Trends in global material flows of critical metals derived from household consumption in an aging society in Japan

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1. Introduction

With expansion of electronics for hybrid vehicle and IT products, the demand for critical metals including rare earth metals has been increasing. These metals are strongly related not only to usefulness for today's our lifestyles but also to new energy technologies such as solar power and wind power to ensure a low carbon society in the future. Reportedly, in terms of life cycle assessment of the entire nation, household consumption is the most important factor related to environmental burdens in economically developed countries.[1), 2)] Nevertheless, few studies have analyzed metal consumption from the viewpoint of household consumption similarly to previous studies particularly addressing greenhouse gas (GHG) emissions and energy consumption.

This study detected global material flows of critical metals caused directly and indirectly by Japanese household consumption using a global link input–output model (GLIO) [3)–5)] with international material flow data. The target metals here are neodymium, cobalt, and platinum of which the demand is expected to increase along with further expansion of new energy technologies. The detected global material flows are called here material flow footprints (MFFs) of the household consumption. Multiplying MFFs by the risk factor of each country involved in the MFFs yielded supply security footprints of household consumption. We calculated the supply security footprints (SSFs) in 2005 and then forecasted them in 2035 considering an aging Japanese society with fewer children in the near future.

2. Methods and data

To examine the effects of the aging and low birthrate trends on the MFFs and SSFs specifically in this study, we defined household attributes (*att* = 1…6) following Kronenberg (2009) [6] by the age of the head of a household (1=20s, –29; 2=30s, 30–39; 4=40s, 40–49; 4=50s, 50–49; 5=60s, 60–69; 6=70s+, 70–). We estimated respective annual expenditures by disaggregating the household sector defined as a single sector in the 2005 Japanese input–output table (JIOT) [7] into the six household sectors with national household statistics. Then we calibrated them with mathematical programming to be consisted with the annual expenditure of each commodity included in the JIOT. Here we explain the calibration methods and the estimation of future household expenditures from the perspective of changing the household composition in Japan from 2010 to 2035.

2.1 Estimates of Consumption Expenditures by Household Attributes

We first calculated the expenditure ratio r_i^{att} of commodity sector *i* per unit expenditure of household *att* as

$$r_i^{att} = \frac{P_i^{att}}{\sum_{i=1}^{N} P_i^{att}} \tag{1}$$

where P_i^{att} is the expenditure (million JPY/m) from the JIOT for commodity sector *i* taken from the National Survey of Family Income and Expenditure (NSFIE) [8] and *N* (=409) is the number of JIOT sectors. We used Equation (2) to calculate s_i^{att}, the share of household *att* accounted for by commodity sector *i*.

$$s_i^{att} = \frac{P_i^{att}}{\sum_{att=1}^{M} P_i^{att}} \tag{2}$$

Here, *M* (=6) is the number of household attributes. Equation (2) captures that, for example, households headed by people in their 60s have higher medical expenses than households with those in their 20s. It is noteworthy that because the commodity sector classification in the NSFIE differs from that in the JIOT, we mapped the expenditure categories in the NSFIE onto commodity sectors *i* in the JIOT. The NSFIE is a public statistical survey that presents consumption expenditures by Japanese households. The NSFIE includes expenditures per household per month by household attribute, such as the income level or size of the household, for 100 categories of expenditures. It is possible to use the NSFIE to ascertain differences in consumption composition quantitatively based on differences in household attributes, but in the NSFIE, no distinction is made between domestic and imported commodities.

As Schreyer (2013) [9] pointed out, major inconsistencies are apparent between the survey data on household consumption (e.g., NSFIE) for different countries and the Social Accounting Matrix [10] (SAM) (e.g., JIOT household consumption expenditures). Eliminating these inconsistencies is an important issue. Even if annual consumption is calculated using multiplying the NSFIE consumption amount by the number of households, then when multiplying that by 12, a large difference becomes apparent between that result and the previously described JIOT household consumption expenditures that are in the SAM.

In this study, we formulated a quadratic programming problem such that the distance function in terms of r_i^{att} and s_i^{att} is minimized under the following constraints (3)–(7).

$$\underset{\tilde{r}_i^{att},\,\tilde{s}_i^{att}}{\text{Min.}} \sum_{att=1}^{M}\sum_{i=1}^{N}\left(\frac{\tilde{r}_i^{att}-r_i^{att}}{r_i^{att}}\right)^2+\sum_{att=1}^{M}\sum_{i=1}^{N}\left(\frac{\tilde{s}_i^{att}-s_i^{att}}{s_i^{att}}\right)^2 \tag{3}$$

s.t.

$$g_i=\sum_{att=1}^{M}\tilde{r}_i^{att}g^{att} \tag{4}$$

$$\sum_{i=1}^{N}\tilde{r}_i^{att}=1 \tag{5}$$

$$\tilde{r}_i^{att}\geq 0 \tag{6}$$

$$\tilde{s}_i^{att}=\tilde{r}_i^{att}g^{att}/g_i \tag{7}$$

Therein, g_i and g^{att} respectively represent the total expenditure for commodity sector *i* in the JIOT and the total expenditure of household *att*. Here, Equation (4) shows that JIOT household consumption expenditures of commodity sector *i* are expected to coincide with the sum of the annual consumption of household attributes. Equations (5) and (6) respectively show that the total of the household expenditure ratios is equal to 1 and each ratio is non-negative. Equation (7) expresses the relation between r_i^{att} and s_i^{att}.

We multiplied the optimal solution $\hat{\tilde{r}}_i^{att}$ by g^{att}, and determined the annual consumption $g_i^{att}=\hat{\tilde{r}}_i^{att}g^{att}$ for sector *i* for each household (million JPY/y). However, for JIOT sectors with no corresponding NSFIE expenditure category (such as waste processing, wholesale, retail, etc.), we calculated g_i^{att} by proportionally distributing the total expenditures according to the JIOT's g_i by the size of g^{att}. These expenditures account for consumer prices. Because the global material flow intensities used in the SSFs are based on producer prices, we converted g_i^{att} to f_i^{att}, the annual consumption for sector *i* for each household at producer prices. Additionally, we included the condition that all expenditures related to education and health care are compensated by the Japanese government.

Using Equations (8) and (9), we multiplied f_i^{att} by the ratio of imports m_i obtained from the JIOT, and determined the consumption of domestic commodities $f_i^{\mathrm{JD},att}$ (million JPY/y) and the consumption of imported commodities $f_i^{\mathrm{JI},att}$ (million JPY/y).

$$f_i^{\mathrm{JD},att} = \left(1 - m_i\right) f_i^{att} \tag{8}$$

$$f_i^{\mathrm{JI},att} = m_i f_i^{att} \tag{9}$$

Consequently, the total consumption figures for the six household attributes found in this study are consistent with the total expenditures on household consumption f in the JIOT (million JPY/y).

2.2 Estimating the Household Expenditures Until 2035

The most recent JIOT is based on 2005 figures. Therefore, we were able to calculate $f_i^{\mathrm{JD},att}$ and $f_i^{\mathrm{JI},att}$ using the method noted above for 2005. Hereinafter, to clarify the target year of estimate y, we denote these values respectively as $f\left(y\right)_i^{\mathrm{JD},att}$ and $f\left(y\right)_i^{\mathrm{JI},att}$. In this study, we specifically addressed changes in household composition associated with Japan's population decline, its aging, and low birthrate trends. We also estimated the future SSFs. Because the predicted number of households published by the National Institute of Population and Social Security Research (2013) [11)] was for 2035, we selected target years between 2005 and 2035, and calculated the SSFs for every five years, as follows: 2005 (y=1), 2010 (y=2), 2015 (y=3), 2020 (y=4), 2025 (y=5), 2030 (y=6), and 2035 (y=7).

We determined the MFF and the SSFs through 2035 by hypothetically calculating the consumption of each household's domestic commodities *i* and imported commodities *i* by comparing them to the number of households for each household attribute $H^{att}\left(t\right)$, as shown in Equations (10) and (11). Element t reflects the target year: 2005 (t=1), 2010 (t=2), 2015 (t=3), 2020 (t=4), 2025 (t=5), 2030 (t=6), and 2035 (t=7).

$$f\left(t\right)_i^{\mathrm{JD},att} = f\left(t-1\right)_i^{\mathrm{JD},att} \times \frac{H\left(t\right)^{att}}{H\left(t-1\right)^{att}} \times \theta(t)_i^{att} \tag{10}$$

$$f\left(t\right)_i^{\mathrm{JI},att} = f\left(t-1\right)_i^{\mathrm{JI},att} \times \frac{H\left(t\right)^{att}}{H\left(t-1\right)^{att}} \times \theta(t)_i^{att} \tag{11}$$

$H(t)^{att}$ refers to levels predicted by the National Institute of Population and Social Security Research. According to its predictions, the total number of households is estimated to rise during 2005–2020, then drop until 2035. It forecasts that the total population will decrease from 2005 mainly because of the declining number of children. Therefore, household size (persons per household) will also shrink with the population, which can influence per-household expenditures. However, expenditures do not always decrease with shrinking household size. For example, most expenditures for food, such as rice and bread, tend to be higher in larger households. Some expenditures such as eating out are higher for single person households than for multifamily households. Such trends are reported in the Family Income and Expenditure Survey (FIES) [12)] published by the National Statistics Bureau, Japan, and published similarly to the NSFIE. Here, using the values of FIES 2005, we defined $\theta(t)_i^{att}$, which represents the influence coefficients on the future household expenditure for sector *i* reflected by the change in household size.

However, no data are available for the change in average household size by household attributes. Therefore, we first approximated the values of household attributes based on the values during 2000–2010 reported in FIES and the total population in Japan reported by the National Institute of Population and Social Security Research. Because these average household sizes were decreasing almost linearly, $J(t)^{att,\mathrm{app}}$ representing the future average household size of household *att* was estimated by adopting the linearization of the 2000–2010 trend. However, summing $J(t)^{att,\mathrm{app}}$ did not give the correct expected future total population statistic by the National Institute of Population and Social Security Research. Therefore, we used quadratic programming to calculate $J(t)^{att}$, which is the future average household size of household *att* consistent with the total population and well-reflecting the trend of $J(t)^{att,\mathrm{app}}$ as shown below.

$$\underset{J(t)^{att}}{\mathrm{Min.}} \sum_{att=1}^{M} \sum_{t=1}^{Y} \left(\frac{J(t)^{att} - J(t)^{att,\mathrm{app}}}{J(t)^{att,\mathrm{app}}} \right)^2 \tag{12}$$

s.t.

$$N(t) = \sum_{att=1}^{M} H(t)^{att} J(t)^{att} \tag{13}$$

Therein, M=6 and Y=7 respectively denote the numbers of household *att* and target years, $N(t)$ denotes the future total population, and $H(t)^{att}$ denotes the future number of households by household *att*.

Secondly, we set $h_l^{(u)}$, which represents the household expenditure on item *l* (*l* = 1…44) by a *u*-person household

(JPY/m) according to FIES. When $J(t)^{att}$ was between *u* and *u*+1, $h_l^{(J(t)^{att})}$ was assumed to follow

$$h_l^{(J(t)^{att})} = (h_l^{(u+1)} - h_l^{(u)})\left\{J(t)^{att} - u\right\} + h_l^{(u)}, \quad (14)$$

which specifies that expenditure changes linearly between $h_l^{(u)}$ and $h_l^{(u+1)}$ ($= h_l^{(J(t)^{att})}$). When $J(t)^{att}$ shifts to $J(t+1)^{att}$ and both are between *u* and *u*+1, the rate of change of expenditures for item *l* is

$$\theta(t)_l^{att} = \frac{h_l^{(J(t+1)^{att})}}{h_l^{(J(t)^{att})}} = \frac{(h_l^{(u+1)} - h_l^{(u)})\left\{J(t+1)^{att} - u\right\} + h_l^{(u)}}{(h_l^{(u+1)} - h_l^{(u)})\left\{J(t)^{att} - u\right\} + h_l^{(u)}}, \quad (15)$$

which gives the influence coefficients $\theta(t)_l^{att}$ on the future household expenditure for sector *i* reflected by change in household size.

From 2005 to 2035, the maximum and minimum average household sizes are, respectively, 3.52 persons by 40s in 2005 and 1.43 persons by 20s. Here *u* is set as *u* = 1…3. Only the average household size by 40s had two sets of boundaries, one of which is $1 \le J(t)^{att} \le 2$ during 2005–2020. The other is $2 \le J(t)^{att} \le 3$ for 2025–2035. Consequently, the influence coefficient between 2020 and 2025 was calculated as follows for *att*=3, *t*=4.

$$\theta(5)_l^3 = \frac{h_l^{(3)} - h_l^{(2)}\{J(5)^3 - 3\}}{h_l^{(4)} - h_l^{(3)}\{J(4)^3 - 4\}} \quad (16)$$

Aggregating items l in FIES to the corresponding NSFIE expenditure categories, it is possible to convert $\theta(t)_l^{att}$ into $\theta(t)_i^{att}$ to represent the influence coefficients for sector *i*.

Because this study specifically examines the SSFs that are impacted by changes in household composition, and because it is not easy to estimate future technological changes, including changes in global supply chains, the global material intensities were fixed, irrespective of the target year. The estimated value for 2005 was used.

3. Results

Here we describe a part of the result in terms of the MFF of neodymium. During 2005–2035, the trends in the MFF of neodymium by the age group of household head of the household show that remarkable reductions occur in the 20s and 30s, while rapidly boost occur in the 70s and older as Fig. 1. The difference of MFF for reductions by 20s

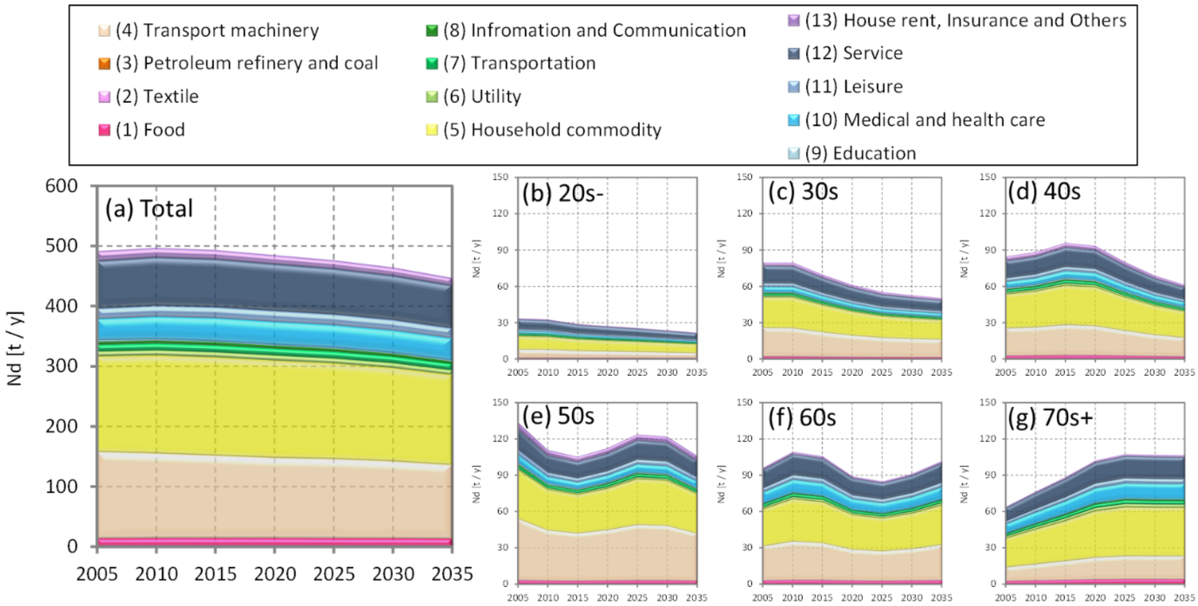

Fig. 1 Variations in the MMF of neodymium of the 13 aggregated sectors during 2005–2035: (a) total footprint, (b)–(g) footprint for each age group.

and 30s and increasing by 60s and 70s and older during the period is nearly the same, which is slightly higher for the MFF of the latter households than for the former ones. Consequently, changing the number of older households with the aging society can be regarded as offsetting the reductions achieved by younger households. As a whole volume, the MFF was estimated as 518.6 t / y in 2005. It then falls, ultimately declining to 454.6 t / y in 2035. This rate of change is about 12% below that of 2005 under the demographic change. This result implies that progression of the aging society, entailing fewer children in Japan, can reduce the MFF of neodymium derived from Japanese household consumption.

The major expenditures that are expected to shape the MFF of neodymium in 2035 are shown in Table 1. According to the table, commodities related to motor vehicles such as “passenger motor car” and “repair of motor vehicles” can be extremely important for the global flow of neodymium. The former is estimated as accounting for the largest MFF of all commodity sectors, dominating over 20% of the total MFF. The MFF induced by the latter is second largest. Additionally, household electric appliances such as refrigerators, washing machines, and other electric equipment can be expected to affect the global flow of neodymium to a great degree. Because the products from these commodity sectors are now collected energetically in Japan, improving neodymium recycling technologies can secure a continued stream of resources. Moreover, it is notable that the MFF induced by demand associated with medical services as "medical instruments" will increase rapidly in association with an aging society. It seems that room remains for reviewing the improvement of supply chains related to medical services particularly addressing that trend.

Table 1 Top 10 household commodity sectors and their highest MFF of neodymium for 2035

Rank	Commodity name	MFF of neodymium [t / y]
1	Passenger motor cars	100.4
2	Repair of motor vehicles	41.5
3	Household electric appliances	30.4
4	Radio and television sets	22.5
5	Trucks, buses and other cars	20.5
6	Medical instruments	20.2
7	Cellular phones	15.1
8	Electric audio equipment	11.9
9	Other electronic components	11.9
10	Retail trade	10.1

Results of the other MFFs and the SSFs by household types will be presented at the conference.

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