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

Dynamic Stock and Flow Analysis of Neodymium in China: 2000-2050

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Abstract

Neodymium is widely used for magnetic materials in electronic devices, electric vehicles and home appliances. Increased neodymium demand and a lack of an established recycling system in China has resulted in supply pressures and lower resource efficiency. Even though neodymium importance has increased, few studies have focused on neodymium resource utilization within China—a major source of this resource. This study traces and forecasts neodymium flows and stocks in China using dynamic material flow analysis from a life cycle perspective. The results show China's demand for neodymium at the use stage has increased over 2000 percent over the past 18 years. By contrast, the production of neodymium has only doubled—indicating existence of illegal mining to meet the increasing neodymium demand. Additionally, the total neodymium net exports have continuously decreased due to shrinking export of primary products and immediate products. Smuggling of primary products remains an issue and needs addressing. Wind turbines and electric vehicles are envisioned to become major neodymium consumption sectors greatly increasing future demand requirements. To

avoid insufficient recycling and excessive mining of neodymium, reasonable production quotas should be established to maintain a supply and demand balance.

Key Words: Neodymium; Dynamic MFA; Stock and flow; Resources demand forecast; Supply risk; Governance

1. Introduction

There are 17 different rare earth elements (REEs). These elements can be categorized into three clusters—lanthanides, scandium, and yttrium. Their unique physical and chemical properties make REEs vital to clean energy technologies and high-performance materials (Ayres and Peiro, 2013; Zhang et al., 2017). Neodymium—a light rare earth elements (LREE)—is an essential material for green technology development (Morimoto et al., 2019). It is listed as a strategic mineral resource by the Ministry of Natural Resources of People's Republic of China during the 13th five-year plan (2016-2020) (Ministry of Natural Resources, 2016).

Neodymium naturally occurs in bastnaesite, monazite and ion-adsorption clays (IACs) in Inner Mongolia, Sichuan, and several southern provinces with concentrations varying from 10% to 30% (Chen et al., 2018; Chen, 2011). Its strong magnetism and high coercivity make neodymium and its compounds useful in various emerging technological fields. Neodymium–iron–boron (NdFeB) permanent magnets are an example critical component of electric vehicles and wind turbines (Ciacci et al., 2019; Sekine et al., 2017). Recent environmental policies have caused greater demand for these products. For example, China's State Council proposed accelerating green and low-carbon development to ensure that the country meets carbon peak and carbon neutrality goals (Council, 2021). This policy and other similar global policies and economic shifts, indicate neodymium demand is likely to increase due to green and low-carbon goals across industries. Neodymium is also widely used in electronic devices, home appliances, electric vehicles and other applications (Habib et al., 2014; Nansai et al., 2015).

China is the largest global neodymium supplier and exporter—dominating the neodymium industrial chain (Du and Graedel, 2013; Geng et al., 2020). The global neodymium reserve is estimated to be 11.6 million tons (Mt)—a 13.6 Mt of neodymium oxide equivalent (USGS, 2020). China owns 2.9 Mt of neodymium, accounting for 23% of global reserves, but responsible for over 60% of global production over the past few decades (CSRE yearbook, 2018). China's expanding demand from various industrial sectors has led to a 50% increase of neodymium mining since 2000, approximately reaching 20,000 tons in 2019 (Ministry of Natural Resources, 2019; USGS, 2020). China's limited refining and separation capacity meant more than 2,000 tons of neodymium is annually exported to other countries in the form of metal and oxide. This result means that neodymium global consumption outside of China depends on raw material imports from China (China Customs, 2019).

Although the Ministry of Industry and Information Technology (MIIT) and the Ministry of Natural Resources (MNR) within China jointly issue annual production quotas of rare earth ores, illegal mining activities exist and are difficult entirely eliminate (Liu, 2016; Tse, 2011). Surging extraction and long-term oversupply have caused the sharp decline of neodymium reserves over the past few decades. There are also significant local ecosystem environmental pressures where mining occurs (Liu, 2016; Werker et al., 2019).

Widely dispersed use of neodymium as led to anemic neodymium recycling rates at less than 1%. The result is that neodymium-containing products represent a significant resource to alleviate increasing future demand requirements (Binnemans et al., 2013; Ciacci et al., 2015; Jowitt et al., 2018).

A lack of control and unknown neodymium flow patterns have contributed to neodymium loss, value deviation, and inefficient use in China (State Council, 2012). Additionally, neodymium's importance to development of high-tech and renewable energy products is not fully reflected and appreciated in policy setting. Therefore, understanding the potential impact of neodymium supply, consumption, and flows from a life cycle perspective is critical for sustainable social and economic development policy and management.

Numerous studies investigating various aspects of neodymium exist. These studies include: accounting of in-use stock (Du and Graedel, 2011c; Du and Graedel, 2013); assessing recycling potential (Peiro et al., 2013; Sprecher et al., 2014); tracing embodied rare earth flows within and across industrial sectors (Wang et al., 2017; Wang et al., 2019); evaluating processing and manufacturing environmental impacts (Lee and Wen, 2018); quantifying neodymium product content (Xu et al., 2016); and neodymium demand forecasting under different scenarios (Nassar et al., 2016; Pavel et al., 2017). These studies represent data sources and foundational information for this study.

Most of these studies may be classified as retrospective analysis and prospective forecasts. For retrospective analysis of neodymium flow, material flow analysis (MFA) is used to aid policy makers, researchers, and industrial stakeholders gain valuable insights to address resource scarcity concerns (Hao et al., 2017). In this regard, Du and Graedel (2011a, 2011b) developed a global neodymium flow model to estimate in-use stock of neodymium and NdFeB magnets. They highlighted the importance of efficient neodymium-related product recycling. Several other studies investigated flows of neodymium and NdFeB magnets at national and regional levels from a full life cycle and neodymium industrial chain based on static and dynamic MFA methods (Habib et al., 2014; Sekine et al., 2017). Guyonnet et al. (2015) and Ciacci et al. (2019) explored neodymium flows and stocks in Europe and found strong imbalances within the neodymium value chain. Swain et al. (2015) evaluated the Korean domestic neodymium consumption structure and recognized the necessity to establish a neodymium recycling and management system. Chen et al. (2018) and Geng et al. (2020) account for neodymium flows in China using static MFA. However, no studies focus on the dynamic evolution of neodymium supply and demand in China.

Neodymium prospective projection studies focus on future demand for renewable energy equipment, electric vehicles, and the energy-metal nexus (Grandell et al., 2016; Månberger and Stenqvist, 2018; Tokimatsu et al., 2018; Valero et al., 2018). Various models incorporate multiple scenarios for demand prediction (Imholte et al., 2018; Moreau et al., 2019; Shammugam et al., 2019; Watari et al., 2020). Alonso et al. (2012) predict demand for neodymium in wind turbines and new energy vehicles using exponential growth models. Elshkaki and Graedel (2013) predicted wind power industry neodymium demand using International Energy Agency (IEA) scenarios. Roelich et al. (2014) estimated neodymium demand for wind turbines and new energy vehicle using the IEA clean energy roadmap 2050 scenarios. Li et al. (2019) estimated the electric vehicle sector neodymium demand Using the Bass diffusion model for different automobile electrification technology pathways in China.

Stock-driven approaches can also support neodymium demand forecasts. Elshkaki and Shen (2019) combined dynamic flows and a stock model with seven energy scenarios to determine potential neodymium demand given a renewable energy transition. Watari et al. (2019) applied a dynamic stock and flow model to assess neodymium demand in transport and electricity sectors. Deetman et al. (2018) integrated a stock dynamic model and shared socioeconomic pathway scenarios to estimate the neodymium demand. Harvey (2018) used a stock-turnover model to forecast the electric vehicle neodymium demand under different GDP growth scenarios using the IEA's long-term plan. Fishman et al. (2018) applied a material stock and flow approach and a logistic consumption model to predict neodymium supply and demand from new energy vehicles in the United States. Li et al. (2020) evaluated the neodymium supply risks in ten different regions under different wind power development scenarios using a stock-driven method.

Given that neodymium is used in both clean energy technologies (electric vehicles and wind turbines) and commercial durables (home appliances, traditional vehicles, and electronic devices) with different development trends—a policy-driven approach using specific product growth rates should be combined with a stock-driven approach—e.g. using the Gompertz function. This integration can more accurately forecast future neodymium demand.

Applying a stock saturation model with a Gompertz function can help determine future inflows by preparing growth curves of per-capita stocks based on assumed neodymium saturation levels (Dong et al., 2019; Liu et al., 2012; Muller et al., 2014; Pauliuk et al., 2013). It would be ideal to consider historical growth rates or based on the outlook of national and industrial development plans in these circumstances (de Koning et al., 2018; Rademaker et al., 2013; Schulze and Buchert, 2016). However, no study has been performed to investigate China’s neodymium flows using these integrated methods.

Given the urgent need for resource security and effective governance of critical metals, it is crucial to investigate neodymium resource utilization along the industrial chain so that sustainable neodymium use policies can be determined. This study aims to identify major challenges and opportunities for neodymium cycles to improve resource efficiency. This study addresses four important challenges: (1) tracing the neodymium flows in different life cycle stages along the whole neodymium industrial chain; (2) analyzing the neodymium demand structure, including both import and export, and assessing the neodymium recycling potential; (3) forecasting future neodymium demand; (4) identifying sustainable neodymium resource development, conservation and recycling strategies and policies.

After this introduction section, section 2 details research methods and data sources. Section 3 presents research results, including the entire flows of neodymium, projections on future neodymium resource supply and demand. Section 4 discusses related policy implications based on the results. Section 5 draws research conclusions for this study.

2. Methods and Data

2.1 Dynamic Material Flow Analysis

MFA is a commonly used method to characterize material cycles—including stocks and flows—so that sustainable material management such as material recycling and recovery can be realized (Zeng and Li, 2015). MFA needs explicit boundaries to be defined. The spatial boundary for this study is mainland China. Taiwan, Hongkong and Macau are excluded from this study due to a lack of relevant data. The temporal boundary is for the years 2000–2050—allowing for both retrospective and prospective neodymium flows investigation in China.

The neodymium life cycle in the anthroposphere is composed of six major stages—illustrated in Figure 1. These stages include mining and beneficiation, refining and separation, fabrication, manufacturing, use, and waste management (Chen et al., 2018; Ciacci et al., 2019; Sekine et al., 2017). Neodymium concentrates come from the beneficiation of rare earth ores—obtained through acid decomposition. Neodymium primary products, including neodymium oxide, neodymium fluoride, neodymium chloride and neodymium carbonate, are separated by solvent extraction and ion exchange. The neodymium metal is smelt through a hydrometallurgical process. Immediate products—NdFeB magnets, NiMH batteries, automotive catalytic converters—are further processed and added into final applications (Li et al., 2016; Zhou et al., 2011).

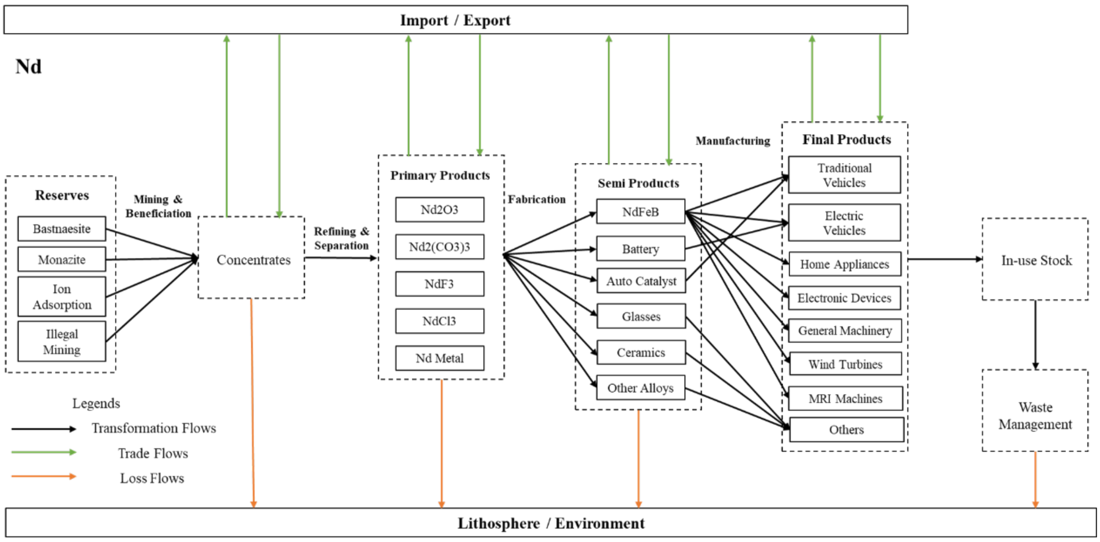


Fig.1. System boundary of neodymium material cycle in China

A bottom-up approach is used to estimate domestic consumption. The consumption of neodymium in each final product is calculated by using equation (1) (Sekine et al., 2017):

$$DC_j(t) = P_j(t) \times MI_j \times AR_j(t) \tag{1}$$

Where *j* refers to types of final products; *t* refers to year; *DC* refers to the total domestic neodymium consumption of final products; P_j refers to the domestic production of a final product unit; MI_j refers to the Nd content in each final product; AR_j refers to the market penetration rate of a final product containing neodymium. It is assumed that the Nd content is fixed in each product and this content does not change during the time horizon. However, the adoption rates of neodymium products may change due to the technological advances in applications. The parameters for multiple product families are summarized in Table 1.

The neodymium inflows, import and export flows into the use stage are calculated using equations (2-4):

$$F_{in,j}(t) = DC_j(t) - E_j(t) + I_j(t) \tag{2}$$

$$E_j(t) = E_{p,j}(t) \times MI_j \times AR_j(t) \tag{3}$$

$$I_j(t) = I_{p,j}(t) \times MI_j \times AR_j(t) \tag{4}$$

Where $F_{in,j}$ refers to neodymium volume entering a domestic market; E_j refers to the neodymium export flows for manufacturing products, $E_{p,j}$ denotes the export volume per unit of final product; and I_j refers to the neodymium import flows for one manufacturing product; $I_{p,j}$ denotes the import volume of one final product. More details about these parameters are listed in supplementary material 1.

The change of in-use stock and neodymium contained end-of life products can be calculated by using equations (5) and (6):

$$F_{out,j}(t) = F_{in,j}(t - t_0) \quad (5)$$

$$\Delta S_j(t) = F_{in,j}(t) - F_{out,j}(t) \quad (6)$$

Where ΔS_j refers to the change of the in-use stock; $F_{out,j}$ refers to the neodymium volume embedded in the end-of life flow of one final product; t_0 refers to the average lifespan of a product. These parameters and values are detailed in Table S3.

Two different methods are selected to predict the future demands based on properties of the twelve final products. The prediction methods used for different products are listed in Table S4. The parameters related to demand forecast summarized in Tables S5 and S6 in the supplementary material 1.

With rapid economic development, the per capita ownership of traditional automobiles, household appliances and electronic products, and other durable consumer goods will reach saturation. Therefore, the demand forecasts of the eight final products—from amongst the twelve—are based on a stock-driven saturation model with saturated ownership levels determined by the Gompertz function. The relationships among ownership, stock, and neodymium demand are shown in equations 7-9:

$$V_j(t) = VS_j \times e^{\alpha e^{\beta GDPP(t)}} \quad (7)$$

$$S_j(t) = V_j(t) \times MI_j \quad (8)$$

$$C_j(t) = S_j(t) - S_j(t-1) + F_{out,j}(t) \quad (9)$$

Where V_j represents the ownership of a given final product j; i refers to one final product, t refers to the investigated year; VS_j denotes the ultimate saturation level of one final product; $GDPP$ is the GDP per capita; α and β are two parameters that determine the shape of the S-curve. MI_j refers to the Nd content in one final product; S_j denotes the stock of one final product; $F_{out,j}$ represents the neodymium volume of one end-of-life product; C_j is the neodymium demand of one final product.

Among the other four final products, electric vehicles and wind turbines belong to emerging industries. It is difficult to determine the stock saturation levels of acoustic devices and electric bicycles. Therefore, the specific growth rate method is selected for these two products. The future demands can be calculated by using equation 8:

$$C_j(t) = C_{0,j} \times (1 + a)^t \tag{10}$$

Where C_j represents the future demand for neodymium, i refers to one final product, t refers to the investigated year; $C_{0,j}$ refers to the demand for neodymium in a specific final product for the baseline year; a denotes the specific growth rate.

Table 1 Various parameters used in this study

Products	Nd Content	Unit	Adoption Rates (%) (2017)	Sources
NdFeB Magnets	18-24	%	100	(Geng et al., 2020)
Batteries	0.14	g/unit	100	(Peiro et al., 2013)
Ceramics	5.5	ppm	100	(Peiro et al., 2013)
Glasses	6.5	ppm	100	(Peiro et al., 2013)
Auto Catalyst Converters	3	g/unit	95	(Peiro et al., 2013)
Other Alloys	0.9	ppm	100	(Peiro et al., 2013)
Conventional Vehicles	130	g/unit	100	(Crock, 2016; Sekine et al., 2017)
Electric Vehicles	610	g/unit	100	(Geng et al., 2020; Sekine et al., 2017)
E-Bikes	103	g/unit	10	(Ciacci et al., 2019; Zhang, 2020)
Wind Turbines	224	kg/MW	25	(Cao et al., 2019; Zhang, 2020)
Air Conditioners	51.5	g/unit	30	(Ciacci et al., 2019; Zhang, 2020)
Washing Machines	42	g/unit	25	(Ciacci et al., 2019; Sekine et al., 2017)
Refrigerators	51.5	g/unit	25	(Sekine et al., 2017; Zhang, 2020)
Microwave Ovens	32.5	g/unit	30	(Habib et al., 2014)
Vacuum Cleaners	24.5	g/unit	8	(Habib et al., 2014)
MRI Machines	400	kg/unit	100	(Sekine et al., 2017; Zhang, 2020)
Desktop Computers	6	g/unit	100	(Althaf et al., 2020; Schulze and Buchert, 2016)
Laptops Computers	1.5	g/unit	100	(Althaf et al., 2020; Schulze and Buchert, 2016)
Mobile Phones	0.3	g/unit	100	(Althaf et al., 2020; Ciacci et al., 2019)
Loudspeakers	0.8	g/unit	100	(Ciacci et al., 2015; Sekine et al., 2017)
CD/DVD players	14.8	g/unit	100	(Geng et al., 2020; Sekine et al., 2017)
Elevators	1740	g/unit	90	(Geng et al., 2020; Habib et al., 2014)
Industrial Robots	540	g/unit	100	(Habib et al., 2014; Sekine et al., 2017)

2.2 Data Sources

The data for this study were collected from various sources. Rare earth concentration production data were obtained from the CSRE yearbook (2009, 2018). The import and export data were obtained from China Customs (2002-2011, 2013-2015, 2017) and UN Comtrade (2000-2001, 2012, 2016). The production data of final products were obtained from the China Wind Energy Association (2018), the China Automotive Technology Research Center (2000-2017), the Ministry of Industry and Information Technology (2000-2017), the China Bicycle Industry Association (2000-2017) and interviews with relevant experts. More details of data sources can be found in the supplementary material 1.

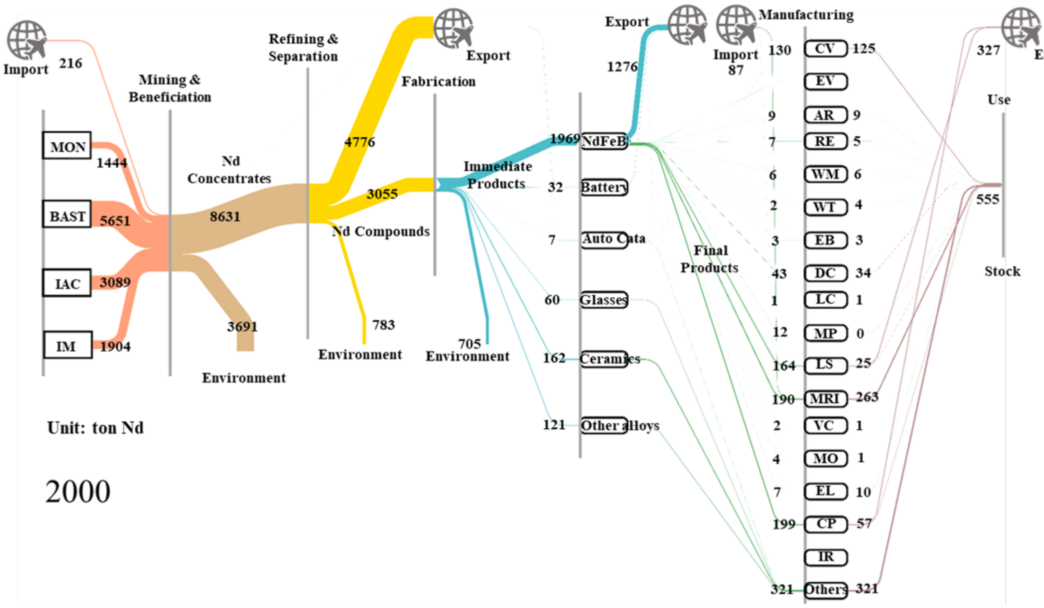
3. Results

3.1 Material flow features of neodymium for the period of 2000-2017

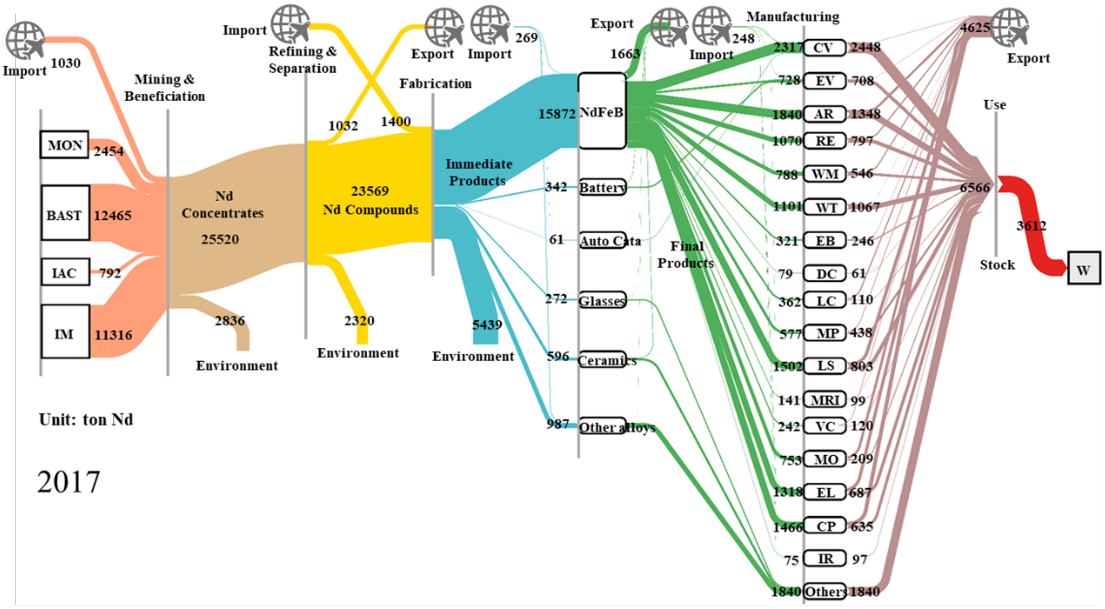
Figure 2 illustrates the neodymium MFA in China. Neodymium is mainly extracted from monazite, bastnaesite and ion adsorption clays. With rapid development of advanced energy-saving manufacturing industries, China’s neodymium mining volume has doubled from 12,000 tons in 2000 to 27,000 tons in 2017, while China's demand for neodymium at the use stage has increased nearly 20 times over the past 18 years.

The production of neodymium concentrates from monazite and gastnaesite has remained stable. However, neodymium concentrate production from ion adsorption clays has declined sharply since 2007 due to stricter environmental conservation pressures (see Figure S2). Neodymium production was 792 tons in 2017—only 11% of the peak value of 7,148 tons occurring in 2006. Notably, it was found that the annually announced official mining volume could not meet the actual demand based on the accounting, which indicates the existence of illegal mining activities to meet demand without official recording.

Although the Ministry of Industry and Information Technology and the Ministry of Natural Resources issued an annual mining quota, unregistered mining activities over the past couple decades increased from 1,900 tons in 2000 to 11,300 tons in 2017—with an average annual growth rate of 10.41%. In 2011, the volume of illegal mining was equal to the officially announced production volume, and in the following years illegal mining became much larger than the registered mining volume. The most serious situation occurred in 2014, when the illegal mining volume accounted for 2/3 of the total production volume. Although the mining rights have been completely integrated, the grey industry chain of rare earth still exists and cannot be eliminated in China.



(a) 2000



(b) 2017

Fig. 2. Neodymium flows in China (a) 2000 and (b) 2017

Note: The flow direction is from left to right in (a), (b), (c) and (d). The width of each flow is proportional to its amount. All values use the unit of metric ton. MON=Monazites, BAST=Bastnaesites, IAC=Ion Adsorption Clays, IM=Illegal Mining, CV=Conventional Vehicles, EV=Electric Vehicles, AC=Air Conditioners, RE=Refrigerators, WM=washing Machines, WT=Wind Turbines, EB=E-bikes, DC=Desktop Computers, LP=laptop Computers, MP=Mobile Phones, LS=Loudspeakers, MRI=Magnetic Resonance Imaging Machines, VC=Vacuum Cleaners, MO=Microwave Ovens, EL=Elevators, CP=CD/DVD Players, IR=Industrial Robots, W=Waste Management.

Neodymium concentrate is refined and separated into primary products including neodymium compounds—neodymium oxide, neodymium chloride and neodymium fluoride—and neodymium metal. Primary products are further processed into neodymium iron boron magnet (NdFeB magnet), cathode material for NiMH battery, colorant additives for glass and ceramics, metal coatings for automotive catalytic converters, and modified materials in other alloys.

The structure of intermediate neodymium products has only slightly changed in the past few decades—although neodymium consumption in intermediate products has increased significantly (see Figure S3). NdFeB magnets have the largest share of intermediate products. Compared with the year 2000, its proportion gradually increased to 87.55% in 2017, with an annual growth rate of 3.76% eventually reaching 15,900 tons in 2017. Rapid development of electric vehicles caused neodymium consumption in batteries to reach 342 tons in 2017, with an average annual growth rate of 14.07%. The neodymium used in other alloys also increased, from 121 tons in 2000 to 987 tons in 2017. Neodymium consumption in glass and ceramics increased by 4.53 times and 3.68 times from 2000 to 2017, reaching 272 tons and 596 tons in 2017, respectively. In addition, between 10 to 60 tons of neodymium have been annually used in automotive catalytic converters.

NdFeB magnets, the intermediate product that consumes most neodymium, is commonly used in electronic devices, home appliances, electric vehicles, wind turbines and other final products. This study enumerated a total of 17 final product families and divided them into 8 categories (see Figure 3 and S4). The total neodymium consumption has largely increased, but the trends of each final application show obvious differences.

The proportion of neodymium consumption in electronic devices has continuously decreased, shrinking from 50% in 2000 to 30% in 2017—although consumption for these final products still reached 4,000 tons in 2017. Among this product family, loudspeakers and CD/DVD players accounted for 74.46%, which were 1,502 tons and 1,466 tons, respectively. Mobile phones, laptop,s and desktop computers used 577 tons, 362 tons and 79 tons of neodymium in 2017, respectively.

After two decades of rapid electronic information industry development in China, the production of electronic devices has reached saturation and started to decrease—with peak neodymium consumption of 5,421 tons occurring in 2012. Alternatively, increasing market growth of high-performance motors resulted in increased home appliances neodymium consumption especially in air conditioners and refrigerators. In 2017, 1,840 tons and 1,070 tons of neodymium were used in air conditioners and refrigerators, with annual growth rates of 34.39% and 32.24% over the past 18 years, respectively.

The demand for neodymium in washing machines, microwave ovens and vacuum cleaners also increased, with 788 tons, 753 tons, and 242 tons respectively consumed in 2017. The proportion of traditional cars in the demand structure is relatively stable, maintaining a 15%-20% fraction. Micromotor and EPS motor usage in conventional vehicles has resulted in neodymium consumption increasing at an average annual growth rate of 17.35%—reaching 2,300 tons in 2017.

A low-carbon economic transformation and energy-saving initiatives in China have resulted in higher neodymium consumption of clean energy technologies and general machinery. The demand for neodymium in electric vehicles, wind turbines, industrial robots, and elevators was 728 tons, 1,100 tons, 1,318 tons and 75 tons in 2017, respectively. The low adoption rate of NdFeB magnets in E-Bikes and magnetic resonance imaging (MRI) machines resulted in neodymium consumption of only 321 tons and 141 tons in 2017, respectively. Based on these observations it can be concluded that home appliances, clean energy technology, and general machinery will be key future neodymium demand sectors. The results of this study show similar patterns to previous studies (e.g. Geng et al. (2020)).

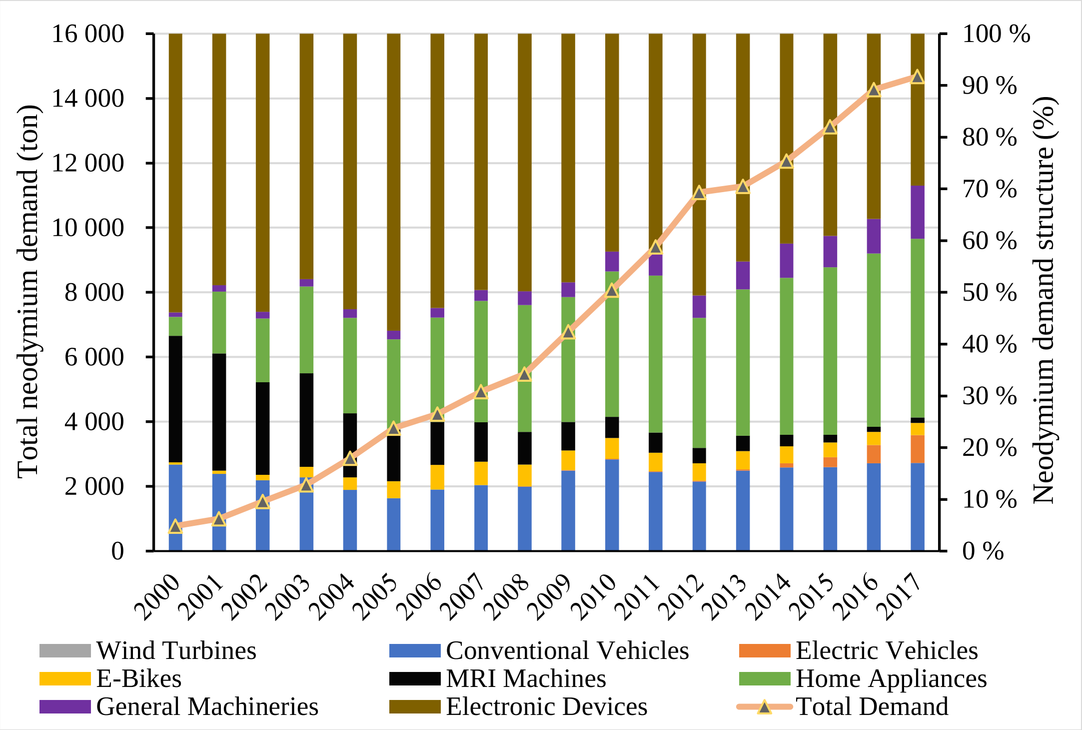


Fig. 3. Neodymium demand structure in China from 2000-2017

The in-use neodymium stock shows a similar trend to its demand. It increased from 555 tons in 2000 to 66,600 tons in 2017, with electronic products, household appliances, and conventional vehicles accounting for 70% of stock. Growth of the electronic information industry increased neodymium stock in CD/DVD players and loudspeakers—representing 6,600 tons and 7,500 tons of neodymium in 2017, respectively. The in-use stock of neodymium in desktop computers, laptops and mobile phones was 928 tons, 902 tons and 2,660 tons in 2017, respectively.

The increasing market growth of energy-saving motors has expanded the in-use stock of neodymium in home appliances, especially in air conditioners, refrigerators, and washing machines showing exponential increases of 9 tons, 5 tons, and 6 tons in 2000 to 9,878 tons and 3,700 tons in 2017, respectively. Neodymium in-use stock from microwave ovens and vacuum cleaners has also increased significantly over the past 18 years, reaching 1,664 tons and 849 tons, respectively, in 2017.

Neodymium stock in traditional cars, electric cars, wind turbines and elevators were 13,700 tons, 1,562 tons, 6,820 tons and 3640 tons in 2017, respectively. As China actively promotes circular economy strategies and is eager to achieve carbon neutrality targets, the neodymium stock in emerging energy-saving fields will also continue to increase.

As shown in Figure 5, final products will generate a large amount of end-of-life neodymium flows after their end-of-life. A lack of recycling systems will likely mean that such end-of-life neodymium will be discarded, incinerated, and landfilled, leading to loss of a significant neodymium stream. There is significant opportunity for recycling neodymium from these end-of-life products. Among these sources, electronic products have generated a total of 7,030 tons of end-of-life neodymium flows in the past 18 years. Conventional vehicles, MRI machines, and E-Bikes have respectively generated a total of 4,088 tons, 3,645 tons and 2,460 tons of end-of-life neodymium flows. These resources account for 92.62% of the total waste flows. End-of-life neodymium recycling will effectively reduce the total demand for primary neodymium.

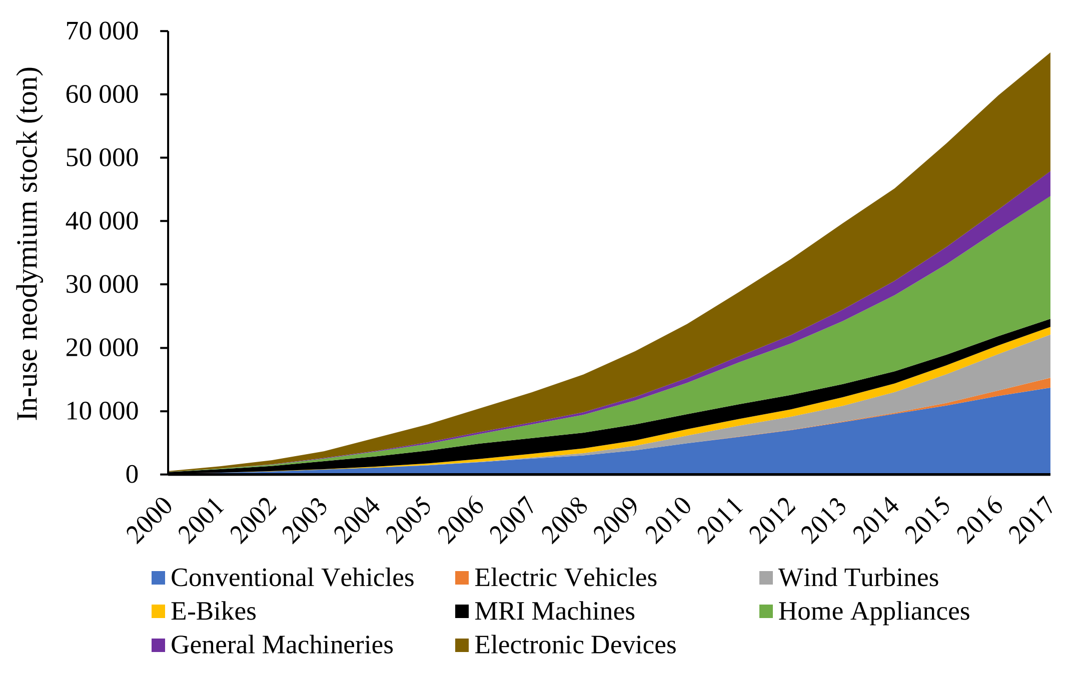


Fig. 4. China’s in-use neodymium stock from 2000-2017

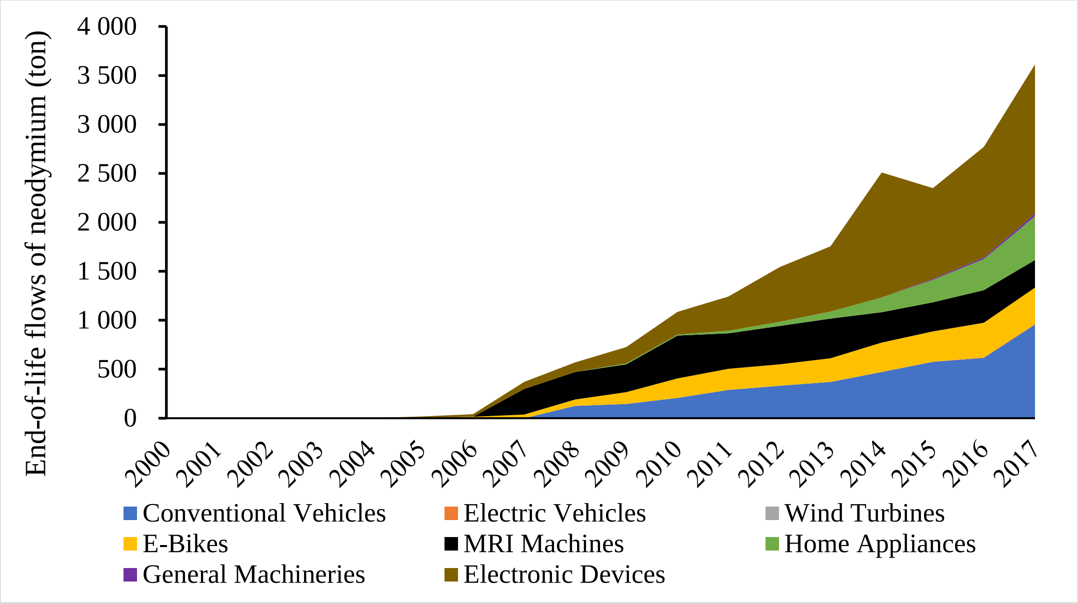


Fig. 5. End-of-life flows of neodymium in China from 2000-2017

As shown in Figure 6, the neodymium export volume initially increases and then gradually decreases after 2007. China imports neodymium concentrates for refining and separation. Imports increased over the past 18 years—reaching 1,340 tons in 2017, while the export is very small. China's surplus refining and separation capacity led to large quantities of primary product neodymium exports before 2006. Dual restrictions of export quotas and tax rates, the export volume of neodymium in primary products fell sharply after peaking at 5,800 tons in 2006 it reduced to 1,032 tons in 2017.

Recent demands by neodymium downstream users means greater intermediate product neodymium imports. Interestingly, the differences between China Customs export data and UN Comtrade import data indicates a history of illegal smuggling activities of neodymium-containing primary products. The actual intermediate product neodymium export volumes—including neodymium compounds and neodymium metal—is 10%-50% higher than the official registered export volume (see Figure S7). The unregistered export volumes reached 2,600 tons, 1,430 tons, and 660 tons in 2002, 2011, and 2012, respectively. This phenomenon can be explained by the rare earth export quota policy. Low export quota years (2000-2003, 2011-2014) result in greater differences and purported smuggling activities. Few differences—less smuggling—occurred in years when export quotas were relaxed and raised to higher levels (in 2004-2010).

Increased export tariffs likely led to lessened registered exports; causing greater differences in actual versus actual export reports. This tariff tax policy led to more intermediate product exports since neodymium metal can be processed into NdFeB magnets to avoiding export quotas associated with neodymium primary products (see Figure S8). The neodymium export volume of intermediate products—including NdFeB, NiMH batteries, glass, and ceramics—peaked at 3,900 tons in 2011 and gradually decreased to 1,880 tons in 2017 resulting in a decrease of 51.79%.

The export volume of neodymium in final products has gradually increased, from 305 tons in 2000 to 4,600 tons in 2017. Overall, the export volume has decreased although the illegal smuggling activities of primary products exist widely.

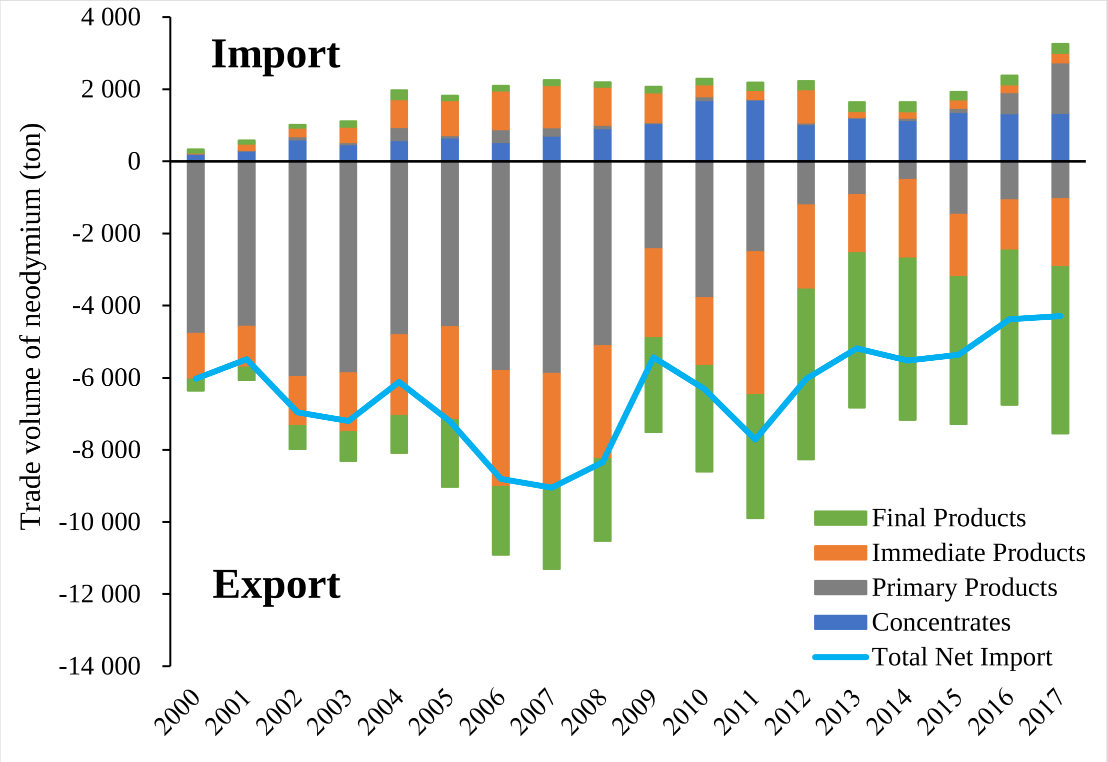


Fig. 6. Trade volume of neodymium in China from 2000-2017

3.2 Neodymium demand prediction

In this study, both a stock-driven approach—the Gompertz model—and a policy-driven approach with specific growth rates are combined to estimate future neodymium demands for final products. Figure 7 summarizes results for four final product groupings—home appliances, general machinery, electronic devices, and miscellaneous or other product families.

Overall, Electronic devices are likely to maintain stable demand reaching maturity and a saturation point for the next decades. Electronic device demand for neodymium will likely slow down and peak at 5,900 tons in 2032. Some electronic devices are likely to decrease due to shifting consumer demands and technological innovations. For example, CD/DVD players will decrease due to a shift in consumer demand for these electronic entertainment devices to be replaced by such innovations as on-line streaming systems. Therefore, in this study, the CD/DVD demand is set to decrease by 1% annually from 2018 to 2030, and by 2% annually from 2031 to 2050. Under this circumstance, neodymium used in CD/DVD players will be reduced to 860 tons in 2050.

Loudspeakers are also expected to experience a similar trend due to the application of piezoelectric acoustic transducers—another innovation replacing older technology. The shift in demand is expected to decrease at an annual rate of 2%, reaching 1,142 tons. The demand for neodymium in desktop computers, laptops and mobile phones will be 1,352 tons, 419 tons and 591 tons in 2050, a respective leveling of demand.

The demand for neodymium in general appliances—including air conditioners, refrigerators, washing machines, microwave ovens and vacuum cleaners—is forecast to increase to 3,636 tons, 2,864 tons, 1,704 tons, 1,796 tons and 701 tons by 2050, respectively. General machinery includes elevator and industrial robot product families. The average annual growth rate is expected to be 10%, reaching 11,500 tons and 1,745 tons by 2050, respectively.

Under the *other* category there are a few variations in final product forecasted demands. Concerns on air quality, climate change and energy shortages imply that the demand for neodymium in electric vehicles and wind turbines will increase rapidly at an annual growth rate of 13%. Electric vehicle neodymium demand is expected to reach 41,100 tons by 2050. Estimates for newly installed wind power capacity is expected to be 20 gigawatts by 2030, and 30 gigawatts by 2050. This means increases in demand for direct-drive permanent magnet generators. Thus, we set an annual growth rate of 7.2% for neodymium in wind turbines between 2018 and 2030, and an annual growth rate of 4.7% between 2030 and 2050. In these scenarios the neodymium demand for direct-drive permanent magnet generators is forecasted to reach 27,600 tons by 2050.

Neodymium demand in conventional vehicles and E-bikes—also under the *other* category of final products—will slowly decrease, reaching 6,200 tons and 1,500 tons. Finally, with the application of superconducting magnet technology, the demand for neodymium in MRI equipment will likely reduce to 25 tons in 2050.

When aggregating these forecasts the expected total demand for neodymium will exceed 30,000 tons by 2025, 50,000 tons by 2035, and more than 100,000 tons by 2050. This overall growth rate points to serious supply challenges occurring over the next three decades.

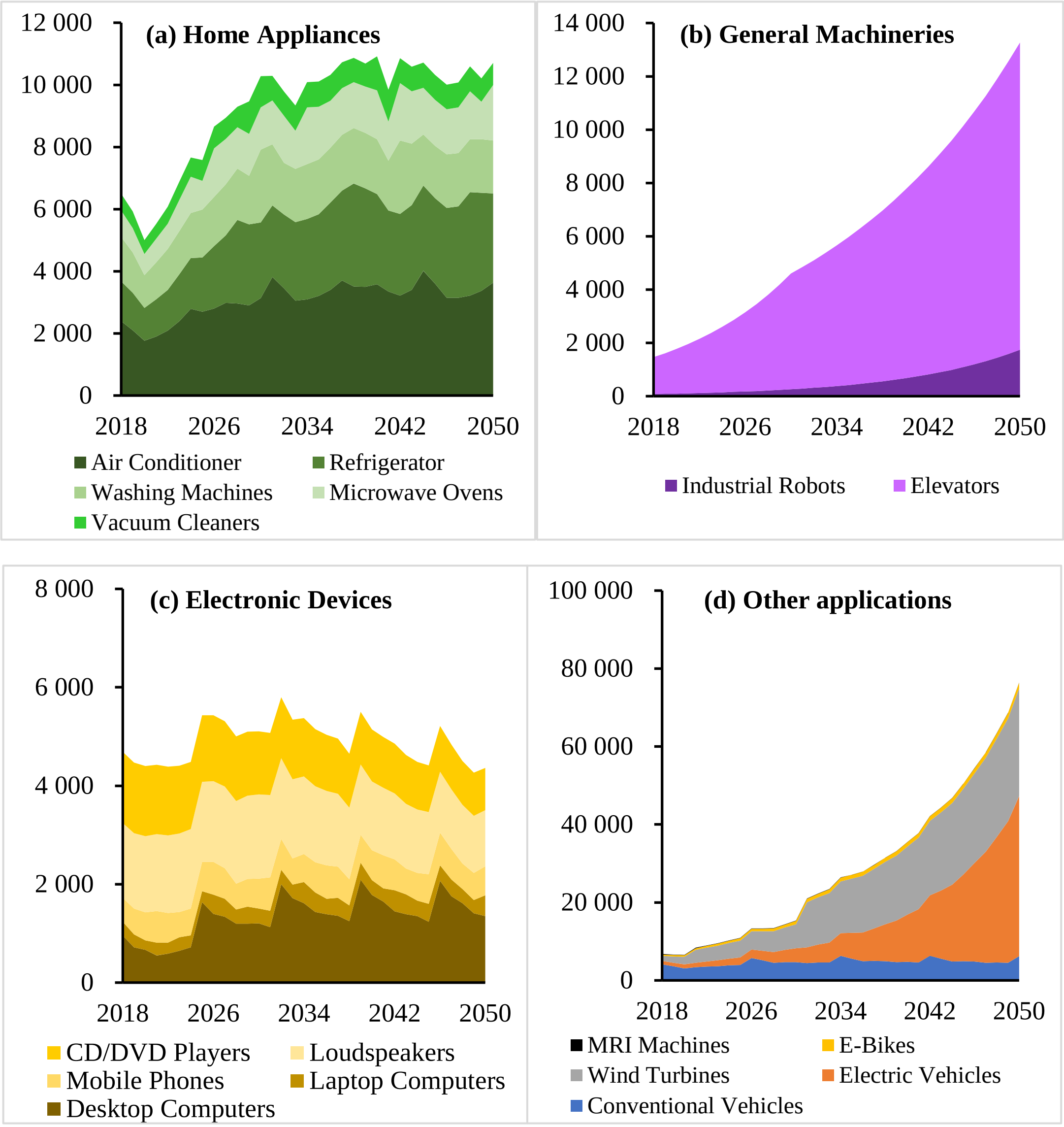


Fig. 7. China's future demands for neodymium in (a) Home appliances; (b) General machineries; (c) Electronic devices and (d) Other applications

3.3 Primary resource supply under different scenarios

In the previous section we provided estimates of neodymium demand over the next three decades. A question arises on whether neodymium production capacity exists to meet this demand. To help evaluate this question, three scenarios set the stage corresponding to domestic Chinese neodymium production growth rates of 2%, 5% and 8%. Figure 8 shows the neodymium supply-demand relationships in China under different scenarios from 2018 to 2050 and with estimates of require recycling of secondary neodymium.

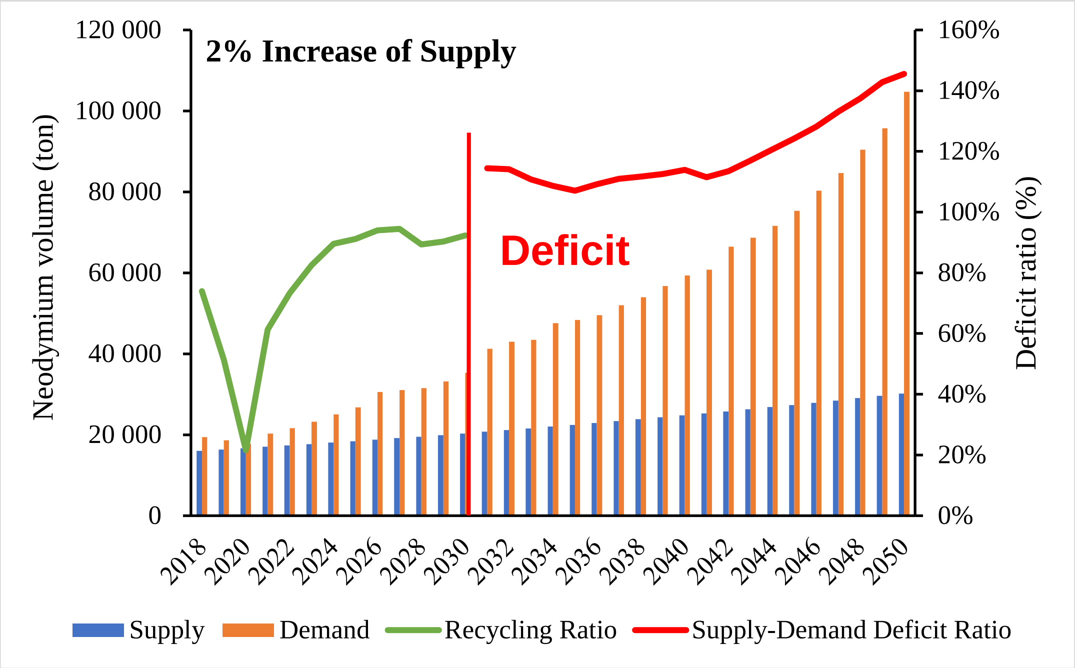
At a low supply growth rate—2% annually—there will likely be a supply deficit after 2030 with the deficit reaching 10%-40%. This result indicates that the neodymium supply is not enough, and that the recycling of neodymium from end-of-life flow cannot meet the demand. This large deficit indicates that dependence on neodymium import from other countries will occur to meet demand. The mining quota should be appropriately increased to meet the soaring demand unless China is willing to import more.

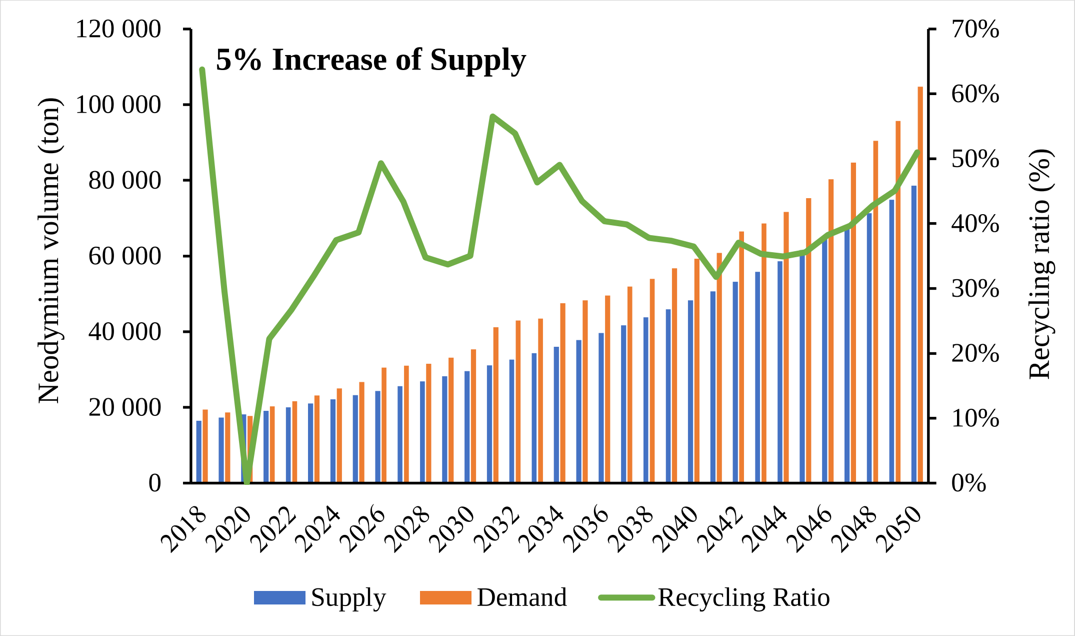
Scenario analysis results indicate that China can support its neodymium supply domestically if the recycling rate remains between 30% and 60% after 2025 based on the moderate growth of domestic production at a 5% supply growth rate. Also, if the supply from domestic ores extraction grows at a high rate of 8% annually, oversupply will occur after 2020. These scenarios point to exploring neodymium recycling strategies so that sustainable neodymium supply can be achieved within minimal corresponding environmental impacts and natural resource usage.

Table 2

Scenarios Settings

Scenarios	Growth Rates
Scenario 1	2% Increase in Supply
Scenario 2	5% Increase in Supply
Scenario 3	8% Increase in Supply


2% Increase of Supply
Deficit
Neodymium volume (ton)
Deficit ratio (%)
120 000
100 000
80 000
60 000
40 000
20 000
0
160%
140%
120%
100%
80%
60%
40%
20%
0%
2018
2020
2022
2024
2026
2028
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
Supply
Demand
Recycling Ratio
Supply-Demand Deficit Ratio


5% Increase of Supply
Neodymium volume (ton)
Recycling ratio (%)
120 000
100 000
80 000
60 000
40 000
20 000
0
70%
60%
50%
40%
30%
20%
10%
0%
2018
2020
2022
2024
2026
2028
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
Supply
Demand
Recycling Ratio

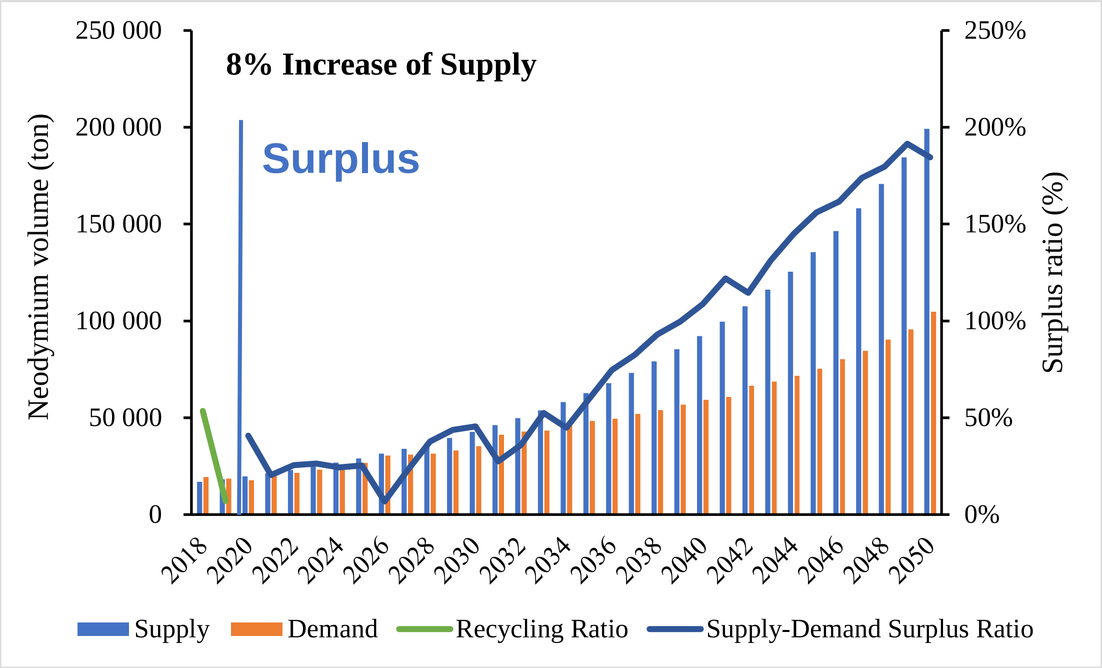


Fig. 8. The relationship between supply and demand of neodymium under (a) 2% Increase of supply; (b) 5% Increase of supply; (c) 8% Increase of supply

3.4 Sensitivity Analysis

The accounting and forecast results of this study are influenced by parameter uncertainties. Parameter uncertainties and variations are modeled using a normal distribution and assessed with three coefficient of variation levels: low variation—directly collected from the statistics—at 2%; medium—using the literature—at 5%; and high—estimated based on assumptions and expert interviews—10% levels (Hao et al., 2020; Liu et al., 2019).

Monte Carlo simulation is applied to examine the impacts of various parameter uncertainties—including production amounts, neodymium content in products, and penetration rates of neodymium in products—on the neodymium flows and stocks. Retrospective and prospective demands, end-of-life flows, and in-use neodymium stocks are each considered in these simulations. The results of the uncertainty analysis are illustrated in Figures S9 and S10.

The results show deviations of retrospective demand, in-use stock, and end-of-life flows range from -2.6% to 2.4%, -9.5% to 10.1%, and -9.8% to 9.4% respectively. Deviations in prospective demand, in-use stock, and end-of-life flows range from -7.7% to 8.3%, -8% to 8.2%, and -8.9% to 9.6%, respectively. The sensitivity analysis show that uncertainties in parameter assumption used in this study have limited impacts on our main findings (within + or – 10%)

with relatively robust results.

4. Policy recommendations

The results obtained in section 3 provide practical policy maker insights for sustainable neodymium management policies. The next three subsections summarize major policy insights from the results.

4.1 Enhancing domestic neodymium sustainable supply regulation

Over the past couple decades China has been able to achieve neodymium self-sufficiency. More than 90% of the neodymium supply derives from domestic rare earth ore extraction. To help manage the depletion of these rare earth ores China set specific annual rare earth metals mining quotas. Yet, these quotas are regularly surpassed due to unregistered mining—cumulatively about 160,000 tons in total from illegal mining activities. Thus, this illegal and unreported mining is still rampant and is partially due to ineffective regulatory enforcement. This represents a major weakness in the current regulatory system for sustainable rare earth mining.

In order to achieve sustainable resources management of neodymium, stricter mining regulation with effective enforcement is required. Although China's six state-owned rare earth groups have effectively monopolized domestic rare earth ores mining, many small private mines remain engaged in illegal mining activities (Langkau and Erdmann, 2021; Lee and Wen, 2018; Packey and Kingsnorth, 2016;). To improve enforcement the government should implement more stringent surveillance measures such as: collecting detailed information of neodymium mining sites across the country; drafting neodymium digital maps; and dynamically monitoring neodymium mining activities. The enforcement will require localized governments—who may stand to profit from some of this illegal mining—to also be involved with performance and incentive systems to apply latest tracing technology.

More importantly, it is necessary for China to set a more reasonable and appropriate annual production quota for rare earth mining. These goals should consider the needs of some areas, but the market lessening illegal trafficking (by allowing for more flows) which may allow for better ability to carefully track illegal mining while meeting downstream demand. In addition, the implementation of resource taxes and price control may avoid the over-supply and production of neodymium and promote the sustainable neodymium supply. Managing these issues will not be trivial with a chance that some of these policies may backfire with greater unsustainability in mining. Overall, if China is serious, then closer monitoring and stiffer penalties will be needed.

4.2 Promoting the recycling of end-of-life neodymium

The mining neodymium process generates large quantities of wastewater and radioactive pollutants—each of which will have a negative local ecosystem impacts. At the other end of the production life cycle neodymium at the waste management stage it is not effectively recycled or reasonably disposed resulting in a neodymium recycling rate of less than 1%. The end-of-life neodymium-containing products incineration and landfilling have caused further environmental damage.

The results show that over 19,000 tons of neodymium is embedded in various products and components and are waiting to be recycled. This quantify of neodymium recycling can reduce the demand for primary—virgin sourced—neodymium. According to our scenario analysis that a moderate exploitation of virgin neodymium—annual production growing at a 5% rate—the neodymium recycling rate in China needs to reach 30%-60% of total annual production to meet annual demands.

There should be a prioritization for product family recycling. In-use neodymium stock in China reached 67,000 tons in 2017, mainly in household appliances and electronic equipment, which indicates that these products will become major sources for end-of-life neodymium recycling. Wind power generators and MRI product families have large quantities of neodymium per unit. Recycling emphasis on these product should be prioritized given the potential feasibility and cost efficiency of harvesting the neodymium from fewer point sources. Opportunities to set up the recycling infrastructure for products should be jointly completed by businesses, communities, and government.

Current efficient neodymium recycling technologies include leaching—over 95% efficient—and molten salt extraction—86.6% efficient. However, the technologies are still immature and primarily at the experimental level. The low economic benefit for neodymium recycling is also a major barrier. The government should invest in construction of REE recycling systems and provide support and subsidies for REE recycling enterprises, design relevant policies to accelerate the integration of production, education and research, and allocate funds for research and development. These are all important foundational governmental activities to support an REE recycling infrastructure.

4.3 Upgrading China’s role in the global neodymium industrial value chain

China dominates the upstream global rare earth industrial value chain based on neodymium MFA results. An excessive supply of primary neodymium product has led to frequent smuggling illegal activity in the past 18 years. China's government should set policy to adjust their role in the global value chain supply structure of rare earth resources. They should *upgrade* their role in the neodymium industrial global value chain by reducing the exploitation of domestic neodymium natural resources and increase neodymium concentrate and primary product imports. They could then export high value-added neodymium-containing products—focusing on downstream production and manufacturing value chain activities.

The proportion of neodymium primary and intermediate product exports has fallen from 75.14% in 2000 to 38.57% in 2017. This result indicates that China's neodymium trade structure along the rare earth industrial value chain has significantly changed over the past couple decades, it remains a net export situation for China. It remains necessary that China import intermediate products—such as high-performance neodymium magnets—to meet the predicted rising demand for neodymium in electric vehicles (41,000 tons in 2050) and wind turbines (27,600 tons in 2050). China should invest in shifting from a raw material exporter to higher value added high-tech neodymium-containing production.

Foreign country dependence on China's neodymium resources is extremely high. However it is not possible for China to maintain neodymium-containing primary product exports at low prices—especially given the relative criticality of neodymium to China’s activities. Based on our patterns and observations in this study China is very likely to impose stricter neodymium production quotas. To reduce potential supply risks foreign countries importing from China need to find alternative countries for neodymium supply; other exporting countries include Vietnam, Myanmar and Brazil. From an anthropogenic perspective, rare earth mines including neodymium, are finite and pose severe environmental pollution from the extraction process. In the long run, reducing the use of neodymium, identifying potential recycling pathways, and developing alternative materials without neodymium will need to be included in the portfolio of sustainable solutions.

5. Conclusion

Neodymium has become a critical rare earth element due to rapid development of high-tech industries. This study introduced a dynamic material flow analysis on neodymium in China for the period 2000-2017. The research results show that the production of neodymium has increased from 12,000 tons in 2000 to 27,000 tons in 2017. However, illegal mining activities also exist, and even exceeded the official production amount. On the demand side, the NdFeB magnet is the most important neodymium intermediate product, which is widely used in home appliances, electronic devices, electric vehicles and wind turbines. Market growth in these products has resulted in a nearly 20-fold neodymium demand increase over the 18 year study period, reaching 15,872 tons in 2017.

Electronic devices and home appliances are the final product families that have the largest share of total neodymium demand, consuming 4,000 tons and 4,700 tons in 2017 respectively. These final product families also represent a significant percentage of in-use neodymium stock. The end-of-life neodymium flows was 3,600 tons in 2017. Due to the lack of a recycling system, less than 1% of neodymium was recycled and reused.

Another important finding is that net neodymium exports gradually decreased, from 6,000 tons in 2000 to 4,200 tons in 2017—mostly due to decreases in primary products and intermediate products. However, some primary products were exported through unreported—smuggling—activities. Although such smuggling activities has reduced in recent years, 276 tons of neodymium in primary products were illegally exported in 2017. The demand for neodymium in electric vehicles and wind turbines will continue to increase in the future—expected to reach 41,000 tons and 26,700 tons in 2050, respectively. The total demand for neodymium may reach 100,000 tons. According to demand forecast results with an assumed annual neodymium supply rate of 5%, the expected 100,000 demand from primary production can only realistically be met if 30%-60% of secondary neodymium is recycled.

Several policy recommendations evolve from these study results. Major ones include enhancing regulation of domestic neodymium supply, promoting the recycling of end-of-life neodymium, and facilitating transition of China’s positioning in the global neodymium industrial value chain. Future research can complete more extensive surveys on the application of neodymium so that the contents and penetration rates of neodymium in different products can be better investigated and data uncertainties can be reduced. It would also be critical to develop and apply more nuanced scenarios by considering local situations so that more accurate results can be obtained to facilitate sustainable management.

Acknowledgment

This study is supported by the National Key Research and Development Project (2019YFC1908501), the Natural Science Foundation of China (72088101, 7169024, 71810107001).

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