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Geopolitics and rare earth metals☆

John Hua Fan, Akihiro Omura *, Eduardo Roca

Department of Accounting, Finance and Economics, Griffith Business School, Griffith University, Australia

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ABSTRACT

Rare earth elements are critical in the production of consumer products, renewables, and green, industrial, and defense products. Using more than thirty years of Japanese import data, we document statistically significant relationships between geopolitics and rare earth metals. We find that the import price per unit of rare earth metals is positively related to geopolitics, while gross import values are negatively related. The negative relationship in the import value appears strongest for rare earth metals sourced from China. Given the strategic and economic significance of rare earth metals, our findings shed light on the economic implications of geopolitical tensions in the decades to come. For users of rare earth elements, an effective risk management program could add value in times of high geopolitical tension. We also highlight rare earth elements' value as a diplomatic tool for global policymakers.

1. Introduction

Rare earth elements (REEs) are termed the "vitamins" and "spice" of a modern economy (Dent 2012; Zepf 2013) because adding small quantities of REEs to metals substantially improve the latter's properties. REEs consist of seventeen elements that are commonly added to elements like iron and boron, to produce materials that neither could achieve alone (Koerth-Baker 2012). Their wide application in technological advancement ranges from consumer products like electric vehicles to infrastructure construction (e.g., wind turbines).

REEs entered the mainstream discourse in 2011 following a diplomatic dispute between China and Japan. China's move to tighten REE exports sent their prices soaring to historic levels (Areddy 2011; Bradsher 2011; The Wall Street Journal 2011). China's dominant position in the global supply chain of REEs is well-documented (See for example Golev, Scott, Erskine, Ali, and Ballantyne 2014.). China's then leader, Deng Xiaoping, observed in the 1990s that "There is oil in the Middle East; there is rare earth in China" (Biedermann 2014, p. 276), so China positions REEs as strategic commodities.

Prior to the rise of China's influence, the US dominated the production and distribution of REEs but ceded supremacy in REEs to China, in all likelihood, because of legal constraints on radioactive elements. After the industry departed the West in the 1980s, China spent the following decades exploring and developing its hinterlands to build the world's largest REE mine in its northern region.

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* Corresponding author. 170 Kessels Road QLD 4111, Australia. Department of AFE, Griffith Business School, Nathan Campus, Griffith University, Australia.

E-mail addresses: j.fan@griffith.edu.au (J.H. Fan), akihiro.omura@griffith.edu.au (A. Omura), e.roca@griffith.edu.au (E. Roca).

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According to Klinger (2017), China pursued REE development not only for economic reasons but also for domestic and international political reasons. Its monopoly on REEs originated from its need for nation-building, its territorial politics with the then Union of Soviet Socialist Republics, and its atomic aspirations. China's REE dominance was fueled by its low labor costs and low environmental standards, which kept the price of REE exports so low that competing was not economically viable for players outside China. However, a prolonged period of over-exploitation led to overcapacity and the release of radioactive and corrosive pollutants into the local environment. These issues, along with the black market's impact on the profits of state-owned enterprises (SOEs), contributed to reducing export quotas, which led to the incident with Japan.

The economic-strategic nexus related to REEs can provide significant power to entities that control their production and distribution. Over the last three decades, China has controlled the global supply of REEs (Strafor 2020). Since there is no globally established exchange for trading in REEs and China may have used (or will use) REEs as a diplomatic tool, some political scientists see China's near monopoly as a threat to regional stability (Milner 1999, Rudra and Jensen, 2011). Others argue that China's export policy on REEs in 2011 was motivated by domestic reasons related to resource conservation and environmental protection and the development of downstream and high-tech industries (Biedermann 2014; Wübbeke 2013). As the supply of REEs, both mined minerals and extracted metals, cannot be increased easily—especially not in a cost-effective manner because of pollution issues—the factors that affect the import/export of these elements are of interest to a wide range of global industries.[1]

China's global dominance in REEs is apparent in both upstream production and downstream industries, including the REE intermediary products, as Mancheri (2015) discuss. China's twelfth five-year-plan, announced in May 2011, set goals for boosting energy efficiency, lowering carbon emissions, and investing in transforming China into the world's top producer of renewable energy. Magnets, phosphors, hydrogen storage materials, and abrasive polishing materials were among the sectors on the priority list for expanding downstream REE industries and promoting advanced manufacturing in China. As a result, the government consolidated the entire REE industry from over 100 firms into 6 SOEs and directly funded national research labs for REE smelting and separation. These SOEs produced 99.9 percent of China's REE production quota for the first half of 2016.[2] After three large mining conglomerates and two research institutes merge in 2022 into the China Rare Earth Group, China will control 30–40 percent of the global supply. Under the direct supervision of the State Council, the newly established SOE is expected to enhance China's power to price key REEs, which is likely to introduce shocks into the supply chain (Zhou and Brooke 2022). Vekasi (2022) posits that further consolidation of the REE industry in China will be motivated by the goals of improving state control, addressing imbalances in the domestic supply and demand, accentuating vertical integration, and promoting price stability.

According to Kalantzakos (2017), China's has two strategic objectives in developing its REE industry: China wants to ensure that it can meet its internal demand for REEs at cheaper costs than the cost it attaches to its exports, and it wants to continue to provide international corporations access to China by allowing them to relocate and keep their production units in China. These businesses would have to pay more than Chinese firms do, but their pricing would still be lower than would be available in the rest of the globe. Since some technologies rely on specific metals (e.g., catalytic converters and permanent magnet motors), and the REE supply chain cannot respond quickly enough to meet demand, Abraham (2015) postulates that Beijing needs to create only enough uncertainty in a foreign high-tech company's REE supply chain to persuade nervous executives that manufacturing in China is easier than doing so elsewhere.

Given the inter-disciplinary interest in REEs as strategic commodities and the qualitative nature of geopolitics, the academic debate on the topic is most prominent in the international relations (IR) and political economy literatures. The IR scholarship in the field of natural resources originates in the 1970s, during the global resource boom. Early studies' focus includes disputes between multinational resource corporations and host governments (Moran 2014; Vernon 1971) and the intersection between resource security and foreign policy strategies (Krasner 1978; Mikesell 1987; Vernon 1983). More recently, IR studies extend to interstate affairs on ownership of, control of, and access to natural resources (Stoddard 2013), so they focus on the relationship between geopolitics and natural resources. The IR literature views this relationship as a zero-sum game and a governance issue that emphasizes cooperative dynamics and interdependence (Dannreuther 2013; Dent 2013).

Political economists, on the other hand, are interested in the conditions under which resource interdependence is securitized[3]—that is, the political process whereby governments consider the inability to access resources an existential threat (Dubash 2011). However, given the qualitative nature of geopolitics, the academic debate on the topic remains conjectural and hypothetical (See, for example, Campbell 2014, Kiggins 2015, and Wilson 2017.). In this paper, we contribute to the literature by offering an empirical and quantitative analysis of geopolitics' impact on the international trade of such strategic commodities as rare earth metals.

Following the literature (e.g., Kiggins 2015), we contend that geopolitical tensions between, on one hand, countries that supply REEs and other countries on the other may have negative impacts on supplier countries' volume of REE exports. We argue that, while the price of REEs may surge in the event of such tension, the effect of a decrease in the quantity exported more than offsets the impact of

[1] Mountain Pass in the U.S., a rare earth mine, had to shut down its production twice in the last two decades (MP Materials, 2020). It was reopened in 2017, and the operating company is sending mined rare earth concentrate to China for further processing (Green, 2019). As of March 2021, the company is working on establishing a refining separation facility.

[2] Shen et al. (2020) argue the shift could also be driven by the conundrum that high value-added RE technologies are concentrated in the US and Japan. Therefore, in value terms, China imports more REE-related products than it exports, even though it is the world's largest exporter of REE raw materials.

[3] The term "securitized" relates to the literature on resource nationalism and securitization of the economy (Drezner et al., 2021), rather than to the financial securitization of assets.

price hikes, thus driving down the total trade value. We test such links by examining the *statistical* association of geopolitics with the trade of REEs (in terms of volume and prices) in the China-Japan sphere. Our empirical results confirm that geopolitics significantly affect the trade of rare earth metals.

Our analysis of trading data for rare earth metals reveals that the prices for rare earth metals imported by Japan are positively related to the exporting country's level of geopolitical risk, suggesting that the intensification of geopolitical conflict between exporting countries and other countries can inflate the price of rare earth metals. Our analysis also reveals that the gross value of imported rare earth metals is negatively related to geopolitical risk, and the strength of that relationship is amplified if the REE comes from China. In addition, when we control for uncertainty in Japan's economic policies, the relationship between imports of rare earth metals and geopolitical risk becomes statistically insignificant, with the exception of geopolitical risk concerning China. This finding further indicates that the amount of REE exported from China is related to geopolitics. Finally, the negative relationship between Japan's imports of rare earth metals and geopolitical risk in China weakened during the World Trade Organization (WTO) dispute on REE export quotas involving China, Japan, and several other countries. Factors like the substantial increase in black market exports and the reduction in export quotas that were induced by domestic political dynamics could have affected our results for this time period.

This paper makes three main contributions to the literature. First, the findings from our empirical and statistical tests on the relationship between geopolitical risk and REEs offer valuable information to a wide range of industries, including the renewable energy/green industry. Second, examining the role of geopolitics in REE trades from a political economy perspective deepens academic discussions on international trade and politics. Third, the study extends our understanding of commodity markets and broadens the application of text-based proxies for geopolitical risk.

The remainder of this paper proceeds as follows. Section 2 provides the institutional background of REEs and the trade of these commodities between China and Japan. Section 3 explains the data and methodology employed in the analysis. Section 4 discusses the results, and Section 5 concludes.

2. REEs and their trade between China and Japan

REEs consist of seventeen elements in Group 3 on the periodic table (Figure A1). The first REE was observed in the late eighteenth century (Arakawa 1984; Long et al. 2012; Massari and Ruberti 2013). The term "rare" does not indicate their rarity in the world's reserves. According to the US Geological Survey (USGS),[4] as of 2019, there were 120 million metric tonnes (MT) of rare earth reserves in the world[5] and 90 million MT of lead, so REEs are not as rare as the name would suggest. The "rarity" of those elements comes from the difficulty in dressing the mineral and extracting the elements (Arakawa 1984), as producing compounds, metals, and alloys can involve as many as several hundred stages (Arakawa 1984; Bulatovic 2010; Paul and Campbell 2011). The world production in 2020 was around 240 thousand MT for REEs, compared to 4.4 million MT for lead.

In addition, REE production involves groundwater pollution and consumption of considerable amounts of water, acidic substances, and electricity (Ecclestone 2010; Fifarek et al. 2008; Klinger 2017). Minerals that contain REEs tend also to contain radioactive elements like uranium (Massari and Ruberti 2013). Some major mining sites in countries like the U.S. had to shut down because of these pollution issues and competition from low-cost producers in China (Fifarek et al., 2008), where some mining sites operate without a formal license and pay low wages (Massari and Ruberti 2013).

REEs have many unique characteristics, including their superconductivity, ferromagnetism, and catalytic, optical, and fluorescent properties (Massari and Ruberti 2013). Because of these characteristics, they have wide application, including in the production of permanent magnets, batteries, optical lenses, semi-conductors, radiation shield materials, abrasive compounds, and fluid catalytic cracking catalysts. The end products are used in a wide range of industries, including the energy, green, electronics, automobile, construction, medical, electricity, and defense industries (Figure A2).

REEs' economic value has surged with the increasing importance of the renewables/green industries. The demand is projected to continue to increase because of their use in hybrid and fully electric vehicles, turbines for wind generators, and energy-efficient light bulbs, among other green products (Humphries 2010). Some studies point out the vital role of REEs' prices in determining the consumption of renewable energy (e.g., Apergis and Apergis 2017), so securing REEs is critical to ensuring achievement of global renewable and green goals.

On the demand side, Stover (2011) and Burnell (2010) estimate that 2-Megawatt (MW) wind turbines consume approximately 360 kg of neodymium and 60 kg of dysprosium, and a hybrid fuel cell battery for vehicles consumes approximately 14 kg of rare earth metals. Fully electric vehicles also consume REEs, although some automobile companies are working on reducing the consumption of REEs per vehicle.[6] Currently, close to 70 million gas-operated passenger cars are produced globally each year,[7] and these sales will be replaced progressively with non-fossil-fuel-based vehicles following world governments' implementations of green initiatives. On the renewable side, global generation of wind power is expected to increase from 1,390 Terawatt hours (TWh) in 2018 to 4,355 TWh by

[4] https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-rare-earths.pdf.

[5] The largest deposit of REEs is in China, followed by Brazil, Vietnam, and Russia.

[6] See, for example, https://www.idtechex.com/en/research-article/will-rare-earths-be-eliminated-in-electric-vehicle-motors/21972.

[7] Refer to https://www.oica.net/category/production-statistics/2019-statistics/.

2030.[8] Since the current world production of REEs is less than 300 thousand MT,[9] the supply and demand environment for REEs is expected to remain tight. In addition to REEs' economic value to the private sector, REEs are used in missile guidance, aerospace, and defense systems, complicating the dynamics of REE markets. The irreplaceability of REEs in such applications gives rise to their status as strategic commodities.

We focus on China and Japan because Japan is one of the world's largest importers of REEs and China one of the world's largest exporters. According to information gathered by Japan Oil Gas and Metals National Corporation (JOGMEC), the total rare earth metals and REE compounds[10] exported by China was 51,190 gross MT in 2017, when Japan imported 12,461 MT (metal content base) of rare earth metals and compounds from China (Fig. 1).[11]

Since Japan and China are significant trading partners in REE, our analysis focuses on REEs imported by Japan (see Fig. 2). In addition, while REEs take various forms, including oxides, compounds, metals, and alloys, after extraction processes, rare earth metal is the largest category imported by Japan (Fig. 3), so our analysis focuses on rare earth metals. Japan's imports of rare earth metals include samarium metal, lanthanum metal, cerium metal, praseodymium metal, neodymium alloy and mischmetal (alloys of various REEs).

Fig. 4 shows the price of rare earth metal that Japan imported from China in 2019, calculated from the total value and the total quantity of rare earth metals (HS code: 2805.30.000). From early 2010 to early 2012, the volume-weighted average price jumped from just above 1000 JPY/kg to well above 20,000 JPY/kg.[12] This period coincides with the time the Chinese government tightened restrictions on REE exports (Shen et al. 2020; Tse 2011), illustrating the importance of Chinese suppliers in the REE market. After a few months, the volume-weighted average price dropped substantially to around 2000 JPY/kg, perhaps because of the economic slowdown in industrialized countries, the decrease in consumption of high technology products, and the possibility that some Chinese suppliers dumped their inventories because they feared that they were going to undergo inspection by Chinese authorities (Lian and Stanway 2011; Massari and Ruberti 2013). In addition, Mancheri et al. (2019) and Vekasi (2019) show that uncertainty in the price of REEs encourages users and investors to diversify their supply. Furthermore, economic sanctions on REEs also encourage users of REEs to recycle and use substitute materials (Gholz and Hughes 2021), which may have affected the price after the tightened exports.

To be more specific, if geopolitical tension disrupts the international trade of REEs, downward pressure on the import/export of REEs may result, driving the prices of those elements upward. A visual depiction of the relationship between the import value of rare earth metal from China to Japan and the geopolitical risk (GPR) index of China appears to support this hypothesis (Fig. 5). However, to investigate this relationship more deeply, we conducted a detailed empirical and statistical analysis of the impact of geopolitical risk on the international trade of REEs.

3. Data and methodology

We use import values of rare earth metals obtained from Japan's Ministry of Finance as an explained variable. We use the import value instead of quantity because rare earth metals consist of multiple REEs in metal form, and the prices and the quantities traded of these REEs differ widely. For example, according to the Shanghai Metals Market, the spot reference price of cerium metal was approximately 30,000 yuan/MT (approximately 4500 USD/kg based on the exchange rate in March 2021), while the price of praseodymium metal was 650,000 yuan/MT (approximately 98,000 USD/kg). To capture the changes in the material mix of the highest-priced rare earth metals in the import data, we use import values as the explained variable.

We collect the import values by gathering the monthly trade statistics released by the Trade Statistics of Japan for each month. We identify the rare earth metal from the trade statistics using the 9-digit statistical code, which consists of a 6-digit harmonized system code (HS Code) and a 3-digit domestic code used by the Japanese ministry to subdivide the traded goods.[13] We collected the data for the period between January 1988 and December 2019, during which time Japan imported rare earth metals from 24 countries, resulting in country-month observations. We exclude countries that have fewer than 30 months of observations and countries that have no local GPR index value. After this cleaning process, our sample consists of 926 country-month observations for the exporting countries of Brazil, China, the U.S., and Thailand. (Countries other than China are included in the analysis to show how the impact of geopolitical tension differs between China and other countries.) The import value fluctuates each month depending on such factors as the date when a large shipment was dispatched, so the data must be smoothed out. In addition, if the level of geopolitical risk has a negative impact on the trade of rare earth metals, the trade becomes zero if the risk rises substantially. Therefore, observations with zero value may contain valuable information. To take these observations into account, we log-transformed the import value after adding a value of 1 to all the observations and then computed a six-month rolling average.

Studies of this nature were not feasible until recently, when textual data analytics and open-source programming languages proliferated. Our main explanatory variable, geopolitics, is measured using the geopolitical risk (*GPR*) index developed by Caldara and

[8] Refer to https://www.iea.org/fuels-and-technologies/wind.
[9] Refer to https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-rare-earths.pdf.
[10] Rare earth metals and REE compounds are two major forms in which REEs are traded.
[11] 34,403 gross MT includes the weight of impurities.
[12] As the trade statistics include more than one element in the rare earth metal category, the estimated price may also be altered by changes in the element/product mix. However, the price of dysprosium obtained from Asian Metal, Inc. also increased during the same period. Therefore, the change in estimated price is likely due to actual price hikes.
[13] The HS code for rare earth metal is 2805.30.000. Rare earth metal consists of general rare earth metal, as well as scandium and yttrium.

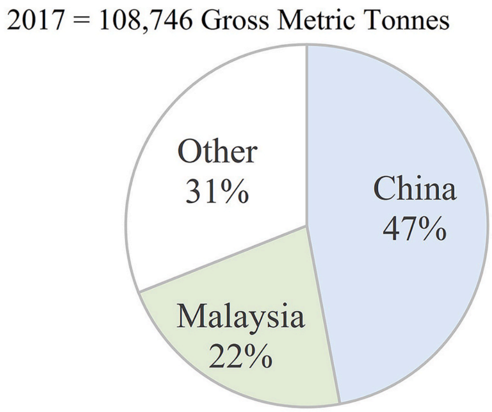

Fig. 1. World Total Rare Earth Metal and Compounds exported in 2017.
Source: Global Trade Atlas, as cited in JOGMEC

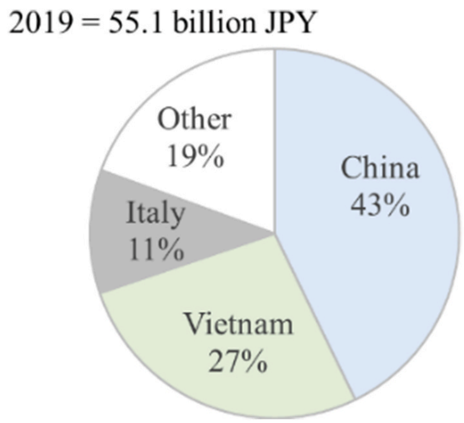

Fig. 2. Rare earth imported by Japan: share of exporting countries.
Source: Authors' estimates using data from Trade Statistics of Japan

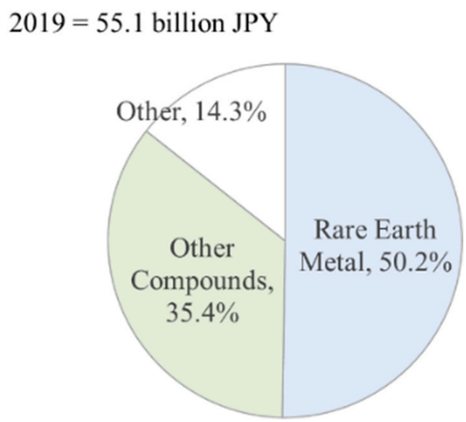

Fig. 3. Rare earth imported by Japan: share of rare earth materials.
Source: Authors' estimates using data from Trade Statistics of Japan

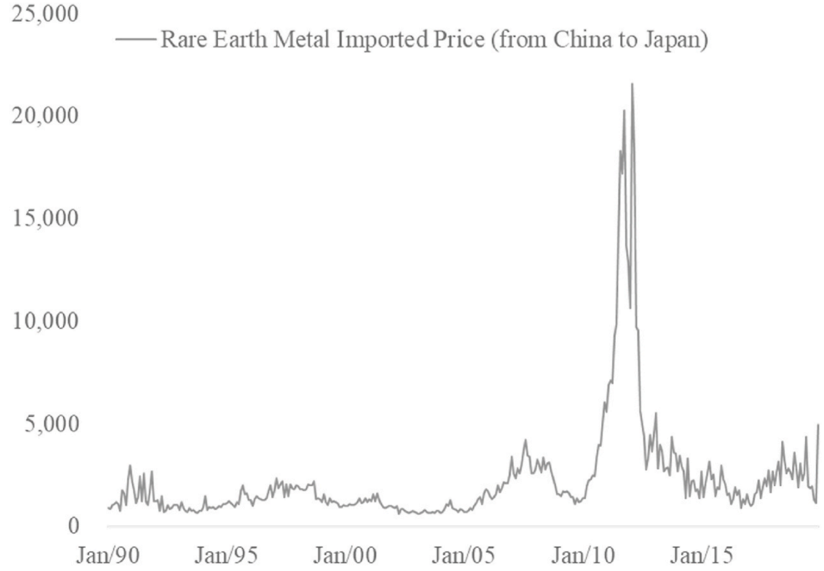

Fig. 4. Price of rare earth metals imported by Japan (from China, JPY/kg), calculated from the total value and quantity of rare earth metals imported by Japan (January 1990–December 2019).
Source: Trade Statistics of Japan

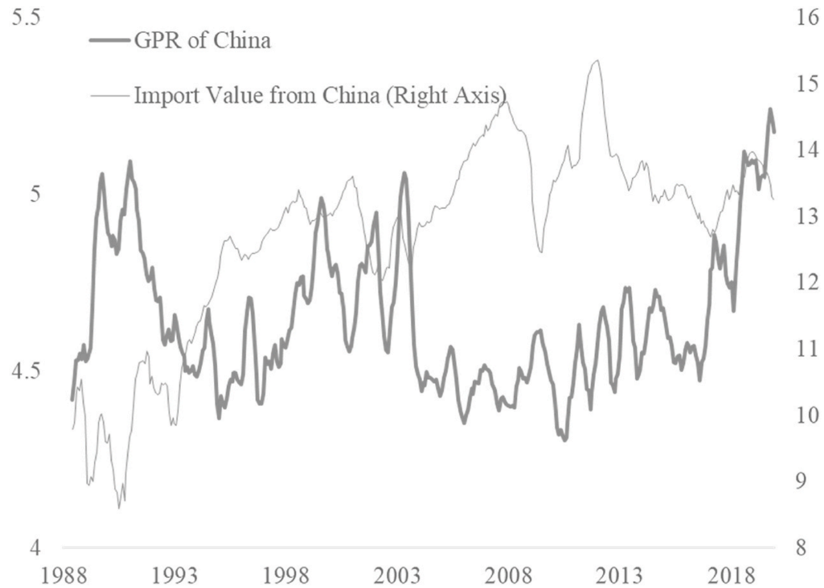

Fig. 5. Rare earth import value (from China to Japan) and the GPR index of China. Note: Both the GPR index and the import value are log-transformed and then converted into six-month rolling averages.

Iacoviello (2022). The GPR index is constructed using text-search algorithms that count the number of geopolitical-risk-related articles from major American and international newspapers[14] during a time period (e.g., on a certain day or month). This number is then divided by the overall number of news articles to measure geopolitical uncertainty. This index captures the tension between a country and other countries instead of between one country and one other country, even though a conflict between two countries may have a negative impact on the export of strategic products to a third country if the product affects the industrial and military competitiveness of the two conflicting countries.

As this study focuses on how geopolitical tension between an exporter and other countries affects exports of a strategic material, our

[14] Publishers of articles on geopolitical risk include *The Boston Globe*, *Financial Times*, *The Guardian*, *The New York Times*, and *The Washington Post*.

analysis uses the exporting country's country-level GPR index. In addition, as the importer's economic policies may affect its purchasing behavior, we include in our analysis the economic policy uncertainty (EPU) index for Japan, an index that Arbatli et al. (2017) construct.[15] Finally, geopolitical tension may affect the price of rare earth metals, and that price change may influence a metal's trading behavior. To account for this possibility, we estimate a rare earth metal's price by dividing the traded value by the quantity for each month for each exporting country. The descriptive statistics and the Pearson's correlation coefficients for the variables are presented in Table 1 and Table 2, respectively. The log-transformed price takes a negative value as a lower bound, as the price is quoted in units of 1000 yen. As expected, the total import value is negatively related to the GPR. The correlation coefficients among the other variables are less than 0.5, indicating that a multicollinearity issue among them is unlikely (Alam et al. 2019).

We use the model in Eq. (1) to examine the effect of exporters' geopolitical risk on the rare earth metals imported by Japan:

$$Import_{t,j} = \alpha + \beta_1 gpr_{t,j} + \beta_2 \left(gpr_{t,j} \times china_{dummy}\right) + \beta_3 epu_t + \beta_4 price_{t,j} + \delta_5 \sum (year\ effects)_t + \varepsilon_{t,j} \tag{1}$$

where $Import_j$ is the total value of the rare earth metal imported from country j, gpr_j is the GPR index of country j, $china_{dummy}$ is a dummy variable that takes the value of 1 if the rare earth metal is imported from China and 0 otherwise, epu is the EPU index of Japan, $price$ is the rare earth price imported from country j,[16] and *year effects* is the year identifier variable. The interaction term between gpr and $china_{dummy}$ captures whether the geopolitical risk that arises from China affects the rare earth exported to Japan differently from the geopolitical risk that arises from other trading partners. The panel regression analysis with the fixed effect is based on Hausman's specification test.

To examine the impact of China's restrictions on rare earth exports, we include an interaction term constructed by combining the interaction term in Eq. (1) with a new dummy variable, $china_{ban}$, which takes the value of 1 for the period between September 2010 (the time that the restriction was first reported by international media)[17] and March 2014 (the time when China lost a related dispute at the WTO),[18] and 0 otherwise. For both models, we use the standard error estimation method developed by Driscoll and Kraay (1998) to address any cross-sectional dependence in the sample. We use the rolling average import value of rare earth metals as the explained variable.[19] This model is shown in Eq. (2).

$$Import_{t,j} = \alpha + \beta_1 gpr_{t,j} + \beta_2 \left(gpr_{t,j} \times china_{dummy}\right) + \sum_{i=3}^{4} \beta_i Control_{t,i} + \delta_5 \sum (year\ effects)_t + \beta_6 \left(gpr_{t,j} \times china_{dummy} \times china_{ban}\right) + \varepsilon_{t,j} \tag{2}$$

Cross-sectional dependence may occur, as a fall in the imports from one country may result in a rise in the imports from other countries, keeping the supply constant.

4. Empirical results

4.1. Price of rare earth metal and GPR

We first examine the impact of exporting countries' geopolitical uncertainty on the price of rare earth metals imported by Japan. The results, presented in Table 3, show that the GPR index of exporting countries and the price of rare earth metal exported to Japan are significantly positively related. This finding is consistent with the hypothesized relationship between geopolitical tensions and the international trade of rare earth metals; therefore, the price of rare earth metals is positively related to the GPR index. We also insert the interaction term (*china_dummy* × GPR), but the coefficient is statistically insignificant[20], indicating that the relationship between geopolitical tensions and the price of rare earth metals is indifferent to which exporting countries are experiencing tensions.

4.2. Rare earth metal exports and GPR

We extend our analysis by examining the relationship between geopolitical risk and countries' exports of rare earth metals. To examine this relationship, we conduct regression analyses using Eq. (1). Table 4's Panel A shows the basic relationship of the exporting countries with the GPR index with and without the interaction term that captures how the relationship changes for exports from China. The results confirm the inverse relationship between the export value and the GPR index, especially from China, which is consistent with what Davis et al. (2019) find using the overall goods exported from China and geopolitical tension data from the GDELT project. As the relationship between the GPR and the import prices shown in Table 3 is positive, the negative relationship between the GPR and the total value of Chinese export observed in Table 4 should arise from the decline in export volumes. These results also confirm that exports from China are more sensitive to changes in the GPR index than exports from other countries are. In particular, the negative

[15] The data are available from https://www.policyuncertainty.com/.

[16] REEs may be traded in various currencies (e.g., USD and yuan), so including the price in the model as a control variable partially controls for and reflects changes in the exchange rates.

[17] Reuters' announcement is at https://uk.reuters.com/article/china-japan-minerals/china-bans-rare-earth-exports-to-japan-after-row-nyt-idUKSGE68M05120100923.

[18] For more detail, refer to Wagner (2014).

[19] For more detail, refer studies like those of Hoechle (2007) and Vogelsang (2012).

[20] Results are not reported but are available on request.

Table 1
Descriptive statistics.

	N	Mean	Std. Dev.	Min	Max
ln(value_ave)	926	9.362	3.724	0.000	15.377
ln(gpr)	926	4.462	0.464	3.165	6.301
ln(epu)	926	4.579	0.300	3.889	5.475
ln(price)	730	1.818	2.145	−1.133	7.657

Note: ln indicates that the variable is log-transformed, value_ave is the six-month average of rare earth metals imported by Japan, gpr is the geopolitical risk index for the exporting country (Caldara and Iacoviello 2022), epu is the EPU index from Arbatli et al. (2017), and price is the price of the rare earth metals imported by Japan.

Table 2
Correlation matrix.

		(1)	(2)	(3)	(4)
(1)	ln(Import)	1.000			
(2)	ln(gpr)	−0.055	1.000		
(3)	ln(epu)	−0.019	−0.076	1.000	
(4)	ln(price)	−0.232	−0.231	−0.125	1.000

Note: This table presents the Pearson's correlation coefficients among the variables used in the analysis.

Table 3
Analysis of the impact of GPR on the imported price of rare earth metals.

ln(gpr)	0.429**	0.429**
(p-value)	(0.035)	(0.035)
ln(epu)		0.041
(p-value)		(0.834)
year dummies	Yes	Yes
N	730	730
R-squared	0.236	0.236

Note: This table shows the results of the regression analysis that tests the relationship between the price of rare earth metals imported by Japan and the GPR index of the exporting country. To improve the conciseness of the presentation, the intercept is not presented in the table. The analysis is conducted based on Eq. (1), but instead of the import value, the price is used as the explained variable. The analysis is also conducted without the interaction term. The standard errors are estimated using the method from Driscoll and Kraay (1998). ***, **, and * indicate that the coefficient is significant at the 1, 5, and 10 percent levels, respectively.

Table 4
Analysis of the relationship between the rare earth metals imported by Japan and the GPR index of exporting countries.

Panel A: Main Results								
			with EPU		with Price		with EPU and Price	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ln(gpr)	−1.024***	−0.843**	−1.025***	−0.844**	−0.287	−0.033	−0.283	−0.020
(p-value)	(0.003)	(0.017)	(0.003)	(0.017)	(0.161)	(0.880)	(0.166)	(0.928)
china_dummy * ln(gpr)		−1.515*		−1.510*		−1.364**		−1.405**
(p-value)		(0.053)		(0.054)		(0.041)		(0.037)
ln(epu)			−0.138	−0.063			0.222	0.333
(p-value)			(0.547)	(0.790)			(0.333)	(0.163)
ln(price)					−0.295***	−0.297***	−0.295***	−0.298***
(p-value)					(0.000)	(0.000)	(0.000)	(0.000)
year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	926	926	926	926	730	730	730	730
R-squared	0.239	0.247	0.239	0.247	0.365	0.379	0.365	0.381
Panel B: Joint Test using the result shown in Column (8) (p-value)								
β [ln(gpr)] + β [china_dummy * ln(gpr)] = 0								(0.018)

relationship is approximately three times stronger for the Chinese exports than it is for other countries, indicating that the rare earth metals China supplies are strongly linked to geopolitical uncertainty. The GPR index does not measure geopolitical conflict with a particular country, but since the rare earth metals that are processed and fabricated in Japan are essential components of products like electronics, automobiles, and weaponry, it is reasonable to conclude that the geopolitical tensions between two countries spilled over to other countries. Our analysis is likely to have captured this spillover effect.[21]

Since international trade has a bilateral nature, a strategic material like a rare earth metal imported by Japan may also be affected by Japan's EPU, so we include the EPU index to control for such an impact. The results are presented in models (3) and (4), shown in Table 4's Panel A. The results for the GPR and the interaction term remain unchanged, but the coefficient obtained for the EPU index is insignificant. We also include the monthly price of rare earth metals imported by Japan in the analysis and present the results in models (5) and (6) and in models (7) and (8) for other countries that have an EPU score. The coefficient obtained for the GPR index is insignificant, while the interaction term remains significantly negative, so the relationship between the GPR index and rare earth exports (with the exception of China) cannot be attributed to price changes.

The GPR index's impact on China's exports is measured as the sum of the coefficient for the GPR index and the interaction term. To determine whether the GPR index for China is statistically valid, we conduct a joint *t*-test that examines whether the sum of these two coefficients is significantly different from zero. The result, reported in Table 4's Panel B, indicates that China's GPR index is statistically significant,[22] supporting our hypothesis that geopolitical tension affects exports of rare earth metals.

International trade can also be affected by domestic political factors in the exporting country. To examine whether this factor affected our results, we reconduct the main analysis using an orthogonalized GPR index after controlling for EPU (https://www.policyuncertainty.com/) in China. The result remains unchanged. We also gauge whether GPR's negative effect on rare earth metals trade is also observed elsewhere by examining Chinese rare earth metals imported by Germany and confirm a significant negative relationship. (Results are available on request.)

4.3. *Impact of restrictions on rare earth metal exports by the Chinese government*

The Chinese government restricted REE exports to Japan after a diplomatic standoff between the two countries elevated in 2010 (See, for example, Bradsher (2010) and Hornby (2010).). At that time, the European Union and the U.S. were also accusing the Chinese government of interfering with the export of REEs (McDowall 2010), which may have altered the relationship between the GPR index and China's exports of rare earth metals. To examine this possibility, we performed an analysis using Eq. (2). The new interaction term that combines the GPR index, the China dummy (i.e., observation for China = 1, and 0 otherwise), and another dummy variable (the dispute interaction) takes the value of 1 for the rare earth export dispute period, and 0 otherwise. The dispute period is assumed to have started when the media reported the restriction that the Chinese government imposed on rare earth exports to Japan in September 2010 and to have ended in March 2014 when the WTO's Dispute Settlement Panel ruled against China after the U.S., the European Union, and Japan brought the case to the WTO.

The results are reported in Table 5. Panels A and B confirm the statistically significant negative relationship between the GPR index and the value of rare earth metal exports from China. In addition, the dispute interaction term obtains a statistically significant coefficient, but its sign is positive; therefore, while the sum of the coefficients obtained for the GPR index and the two interaction terms is still negative—that is, the export and the GPR of China were negatively related even during the dispute period—the relationship weakened during the dispute. [23] The export quotas China imposed on the REEs dropped considerably,[24] but as some have argued, illegal (unrecorded) exports of some REEs from China increased substantially during this period (Plumer 2014).[25] These unrecorded exports would have weakened the negative relationship between the GPR index and the trade in rare earth metals. In addition, as Wübbeke (2013) argues, China's domestic political factors may have affected the decision to cut the export quotas and contributed to weakening the relationship.

Our findings suggest that the REE trade is strongly influenced by geopolitical risk and that China's dominance of the entire REE supply chain poses a risk to the continuity of many industries that rely on these critical inputs. For these reasons, the debate has shifted to the means and conditions required to build alternative REE supply chains that reduce a user's dependence on a single source of supply. This issue was exacerbated with the COVID-19 pandemic. Ilankoon et al. (2022) identify thirteen constraints to developing alternative REE supply chains outside of China, ranked by conducting a survey of REE industry experts and international companies. Four of the thirteen constraints are statistically significant: Chinese REE supply chain controls and business uncertainties; waste

[21] We also examined Google Trends as a potential data source to identify the period of heightened risk of politicization of the economic relationship between Japan and China. We used the keywords China risk, "中国リスク" and "チャイナリスク"; worsened Japan/China relations, "日中関係 悪化"; and heightened tension between Japan/China, "日中関係 緊張." Since these keywords receive low volume of search attempts, the absence of high-quality trend data casts doubt on the value of applying Google Trends data in specialized research like that on REE and geopolitics.

[22] A negative and significant relationship between the rare earth metal exported from China and the GPR is also confirmed when a time-series regression analysis is conducted on the data for China with the same control variables. (The level data are found to be stationary.)

[23] As Fig. 4 shows, the price of rare earth surged around 2010 but then dropped back to pre-2010 levels before the end of the WTO dispute. The result remains consistent when a narrower conflict period (2010–2011) is considered.

[24] Exports to Japan were unofficially banned for a short time, as reported by news media (See, for example, Liu and Maughan (2012), Areddy et al. (2010), and Hornby (2010).).

[25] Some statistics show that there were more unrecorded rare earth exports than recorded exports in 2011 in China (Shen et al., 2020).

Table 5
Analysis of the impact of restrictions on the export of REEs imposed by the Chinese government.

Panel A	
ln(gpr)	0.008
(p-value)	(0.970)
china_dummy * ln(gpr)	−1.317**
(p-value)	(0.044)
china_ban * china_dummy * ln(gpr)	0.377***
(p-value)	(0.000)
ln(epu)	0.314
(p-value)	(0.219)
ln(price)	−0.340***
(p-value)	(0.000)
year dummies	Yes
N	730
R-squared	0.410
Panel B: Joint Test (p-value)	
β [ln(gpr)] + β [china_dummy * ln(gpr)] = 0	(0.027)

Note: This table shows the results of the regression analysis conducted using Eq. (2). To improve the conciseness of the presentation, the intercept is not presented in table. A six-month rolling average monthly import value is used for the import variable. The import value is log-transformed. *china_ban* is a dummy variable that takes the value of 1 for the period in which the restrictions on rare earth exports were imposed by the Chinese government (September 2010–March 2014), and 0 otherwise. *china_dummy* takes the value of 1 if the rare earth metal was imported from China, and 0 otherwise. Panel B presents the results of a joint *t*-test that examines whether the coefficients obtained from the GPR index and the interaction term between *china_dummy* and the GPR index are jointly significantly different from 0. The standard errors are estimated using the method from Driscoll and Kraay (1998). ***, **, and * indicate that the coefficient is significant at the 1, 5, and 10 percent levels, respectively.

management, recycling and substitution challenges; separation challenges and high investments; and geological variabilities. The author suggest that REE supply chains outside of China could be seen sometime between 2030 and 2050.

Although China holds more patents in REE technology than all other producing nations combined and is the only country that has a full industrial chain of REE, Ferreira and Critelli (2022) postulate that the dynamics of China's REE pricing power has been undergoing changes in recent years. They summarize that the channels through which China's policies can impact the West's production and supply chains include squeezing competitor margins, discouraging recycling, and eroding the need for strategic stockpiles. The authors note that, as China has shifted its focus from upstream to downstream REE production and committed to renewables, its demand for REE now exceeds domestic supply. They conclude that the development of alternative supply chain outside of China requires substantial government funding.

4.4. Robustness check

To check the robustness of our results, we conduct the analyses presented above again by controlling for Japan's seasonally adjusted industrial production (in the form of monthly change). The conclusion remains unchanged.[26] In addition, we reconduct the analyses using different rolling windows to average the rare earth metals imported by Japan (i.e., 5 months, 4 months, 3 months, 2 months, and without averaging). Table 6 reproduces the analyses presented in Table 4's Columns (7) and (8), and Table 7 reproduces the analyses presented in Table 5. The results are consistent with our initial hypothesis and the results obtained earlier.

5. Conclusion

This paper investigates the statistical relationship between geopolitical risk and the export and prices of REEs. Using Japanese rare earth metals trading data from 1988 to 2019, we find that heightened geopolitical risk is associated with higher rare earth metals prices (i.e., weighted average price per kg of the metal) and that such risk is associated with lower overall export values, especially for the

[26] Results are not reported but are available on request.

Table 6
Examining the impact of altering time windows for rolling averages of import values.

Panel A: Regression Analysis Results

	5-mo. Avg.		4-mo. Avg.		3-mo. Avg.		2-mo. Avg.		No Avg.	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
ln(gpr)	−0.320	−0.067	−0.273	−0.009	−0.270	−0.013	−0.296	−0.061	−0.339*	−0.156
(p-value)	(0.101)	(0.744)	(0.153)	(0.963)	(0.165)	(0.947)	(0.122)	(0.733)	(0.057)	(0.318)
china_dummy * ln(gpr)		−1.354**		−1.410**		−1.372**		−1.256**		−0.974**
(p-value)		(0.035)		(0.020)		(0.017)		(0.019)		(0.023)
ln(epu)	0.346	0.453*	0.455*	0.566**	0.474*	0.582**	0.260	0.359	0.153	0.230
(p-value)	(0.142)	(0.065)	(0.052)	(0.021)	(0.059)	(0.026)	(0.270)	(0.144)	(0.406)	(0.214)
ln(price)	−0.285***	−0.288***	−0.294***	−0.297***	−0.345***	−0.348***	−0.350***	−0.353***	−0.475***	−0.477***
(p-value)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	730	730	730	730	730	730	730	730	730	730
R-squared	0.357	0.371	0.352	0.367	0.356	0.37	0.342	0.353	0.454	0.462

Panel B: Joint Test (p-value)

β [ln(gpr)] + β [china_dummy * ln(gpr)] = 0	5-mo. Avg. (0.015)	4-mo. Avg. (0.012)	3-mo. Avg. (0.011)	2-mo. Avg. (0.012)	No Avg. (0.010)

Note: This table reproduces the analysis presented in Column (8) of Table 4 by altering the rolling period for the average value of imported rare earth metals. To improve the conciseness of the presentation, the intercept is not presented in the table. The first row of Panel A indicates how many months are used for the rolling window. (For example, "5-mo. avg." indicates that a 5-month rolling average is used in the analysis.) Panel B presents the results of a joint *t*-test that examines whether the coefficients obtained from the GPR index and the interaction term between *china_dummy* and the GPR index are jointly significantly different from 0. The joint t-tests are conducted on the analyses in the even columns. The standard errors are estimated using the method from Driscoll and Kraay (1998). ***, **, and * indicate that the coefficient is significant at the 1, 5, and 10 percent levels, respectively.

Table 7
Impact on the role of China's restrictions of altering windows for the rolling average of imported values.

Panel A: Fixed-Effect

	Rolling Average				
	5 Months	4 Months	3 Months	2 Months	No Average
ln(gpr)	−0.040	0.017	0.013	−0.036	−0.135
(p-value)	(0.842)	(0.927)	(0.944)	(0.834)	(0.369)
china_dummy * ln(gpr)	−1.269**	−1.329**	−1.292**	−1.178**	−0.906**
(p-value)	(0.043)	(0.025)	(0.022)	(0.025)	(0.033)
china_ban * china_dummy * ln(gpr)	0.365***	0.352***	0.345***	0.336***	0.291***
(p-value)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(epu)	0.435*	0.549**	0.565**	0.342	0.216
(p-value)	(0.093)	(0.032)	(0.035)	(0.179)	(0.265)
ln(price)	−0.329***	−0.336***	−0.387***	−0.390***	−0.509***
(p-value)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
year dummies	Yes	Yes	Yes	Yes	Yes
N	730	730	730	730	730
R-squared	0.399	0.392	0.393	0.375	0.481

Panel B: Joint Test on β [ln(gpr)] + β [china_dummy * ln(gpr)] = 0; (p-value)

Rolling Average 5 Months	4 Months	3 Months	2 Months	No Average
(0.023)	(0.018)	(0.017)	(0.018)	(0.016)

Note: This table reproduces the analysis presented in Table 5 by altering the rolling window for the average value of imported rare earth metals. To improve the conciseness of the presentation, the intercept is not presented in the table. The first row of Panel A indicates how many months are used in the rolling window. (For example, "5-mo. avg." indicates that a 5-month rolling average is used in the analysis.) Panel B presents the results of a joint *t*-test that examines whether the coefficients obtained from the GPR index and the interaction term between *china_dummy* and the GPR index are jointly significantly different from 0. The joint t-tests are conducted on the analyses in the even columns. The standard errors are estimated using the method from Driscoll and Kraay (1998). ***, **, and * indicate that the coefficient is significant at the 1, 5, and 10 percent levels, respectively.

Japan-China trade. These results indicate that the positive effect of a price increase is not enough to offset the negative effect of reduced quantities exported, thus driving down the overall value exported. We also find that the negative relationship between the imports of rare earth metals and geopolitical risk in China weakened during the WTO dispute between China and Japan. This weakening can be partly explained by the increase in unrecorded exports and China's domestic political factors. Our results contribute to the literature on international political economy and to the IR literature by providing empirical evidence that confirms the link between geopolitics and the international trade in strategic natural resources–in this case, rare earth metals.

Prior to focusing on the empirics, we took a deep dive into the sourcing, production, and distribution of rare earth metals and documented those unique features that are important for empirical research. As a result, our findings offer meaningful insights to a wide range of audiences, including renewable and green industries, technology companies, rare earth miners, regulators, governments, and international organizations. For users of REEs, the prevailing link between REE and geopolitical risk suggests that an effective hedging and risk-management program could add economic value when geopolitical tensions are high. For policymakers, our evidence suggests that REE-exporting nations could use REEs as a diplomatic tool in managing their political relationships with other nations. Finally, our results lend support to Caldara and Iacoviello's (2022) efforts to capture geopolitical tensions through the GPR index. Overall, our work deepens academic discussions on international trade and political economy and extends the commodities literature's understanding of rare earth metals.

Data availability

Data will be made available on request.

Appendices.

Group

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H																	He
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg											Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	La - Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	Ac - Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds								

Lanthanides: La - Lu

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu

Actinides

Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Figure A1. Periodic table with rare earth elements

Note: Rare earth elements are highlighted in blue.

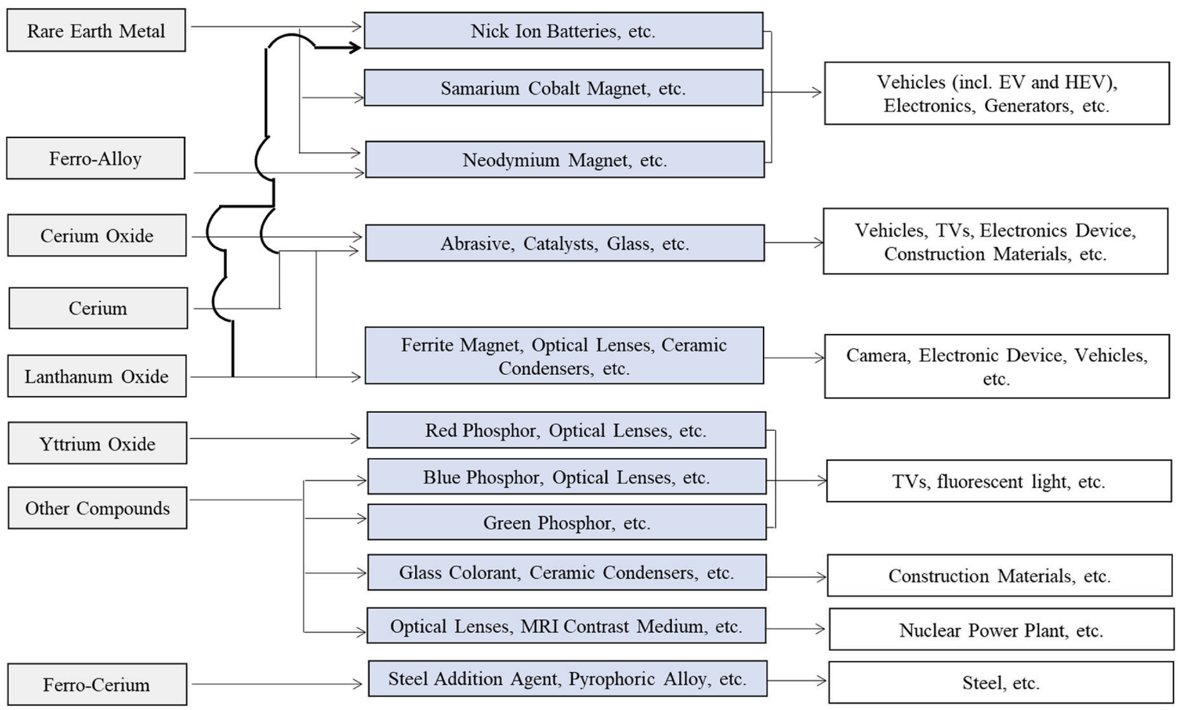

Fig. A2. Material flow of Rare Earth
Source: Authors' estimates, information from JOGMEC

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