

Global Flows of Critical Metals Necessary for Low-Carbon Technologies: The Case of Neodymium, Cobalt, and Platinum

Keisuke Nansai,^{*,†} Kenichi Nakajima,[†] Shigemi Kagawa,[‡] Yasushi Kondo,[§] Sangwon Suh,^{||}
Yosuke Shigetomi,^{†,⊥} and Yuko Oshita[#]

[†]Center for Material Cycles and Waste Management Research, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, 305-8506, Japan

[‡]Faculty of Economics, Kyushu University, 6-19-1 Hakozaki, Higashi-ku, Fukuoka, 812-8581, Japan

[§]Faculty of Political Science and Economics, Waseda University, 1-6-1 Nishi-Waseda, Shinjuku-ku, Tokyo, 169-8050, Japan

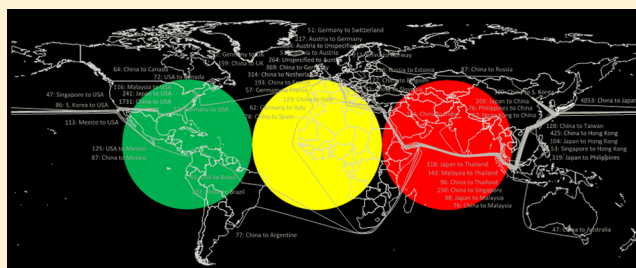
^{||}Bren School of Environmental Science and Management, University of California Santa Barbara, 3422 Bren Hall, CA, USA

[†]Graduate School of Energy Science, Kyoto University, Sakyo-ku, Kyoto 606-8501, Japan

[#]Faculty of Maritime Sciences, Kobe University, 5-1-1 Fukaeminami-machi, Higashinada-ku, Kobe, 658-0022, Japan

S Supporting Information

ABSTRACT: This study, encompassing 231 countries and regions, quantifies the global transfer of three critical metals (neodymium, cobalt, and platinum) considered vital for low-carbon technologies by means of material flow analysis (MFA), using trade data (BACI) and the metal contents of trade commodities, resolving the optimization problem to ensure the material balance of the metals within each country and region. The study shows that in 2005 international trade led to global flows of 18.6 kt of neodymium, 154 kt of cobalt, and 402 t of platinum and identifies the main commodities and top 50 bilateral trade links embodying these metals. To explore the issue of consumption efficiency, the flows were characterized according to the technological level of each country or region and divided into three types: green (“efficient use”), yellow (“moderately efficient use”), and red (“inefficient use”). On this basis, the shares of green, yellow, and red flows in the aggregate global flow of Nd were found to be 1.2%, 98%, and 1.2%, respectively. For Co, the respective figures are 53%, 28%, and 19%, and for Pt 15%, 84%, and 0.87%. Furthermore, a simple indicator focusing on the composition of the three colored flows for each commodity was developed to identify trade commodities that should be prioritized for urgent technical improvement to reduce wasteful use of the metals. Based on the indicator, we discuss logical, strategic identification of the responsibilities and roles of the countries involved in the global flows.



1. INTRODUCTION

Low-carbon technologies such as electric vehicles, fuel cells and photovoltaic power generation are expected to be the leading contenders for establishing a low-carbon society. These technologies utilize the specific physical properties of a handful of metals in core components such as motors and batteries. The countries where some of these metals are mined are located eccentrically around the world and the metals are sometimes used for diplomatic leverage, leading to considerable concern about supply risks and the metals often being referred to as critical metals.^{1–4} Mining of the metal ores also causes serious environmental damage around extraction sites^{5–9} and final disposal of the metal-containing products is likewise often accompanied by environmental and health impacts.^{10,11} On the policy side, the European Commission¹² and the U.S. Department of Energy,¹³ for example, have published reports concluding that certain metals, including rare earths, are critical to the emerging clean energy economy. As these reports imply, there is serious concern that the spread of green technologies by

countries endeavoring to limit their greenhouse gas emissions will inevitably increase demand for the metals in question, leading to a tightening of supply. As we strive to reduce global carbon emissions, it is therefore essential to limit the current growth of metals consumption while still meeting rising demand for them.¹⁴ In other words, in those countries and regions involved in any way with the global flow of the metals in question it is necessary to use these metals more efficiently, that is, less wastefully, to reduce unnecessary mining.

As summarized in Reck and Graedel,¹⁵ several material flow analyses have identified the life cycles of up to 15 types of critical metals,^{16–19} including rare earth elements, and estimated global stocks,^{17,18} going on to recommend establishment of a closed-loop material system in the global economy that recognizes

Received: July 29, 2013

Revised: December 30, 2013

Accepted: January 5, 2014

Published: January 6, 2014

technological and social limitations. However, these studies have not yet led to an analysis of how individual countries in the global economy are involved in such flows of critical metals and given little attention to the responsibilities and roles to be adopted by those countries other than recommending recycling based on so-called urban mining to reduce unnecessary consumption of the metals embodied in the flows.

Against this background, the objective of this study is to estimate and characterize the global flows of three critical metals necessary for low-carbon technologies: neodymium^{17,20} (Nd) (used, for example, in motor magnets), cobalt²¹ (Co) (e.g., battery electrodes) and platinum^{22–24} (Pt) (e.g., fuel cell electrolytes). The study also aims to develop a simple indicator to identify trade commodities meriting international priority with respect to improving the performance of production technologies and social systems governing use of these critical metals. Using this indicator, we furthermore discuss logical and strategic identification of the responsibilities and roles of the countries involved in the global flows.

2. MATERIALS AND METHODS

2.1. Estimate of Global Flows of Neodymium, Cobalt and Platinum. A material flow analysis (MFA) was conducted on neodymium, cobalt, and platinum, which are among the critical metals most widely used in low-carbon technologies. For considerations of space, we suffice here with a brief description of MFA methodology, with detailed descriptions of methodology^{25,26} and data^{27–30} being provided in the Supporting Information (SI). To create a complete global MFA system boundary, this study considered 231 countries and regions as listed in Table S1 in the SI. From the commodities traded internationally, all commodities k considered to contain the metals to be estimated (Nd, Co, and Pt) were then selected. To this end, the Harmonized System (“HS-”) codes (double-digit or six-digit), that is, international standard trade category codes, were used. This led to selection of 153 commodities containing Nd, 160 commodities containing Co (including copper ore) and 151 commodities containing Pt.

We then examined the volumes of each of the selected commodities k traded between country i and country j , $v_{ij}^{(k)}$. The trade volumes of the commodities k were organized based on free on board (FOB) price (1000 US dollar/year) or weight (t/year) taking 2005 as the target year using the Base pour l'Analyse du Commerce International (BACI)²⁷ or International Trade Database at the Product Level, which is an improvement of the UN Comtrade database. However, some of the HS-codes, even in the six-digit category, integrate multiple commodities, including instances where, among the many commodities, only one contains the metal(s) in question. Hence, in this study, the trade volumes of each commodity obtained from BACI were assigned a cutoff value $r_i^{(k)}$ between 0 and 1, which was multiplied by the trade volume to increase the accuracy of the estimated trade volume of the commodity containing the critical metal(s) of interest. The percentage metal content $c_i^{(k)}$ (t/1000 US dollar or t/t) of each selected commodity was then determined. Next, the initial estimates of metals $t_{ij}^{(k)}$ moving between countries in commodity trade were calculated by multiplying the international trade volume of each commodity, the assigned cutoff value and the percentage metal content: $t_{ij}^{(k)} = v_{ij}^{(k)} \times r_i^{(k)} \times c_i^{(k)}$. Finally, a calibration was made to the above initial estimates to satisfy the material balance of the metal within each country by resolving the quadratic problem (as explained in the SI).

2.2. Partitioning Global Flows on the Basis of Technology Level. 2.2.1. Classification of Flows As Green, Yellow or Red.

The estimated $t_{ij}^{(k)}$ indicates the amount of metal contained in commodity k that is produced in country i and moved to country j , where it is consumed or processed further and possibly exported to another country. To obtain a comprehensive overview of the structure of the flows with a view to exploring wasteful consumption, we partitioned the flows by examining the technological characteristics of the import and export country. Such an analysis provides a ready way to identify “hotspots” of metal consumption where this is major room for improvement. Conceptually, it is desirable that these characteristics are assessed using a quantitative indicator such as the material-use efficiency^{31,32} of the metal in producing or using commodity k in each country. As an MFA indicator, material-use efficiency is defined as the amount of raw material effectively utilized divided by the total amount consumed and gives an indication of the degree to which byproducts are recycled and waste generation is suppressed. Here, the assumption is made that all countries can be approximately characterized as having either a high or low material-use efficiency, so that global flows of the metals can be classified into one of three material-use efficiency classes, as described below.

In the first class of material-use efficiency, it is assumed that country i exporting commodity k has high-level production technologies and material-use efficiencies, and is capable of nonwasteful use of the metal in its products. At the same time, country j importing commodity k also has high-level production technologies and is capable of nonwastefully using commodity k containing the metal. In addition, even when country j consumes commodity k , it has a high technological level for recovering resources from spent products, such as mobile phones. This is in addition to it being a country that can establish and implement advanced social systems for recovering critical metals, making it a country with a high overall material-use efficiency.

In the above cases, critical metals moved by country i to country j are produced based on a high material-use efficiency and subsequently consumed with a high material-use efficiency. This results in the highest material-use efficiency between two countries for the amount of metal $t_{ij}^{(k)}$ moved, so it can be classified as a flow that boosts nonwasteful use of critical metals. In this paper, such a flow is referred to as a “green flow”.

In the second class, either the exporting country i or the importing country j does not have a high technological level or advanced social systems. If exporting country i currently has a low technological level, the amount of metal $t_{ij}^{(k)}$ moved in commodity k has a low material-use efficiency. Even if commodity k is subsequently used more extensively with a high material-use efficiency in the importing country j with a high technological level, the material-use efficiency between the two countries for the amount of metal $t_{ij}^{(k)}$ moved is considered to be only moderate. In such a case, the flow can be considered to be inferior to the first class (i.e., green flows), where both countries have high technological and social levels. In this paper, such a flow is referred to as a “yellow flow” (“moderately efficient use”).

The same applies in the reverse situation. If exporting country i has a high technological level, commodity k is produced with a high material-use efficiency. If commodity k is used in importing country j with a low technological level, then the efficiency is poor, or the spent products cannot be collected or resources recycled, making the material-use efficiency low. As a result, the material-use efficiency between the two countries for the amount of metal $t_{ij}^{(k)}$ moved is inferior to when both countries have high

technological and social levels, that is, a green flow. However, determining when to characterize material-use efficiency as being superior or inferior to the previous case (yellow flow) in which the importing country has a low technological level and the exporting country has a high technological level is not straightforward. In this study, such a flow is therefore also classified as a “yellow flow.”

In the final class, both the exporting country i and the importing country j have low levels of production technologies and social systems. The material-use efficiency between the two countries for the amount of metal $t_{ij}^{(k)}$ moved is lowest of all. This leads to an increase in the amount of mining. In this paper, this flow is classified as being the least efficient for the amount moved and is classified as a “red flow” (“inefficient use”).

2.2.2. Strengths, Limitations and Possibilities of the Classification. Partitioning the global flows $t_{ij}^{(k)}$ of metals based on the polarized characteristics of countries i, j with respect to commodity k as set out above is an extremely simple method. Despite its simplicity, though, the strength of this approach is its usefulness in reviewing the structure of an extremely large number of complex global flows. Moreover, this simple method is readily applicable to other environmental and social issues. Partitioning the flows in terms of the degree of impact on biodiversity associated with metal use in each country, for instance, would yield a general picture of the hotspots of flows related to threatened species. Alternatively, flow partition based on the trade risk of each country would permit identification of the bottlenecks of critical metal flows. Additionally, because of the classification's focus on countries, this approach can be readily used to design a framework of international cooperation and partnership to resolve the environmental and social issues associated with international trade in metals.

The main drawback of this approach lies in two difficulties in data collection. The first relates to the need for data on all the countries involved in the flows. In some cases it is necessary to use proxy values or indicators that provide only an indirect indication of the country's characteristics of interest. The second relates to the need to assign a representative single value to each country because of the assignment of polarized characteristics. This means that even if there are a few companies with a high technological level in a country, if the most of companies have a low technological level, the overall level of the country is defined as low. Due attention therefore needs to be given to the limitations implied in classifying flows by means of such proxy data or single values.

Classifying the metal flows into three types is equivalent to dividing a network into two subsets, assuming that the countries and regions i, j are nodes and that the flows are edges. This division has the same aim as the methodology of network partitioning employed in network theory to elucidate the network structure, a method that has recently been applied to the structural analysis of carbon footprints.^{33,34} By adopting the methodology of network partitioning and developing it further in more in-depth studies, it is anticipated that the structural characteristics of international resource flows can be comprehensively elucidated, thus laying the groundwork for proposals for international policies on resource use efficiency.

2.2.3. Assumptions on Technological and Social Levels of Each Country. In order to categorize critical metals use in producing or using commodity k by countries into those with high-level production technologies and social systems (H countries) and those with low-level production technologies and social systems (L countries), countries need to be

distinguished according to the technologies and recycling systems they have implemented. Unfortunately, conducting dedicated national surveys to examine these issues in any detail would be very costly in terms of time and labor, while at the same time technologies for using and recycling critical metals are constantly evolving. Furthermore, there are currently no data or statistics available that quantitatively assess technological information relating to critical metals. We therefore attempted to classify countries based on their potential for technological improvement using available statistics on the general technological level of each country. To this end we used the Global Competitiveness Report³⁵ published by the World Economic Forum as a source of surrogate data on the technological and social levels of individual countries. Specifically, from among the more than 100 indicators evaluated by the report for 144 major countries, we focused on the following seven indicators relating to science and technology: [1] Availability of latest technologies, [2] Firm-level technology absorption, [3] Capacity for innovation, [4] Quality of scientific research institutions, [5] Company spending on R&D, [6] University-industry collaboration in R&D and [7] Governmental procurement of advanced tech products. We then took countries scoring above average on all seven indicators to be countries having high-level production technologies and social systems (H countries), with the remaining countries being classified as having low-level production technologies and social systems (L countries). Although these H and L countries should in principle be defined in relation to a specific commodity k , this study applied the same H and L classification of countries to all commodities. In alphabetical order, the following 29 nations emerged as H countries: Australia, Austria, Belgium, Brazil, Canada, Denmark, Estonia, Finland, France, Germany, Hong Kong, Iceland, Israel, Japan, South Korea, Luxembourg, Malaysia, Netherlands, New Zealand, Norway, Portugal, Puerto Rico, Qatar, Saudi Arabia, Singapore, Switzerland, Taiwan, United Kingdom, and United States.

2.3. A Simple Indicator to Prioritize Commodities for Enhanced Critical Metal Use: Green-, Yellow-, and Red-Flow Commodities. As outlined above, we here propose a simple indicator to prioritize myriad commodities in international trade in order to improve the efficiency of critical metal use. The indicator characterizes trade commodities as green-, yellow-, and red-flow commodities according to the extent to which the three color flows (green, yellow, and red) are involved in the flow of commodities containing critical metals.

To this end, first the amounts of critical metals $t_{ij}^{(k)}$ contained in commodity k were classified as green, yellow, and/or red flows, using eqs 1–3, below. When green flows are largest, commodity k is classified as a “green-flow commodity”, when yellow flows are largest as a “yellow-flow commodity”, and when red flows are largest as a “red-flow commodity”. When two values were the same, the next lowest color classification was used as a conservative estimate, and when all three values were the same the commodity was labeled a red-flow commodity. Introducing H for the aggregate of country i and country j both having high-level production technologies and social systems, and L for the aggregate of country i and country j both having low-level production technologies and social systems, this gives

$$\text{greenflow}^{(k)} = \sum_{i \in H} \sum_{j \in H} t_{ij}^{(k)} \quad (1)$$

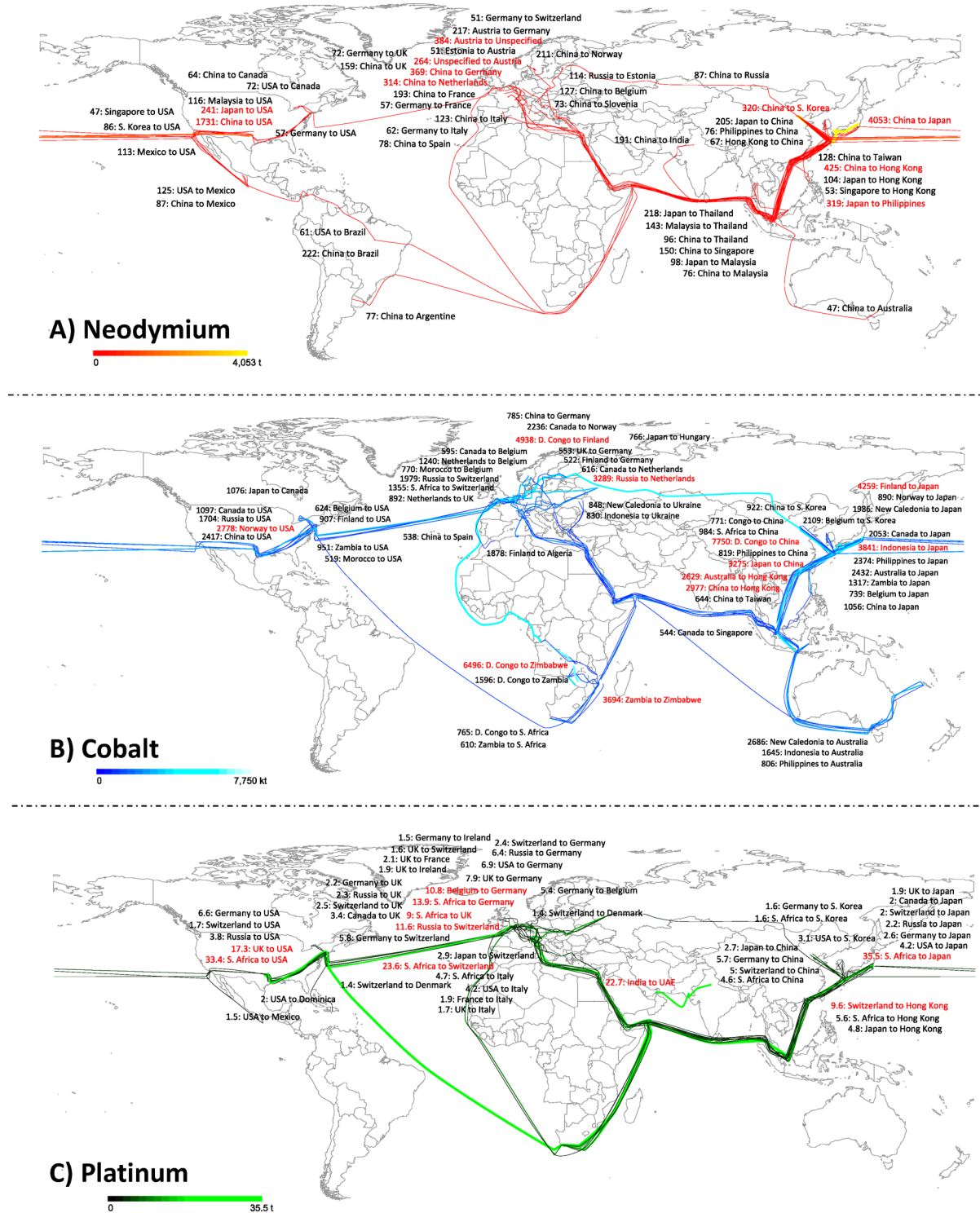


Figure 1. The 50 largest global flows of critical metals through international trade in 2005 (A: neodymium, B: cobalt, C: platinum); for the top 10 flows, the countries and volumes of critical metal involved (tonne for neodymium and platinum, kt ($10^3 \times$ tonne) for cobalt) are indicated in red letters.

$$\text{yellowflow}^{(k)} = \sum_{i \in H} \sum_{j \in L} t_{ij}^{(k)} + \sum_{i \in L} \sum_{j \in H} t_{ij}^{(k)} \quad (2)$$

$$\text{redflow}^{(k)} = \sum_{i \in L} \sum_{j \in L} t_{ij}^{(k)} \quad (3)$$

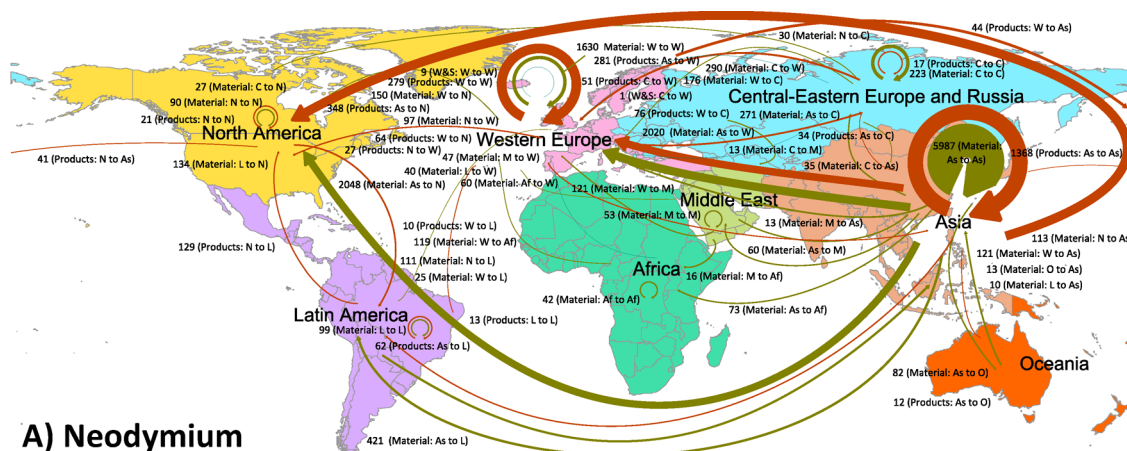
When $\text{greenflow}^{(k)} > \text{yellowflow}^{(k)}$, and $\text{greenflow}^{(k)} > \text{redflow}^{(k)}$, commodity k is defined as a green-flow commodity.

When $\text{yellowflow}^{(k)} \geq \text{greenflow}^{(k)}$ and $\text{yellowflow}^{(k)} > \text{redflow}^{(k)}$, commodity k is defined as a yellow-flow commodity.

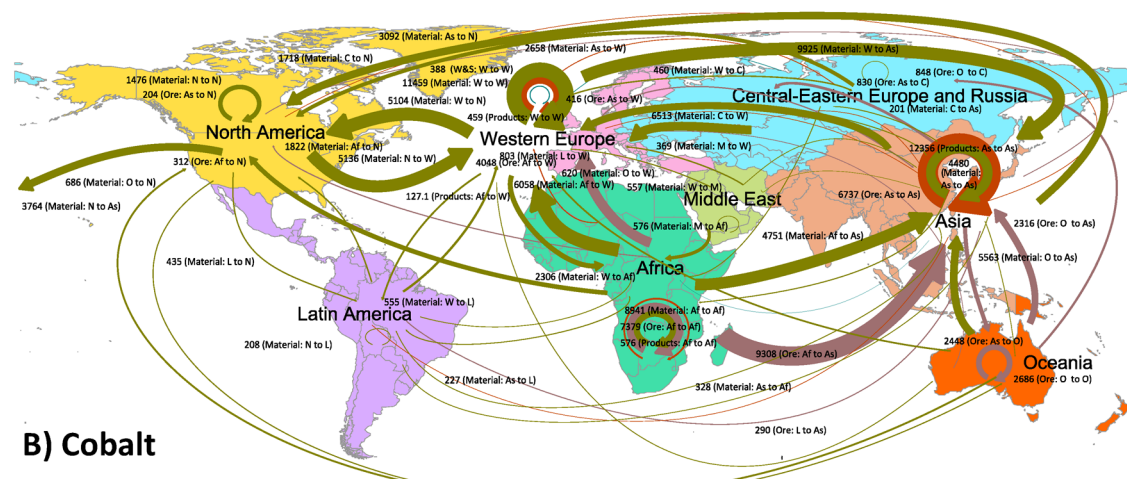
When $\text{redflow}^{(k)} \geq \text{greenflow}^{(k)}$ and $\text{redflow}^{(k)} \geq \text{yellowflow}^{(k)}$, commodity k is defined as a red-flow commodity.

3. RESULTS

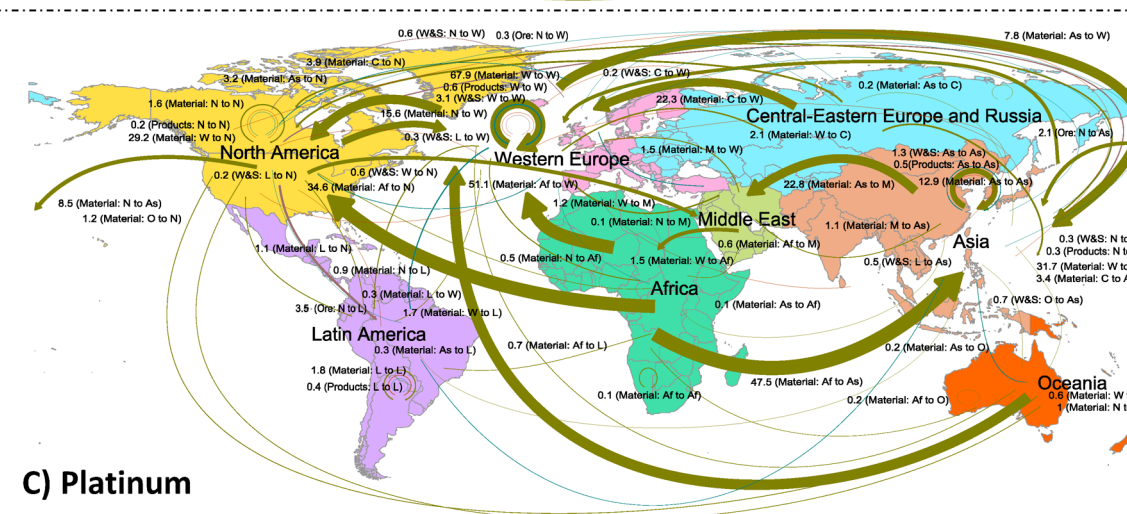
3.1. Total Flow, Major Commodities, Top Importers and Exporters. **3.1.1. Neodymium (Nd).** The results show that,



A) Neodymium



B) Cobalt



C) Platinum

Figure 2. (A) Global flows of neodymium among eight regions by four types of trade commodity (ore, materials, products and W&S (waste and scrap)) in 2005; each legend indicates the volume of neodymium in tonnes, the commodity type and the regions driving the flow (As: Asia, Af: Africa, C: Central-Eastern Europe and Russia, L: Latin America, M: Middle East, N: North America, O: Oceania, W: Western Europe). (B) Global flows of cobalt among eight regions by the trade commodity type in 2005; each legend indicates the volume of cobalt in kt larger than 200 kt. (C) Global flows of platinum among eight regions by trade commodity type in 2005; each legend indicates the volume of platinum in tonne larger than 0.2 tonne.

in 2005, 12 540 t ($1 \text{ t} = 10^3 \text{ kg}$) of Nd ore was mined and 18 565 t of Nd was moved on global markets. Metals move between countries and regions at various points in the course of their lifecycle: after mining, during conversion from ore to bare metal, following production of semiprocessed goods, components and

products, and for disposal of scrap and waste material. The amount of metal is counted each time it moves, resulting in a volume moved that is greater than the volume mined. Thus, the gross quantity of Nd feeding into product supply chains around the world is about 1.5 times larger than the quantity mined. The

implication is that the greater the amount of metal moved relative to the amount mined, the greater the international fragmentation of labor involved in the metal's fabrication and processing.

Aggregating the 153 types of traded commodities containing Nd into the four categories of ore, materials, products, and scrap and waste reveals that the contribution of the latter three categories to global Nd flows is 15 586 t for materials, 2968 t for products, and 11 t for scrap and waste, with no flow as ore. Specifically, at the commodity level (HS-code), HS-280530 (Rare-earth metals, scandium, and yttrium) accounts for 6294 t, followed by 2693 t for HS-850511 (Permanent magnets and magnetized articles of metal) and 2219 t for HS-284960 (Rare-earth metal compounds).

When all commodities containing Nd are included, the major exporting countries are not necessarily Nd-mining countries. The top three exporters of Nd are China (9874 t), Japan (1494 t), and Germany (765 t). The four commodity types exported from China consist of 8662 t as materials, representing 88% of the total exported, and 1214 t (12%) as products. From Japan and Germany, in contrast, 615 t (41%) and 460 t (60%) are exported as materials and 879 t (59%) and 296 t (39%) as products, respectively. The top three *importers* of Nd, on the other hand, are Japan (4218 t), the U.S. (2695 t) and Germany (987 t). Japanese Nd imports consist of 4128 t as materials, which account for 98% of the total Nd imported. For the U.S. and Germany, the share of Nd imported as products is smaller than in the case of Japan, with materials accounting for 2298 t (85%) and 868 t (88%), respectively, and products for 396 t (15%) and 119 t (12%).

3.1.2. Cobalt (Co). In 2005, 1072 kt (1 kt = 10^6 kg) of Co was mined, with 154 kt of Co being moved on international markets: 38.3 kt as ore (excluding copper ore not currently used as a source of Co), 93.1 kt as materials, 2.16 kt as products and 0.81 kt as scrap and waste. Among the 160 different commodities containing Co, the top three global flows were 64.5 kt of HS-810510 (Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; waste and scrap; powders), 21.7 kt of HS-260500 (Cobalt ores and concentrates) and 20.1 kt of HS-850780 (Electric accumulators). The top three exporting countries of Co-containing commodities are the Democratic Republic of the Congo (22 kt), China (13 kt) and Japan (10 kt). For Congo, the flows consist mainly of exports of commodities categorized as ore, accounting for 74% of its Co exports. In the case of China and Japan, in contrast, 59.0% and 75.9% of the commodity export flows are products. The top three *importers* of Co, on the other hand, are Japan (22.9 kt), China (18.7 kt), and the United States (14.5 kt). Japan and the United States receive Co mainly as a material, accounting for 60.4% and 79.4% of their total Co imports, while China imports 52.6% of its Co as ore.

3.1.3. Platinum (Pt). In 2005, 259 t of Pt was mined from the ground. Global Pt flows were estimated at 402 t, comprising 6.2 t as ore, 384 t as material, 3.2 t as products and 8.9 t as scrap and waste. Flows of HS-711011 (Unwrought or in powder form platinum content) comprise 321 t and HS-711019 (Other platinum content) 48 t. These amounts are followed by a 8.7 t flow of HS-711290 (Waste and scrap of precious metal or of metal clad). For Pt, the top three exporting countries are South Africa (135 t), the UK (41 t) and Germany (39 t). These flows consist primarily of Pt exported as material: 99.9% for South Africa, 98.3% for UK, and 96.3% for Germany. The top three *importing* countries are the U.S. (72 t), Germany (55 t), and Japan (54 t), with the main flows of Pt to these counties taking

the form of material, viz. 98.7% to the U.S., 96.1% to Germany, and 92.8% Japan.

3.2. Mapping the Major Global Flows. **3.2.1. Neodymium (Nd).** Figure 1A shows the 50 largest Nd flows among the global flows estimated; the top three routes are dominated by exports from China, viz. from China to Japan (4053 t), the USA (1731 t) and Hong Kong (425 t). These are followed by Austria to Unspecified regions (the region category in BACI), at 384 t, and China to Germany, at 369 t. Figure 2A summarizes the flows of Nd among countries in eight regions of the world (North America, Latin America, Western Europe, Africa, Middle East, Central-Eastern Europe and Russia, Asia and Oceania). The flows are colored to represent the type of commodity (ore, materials, products, and waste and scrap). Immediately, the flow of materials within Asia stands out. While flows of materials from Asia to Western Europe and North America are comparatively large, it is the flows of Nd-containing *products* from Asia to foreign countries that dominate global flows.

3.2.2. Cobalt (Co). Figure 1B, in turn, shows the 50 largest flows of Co (excluding Co in copper ore) between countries. The top five flows are from Congo to China (7.7 kt), followed by Congo to Zimbabwe (6.5 kt), Congo to Finland (4.9 kt), Finland to Japan (4.3 kt) and Indonesia to Japan (3.8 kt). Figure 2B, characterizing Co flows among eight regions of the world, shows that Co moves as ore from Africa, where it is mined, to Asia and Western Europe, where it is processed to materials. It is then exported to broader regions, with the largest flow comprising material within Western Europe, followed by the flow from Western Europe to Asia. With respect to product flows, those within Asia and from Asia to other regions are comparatively large, indicating that the flows in the international supply chain of Co generally proceed from Africa to Western Europe and then to Asia.

3.2.3. Platinum (Pt). In the case of Pt, illustrated in Figure 1C, the flow from South Africa to Japan (35 t) emerges as the largest, followed by the flows from South Africa to the United States (33 t), South Africa to Switzerland (24 t), India to the United Arab Emirates (23 t) and the UK to the United States (17 t). Figure 2C shows the regional characteristics and flows of Pt among eight regions of the world. The flow of Pt as material consists primarily of the movement from Africa, where it is mined, to Asia, Western Europe and North America. Pt moves as material within Western Europe, then flows from Western Europe to Asia and North America.

3.3. Measuring the Indicator: Green, Yellow, and Red-Flow Commodities. The shares of green, yellow, and red flows in total global flows of Nd are 1.2%, 98%, and 1.2%, respectively. In the case of Co, the respective figures are 53%, 28%, and 19%, whereas for Pt they are 15%, 84%, and 0.87%.

By way of example, Figure 3 shows the trading volumes of Nd contained in the commodity HS-852520 (Transmission apparatus for radiotelephony incorporating reception apparatus) in 2005. On the *x*-axis, importing *L*-countries are countries 1–201 and *H*-countries are 202–231. For descriptive purposes, in each category the countries are ranked according to their GDP. On the *y*-axis, exporting countries are arranged in the same order, while the *z*-axis indicates the quantity of Nd contained in the commodity in question. The area enclosed by countries 1–201 on the *x*- and *y*-axes indicates red flows (“Low to Low”), which comprise 11% of the overall flow. The area enclosed by countries 202–231 on the *x*- and *y*-axes represents the green flow (“High to High”) and comprises 36% of the overall flow, while the remainder of the area represents the yellow flow (“High to Low”,

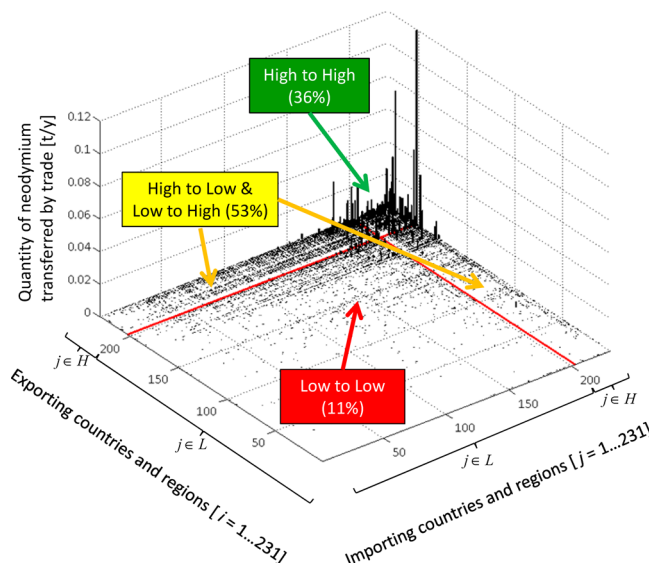


Figure 3. Global flows of neodymium contained in transmission apparatus for radiotelephony incorporating reception apparatus (HS-852520); an example of the trade commodity characterization (red, yellow, and green-flow commodities) based on the relative shares of red, yellow, and green flows of the commodity in question. High, Low refer to the technological level of the country (see text).

“Low to High”), which is the largest of all at 53%. We therefore regard this commodity as a yellow-flow commodity.

When we similarly categorized 153 types of internationally traded commodities containing Nd, 19 were found to be green-flow commodities, 96 were yellow-flow commodities and the remainder 38 were red-flow commodities. SI Table S2 reports the categories of trade commodities containing Nd, whereas Table 1A shows those commodities with the three largest red, yellow, and green flows (Table 1B for Co, Table 1C for Pt). Among the red-flow commodities, those with the largest flows and deserving greatest attention are HS-845019 (Washing machines of a dry linen capacity not exceeding 10 kg) (15.0 t), HS-850780 (Other electric accumulators) (14.8 t) and HS-841869 (Refrigerating and freezing equipment except refrigerators, freezers, cabinets, display counters, showcases, and similar furniture) (13.4 t). The yellow-flow commodities with the three largest flows are HS-280530 (rare-earth metals, scandium, and yttrium, whether or not intermixed or interalloyed) (6294 t), HS-850511 (Permanent magnets and articles intended to become permanent magnets of metal) (2694 t) and HS-284690 (Compounds, inorganic or organic, of rare-earth metals, of yttrium or of scandium or of mixtures of these metals (excl. cerium)) (2219t).

We also categorized 159 types of internationally traded commodities containing Co (excluding copper ore), of these, 22

Table 1. Commodities with the Three Largest Flows among the Red, Yellow, and Green-Flow Commodities Containing Critical Metals in 2005 (A: Neodymium, B: Cobalt, C: Platinum)

(A) neodymium (Nd)				
	rank	HS code	commodity name	volume [kt/y]
red-flow commodities	1	845 019	household/laundry-type washing machine of a dry linen capacity of less than 10 kg	15.0
	2	850 780	electric accumulators	14.8
	3	841 869	refrigerating or freezing equipment	13.4
yellow-flow commodities	1	280 530	rare-earth metals, scandium and yttrium	6294
	2	850 511	permanent magnets and art intended to become permanent magnets of metal	2693
	3	284 690	compounds of rare-earth metal of yttrium, scandium or mix of these metals (excl. cerium)	2219
green-flow commodities	1	870 324	automobiles with reciprocating piston engine displacing >3000 cm ³	49.5
	2	870 323	automobiles with reciprocating piston engine displacing >1500 cc to 3000 cc	35.6
	3	901 813	magnetic resonance imaging apparatus	20.4
(B) cobalt (Co)				
	rank	HS code	commodity name	volume [kt/y]
red-flow commodities	1	260 500	cobalt ores and concentrates	21 678
	2	870 333	automobiles with diesel engine displacing more than 2500 cc	708
	3	841 869	refrigerating or freezing equipment	350
yellow-flow commodities	1	850 780	electric accumulators	20 058
	2	260 400	nickel ores and concentrates	16 702

(B) cobalt (Co)				
	rank	HS code	commodity name	volume [kt/y]
green-flow commodities	1	810 510	cobalt, unwrought, matte and other intermediate products, waste, scrap and powders	64 548
	2	282 200	cobalt oxides and hydroxides; commercial cobalt oxides	13 768
	3	282 734	cobalt chloride	1483
(C) platinum (Pt)				
	rank	HS code	commodity name	volume [t/y]
red-flow commodities	1	845 019	household/laundry-type washing machine of a dry linen capacity of less than 10 kg	0.28
	2	841 830	freezers of the chest type, not exceeding 800 l capacity	0.20
	3	841 821	refrigerators, household type, compression-type	0.20
yellow-flow commodities	1	711 011	platinum unwrought or in powderform	321
	2	261 690	precious metal ores and concentrates	6.2
	3	852 520	transmission apparatus for radiotelephony incorporating reception apparatus	2.3
green-flow commodities	1	711 019	platinum in other semimanufactured forms	48.4
	2	711 290	waste and scrap of precious metal or of metal clad with precious metal	8.7
	3	381 512	supported catalyst with precious metal or compounds thereof as the active substance	1.4

are green-flow commodities, 49 are yellow-flow commodities and the remaining 88 are red-flow commodities. For the 151 types of commodities containing Pt, 14 emerge as green-flow commodities, 58 as yellow-flow commodities, and the remaining 79 as red-flow commodities. The full lists of commodities containing Co and Pt are provided in SI Tables S3 and S4.

4. DISCUSSION

4.1. From Red and Yellow to Green-Flow Commodities.

One of the ways in which nonwasteful use of critical metals can be enhanced is by countries improving their efficiency of material use. To improve such efficiency worldwide, countries with advanced production technologies and social systems to support them should strategically spread these technologies and systems to countries that are technologically less advanced. The red, yellow, and green flow categories employed in the present study can be used to prioritize those production technologies and systems that are most in need of being disseminated.

Many of the commodities categorized as red-flow commodities have supply chains that pass through *L*-countries as exports or imports. Consequently, improving technologies for producing and using red-flow commodities should be afforded very high priority. There are only a limited number of *H*-countries that produce or use red-flow commodities, and these countries need to play an international role in disseminating efficient production technologies to *L*-countries exporting such commodities. Similarly, since few *H*-countries import red-flow commodities, they could provide the appropriate technologies for improving the material-use efficiencies of critical metals to *L*-countries importing such commodities.

The next priority should be yellow-flow commodities whose supply chains pass through *L*-countries, either as exports or imports. Among yellow-flow commodities, first there is the case where the exporting country is an *H*-country (i.e., *H* to *L*). Since there are relatively few *H*-countries importing yellow-flow commodities, these *H*-countries need to assist the many *L*-countries importing yellow-flow commodities in order to improve the material-use efficiency of the latter countries. Conversely, among yellow-flow commodities, in cases where the importing country is an *H*-country (*L* to *H*), it is desirable for *H*-countries that export yellow-flow commodities to play a role in transferring their production technologies to the many *L*-countries exporting such commodities. These differences in the types of yellow-flow commodities (*H* to *L* or *L* to *H*) are shown in SI Tables S2–S4.

Finally, there are green-flow commodities that are traded between *H*-countries. For these commodities, it is essential for *H*-countries to constantly try to improve their own production and usage technologies. Additionally, to reduce actual demand for critical metals, these *H*-countries need to invest in recycling technologies for green-flow commodities and to focus on social frameworks for reusing these commodities.

4.2. Significant Contributors Among *H*-Countries.

Based on the technical level of each country derived from the indicators of the Global Competitiveness Report (see Section 2.2.3), a specific analysis was undertaken to ascertain what specific contribution by which country would be important for upgrading red-flow commodities to yellow and green-flow commodities. SI Table S2 shows the top three *H*-countries with the largest imports and exports of red-flow commodities containing Nd (see SI Table S3 for Co and SI Table S4 for Pt). It would be desirable for *H*-countries importing red-flow commodities to transfer their own technologies to *L*-countries,

that is, induce the latter to adopt technologies contributing to more efficient resource use. For instance, the key importing *H*-countries of HS-845019 (Washing machines of a dry linen capacity not exceeding 10 kg) listed in Table 1 are Malaysia, Norway, and France. The top three *H*-countries importing HS-850780 (Electric accumulators) are Finland, Austria, and Malaysia, whereas the top three importers of HS-841869 (Refrigerating and freezing equipment except refrigerators, freezers, cabinets, display counters, showcases, and similar furniture) are Germany, Austria, and France.

On the other hand, the key exporting *H*-countries of HS-845019 (washing machines of a dry linen capacity not exceeding 10 kg) are Denmark, Hong Kong, and France. The top three *H*-countries exporting HS-850780 (electric accumulators) are Estonia, Germany, and Switzerland, whereas the top three exporters of HS-841869 (refrigerating and freezing equipment except refrigerators, freezers, cabinets, display counters, showcases, and similar furniture) are Switzerland, Germany, and Estonia. The dissemination and transfer of production technologies for the red-flow commodities associated with these countries will, once again, increase the sustainability of resource use.

Similarly, SI Table S2 indicates the *H*-countries with the highest imports and exports of yellow-flow commodities (*L* to *H* and *H* to *L*, respectively). Considering the yellow-flow commodities in Table 1, HS-280530 (Rare-earth metals, scandium, and yttrium) are type *L* to *H*, and in this case contributions can be made by the top three exporters among *H* countries: Austria, Japan, and Malaysia. HS-850511 (Permanent magnets and articles intended to become permanent magnets of metal) and HS-284690 (Compounds of rare-earth metals/yttrium/scandium/mix of these metals excl. cerium) are also of type *L* to *H*. Among *H*-countries, Japan, Germany, and the U.S. are the top three exporters of HS-850511 and Austria, France, and Estonia of HS-284690.

Since such commodities contain the most Nd, encouraging the *H*-countries to take the initiative to supply technologies to boost material-use efficiencies for Nd will benefit the entire world as well as *L*-countries. In this way, *H*-countries can indirectly facilitate the procurement of Nd from international flows of Nd. That is, by considering the strategic supply of technologies, it is possible to create synergistic benefits at the national and global level. By making *H*-countries understand the role expected of them, it may be possible to enhance the speed and likelihood of sustainable resource-use practices being adopted in the future.

4.3. Toward Further Rigorous Analysis. To achieve the aim of more sustainable resource use, there is also a need for policies that strongly encourage such technologies as well as associated R&D. At the same time, though, considerable caution needs to be applied with respect to the technological levels assumed in this study, as these were determined solely on the basis of information about the general scientific and technological status of individual countries. In order to rigorously and accurately characterize the commodities involved, the critical-metal production and processing technologies actually used in each country will need to be assessed, and policy decisions made on the basis of observed strengths and weaknesses. As with the Global Competitiveness Report employed in the present study, it is desirable to implement the necessary research through international cooperation. As a starter, it would suffice to conduct a questionnaire survey on the critical-metal production and processing technologies used by the world's major industries,

encompassing the entire life cycle of the metal from mining through to recycling and disposal.

Finally, innovation and dissemination of new energy technologies and low-carbon technologies involving growing consumption of critical metals are both necessary conditions for supporting a world population of over 9 billion people while at the same time limiting greenhouse gas emissions. To achieve these aims, as has here been illustrated with the example of certain H-countries with respect to red-flow and yellow-flow Nd-containing commodities, it is essential for such countries to objectively consider their own positions and responsibilities in the international circulation of precious resources and to fulfill the roles required of them. In addition, it may be necessary to formulate international rules relating to trade, financial assistance, and technical assistance that will facilitate fulfillment of these roles and responsibilities.

■ ASSOCIATED CONTENT

■ Supporting Information

The SI provides detailed descriptions of the methodologies used in the material flow analysis, including formulation of the quadratic problem involved in calibrating any inconsistency in the material balance within each country and region. Additional results are provided, particularly on Co and Pt. This material is available free of charge via the Internet at <http://pubs.acs.org>.

■ AUTHOR INFORMATION

Corresponding Author

*Phone: +81 29-850-2889; fax: +81 29-850-2917; e-mail: nansai.keisuke@nies.go.jp.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This research was supported in part by the Environment Research & Technology Development Fund (K122024 and S6-4) of the Ministry of Environment, Japan. We are grateful to Nigel Harle of Gronsveld, The Netherlands, for his correction of the English.

■ REFERENCES

- (1) Alonso, E.; Gregory, J.; Field, F.; Kirchain, R. Material availability and the supply chain: Risks, effects, and responses. *Environ. Sci. Technol.* **2007**, *41* (19), 6649–6656.
- (2) Nassar, N. T.; Barr, R.; Browning, M.; Diao, Z. W.; Friedlander, E.; Harper, E. M.; Henly, C.; Kavlak, G.; Kwatra, S.; Jun, C.; Warren, S.; Yang, M. Y.; Graedel, T. E. Criticality of the geological copper family. *Environ. Sci. Technol.* **2012**, *46* (2), 1071–1078.
- (3) Erdmann, L.; Graedel, T. E. Criticality of non-fuel minerals: A review of major approaches and analyses. *Environ. Sci. Technol.* **2011**, *45* (18), 7620–7630.
- (4) Graedel, T. E.; Barr, R.; Chandler, C.; Chase, T.; Choi, J.; Christoffersen, L.; Friedlander, E.; Henly, C.; Jun, C.; Nassar, N. T.; Schechner, D.; Warren, S.; Yang, M. Y.; Zhu, C. Methodology of metal criticality determination. *Environ. Sci. Technol.* **2012**, *46* (2), 1063–1070.
- (5) Tarras-Wahlberg, N. H.; Flachier, A.; Lane, S. N.; Sangfors, O. Environmental impacts and metal exposure of aquatic ecosystems in rivers contaminated by small scale gold mining: The Puyango River basin, southern Ecuador. *Sci. Total Environ.* **2001**, *278* (1–3), 239–261.
- (6) Mudd, G. M. Global trends in gold mining: Towards quantifying environmental and resource sustainability? *Resour. Policy* **2007**, *32* (1–2), 42–56.
- (7) UNEP. *Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles, A Report of the Working Group on the Global Metal Flows to the International Resource Panel*; van der Voet, E., Salminen, R., Eckelman, M., Mudd, G., Norgate, T., Hirschier, R.; United Nations Environment Programme, 2013.
- (8) Mudd, G. M. The Environmental sustainability of mining in Australia: Key mega-trends and looming constraints. *Resour. Policy* **2010**, *35* (2), 98–115.
- (9) David, G.; Leopold, M.; Dumas, P. S.; Ferraris, J.; Herrenschmidt, J. B.; Fontenelle, G. Integrated coastal zone management perspectives to ensure the sustainability of coral reefs in New Caledonia. *Mar. Pollut. Bull.* **2010**, *61* (7–12), 323–334.
- (10) Tue, N. M.; Suzuki, G.; Takahashi, S.; Isobe, T.; Trang, P. T. K.; Viet, P. H.; Tanabe, S. Evaluation of dioxin-like activities in settled house dust from Vietnamese E-waste recycling sites: Relevance of polychlorinated/brominated dibenzo-p-dioxin/furans and dioxin-like PCBs. *Environ. Sci. Technol.* **2010**, *44* (23), 9195–9200.
- (11) Robinson, B. H. E-waste: An assessment of global production and environmental impacts. *Sci. Total Environ.* **2009**, *408* (2), 183–191.
- (12) EU. *Critical Raw Materials for the EU*; The Ad-hoc Working Group on Defining Critical Raw Materials, 2010.
- (13) U.S.D.O.E *Critical Materials Strategy*; U.S. Department of Energy, 2011.
- (14) Alonso, E.; Sherman, A. M.; Wallington, T. J.; Everson, M. P.; Field, F. R.; Roth, R.; Kirchain, R. E. Evaluating rare earth element availability: A case with revolutionary demand from clean technologies. *Environ. Sci. Technol.* **2012**, *46* (6), 3406–3414.
- (15) Reck, B. K.; Graedel, T. E. Challenges in Metal Recycling. *Science* **2012**, *337* (6095), 690–695.
- (16) Talens Peiro, L.; Villalba Mendez, G.; Ayres, R. U. Material flow analysis of scarce metals: Sources, functions, end-uses and aspects for future supply. *Environ. Sci. Technol.* **2013**, *47* (6), 2939–2947.
- (17) Du, X. Y.; Graedel, T. E. Global rare earth in-use stocks in NdFeB permanent magnets. *J. Ind. Ecol.* **2011**, *15* (6), 836–843.
- (18) Du, X. Y.; Graedel, T. E. Global In-Use Stocks of the Rare Earth Elements: A First Estimate. *Environ. Sci. Technol.* **2011**, *45* (9), 4096–4101.
- (19) Du, X. Y.; Graedel, T. E., Uncovering the global life cycles of the rare earth elements. *Sci. Rep.* **2011**, *1*.
- (20) Rademaker, J. H.; Kleijn, R.; Yang, Y. Recycling as a strategy against rare earth element criticality: A systemic evaluation of the potential yield of NdFeB magnet recycling. *Environ. Sci. Technol.* **2013**, *47* (18), 10129–10136.
- (21) Harper, E. M.; Kavlak, G.; Graedel, T. E. Tracking the metal of the goblins: Cobalt's cycle of use. *Environ. Sci. Technol.* **2012**, *46* (2), 1079–1086.
- (22) Saurat, M.; Bringezu, S. Platinum group metal flows of Europe, Part II exploring the technological and institutional potential for reducing environmental impacts. *J. Ind. Ecol.* **2009**, *13* (3), 406–421.
- (23) Saurat, M.; Bringezu, S. Platinum Group Metal Flows of Europe, Part I. *J. Ind. Ecol.* **2008**, *12* (5–6), 754–767.
- (24) Alonso, E.; Field, F. R.; Kirchain, R. E. Platinum availability for future automotive technologies. *Environ. Sci. Technol.* **2012**, *46* (23), 12986–12993.
- (25) Nakamura, S.; Nakajima, K.; Kondo, Y.; Nagasaka, T. The waste input-output approach to materials flow analysis—Concepts and application to base metals. *J. Ind. Ecol.* **2007**, *11* (4), 50–63.
- (26) Nakajima, K.; Nansai, K.; Matsubae, K.; Kondo, Y.; Kagawa, S.; Inaba, R.; Nakamura, S.; Nagasaka, T. Identifying the substance flow of metals embedded in Japanese international trade by use of waste input-output material flow analysis (WIO-MFA) model. *ISIJ Int.* **2011**, *51* (11), 1934–1939.
- (27) CEPII. *BACI (Base pour l'Analyse du Commerce International): A CEPII World Database of International Trade at the Product Level*, 2011.
- (28) JIOT. *2000 Input-Output Tables*; National Federation of Statistical Associations, Ministry of Internal Affairs and Communications: Tokyo, Japan, 2004.

- (29) JIOT. 1995–2000–2005 *Linked Input-Output Tables*; National Federation of Statistical Associations, Ministry of Internal Affairs and Communications: Tokyo, Japan, 2011.
- (30) Survey, U. G. *Minerals Yearbook Vol I: Metals and Minerals*; Washington DC, 2011.
- (31) Hashimoto, S.; Moriguchi, Y.; Saito, A.; Ono, T. Six indicators of material cycles for describing society's metabolism: Application to wood resources in Japan. *Resour., Conserv. Recycl.* **2004**, *40* (3), 201–223.
- (32) Hashimoto, S.; Moriguchi, Y. Proposal of six indicators of material cycles for describing society's metabolism: From the viewpoint of material flow analysis. *Resour., Conserv. Recycl.* **2004**, *40* (3), 185–200.
- (33) Kagawa, S.; Suh, S.; Kondo, Y.; Nansai, K. Identifying environmentally important supply chain clusters in the automobile industry. *Econ. Syst. Res.* **2013**, *25* (3), 265–286.
- (34) Kagawa, S.; Okamoto, S.; Suh, S.; Kondo, Y.; Nansai, K. Finding environmentally important industry clusters: Multiway cut approach using nonnegative matrix factorization. *Soc. Networks* **2013**, *35* (3), 423–438.
- (35) Schwab, K. *The Global Competitiveness Report 2012–2013: Full Data ed.*; The World Economic Forum, 2012.