPX), respectively. The methodology of MF calculation using the GLIO model is described in detail in the Supporting Information (SI).

2.3. Mining Risk Allocation Based on Material Footprint. We combined the metal output g_p^{JPD} induced by Japanese domestic final demand and the mining risk value η_p of mining country p to quantify the mining risk footprint of the Japanese economy. The basic concept of an environmental footprint index involves allocation of an environmental burden, such as carbon emissions, to each country that induces the environmental burden on the basis of some allocation factor closely related to generation of the burden. In this study, employing this footprint concept, we established two definitions in calculating the mining risk footprint. The first is that when the mining risk of mining country p is quantified as η_p, η_p exhibits linearity and additivity. Thus, for example, the total mining risk in the world η_{total} is defined by the total sum ($\eta_{\mathrm{total}} = \sum_p \eta_p$) of η_p. The second is that η_p is allocated to country q that induces the mining in country p in proportion to the share of output induced by country q's final demand in the total output of country p. Specifically, when the annual total output of country p is g_p and the output induced by country q's final demand is g_p^q, the fraction η_p (g_p^q/g_p) of country p's mining risk is attributed to country q. This study focuses on Japan as country q and derives the output induced by Japanese domestic final demand, g_p^{JPD}. Thus, country p's mining risk attributable to Japan is calculated as η_p (g_p^{JPD}/g_p), and the global mining risk

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attributable to Japanese domestic final demand is calculated as shown in eq 1. In this study, we refer to υ^{JPD} as the mining risk footprint (MRF) of the critical metals on which Japanese domestic final demand depends. The mining risk footprint of export demand υ^{JPX} can be derived by replacing g_p^{JPD} by g_p^{JPX}.

$$\upsilon^{JPD} = \sum_{p} \frac{\eta_p g_p^{JPD}}{g_p} \tag{1}$$

In defining the mining risk of mining country p, in this study we proceeded from the policy potential index (PPI) cited for each country in the publically available Fraser Institute Report.[37] The PPI is a composite index that captures the opinions of managers and executives regarding the effects of policies in jurisdictions with which they are familiar. All the policy issues surveyed (viz., uncertainty concerning the administration, interpretation, and enforcement of existing regulations such as environmental regulations; regulatory duplication and inconsistencies; taxation; uncertainty concerning disputed land claims and protected areas; infrastructure; socio-economic agreements; political stability; labor issues; geological database; security) were included, with the exception of corruption and growing or lessening uncertainty.

In light of these issues used to characterize PPI, this study assumed that this index is a good proxy for the mining risk of a country that mines minerals. In cases where PPIs have been assigned to specific regions within a country, we regarded the simple mean of these values as the country's PPI. Because PPI values, which range from 0 to 100, are larger for countries with a lower mining risk, we converted the PPI of each country (PPI_p) to the deviation value of PPI_p ($dval(PPI)_p$) using eq 2 to set the global average of PPI_p at 50, with a larger value indicating a country with a higher risk. Here, PPI_{ave} denotes the average of PPI_p and $stdev(PPI)$ represents the standard deviation of PPI_p. For countries whose PPI is not given in the Fraser Institute Report, we used the global average or $dval(PPI)_p = 50$ as that country's value.

$$dval(PPI)_p = \frac{-(PPI_p - PPI_{ave})}{stdev(PPI)} \times 10 + 50 \tag{2}$$

Because each mining country is assigned a single PPI, this involves no evaluation according to the type of metal mined: the country has the same PPI value for every type of metal mined there. In order to characterize $dval(PPI)_p$ by metal type, we weighted $dval(PPI)_p$ by the square of the market share of the output of the metal of interest in country p (g_p) in the global total $\sum_p g_p$ as shown in eq 3.

$$\eta_p = dval(PPI)_p \times \left(\frac{g_p}{\sum_p g_p} \right)^2 \tag{3}$$

This weighting is equivalent to the method[21] used for determining the supply risk of a metal by weighting World Governance Indicators of the World Bank by the Hirfindahl-Hirschman index (HHI)[38] expressed by the square of the market share in eq 3. It is assumed here that the higher the HHI or market power with respect to a given metal in country p, the greater the potential influence of government policy and action in that country on the mining risk η_p for the metal becomes.

As the unit of the mining risk η_p is dimensionless, that of υ^{JPD} in eq 1 also becomes dimensionless. For descriptive purposes, this study refers to units of υ^{JPD} as "points". Normalization of η_p using eq 3 permits comparison of υ^{JPD} across metals (a larger value meaning higher risk) and addition of υ^{JPD} for each metal.

2.4. Sensitivity Analysis of the Mining Risk Footprint. As formulated in eq 1, the mining risk footprint υ^{JPD} depends on the material footprint g_p^{JPD} and the mining risk η_P. Because of our use of a GLIO model, the uncertainty of g_p^{JPD} derives both from the uncertainties of MRIO models, originating in input coefficients, final demand, and sectoral resolution of the Leontief system,[39,40] and from those of critical metal MFAs, originating in statistical variation, variability, and so on.[41] Based on our previous study,[9] which examined the validity of several environmental footprints derived using a GLIO model, the effect of these uncertainties on a material footprint may be substantial. However, the value of η_P is a kind of social indicator and is quantified by more subjective evaluation compared with g_p^{JPD}. We therefore focused on the uncertainty of η_P and conducted a sensitivity analysis on υ^{JPD}.

Unfortunately, due to the limited number of other indicators available that can be assumed to relate to the risks of mining, in addition to η_P based on PPI, as set out above, we could prepare just two values: η_P^{CMP}, based on the CMP (Current Mineral Potential index) of the Fraser Institute Report,[37] and η_P^{RNI}, based on the RNI (resource nationalism index) of Maplecroft.[42] Using these mining risks (η_P^{CMP}, η_P^{RNI}), υ^{JPD} was then computed, and its difference from υ^{JPD} based on PPI calculated. CMP assesses the mineral potential or endowment in a jurisdiction and whether the current policy environment (i.e., regulations, land use restrictions, taxation, political risk, and uncertainty) encourages or discourages exploration. RNI measures the risk to business of a country taking greater control of (economic) activity and the revenue accruing from its natural resource sector. It focuses on key risk drivers, including the stability and transparency of a country's political and legal institutions, its recent history of resource nationalism, and economic and fiscal factors. The deviation values of PPI, CMP and RNI for each country are listed in Table S1 in the SI.

2.5. Limitations of Model and Data. With a view to improving the reliability of the analysis using the GLIO model, in this section we briefly consider its limitations as well as the challenges associated with data organization. The aspect of the model most relevant for the reliability of identifying the MF of critical metals is the specification of the sectors using products containing the metals of interest. The best characteristic of the GLIO model is its detailed description of domestic product flows based on a classification into 406 sectors. Even so, in some cases a single sector actually produces multiple products, of which only some contain the critical metals in question. It is therefore important to distinguish which products in which sectors specifically contain one or more of the metals in order to avoid unrealistic description of metal flows. In an initial attempt to capture only the production flows of sectors manufacturing or using products containing the metals, this study applied a supply chain filter to eliminate other, nonrelevant flows. We realize, however, that there is still room for improvement in specifying the contribution of each good and service to a nation's MF.

Specifically, the problem with using a supply chain filter to eliminate product flows not containing the metals in question is that it also cuts off the upstream supply chain, which in some cases may involve the use of certain products containing the metals. Ideally, this problem should be solved by refining the supply chain for products containing the metals in question and

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disaggregating sectors. Prioritizing which sectors to refine requires technical knowledge relating to use of these metals and efforts to bolster quantitative information by means of MFA.

3. RESULTS

3.1. Material Footprint of Japan: Neodymium, Cobalt and Platinum.

3.1.1. Neodymium. The MF of neodymium associated with Japanese domestic final demand, that is, the amount of consumption-based neodymium mining, is estimated to be 1.0×10^3 t for 2005, equivalent to 8% of global neodymium output. Figure S1 in the SI provides a decomposition of the MF by country and shows that the number of neodymium mining countries is extremely limited. A quick glance reveals that neodymium mining for Japanese domestic final demand is concentrated almost entirely in China. Domestic final demand can be broken down into five categories: household consumption, government expenditure, public fixed-capital investment, private fixed-capital investment, and "other". The contributions of each are shown in Table 1.

Table 1. Neodymium Material Footprint, Mining Risk Footprint, And Mining Risk Footprint Per Unit Demand by Final Demand Category for Japan in 2005

num.	final demand category for Japan	material footprint [t-Nd/y]	mining risk footprint [point]	mining risk footprint per unit demand [point/M-JPY]
1	household consumption	3.5×10^2	1.5	5.5×10^{-9}
2	governmental expenditure	4.0×10	1.7×10^{-1}	1.9×10^{-9}
3	public fixed-capital investment	3.1×10	1.3×10^{-1}	5.6×10^{-9}
4	private fixed-capital investment	5.2×10^2	2.2	2.5×10^{-8}
5	other	6.7×10	2.9×10^{-1}	1.4×10^{-8}
6	export	3.0×10^3	1.3×10	1.8×10^{-7}
7	**total domestic final demand (sum of [1] to [5])**	$\mathbf{1.0 \times 10^3}$	**4.3**	$\mathbf{8.5 \times 10^{-9}}$
8	**total final demand (sum of [1] to [6])**	$\mathbf{4.0 \times 10^3}$	$\mathbf{1.7 \times 10}$	$\mathbf{3.0 \times 10^{-8}}$

The category with the highest contribution is private investment, accounting for 5.2×10^2 t, or 52% of the total MF (1.0×10^3 t), indicating that the MF of neodymium is driven above all by private investment. Household consumption accounts for the next largest share, 35% (3.5×10^2 t). The other final demand categories contribute far less, with "other" accounting for 6.7×10 t, and government expenditure and public investment for 4.0×10 t and 3.1×10 t, respectively.

For private investment and household consumption, we analyzed which sectors' (commodities') demand contributed most to the MF. Hereafter, sector numbers beginning with JD indicate domestically produced products and those with JI imports. First, in private investment, the top five commodities determining the MF are electronic computing equipment (accessory equipment) (JI242), which is an import and at 1.2×10^2 t accounts for the largest share; passenger motor cars (JD249, 7.0×10 t); trucks, buses, and other cars (JD250, 4.6×10 t); electronic computing equipment (except personal computers) (JI241, 4.0×10 t); and personal computers (JI240, 3.9×10 t). In the household consumption category, on the other hand, three of the top four demand categories contributing to the MF relate to private vehicles: passenger motor cars (JD249, 9.8×10 t); repair of motor vehicles (JD378, 4.9×10 t); and trucks, buses, and other cars (JD250, 2.1×10 t). The top five commodities in terms of neodymium consumption is completed by personal computers (JI240, 2.5×10 t) and electric audio equipment (JD234, 1.4×10 t).

Table 1 reveals that exports directly and indirectly cause 3.0×10^3 t of neodymium mining, indicating that they have almost triple the MF of domestic final demand. In 2005 total Japanese domestic final demand stood at about 505 trillion yen, of which only 74 trillion yen was for exports, indicating that Japanese exports are on average composed of commodities with a large neodymium MF. Once more identifying the sectors making the largest contributions, the top five are other electrical devices and parts (JD230, 2.2×10^3 t), other electronic components (JD248, 2.1×10^2 t), motor vehicle parts and accessories (JD254, 1.7×10^2 t), passenger motor cars (JD249, 1.7×10^2 t), and electronic computing equipment (JD242, 3.5×10 t).

3.1.2. Cobalt. The MF of cobalt associated with Japanese domestic final demand in 2005 is estimated at 9.3×10^3 t. This represents 0.9% of gross global output (including cobalt extraction accompanying copper ore, or 6% if this is excluded). Figure S2 in the SI gives a breakdown of the cobalt MF by mining country. Unlike the previous case of neodymium, where extraction is concentrated almost entirely in China, the MF footprint for cobalt spans multiple countries. The five accounting for the highest cobalt output are the Democratic Republic of the Congo (1.5×10^3 t), Indonesia (1.4×10^3 t), Canada (1.1×10^3 t), Australia (1.0×10^3 t), and the Philippines (8.5×10^2 t).

The breakdown of domestic final demand in Table 2 shows that, as was the case for neodymium, private fixed-capital investment is the leading contributor to demand, accounting for 3.7×10^3 t of the 9.4×10^3 t, or 39%. Household consumption is the next largest contributor at 3.5×10^3 t (37%), and is comparable to private fixed-capital investment, thus differing from the pattern observed with neodymium. The third-largest contributor is "other" (9.9×10^2 t), followed by government

Table 2. Cobalt Material Footprint, Mining Risk Footprint, And Mining Risk Footprint Per Unit Demand by Final Demand Category for Japan in 2005

num.	final demand category for Japan	material footprint [t-Co/y]	mining risk footprint [point]	mining risk footprint per unit demand [point/M-JPY]
1	household consumption	3.5×10^3	6.3×10^{-3}	2.5×10^{-11}
2	governmental expenditure	7.5×10^2	1.5×10^{-3}	1.6×10^{-11}
3	public fixed-capital investment	4.6×10^2	9.0×10^{-4}	3.8×10^{-11}
4	private fixed-capital investment	3.7×10^3	7.1×10^{-3}	7.9×10^{-11}
5	other	9.9×10^2	2.0×10^{-3}	9.9×10^{-11}
6	export	1.3×10^5	2.6×10^{-2}	3.6×10^{-10}
7	**total domestic final demand (sum of [1] to [5])**	$\mathbf{9.4 \times 10^3}$	$\mathbf{1.8 \times 10^{-2}}$	$\mathbf{3.6 \times 10^{-11}}$
8	**total final demand (sum of [1] to [6])**	$\mathbf{2.2 \times 10^5}$	$\mathbf{4.5 \times 10^{-2}}$	$\mathbf{7.7 \times 10^{-11}}$

expenditure (7.5×10^2 t), and public and private investment (4.6×10^2 t).

The major products contributing to the MF created by the formation of private capital are passenger motor cars (JD249, 4.7×10^2 t), trucks, buses and other cars (JD250, 2.7×10^2 t), and medical instruments (JD270, 2.3×10^2 t). Completing the top five contributing categories are nonresidential construction (nonwooden) (JD284, 1.5×10^2 t) and residential construction (wooden) (JD281, 1.4×10^2 t), which trigger production of gas and oil appliances and heating and cooking equipment.

The composition of the MF accounted for by household consumption is similar to that deriving from private capital investment, with demand relating to automobiles once more playing a leading role: passenger motor cars (JD249, 6.5×10^2 t), repair of motor vehicles (JD378, 2.3×10^2 t), and trucks, buses, and other cars (JD250, 1.2×10^2 t). The top 5 is completed by household electrical appliances (except air-conditioners) (JD232, 1.7×10^2 t) and house rent (imputed house rent) (JD310, 1.1×10^2 t), which induces construction repair.

At 1.3×10^4 t, the MF associated with exports is significantly higher than that due to domestic final demand. As with neodymium, Japanese exports have a much more metal-intensive demand structure than domestic demand. The top five commodities making up the MF of exports are other nonferrous metals (JD178, 2.9×10^3 t), other nonferrous metal products (JD186, 2.0×10^3 t), passenger motor cars (JD249, 1.2×10^3 t), other electronic components (JD248, 5.6×10^2 t), and motor vehicle parts and accessories (JD254, 5.0×10^2 t). Besides automobiles, exports of intermediate products and materials thus also make a major contribution.

3.1.3. Platinum. The platinum output induced by domestic final demand was quantified at 2.1×10 t, representing 8% of gross world output. Figure S3 in the SI provides a global breakdown, showing that South Africa accounts for by far the largest share: 1.7×10 t, followed at a distance by Russia (1.7 t), the UK (7.7×10^{-1} t), Canada (7.1×10^{-1} t), and Belgium (2.9×10^{-1} t). This reflects the fact that Japanese demand is met to some extent by output from urban mining, that is, platinum supplied through recycling in the UK and Belgium.

A breakdown of the domestic final demand in Table 3 shows that, as in the case of neodymium and cobalt, private capital investment makes the largest contribution, accounting for 8.5 t, or 41% of the total MF of 2.1×10 t. Household consumption, meanwhile, accounts for 7.2 t, government expenditures for 2.3 t, "other" for 2.1 t, and public fixed-capital investment for 8.1×10^{-1} t.

The MF funded by private capital derives above all from demand for passenger motor cars (JD249, 1.1 t) and trucks, buses and other cars (JD250, 6.2×10^{-1} t), with automobile-related demand followed by demand for medical instruments (JD270, 6.1×10^{-1} t), nonresidential construction (nonwooden) (JD284, 3.6×10^{-1} t), and residential construction (nonwooden) (JD282, 3.6×10^{-1}t). The MF of these construction sectors arises because of the induced demand for other electrical devices and parts, gas and oil appliances, and heating and cooking equipment. In the case of household consumption, demand for passenger motor cars (JD249, 1.5 t) accounts for the bulk of the MF, followed by repair of motor vehicles (JD378, 4.1×10^{-1} t), trucks, buses and other cars (JD250, 2.8×10^{-1} t), jewelry and adornments (JD276, 2.8×10^{-1} t), and household electrical appliances (except air-conditioners) (JD232, 2.7×10^{-1} t).

Table 3. Platinum Material Footprint, Mining Risk Footprint, And Mining Risk Footprint Per Unit Demand by Final Demand Category for Japan in 2005

num.	final demand category for Japan	Material footprint [t-Pt/y]	Mining risk footprint [point]	Mining risk footprint per unit demand [point/M-JPY]
1	household consumption	7.2	7.6×10^{-1}	2.8×10^{-9}
2	governmental expenditure	2.3	2.5×10^{-1}	2.7×10^{-9}
3	public fixed-capital investment	8.5×10^{-1}	8.8×10^{-2}	3.7×10^{-9}
4	private fixed-capital investment	8.5	9.0×10^{-1}	9.9×10^{-9}
5	other	2.1	2.2×10^{-1}	1.1×10^{-8}
6	export	3.1×10	3.3	4.5×10^{-8}
7	**total domestic final demand (sum of [1] to [5])**	$\mathbf{2.1 \times 10}$	**2.2**	$\mathbf{4.4 \times 10^{-9}}$
8	**total final demand (sum of [1] to [6])**	$\mathbf{5.2 \times 10}$	**5.6**	$\mathbf{9.6 \times 10^{-9}}$

The MF of platinum deriving from export demand is estimated at 3.1×10 t, and, as with the two previously described metals, exports have a larger MF than domestic final demand. About 1/3 of the export-induced MF is due to other electrical devices and parts (JD230, 8.8 t), with the top five contributors being completed by exports of other nonferrous metal products (JD186, 5.9 t), passenger motor cars (JD249, 2.6 t), other electronic components (JD248, 1.5 t), and internal combustion engines for motor vehicles and parts (JD253, 1.2 t).

3.2. Mining Risk Footprint of Japan and Commodities with the Greatest Mining Risk Footprint.

3.2.1. Neodymium. Table 1 summarizes the Japanese economy's mining risk footprint (MRF, expressed in points) for neodymium for each of the final demand categories. The MRF of total final demand (domestic + export) was calculated at 1.7×10 points, which corresponds to 33% of the global total for the mining risk of neodymium. Figure 1 illustrates the global distribution of the MRF of neodymium by total final demand and clearly shows that it is concentrated almost entirely in China (1.7×10 points).

The MRF of domestic final demand is just 4.3 points, which means the mining risk borne by Japan is brought about mainly by exports (1.3×10 points). In domestic final demand, private fixed-capital investment (2.2 points) and household consumption (1.5 points) are the main drivers of the mining risk of neodymium, as was the case for the MF. These values differ by a factor of only 1.5, but the MRF per unit demand of the former is 2.5×10^{-8} points/M-JPY, compared with 5.5×10^{-9} points/M-JPY for the latter, indicating the mining risk intensity of the first, and implying that reducing this demand through lifetime extension of durable goods would significantly mitigate the risk. For exports, the MRF per unit demand is 1.8×10^{-7} points/M-JPY, which suggests that in promoting economic growth by relying on exports, Japan needs to pay close attention to mining risk management.

Among domestic products, the three commodities with the greatest MRF per unit demand for neodymium are other electrical devices and parts (JD230, 9.5×10^{-6} points/M-JPY), other electronic components (JD248, 4.5×10^{-7} points/M-

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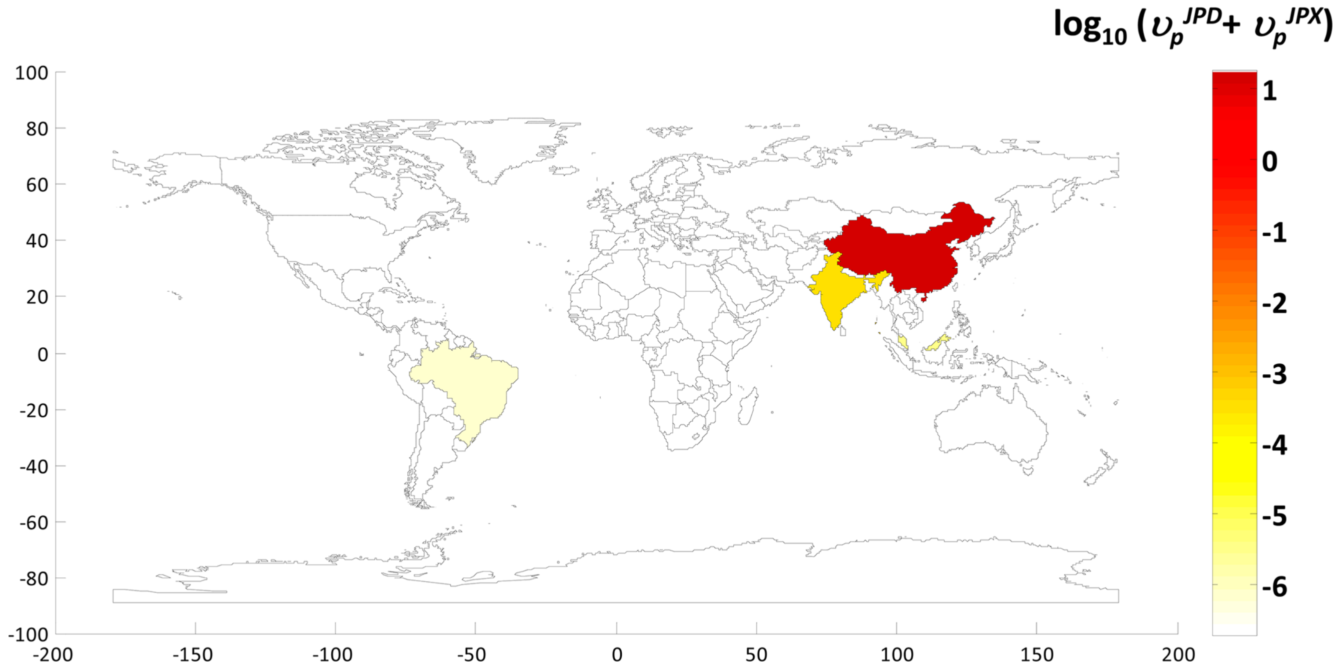

Figure 1. Global distribution of mining risk footprints of neodymium associated with Japanese total final demand in 2005.

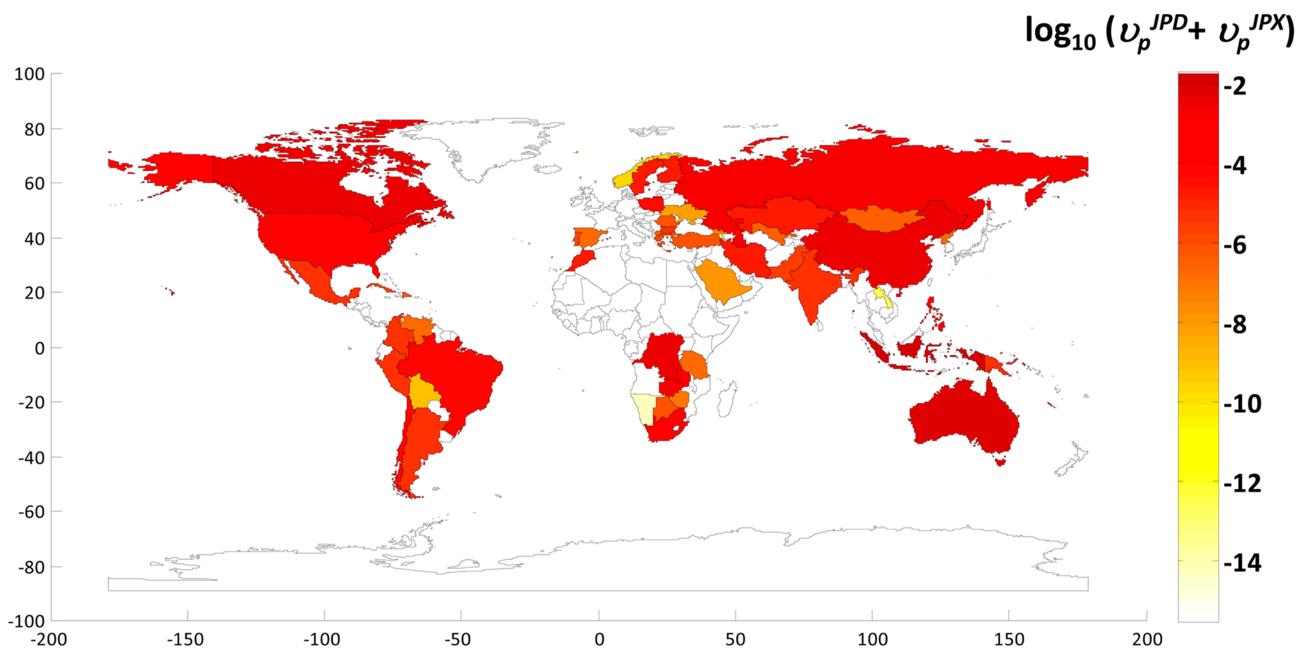

Figure 2. Global distribution of mining risk footprints of cobalt associated with Japanese total final demand in 2005.

JPY), and rotating electrical equipment (JD219, 3.9×10^{-7} points/M-JPY). It is therefore these domestic commodities that should be prioritized in Japan for re-evaluation with a view to reducing the mining risk of their supply chains.

3.2.2. Cobalt. The MRF of cobalt associated with total final demand was quantified as 4.5×10^{-2} points, representing just 1% of the world total, as shown in Table 2. It was found that the mining risk of cobalt for the Japanese economy is far less concentrated than in the case of neodymium. Figure 2, depicting the global distribution of MRF by country, shows that Indonesia (2.0×10^{-2} points) dominates, with relatively minor risks associated with Australia (6.0×10^{-3} points), the Democratic Republic of Congo (5.0×10^{-3} points), Canada (4.1×10^{-3} points), and China (3.7×10^{-3} points).

The breakdown of the MRF by total final demand in Table 2 reveals that exports make the greatest contribution (2.6×10^{-2} points), echoing the case of neodymium, followed by private fixed-capital investment (7.1×10^{-3} points), and household consumption (6.3×10^{-3} points). Unlike the case of neodymium, though, the MRF deriving from private fixed-capital investment and household consumption are very similar in value. Comparing the MRF per unit demand in each of the final demand categories reveals that exports have the highest mining risk intensity (3.6×10^{-10} points/M-JPY), followed by "other" (9.9×10^{-11} points/M-JPY), and private fixed-capital

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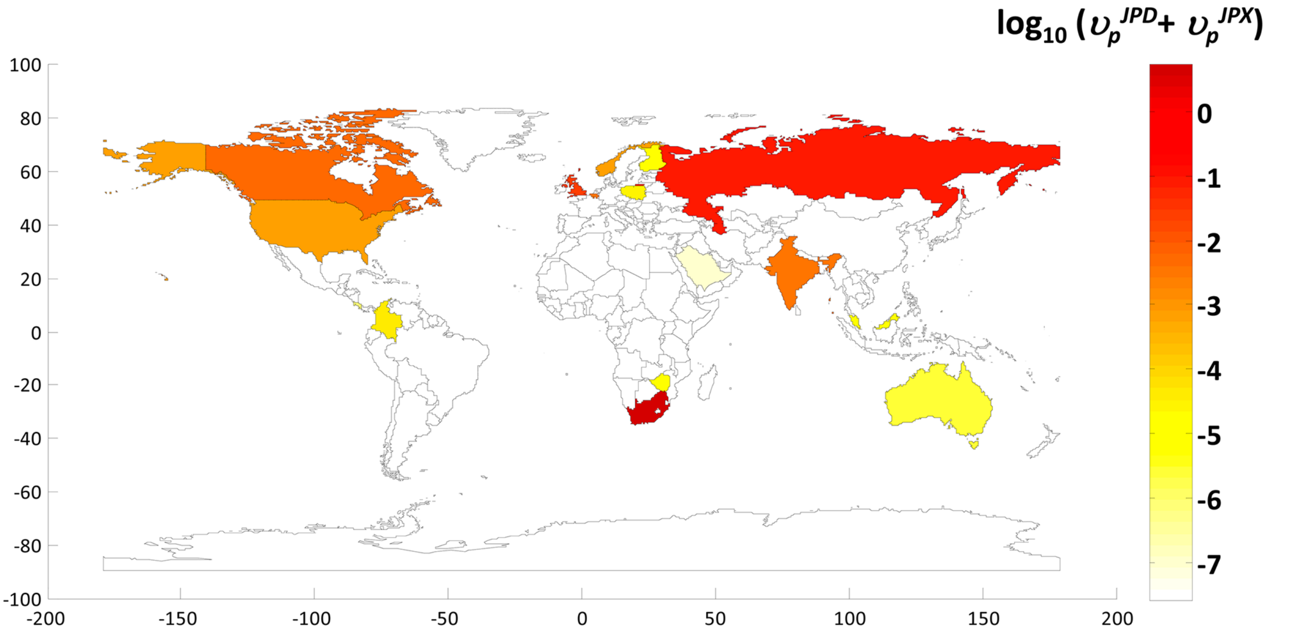

Figure 3. Global distribution of mining risk footprints of platinum associated with Japanese total final demand in 2005.

investment (7.9×10^{-11} points/M-JPY). The fact that the value for private fixed-capital investment is some three times higher than that for household consumption (2.5×10^{-11} points/M-JPY) implies that forecasting changes in the former is important, because even small fluctuations in it considerably affect the Japanese mining risk.

The three domestic commodities with the greatest cobalt MRF were identified as other nonferrous metals (JD178, 3.5×10^{-8} points/M-JPY), other nonferrous metal products (JD186, 1.5×10^{-8} points/M-JPY), and other industrial inorganic chemicals (JD112, 4.2×10^{-9} points/M-JPY).

3.2.3. Platinum. As summarized in Table 3, in the case of platinum total Japanese final demand induced an MRF of 5.6 points, which means the mining risk of platinum use in Japan is less than for neodymium, but a lot higher than for cobalt. Figure 3 provides a breakdown of these 5.6 points by country and shows that by far the greatest mining risk derives from South Africa (5.4 points), followed at a distance by Russia (1.0×10^{-1} points). The final demand categories contributing most to the total MRF are exports (3.3 points), private fixed-capital investment (9.0×10^{-1} points), and household consumption (7.6×10^{-1} points). It was thus quantitatively confirmed that the MRFs for the three critical metals in question are all dominated by exports and private fixed-capital investment.

In terms of MRF per unit demand, exports score highest by far among final demand categories (4.5×10^{-8} points/M-JPY), followed by "other" (1.1×10^{-8} points/M-JPY), and private fixed-capital investment (9.9×10^{-9} points/M-JPY). Household consumption has the second-smallest mining-risk intensity (2.8×10^{-9} points/M-JPY). Among household products, a breakdown of MRF by commodity identified other nonferrous metal products (JD186, 3.1×10^{-6} points/M-JPY), other electrical devices and parts (JD230, 9.9×10^{-7} points/M-JPY), and nonferrous metal castings and forgings (JD184, 5.5×10^{-7} points/M-JPY) as the top three MRF-intensive commodities for platinum.

3.3. Robustness of MRFs in Terms of Mining Risk Data. The sensitivity analysis of the MRFs performed using alternative parameters for mining risk (η_p^{CMP}, η_p^{RNI}) yielded figures of 1.7×10 points (with η_p^{CMP}) and 1.8×10 points (with η_p^{RNI}) for the MRF of total final demand for neodymium, and 4.3 points (with η_p^{CMP}) and 4.5 points (with η_p^{RNI}) for the MRF of domestic final demand for this metal. Considering that the MRF-values obtained using η_p were 1.7×10 points for total final demand and 4.3 points for domestic final demand, we would conclude that the uncertainty of the MRFs for neodymium deriving from differences in mining risk data is very small.

For cobalt, the MRFs of total final demand based on η_p^{CMP} and η_p^{RNI} are 4.3×10^{-2} points and 4.9×10^{-2} points, respectively, which are very close to the value based on η_p: 4.5×10^{-2} points. For domestic final demand, the MRFs were 1.8×10^{-2} points based on η_p^{CMP} and 2.0×10^{-2} points based on η_p^{RNI}, which are again very similar to the value obtained using η_p: 1.8×10^{-2} points. This appears to indicate the robustness of the MRF for cobalt in terms of the type of mining risk data employed.

Similar conclusions can be drawn for the MRFs for platinum. The MRFs of total final demand based on η_p^{CMP} and η_p^{RNI} were calculated as 5.9 and 5.6 points, respectively, and those for domestic final demand as 2.4 and 2.2 points. With η_p, the MRF for total final demand was 5.6 points and that for domestic final demand 2.2 points. Compared with neodymium and cobalt, the difference between η_p and η_p^{CMP} is slightly greater, but the overall robustness of MRFs is again generally confirmed.

4. DISCUSSION

In this study we have quantified the MF of Japan for critical metals (neodymium, cobalt, and platinum) essential to low-carbon technologies, identifying the global outputs of these metals triggered by Japanese final demand, which includes, importantly, exports. The results imply that the Japanese economy is taking high mining risks through its use of neodymium, in particular. Applying the footprint concept to quantify the mining risk embodied in the MF, we have also developed a new indicator that we call the mining risk footprint (MRF). Especially for a resource-poor country like Japan, this

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clarification of the MF and MRF of critical metals has three main policy implications.

First, because the MF not only encompasses the bilateral imports and exports of ores and raw metals but also establishes a linkage between the country where a metal is mined and the country where it is finally consumed, it helps final consumers understand the intricate network of direct and indirect dependency on overseas resources. The analyses performed on the 2005 Japanese economy reveal that export demand creates an enormous MF. This implies that Japan's ability to export depends not only on overseas economies that supply intermediate products but also on those mining natural resources, thus reaffirming the importance of integrating economic and resource-management policies. As the population making up Japan's domestic market declines and ages, export demand is becoming increasingly important for the national economy, for example. If export demand is to be sustained, policies may need to be introduced to reduce the country's dependence on foreign-sourced critical metals by means of recycling, alternatives, and technological innovations, for example.

The MF for Japanese commodities derived in this study can be applied to predict the future MF of the Japanese economy and identify key commodities that might push the MF upward, as was done in the previous study,[43] by combining the MF of each commodity with estimates of future demand. The perspective offered by MF can serve as a linchpin for the design of future resource policy in Japan, since identifying such key commodities would enable prioritization not only of production and recycling technologies in need of improvement, but also of policies promoting longer-term use of products and improved end-of-life collection and recycling.

Second, this paper highlights the importance of a robust understanding of the sourcing of materials and the structure of global supply chains for measuring the risks associated with natural resource use. It is not only the total mass of materials, but also their identity, scarcity, and source, and the structures of specific supply chains that together explain the risks associated with economic use of such materials. In the U.S. and UK, for example, governments have established five dimensions[20] and eight factors,[24] respectively, for the purpose of resource criticality assessment, with the influence of state policies and actions in supplying regions on metal availability is now one of the pivotal assessment criteria employed by both countries. MRF is a further, quantitative elaboration of such a criterion, and would greatly support the evaluation of resource criticality.

Third, our study shows the importance of understanding the nexus between materials and energy policies[44] in Japan. The importance of MF measurement in the context of critical metals will increase as Japan progresses toward a low-carbon society, because Japan, which imports almost 100% of its metal resources, has to face a trade-off between greenhouse gas (GHG) mitigation and scarce metals consumption, an issue likewise of concern to the economy of the European Union.[45] In other words, moving toward a low-carbon society by focusing solely on GHG emission reduction may result in an increased MF, increased resource supply risks, and increased environmental impacts in mining countries.[46] In its efforts to transition smoothly and stably to a low-carbon society, one of the crucial political challenges facing Japan is therefore to measure and manage the mining risk footprint of critical metals in parallel with the carbon footprint through which we currently understand the dynamics and effects of such a transition. A sustained, periodic monitoring program is therefore essential. The MRF of individual Japanese commodities compiled here would provide consumers and corporations opportunities to contribute to the measurement and management of resource supply risks, in the same way that the carbon footprints of products or organizations[47,48] have been playing a successful role in GHG management. This is a common challenge faced by many countries that rely on other nations for critical metals and that are promoting the transition to low-carbon societies by focusing on new energy technologies.

Lastly, it should be stressed that there remain several key challenges in quantifying a society's footprint by means of input-output analysis. As reflected in the sensitivity analysis, one of the factors inducing uncertainty in the MRF is the type of political risk data employed as a social indicator, although in this study this influence appeared to be within tolerance limits. Beyond concerns regarding uncertainties with models and data, however, further efforts are required to establish the compelling logic of the combination of an input-output model and a social indictor, especially a dimensionless one like PPI. Similarly to the concept of social life cycle assessment,[49,50] the validity of attributing a social indicator to products or processes in an input-output table and of assuming linearity between indicator and product output requires further enhancement before a social footprint generated with input-output analysis can be adopted as a concrete political goal for social sustainability.

■ ASSOCIATED CONTENT

Supporting Information

The SI provides detailed descriptions of the methodologies employed in quantifying the MFs using GLIO. Figures S1 to S3 map the global distribution of the Japanese material footprints for Nd, Co, and Pt, and Table S1 provides the deviation values of PPI, CMP and RNI for 231 countries. This material is available online free of charge at http://pubs.acs.org.This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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