Environmental Science & Technology

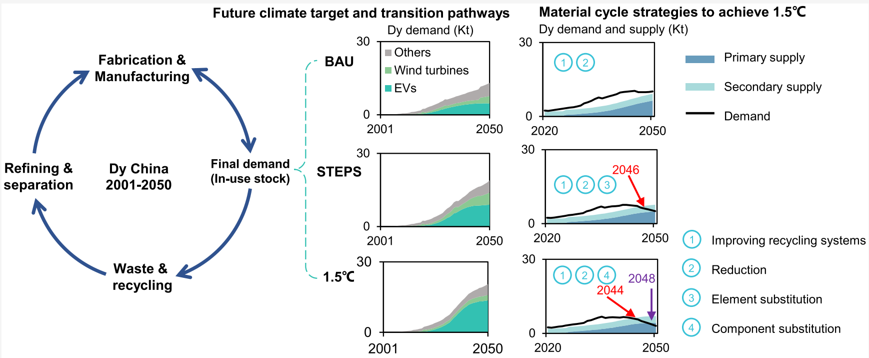
pubs.acs.org/est

Policy Analysis

Unlocking Dysprosium Constraints for China's 1.5 °C Climate Target

Tao Dai,[#] Yan-Fei Liu,[#] Peng Wang,* Yang Qiu, Nabeel Mancheri, Wei Chen, Jun-Xi Liu, Wei-Qiang Chen,* Heming Wang, and An-Jian Wang*

Cite This: *Environ. Sci. Technol.* 2023, 57, 14113−14126



ABSTRACT: Some key low-carbon technologies, ranging from wind turbines to electric vehicles, are underpinned by the strong rare-earth-based permanent magnets of the Nd, Pr (Dy)−Fe−Nb type (NdFeB). These NdFeB magnets, which are sensitive to demagnetization with temperature elevation (the Curie point), require the addition of variable amounts of dysprosium (Dy), where an elevation of the Curie point is needed to meet operational conditions. Given that China is the world's largest REE supplier with abundant REE reserves, the impact of an ambitious 1.5 °C climate target on China's Dy supply chain has sparked widespread concern. Here, we explore future trends and innovation strategies associated with the linkage between Dy and NdFeBs under various climate scenarios in China. We find China alone is expected to exhaust the global present Dy reserve within the next 2−3 decades to facilitate the 1.5 °C climate target. By implementing global available innovation strategies, such as material substitution, reduction, and recycling, it is possible to avoid 48%−68% of China's cumulative demand for Dy. Nevertheless, ongoing efforts in REE exploration and production are still required to meet China's growing Dy demand, which will face competition from the United States, European Union, and other countries with ambitious climate targets. Thus, our analysis urges China and those nations to form wider cooperation in REE supply chains as well as in NdFeB innovation for the realization of a global climate-safe future.

KEYWORDS: *Dysprosium, China 1.5 °C Climate Target, Rare Earth, NdFeB Magnets, Technology Innovations*

1. INTRODUCTION

The conflicts between critical minerals supply and climate change mitigation pathways have received a growing interest.[1−3] Rare earth elements (REEs) are of great concern[4] due to their high criticality for low-carbon technologies.[5] Dysprosium (Dy), as one of the most risky and critical REEs, is used as an additive in the strongest magnets, neodymium−iron−boron permanent magnets (NdFeBs),[6] because it can improve coercivity and high-temperature properties to keep excellent magnetic performance.[7] These unique properties make Dy indispensable to support the rapid development of electric vehicles (EVs) equipped with synchronous NdFeB-based motors,[8] offshore wind turbines equipped with synchronous NdFeB-generators,[9] and other key applications where miniaturization rendered possible thanks to NdFeB is of major importance (e.g., air conditioner, industrial robot, hard disks, smartphones, portable electric and electronic equipment, defense systems). Accordingly, Dy is deemed a critical material by the United States (US),[10,11] Japan,[12] European Union (EU),[13,14] and Australia,[15,16] etc., which have released a series of reports to ensure supply to meet the increasing demand (Tables S2−S4). To avert the pressing global climate crisis, China has launched an ambitious low-carbon transition in line with its 1.5 °C climate target. Previous related work has explored the need and feasibility of decarbonization efforts in energy,[17] transportation,[18,19] material production,[20,21] or other systems.[22] Compared to those, the conflicts amid the linkages between China's critical mineral supply chains and climate change mitigation pathways are not well explored.[23] This is

Received: February 16, 2023
Revised: August 29, 2023
Accepted: August 29, 2023
Published: September 14, 2023

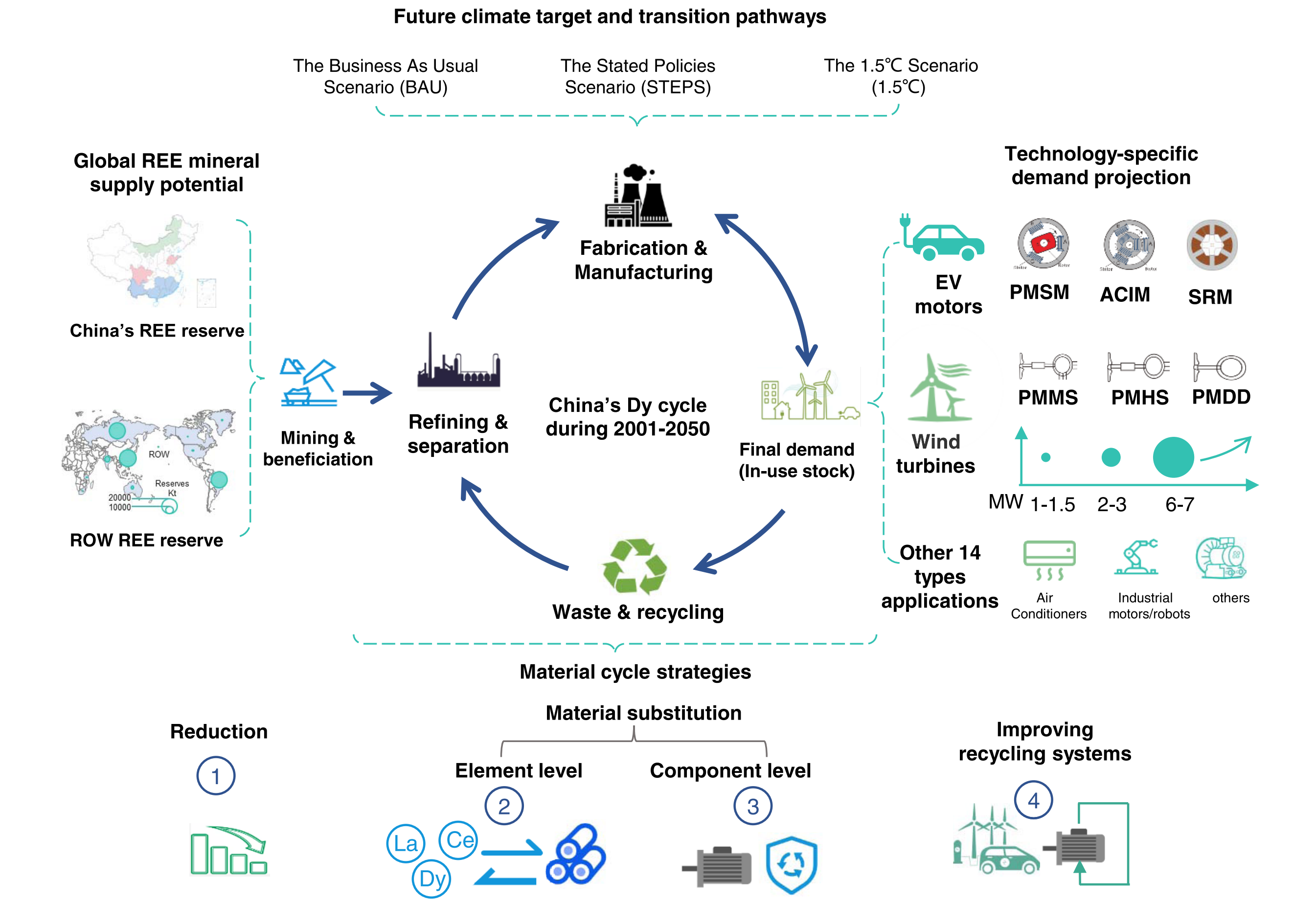


Figure 1. Framework for Dy-NdFeB future projection and decoupling strategies analysis (permanent magnet synchronous motor (PMSM), AC induction motor (ACIM), switched reluctance motor (SRM); permanent magnet gear middle speed (PMMS), permanent magnet gear high speed (PMHS), permanent magnet direct drive (PMDD)).

particularly true for REEs given that China has abundant REEs reserve and significance influence in global REEs market.[24] However, under the 1.5 °C climate target, China is devoted to expanding its deployment of EVs, wind turbines, and other necessary low-carbon technologies at unprecedented scales and rates. Hence, we see an urgent need to focus on Dy and explore its future demand and supply under different climate scenarios, as to investigate the potential supply bottlenecks and solutions of REEs supply toward China's low-carbon transition.

Previous studies on Dy have traced its historical flows and stocks at global,[25,26] regional (e.g., Europe),[27] and national (e.g., Japan,[28] China[7,29]) levels using material flow analysis. Moreover, studies focusing on the future demand of Dy have upsurged at both global,[9,30−35] and national (e.g., US,[32,36] Germany,[37] Netherlands,[38] Japan,[39] China[40−43]) levels for specific applications, and the results indicate that Dy demand is expected to rise rapidly. However, most of those previous studies only focus on one specific application of Dy, while the comprehensive and forward-looking analysis of all end-use applications with the consideration of technical innovations in NdFeBs has rarely been explored. This may lead to the limited understanding of potential mitigation strategies. Notably, the development of material substitution, reduction and improvements in recycling are three potential decoupling measures.[11,44,45] For instance, many corporations are currently engaged in creating new types of magnets to reduce or eliminate of REEs or Dy in NdFeBs (e.g., Toyota,[46] Tesla,[47] Niron Magnetics,[48] Hitachi[49]). Moreover, many motors producers have already prioritized lowering or eliminating REEs in motors via various approaches (e.g., traction motor,[50,51] electrically excited synchronous motor (EESM),[52,53] switched reluctance motor[45]). Given that more EVs and wind turbines start to reach their end-of-life (EoL) in the coming decades, secondary supply through recycling will become more feasible,[54,55] together fueled by some emerging efforts on recycling processes.[56] However, it is still unclear what would be the future trend of Dy demand and what would be the impacts of these potential decoupling measures on Dy supply and demand. Besides, in most studies focusing on future primary supply, the life-cycle losses,[57] which are significant for those critical minerals, are not considered in assessing the future demand and supply changes. This calls for a comprehensive and in-depth investigation on the nexus between the Dy supply chain with NdFeBs demand and the effectiveness of various decoupling strategies to guide further strategic policies.

In this study, we examine China's Dy demand and supply associated with NdFeBs demand during 2021−2050 with three climate scenarios (the business-as-usual scenario (BAU), the stated policies scenario (STEPS), and the 1.5 °C scenario (1.5 °C), with details in *Methods* part) by integrating the history of the Dy cycle through material flow analysis during 2001−2020 (Figure 1). In particular, we provide a comprehensive projection of Dy demand in all expected NdFeB applications

https://doi.org/10.1021/acs.est.3c01327
Environ. Sci. Technol. 2023, 57, 14113−14126

Table 1. Description and Assumptions of Key Model Parameters

Key Parameters	Descriptions/Assumptions	Details
Population	In response to the aging population, the Chinese government implemented separate "two-child" and "two-child policy" in 2014 and a "three-child policy" in 2021. We used the medium scenario that the people will start decreasing from 2032 and will be 1.3694 billion in 2050.[62]	Table S14
Urbanization rate	The urbanization rate will reach 80% in 2050.[63] The total of urban families is 2.9 persons per family and rural families are 3.9 persons per family.[64]	Table S14
Stock-driven model	Vehicles,[65] electric bicycles, wind turbines,[66] refrigerators, wash machines, air conditioners, microwave ovens, vacuum cleaners, desktops laptops, domestic robots, mobile phones.[59,64,67]	Table S15
Specific growth rate method	High-speed trains,[67] elevators, industrial robots, MRI machines.[59]	Table S16
Passenger vehicle ownership and BEV market share	Passenger vehicle ownership and battery electric vehicles (BEVs) market share is assumed to increase. With 425 vehicles per 1000 people, and BEVs approximately 17.4% of passenger vehicle ownership by 2050 in the BAU scenario; 350 vehicles per 1000 people, BEVs approximately 50% of passenger vehicle ownership by 2050 in the STEPS scenario; 350 vehicles per 1000 people, BEVs approximately 75.8% of passenger vehicle ownership by 2050 in the 1.5 °C scenario.[65]	Figure S6
Wind turbines installation	The accumulative amount of new wind turbines installation is 1826 GW, 3006 GW, and 4186 GW in the studied scenarios.[68]	Figure S6

with a coverage of different phases of Dy supply chain from mining, refinery, trade, throughout to final recycling. Our results indicate that there will be a rising Dy supply shortage that may hinder China's 1.5 °C climate target. Meanwhile, decoupling strategies including material substitution, reduction and recycling available at the global level could effectively alleviate Dy shortage, and further achieve a closed-loop in the long term (2036−2050). However, the supply shortage is likely to be inevitable in the short- to medium-term (2021−2035), and China's Dy demand will need to partially rely on import from other countries. Thus, facing various constraints and the urgent need for low-carbon transition, we appeal to promote the linked cooperation between global climate change mitigation with international cooperation at supply chains of REE as well as other critical materials.

2. MATERIALS AND METHODS

2.1. Linking NdFeBs Demand with Dy Supply Chains. *2.1.1. System Boundary and Definition.* The framework for the Dy cycle is shown in Figure S4. The Dy flows and stocks in mainland China during the period 2001−2050 are examined. The anthropogenic Dy cycle in the lithosphere can be divided into six stages: mining and beneficiation, refining and separation, fabrication, manufacturing, use, and waste and recycling. Dy flows into the refining and separation can be divided into two sources: Dy compounds from mining and beneficiation (primary supply) and Dy old scrap recycled from EoL (secondary supply). The quantification process is given as follows:

2.1.1.1. Historical Dy Stocks and Flows. Based on the historical Dy flows and stocks in previous studies,[7,58] we study the flows and stocks of Dy from 2001 to 2020 using a top-down dynamic material flow (MFA) method. The domestic Dy demand is calculated by eqs 1−2:[59,60]

$$\mathrm{DC}_j(t) = \mathrm{FC}_j(t) \times C_j(t) \times \mathrm{MR}_j(t) \tag{1}$$

$$\mathrm{DC}_{\mathrm{Dy}}(t) = \sum \mathrm{DC}_j(t) \tag{2}$$

where j and t represent a final product and year; $\mathrm{DC}_j(t)$ represents Dy demand of a final product j; $\mathrm{FC}_j(t)$ represents the final product j demand; $C_j(t)$ and $\mathrm{MR}_j(t)$ represent the Dy intensity and the market penetration rate; and $\mathrm{DC}_{\mathrm{Dy}}(t)$ represents the Dy demand of all final products. It is assumed that the Dy intensity is fixed and does not change in each final product during the studied period. However, the market penetration rate of final products could change due to technology advancements. We have detailed the quantification of historical Dy stocks and flows from 2001 to 2020 in Table S6−S11. The cumulative Dy cycle in China from 2001 to 2020 is shown in Figure S7.

2.1.1.2. Future Dy Stocks and Flows. We apply the stock-driven model and specific growth rate to simulate future final products demand from 2021 to 2050.[59] With the rapid development of the economy, the per thousand ownerships of vehicles, the per hundred ownerships of mobile phones and laptops, and the per hundred families of household appliances, computers, and electric bicycles will gradually saturate. The stock-driven approach by logistic growth model to predict future demand can be calculated by eqs 3−6.[61]

$$N_j(t) = N_{j\max}/(1 - A_j \times e^{(-B\times(t-t_0))}) \tag{3}$$

$$A_j = -e^{(-B_j\times(t_{1/2}-t_0))} \tag{4}$$

$$S_j(t) = N_j(t) \times H(t) \tag{5}$$

$$\mathrm{CF}_j(t) = S_j(t) - S_j(t-1) + \mathrm{Outflow}_j(t) \tag{6}$$

where j and t represent a final product and year; $N_j(t)$ represents the ownerships of the quantities; $N_{j\max}$ represents the ownerships of the saturation quantities; t_0 represents the initial year; and A_j and B_j are two parameters: A_j can be calculated by eq 4, and B_j is the growth rate of retention rate. $H(t)$ presents the total quantities of households or the total quantities of population; $S_j(t)$ presents the stock; and $\mathrm{CF}_j(t)$ and $\mathrm{Outflow}_j(t)$ represent the final products demand and the old scrap.

It is difficult to calculate the stocks of the other final products (Table S16). Therefore, we use the specific growth rate method to calculate the demand, as shown in eq 7.

$$\mathrm{CS}_j(t) = \mathrm{CS}_j(0) \times (1 + a_j)^t \tag{7}$$

where $\mathrm{CS}_j(t)$ is the final product demand; $\mathrm{CS}_j(0)$ is the base year demand; and a_j is the specific growth rate.

The key model parameters are shown in Table 1.

2.2. Scenario Integration and Simulation. *2.2.1. Climate Change Targets Scenarios.* Three climate scenarios are considered to represent different future demand trajectories of vehicles and wind turbines, namely the Business As Usual Scenario (BAU), Stated Policies Scenario (STEPS), and 1.5 °C Scenario (1.5 °C), which are adopted from World Resources Institute (for vehicles)[65] and literature (for wind turbines).[68] The BAU scenario incorporates the policies and measures that governments have already put in place, as well as the likely effects of announced policies that are expressed in official

https://doi.org/10.1021/acs.est.3c01327
Environ. Sci. Technol. 2023, 57, 14113−14126

targets or plans. The STEPS scenario means estimating the most feasible vehicle and wind power technology paths in the future and analyzing the emission reduction potential, in combination with current and most likely future policies. The 1.5 °C scenario represents the achievement of net zero emissions in the transportation and energy sectors by 2050.

2.2.2. Decoupling Strategies Scenarios. In this work, material substitution and reduction are envisioned to enhance current efforts to reduce Dy demand. Such strategies include reduction scenario (NdFeB with lower Dy intensity, defined reduction); two material substitution scenarios (state-of-the-art NdFeB with zero Dy, defined element substitution; and next-generation REE-free motors innovation, defined component substitution). We design three scenarios based on three strategies: reduction, reduction and element substitution, and reduction and component substitution. The main assumptions of three strategies are described in Table 2. Besides, we design two recycling scenarios to estimate the potential secondary Dy supply. One assumed that the EoL recycling rate would reach 40% by 2050[69] based on historical levels, which is defined as reference recycling. The other assumed state-of-the-art motor recovery technology from 2025 onward[56] and established the recycling policy, regulation, or legislation for EoL, which defined improving recycling systems.

2.3. Future Dy Supply Chain Analysis. *2.3.1. Primary Supply.* We designed two primary supply scenarios. One is called primary supply (with quota) scenario, which contains the primary supply (quota) and the primary supply (others). China has been implementing a production quota policy for REE mining. Dy is mined along with other REEs, and the rapidly growing Dy production could lead to a surplus of other REEs. Thus, the primary supply (quota) from 2021 to 2030 is based on the previous research.[74] It is assumed to increase with an annual growth rate of 1.5% from 2031 to 2050 (details in Figure S12). The primary supply (others) mainly includes import volumes from other countries. The other scenario is called primary supply (without quota). Given the significant of Dy supply in the 1.5 °C climate target, China abandons its production quota policy and further rapidly expand the primary capacity to meet the demand.

2.3.2. Secondary Supply. The secondary supply is modeled in different scenarios as follows:

2.3.2.1. Reference Recycling Scenario. The secondary supply can be estimated by eq 8 during 2021−2050.

$$\mathrm{SS}_j(t) = \mathrm{Outflow}_j(t) \times \mathrm{EE}_j(t) \tag{8}$$

where j and t refer to a final product and year; $\mathrm{SS}_j(t)$ and $\mathrm{EE}_j(t)$ refer to secondary supply and recycling rate; and $\mathrm{Outflow}_j(t)$ represents the old scrap.

2.3.2.2. Improving Recycling Systems Scenario. The secondary supply can be estimated by eqs 8 and 9 during 2021−2025 and eqs 10 and 8 during 2026−2050.

$$\mathrm{EE}_j(t) = \mathrm{CR}_j(t) \times \mathrm{DR}_j(t) \times \mathrm{RR}_j(t) \tag{9}$$

$$\mathrm{EE}_j(t) = \mathrm{CR}_j(t) \times \mathrm{RR}_j(t) \tag{10}$$

where $\mathrm{CR}_j(t)$, $\mathrm{DR}_j(t)$, and $\mathrm{RR}_j(t)$ refer to the final product collection rate, component efficiency rate disassembly, and efficiency rate recycling, respectively.

2.3.3. Import Volumes and Import Dependency. We assume the Dy concentrates trade is the same as that in 2020 in our studies in the following three decades (Figure S5), due to

Table 2. Main Assumptions of Material Substitution, Reduction, and Recycling Strategies

Scenarios	Strategies	Descriptions/Assumptions	Detail
Reduction	NdFeB with lower Dy intensity	Assume that evolutionary progress will reduce the amount of Dy in NdFeB, which is defined as reduction.[40,43,70,71] For example, Toyota creates a new magnet aimed at reducing REEs by up to 50%.[46] China develops heavy rare earth elements (HREEs) reduction technologies such as grain refinement, grain boundary diffusion, and grain boundary regulation.[72] Tesla in US managed to reduce 25% REE contented in their Model 3 in 2017−2022.[47]	Table S19
Material substitution	State-of-the-art NdFeB with zero Dy	Assume that state-of-the-art NdFeB with zero Dy, which is defined as element substitution.[40,43,70,71] For example, Dy and neodymium (Nd) were replaced with lanthanum (La) and cerium (Ce) to suppress the deterioration of coercivity and heat resistance and reduce costs by Toyota.[46] Niron Magnetics in US develops a new Niron Clean Earth Magnet, which manufacturing process combines mature metallurgical methods to deliver high performance magnets at half the cost, and have already partnered with 6 global leading magnet equipment manufacturers.[48]	Table S19
	Next-generation REE-free motors innovation	Assume that revolutionary breakthrough for next-generation REE-free motors innovation, which is defined as component substitution, such as new traction motors.[40,43,70,71,73] Mahle develops a new magnet-free, 95% efficient electric motor with REEs-free. Through inductive and contactless power transmission, new traction motors are wear-free and particularly efficient at high speeds. It will be expected to begin mass production for passenger vehicles in 2023 or 2024.[50]	Table S20
Improving recycling systems	State-of-the-art motor recovery technology	Assume that state-of-the-art motor recovery technology, such as pyrometallurgical recycling process. Nissan and Waseda University in Japan jointly developed a recycling process for electrified vehicle motors. The new process efficiently recovers high-purity REE compounds from motor magnets, a practical application targeted for 2025 toward the 1.5 °C climate target. It can recover 98% of the motor's HREEs. This method also reduces the recovery process and work time by approximately 50% compared to the current way because there is no need to demagnetize the magnets, nor remove and disassemble them.[56]	Table S22
	Recycling policy, regulation, or legislation	Assume that the EoL follows the principle of "Extended Producer Responsibility" and established the policy, regulation, or legislation (i.e., E-waste).[54,55]	Table S23
Reference recycling		Assume that the EoL recycling rate would reach 40% by 2050[69] based on historical levels.	

https://doi.org/10.1021/acs.est.3c01327
Environ. Sci. Technol. 2023, 57, 14113−14126

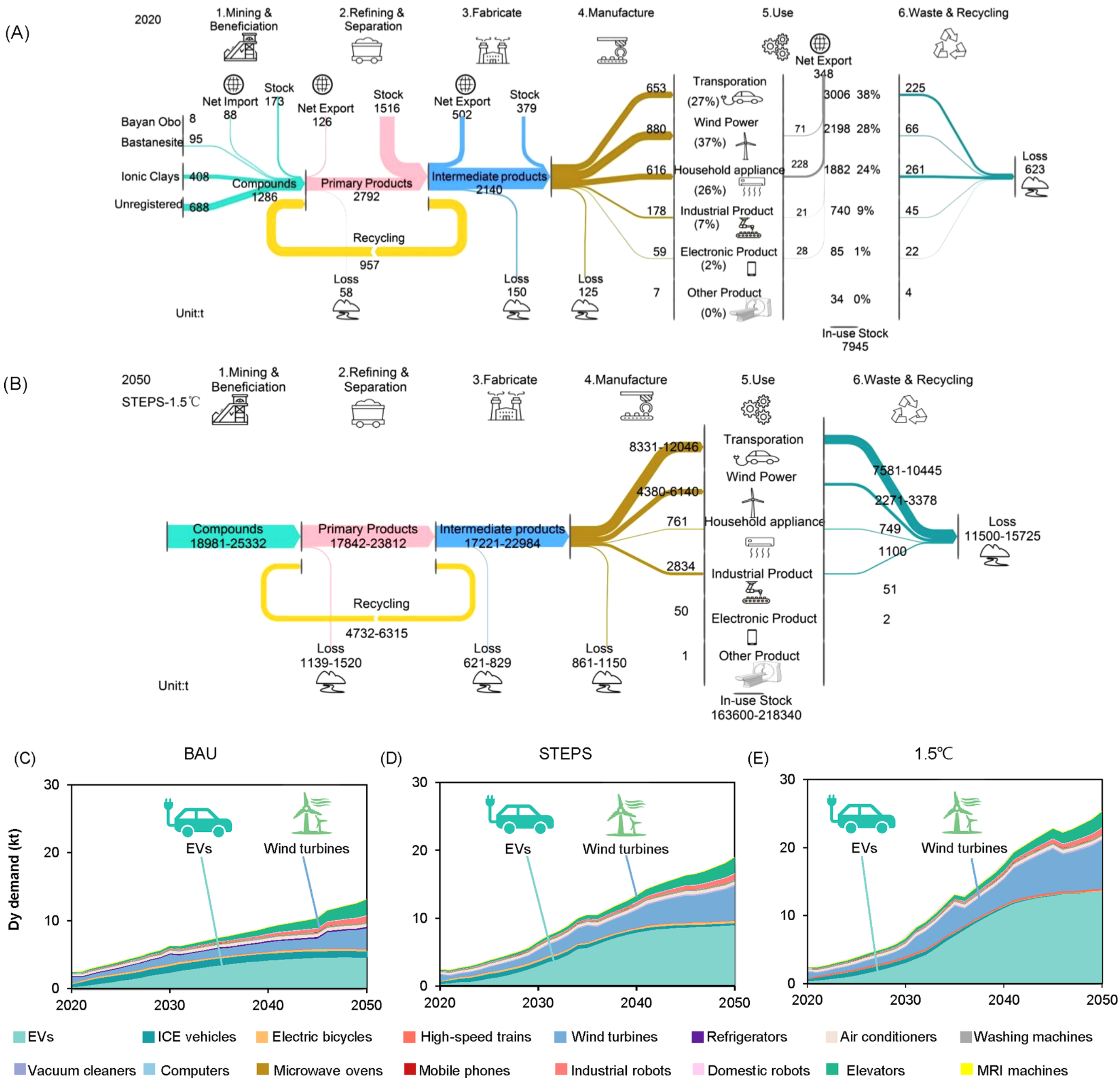


Figure 2. China's Dy flows, stocks, and future demand. (A) Supply chain of China's Dy cycles in 2020. (B) Supply chain of China's Dy cycles in 2050 under the STEPS and 1.5 °C scenarios. (C−E) Dy demand under the BAU, STEPS, and 1.5 °C scenarios.

difficulty in assuming future trade pattern changes. In other words, the import share from other countries is as the same as that in 2020. The import volumes from 2021 to 2050 can be calculated by eq 11, and the import dependency can be calculated by eq 12.

$$\mathrm{IM}_{\mathrm{Dy}}(t) = \mathrm{DC}_{\mathrm{Dy}}(t) - S_{\mathrm{Dy}}(t) \tag{11}$$

$$\mathrm{IMD}_{\mathrm{Dy}}(t) = \frac{\mathrm{IM}_{\mathrm{Dy}}(t)}{\mathrm{DC}_{\mathrm{Dy}}(t)} \times 100\% \tag{12}$$

where $\mathrm{IM}_{\mathrm{Dy}}(t)$ presents the import volumes; $\mathrm{IMD}_{\mathrm{Dy}}(t)$ represents the import dependency; $S_{\mathrm{Dy}}(t)$ presents the total supply (primary supply (quota) plus secondary supply); and $\mathrm{DC}_{\mathrm{Dy}}(t)$ represents the Dy demand.

2.4. Uncertainty Analysis. We model with a normal distribution to characterize the combined impact of parameters uncertainties. The uncertainty ranges are categorized into low, medium, and high.[75] The low level (2%) refers to the data directly collected from the official statistics that are more reliable such as parameters of REE concentrates, final products, and trade volume. The medium level (5%) refers to the data collected from the literature that are medium reliable, such as parameters of market penetration, Dy intensity, and final product demand. The high level (10%) refers to the data estimated based on data sources that are less reliable, such as the parameters of recycling rate, material substitution rate, and reduction rate. To explore the uncertainties of our results, we performed Monte Carlo simulation for 10,000 times, and the final results can be found in Figure S29 of Supporting

https://doi.org/10.1021/acs.est.3c01327
Environ. Sci. Technol. 2023, 57, 14113−14126

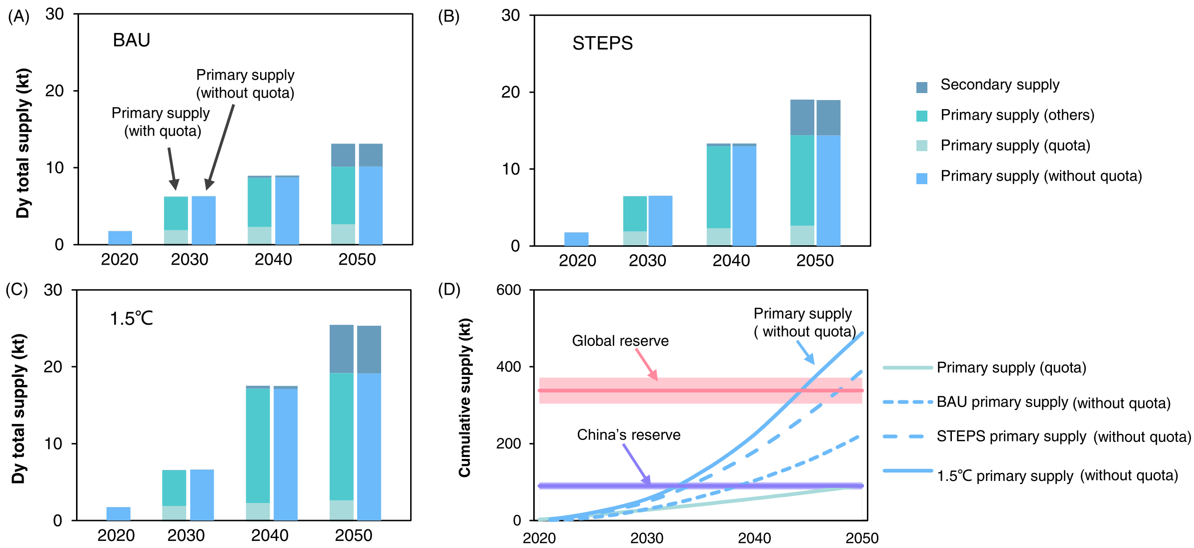


Figure 3. Future Dy total supply and cumulative primary supply. (A–C) Dy total supply (primary supply plus secondary supply) under the BAU, STEPS, and 1.5 °C scenarios. (D) Dy cumulative primary supply (without quota) relative to China's and global present Dy reserve.

Information. Meanwhile, we further explore the validity and limitation of our work in the discussion part.

3. RESULTS

3.1. Skyrocketing Dy Demand in Low-Carbon NdFeB Applications. We first traced Dy flows along China's supply chain in 2020 and their corresponding future potential changes under different climate scenarios (Figure 2A–B). We find Dy demand will rise by around 5–10-fold, from 2.4 kt/year in 2020 to 13.1, 19.0, and 25.3 kt/year by 2050 under the BAU (Figure 2C), STEPS (Figure 2D), and 1.5 °C scenarios (Figure 2E), respectively. The cumulative Dy demand during 2021–2050 will be 228.8 kt, 309.4 kt, and 392.7 kt under the three scenarios, respectively, approximately 17–30-fold compared with that in past three decades.

In terms of the applications that drive Dy demand, we analyze Dy demand in two different types of NdFeBs applications (i.e., emerging low-carbon applications and traditional applications). We find that the share of Dy demand in low-carbon applications is expected to increase from 42% to approximately 82% in the 1.5 °C scenario over the next three decades. In particular, the future Dy demand will be dominated by EVs, which will increase significantly by 14-fold from 2020 to 2050 (reaching 4.6 kt/year) under the BAU scenario. Under the more ambitious STEPS and 1.5 °C scenarios, the Dy demand in EVs will further rise by 27- and 41-fold, respectively, over the same period. The cumulative Dy demand in EVs during 2021–2050 will reach as high as 94.6, 158.7, and 218.1 kt under the BAU, STEPS, and 1.5 °C scenarios, respectively, which account for 41%–56% of Dy cumulative demand. Wind turbines, despite the wide attention captured in previous studies,[9,34,76,77] will only account for 18%–24% of Dy cumulative demand, although its demand for Dy will surge by 3–8-fold up to 2050 under three studied scenarios. The cumulative Dy demand in the wind turbines will reach 40.3, 68.2, and 96.1 kt under the three studied scenarios during 2021–2050. In addition, Dy demand in traditional applications will account for only 18%–41% of Dy cumulative demand during 2021–2050. Among which, elevators and industrial robots are the major applications, whose demands for Dy will be 2.3 and 0.8 kt/year in 2050, respectively, under three climate scenarios.

3.2. Unearthing Global Present Dy Minerals to Support China's NdFeB Demand. We investigate the future potential sources of Dy supply to meet the expected demand in China in Figure 3. For the purpose of resource conservation and environmental protection, China's domestic Dy primary supply is regulated with a production quota policy.[78] China implemented production quotas for REE concentrates in 2006, and HREEs production accounted for 13.7% of the total REE production by 2020 (Figure S11). If this quota policy continues, and the future global Dy primary supply is assumed to follow the projection provided by Roskill,[74] as shown in the primary supply (with quota) scenario, China's Dy primary supply (quota) will be 2.7 kt/year in 2050 under all of the three scenarios, which can meet only 11%–21% of its domestic demand of that year, so it indicates that China has to seek other sources of Dy (e.g., from import, marked as primary supply (others) in Figure 3A–C) to meet its domestic demand. In 2050, China's primary supply (others) will reach 7.4 kt/year in the BAU scenario, 11.6 kt/year in the STEPS scenario, and 16.4 kt/year in the 1.5 °C scenario (Figure 3D).

However, if China abandons its production quota policy (as shown in the primary supply (without quota) scenario in Figure 3A–C, the Dy primary supply in 2050 can be enlarged by 4–8-fold compared to the case with the production quota policy (reaching 10.2 kt/year in the BAU scenario, 14.4 kt/year in the STEPS scenario, and 19.1 kt/year in the 1.5 °C scenario in 2050), enabling the domestic supply to meet its demand at the cost of negative environmental impacts. Under three climate scenarios, China's domestic gross cumulative demand for Dy would be as high as 286.3 385.1, and 488.5 kt, respectively. Unless further exploration for REE in China and worldwide is actively conducted and new reserves are identified, the projected high Dy demand may lead to the depletion of China's present Dy reserve before 2035 in all three scenarios and even to the depletion of global present Dy reserve in 2045. Furthermore, if China only sources Dy from its own present Dy reserve, it is unlikely to achieve its ambitious climate targets and even the BAU scenario. Such a

https://doi.org/10.1021/acs.est.3c01327
Environ. Sci. Technol. 2023, 57, 14113–14126

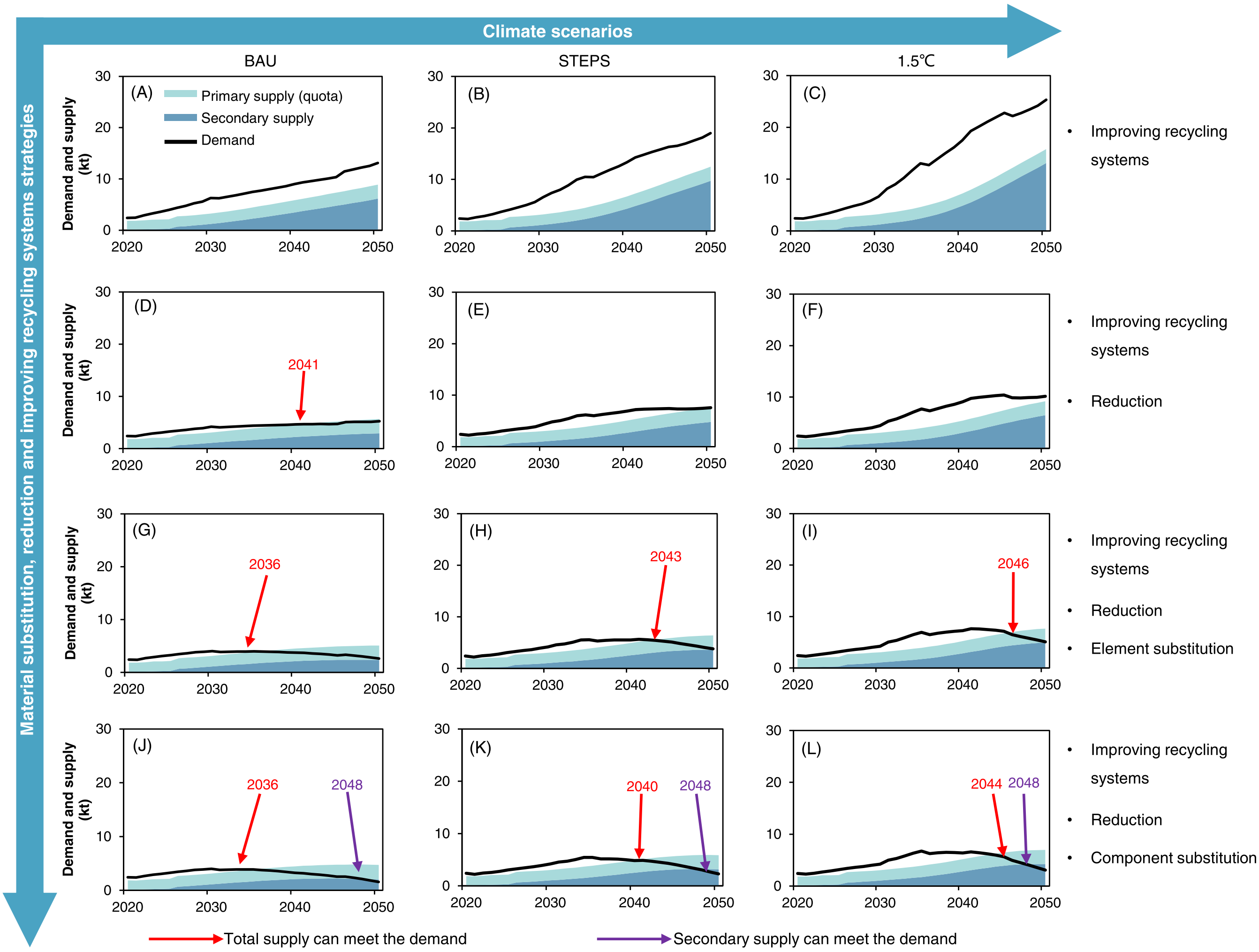


Figure 4. Dy demand and supply combine with material substitution, reduction, and improving recycling systems strategies. (A−C) Dy demand and supply with improving recycling systems strategy under the BAU, STEPS, and 1.5 °C scenarios. (D−F) Dy demand and supply with improving recycling systems and reduction strategies under the BAU, STEPS, and 1.5 °C scenarios. (G−I) Dy demand and supply with improving recycling systems, reduction, and element substitution strategies under the BAU, STEPS and 1.5 °C scenarios. (J−L) Dy demand and supply with improving recycling systems, reduction, and component substitution strategies under the BAU, STEPS, and 1.5 °C scenarios.

Dy shortage may lead to a gap of around 77 million of EVs and 3040 GW of planned wind turbines capacity that are needed to achieve the climate target under 1.5 °C scenario by 2050 (Figure S21).

3.3. Impacts of Available Decoupling Strategies. We further explore China's Dy supply shortage and the potentials that NdFeB's innovation strategies could alleviate in Figure 4. Several widely proposed strategies[8,9,29,79] are considered, including reduction (NdFeB with lower Dy intensity), material substitution (element substitution (state-of-the-art NdFeB with zero Dy), component substitution (next-generation REE-free motors innovation), and improving recycling systems (state-of-the-art motor recovery technology, and recycling policy, regulation, or legislation). These strategies are assessed through a total of 12 scenarios (as detailed in Table 2). We find that the demand side strategies (e.g., reduction, element substitution, component substitution) can effectively decrease the cumulative Dy demand (during 2021−2050) by 32%−52% (Figure 4). Simultaneously, with the implementation of improved recycling systems improvements, the secondary supply in 2050 would potentially increase to 6.2 kt/year in the BAU scenario, 9.7 kt/year in the STEPS scenario, and 13.1 kt/year in the 1.5 °C scenario, approximately 2−5-fold compared to the primary supply (with quota) of the same year. The cumulative secondary supply from 2021 to 2050 will reach 78.8 104.6, and 125.9 kt under three studied scenarios, respectively, which is equivalent to 6%−7% of cumulative Dy supply shortage during the same period.

In the short- to medium-term (2021−2035), despite these considered efforts on both the supply and demand sides, Dy shortage is likely to be inevitable for China under all scenarios. Our results show that Dy supply shortage will peak at 1.1 kt/year in 2025, 1.8 kt/year in 2034, and 3.0 kt/year in 2035, in the BAU, STEPS, and 1.5 °C scenarios respectively when strategies including reduction, element substitution, and improving recycling systems (Figure 4G−I). Cumulatively, there will still be a 10%-23% shortage of Dy supply before the total supply can meet demand. In the long term (2036−2050), we find China's Dy demand can be met with the total supply in most scenarios (with the earliest being by 2036) except for the STEPS and 1.5 °C scenarios with strategies including reduction and improving recycling systems. Moreover, we find the secondary Dy supply could solely meet demand after 2048 in the BAU, STEPS, and 1.5 °C scenarios when strategies

https://doi.org/10.1021/acs.est.3c01327
Environ. Sci. Technol. 2023, 57, 14113−14126

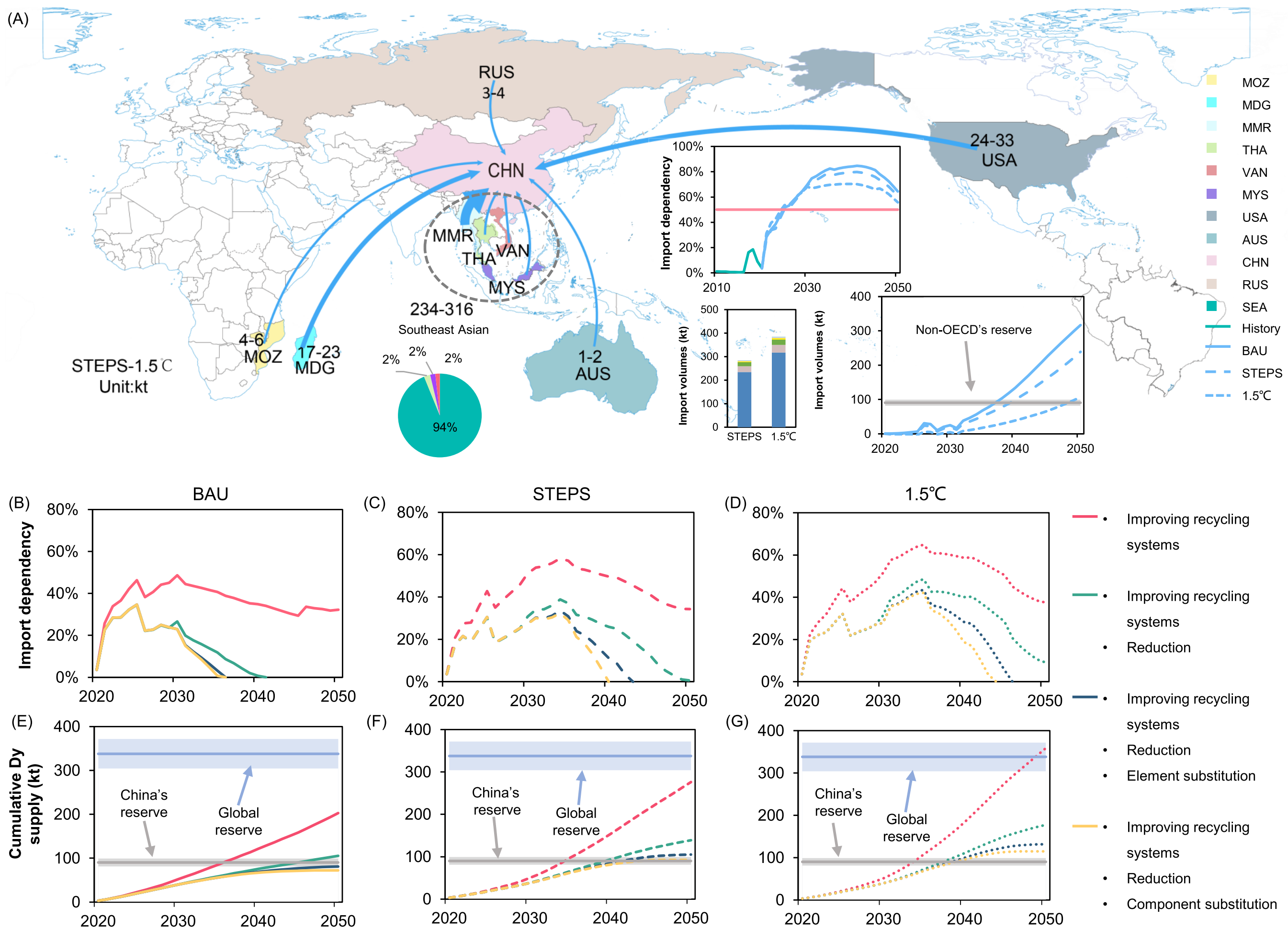


Figure 5. The change of Dy import dependency and the cumulative import volumes. (A) Dy cumulative import volumes from global during 2021−2050 under the STEPS and 1.5 °C scenarios (MOZ: Madagascar; MDG: Mozambique; MMR: Myanmar (Burma); THA: Thailand; VAN: Vietnam; MYS: Malaysia; USA:US; AUS: Australia; CHN: China; RUS: Russian Federation; SEA: The Southeast Asian). (B−D) Dy import dependency with material substitution, reduction and improving recycling systems strategies under the BAU, STEPS and 1.5 °C scenarios. (E-G) Dy cumulative primary supply related to China's and global Dy reserve during 2021−2050 with material substitution, reduction, and improving recycling systems strategies under the BAU, STEPS, and 1.5 °C scenarios.

including reduction, component substitution, and improving recycling systems (Figure 4J−L). This also indicates that combined efforts in technology advancement, investment, and laws that are intended to form a circular economy framework could help to achieve the closed loop of Dy.

3.4. China's Inevitable Reliance on Global Resources. We also quantify China's Dy supply from import as well as its import dependency (the ratio of demand minus supply) to demand) during 2021−2050, as shown in Figure 5. We find that China needs to import as much as 195.4, 295.2, and 398.6 kt Dy gross under the three studied scenarios during 2021−2050 to meet its demand (Figures S16 and 5A). As a result, China's import dependency for Dy will rise rapidly and exceeds 50% after 2025 in all scenarios. Moreover, the import dependency will continue to grow and peak at 70% in 2035 in the BAU scenario, 80% in 2040 in the STEPS scenario, and 85% in 2041 in the 1.5 °C scenario. Such a high import dependency implies that China will not only lose the advantage in domestic resources, but also consume the resources from the rest of the world. For example, Myanmar,[80] which is one of the non-OECD Asia countries, has become one of the world's major sources of HREEs resources. Yet our results indicate that China would potentially import a cumulative of 156.5, 234.9, and 317.0 kt Dy from the non-OECD Asia under three studied scenarios during 2021−2050. This is likely to deplete the present Dy reserve in these countries in 2050, 2041, and 2038, respectively (Figure 5A). Besides, China's cumulative Dy import from Myanmar will increase to 155.2 kt in the BAU scenario, 220.4 kt in the STEPS scenario, and 297.4 kt in the 1.5 °C scenario, followed by the US (16.1, 24.3, and 32.8 kt, respectively, under the three scenarios) and Madagascar (11.3, 17.1, and 23.1 kt, respectively, under the three scenarios) (Figures S16 and 5A).

If the above-mentioned strategies on material substitution, reduction, and improving recycling systems were implemented, the import dependency can be reduced to a large extent and its peak will not exceed 50% (Figure 5B−D). Still, China will not have enough Dy reserve to support its Dy demand needed to achieve 1.5 °C scenario, and China's present Dy reserve will be depleted around 2040 (Figure 5F). Moreover, in the short- to medium-term (2021−2035), the import dependency will be around 20%−60%. This further implies that global cooperation in REE supply will be essential for China to achieve its ambitious low-carbon future.

3.5. Uncertainties and Limitations. Due to the uncertain integration of multiple input variables, most flows and stocks had acceptable uncertainties, and the results are shown in Figure S29. The import dependency shows a relatively high variation of ±10.2% due to the uncertainty related to many input variables (e.g., import volumes and Dy intensity). The Dy demand under the BAU scenario, STEPS scenario, and 1.5 °C scenario has a relatively high uncertainty (±9.8%) caused by market penetration rates and Dy intensities of final products, which are deemed to be the uncertainty sources with the largest impacts. Given that those are key parameters for future trends, our analysis of emerging technologies (i.e., reduction and material substitution) on Dy demand can be viewed to explore their potential impacts on our results as well. Furthermore, given the limited transparency in data of the Dy supply chain in China, our MFA results are also obtained with substantial uncertainties. To overcome this, we have employed a diverse range of methodologies to validate them, together with the help of mass balance principle and cross check with different data sources (see Table S5). Still, we also suggest more transparency in the Dy supply chain.

Despite these uncertainties, our study shows considerable consistency with the results of previous published studies (Table S27). For instance, the Dy demand of wind power in our study falls within the range of numbers reported in Wang et al.[42] and Li et al.[9] (as explored in Table S27). Regarding the Dy demand in automobiles and electric vehicles, there is a limited difference with the previous studies (Table S27).

4. DISCUSSION

National efforts to mitigate climate change and treating it as an international crisis can not only achieve various local benefits (e.g., air pollutions, public health,[81] etc.) but also bring wider impacts for global well-beings.[82] China, as the world's largest emitter of CO_2,[83] has pledged to achieve carbon neutrality by 2060,[84] which can individually mitigate global warming[85] and further help to stimulate wider efforts toward Paris agreement. Previous studies[69,86,87] highlighted that the future Dy demand will rapidly increase, and our systematic analysis further reveals that China's low-carbon transition may deplete not only the China's present Dy reserve but also the global reserve. In a pervasive view, China's present Dy reserve can only support the development of 19% of the required EVs (i.e., 18 of 95 million units) and build 27% of planned wind turbines (i.e., 1146 of 4186 GW) based on the current Dy use rates of these technologies under the 1.5 °C scenario (details in Figure S21). Together with other studies,[29,88,29] our results confirm the ambitious climate targets may face severe constraints from HREEs and other critical minerals (e.g., cobalt,[29,88] lithium[29]), which desire wider attentions under Nationally Determined Contributions (NDCs) planning.

Our results indicate that the Dy supply constraint, as a limiting factor for clean energy transition, may become severe along the pathway of global climate change mitigation, particularly for those nations without stable Dy supply. Indeed, China has long been considered abundant in REE reserve,[69,89] and our study reveals China, by itself, will deplete both the domestic and global present Dy reserves in the studied scenarios. Aside from China, EU, US, Japan, and other counties are also promoting their own ambitious net-zero targets by or before 2050,[45,90,91] which will also require large-scale roll-out of EVs and wind turbines. These actions will further exacerbate the REE supply shortage and accelerate the depletion of the global REE reserve. If the relevant resource supplies are not well managed, then there would be more frequent supply risks and market manipulations that may be intensified by geopolitical competition. This is especially true given the fact that the current global REE market is highly volatile due to geopolitics. Thus, the ongoing 1.5 °C climate target will cause higher dependences for the US, EU, and even China on some emerging HREEs suppliers (e.g., Myanmar, Madagascar, Vietnam, Russia, Greenland, etc.). Again, the rising markets in those nations will require higher efforts to develop new forms of international cooperation to secure the Dy and other REEs which facilitate global efforts on climate change mitigation. This would move a step toward implementing the recommendations in the UN International Resource Panel report titled "Mineral Resources Governance in the 21st Century: Gearing Extractive Industries toward Sustainable Development".[92]

Aside from physical production constraint, there are various other constraints on the Dy supply that are worth noticing. In particular, the REE mining has environmental impacts ranging from pollution (permanent loss of ecosystems, soil erosion, air pollution),[81,93−95] high energy, water, CO_2 emission, and waste materials generations.[95,96] In addition, the further refinery and separate of Dy become very challenging due to the concentration of radioactive waste like thorium.[95,96] In those emerging suppliers, Greenland has great potential to develop new REE mines, but Greenland's parliament has passed legislation that ceases development of the Kuannersuit mine.[97] There have been public concerns in REE mining and processing countries like Malaysia.[98] As an emerging Dy supplier, China's import volumes from Myanmar are highly volatile due to the political situation,[99] high environment impact, alleged human right violations, and the price hike of Dy_2O_3 (which has risen approximately 50% since 2021) (Figure S25). In other words, how to ensure the stability and sustainability of REE trade is also a severe challenge.

Therefore, international collaborations on REE supply chains are highly needed at the upstream, downstream, and recycling sides. First, global efforts are required to explore and develop new REE (particularly HREEs) projects. Meanwhile, there is a need to distinguish between light rare earth elements (LREEs) and HREEs (or at element level) reserves and provide solid information in various REE projects investigation, to avoid misleading market actions (e.g., Turkey discovered 694 Mt of REEs reserves).[100] Furthermore, the most challenging aspect is the mining and extraction of REE, particularly green processing technologies that deal with radioactive and other wastes. The development of these technologies requires global cooperation and the construction of multiple separation factories. Second, our findings illustrate that the Dy shortage can be reduced by 65%−74% through material substitution, reduction, and improving recycling systems in 2035 under the 1.5 °C scenario. These strategies are very promising and have been developed by Germany (e.g., traction motor with magnet-free),[50] Japan (e.g., new magnet with HREEs free,[46] reduction[49]), US (e.g., traction motor with HREEs free),[51] Korea (e.g., reduction technology),[101] which are summarized in Tables S19−S20. Similarly, improving recycling systems technologies have also been developed in countries like Japan,[56] US,[102] and Korea[103] (summarized in Table S22). We further summarized 17 types of breakthrough technologies into 4 overarching categories in Figure S17: (a) Dy-less technologies, (b) Dy-free magnets (1−3), (c) Dy-free motors (4−9), and (d) improving recycling systems technologies. In general, we highlight their priorities in different time periods. In the short term (2021−2025), the priority should focus on the commercialization of Dy-less technologies, which turns to be the most effective strategies given their technical readiness and less demand for Dy. In the medium term (2026−2035), our study highlights the importance of advancing technologies of Dy-free magnets and motors, which can further reduce the Dy demand and alleviate the Dy shortage. In the long term (2036−2050), the "improving recycling systems" may be the most effective strategies, given massive of final products reach their EoL.

It is worth noting that given the distributed strengths of green mining, extraction, processing, and recycling of REE in different nations, there are three global actions to establish an international collaboration based on the existing framework of global cooperation on climate change mitigation (e.g., UN Climate Change Conference). First, we need an international organization that compiles and synthesizes comprehensive solutions to alleviate critical material shortages and facilitates the communication of vital information that is needed for policy decisions. International Energy Agency (IEA) is likely a good choice for this linkage. Second, we also need an international organization that can facilitate the timely exchange of exploration information and accelerate the sharing of those advanced technologies that can promote the efficient and sustainable REE supply by establishing international collaborations across the value chain. Rare Earth Industry Association (REIA) or United States Geology Survey (USGS) is likely to be a good choice as a facilitator. Third, it is important to establish a global organization that serves as a facilitator for collaboration among stakeholders involved in the advancement of Dy-less technologies, Dy-free magnets or motor technologies, and recycling technologies. This organization aims to promote international cooperation and reduce geopolitical conflicts. REIA is likely to be a good choice as a facilitator.

In addition to material substitution, system substitution represents a viable strategy for mitigating the Dy shortage. A shift away from wind power to other low/zero carbon electricity production technologies (e.g., solar photovoltaic (PV), nuclear power, and geothermal energy) would reduce REE demand. Currently, the IEA, International Renewable Energy Agency (IRENA), the European Commission,[104] etc. have a comprehensive analysis of solar PV development, and solar PV capacity has been experiencing a surge, with a 21-fold increase from 2010 to 2021.[105] However, the shortages in crystalline silicon can be a bottleneck in solar PV technology.[9,106] Furthermore, expanding solar PV capacity may require building smarter long-distance transmission lines to overcome to regional variability of electricity supply and demand.[107] Nuclear power accounted for approximately 10% of global electricity generation in 2020,[108] and many countries have announced plans to invest in nuclear power.[109] However, nuclear power is a complex technology, with political, economic, environmental, financial, and social dimensions.[110] Furthermore, nuclear power technologies face also restrictions due to concerns related to safety and nuclear waste managements,[108] and nuclear power has begun to fade in advanced economies.[107] Thus, global efforts are required to promote a comprehensive framework for minerals and metals production,[45,111,112] and this framework is key to achieve the global transition toward a net zero-carbon energy production. For the transportation sector, the shared mobility services, active transportation, and public transportation could help to reduce resources-intensive passenger vehicle ownership levels by 35%,[109,113] which can also contribute to the reduction of REEs demand. Therefore, global efforts are required to establish the public transportation networks, provide the access to ride-hailing services, and improve shared mobility services to facilitate a low-carbon transition in the transportation sector.

In summary, climate change is a global public bad.[114] Dy and other critical minerals are not equally distributed at the global level. This huge mismatch between national critical mineral supply and their demand due to mitigation efforts needs to be well balanced through global cooperative actions. We show the Dy supply shortage is likely to be inevitable in China as well as for other regions, such as the US, Europe, etc. Thus, there is a need to urge linked cooperation between climate change mitigation and critical mineral supply to guarantee our climate-safe future.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.3c01327.

Background, key parameters, supplement results, and uncertainty (PDF)

Supporting Information data source (XLSX)

■ AUTHOR INFORMATION

Corresponding Authors

Peng Wang − *Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China; University of Chinese Academy of Sciences, Beijing 100049, China;* orcid.org/0009-0001-1145-9605; Phone: +13700470472; Email: pwang@iue.ac.cn

Wei-Qiang Chen − *Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China; University of Chinese Academy of Sciences, Beijing 100049, China;* orcid.org/0000-0002-7686-2331; Phone: +86 592 6190 763; Email: wqchen@iue.ac.cn

An-Jian Wang − *Institute of Mineral Resource, Chinese Academy of Geological Sciences, Beijing 100037, China; Research Center for Strategy of Global Mineral Resources, Chinese Academy of Geological Sciences, Beijing 100037, China*; Phone: +13601166429; Email: ajwang@cags.ac.cn

Authors

Tao Dai − *Institute of Mineral Resource, Chinese Academy of Geological Sciences, Beijing 100037, China; Research Center for Strategy of Global Mineral Resources, Chinese Academy of Geological Sciences, Beijing 100037, China*

Yan-Fei Liu − *School of Earth Sciences and Resources, China University of Geosciences (Beijing), Beijing 100083, China*

Yang Qiu − *Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, Maryland 20740, United States*

Nabeel Mancheri − *Rare Earth Industry Association, 3000 Leuven, Belgium*

Wei Chen − *University of Science and Technology of China, Hefei 230026, China*

Jun-Xi Liu − *Department of Materials Engineering, Graduate School of Engineering, The University Tokyo (Hongo Campus), 113-8654 Bunkyo City, Tokyo, Japan*

Heming Wang − *State Environmental Protection Key Laboratory of Eco-Industry, Northeastern University, Shenyang, Liaoning 110819, China*

Complete contact information is available at:
https://pubs.acs.org/10.1021/acs.est.3c01327

Author Contributions

[#]T.D and Y.F.L contributed to the work equally and should be regarded as cofirst authors. P.W. and W.Q.C conceived the idea and the research. T.D, P.W., and Y.Q. developed the framework. Y.F.L, H.M.W, W.C., and J.X.L contributed to scenarios design and data collection. W.Q.C., P.W., N.A.M., and A.J.W. enhanced the scenarios and discussion international alliance. T.D., Y.F.L., and P.W. drafted the article. T.D., Y.F.L., P.W., Y.Q., and W.C. analyzed the results and contributed to writing this article.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This study is funded by the National Key Research and Development Program of China (2021YFC2901801), the National Natural Science Foundation of China (No. 71961147003, and 72274187, 72088101), as well as two industrial projects (No. 20224ABC03W05 and BFXT-2021-D-00061).

■ REFERENCES

(1) Ali, S. H.; Giurco, D.; Arndt, N.; Nickless, E.; Brown, G.; Demetriades, A.; Durrheim, R.; Enriquez, M. A.; Kinnaird, J.; Littleboy, A.; Meinert, L. D.; Oberhansli, R.; Salem, J.; Schodde, R.; Schneider, G.; Vidal, O.; Yakovleva, N. Mineral Supply for Sustainable Development Requires Resource Governance. *Nature.* **2017**, *543*, 367−372.

(2) Sovacool, B. B. K.; Ali, S. H.; Bazilian, M.; Radley, B.; Nemery, B.; Okatz, J.; Mulvaney, D. Sustainable Minerals and Metals for a Low-carbon Future. *Science.* **2020**, *367*, 30−33.

(3) Goldthau, A.; Hughes, L. Protect Global Supply Chains for Low-carbon Technologies. *Nature.* **2020**, *585*, 28−30.

(4) Lee, J. C. K.; Wen, Z. Pathways for Greening the Supply of Rare Earth Elements in China. Nat. *Sustain.* **2018**, *1*, 598−605.

(5) Liu, Q.; Sun, K.; Ouyang, X.; Sen, B.; Liu, L.; Dai, T.; Liu, G. Tracking Three Decades of Global Neodymium Stocks and Flows with a Trade-Linked Multiregional Material Flow Analysis. *Environ. Sci. Technol.* **2022**, *56*, 11807−11817.

(6) Smith, B. J.; Riddle, M. E.; Earlam, M. R.; Iloeje, C.; Diamond, D. *Rare Earth Permanent Magnets-Supply Chain Deep Dive Assessment*; U.S. Department of Energy, 2022.

(7) Wang, Q.; Chen, W.; Wang, P.; Dai, T. Illustrating the Supply Chain of Dysprosium in China through Material Flow Analysis. *Resour. Conserv. Recycl.* **2022**, *184*, 106417.

(8) Heldwein, O. Raw Material Gaps on the Way to Net Zero by 2050? A Case Study for Nd Focusing on Wind Energy and EVs. Master Thesis, Technische Universität Wien, 2022. DOI: 10.34726/hss.2022.103423.

(9) Li, J.; Peng, K.; Wang, P.; Zhang, N.; Feng, K.; Guan, D.; Meng, J.; Wei, W.; Yang, Q. Critical Rare-Earth Elements Mismatch Global Wind-Power Ambitions. *One Earth.* **2020**, *3*, 116−125.

(10) USGS. *Methodology and Technical Input for the 2021 Review and Revision of the U.S. Critical Minerals List*; U.S. Department of the Interior, U.S. Geological Survey, 2021. https://pubs.usgs.gov/of/2021/1045/ofr20211045.pdf.

(11) U.S. Department of Energy. *Critical Minerals and Materials Strategy*; U.S. Department of Energy, 2021. https://www.energy.gov/sites/prod/files/2021/01/f82/DOE%20Critical%20Minerals%20and%20Materials%20Strategy_0.pdf.

(12) Hatayama, H.; Tahara, K. Criticality Assessment of Metals for Japan's Resource Strategy. *Mater. Trans.* **2015**, *56*, 229−235.

(13) European Commission. *Study on the EU's list of Critical Raw Materials—Final Report.* European Commission, 2020. https://op.europa.eu/en/publication-detail/-/publication/c0d5292a-ee54-11ea-991b-01aa75ed71a1/language-en.

(14) European Commission. *Critical Raw Materials for Strategic Technologies and Sectors in the EU-A Foresight Study*; European Commission, 2020.

(15) Australian Government, Australian Trade and Investment Commission. *Critical Minerals Strategy 2022*; Australian Government, Department of Industry, Science and Resources. 2022.

(16) Australian Government, Australian Trade and Investment Commission. *Rare Earth Elements—Reliable, Responsible, Australian—A Critical Mineral Snapshot, Based on the Austrailian Prospectus 2020*, 2020.

(17) Duan, H.; Zhou, S.; Jiang, K.; Bertram, C.; Harmsen, M.; Kriegler, E.; van Vuuren, D. P.; Wang, S.; Fujimori, S.; Tavoni, M.; et al. Assessing China's Efforts to Pursue the 1.5 °C Warming Limit. *Science* **2021**, *372*, 378−385.

(18) Benveniste, H.; Oppenheimer, M.; Fleurbaey, M. Climate Change Increases Resource-Constrained International Immobility. *Nat. Clim. Chang.* **2022**, *12*, 634−641.

(19) Yang, X.; Nielsen, C. P.; Song, S.; McElroy, M. B. Breaking the Hard-to-abate Bottleneck in China's Path to Carbon Neutrality with Clean Hydrogen. *Nat. Energy.* **2022**, *7*, 955−965.

(20) Wang, P.; Ryberg, M.; Yang, Y.; Feng, K.; Kara, S.; Hauschild, M.; Chen, W. Q. Efficiency Stagnation in Global Steel Production Urges Joint Supply- and Demand-side Mitigation Efforts. *Nat. Commun.* **2021**, *12*, 2066.

(21) Raabe, D.; Tasan, C. C.; Olivetti, E. A. Strategies for Improving the Sustainability of Structural Metals. *Nature.* **2019**, *575*, 64−74.

(22) Iyer, G.; Ou, Y.; Edmonds, J.; Fawcett, A. A.; Hultman, N.; McFarland, J.; Fuhrman, J.; Waldhoff, S.; McJeon, H. Ratcheting of Climate Pledges Needed to Limit Peak Global Warming. *Nat. Clim. Chang.* **2022**, *12*, 1129−1135.

(23) Wang, P.; Wang, H.; Chen, W.; Pauliuk, S. Carbon Neutrality Needs a Circular Metal-energy Nexus. *Fundamental Research.* **2022**, *2*, 392−395.

(24) Borst, A. M.; Smith, M. P.; Finch, A. A.; Estrade, G.; Villanova-de-Benavent, C.; Nason, P.; Marquis, E.; Horsburgh, N. J.; Goodenough, K. M.; Xu, C.; Kynicky, J.; Geraki, K. Adsorption of rare earth elements in regolith-hosted clay deposits. *Nat. Commun.* **2020**, *11*, 4386.

(25) Du, X.; Graedel, T. E. Global in-use stocks of the rare Earth elements: a first estimate. *Environ. Sci. Technol.* **2011**, *45*, 4096−4101.

(26) Du, X.; Graedel, T. E. Uncovering the global life cycles of the rare earth elements. *Sci. Rep.* **2011**, *1*, 145.

(27) Guyonnet, D.; Planchon, M.; Rollat, A.; Escalon, V.; Tuduri, J.; Charles, N.; Vaxelaire, S.; Dubois, D.; Fargier, H. Material flow analysis applied to rare earth elements in Europe. *J. Clean. Prod.* **2015**, *107*, 215−228.

(28) Sekine, N.; Daigo, I.; Goto, Y. Dynamic Substance Flow Analysis of Neodymium and Dysprosium Associated with Neodymium Magnets in Japan. *J. Ind. Ecol.* **2017**, *21*, 356−367.

(29) Zeng, A.; Chen, W.; Rasmussen, K. D.; Zhu, X.; Lundhaug, M.; Muller, D. B.; Tan, J.; Keiding, J. K.; Liu, L.; Dai, T.; Wang, A.; Liu, G. Battery Technology and Recycling alone Will Not Save the Electric Mobility Transition from Future Cobalt Shortages. *Nat. Commun.* **2022**, *13*, 1341.

(30) Zhou, B.; Li, Z.; Chen, C. Global Potential of Rare Earth Resources and Rare Earth Demand from Clean Technologies. *Minerals.* **2017**, *7*, 203.

(31) Li, C.; Mogollón, J. M.; Tukker, A.; Dong, J.; von Terzi, D.; Zhang, C.; Steubing, B. Future Material Requirements for Global Sustainable Offshore Wind Energy Development. *Renew. Sust. Energy Rev.* **2022**, *164*, 112603.
(32) Farina, A.; Anctil, A. Material Consumption and environmental impact of wind turbines in the USA and globally. *Resour. Conserv. Recycl.* **2022**, *176*, 105938.
(33) Ballinger, B.; Schmeda-Lopez, D.; Kefford, B.; Parkinson, B.; Stringer, M.; Greig, C.; Smart, S. The vulnerability of electric-vehicle and wind-turbine supply chains to the supply of rare-earth elements in a 2-degree scenario. *Sustain. Prod. Consum.* **2020**, *22*, 68−76.
(34) Junne, T.; Wulff, N.; Breyer, C.; Naegler, T. Critical materials in global low-carbon energy scenarios: The case for neodymium, dysprosium, lithium, and cobalt. *Energy.* **2020**, *211*, 118532.
(35) Kalvig, P.; Machacek, E. Examining the rare-earth elements (REE) supply-demand balance for future global wind power scenarios. *Geol. Surv. Den. Greenl. Bull.* **2020**, *41*, 87−90.
(36) Nassar, N. T.; Wilburn, D. R.; Goonan, T. G. Byproduct metal requirements for U.S. wind and solar photovoltaic electricity generation up to the year 2040 under various Clean Power Plan scenarios. *Applied Energy.* **2016**, *183*, 1209−1226.
(37) Shammugam, S.; Gervais, E.; Schlegl, T.; Rathgeber, A. Raw metal needs and supply risks for the development of wind energy in Germany until 2050. *J. Clean. Prod.* **2019**, *221*, 738−752.
(38) van Oorschot, J.; Sprecher, B.; Roelofs, B.; van der Horst, J.; van der Voet, E. Towards a low-carbon and circular economy: Scenarios for metal stocks and flows in the Dutch electricity system. *Resour. Conserv. Recycl.* **2022**, *178*, 106105.
(39) Seo, Y.; Morimoto, S. Comparison of dysprosium security strategies in Japan for 2010−2030. *Resour. Policy.* **2014**, *39*, 15−20.
(40) Li, X.; Ge, J.; Chen, W.; Wang, P. Scenarios of rare earth elements demand driven by automotive electrification in China: 2018−2030. *Resour. Conserv. Recycl.* **2019**, *145*, 322−331.
(41) Elshkaki, A. Long-term analysis of critical materials in future vehicles electrification in China and their national and global implications. *Energy.* **2020**, *202*, 117697.
(42) Wang, P.; Chen, L.; Ge, J.; Cai, W.; Chen, W. Incorporating critical material cycles into metal-energy nexus of China's 2050 renewable transition. *Appl. Energy.* **2019**, *253*, 113612.
(43) Elshkaki, A.; Shen, L. Energy-material nexus: The impacts of national and international energy scenarios on critical metals use in China up to 2050 and their global implications. *Energy.* **2019**, *180*, 903−917.
(44) Gielen, D; Lyons, M. *Critical Materials for the Energy Transition: Rare Earth Elements*; International Renewable Energy Agency, 2022.
(45) IEA. *The Role of Critical Minerals in Clean Energy Transitions*; International Energy Agency, 2022.
(46) Toyota Motor Corporation. Toyota develops new magnet for electric motors aiming to reduce use of critical rare-earth element by up to 50%. *Toyota Motor Corporation Official Global Newsroom*, 2018. https://global.toyota/en/newsroom/corporate/21139684.html (accessed on Dec 19, 2021).
(47) Dow, J. Tesla is going (back) to EV motors with no rare earth elements. *Electrek*. https://electrek.co/2023/03/01/tesla-is-going-back-to-ev-motors-with-no-rare-earth-elements/ (accessed on Feb 12, 2022).
(48) Niron Magnetics. *High Performance, Low-Cost Permanent Magnets*. https://www.nironmagnetics.com/#Magnets%E2%80%8B, (accessed on Nov 6, 2022).
(49) Widmer, J. D.; Martin, R.; Kimiabeigi, M. Electric vehicle traction motors without rare earth magnets. *SM&T.* **2015**, 3, 7−13.
(50) Mahle develops highly efficient magnet-free electric motor. *Mahle Newsroom*, 2021. https://newsroom.mahle.com/global/media/global_news/2021/05-magnet-free-hv-motor/en-us_20210505_press_release_magnet_free-hv_motor.pdf.
(51) Raminosoa, T.; Wiles, R.; Cousineau, J. E.; Bennion, K.; Wilkins, J. *A High-Speed High-Power-Density Non-Heavy Rare-Earth Permanent Magnet Traction Motor*; National Renewable Energy Laboratory (NREL), 2020.
(52) Butcher, L. Renault teams up with Valeo and Siemens on rare earth-free EV motor. *Automotive Powertrain Technology International*, 2022.https://www.automotivepowertraintechnologyinternational.com/news/electric-powertrain-technologies/renault-teams-up-with-valeo-and-siemens-on-rare-earth-free-ev-motor.html, (accessed on Nov 12, 2022).
(53) Renault, Siemens and Valeo to develop rare-earth-free motors. *Drives & Controls*, 2022. https://drivesncontrols.com/news/fullstory.php/aid/6953/_Renault,_Siemens_and_Valeo_to_develop_rare-earth-free_motors.html (accessed on Nov 15, 2022).
(54) Ramprasad, C.; Gwenzi, W.; Chaukura, N.; Izyan Wan Azelee, N.; Upamali Rajapaksha, A.; Naushad, M.; Rangabhashiyam, S. Strategies and options for the sustainable recovery of rare earth elements from electrical and electronic waste. *Chem. Eng. J.* **2022**, *442*, 135992.
(55) Forti, V.; Peter Baldé, C.; Kuehr, R.; Bel, G. *The Global E-Waste Monitor 2020: Quantities, Flows, and the Circular Economy Potential*; United Nations University, International Telecommunication Union, and International Solid Waste Association, 2021.
(56) Nissan Motor Copporation. Nissan and Waseda University in Japan testing jointly developed recycling process for electrified vehicle motors. *Nissan News*. https://global.nissannews.com/en/releases/nissan-waseda-university-in-japan-testing-jointly-developed-recycling-process-for-ev-motors (accessed on Nov 12, 2022).
(57) Charpentier Poncelet, A.; Helbig, C.; Loubet, P.; Beylot, A.; Muller, S.; Villeneuve, J.; Laratte, B.; Thorenz, A.; Tuma, A.; Sonnemann, G. Losses and lifetimes of metals in the economy. *Nat. Sustain.* **2022**, *5*, 717−726.
(58) Xiao, S.; Geng, Y.; Pan, H.; Gao, Z.; Yao, T. Uncovering the key features of dysprosium flows and stocks in China. *Environ. Sci. Technol.* **2022**, *56*, 8682−8690.
(59) Yao, T.; Geng, Y.; Sarkis, J.; Xiao, S.; Gao, Z. Dynamic neodymium stocks and flows analysis in China. *Resour. Conserv. Recycl.* **2021**, *174*, 105752.
(60) Zhang, L.; Yuan, Z.; Bi, J. Predicting future quantities of obsolete household appliances in Nanjing by a stock-based model. *Resour Conserv Recycl.* **2011**, *55*, 1087−1094.
(61) Guo, X.; Zhang, J.; Tian, Q. Modeling the potential impact of future lithium recycling on lithium demand in China: A dynamic SFA approach. *Renewable Sustainable Energy Rev.* **2021**, *137*, 110461.
(62) The United Nations Population Division. *World Population Prospects 2019*. https://www.un.org/development/desa/pd/news/world-population-prospects-2019-0 (accessed on Feb 12, 2022).
(63) United Nations, Department of Economic and Social Affairs, Population Division. *World Urbanization Prospects 2018*. https://population.un.org/wup/Download/. (accessed on Feb 12, 2022).
(64) Zhou, Y. *Dynamic Material Flow Analysis of Indium in China* (in Chinese); China University of Geosciences: Wuhan, 2021.
(65) Xue, L.; Jin, Y.; Yu, R.; Liu, Y.; Ren, H. *Toward 'Net Zero' Emissions in the Road Transport Sector in China*; World Resources Institute, 2019. https://wri.org.cn/sites/default/files/2021-12/toward-net-zero-emissions-road-transport-sector-china-CN.pdf.
(66) International Energy Agency. *World Energy Outlook 2021*, 2021. https://iea.blob.core.windows.net/assets/4ed140c1-c3f3-4fd9-acae-789a4e14a23c/WorldEnergyOutlook2021.pdf.
(67) Dong, D.; Tukker, A.; Van der Voet, E. Modeling copper demand in China up to 2050: A business-as-usual scenario based on dynamic stock and flow analysis. *J. Ind. Ecol.* **2019**, *23*, 1363−1380.
(68) Zhang, S.; Chen, W. Assessing the energy transition in China towards carbon neutrality with a probabilistic framework. *Nat. Commun.* **2022**, *13*, 87.
(69) Habib, K.; Wenzel, H. Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling. *J. Clean. Prod.* **2014**, *84*, 348−359.
(70) Pavel, C. C.; Lacal-Arántegui, R.; Marmier, A.; Schüler, D.; Tzimas, E.; Buchert, M.; Jenseit, W.; Blagoeva, D. Substitution strategies for reducing the use of rare earths in wind turbines. *Resour. Policy.* **2017**, *52*, 349−357.

(71) Pavel, C. C.; Thiel, C.; Degreif, S.; Blagoeva, D.; Buchert, M.; Schüler, D.; Tzimas, E. Role of substitution in mitigating the supply pressure of rare earths in electric road transport applications. *SM&T.* **2017**, *12*, 62−72.
(72) Beijing Zhong Ke San Huan Hi-Tech Co., Ltd. *Annual Report of Beijing Zhong Ke San Huan Hi-Tech Co., Ltd. in 2021*; Beijing Zhong Ke San Huan Hi-Tech Co., Ltd., 2021.
(73) Palmer, C. The drive for electric motor innovation. *Engineering.* **2022**, *8*, 9−11.
(74) Roskill. *Rare Earths: Outlook to 2030*; Roskill, 2020.
(75) Wang, Q.; Wang, P.; Qiu, Y.; Dai, T.; Chen, W. Byproduct surplus: lighting the depreciative Europium in China's rare earth boom. *Environ. Sci. Technol.* **2020**, *54*, 14686−14693.
(76) de Koning, A.; Kleijn, R.; Huppes, G.; Sprecher, B.; van Engelen, G.; Tukker, A. Metal supply constraints for a low-carbon economy? *Resour. Conserv. Recycl.* **2018**, *129*, 202−208.
(77) Elshkaki, A.; Graedel, T. E. Dysprosium, the balance problem, and wind power technology. *Appl. Energy.* **2014**, *136*, 548−559.
(78) Shen, Y.; Moomy, R.; Eggert, R. G. China's public policies toward rare earths, 1975−2018. *Miner. Econ.* **2020**, *33*, 127−151.
(79) Dunn, J.; Slattery, M.; Kendall, A.; Ambrose, H.; Shen, S. Circularity of Lithium-Ion Battery Materials in Electric Vehicles. *Environ. Sci. Technol.* **2021**, *55*, 5189−5198.
(80) Liu, S.; Fan, H.; Liu, X.; Meng, J.; Butcher, A. R.; Yann, L.; Yang, K.; Li, X. Global rare earth elements projects: New developments and supply chains. *Ore Geol. Rev.* **2023**, *157*, 105428.
(81) Zhang, T.; Zhang, P.; Peng, K.; Feng, K.; Fang, P.; Chen, W.; Zhang, N.; Wang, P.; Li, J. Allocating environmental costs of China's rare earth production to global consumption. *Sci. Total Environ.* **2022**, *831*, 154934.
(82) Patz, J. A.; Campbell-Lendrum, D.; Holloway, T.; Foley, J. A. Impact of regional climate change on human health. *Nature.* **2005**, *438*, 310−317.
(83) BP. *Statistical Review of World Energy 2021*, 2022. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf.
(84) Sun, L.; Cui, H.; Ge, Q. Will China achieve its 2060 carbon neutral commitment from the provincial perspective? *Adv. Clim. Change Res.* **2022**, *13*, 169−178.
(85) Li, L.; Zhang, Y.; Zhou, T.; Wang, K.; Wang, C.; Wang, T.; Yuan, L.; An, K.; Zhou, C.; Lu, G. Mitigation of China's carbon neutrality to global warming. *Nat. Commun.* **2022**, *13*, 5315.
(86) Valero, A.; Valero, A.; Calvo, G.; Ortego, A. Material bottlenecks in the future development of green technologies. *Renew. Sust. Energy Rev.* **2018**, *93*, 178−200.
(87) Watari, T.; McLellan, B.; Ogata, S.; Tezuka, T. Analysis of Potential for Critical Metal Resource Constraints in the International Energy Agency's Long-Term Low-Carbon Energy Scenarios. *Minerals.* **2018**, *8*, 156.
(88) Watari, T.; Nansai, K.; Nakajima, K. Review of critical metal dynamics to 2050 for 48 elements. *Resour. Conserv. Recycl.* **2020**, *155*, 104669.
(89) Hoenderdaal, S.; Tercero Espinoza, L.; Marscheider-Weidemann, F.; Graus, W. Can a dysprosium shortage threaten green energy technologies? *Energy.* **2013**, *49*, 344−355.
(90) International Energy Agency. *Net Zero by 2050-A Roadmap for The Global Energy Sector*, 2021. https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.
(91) van Soest, H. L.; den Elzen, M. G. J.; van Vuuren, D. P. Net-zero emission targets for major emitting countries consistent with the Paris Agreement. *Nat. Commun.* **2021**, *12*, 2140.
(92) Ayuk, E. T.; Pedro, A. M.; Ekins, P. *Mineral Resource Governance in the 21st Century: Gearing Extractive Industries Towards Sustainable Development*; UN International Resources Panel, 2020.
(93) Liu, H. *Rare Earth: Shades of Grey-Can. China Continue to Fuel Our Global Clear& Smart Future?*; China Water Risk, 2016.
(94) Elshkaki, A. Sustainability of emerging energy and transportation technologies is impacted by the coexistence of minerals in nature. *Communications Earth & Environment.* **2021**, *2*, 186.
(95) Schreiber, A.; Marx, J.; Zapp, P. Life Cycle Assessment studies of rare earths production - Findings from a systematic review. *Sci. Total Environ.* **2021**, *791*, 148257.
(96) Golroudbary, S. R.; Makarava, I.; Kraslawski, A.; Repo, E. Global environmental cost of using rare earth elements in green energy technologies. *Sci. Total Environ.* **2022**, *832*, 155022.
(97) Gislam, S. Greenland bans uranium mining, halting rare earths project. *Industry Europe*, 2021. https://industryeurope.com/sectors/metals-mining/greenland-imposes-uranium-mining-ban-halting-huge-rare-earths-project/ (accessed on Mar 11, 2022).
(98) Hindu, T. Thousands of Malaysians protest against rare earth plant. *The Hindu*, 2012. https://www.thehindu.com/news/international/thousands-of-malaysians-protest-against-rare-earth-plant/article2934898.ece, (accessed on Mar 10, 2022).
(99) Zhang, H.; Li, X. Myanmar rare earths heading toward China encounter shipment obstacles amid upheaval. *Global Times*, 2021. https://www.globaltimes.cn/page/202103/1218983.shtml (accessed on Nov 10, 2022).
(100) Turkey Probably Hasn't Found the Rare Earth Metals It Says It Has. *Wired*, 2022. https://www.wired.com/story/turkey-rare-earth-metals/ (accessed on Nov 12, 2022).
(101) Seok, C.; Choi, H.; Seo, J. Design and analysis of a novel spoke-type motor to reduce the use of rare-earth magnet materials. *IET Electric Power Applications.* **2021**, *15*, 1479−1487.
(102) Chinwego, C.; Wagner, H.; Giancola, E.; Jironvil, J.; Powell, A. Technoeconomic Analysis of Rare-Earth Metal Recycling Using Efficient Metal Distillation. *Jom.* **2022**, *74*, 1296−1305.
(103) Rasheed, M. Z.; Song, M.-s.; Park, S.-m.; Nam, S.-w.; Hussain, J.; Kim, T.-S. Rare Earth Magnet Recycling and Materialization for a Circular Economy—A Korean Perspective. *Appl. Sci.* **2021**, *11*, 6739.
(104) Carrara, S.; Alves, D. P.; Plazzotta, B.; Pavel, C. *Raw Materials Demand for Wind and Solar PV Technologies in the Transition Towards a Decarbonised Energy System*; European Commission, 2020.
(105) International Renewable Energy Agency. *World Energy Transitions Outlook 2022: 1.5 °C Pathway*, 2022. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Mar/IRENA_World_Energy_Transitions_Outlook_2022.pdf?rev=6ff451981b0948c6894546661c6658a1.
(106) Liesbet, G.; Acker, Kv. *Metals for Clean Energy: Pathways to Solving Europe's Raw Materials Challenge*; KU Leuven, 2022.
(107) International Energy Agency. *Nuclear Power in a Clean Energy System*, 2019. https://iea.blob.core.windows.net/assets/ad5a93ce-3a7f-461d-a441-8a05b7601887/Nuclear_Power_in_a_Clean_Energy_System.pdf.
(108) International Energy Agency. *Nuclear Power and Secure Energy Transitions: From Today's Challenges to Tomorrow's Clean Energy Systems*, 2022. https://iea.blob.core.windows.net/assets/016228e1-42bd-4ca7-bad9-a227c4a40b04/NuclearPowerandSecureEnergyTransitions.pdf.
(109) International Energy Agency. *World Energy Outlook 2022*, 2022. https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf.
(110) International Atomic Energy Agency. *Potential Role of Nuclear Energy in National Climate Change Mitigation Strategies*, 2021. https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1984web.pdf.
(111) International Energy Agency. *Energy Technology Perspectives 2023*. https://iea.blob.core.windows.net/assets/a86b480e-2b03-4e25-bae1-da1395e0b620/EnergyTechnologyPerspectives2023.pdf.
(112) International Resource Panel. *Mineral Resource Governance in the 21st Century: Gearing Extractive Industries Towards Sustainable Development*. https://www.resourcepanel.org/reports/mineral-resource-governance-21st-century.
(113) International Energy Agency. *An Energy Sector Roadmap to Carbon Neutrality in China*, 2021. https://iea.blob.core.windows.net/assets/9448bd6e-670e-4cfd-953c-32e822a80f77/AnenergysectorroadmaptocarbonneutralityinChina.pdf.

https://doi.org/10.1021/acs.est.3c01327
Environ. Sci. Technol. 2023, 57, 14113−14126

(114) Hoenderdaal, S.; Tercero Espinoza, L.; Marscheider-Weidemann, F.; Graus, W. Can a dysprosium shortage threaten green energy technologies? *Energy*. **2013**, *49*, 344−355.

https://doi.org/10.1021/acs.est.3c01327
Environ. Sci. Technol. 2023, 57, 14113−14126