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# Supply and demand conflicts of critical heavy rare earth element: Lessons from gadolinium

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ABSTRACT

Our understanding of supply and demand conflicts of critical minerals is quite limited, which may inhibit strategies in their criticality mitigation. This is particularly severe for gadolinium (Gd), as a heavy rare earth element, given its small amounts in supply and wide applications ranging from glass to NdFeB magnets. This study (1) developed a sophisticated accounting framework to measure the supply and demand trends of Gd within China from 1990 to 2018 and (2) provided a qualitative review and discussions on Gd supply-demand balance in a holistic perspective. Our findings suggest that the balance of Gd supply and demand shows a cyclical trend, termed as periodic "scarcity-abundance" pattern, influenced by changes in environmental regulations, trade structures, and technological applications. This highlights the importance of the joint measurement of both supply and demand of critical minerals for their criticality mitigation.

## 1. Introduction

Measuring supply and demand is a crucial aspect of supply chain analysis for critical minerals, as it helps to identify the allocation of resources within the supply chain (Tokimatsu et al., 2017). The supply and demand of critical minerals are often affected by factors such as resource competition, environmental regulations, technological evolution, and low-carbon energy transformation, resulting in dynamic changes and imbalances (May et al., 2012; Wellmer and Scholz, 2017). Therefore, a dynamic analysis of supply and demand is necessary to accurately identify, assess, and manage critical minerals. While some studies on critical minerals supply chains consider both supply and demand sides, the current focus of critical minerals management at the national level tends to be on supply risk alone (European Commission, 2017; Lusty et al., 2021; Nassar N T, 2021). This supply-side focus results in a unilateral understanding of the material cycle and can lead to misguided decisions on minerals management.China plays a crucial role in the global critical mineral supply chain. China dominates the production of REEs and accounted for over 60 % of global ores' production and over 88 % of global refined products' production of rare earth elements in 2021 (WU et al., 2023). Meanwhile, under the influence of the energy transition, there is also a strong demand for rare earth resources in China (Li et al., 2019). This high global share of China in both supply and demand side is also appeared in other critical minerals' supply chains (Dou et al., 2023). Hence, researchers should focus more on the general issue of dominance of a few producers (predominantly China) for REEs and other critical metals on a holistic perspective.

Gadolinium (Gd) is a typical case that exemplifies the dynamic conflicts between supply and demand due to its limited sources of supply and wide range of applications. As one of the heavy rare earth elements (REEs), Gd is less abundant in the Earth's crust (approximately 6.2 mg/kg) (Greenwood and Earnshaw, 1997) and has a lower content in many rare earth ores (about 0.05 % in Bastnaesite) (Duraiswami and Shaikh, 2014). As one of the four elements (Fe, Co, Ni, Gd) that are ferromagnetic at room temperature (Martins and Wurth, 2016; Pyykkö, 2015), Gd has unique applications, such as contrast agents for magnetic resonance imaging (MRI), which differentiate it from other REEs. However, Gd also has general applications similar to other REEs, such as in glass and phosphors (Roskill, 2017).

A comprehensive framework including detailed data is essential for quantifying material flow from a life cycle perspective and measuring supply and demand conflicts. Inaccurate frameworks and data can mislead the understanding of the material cycle and hinder policy implementation for mineral management. This is particularly critical for

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the study of REEs due to their widespread applications. Most research on REEs focuses on neodymium (Nd) (Geng et al., 2021; Liu et al., 2022; Yao et al., 2021) and dysprosium (Dy) (Q.-C. Wang et al., 2022; Xiao et al., 2022), and evaluates the impact of NdFeB magnet industry development on the growth of Nd/Dy demand. However, only a few studies (Du and Graedel, 2011; Zhao et al., 2023) have established a relatively complete framework for the supply and demand of Gd, and even fewer have considered its unique application in NdFeB magnets as a less expensive substitute for Nd (see Fig. S1) and its substantial Gd usage (Roskill, 2017; Yan et al., 2012). The impact of the NdFeB magnet industry development on supply and demand of Gd has not been focused on in previous MFA studies. And the Roskill report only provided a rough estimate of Gd usage in NdFeB magnets.

Prices reflect the changes in the minerals supply and demand (Dou et al., 2023). Generally, Gd is considered a mineral with long-term surplus. However, given the price increases of gadolinium since 2021 (see Fig. S1) and the development of the NdFeB permanent magnet industry, there may be some changes occurring in the Gd supply and demand balance. Therefore, a holistic and detailed views on the Gd market is needed, especially considering the impact of Gd usage in NdFeB magnets.

The objective of this study is to address this gap and present a comprehensive overview of the Gd supply chain in China from 1990 to 2018, with a focus on analyzing the supply-demand balance of Gd flows. The remaining sections of this paper are organized as follows: Section 2 outlines the framework and the detailed accounting methods applied for quantifying Gd's supply-demand balance. Section 3 presents our findings on the supply and demand of Gd in China. In Section 4, we further review and discuss the impact of changes in technical applications on Gd's supply-demand balances and provide a comprehensive analysis of the measures required to address Gd's shortage in the future.

## 2. Material and methods

### 2.1. System boundary and definition of supply-demand

This study utilizes a dynamic material flow analysis-based (MFA-based) accounting framework to quantify the supply and demand conflicts of Gd at the national level (Chen and Graedel, 2012; Paul H and Helmut, 2017). We examine the flows and stock of Gd from production to recycling in China from 1990 to 2018, including: (1) China's dominant global rare earth supply since the 1990s, (2) the production quota that began in 2006, (3) the rare earth trade dispute that occurred in 2010, and (4) China's growing rare earth import in 2018. The system definition and framework are depicted in Fig. 1, where all flows and stocks are measured using the mass of Gd. A detailed explanation of the accounting method is presented in the Supporting Information (see Table S1).

In the context of the mining and refining of REEs, these elements are often found in similar deposits and are extracted and refined together as co-products. As a result, the surplus REEs usually exist in the form of separation and refining products. Hence, in this study, we define the stages of "Mining & Beneficiation" and "Refining & Separation" as Gd's supply, while all other stages are defined as Gd's demand.

### 2.2. Supply accounting

#### 2.2.1. Inflow and outflow

All calculations are based on the mass balance principle of MFA: the total input (inflows, including production and import) measured in weight is equal to the total output (outflows, including consumption, export, and loss) measured in weight for each process. Gd outflow was calculated based on their inflow from mining to separation and refining. The Gd outflow into each process can be calculated by Eq (1):

$$F^{outflow}(t) = \sum_{1}^{k} \left( F_{t,k}^{inflow} \times C_{t,k} \times R_{t,k} \right) \quad (1)$$

where $F^{outflow}(t)$ and $F_{t,k}^{inflow}$ refers to the outflow/inflow of producing Gd-containing product $k$ in the year $t$; $C_{t,k}$ means Gd content in the Gd-containing product $k$ of the year $t$; $R_{t,k}$ is the resource recovery rate of Gd-containing.

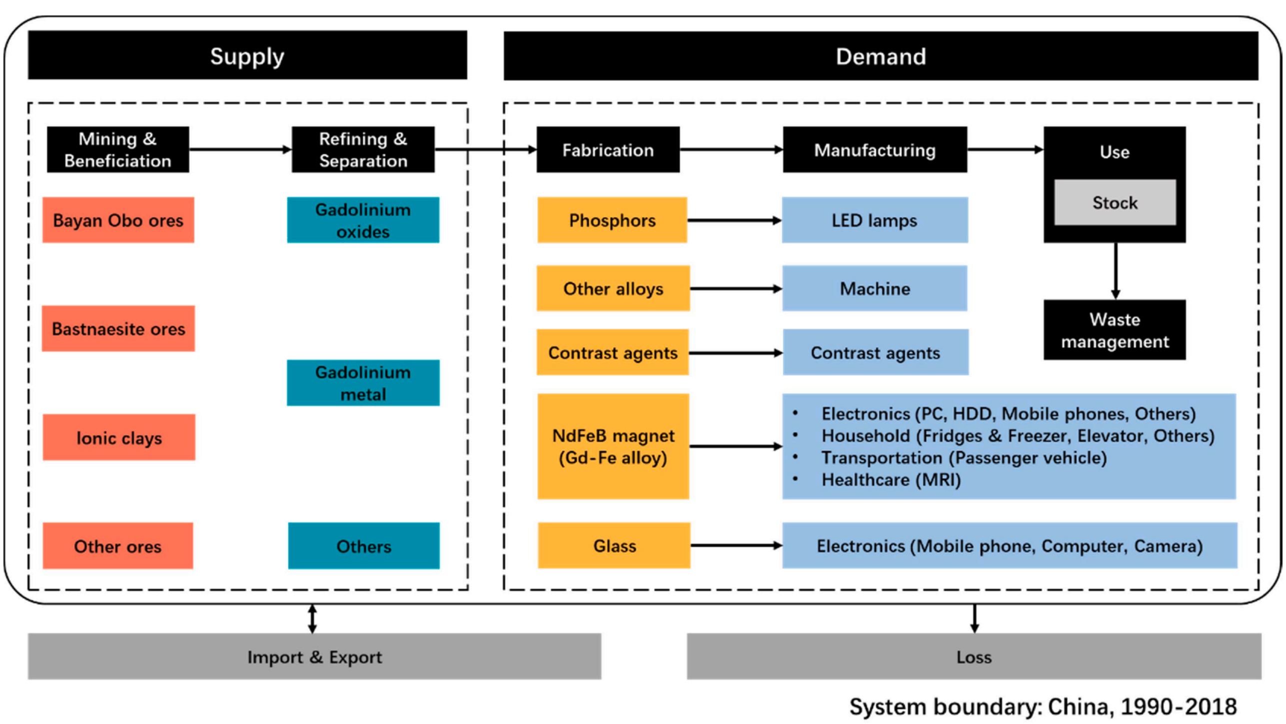


**Fig. 1.** The accounting framework of Gd's supply and demand.

#### 2.2.1. Gd oxides trade

Gadolinium oxides' trade data was estimated by Eq (2) and based on the trade data of "Other rare earth oxides (28,469,019)" in China Customs Statistics Yearbook and Gd content in "other" rare earth oxides production in different countries (see Table S2).

$$F_t^{import} = \sum_1^i \left( V'_{t,i} \times \frac{P_{t,i}}{P'_{t,i}} \times \mathrm{C} \right)$$
$$F_t^{export} = V'_t \times \frac{P_{t,i=China}}{P'_{t,i=China}} \times C \qquad (2)$$

Where $F_t^{import}$ and $F_t^{export}$ means the amount of Gd content in imported/exported Gadolinium oxides in the year $t$; $V'_{t,i}$ is the volume of other rare earth oxides (28,469,019) trade between China and country $i$ in the year $t$; $P_{t,i}$ is the production of Gd in country $i$ in the year $t$; $P'_{t,i}$ is the sum of production of "other" REEs, defined by HS code 28,469,019 in country $i$ in the year $t$; $C$ means Gd content in Gadolinium oxides.

### 2.3. Demand accounting

#### 2.3.1. Inflow and outflow

In this study, "fabrication", "manufacturing", "use", and "waste management" stages are defined as Gd's demand. If the outflows and split ratios in the fabrication stage cannot be obtained, the outflow of producing each product was calculated based on their inflow in the manufacturing stage, the Gd content, and the market share, as shown in Eq (3):

$$F^{outflow}(t) = \sum_1^k \left( F_{t,k}^{inflow} \times C_{t,k} \times M_{t,k} \right) \qquad (3)$$

where $M_{t,k}$ is the market share of Gd-containing product $k$ in the year $t$.

#### 2.3.2. In-use stock

Gd in-use stock is the amount in active use in society. The in-use stock changes annually, and this study used the top-down approach to determine Gd in-use stocks. The basic principle is that in-use stock for the current year is calculated based on the stock for the previous year, as well as the current year's net inflow, as expressed by Eqs. (4) and (5):

$$F_{t_1}^{stock} = F_{t_0}^{stock} + \sum_{t=t_0}^{t_1} \left( F_t^{inflow} - F_t^{outlow} \right) \qquad (4)$$

$$F_t^{outlow} = \sum_{m=1}^{lifetime} F_{t-m}^{inflow} \times P_m \qquad (5)$$

where $F_{t_1}^{stock}$ and $F_{t_0}^{stock}$ are the in-use stock at the year $t_1$ and year $t_0$, respectively; $F_t^{inflow}$ and $F_t^{outlow}$ means Gd's input/output volume in the use stage of the year $t$. $P_m$ is the probability of product serving for $m$ years, estimated using Normal distribution.

#### 2.3.3. Gd use in NdFeB magnets

We used a bottom-up approach to estimate the Gd usage in NdFeB magnets with different grades. Given that the addition of Gd at over 1.0 wt. % reduces magnet performance (see Fig. S2), it is almost never added to high-performance NdFeB magnets with higher grades (e.g., UH/EH/SH (Ultra High/Extreme High/Super High)), which are used in PHEV and wind turbines. For NdFeB magnets with grade H, Gd is added in moderation to achieve a balance between cost and performance. Only "low-performance" NdFeB magnets with grade N/M (N: the initial letter of Neodymium, M: Medium) contain excess Gd to save cost (Yan et al., 2012). Therefore, we distinguished the Gd content of various applications according to the magnet grade as shown in Table 1 (Smith and Eggert, 2016; U.S. Department of Energy, 2022; Yushuo strong magnets, 2023). Based on the estimated Gd content and the production of various NdFeB magnets, the Gd usage of different NdFeB magnet applications is calculated.

**Table 1**
Grade of NdFeB magnets, application, and estimated Gd content.

| Application | Grade of NdFeB magnets | | |
|---|---|---|---|
| PC | | H | |
| HDD | M | | |
| Mobile phones | | H | |
| Headphones Loudspeaker | M | | |
| DVD player | N | | |
| Fridges & Freezer | N | | |
| Elevator | | H | |
| Air conditions | | | UH |
| Washing machine | N | | |
| Electric bikes | | H | |
| PHEV | | | EH |
| Passenger vehicle (ICE) | | H | |
| MRI | N | | |
| Wind | | | SH |
| Robots | | H | |
| **Gd content** | **5.0 %** | **1.5 %** | **0 %** |

### 2.4. Forecast of Gd supply-demand in 2030

In this study, the domestic supply and demand of Gd in China from 2019 to 2030 is predicted using the historical growth rate as a basis. Due to the uncertainty of heavy rare earth trade in the future, import and export are not taken into account. The growth rate of domestic supply from Bayan Obo ores and bastnaesite ores is estimated based on the historical growth rate of the production quota for light rare earths during the period of 2018 to 2022. It's assumed that Gd production from ionic clays in southern provinces of China would remain constant due to most mines not meeting China's environmental regulations and being closed at present. The domestic demand for Gd applications is estimated to grow at the same rate as in previous years. The average annual growth rate of each type of application is calculated based on the average growth rate from 2016 to 2018, with the assumption that the Gd content in Gd-containing products would remain constant.

### 2.5. Data sources

The data used in this study is taken from various sources, such as national statistical yearbooks, published books, academic literature, and industry reports. The production data in the life stage of "Mining & Beneficiation" and "Refining & Separation" are collected from *the National Minerals Information Center of the United States Geological Survey* and the *Yearbook of Chinese society of rare earths* (the Chinese Society of Rare Earths, 2019; the National Minerals Information Center of the United States Geological Survey, 2023). The production data in the life stage of "Manufacturing" and "Use" are collected from *China Statistical Yearbook, China Electronics Industry Yearbook, the Chinese society of rare earths Yearbook*, the industry reports of *Roskill*, and others (Ministry of Industry and Information Technology of the People's Republic of China, 2019; National Bureau of Statistics, 2019; Roskill, 2017; the Chinese Society of Rare Earths, 2019). The trade data are obtained from *United Nations Trade Database* and *China Customs Statistics Yearbook* (China Customs, 2019; the United Nations, 2023). The lifetime data used for in-use stock calculation is obtained in academic literature (see Table S3). The Gd content and other information about its use in NdFeB are obtained through adequate expert consultation. Detailed information on data sources is presented in Table S1.

## 3. Results

### 3.1. Gd demand and supply imbalances

Overall, Gd's supply and demand balance is surplus in China. Between 1990 and 2018, China produced 34 kgtons of Gd metals/compounds in the "Refining and Separation" stage, with 53 % originating from the southern provinces of China. During the same period, the majority (78 %) of the Gd mineral (14 kgtons) consumed was used as a final product in China.

The study's results demonstrate that Gd's supply and demand balance follows a pattern of periodic " scarcity-abundance " between 2000 and 2018 (see Fig. 2). In 2000, there was an 80-ton Gd shortage resulting from lower domestic supply and higher resource export (846 tons) of Gd minerals in China. Approximately 76 % of Gd was exported as Gd metals/compounds. From 2000 to 2006, Gd production from ionic clays rose by 1.3 times to 1824 tons, resulting in a 720-ton Gd surplus in 2006. In 2011, China's Gd market experienced a shortage (670 tons) due to the diminishing Gd supply and rising Gd exports. In 2018, in response to sudden changes in the trade structure, 2219 tons of net imports make up the strong Gd demand of the manufacturing industry in China, resulting in a 2040 tons surplus.

As shown in Fig. 3a, China's Gd mineral production increased by 13 times between 1990 and 2006, from 180 tons per year to 2300 tons per year. However, during 2006–2018, the supply of Gd has declined from 2342 tons to 966 tons because of the decline of production from ionic clays. Moreover, their Gd content was seven times higher than that in Bayan Obo ores and bastnaesite ores, as shown in Fig. 3c. These mines from ionic clays contributed 78 % of China's Gd supply in 2006 (1800 tons) and 79 % of its supply growth during 1990–2006 (1700 tons). In 2014, the mineral production of Gd in China fell to a low of 550 tons/yr, before rising to about 970 tons/yr in 2018 (only 22 % of the Gd mineral was mined from ionic clays).

China has been the world's largest rare earth exporter, cumulatively exporting 16 kilotons of Gd minerals during 1990–2018, as shown in Fig. 3b. However, China's rare earth exports have declined during 2010–2011. In 2013, the export of Gd minerals dropped to 232 tons/yr, and since then, China's Gd mineral exports have remained relatively stable, as depicted in Fig. 3d. Meanwhile, in 2018, China imported significant amounts of high Gd content rare earths from Myanmar (2000 tons Gd) and Malaysia (300 tons Gd), as illustrated in Fig. 3c. This shift in China's Gd mineral trade has resulted in net imports and effectively replenished the Gd supplies in China.

### 3.3. The substantial increase of Gd demand in NdFeB magnets

Fig. 4a illustrates that Gd's main applications are found in glass and NdFeB magnets. Prior to 2004, glass was the largest end-user of Gd in China, accounting for over 36 % of Gd's total demand. In 2005 the demand for Gd in NdFeB magnets in China reached 240 tons/yr, surpassing glass as the largest end-user of Gd. In 2018, the demand for Gd in NdFeB magnets increased further to 608 tons/yr, accounting for 59 % of Gd's total demand.

As shown in Fig. 4b, electronics, particularly headphones and loudspeakers (see Fig. S3), is the primary application among the four major permanent magnet applications of Gd mineral. In 2018, electronics contributed 63 % of Gd demand in NdFeB magnets (310 tons) and 63 % of its growth during 1990–2018.

The in-use stocks of Gd increased continuously with an annual growth rate of 24 % from 1990 to 2018, reaching about 6000 tons in 2018 (see Fig. 4c). NdFeB magnet's share in total Gd stocks increased from 15 % in 1990 to 75 % in 2018, indicating that it was the major driver of the growth in Gd stocks. However, 46 % of Gd waste was in glass during 1990–2018 (see Fig. 4d). Gd waste in NdFeB magnets reached 230 tons/yr and exceeded that in glass (224 tons/yr) in 2016.

### 3.4. The potential risk of Gd shortage in the 2030s

The demand for Gd is expected to increase rapidly driven by the growth of the NdFeB magnets industry. However, based on historical data of rare earth production and NdFeB magnets production, it is anticipated that ionic clays will not effectively replenish the Gd supply,

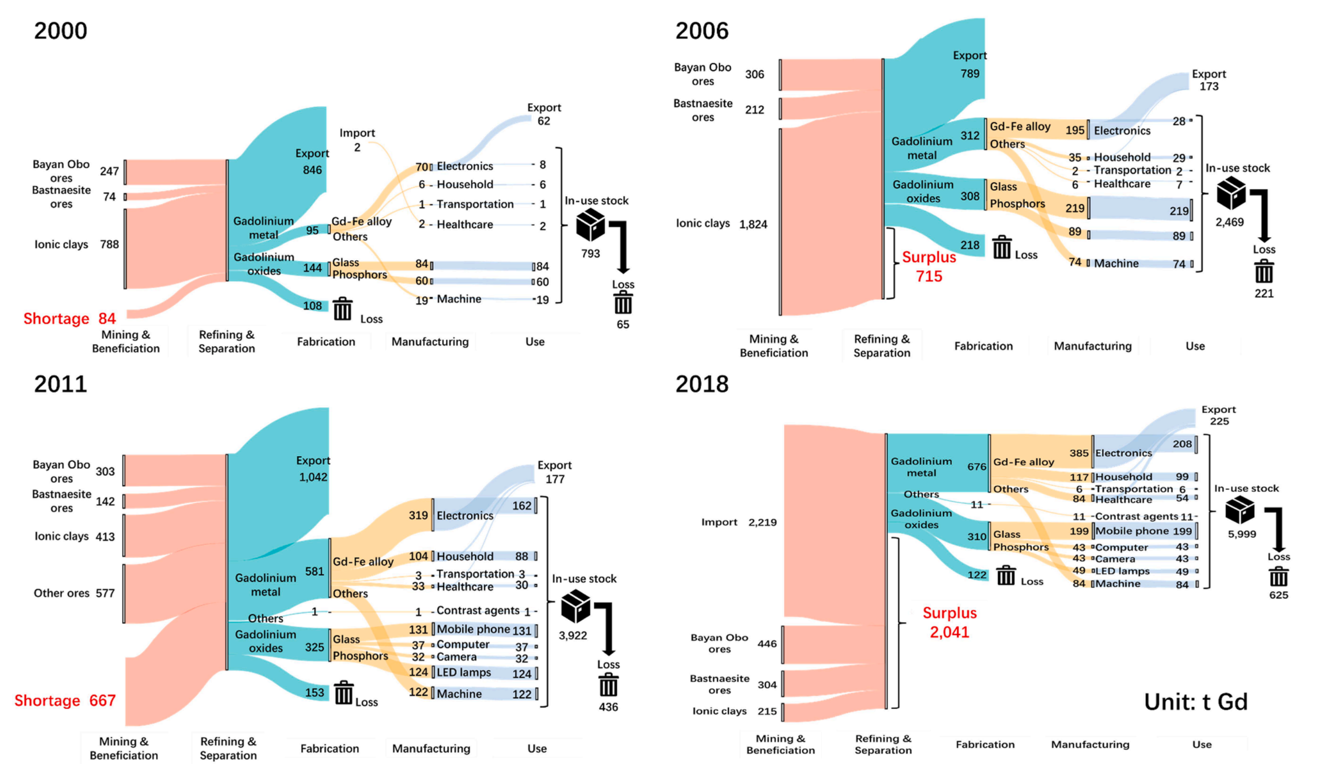


**Fig. 2.** Changes in China's Gd supply and demand conflicts in 2000, 2006, 2011, and 2018.3.2. The rapid decline of domestic supply and export.

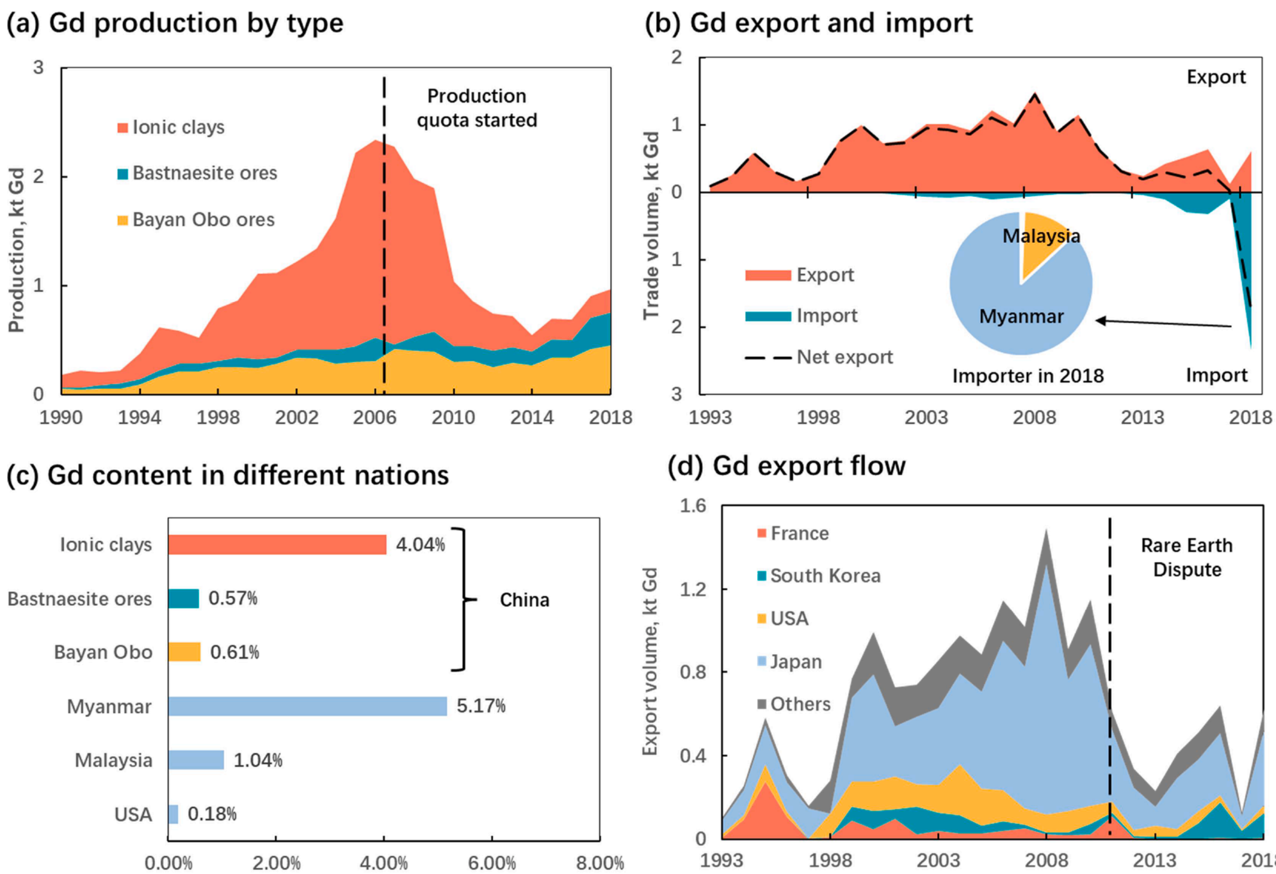


**Fig. 3.** Production (a), trade (b, d), and content (c) of gadolinium minerals in China, 1990–2018.

accounting for only 11 % of China's Gd supply (see Fig. 5b). Bayan Obo ores and Bastnaesite ores have become the primary sources of China's Gd supply, contributing with 78 % of the Gd supply in 2018 and projected to contribute with 89 % of the Gd supply in 2030 (see Fig. 5b). Furthermore, with the expansion of the magnets industry, more than 70 % of Gd will be utilized in N&M grade NdFeB magnets (see Fig. 5c). Based on the historical growth rate, it is predicted that there will be a Gd shortage of approximately 830 tons in 2030.

## 4. Discussion

### *4.1. Failure of present supply-side attention on addressing critical mineral challenges*

Currently, the management of critical minerals in the USA and other countries is primarily based on quantitative assessments of minerals' "criticality" (European Commission, 2017; Lusty et al., 2021; Nassar, 2021). These assessments typically focus on the supply side and quantify supply risk based on the geographic concentration of production, net import reliance, and downstream applications' vulnerability. And the vulnerability of downstream applications, as a dimension to reflect demand, is measured using economic indicators (e.g., GDP) rather than weight indicators (e.g., minerals demand). This is mainly because USA and other countries, as the importers and consumers of critical minerals, are more concerned about security on the supply side, like supply and trade disruption. However, supply-side assessments can be misleading when it comes to understanding the material cycle, especially with respect to future material cycles. On the demand side, such assessments can mislead the prediction of demand changes driven by technological advances (such as the emergence of LED lighting technology, which reduces the demand for europium that was previously used in fluorescent lamps, or the development of electric vehicles, which increases demand for lithium in lithium-ion batteries) (Guo et al., 2021; Wang et al., 2020). On the supply side, such assessments can overlook the potential for secondary supply of critical minerals (such as end-of-life wind turbines as a potential source of recycled neodymium) (Fishman and Graedel, 2019).

Present critical minerals management on the supply-side cannot address the supply and demand conflicts instead of aggravating supply chain security risk from the demand-side. Policymakers' emphasis on minerals competition and supply security can lead to overestimation of the value and scarcity of critical minerals, resulting in increased fear among downstream industry managers regarding their minerals use. This fear can drive up the costs of mineral use and product manufacturing, causing downstream industries to reduce mineral usage and develop alternative materials, ultimately hindering technological innovation and development. A more comprehensive approach to critical minerals management is needed, one that considers both supply and demand factors, and takes into account potential secondary sources and end-of-life recycling. This approach will help ensure a sustainable and secure supply of critical minerals while promoting technological innovation and development in downstream industries.

### *4.2. Role of technical applications change in supply-demand conflicts*

The downstream application structure of critical minerals is greatly influenced by changes in technical applications, which in turn affects the balance of supply and demand. The development of the NdFeB magnets industry has had a significant impact on the demand for Gd in China. From 2000 to 2018, the demand for Gd increased rapidly by an average of 9 % per year due to the changing application structure. NdFeB magnets became the most important application of Gd in 2005. The production expansion also led to China's regional advantage in developing downstream industries. During the 1990s and 2000s, the US and

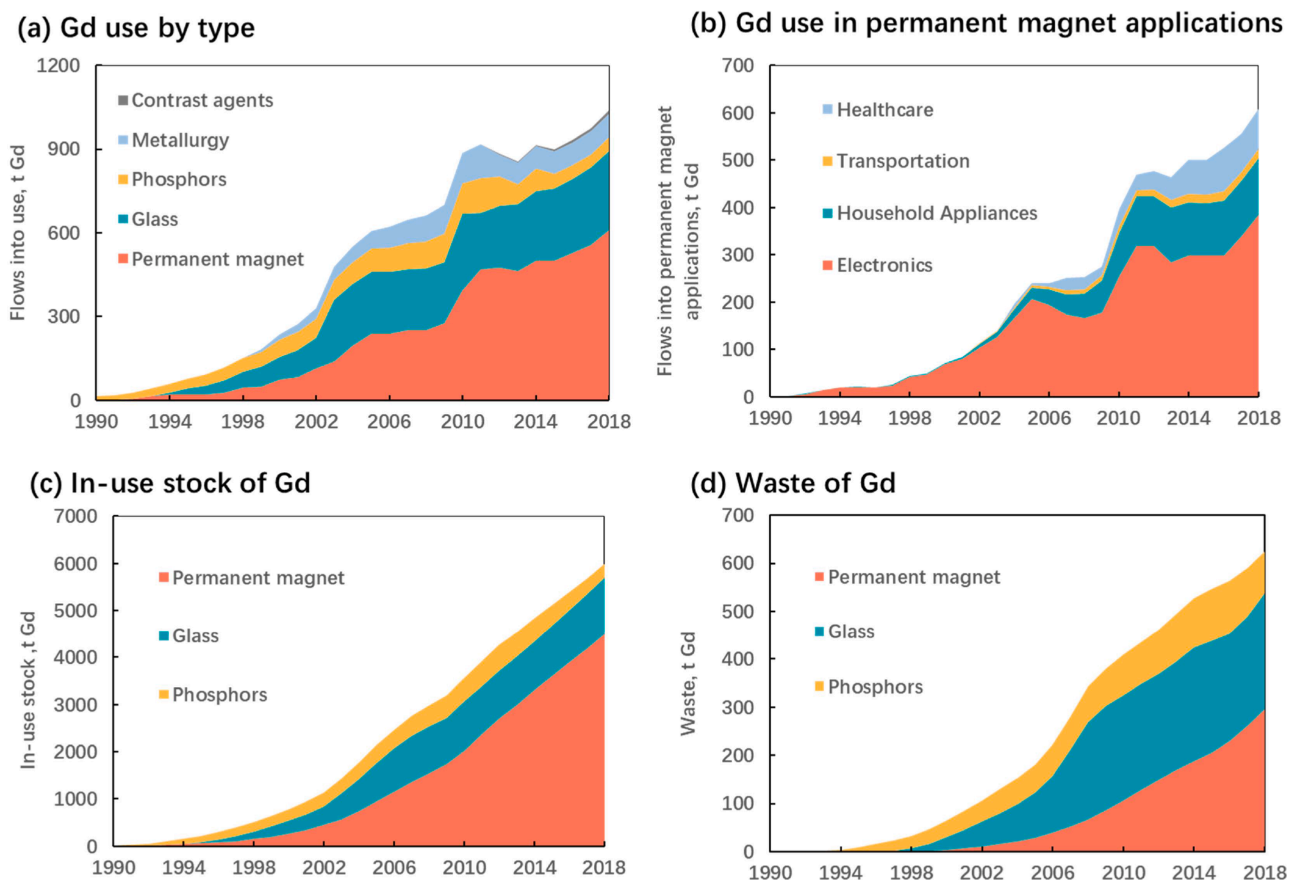


**Fig. 4.** Flows of Gd into use stage (a, b), in-use stock (c) and waste (d) of gadolinium: China, 1990–2018.

Japan's rare earths magnetic facilities and technologies moved to China. Magnequench and Seiko Epson Corporation, for example, shifted their magnets production to China in 2000 and 1995, respectively (Clair, 2006; Nikkei Net Interactive, 2002). This shift in production to China contributed to the rapid increase in Gd demand by 14 % per year from 2000 to 2010. However, the Gd surplus decreased to ~150 tons in 2010 due to the combined influence of increasing Gd demand in NdFeB magnets and reducing Gd supply.

The shift in technical applications of critical minerals also brings about new challenges, such as rising costs and the emergence of substitute products, which impact the demand for these minerals. The surge in demand for Gd began after 2011, when Nd prices soared, and Gd was used as a cheaper alternative in NdFeB magnets. Despite the recent decline in Nd and other REEs' prices, the excessive use of Gd in NdFeB magnets has continued to increase due to China's rapid production expansion of these magnets. By 2016, 57 % of Gd (527 tons) was consumed in NdFeB magnets, leading to a Gd shortage of 240 tons. Although the shortage was offset by the import of rare earths in 2018, the demand for Gd, especially for NdFeB magnets, is expected to continue to rise.

### *4.3. Future emerging applications will further expand Gd's demand*

The balance of supply and demand for critical minerals is not only affected by current technical applications, but also by emerging applications. Gd, for instance, has potential applications in magnetic cooling (Mozharivskyj Molecular Sciences and Chemical Engineering, 2016) and high-temperature superconductors (Cardwell et al., 2010; Shi et al., 2008). These emerging applications may bring potential shortage risk and further affect the balance of supply and demand for Gd. The development of emerging applications driven by low/zero carbon economy (Breyer et al., 2022; Smith Stegen, 2015; P. Wang et al., 2022), such as magnetic refrigeration and high-temperature superconductors, will likely increase the demand for Gd. Each 100 W magnetic refrigerator requires a minimum of 300 tons of Gd (Bjørk et al., 2011). Therefore, if the production of magnetic refrigerators increases to 1 % of China's refrigerator production in 2030, the Gd shortage will increase by 50 %.

Under the influence of factors such as technology, policies, and market supply and demand, the scarcity or abundance of resources may be continuously changing (May et al., 2012; Wellmer and Scholz, 2017). Considering the potential market demand for emerging applications of Gd in the context of carbon neutrality goals, it is important to monitor changes in Gd supply and demand and conduct comprehensive and dynamic analysis of the entire supply chain using material flow analysis methods.

### *4.4. Strategies to cope with the Gd supply storage challenges*

The increasing use of Gd in NdFeB magnets and the limited supply of Gd in China will result in a Gd shortage of approximately 830 tons in 2030. In order to address this issue, several measures can be taken:

(1) *Recycling Gd from NdFeB magnets applications.* In 2018, 5200 tons of Gd have stocked in waste products, more than five times China's production in the current year. Hence, it is feasible to address potential Gd shortages through recycling, especially the NdFeB magnets recycling (Rademaker et al., 2013). However, the recycling of Gd from waste products is not yet in place and still faces great challenges, such as low collection rate among waste streams, inefficient sorting and dismantling, and high recycling

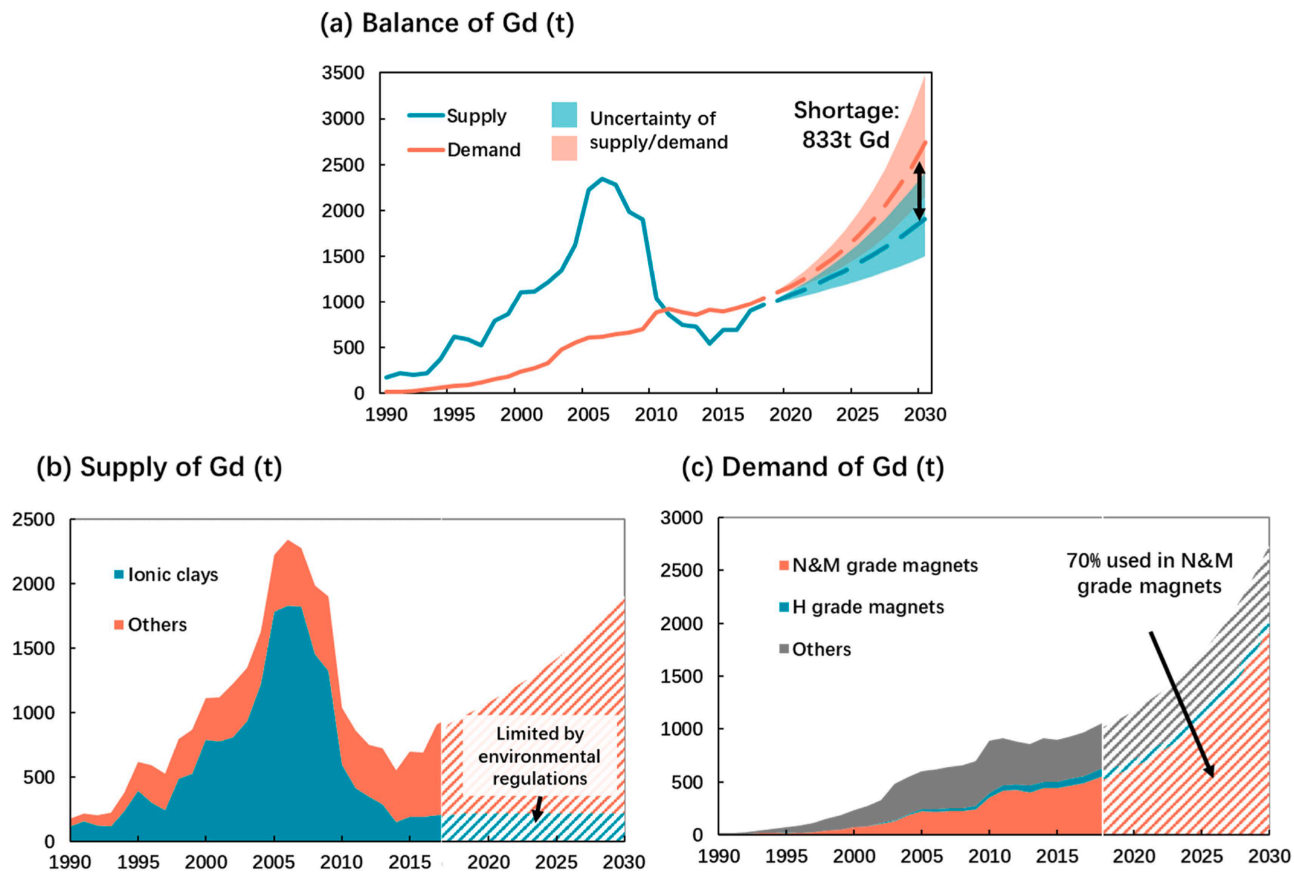


**Fig. 5.** The balance between supply and demand of Gd in China, 1990–2030.

cost (Reck and Gradel, 2012). Viable solutions addressing the various challenges of recycling Gd are needed.

(2) *Strengthen global cooperation on Gd supply chains.* Geopolitics can indeed impact the supply chains of critical minerals, subsequently affecting global energy transition efforts. However, the stability of critical minerals supply chains and the achievement of carbon neutral targets require global cooperation. With the maturity of technologies like magnetic cooling, Gd may play a crucial role in the future global energy transition. Hence, it is essential to reduce Gd supply chain risk. Currently, China (resource supply), the U.S. (production of high-performance NdFeB magnets and applications) and Europe (production of applications) play different roles in the rare earth supply chain and have different advantages in various supply chain stages (Ren et al., 2021; The White House, 2021; WU et al., 2023). These countries need to engage in technological and industrial cooperation to collectively enhance the resilience of the rare earth supply chain and promote the achievement of carbon neutral targets.

(3) *Downstream technical innovations to reduce Gd usage.* Substituting expensive minerals with surplus minerals in manufacturing (like cerium (Ce) and Gd used in NdFeB magnets) is a common measure to reduce cost. But the demand for Gd in emerging applications (like magnetic cooling) should be met as a priority. Based on the results of this study and existing studies, Gd usage in NdFeB magnets should be limited to less than 1 %. Further research on reducing Gd usage is necessary to guide industry transformation to produce NdFeB magnets and magnetic cooling applications with low Gd content.

### *4.5. Limitations*

This study focused on the impact of Gd usage in NdFeB magnets on its' supply and demand. The Gd usage is estimated based on the static Gd content of different NdFeB magnet applications. According to the expert consultation, the practice of adding Gd into NdFeB magnets in Chinese companies has persisted for over a decade. Considering the recent price hikes after 2011and 2021, these companies may lean toward increasing the Gd content in NdFeB magnets to reduce Nd content and then reduce cost. Consequently, it is important to estimate the dynamic Gd content within various NdFeB magnet applications over time for future research. This will be crucial in studying the impact of rare earth price fluctuations on Gd supply and demand. Furthermore, given the closure of certain rare earth mines in Myanmar, a more detailed scenario analysis on the prospective global Gd production is necessary for assessing the potential risk of Gd shortages in the future.

## 5. Conclusion

This study (1) developed a comprehensive quantitative modelling of the Gd supply chain in China from 1990 to 2018 and (2) provided a qualitative review and discussions on Gd supply-demand balance in a holistic perspective. The results indicate that China's production of Gd mineral from 1990 to 2018 totaled 34,000 tons, of which 53 % was sourced from ionic clays in southern provinces of China. However, Gd production in China declined from 2300 tons per year in 2006 to 970 tons per year in 2018 due to stricter environmental regulations. On the demand side, Gd's largest end-user in China is in low-performance NdFeB magnets, accounting for 52 % of Gd's total demand in 2018. As the usage of Gd in NdFeB magnets increases, a shortage of approximately 40 tons of Gd appeared in 2018, and this shortage is expected to expand to 833 tons in 2030 (if import and export are not taken into account).

This study sheds light on the potential threat of a Gd shortage driven by its use in NdFeB magnets. To mitigate this threat, this study recommends improving recycling methods, expanding imports, and strictly controlling Gd usage. Furthermore, our analysis highlights the importance of joint management and measurement of critical minerals at both the supply and demand sides.

## CRediT authorship contribution statement

**Shen Zhao:** Formal analysis, Investigation, Data curation, Formal analysis, Writing – original draft. **Peng Wang:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Wei Chen:** Investigation, Data curation, Formal analysis. **Lu Wang:** Investigation, Data curation, Writing – review & editing. **Qiao-Chu Wang:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Wei-Qiang Chen:** Writing – review & editing, Funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The authors do not have permission to share data.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.107254.

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