Research paper
6th PLATE 2025 Conference
Aalborg, Denmark, 2-4 July 2025

Can Circular Economy Strategies Limit the Prospective Dysprosium Demand in the European Union?

Disna Eheliyagoda[a,b], Badrinath Veluri[b], Gang Liu[c,d], Devarajan Ramanujan[a]
a) Department of Mechanical and Production Engineering, Aarhus University, Aarhus, Denmark
b) Grundfos A/S, Bjerringbro, Denmark
c) College of Urban and Environmental Sciences, Peking University, Beijing, China
d) Department of Green Technology, University of Southern Denmark, Odense, Denmark

Keywords: Dysprosium; rare earths; demand; climate targets; circular economy.

Abstract: Dysprosium (Dy) is a high critical rare earth element, which is basically used for improving the thermo-magnetic properties in various low carbon products. This research provides a detailed examination on the evolution of Dy demand, in-use stock, and end-of-life (EoL) under ambitious climate targets and demand shrinkages that can be expected due to the implementation of two circular economy strategies: material efficiency and end-of-life recycling in 13 product sectors in the European Union from 2022 to 2050. Our results indicate that future Dy demand, in-use stock accumulation, and EoL generation are likely to be exacerbated by High-APS (Announced Pledges Scenario) and High-NZE (Net Zero Emissions by 2050 Scenario). Moreover, the circular economy strategies used in this study will contribute to significant decreases in the future Dy demand when such strategies are combined and applied in a high magnitude under High-APS and High-NZE scenarios. Recent efforts in the partial and full elimination of Dy mainly in high-tech products such as wind turbines and electrical vehicles are admirable, however, it is necessary to more focus on improving the implementation of circular economy strategies in manufacturing processes to mitigate future Dy supply uncertainties in the European Union.

Introduction

Rare earth elements (REEs) are critical materials for almost all regions due to the growing demand for low-carbon technologies (Eheliyagoda et al., 2023; Liu et al., 2022). The European Union (EU) is having a greater concern to become the global leader of manufacturing low-carbon emitting products that thrives the demand for REEs. Neodymium-iron-boron permanent magnets (NdFeBs) are the characteristic semi-products used to manufacture numerous low-carbon products in which a REE called dysprosium (Dy) is added to sharpen their high magnetic properties (Dai et al., 2023). However, Dy has already been identified as one of the most critical rare earths to the EU in meeting the future demand for clean energy products (European Commission, 2023).

Several factors can be highlighted regarding the high-risk status of Dy in the EU. First, Dy primary production is highly concentrated to outside the EU region, fundamentally to the Southern China (Seo and Morimoto, 2014). Dy belongs to the heavy rare earths group, but any of such minable reserves are not discovered within the EU to the authors knowledge. Due to this geological limitation, the EU should totally rely on imports of Dy materials to fulfill their demand that is expected to be even more in the future as a response to the European climate targets on reaching net-zero emissions. This eventually creates a competition for the Dy demand in the global market, so that, an uncertainty can be aggregated on the stability of affordable price ranges, which may directly affect to the EU clean high-tech manufacturing sector. Second, almost 100% of the heavy rare earth supply to the EU highly depends on China's exports. The limited consideration in the source diversification may increase future uncertainties in the supply chain. Last but not least, the promotion of the use of secondary REE materials in the products is under the least prioritized concern in the EU, which continues the demand for more virgin minerals. For instance, the recycling of REEs still maintains under a much lower rate, which has been denoted as less than 1% by some studies (Wang et al., 2022; Xiao et al., 2022).

Circular economy strategies play a vital role in decoupling the primary resource demand and increasing the longevity of products. Due to the geological unavailability for economically viable heavy rare earth reserves, focusing on circular economy principles can have a promising impact in addressing future Dy supply gaps for the EU. Therefore, this study aims to, (1) forecast the Dy demand, in-use stock accumulation, and end-of-life generation until 2050 considering three climate scenarios (i.e., the stated policies scenario (STEPS), the announced pledges scenario (APS), and the net zero emissions by 2050 scenario (NZE)) and, (2) model the impact of 2 circular economy strategies: material efficiency and end-of-life recycling in the future Dy demand decrease in the European Union.

Materials and Methods

System boundary and definition

This study used the EU (i.e., 27 countries) as the spatial boundary and the period between 2022 and 2050 as the temporal boundary. Accordingly, Dy flows, stocks, and end-of-life (EoL) from 2022 to 2050 were projected for the EU. Mining and beneficiation, refining and separation, fabrication, manufacturing, consumption, and end-of-life (EoL) management are the six life stages that make up the EU Dy cycle (Rasmussen et al., 2019). The historical figure of the EU Dy flows and stocks (i.e., from 1988 to 2021) was directly taken from a recent study published by Eheliyagoda et al. (2023) to construct future scenarios. Based on our earlier research, 13 product categories: computers, mobile phones, wind turbines, refrigerators, air conditioners, washing machines, e-bikes, electric vehicles, high-speed trains, ICE vehicles, industrial robots, MRI machines, and elevators were chosen to estimate the future Dy demand, in-use stock accumulation, and EoL generation under climate targets of the EU.

Dysprosium demand, in-use stock, and end-of-life forecasts

The application demand between 2022 and 2050 was calculated using several methods such as particular annual growth rates and logistic regression. A three-scenario strategy has been proposed by the International Energy Agency (IEA) to examine patterns in future global energy demand. They are Stated Policies Scenario (STEPS), Announced Pledges Scenario (APS), and Net Zero Emissions by 2050 Scenario (NZE). Accordingly, we used global level IEA consumption data on electric vehicles and wind turbines to derive their future European Dy demand scenarios. By observing the patterns of variations in the Dy consumption under these three ambitious climate targets, we nominated the STEPS as a low scenario, and the APS and NZE as high scenarios in the present study. Except for electric vehicles and wind turbines, the other product demand predictions for these three scenarios were based a variety of approaches. The EU future demands of the other products (excluding electric vehicles and wind turbines) were estimated under Low-STEPS, High-APS, and High-NZE scenarios, taking parameters such as changes in the number of households, device ownership, and regional population. The logistic growth model was appropriately used to project future scenarios. After forecasting demands of products, the stock-driven method was applied to estimate the in-use stock accumulation and EoL generation of each product. The in-use stock and EoL projections were based on the lifetime distribution function of commodities including Weibull and Normal distributions.

Demand reduction projections due to the application of circular economy strategies

This study used two circular economy strategies: material efficiency and end-of-life (EoL) recycling to measure the possible impact in the Dy demand decrease from 2022 to 2050 in the EU. These strategies were evaluated via five scenarios under each demand-side scenario (e.g., Low-STEPS, High-APS, and High-NZE). The forecasts were based on anticipated technological and strategical transformations from 2022 to 2050, with some assumptions supported by previous literature and industrial/technical reports (Dai et al., 2023; European Commission, 2023). In preparing material efficiency scenarios, we undertook a gradual decrease of 10%, 50%, and 50% in Dy amounts across various products by 2050 under Low-STEPS, High-APS, and High-NZE scenarios respectively based on technological advancements. In this case, a low technological modification is associated with Low-STEPS, whereas high technological modifications are associated with High-APS and High-NZE scenarios. It was assumed that the Dy amount per product would decrease annually according to the polynomial regression. End-of-life (EoL) recycling scenarios were developed with the aim of facilitating sustainable resource use in the future through industrial, technological, and strategic transitions. We used two criteria in evaluating the situation: one based on a likely scenario (e.g., rational recycling), and the other on a speculative scenario (e.g., hypothetical recycling) to determine the optimal action. We assigned 1%, 25%, and 25% annual recycling rates until 2050 to Low-STEPS, High-APS, and High-NZE scenarios respectively to capture results under the rational EoL recycling condition. Furthermore, 30%, 90%, and 90% annual recycling rates until 2050 were assigned to Low-STEPS, High-APS, and High-NZE scenarios respectively to capture results under the hypothetical EoL recycling condition. Scenarios to represent the combined effect of these two circular strategies were also processed for identifying the best course of action.

Results

Dysprosium demand, in-use stock, and end-of-life projections under ambitious climate targets in the European Union

Figure 1 shows Dy application demand, in-use stock accumulation, and EoL generation of different product categories under Low-STEPS, High-APS, and High-NZE scenarios in the EU. The EU Dy demand will increase from 119 t to 235 t under Low-STEPS scenario, from 128 t to 445 t under High-APS scenario, and 128 t to 399 t under High-NZE scenario between 2022 and 2050. Furthermore, the in-use stock accumulation will rise from 0.86 kt to 3.48 kt under Low-STEPS scenario, from 0.87 kt to 6.19 kt under High-APS scenario, and from 0.87 kt to 6.59 kt under High-NZE scenario from 2022 to 2050. Moreover, total EoL generation will grow from 37 t to 174 t under Low-STEPS scenario, from 37 t to 277 t under High-APS scenario, and from 37 t to 309 t under High-NZE scenario between 2022 and 2050. Overall, wind turbines, electric vehicles, high-speed trains, and industrial robots will play the pivotal role in enhancing the future Dy demand and in-use stock. On the other hand, wind turbines, electric vehicles, and industrial robots will more contribute to increase the Dy EoL generation in the EU.

Impact of circular economy strategies in the dysprosium demand prospects in the European Union

Circular economy strategies can play an immense role to complement primary resource consumption in terms of critical materials (Wang et al., 2024). As shown in Figure 2, Dy demand can be decreased to a considerable extent from the implementation of circular strategies in higher proportions under High-APS and High-NZE scenarios in the future. Due to the implementation of the material efficiency strategy, the estimated Dy demands will decline to 188 t, 212 t, and 223 t under the High-APS climate scenario and to 274 t, 214 t, and 200 t under the High-NZE climate scenario by 2030, 2040, and 2050 respectively. Even though rational EoL recycling itself will not contribute to sufficient Dy demand reductions under all demand-side scenarios, hypothetical EoL recycling itself will alter the Dy demand to over a half of amount out of the estimated Dy demand accounting for 196 t and 121 t in High-APS and High-NZE scenarios by 2050. The combination of material efficiency and rational EoL recycling brings an excellent complement for the primary consumption showing up to 177 t and 146 t Dy demand shrinkages under High-APS and High-NZE scenarios by 2050 respectively. Moreover, the combination of material efficiency and hypothetical EoL recycling depicts up to 57 t and 7 t Dy demand reductions under High-APS and High-NZE scenarios by 2050 respectively. However, the Low-STEPS scenario will not adequately provide Dy demand decreases under the concerned circular economy strategies, which can be attributed to its status in the less technological transition. Overall, the combined effect and high magnitude in the substitution of circular economy strategies can make significance demand reductions in High-APS and High-NZE scenarios in upcoming decades.

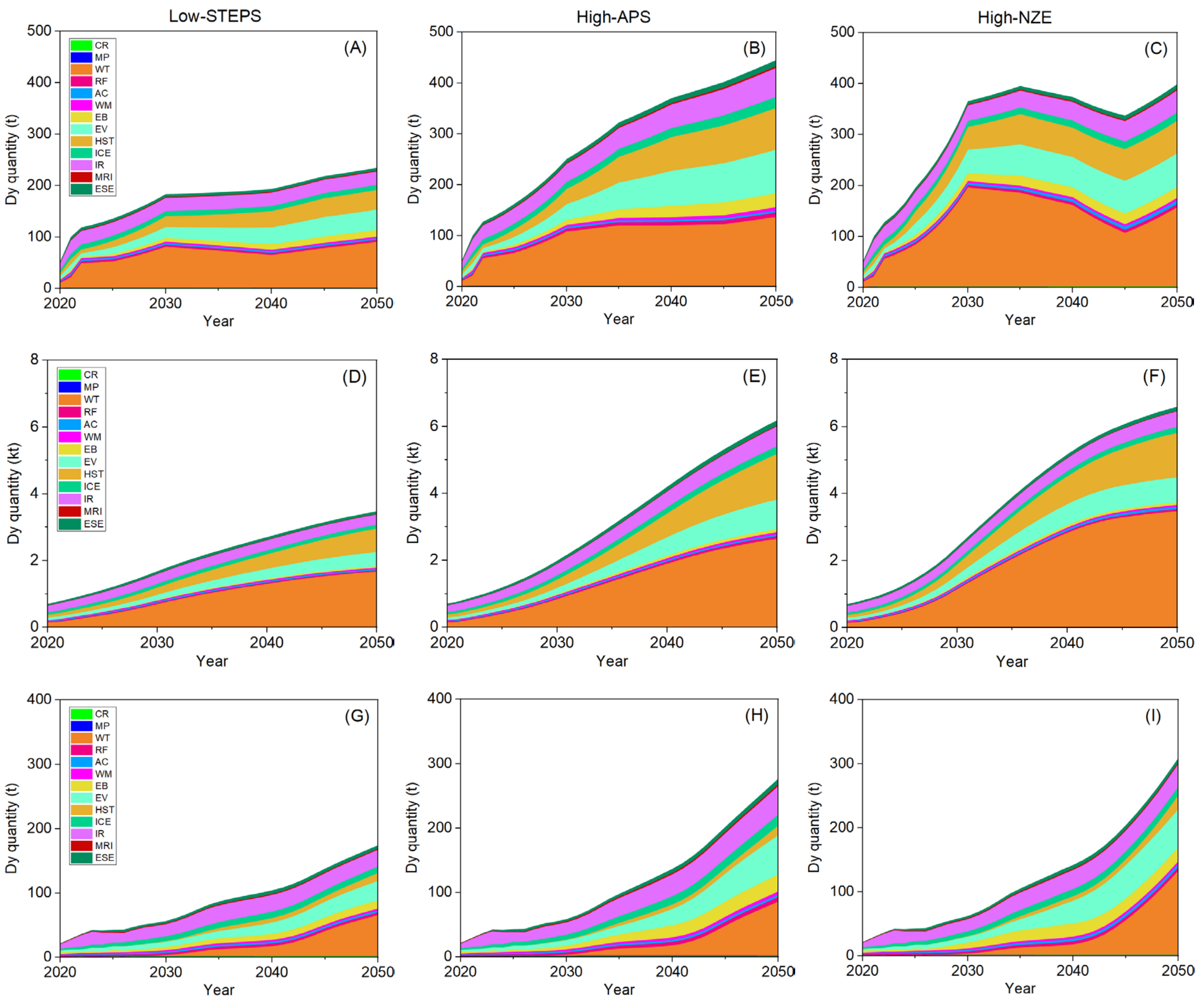

Figure 1 Dysprosium consumption, accumulation, and waste generation patterns under climate scenarios from 2020 to 2050 in the European Union. (A-C) Demand, (D-F) In-use stock, (G-I) End-of-life. Note: STEPS: Stated Policies Scenario, APS: Announced Pledges Scenario, NZE: Net Zero Emissions by 2050 Scenario, CR: computer, MP: mobile phone, WT: wind turbine, RF: refrigerator, AC: air conditioner, WM: washing machine, EB: e-bike, EV: electric vehicle, HST: high-speed train, ICE: internal combustion engine vehicle; IR: industrial robot, MRI: magnetic resonance imaging machine, and ESE: elevator.

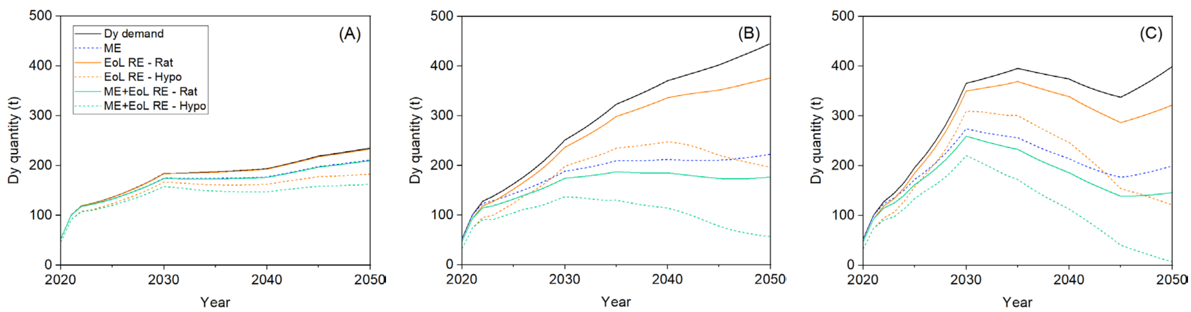

Figure 2 Effect of implementing circular economy strategies for dysprosium decoupling in the European Union. (A) Low-STEPS scenario, (B) High-APS scenario, (C) High-NZE scenario. Note: ME: material efficiency, EoL RE – Rat: end-of-life recycling – rational, EoL RE – Hypo: end-of-life recycling – hypothetical, ME+EoL RE – Rat: material efficiency + end-of-life recycling – rational, and ME+EoL RE – Hypo: material efficiency + end-of-life recycling – hypothetical.

Discussion

Regulatory and economic barriers on rare earth permanent magnet end-of-life applications in the European Union

A major policy-related challenge within the EU legislative framework is the lack of specific regulations requiring the provision of information about the magnets used in various EoL applications. Without standardized labeling or markings, magnet scrap must be manually extracted, sorted, and analyzed to identify the type of magnet and its material composition when EoL products are collected. This lack of clear information leads to significant uncertainty, making the recycling process both economically inefficient and more complex. The difficulty in accurately identifying magnet materials increases the time and costs associated with recycling, impeding the scalability of such processes. Implementing clear labeling requirements could significantly improve recycling efficiency, simplify sorting procedures, and support the sustainable recovery of valuable materials like rare-earth magnets, contributing to both economic and environmental goals. Another obstacle is the lack of sufficient financial incentives in the EU to support the secondary market for rare-earth magnets. Despite technological progress in rare earth recycling, secondary production remains at a considerable competitive disadvantage compared to primary production. This disparity makes it difficult for recycled rare-earth magnets to compete in terms of cost and scale, restricting the growth of a sustainable secondary market. Without stronger financial support or incentives, advancing toward a circular economy for rare earth materials becomes more challenging, limiting the potential for more sustainable and economically viable recycling solutions (Rizos et al., 2024).

The high cost involved in the recycling of magnets, especially during the extraction phase creates challenges in competing with the production of primary magnets. Furthermore, the price volatility of rare earths presents another obstacle as these fluctuations hinder the creation of sustainable business models for magnet recycling. Such instability makes it difficult to establish profitable recycling operations, slowing the development of a stable and sustainable secondary market for rare-earth magnets (Rizos et al., 2024).

Challenges and technical implications to meet future dysprosium constraints in the European Union

The EU high-tech manufacturing industry is expected to have a key role in shaping the future Dy demand. Based on foreseeable trends in the Dy demand, companies are moving to largely reduce or eliminate the usage of Dy from high-tech products such as electric vehicles and wind turbines. The unavailability of heavy rare-earth reserves, full import dependency, and the high cost incurred in the primary Dy importation can be denoted as main reasons that the EU should address to mitigate future supply uncertainties. To cope with uncertainties in the primary Dy supply, the EU is transforming to improve circular economy strategies in their production processes. Even though these strategies may not contribute to fully accommodate the primary supply issue, a considerable transition can be expected in the use reduction of Dy along with increasing the secondary supply. New varieties of NdFeB magnets with no or very little Dy have already been developed by a number of original equipment manufacturers (OEMs) (Dai et al., 2023). Furthermore, producers of NdFeB motors, which constitute significant amounts of Dy have begun manufacturing less REE or Dy products through various methods to lower costs and streamline supply chains (Sepehri-Amin et al., 2018). Moreover, Western nations have initiated research and development efforts to manufacture REE-free synchronous motors (e.g., the EU, France, and Slovenia), REE-free asynchronous motors (e.g., the EU), and magnet-free electric traction motors (e.g., Germany) (Dai et al., 2023). In order to fulfill the EU's future Dy demand, such techniques would be worth considering.

Longevity strategies to extend the lifetime of dysprosium-containing products

As the demand for dysprosium-containing products, particularly in electronics, electric vehicles, and renewable energy technologies, continues to rise, it becomes imperative to focus on strategies that extend their life cycle. Design approaches that prioritize durability, modularity, and energy efficiency can significantly enhance the longevity of products, ensuring that dysprosium-based components, such as magnets, remain functional over extended periods. Moreover, regular maintenance, including monitoring for wear and implementing preventive upkeep, is essential in prolonging the operational lifespan of these products. Consumer education on proper usage and maintenance further contributes to preserving the integrity of dysprosium-containing systems. In addition, remanufacturing and recycling offer sustainable alternatives by reducing the need for new dysprosium extraction. Through the disassembly and refurbishment of products with recycled components, these practices minimize waste and conserve critical resources. By integrating these strategies, it is possible to mitigate the environmental impact associated with dysprosium, fostering a circular economy where valuable materials are reused and kept in circulation, thereby reducing reliance on mining efforts.

Conclusions

This study projected the evolution of the EU Dy demand, in-use stock, and end-of-life (EoL) based on the anticipated climate targets and the effect of two circular economy strategies (i.e., material efficiency and end-of-life recycling) in altering the demand between 2022 and 2050. Our findings show that High-APS and High-NZE scenarios are likely intensify the future Dy demand, in-use stock accumulation, and EoL generation. Industrial sectors such as wind turbines, electric vehicles, and industrial robots are more inclined to require Dy in the EU. Furthermore, the combination and the high scale of substitution of circular economy strategies can lead to significant demand reductions in the coming decades under High-APS and High-NZE scenarios. The EU efforts in recent technological advancements to minimize the Dy consumption are admirable, but they may not be able to fully address future Dy supply uncertainties. Therefore, it is important to more focus on the implementation of multiple circular economy strategies in their production processes to cope up future challenges in the Dy supply shortage and to improve the sustainable resource use in the EU manufacturing sector.

Acknowledgments

The authors would like to acknowledge the financial support from the Innovation Foundation Denmark, under the grant "μcircmag: Multi-Scale Circularity Assessment for Permanent Magnet Motors Supporting Green Transition". This paper represents original findings and opinions of the authors. No official recommendation or endorsement of the presented work is implied by Grundfos A/S or the disclosed funding agency.

References

Dai, T., Liu, Y. F., Wang, P., Qiu, Y., Mancheri, N., Chen, W., Liu, J. X., Chen, W. Q., Wang, H. & Wang, A. J. (2023). Unlocking Dysprosium Constraints for China's 1.5 degrees C Climate Target. Environmental Science & Technology, 57, 14113-14126. https://doi.org/10.1021/acs.est.3c01327

Eheliyagoda, D., Ramanujan, D., Veluri, B., Liu, Q. & Liu, G. (2023). Tracing the multiregional evolution of the global dysprosium demand-supply chain. Resources, Conservation and Recycling, 199, 107245. https://doi.org/10.1016/j.resconrec.2023.107245

European Commission (2023). Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU - a foresight study. https://data.europa.eu/doi/10.2760/386650

Liu, Q., Sun, K., Ouyang, X., Sen, B., Liu, L., Dai, T. & Liu, G. (2022). Tracking Three Decades of Global Neodymium Stocks and Flows with a Trade-Linked Multiregional Material Flow Analysis. Environmental Science & Technology, 56, 11807-11817. https://doi.org/10.1021/acs.est.2c02247

Rasmussen, K. D., Wenzel, H., Bangs, C., Petavratzi, E. & Liu, G. (2019). Platinum demand and potential bottlenecks in the global green transition: a dynamic material flow analysis. Environmental Science & Technology, 53, 11541-11551. https://doi.org/10.1021/acs. est.9b01912

Rizos, V., Righetti, E. & Kassab, A. (2024). Understanding the barriers to recycling critical raw materials for the energy transition: The case of rare earth permanent magnets. Energy Reports, 12, 1673-1682. http://doi.org/10.1016/j.egyr.2024.07.022

Seo, Y. & Morimoto, S. (2014). Comparison of dysprosium security strategies in Japan for 2010-2030. Resources Policy, 39, 15-20. https://doi.org/10.1016/j.resourpol.2013.10.007

Sepehri-Amin, H., Hirosawa, S. & Hono, K. (2018). Chapter 4 - Advances in Nd-Fe-B Based Permanent Magnets. Handbook of magnetic Materials, 27, 269-372. https://doi.org/10.1016/bs.hmm.2018.08.003

Wang, P., Yang, Y. -Y., Heidrich, O., Chen, L. -Y., Chen, L. -H., Fishman, T. & Chen, W. -Q., (2024). Regional rare-earth element supply and demand balanced with circular economy strategies. Nature Geoscience, 17, 94-102. https://doi.org/10.1038/s41561-023-01350-9

Wang, Q. -C., Chen, W. -Q., Wang, P. & Dai, T. (2022). Illustrating the supply chain of dysprosium in China through material flow analysis. Resources, Conservation and Recycling, 184, 106417. https://doi.org/10.1016/j.resconrec.2022.106417

Xiao, S., Geng, Y., Pan, H., Gao, Z. & Yao, T. (2022). Uncovering the key features of dysprosium flows and stocks in China. Environmental Science & Technology, 56, 8682-8690. https://doi.org/10.1021/acs.est.1c07724