Research paper

The Evolution of Neodymium Cycle, Urban Minerals, and Trade in China

Xin Xiong[1,2], Liang Zhao[1,3], Guochang Xu[4], Xianlai Zeng[2*]

Handling Editor: Judith Plummer-Braeckman

Received: 19.03.2025 / Accepted: 23.05.2025

Abstract

Neodymium is a critical element for the global transition to clean energy, yet its long-term supply is constrained by trade dependencies, resource depletion, and persistently low recycling rates. This study employs a dynamic substance flow analysis to quantify China's cycle of neodymium from 2001 - 2021, and to assess the contribution of urban mining—i.e., the recovery of neodymium from end-of-life products (or called urban minerals)—to domestic resource availability. We also evaluate the effectiveness of recent government measures aimed at curbing illegal mining and stabilising domestic supply. With demand for neodymium set to rise sharply in tandem with electric vehicle and renewable-energy deployment, the results underscore the importance of: (1) scaling up closed-loop recycling infrastructures, (2) reinforcing regulatory oversight and enforcement, and (3) diversifying trade partnerships to bolster supply security. By shifting the balance toward secondary resources and robust governance, China can reduce its dependence on primary extraction and enhance the resilience of its neodymium supply chain.

Keywords: Neodymium · Substance Flow Analysis · Urban Mining · Sustainability · Resource Management

1. INTRODUCTION

In recent years, countries worldwide have reached a consensus on the importance of bolstering sustainable development in a green economy (Eheliyagoda et al., 2023). As part of this effort, major economies have implemented relevant policies and actions to transform and enhance their energy structures, with the goal of meeting the environmental protection targets outlined in the Paris Agreement (Dong et al., 2018; Fahmy, 2021). Against this background, the global economic and industrial structure is undergoing significant changes, driven by rapid advancements in wind power, energy-efficient household appliances, and new energy vehicles (Bhattarai et al., 2022; Liu et al., 2023). China's new energy sector has entered a phase of growth, marketisation, and high-quality development, resulting in a surge in demand for rare earth resources, particularly neodymium

[1] School of Sustainable Energy and Resources, Nanjing University, Suzhou, 215163, China

[2] School of Environment, Tsinghua University, Beijing, 100084, China

[3] MOE Key Laboratory of Surficial Geochemistry, School of Earth Sciences and Engineering, Nanjing University, Nanjing, 210046, China

[4] Material Cycles Division, National Institute for Environmental Studies, Onogawa 16-2, Tsukuba 305-8506, Japan;

[*]Corresponding author: xlzeng@tsinghua.edu.cn

(Nd) (Claudio-Quiroga et al., 2023; Fang et al., 2023). Monitoring neodymium resources throughout the supply chain is crucial for advancing the green and low-carbon energy transition and achieving carbon neutrality and peak carbon goals (Raza et al., 2023; Xiong, Zeng, et al., 2023).

China, the world's largest producer and consumer, contains Earth's largest rare-earth deposits (Yao et al., 2021). Recent data indicate that globally proven reserves stand at approximately 110 million tons (in oxide form), about 35% of which are found within China, followed by Vietnam, Brazil, and Russia (Baidu, 2024), in descending order. Nevertheless, China's neodymium resources face the dual challenge of surging demand coupled with growing supply limitations. A stable neodymium supply is indispensable for supporting the rapid development of electric vehicle (EV) motors, wind turbine generators, and other key applications that contain NdFeB magnets, such as hard disks, smartphones, and cooling units (Sherwood et al., 2022). Given the growth of these sectors, a continuous increase in the demand for neodymium is expected (Hu et al., 2024). However, the Chinese government's restrictions on rare earth mining quotas (Xiao et al., 2022) coupled with stringent environmental protection regulations implemented in recent years, this portends a reduction in the supply of neodymium raw materials to downstream products.

Urban mining, reclaiming valuable materials from product waste (or called old scrap, urban minerals or anthropogenic minerals), is an effective way to obtain secondary resources and offers substantial environmental benefits (Bernardes et al., 2024; Cho et al., 2024). By processing neodymium-containing urban minerals (Vanegas et al., 2017), a closed loop promotes the cyclic use of neodymium and lowers the energy required for material extraction (Eheliyagoda et al., 2024; X. Liu et al., 2022). Urban mining also mitigates the negative environmental impacts of traditional mineral processing, such as water contamination, air pollution, and habitat destruction, by reducing the need for new mining operations (Carlet al., 2022). Therefore, it is crucial to analyse the metabolic processes of neodymium resources throughout their life cycle and identify changing patterns in material flow, considering their global trades. Accordingly, some pioneer studies used substance flow analysis (SFA) to quantify the social metabolic processes of materials and critical metals (Guo et al., 2016), as well as to analyse their environmental and economic effects (Malin et al., 2014; Zhao, 2022; Rostek et al., 2022). Regarding neodymium, Liu et al. (2022) analysed global neodymium stocks and flows with trade-related multi-regional material flows. Yao et al. (2021) analysed the material flows of neodymium in China.

To provide valuable insights into optimising the management of urban neodymium minerals in China and strengthening the robustness of China's neodymium supply, we traced China's stocks and flows from 2001 - 2021 based on a dynamic SFA approach, covering the entire life cycle from extraction to production, manufacturing, use, and waste management (Glöser et al., 2013). Compared with previous studies, Yao et al. (2021) and Liu et al. (2022) examined neodymium material flows globally and in China, but our analysis goes a step further, examining trade relations between China and major trading countries, which contributes to building strong international partnerships and trade agreements, reducing dependence on any single source, and enhancing supply security.

2. METHODS AND DATA

2.1 Data Sources

This study used a diverse range of data encompassing the production, trade, and lifespan metrics of products containing neodymium. The primary source for the production data of concentrates is the China Rare Earth Yearbook, whereas the production figures for neodymium-infused products were extracted from the China Statistical Yearbook. The China Customs Database provides international trade data on these neodymium-based products. Published papers were the main source of data on the loss rate at each stage and the lifespan distribution of neodymium products. For details, please refer to Tables S1-S6 in the Supporting Information (SI).

2.2 System Definition

From a temporal perspective, SFA can be categorised as static or dynamic. The static SFA provides a snapshot of substance flow and inventory within a defined timeframe (Zhu et al., 2024), disregarding the average lifespan of products. This system is based solely on the fundamental principle of mass conservation. However, the dynamic SFA model's substance flow and stock can potentially be influenced by all previous system states. Consequently, it focuses more on the system's flow and stock trends and can be utilised to forecast future trends over a specific period (Song et al., 2022). Because SFA is a systematic approach to analysing material flows and inventories in a temporally and spatially defined system (Li et al., 2023), the first step in this study is to establish clear boundaries (Zheng et al., 2022). In this study, the temporal boundary was set from 2001 - 2021, and the spatial boundary is confined to mainland China.

Figure 1 illustrates China's SFA framework for the neodymium cycle, which consists of six stages. The first stage of material extraction is mining and beneficiation. neodymium is typically found in minerals such as bastnaesite, monazite, and ion-adsorption clays. The mining process involves flotation (re-election and magnetic separation) to remove impurities and increase the concentration of neodymium compounds (Yao et al., 2021). The second stage is refining and separation. The concentrate obtained from mining is a mixture of various rare earth elements. Neodymium-containing compounds like neodymium chloride, neodymium oxide, and neodymium fluoride are separated through solvent extraction and ion exchange. Neodymium metal is then obtained via hydrometallurgical smelting (Geng et al., 2021).

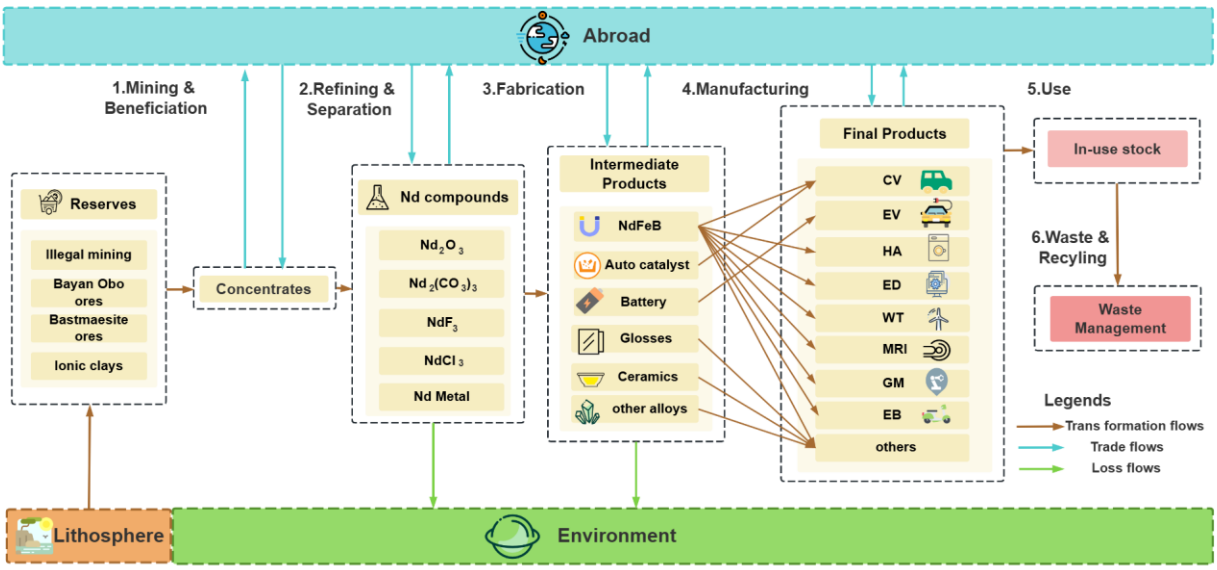


Figure 1. Substance Flow Analysis Framework for Neodymium in China. Note: Nd signifies neodymium, CV signifies conventional vehicles, EV signifies electric vehicles, HA signifies household appliances, ED signifies electronic devices, WT signifies wind turbines, MRI signifies magnetic resonance imaging machines, GM signifies general machinery, and EB signifies electric bicycles

The third stage of product manufacturing is intermediate product fabrication. Neodymium-containing compounds or metals are processed into intermediate products. These include NdFeB magnets, metal coatings for automotive catalytic converters, cathode materials for NiMH batteries, ceramics, colourant additives for glass, and modified materials for other alloys (Yao et al., 2021). The fourth stage is the final product manufacturing. The intermediate products are transformed into final products. This study investigated 17 such products, grouped into eight categories: conventional vehicles, electric vehicles, household appliances, electronic devices, wind turbines, MRI equipment, general machinery, and electric bicycles. The household appliances include washing machines, refrigerators, vacuum cleaners, microwave ovens, and air conditioners; electronic products include mobile phones, laptops, desktop computers, CD/DVD players, and loudspeakers; and general-purpose machinery, including elevators and industrial robots (Geng et al., 2021).

The fifth stage of the neodymium cycle is the use or consumption. Products contained neodymium are used to provide services to society. These products become part of the socioeconomic system's in-use stocks during their service life. The final stage is waste management and recycling: Once the products reach the end of their service life, they become urban minerals. Some neodymium is recycled (including new and old scrap) and re-enters the process flow.

2.3 Flows and Stocks Accounting

The SFA follows the principle of mass balance, and the flow balance formula for neodymium in each life cycle is (Su et al., 2023):

$$F_{i,t}^{input} + F_{i,t}^{import} = F_{i,t}^{output} + F_{i,t}^{export} + F_{i,t}^{loss} \tag{1}$$

where i represents the life stage i covered in Figure 1; t represents the study year; $F_{i,t}^{input}$ is the neodymium flow in the life stage i that enters the system to produce neodymium-containing products in year t; $F_{i,t}^{import}$ is the imported volume in products of the life stage i in year t; $F_{i,t}^{output}$ is the outbound flow in the life stage i in year t; $F_{i,t}^{export}$ is the exported volume in products of the life stage i in year t; $F_{i,t}^{loss}$ is the possible neodymium loss of the life stage i in year t.

Based upon the mass balance principle, China's neodymium flows and stocks are categorised into five accounting processes.

(1) Domestic flow is the basic flow of neodymium, and it includes five stages: mining, fabrication, manufacturing, use, waste, and recycling. They are calculated to get the inflow of neodymium elements in each stage based on the production and neodymium content data of concentrate, primary products, intermediate products, and final products. These flows can be calculated according to Eq. (2) (Yao et al., 2021). Table S1 in the SI lists the neodymium content of the products in each stage.

$$F_{i,t}^{input} = \sum_t^i V_p^{production} \times C_p \times M_p \tag{2}$$

where $V_p^{production}$ represents the production of products; C_p is the neodymium content in products p (see SI Table S1 for the content); M_p represents the market penetration rate of products (SI Table S2). The adoption rate of products may change owing to technological advances in various applications.

(2) International trade flows indicate the imported and exported volumes of products. The trade volume of products is obtained by searching the General Administration of Customs based on the 8-digit trade code of each type of product (SI Table S3). The trade flow at each life cycle stage is obtained by multiplying the trade volume of products by the average content [Eqs. (3) and (4)] (Yao et al., 2021).

$$F_{i,t}^{import} = \sum_t^i V_p^{import} \times C_p \times M_p \tag{3}$$

$$F_{i,t}^{export} = \sum_{t}^{i} V_p^{export} \times C_p \times M_p \quad (4)$$

where V_p^{import} and V_p^{export} represent the imported and exported volume of products, respectively.

(3) Loss flows: loss flows are the losses incurred by the neodymium industry in refining & separation and manufacturing stages and are obtained by multiplying the product inflow and loss coefficients in each stage, which can be calculated according to Eq. (5) (Yao et al., 2021).

$$L_{i,t} = F_{i,t}^{input} \times R_{i,t}^{loss} \quad (5)$$

where $L_{i,t}$ represents the loss of the life stage i in year t. $R_{i,t}^{loss}$ is the loss rate of life the stage i in year t (SI Table S4).

(4) Supply and demand flows: flows at the refining and separation stage are calculated based on the supply of neodymium concentrates according to the top-down method. Flows at the product manufacturing stage and product use stage are calculated using the bottom-up method. When there is a mismatch between the supply of concentrates and the demand for them, this gap is considered to be caused by hibernating stock and illegal mining.

(5) In-use stocks: The in-use stock is the amount of minerals accumulated in the anthroposphere in the form of products in the manufacturing stage, quantified by summing the annual change in stock from the initial year (defined as 2001) to a given year. Stocks and the recycling potential of urban minerals can be calculated in accordance with Eqs. (6)-(8) (Yao et al., 2021).

$$S_{p,t_1} = S_{p,t_0} + \sum_{t=t_0}^{t_1} \left(F_{p,t}^{input} - F_{p,t}^{output}\right) \quad (6)$$

$$F_{p,t}^{output} = \sum_{m=1}^{lifetime} F_{p,t-m}^{input} \times \varphi(m) \quad (7)$$

$$S_{t_1} = \sum_{p=1}^{a} S_{p,t_1} \quad (8)$$

where S_{p,t_0} and $S_{p,t_1}$are the stocks in product p at the initial year t_0 and the given year t_1, respectively, assuming S_{p,t_0} = 0; $F_{p,t}^{input}$, $F_{p,t}^{output}$ are the inflow and outflow in the use stage, respectively; $\varphi(t)$ represent the probability that the product p will serve for m years, which can be estimated with a normal distribution or with a Weibull distribution (Lin et al., 2022); and S_{t_1} represents the total stock in use in a given year t_1, as a sum of the stocks for all final products in product group *p*.

The Weibull life distribution is a life probability distribution model widely used in reliability engineering that can describe the relationship between persistent stress and life (or failure cycle). Due to its advantageous handling of functional equations and high data fit, the Weibull life distribution model is used in this study to simulate the service life of final products. Its probability density function is shown in Eq. (9), and the Weibull distribution parameters of each final product are shown in SI Table S5 (Xiong, Zeng, et al., 2023).

$$\varphi(m) = \begin{cases} \frac{\beta}{\eta}\left(\frac{m}{\eta}\right)^{\beta-1} e^{-\left(m/\eta\right)^{\beta}}, & m \geq 0 \\ 0, & m < 0 \end{cases} \quad (9)$$

where β refers to the shape parameter, and η refers to the scale parameter.

2.5 Uncertainty Analysis

Dynamic SFA is heavily dependent on a substantial volume of data. Consequently, any limitations in the quality or quantity of data can lead to uncertainties in the analysis. An uncertainty analysis is essential to gauge the impact of parameter uncertainties on the results. Such uncertainties are assumed to follow a normal distribution with three coefficients of variation (CV), i.e., 2%, 5% and 10% (Xue et al., 2021).

Official statistics, such as the production of concentrates, products, imports, exports, are deemed more reliable and are associated with a CV of 2%. Data sourced from published papers, for instance, the neodymium content in products, are considered moderately reliable with a CV of 5%. Data gathered through assumptions or expert interviews is deemed a less rigorous source of data, so it is assigned a CV of 10%. Monte Carlo simulation was used to estimate the uncertainty of the demand and in-use stocks.

3. RESULTS

3.1 Characterization of Neodymium Flows from 2001 - 2021

Figure 2 shows the whole life cycle flow of neodymium in China from 2001-2021. Throughout this cycle, a total of 737 kt of neodymium transitioned from the lithosphere into the anthropogenic system. In the realm of domestic mining (excluding illegal practices), concentrate production commenced in 2001 at 13 kt and steadily increased each year, reaching its peak in 2006 at 20 kt (Figure 3a). However, China's neodymium production experienced a decline starting in 2009 (with 20 kt) and only began significant growth again in 2015 (reaching 14 kt).

During the period 2001-2021, China remained largely self-sufficient in neodymium production, with net imports accounting for a mere 78 kt. The Bayan Obo mine stood out as the primary source, contributing 60% of the overall neodymium supply. Over time, the neodymium supply from bastnaesite ores and Southern ionic clay ores each constituted 20% of the total supply. While bastnaesite ores maintained relative stability, the supply from Southern ionic clay ores has steadily decreased since 2011. Considering the current supply dynamics, China's future neodymium supply will heavily rely on Bayan Obo ores and bastnaesite ores. Despite annual mining quotas issued by the Chinese government, illegal mining has persisted due to the high demand for neodymium in downstream industries. Illegal mining activities between 2001 and 2021 amounted to 318 kt. Overall, the proportion of illegal mining accounts for almost half of the total amount mined, which has a serious negative impact on the local environment and the international rare earth market.

During the refining and separation phase, the concentrate is broken down into primary products. These include metallic and various compounds such as neodymium oxide, neodymium chloride, and neodymium fluoride. During the period 2001-2021, there was a loss flow of 74 kt, with an additional 21 kt of compounds becoming hibernating stock (Figure 2a).

In the fabrication phase, these primary products are transformed into intermediate products. From 2001 - 2021, approximately 465 kt of neodymium were converted into these intermediate products. The largest consumer of neodymium resources was NdFeB magnets, which accounted for 431 kt. This was followed by other alloys (15 kt), ceramics (9.1 kt), NiMH batteries (4.9 kt), glass (4.4 kt), and automotive catalysts (782 t). The distribution of neodymium among these intermediate products has varied over the years. For instance, the percentage of neodymium used in NdFeB magnets rose from 79% in 2001 to 90% in 2004 and has oscillated between 89% and 95%. This trend shows the rapid growth of China's NdFeB product industry over the past two decades. While the consumption of neodymium in other products also increased during the study period, these figures remained significantly lower than those of NdFeB products. The loss flow at this stage amounted to 151 kt.

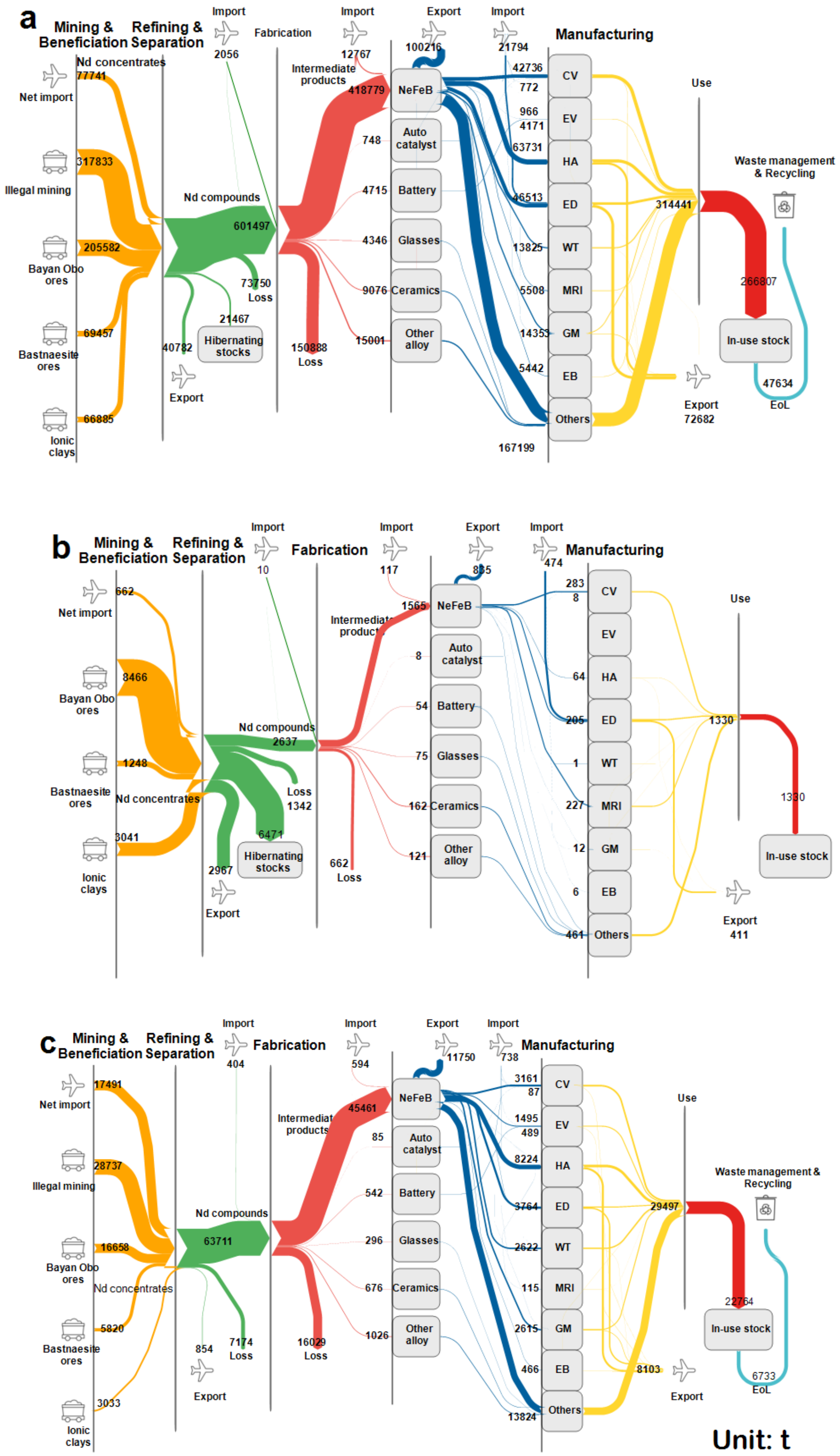


*Figure 2. China's Neodymium Flows. **a** cumulative flow from 2001 - 2021; **b** in 2001; **c** in 2021. Note: CV signifies conventional vehicles, EV signifies electric vehicles, HA signifies household appliances, ED signifies electronic devices,*

WT signifies wind turbines, MRI signifies magnetic resonance imaging machines, GM signifies general machinery, and EB signifies electric bicycles

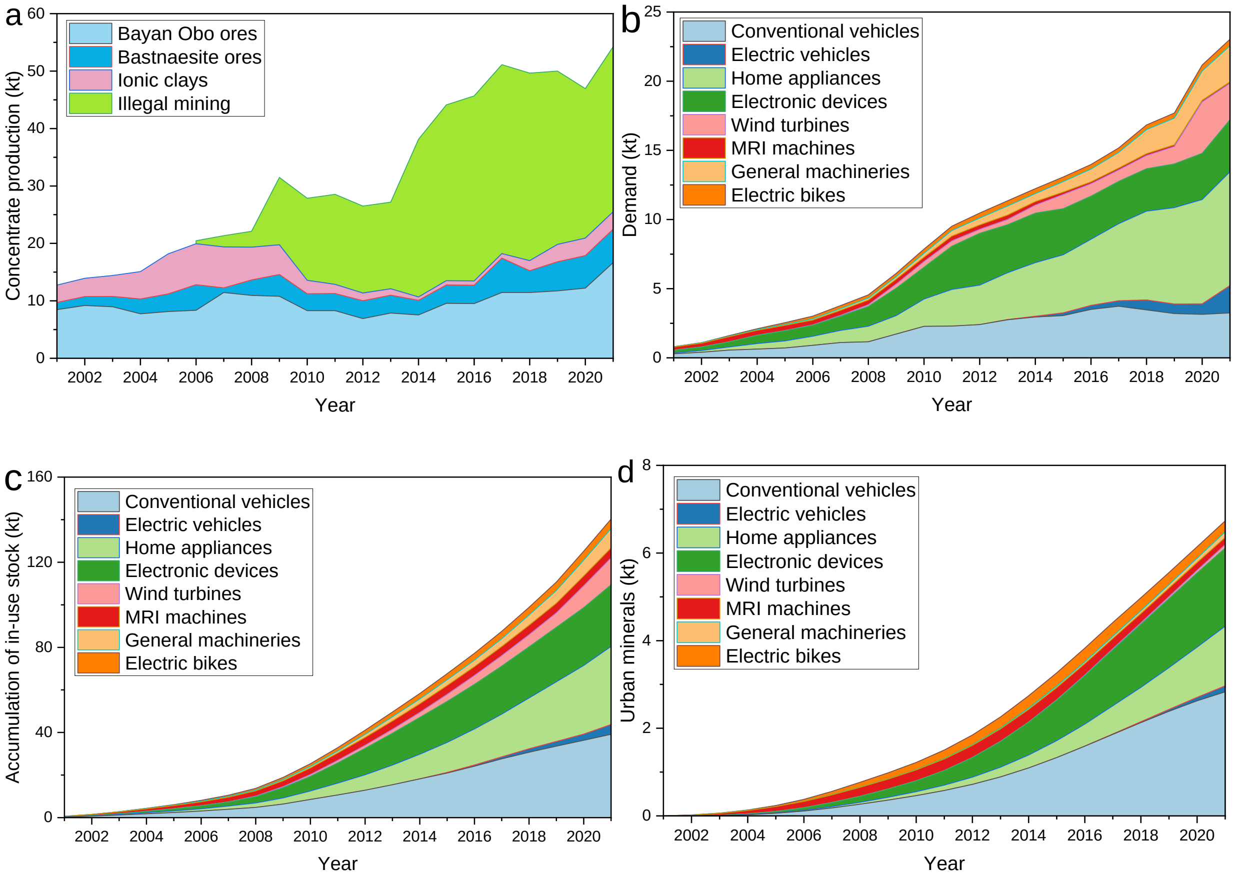


Figure 3. Flow of Neodymium During its Lifecycle. ***a*** *concentrate production;* ***b*** *demand;* ***c*** *accumulation of in-use stock;* ***d*** *urban minerals*

During the production process, approximately 387 kt of neodymium were transformed into the final products, with 73 kt being exported. The most widely used intermediate products were NdFeB magnets, followed by NiMH batteries and automotive catalysts. These can typically be found in vehicles, home appliances, electronic devices, and wind turbines.

Between 2001 and 2021, automobiles cumulatively consumed 5.1 kt of neodymium, with conventional vehicles accounting for 89% and electric vehicles for 11%. After a period of rapid growth, the conventional vehicle market began to stabilise. However, in the context of "carbon neutrality," electric vehicles are poised for significant developments, suggesting that neodymium will increasingly become a key component in new clean energy products. Home appliances use 64 kt of neodymium. The distribution of neodymium usage across five types of appliances: air conditioners, refrigerators, microwave ovens, washing machines, and vacuum cleaners was 47%, 20%, 15%, 14%, and 4%, respectively. Electronic devices utilised 65 kt of neodymium. The distribution of neodymium usage across five types of devices: loudspeakers, desktop computers, laptop computers, mobile phones, and CD/DVD players was 63%, 25%, 6%, 4%, and 2%, respectively. Due to technological advances, neodymium is being increasingly used in sophisticated applications of electronic devices. General machinery consumed 15 kt of neodymium, with elevators and industrial robots accounting for 96% and 4%, respectively. Despite the late start in using NdFeB magnets for industrial robots, their rapid development is a challenge to the supply of neodymium. Furthermore, wind turbines, MRI machines, and electric bicycles consumed 13.8 kt, 5.8 kt, and 5.4 kt of neodymium, respectively (Figure S1). With the International Renewable Energy Agency's (IRENA) encouragement for countries to actively promote the energy transition and support the development of clean energy technologies during the post-pandemic economic recovery, the supply of neodymium is increasingly becoming important in the wind turbine manufacturing industry (Figure 3b).

When products reach the end of their lifespan, they become urban mineral for waste management. According to this analysis, this amounted to a total of 48 kt of neodymium between 2001-2021. Despite this, the recycling rate of neodymium for these urban minerals has remained below 1% for the past two decades (Yao et al., 2021). This indicates that we haven't yet achieved a closed-loop lifecycle for neodymium. Of the neodymium present in urban minerals that entered waste management, only a tiny fraction was recycled and reused. Most of them ended up in landfills and incinerators or became hibernated stock in warehouse storage.

3.2 In-Use Neodymium Stocks and Potential of Urban Minerals

With the rapid development of China's economy and technology, the demand for finished products is increasing. This has led to an influx of products into the socio-economic system, resulting in large stocks. From 2001 - 2021, the in-use stock dramatically increased, from 0.628 kt in 2001 to 33 kt in 2011 and further to 140 kt in 2021(Figure 3c).

Conventional vehicles comprised the largest share of in-use neodymium stock. This can be attributed to the swift growth in vehicle ownership over the past two decades. The neodymium stock in conventional vehicles increased from 0.292 kt in 2001 to 39 kt in 2021. This suggests a vast potential for recycling once these vehicles are scrapped. As many of the vehicles from this vehicle-ownership boom in China will be reaching their end-of-life in the near future, it is even more imperative to develop efficient recycling systems to handle this new waste stream. Home appliances contributed the second-largest proportion of in-use neodymium stock. This is largely due to improved living standards and increased income, leading Chinese households to purchase more home appliances. In 2021, the in-use neodymium stock of air conditioners, washing machines, and refrigerators was the top three, reaching 20 kt, 6.7 kt, and 6.0 kt, respectively. Due to the superior magnetic performance, high coercivity, good stability, and excellent magnetic properties, NdFeB magnets have been widely used in the manufacturing of various electronic products. By 2021, the in-use neodymium stock of desktop computers, speakers, laptops, mobile phones, and CD/DVD players reached 14 kt, 11 kt, 2.3 kt, 0.812 kt, and 0.691 kt, respectively. This highlights the extensive application and importance of neodymium in daily life (Figure S2).

Figure 3d shows the recycling potential of urban minerals. The recycling potential has been steadily growing, reaching 6.7 kt by 2021 (Figure 3d). This represents an average annual growth rate of 16%. The recycling potential of vehicles increased from 0.579 kt in 2011 to 3.0 kt in 2021 (Figure S3). However, due to the late development of electric vehicles, they only made up about 1.5% of the total recycling potential. Household appliances have followed a similar upward trend as vehicles, increasing from 0.123 kt in 2011 to 1.4 kt in 2021 (Figure 3d). The recycling potential of air conditioners, refrigerators, vacuum cleaners, washing machines, and microwave ovens were 40 t, 27 t, 23 t, 16 t, and 16 t respectively in 2011, and these figures rose to 589 t, 375 t, 63 t, 219 t, and 113 t respectively in 2021 (Figure S3). The recycling potential of electronic devices increased from 0.334 kt in 2011 to 1.8 kt in 2021 (Figure 3d). The recycling potential of desktop computers, laptops, mobile phones, speakers, and CD/DVD players increased by five times, three times, five times, 18 times, and three times, respectively. The recycling potential of the remaining final products was relatively small, accounting for only 17% of the recovery potential.

3.3 Illegal Mining Issue of Neodymium

Over the last two decades, the neodymium supply has fluctuated, showing ups and downs. When we compare the production of concentrate with its usage in intermediate products, it is clear that there's a supply-demand imbalance (Figure 4a). From 2001 to 2005, the production of concentrate exceeded the manufacturing industry's demand. This led to the formation of a hibernating stock, which grew from 6.5 kt in 2001 to 7.8 kt in 2002, and fell to 1.0 kt in 2005 (Figure 4b). Starting from 2006, the official production of concentrate faced a shortage, and the supply was not sufficient to meet the demand of the manufacturing industry. This triggered illegal mining activities. Illegal mining refers to the unregulated and unauthorised extraction of minerals, often violating environmental laws and safety standards (Packey & Kingsnorth, 2016). Despite the Chinese government's efforts to regulate mining, illegal operations have continued to expand. In 2006, the volume of illegally mined was 525 t. This figure gradually increased to 15 kt in 2013, peaking in 2017 and then beginning to slow down, with the volume in 2021 estimated to be 28 kt (Figure 4b).

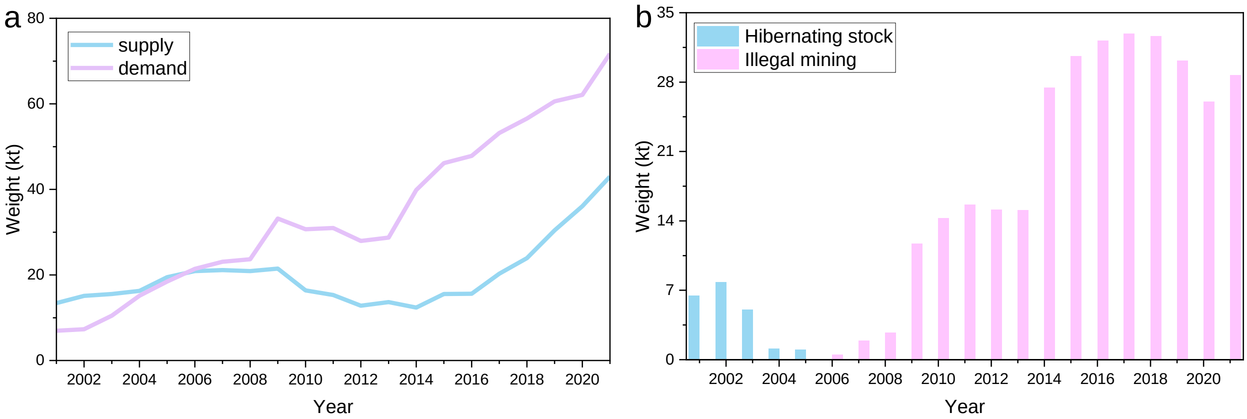


*Figure 4 Historical Evolution of Neodymium. **a** supply and demand, and price; **b** hibernating stocks and illegal mining*

The promulgation of the Rare Earth Management Regulations and the associated valuation and technical guidelines in 2024 marks a significant step in China's efforts to curb illegal rare earth mining. The new policies provide a legal framework for stricter enforcement, improved valuation of illegally extracted minerals, and enhanced accountability for resource destruction.

These developments offer valuable insights for global resource governance. First, strengthening regulatory mechanisms with clear valuation methodologies can improve enforcement efficiency and deterrence. Second, integrating environmental damage assessments into legal frameworks ensures that the ecological costs of illegal mining are adequately addressed. Lastly, international cooperation on rare earth supply chain transparency and sustainability standards can further mitigate illicit extraction and promote responsible resource utilisation. Future policy efforts should focus on refining enforcement strategies, leveraging technological advancements for real-time monitoring, and fostering international collaboration to combat illegal mining effectively.

3.4 International Neodymium Trade

Figure 5 traces the historical progression of China's neodymium trade volume from 2001 - 2021. In general, both imports and exports of neodymium in China have been on the incline. The import of concentrate surged from 0.662 kt in 2001 to 17 kt in 2021 (as shown in Figure 5a), with exports corresponding proportionally to only 0.4% of the imports in this time period. This indicates that China was a predominant importer of concentrate. Moreover, the export of primary products has consistently outpaced imports of primary products, with metals and oxides being the two main exported primary products. They contributed 70% and 29% of total primary product exports, respectively (refer to Figure 5b).

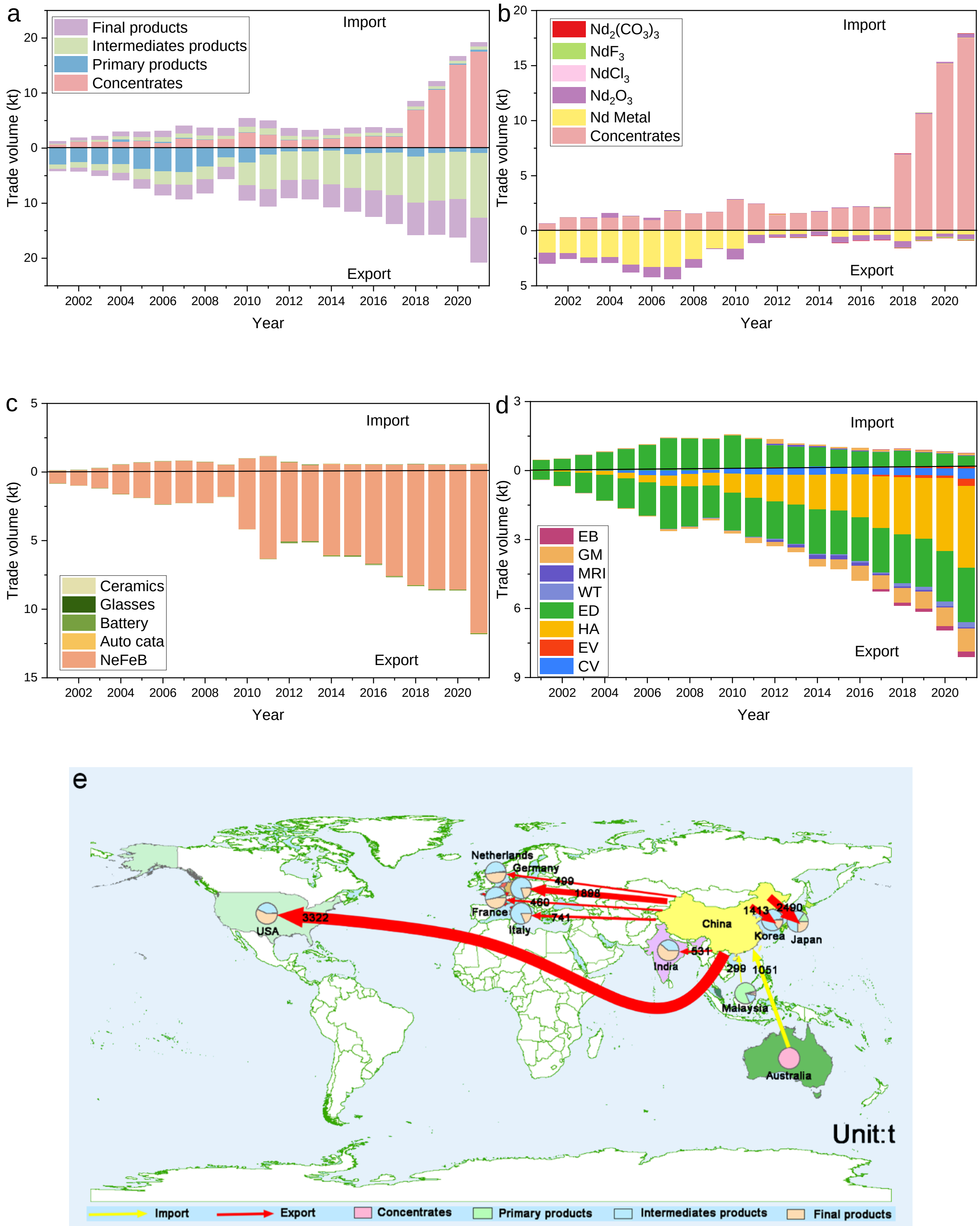


*Figure 5. Evolution of Products Trade Volumes and Trade Flows Between China and Its Major Trade Partners. **a** total trade volume; **b** trade in concentrates and primary products; **c** trade in intermediate products; **d** trade in final products; **e** trade flows in 2021. Note: CV signifies conventional vehicles, EV signifies electric vehicles, HA signifies household appliances, ED signifies electronic devices, WT signifies wind turbines, MRI signifies magnetic resonance imaging*

machines, GM signifies general machinery, and EB signifies electric bicycles. In addition, the pie charts show trade volume proportions of four neodymium-containing commodities

In terms of structure, intermediate products and final products constitute the majority of export products. Throughout the study period, China exported a total of 100 kt of intermediate products to cater to international market demand (see Figure 5c). Of these, NdFeB magnets were the most traded, making up 99% of the exported intermediate products. This was followed by NiMH batteries, which accounted for 0.7%, while other types made up a minor share of 0.3%. Owing to technological advancements and the role of upgrading in the international neodymium industry chain, the export volume of final products from China has been on the rise, increasing from 0.411 kt in 2001 to 8.1 kt in 2021 (as depicted in Figure 5d). Among these, both the export volume of final products, such as electric vehicles, household electrical appliances, and wind turbines, have been increasing. Conversely, the proportion of final products like electronic devices has been rapidly decreasing.

Figure S4 and Figure 5e illustrate the evolution of China's neodymium trade network in the years 2001, 2011, and 2021. The primary sources of China's concentrate and primary product importers were Australia and Malaysia, with Australia being the most significant contributor. The import volume of concentrate has substantially increased, rising from 148 t in 2001 to 737 t in 2011, and peaking at 1.1 kt in 2021.

When it comes to exports, China primarily sends primary products to Japan and the United States. In 2011, the export volumes to Japan and the United States were 1.6 kt and 0.335 kt, respectively. The trade of intermediate and final products involves a more diverse set of partners. China exports intermediate products to countries such as Japan, the United States, South Korea, India, and several European nations. In 2021, the export volumes of primary products to Germany, South Korea, and India were 1.5 kt, 1.1 kt, and 0.204 kt, respectively. The main export product in this category was NdFeB magnets. As for final products, the main destinations are the United States, Japan, and Germany. The export volumes in 2021 were 1.9 kt, 0.631 kt, and 0.390 kt, respectively. Many of these exports were household appliances and general machinery.

4. DISCUSSION AND IMPLICATIONS

4.1 Uncertainty Analysis

Figure S5 illustrates the results of the uncertainty analysis, including neodymium demand, in-use stocks, and urban minerals. The deviations of these parameters range from -2.2% to 2.6%, -9.7% to 9.1%, and -9.9% to 9.6%, respectively. Such results indicate that the uncertainty in these parameters has a marginal impact (within±10%) on the main conclusions, which means that our results are robust. We have explicitly noted, however, that just as primary production incurs material losses, recycling pathways also exhibit recovery inefficiencies. Quantifying these requires detailed, product-level recovery and loss coefficients, which lie beyond the scope of the present study.

4.2 Directions for Future Research

A deeper understanding of the diverse recycling pathways for NdFeB magnets—ranging from manual demagnetisation of consumer electronics components to high temperature treatment of wind turbine assemblies—will require application-specific life-cycle inventories and standardised protocols that capture real-world recovery efficiencies and material losses. Moreover, the temporal dynamics of in-use stock retirement must be quantified so that models can forecast when secondary supplies will begin to meaningfully offset primary production. Given the lag time for products to reach end-of-life, primary inputs will continue to play a critical role in meeting short- to medium-term magnet demand until urban mineral recovery rates and processing capacities can be substantially scaled up.

Future studies should therefore focus on assembling detailed, product-level recovery and loss coefficients, integrating these data into dynamic substance flow models to properly allocate both recovered and unrecovered neodymium fractions, and simulating supply-chain resilience under varying scenarios of recycling expansion, primary-mining regulation, and evolving trade policies(Liu et al., 2025). By linking improved empirical data with robust modelling frameworks, such work will enable policymakers and industry stakeholders to design balanced strategies that ensure material security, environmental stewardship, and socioeconomic stability throughout the value chain (Liu et al., 2024).

4.3 Implications

While enhanced urban minerals recovery can alleviate pressure on domestic mining, the lag time for in-use stocks to re-enter the waste stream means that primary neodymium inputs will remain essential in the near to medium term. Policymakers should therefore balance incentives for recycling against sustained support for regulated primary extraction to ensure uninterrupted magnet supply.

China’s 2024 Rare Earth Management Regulations now mandate thorough environmental impact assessments, ecological compensation funds, and restoration bonds, backed by third-party monitoring and enforced penalties. These measures embed ecological costs into the operational framework of both mining and separation activities, thus aligning legal liability with the “polluter pays” principle and actively safeguarding ecosystem integrity.

The shift toward urban mining creates jobs in collection, sorting, and processing facilities, yet may reduce employment in primary-mining regions. Anticipating these workforce shifts, governments should invest in retraining programs, offer incentives for recycling-sector expansion in former mining communities, and strengthen social safety nets to facilitate an equitable labour transition.

ACKNOWLEDGEMENTS

The work is financially supported by the National Natural Science Foundation of China (grant numbers 92462301) and the Postgraduate Research & Practice Innovation Program of Jiangsu Province (KYCX25_0345).

AUTHOR CONTRIBUTIONS

Xin Xiong: Methodology, Conceptualisation, Writing – original draft, Resources, Data curation.
Liang Zhao: Writing – review & editing, Resources, Methodology, Conceptualisation.
Guochang Xu: Methodology, Conceptualisation, Writing –review & editing, Resources, Data curation.
Xianlai Zeng: Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualisation.
Competing interests - The authors declare no competing interests.

DECLARATIONS

REFERENCES

Baidu (2024). China's rare earth position is stable, occupying an important share globally. Retrieved April 21 from https://baijiahao.baidu.com/s?id=1806983668036295197&wfr=spider&for=pc

Bernardes, M., Moraes, F. T. F., Tanaka, K. H., & Lima, R. D. (2024). Engaging the End User in Waste from Electrical and Electronic Equipment Management: An Action Research Study. Systemic Practice and Action Research, 37(1), 105-126.

Bhattarai, U., Maraseni, T., & Apan, A. (2022). Assay of renewable energy transition: A systematic literature review. Science of the Total Environment, 833, 155159.

Carl G., Steven B., Komal H. (2022). Pre-processing of e-waste in Canada: Case of a facility responding to changing material composition. Resources, Environment and Sustainability, 9, 100069.

Cho, N. H., Lee, S. J., Kang, Y. Y., Yoon, Y. S., & Jeon, T. W. (2024). Enhancement of recycling system for large WEEE plastics in Korea via material flow analysis (MFA) and hazardous substances assessment. Resources, Conservation & Recycling, 204, 107-481.

Claudio-Quiroga, G., Gil-Alana, L. A., & Maiza-Larrarte, A. (2023). Mineral prices persistence and the development of a new energy vehicle industry in China: A fractional integration approach. Resources Policy, 82, 103433.

Dong, C., Dong, X., Jiang, Q., Dong, K., & Liu, G. (2018). What is the probability of achieving the carbon dioxide emission targets of the Paris Agreement? Evidence from the top ten emitters. Science of the Total Environment, 622, 1294-1303.

Eheliyagoda, D., Ramanujan, D., Veluri, B., Liu, Q., & Liu, G. (2023). Tracing the multiregional evolution of the global dysprosium demand-supply chain. Resources, Conservation & Recycling, 199, 107245.

Eheliyagoda, D., Xiong, X., & Zeng, X. (2024). The Position of China in Neodymium Utilization: Trend and Challenges. ACS Sustainable Resource Management, 1(12), 2621-2629.

Fahmy, H. (2021). The rise in investors' awareness of climate risks after the Paris Agreement and the clean energy-oil-technology prices nexus. Energy Economics, 106, 105738.

Fang, G., Gao, Z., & Sun, C. (2023). How the new energy industry contributes to carbon reduction? — Evidence from China. Journal of Environmental Management, 329, 117066.

Geng, J., Hao, H., Sun, X., Xun, D., Liu, Z., & Zhao, F. (2021). Static material flow analysis of neodymium in China. Journal of Industrial Ecology, 25(1), 114-124.

Glöser, S., Soulier, M., & Espinoza, L. A. T. (2013). Dynamic Analysis of Global Copper Flows. Global Stocks, Postconsumer Material Flows, Recycling Indicators, and Uncertainty Evaluation. Environmental Science & Technology, 47(12), 6564-6572.

Guo, H., & Zhang, T. (2016). Sinks of steel in china–addition to in-use stock, export and loss. Frontiers of Environmental Science & Engineering, 10(1).

Hu, Z., Yu, B., Liu, L.-C., & Wei, Y.-M. (2024). Evaluating rare-earth constraints on wind power development under China's carbon-neutral target. Science of the Total Environment, 912, 168634.

Li, Y., Wang, Y., & Ge, J. (2023). Tracing the material flows of dysprosium in China from 2010 to 2020: An investigation of the partition characteristics of different rare earth mining areas. Resources Policy, 85, 103836.

Lin, M., Wu, Y., Qin, B., Cao, W., Liu, J., Xu, Z., & Ruan, J. (2022). Response to the Upcoming Emerging Waste: Necessity and Feasibility Analysis of Photovoltaic Waste Recovery in China. Environmental Science & Technology, 56(23), 17396-17409.

Liu, Q., Sun, K., Ouyang, X., Sen, B., Liu, L., Dai, T., & Liu, G. (2022). Tracking Three Decades of Global Neodymium Stocks and Flows with a Trade-Linked Multiregional Material Flow Analysis. Environmental Science & Technology, 56(16), 11807-11817.

Liu, W., Chen, L., Luo, F., Zhao, Y., Li, X., & Zeng, X. (2025). Novel assessment of China's cobalt supply chain resilience based on DPSIR model and machine learning. Resources, Conservation and Recycling, 215, 108107.

Liu, W., Li, X., Liu, C., Wang, M., & Liu, L. (2023). Resilience assessment of the cobalt supply chain in China under the impact of electric vehicles and geopolitical supply risks. Resources Policy, 80, 103183.

Liu, W., Li, X., Wang, J., Zhong, J., Wang, M., & Yang, J. (2024). Knowledge mapping of research on securing the supply chain for critical minerals: A scientometrics and text mining approach. Journal of Cleaner Production, 434, 140312.

Liu, X., Lu, X., Feng, Y., Zhang, L., & Yuan, Z. (2022). Recycled WEEE plastics in China: Generation trend and environmental impacts. Resources, Conservation and Recycling, 177, 105978.

Malin Zu. (2025). Material flow analysis and modelling of the feedstock potential for recycling polystyrene. Circular Economy, 4(1), 100127.

Packey, D. J., & Kingsnorth, D. (2016). The impact of unregulated ionic clay rare earth mining in China. Resources Policy, 48, 112-116.

Raza, S., Ghasali, E., Raza, M., Chen, C., & Li, B. (2023). Advances in technology and utilization of natural resources for achieving carbon neutrality and a sustainable solution to neutral environment. Environmental Research, 220, 115135.

Rostek, L., Espinoza, L. T., Goldmann, D., & Loibl, A. (2022). A dynamic material flow analysis of the global anthropogenic zinc cycle: Providing a quantitative basis for circularity discussions. Resources, Conservation and Recycling, 180, 106154.

Sherwood, J., Gongora, G. T., & Velenturf, A. (2022). A circular economy metric to determine sustainable resource use illustrated with neodymium for wind turbines. Journal of Cleaner Production, 376, 134305.

Song, X., Geng, Y., Zhang, Y., Zhang, X., Gao, Z., & Li, M. (2022). Dynamic potassium flows analysis in China for 2010–2019. Resources Policy, 78, 102803.

Su, C., Geng, Y., Zeng, X., Gao, Z., & Song, X. (2023). Uncovering the features of nickel flows in China. Resources, Conservation & Recycling, 188, 106702.

Vanegas, P. , Peeters, J. R. , Cattrysse, D. , Dewulf, W. , & Duflou, J. R. (2017). Improvement potential of today's weee recycling performance: the case of lcd tvs in belgium. Frontiers of Environmental Science & Engineering, 11(5), 15.

Xiao, S., Geng, Y., Pan, H., Gao, Z., & Yao, T. (2022). Uncovering the Key Features of Dysprosium Flows and Stocks in China. Environmental Science and Technology, 56(12), 8682-8690.

Xiong, X., Zeng, X., Zhang, Z., Pell, R., Matsubae, K., & Hu, Z. (2023). China’s recycling potential of large-scale public transport vehicles and its implications. Communications Engineering, 2(1), 56.

Xue, R., Yong, G., Xin, S., Han, H., & C, S. (2021). Dynamic material flow analysis of natural graphite in China for 2001-2018. Resources, Conservation and Recycling, 173.

Yao, T., Geng, Y., Sarkis, J., Xiao, S., & Gao, Z. (2021). Dynamic neodymium stocks and flows analysis in China. Resources Conservation and Recycling, 174(6), 105752.

Zhao, G. , Geng, Y. , Tang, C. , Hao, H. , Bleischwitz, R. , & Tian, X. (2022). Improving aluminium resource efficiency in china: based upon material flow analysis and entropy analysis. Circular Economy, 1(1), 100005.

Zheng, B., Zhang, Y. W., Geng, Y., Wei, W., Ge, Z., & Gao, Z. (2022). Investigating lanthanum flows and stocks in China: A dynamic material flow analysis. Journal of Cleaner Production, 368, 133204.

Zhu, E., Geng Y., Xiao, S., Guo, T., Gao, Z., Gao, Z. (2024). Mapping the evolution of manganese flows and stocks in China from 2000 to 2021, Resources, Environment and Sustainability, 16,100152.

SUPPLEMENTARY INFORMATION

CONTENTS

Table S1. Neodymium Content of Products

Products	Neodymium content		
	Min	Mean	Max
NdFeB magnets (%)	18.000	21.000	24.000
NiMH batteries (g/unit)	0.119	0.140	0.161
Other alloys (ppm)	0.765	0.900	1.035
Ceramic (ppm)	4.675	5.500	6.325
Glass (ppm)	5.525	6.500	7.475
Auto catalysts (g/unit)	2.295	2.7	3.105
Conventional vehicles (g/unit)	43.380	124.53	205.680
Electric vehicles (g/unit)	293.380	559.530	825.680
Wind turbines (kg/MW)	124.000	167.000	210.000
Mobile phones (g/unit)	0.050	0.125	0.200
Laptops (g/unit)	0.600	1.350	2.100
Desktop-PCs (g/unit)	2.950	3.850	3.850
CD/DVD players (g/unit)	0.417	0.490	0.564
Loudspeakers (g/unit)	0.300	0.800	1.400
Industrial robots (g/unit)	145.600	543.200	940.800
Elevators (g/unit)	1.479	1.740	2.001
Washing machines (g/unit)	28.000	42.000	56.000
Refrigerators (g/unit)	28.000	51.700	75.400
Vacuum cleaners (g/unit)	23.200	24.560	26.100
Microwave ovens (g/unit)	31.900	32.450	33.000
Air conditioners (g/unit)	28.000	51.500	75.000
MRI (kg/unit)	300.000	382.500	465.000
Electric bicycles (g/unit)	50.000	102.500	155.000

Note: Data sourced from (Geng et al., 2020)

Table S2. Market Penetration Rate of Neodymium-Containing Products

Year	Air Conditioner	Refrigerator	Washing Machines	Microwave Ovens	Vacuum Cleaners	Desktop Computers	Laptop Computers	Mobile Phones	Conventional Vehicles	Electric Vehicles	Wind Turbines	Electric Bikes	MRI Machines	Industrial Robots	Elevators	Loudspeakers	CD/DVD Players
2001	2%	2%	2%	2%	1%	100%	100%	100%	100%	0%	10%	10%	100%	0%	15%	100%	100%
2002	3%	3%	3%	3%	2%	100%	100%	100%	100%	0%	10%	10%	90%	0%	18%	100%	100%
2003	4%	4%	4%	4%	2%	100%	100%	100%	100%	0%	10%	10%	90%	0%	20%	100%	100%
2004	5%	5%	5%	5%	3%	100%	100%	100%	100%	0%	10%	10%	80%	0%	25%	100%	100%
2005	6%	6%	6%	6%	3%	100%	100%	100%	100%	0%	10%	10%	80%	0%	27%	100%	100%
2006	7%	7%	7%	7%	4%	100%	100%	100%	100%	0%	10%	10%	70%	0%	30%	100%	100%
2007	8%	8%	8%	8%	4%	100%	100%	100%	100%	0%	10%	10%	70%	0%	32%	100%	100%
2008	10%	9%	9%	10%	5%	100%	100%	100%	100%	100%	12%	10%	60%	0%	35%	100%	100%
2009	12%	10%	10%	12%	5%	100%	100%	100%	100%	100%	13%	10%	60%	0%	40%	100%	100%
2010	14%	12%	12%	14%	6%	100%	100%	100%	100%	100%	13%	10%	50%	0%	45%	100%	100%
2011	16%	14%	14%	16%	6%	100%	100%	100%	100%	100%	13%	10%	50%	0%	50%	100%	100%
2012	18%	16%	16%	18%	7%	100%	100%	100%	100%	100%	13%	10%	40%	100%	55%	100%	100%
2013	20%	18%	18%	20%	7%	100%	100%	100%	100%	100%	14%	10%	40%	100%	60%	100%	100%
2014	22%	20%	20%	22%	8%	100%	100%	100%	100%	100%	15%	10%	30%	100%	65%	100%	100%
2015	24%	22%	22%	24%	8%	100%	100%	100%	100%	100%	20%	10%	30%	100%	70%	100%	100%
2016	26%	24%	24%	26%	8%	100%	100%	100%	100%	100%	23%	10%	20%	100%	80%	100%	100%
2017	30%	25%	25%	30%	8%	100%	100%	100%	100%	100%	25%	10%	10%	100%	90%	100%	100%
2018	32%	26%	26%	32%	9%	100%	100%	100%	100%	100%	27%	10%	10%	100%	90%	100%	100%
2019	34%	27%	27%	34%	9%	100%	100%	100%	100%	100%	29%	10%	10%	100%	90%	100%	100%
2020	36%	28%	28%	36%	9%	100%	100%	100%	100%	100%	31%	10%	10%	100%	90%	100%	100%
2021	38%	29%	29%	38%	9%	100%	100%	100%	100%	100%	33%	10%	10%	100%	90%	100%	100%

Note: Data sourced from (Yao et al., 2021; Zheng et al., 2023)

Table S3. HS Code of Neodymium-Containing Products

Product Category	HS Code	Product Catalog	Unit
Concentrates	25309020	Rare earth metal ores	kg
	26122000	Thorium ores and concentrates	kg
	26151000	Zirconium ores and concentrates	kg
Primary Products	28469013	Neodymium oxide	kg
	28469024	Neodymium chloride	kg
	28469034	Neodymium fluoride	kg
	28469044	Neodymium carbonate	kg
	28053011	Neodymium, not mixed or fused	kg
Immediate Products	38151200	Reaction initiators, reaction accelerators and catalytic preparations, not elsewhere specified or included: Supported catalysts: With precious metal or precious metal compounds as the active	kg
	69041000	Ceramic building bricks	kg
	69049000	Ceramic flooring blocks, supports or filler tiles and the like (excluding building bricks)	kg
	70031100	Glass; cast glass and rolled glass, non-wired sheets, coloured throughout the mass (body tinted), opacified, flashed or having and absorbent or reflecting layer	kg
	70031200	Glass; cast glass and rolled glass, non-wired sheets, coloured through the mass (body tinted), opacified, flashed or having and absorbent, reflecting or non-reflecting layer	kg
	70031900	Glass; cast glass and rolled glass, non-wired sheets, (excluding those coloured throughout the mass (body tinted) opacified, flashed or having an absorbent or reflecting layer)	kg
	70032000	Glass; cast glass and rolled glass, wired sheets, whether or not having an absorbent or reflecting layer but not otherwise worked	kg
	70033000	Glass; cast glass and rolled glass, profiles, not otherwise worked	kg
	72029911	Rapidly solidified permanent magnets	kg
	72029912	NdFeB magnetic powders	kg
	72029919	Other NdFeB alloys	kg
	850511	Permanent magnets and articles intended to become permanent magnets after magnetisation of metal	kg
	85075000	Electric storage batteries, including separators therefor, whether or not rectangular (including square); parts thereof: (con.) Nickelmetal hydride	per unit

		batteries	
Manufacturing Products	84151010	Separate window or wall air conditioners	per unit
	84151021	Cooling ≤ 4000 kcal/hour window or wall air conditioners	per unit
	84151022	Cooling > 4000 kcal/hour window or wall air conditioners	per unit
	84182110	Compressed household refrigerators, capacity > 150L	per unit
	84182120	Compressed household refrigerators, capacity 50 L < capacity ≤ 150 L	per unit
	84182130	Compressed household refrigerators, capacity ≤ 50L	per unit
	84182200	Electric absorption household refrigerators	per unit
	84182910	Semiconductor household refrigerators	per unit
	84182990	Other household refrigerators	per unit
	84281000	Lifts and skip hoists; for lifting, handling, loading or unloading	per unit
	84282000	Elevators and conveyors; pneumatic, for lifting, handling, loading or unloading	per unit
	84283100	Elevators and conveyors; continuous-action, specially designed for underground use, for goods and materials, n.e.s. in heading no. 2428	per unit
	84283200	Elevators and conveyors; continuous-action, for goods or materials, bucket type, n.e.c. in item no. 8428.20 or 8428.31	per unit
	84283300	Elevators and conveyors; continuous-action, for goods or materials, belt type, n.e.c. in item no. 8428.20 or 8428.31	per unit
	84283900	Elevators and conveyors; continuous-action, for goods or materials, n.e.c. in item no. 8428.20, 8428.31, 8428.32 or 8428.33	per unit
	84284000	Escalators and moving walkways	per unit
	84501110	Wave wheel type automatic washing machines, dry weight ≤ 10kg	per unit
	84501120	Drum type automatic washing machines, dry weight ≤ 10kg	per unit
	84501190	Other fully automatic washing machines, dry weight ≤ 10kg	per unit
	84501200	Other washing machines with centrifugal dryer, dry weight ≤ 10kg	per unit
	84501900	Other washing machines, dry weight ≤ 10kg	per unit
	84502000	Washing machines, dry weight > 10 kg	per unit
	84502011	Fully automatic wave wheel washing machines,	per unit

		dry weight > 10kg	
	84502012	Fully automatic drum washing machines, dry weight > 10kg	per unit
	84502019	Other fully automatic washing machines, dry weight > 10kg	per unit
	84502090	Other washing machines, dry weight > 10kg	per unit
	84713000	Portable digital automatic data processing equipment with weight ≤ 10kg	per unit
	84714140	Other micro digital automatic data processors	per unit
	85023100	Wind turbines	KW
	85081100	Vacuum cleaners; parts thereof: With self-contained electric motor: Of a power not exceeding 1,500 W and having a dust bag or other receptacle capacity not exceeding 20 l	per unit
	85081900	Vacuum cleaners; parts thereof: With self-contained electric motor: Other	per unit
	85165000	Other electrothermic appliances of a kind used for domestic purposes; parts thereof: Microwave ovens	per unit
	85182100	Single speakers	per unit
	85182200	Multiple speakers	per unit
	85182900	Other speakers	per unit
	85198100	Sound recording or reproducing apparatus; using magnetic, optical or semiconductor media	per unit
	85219000	Video recording or reproducing apparatus other than magnetic tape-type	per unit
	84289000	Lifting, handling, loading or unloading machinery; n.e.c. in heading no. 8425, 8426, 8427 or 8428	per unit
	87032130	Gasoline cars, displacement ≤ 1000ml	per unit
	87032150	Gasoline passenger cars, displacement ≤ 1000ml	per unit
	87032190	Other gasoline passenger cars, displacement ≤ 1000ml	per unit
	87032230	Gasoline cars, 1000ml < displacement ≤ 1500ml	per unit
	87032240	Gasoline SUVs (4-wheel drive) 1000ml < displacement ≤ 1500m	per unit
	87032250	Gasoline passenger cars, 1000ml displacement < 1500ml	per unit
	87032290	Other gasoline passenger cars, 1000 < displacement ≤ 1500ml	per unit
	87032341	Gasoline cars, 1500ml < displacement ≤ 2000ml	per unit
	87032342	Gasoline SUVs (4-wheel drive) 1500ml < displacement ≤ 2000ml	per unit
	87032343	Gasoline passenger cars, 1500ml < displacement ≤	per unit

		2000ml	
	87032349	Other gasoline passenger cars, 1500 < displacement ≤ 2000ml	per unit
	87032351	Gasoline cars, 2000ml < displacement ≤ 2500ml	per unit
	87032352	Gasoline SUVs (4-wheel drive) 2000 < displacement ≤ 2500ml	per unit
	87032353	Gasoline passenger cars, 2000ml < displacement ≤ 2500ml	per unit
	87032359	Other gasoline passenger cars, 2000 < displacement ≤ 2500ml	per unit
	87032361	Gasoline cars, 2500ml < displacement ≤ 3000ml	per unit
	87032362	Gasoline SUVs (4-wheel drive) 2500 < displacement < 3000ml	per unit
	87032363	Gasoline passenger cars, 2500ml < displacement ≤ 3000ml	per unit
	87032369	Other gasoline passenger cars, 2500 < displacement ≤ 3000ml	per unit
	87032411	Gasoline cars, 3000ml < displacement ≤ 4000ml	per unit
	87032412	Gasoline SUVs (4-wheel drive) 3000 < displacement ≤ 4000ml	per unit
	87032413	Gasoline passenger cars, 3000ml < displacement ≤ 4000ml	per unit
	87032421	Gasoline cars, displacement > 4000ml	per unit
	87032422	Gasoline SUVs, displacement > 4000ml	per unit
	87032423	Gasoline passenger cars, displacement > 4000ml	per unit
	87032429	Other gasoline passenger cars, displacement > 4000ml	per unit
	87033111	Diesel cars, displacement ≤ 1000ml	per unit
	87033121	Diesel cars, 1000ml displacement ≤ 1500ml	per unit
	87033123	Diesel passenger cars, 1000ml < displacement ≤ 1000ml	per unit
	87033211	Diesel cars, 1500ml < displacement ≤ 2000ml	per unit
	87033212	Diesel SUVs, 1500ml < displacement ≤ 2000ml	per unit
	87033213	Diesel passenger cars, 1500ml < displacement ≤ 2000ml	per unit
	87033221	Diesel cars, 2000ml < displacement ≤ 2500ml	per unit
	87033222	Diesel SUVs, 2000ml < displacement ≤ 2500ml	per unit
	87033223	Diesel passenger cars, 2000ml < displacement ≤ 2500ml	per unit
	87033229	Other diesel passenger cars, 2000 < displacement ≤ 2500ml	per unit
	87033311	Diesel cars, 2500ml < displacement ≤ 3000ml	per unit
	87033312	Diesel SUVs, 2500ml < displacement ≤ 3000ml	per unit

	87033313	Diesel passenger cars, 2500ml < displacement ≤ 3000ml	per unit
	87033319	Other diesel passenger cars, 2500 < displacement ≤ 3000ml	per unit
	87033321	Diesel cars, 3000ml < displacement ≤ 4000ml	per unit
	87033322	Diesel SUVs, 3000ml < displacement ≤ 4000ml	per unit
	87033323	Diesel passenger cars, 3000ml < displacement ≤ 4000ml	per unit
	87033361	Diesel cars, displacement > 4000ml	per unit
	87033362	Diesel SUVs, displacement > 4000ml	per unit
	87033363	Diesel passenger cars, displacement > 4000ml	per unit
	87033369	Other diesel cars, displacement > 4000ml	per unit
	87039000	Unlisted passenger vehicles	per unit
	87042100	Other diesel trucks, gross vehicle weight ≤ 5 tons	per unit
	87042230	Other diesel trucks, 5 tons < gross vehicle weight < 14 tons	per unit
	87042240	Other diesel trucks, 14 tons ≤ gross vehicle weight ≤ 20 tons	per unit
	87042300	Other diesel trucks with gross vehicle weight > 20 tons	per unit
	87043100	Other gasoline trucks, gross vehicle weight ≤ 65 tons	per unit
	87043230	Other gasoline trucks, 5 tons < gross vehicle weight ≤ 8 tons	per unit
	87043240	Other gasoline trucks, gross vehicle weight > 8 tons	per unit
	87049000	Unlisted freight motor vehicles	per unit
	87119010	Electric motorcycles and electric bicycles	per unit
	90181300	Nuclear magnetic resonance imaging devices	per unit

Note: Data sourced from Yao et al. (2021))

Table S4. List of Loss Rates

Process	Loss rate	Data source
Refining and separation	10%	(Zheng et al., 2023)
Fabrication	25%	(Wang et al., 2020)

Table S5. Parameters of Weibull lifespan Distribution for Neodymium-Containing Products

Neodymium-containing products	η (scale)	β (shape)
Air Conditioner	14.3	2.2
Refrigerator	11.3	2.8
Elevators	31.5	1.46
Industrial Robots	12.7	2.45
Washing Machines	13.3	2.8
Laptop Computers	8.4	2.2
Desktop Computers	7.4	2.6
Wind Turbines	20	3.5
Vacuum Cleaners	10.3	1.5
Microwave Ovens	14.7	0.8
Mobile Phones	3.4	2.3
Loudspeakers	15.6	3.3
CD/DVD Players	10	2.1
MRI Machines	7.6	1.4
Conventional Vehicles	8	3
Electric Vehicles	8	3.5
Electric Bikes	4	1.38

Note: Data sourced from Zheng et al. (2023)

Table S6. Data Sources of Neodymium-Containing Products

Data	Sources
Production of concentrates	(CSRE, 2010-2019; MNR, 2020-2021)
Production of primary products	Calculation based on Mass Balance Law
Production of NdFeB	(Chen et al., 2016; CREIA, 2015-2021)
Production of NiMH batteries	(Yao et al., 2021)
Production of glasses	(Yao et al., 2021)
Production of ceramics	(Yao et al., 2021)
Production of other alloys	(Yao et al., 2021)
Production of conventional vehicles	(CISY, 2001-2022)
Production of electric vehicles	(CISY, 2001-2022)
Production of air conditioners	(CISY, 2001-2022)
Production of refrigerators	(CISY, 2001-2022)
Production of washing machines	(CISY, 2001-2022)
Production of microwave ovens	(CISY, 2001-2022)
Production of vacuum cleaners	(CISY, 2001-2022)
Production of wind turbines	(CWEA, 2018)
Production of electric bicycles	(CISY, 2001-2022)
Production of desktop computers	(CISY, 2001-2022)
Production of laptop computers	(CISY, 2001-2022)
Production of mobile phones	(CISY, 2001-2022)
Production of loudspeakers	(CISY, 2001-2022)
Production of MRI machines	(Yao et al., 2021)
Production of CD/DVD players	(CISY, 2001-2022)
Production of elevators	(Yao et al., 2021)
Production of industrial robots	(CISY, 2001-2022; Yao et al., 2021)
Trade volume	(CC, 2015-2021; SCDRC, 2001-2014)
Hibernating stock	The difference between the apparent production of neodymium concentrates and the consumption of neodymium compounds.
Illegal mining	The difference of apparent production of neodymium concentrates and consumption of neodymium compounds.

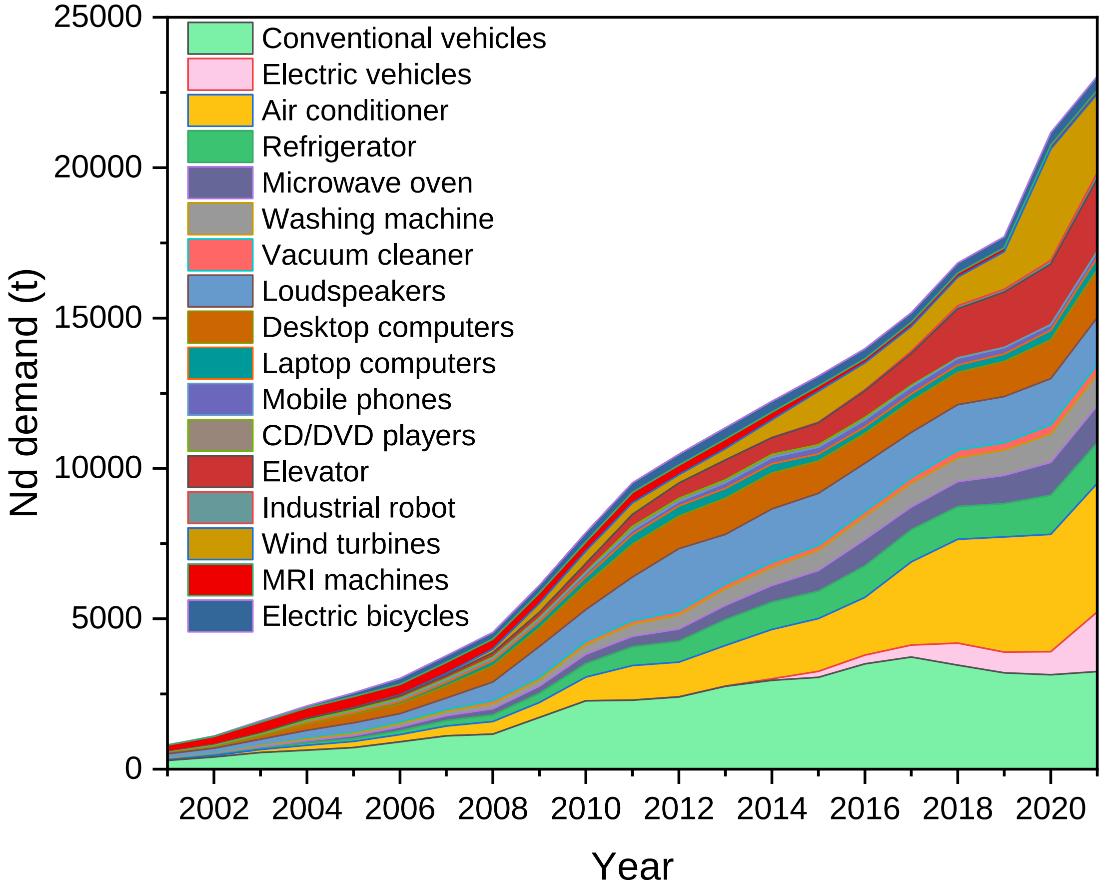


Figure S1. Demand for Neodymium in Various Neodymium-Containing Products

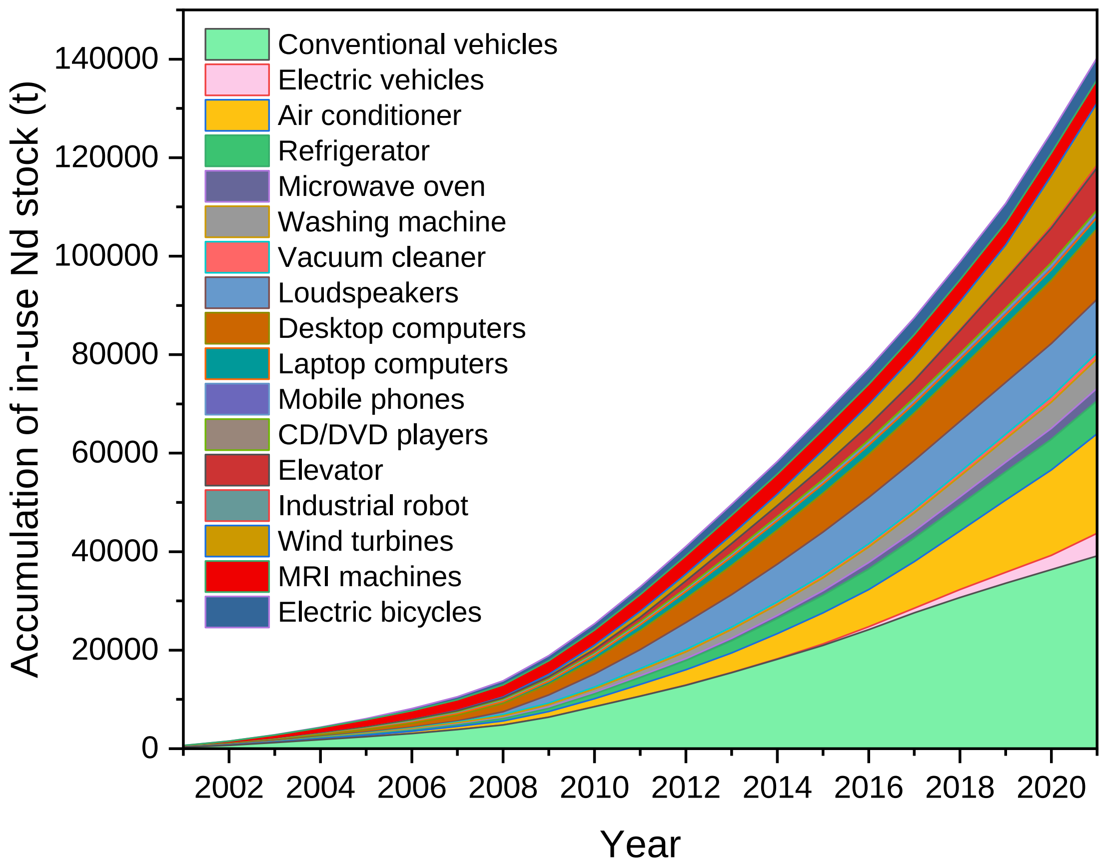


Figure S2. Accumulation of In-Use Neodymium Stock in Various Neodymium-Containing Products

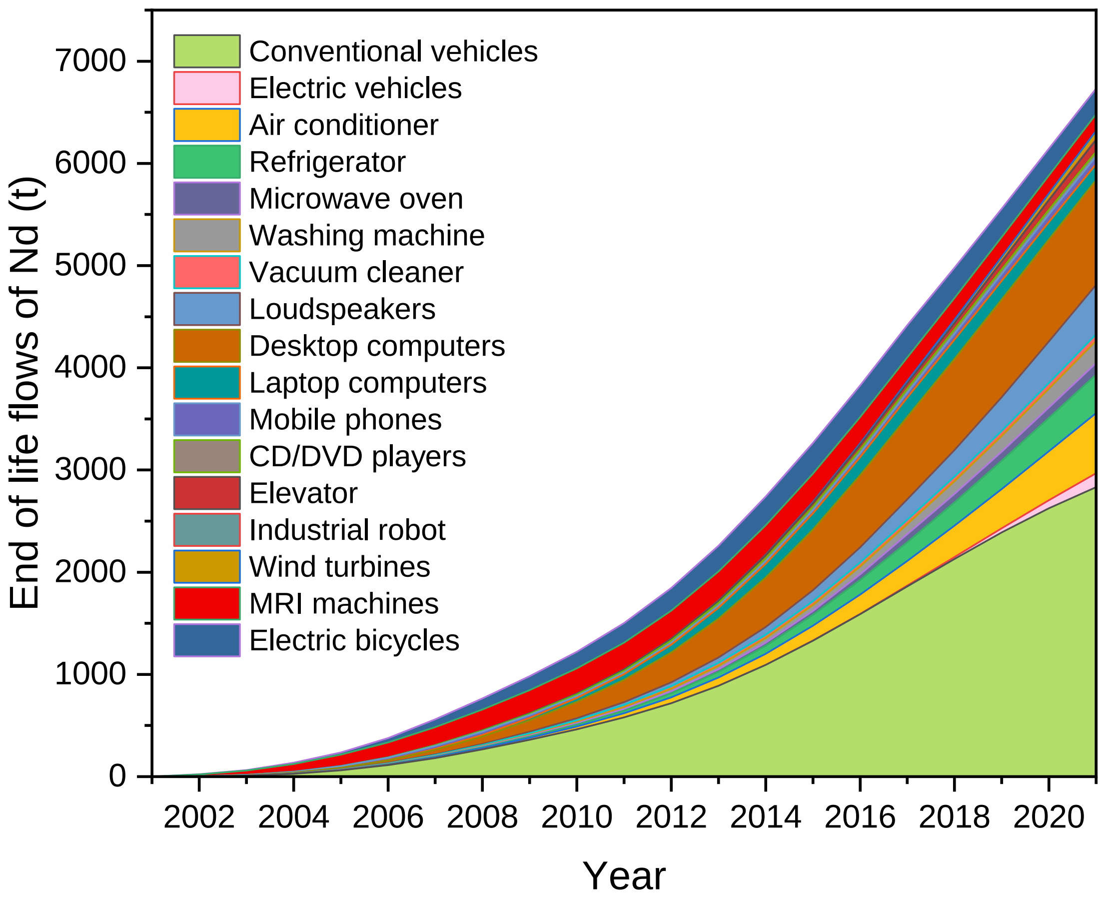


Figure S3. End-of-life flows of Neodymium in Various Neodymium-Containing Products

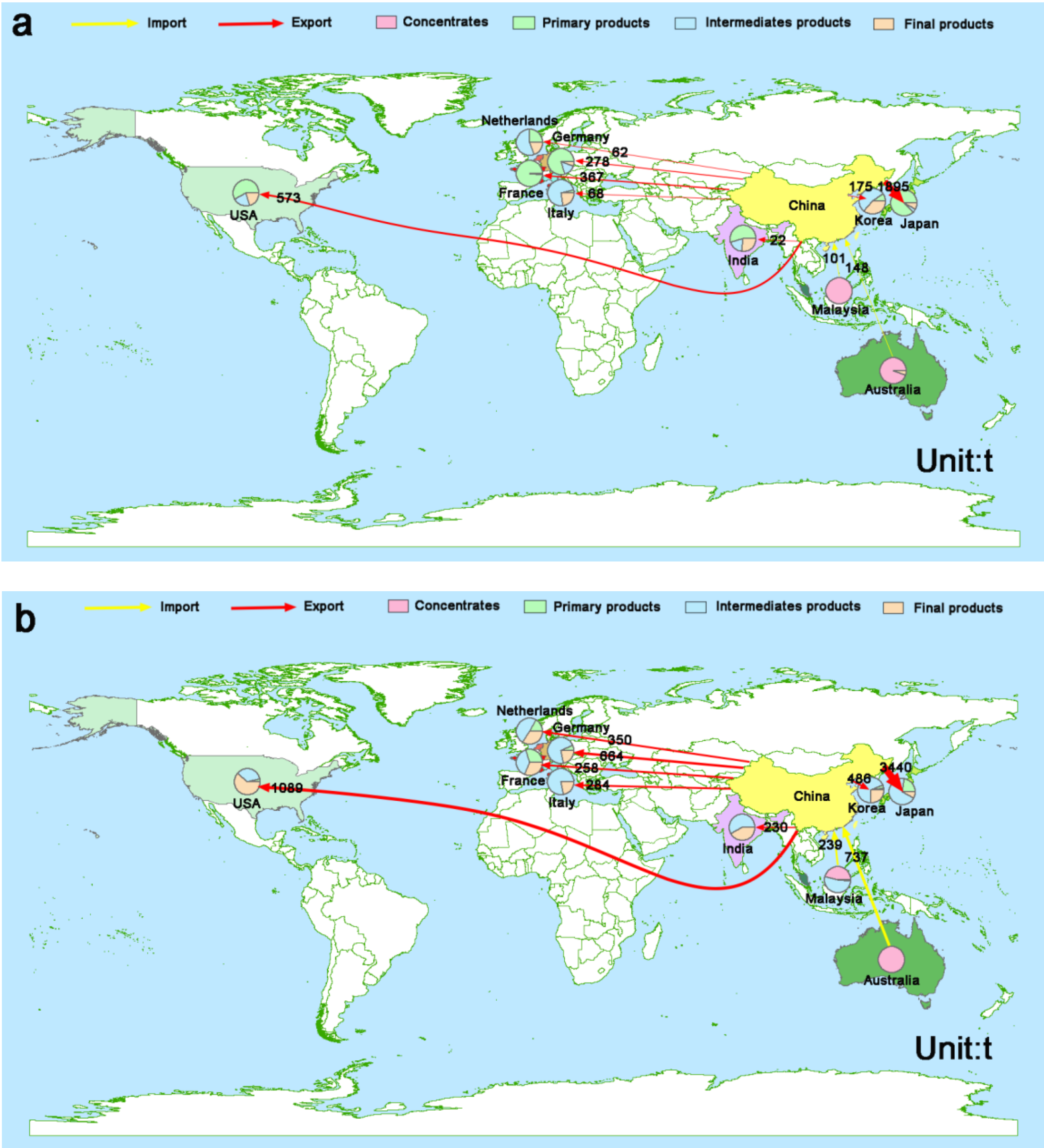
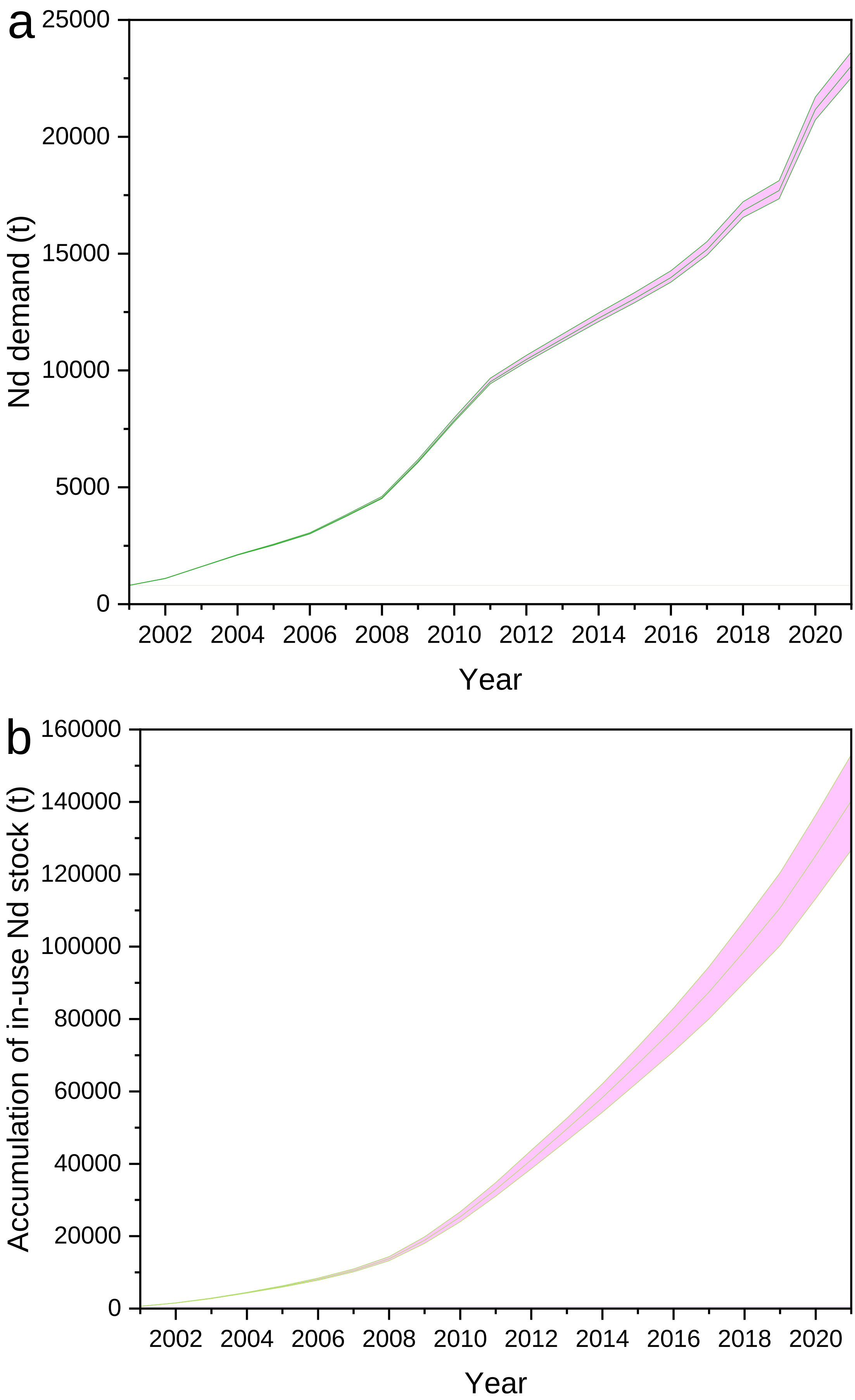


Figure S4. Neodymium Trade Flows Between China and Its Major Neodymium Trade Partners in 2001 a and 2011 b

Note: The pie charts show trade volume proportions of four neodymium-containing commodities.


a
b
Nd demand (t)
Accumulation of in-use Nd stock (t)
Year
25000
20000
15000
10000
5000
0
160000
140000
120000
100000
80000
60000
40000
20000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020

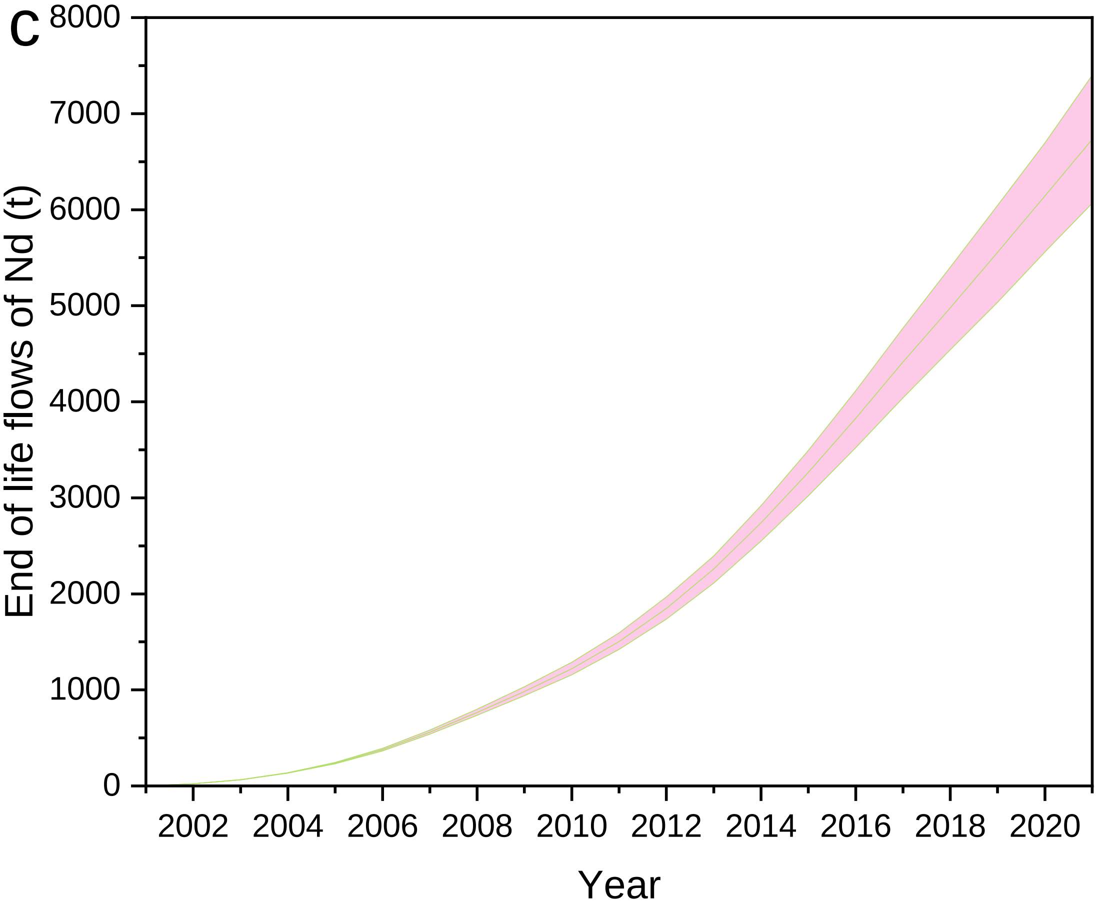


Figure S5. Uncertainty Analysis of (a) Demand, (b) in-Use Stock, and (c) End-of-Life Flows of Neodymium from 2001-2021

REFERENCES

CC. (2015-2021). *China Customs*. http://stats.customs.gov.cn/

Chen, Z., Ye, S., & Xu, P. (2016). Analysis and prospect of rare earth market since 2010. *Rare earth information*, *06*, 10-15.

CISY. (2001-2022). China Industrial Statistical Yearbook.

CREIA. (2015-2021). *China Rare Earth Industry Association:Rare earth industry operation report*.

CSRE. (2010-2019). *China Society Rare Earth yearbook*.

CWEA. (2018). *China Wind Energy Association : China Wind Power Map 2018*. http://www.cwea.org.cn/industry_data_2018.html

Geng, J., Hao, H., Sun, X., Xun, D., Liu, Z., & Zhao, F. (2020). Static material flow analysis of neodymium in China. *Journal of Industrial Ecology*.

MNR. (2020-2021). *Ministry of Natural Resources : Indicators for the total amount of rare earth ore tungsten mining control*. http://gi.mnr.gov.cn/202109/t20210930_2683341.html

SCDRC. (2001-2014). *State Council Development Research Center Information Network*. http://www.drcnet.com.cn/www/int/#

Wang, Q. C., Wang, P., Qiu, Y., Dai, T., & Chen, W. Q. (2020). Byproduct Surplus: Lighting the Depreciative Europium in China's Rare Earth Boom. *Environmental Science & Technology*(22), 54.

Yao, T., Geng, Y., Sarkis, J., Xiao, S., & Gao, Z. (2021). Dynamic neodymium stocks and flows analysis in China. *Resources Conservation and Recycling*, *174*(6), 105752. https://doi.org/10.1016/j.resconrec.2021.105752

Zheng, B., Zhang, Y. W., Geng, Y., Wei, W., Tan, X., Xiao, S., & Gao, Z. (2023). Measuring the anthropogenic cycles of light rare earths in China : Implications for the imbalance problem. *Science of the Total Environment*, *879*, 163215.