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Recovering Rare Earth Elements from E-Waste: Potential Impacts on NdFeB Magnet Supply Chains and the Environment

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Abstract

Recent policy initiatives in the United States and beyond have called for decreasing reliance on China for rare earth elements and related downstream products, such as neodymium iron boron (NdFeB) magnets. Among these initiatives, recycling of rare earth elements and NdFeB magnets from electronic waste (e-waste) has emerged as an approach to reduce both import dependence on China and the environmental impacts of mining and refining these products. This paper highlights several methods for recycling NdFeB magnets from e-waste and assesses potential impacts on supply chains and the environment from the commercial adoption of these recycling techniques.

Keywords: Rare earths, rare earth elements, rare earth magnets, rare earth recovery, neodymium iron boron magnets, NdFeB, critical minerals, supply chains, electronic waste, e-waste, e-waste recycling, magnet-to-magnet recycling

USITC filter: Value chain, advanced technology, environment, China
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Introduction

Demand for rare earth elements (REEs) and downstream products containing REE inputs—including neodymium iron boron (NdFeB)[1] magnets—continues to grow, partly as a result of their increased use in low-carbon technologies and electronics. As the strongest permanent magnets, NdFeB magnets are used in both conventional consumer electronics and increasingly in green technologies such as electric vehicles and wind turbines.[2] Supply chains for these products are highly concentrated in China, which supplied 69 percent of REE mine production in 2023 and 92 percent of NdFeB magnet production in 2022. China's sustained dominance in production and processing of REEs and U.S. reliance on imports of these products from China have spurred U.S. domestic policy efforts to diversify these supply chains.

Generally, high supply chain concentration exposes the United States to economic shocks or other crises such as wars, natural disasters, or health crises, increasing risk associated with the inability to quickly adapt sourcing.[3] The COVID-19 pandemic broadly demonstrated the consequences of supply chain concentration. In the REE supply chain, the 2010 China-Japan maritime dispute famously led to China temporarily halting REE exports to Japan.[4] Though short-lived, the export ban disruption created significant panic, demonstrating the need for Japan to diversify its REE imports. Rising trade tensions between the United States and China in recent years amplify concerns that China could restrict exports of REEs or downstream products (e.g., NdFeB magnets), with significant consequences for the U.S. economy and national security. These concerns were most recently reinforced by China's June 2024 announcement of additional rare earth regulations to protect domestic industry by establishing a rare earth product tracking system in the country.[5]

A 2022 U.S. Department of Energy assessment of NdFeB magnet supply chains used a country-level Herfindahl-Hirschman index (HHI), a measure for concentration of global production, to determine domestic supply chain risk.[6] The high geographic concentration of NdFeB magnet manufacturing in China indicated an HHI of 8,514, which is considered high risk.[7] Diversification and dispersion of global production of NdFeB magnets is needed to lower the HHI to moderate risk (typically below 2,500). Because NdFeB magnet production outside of China is minimal, an increase in U.S. production would decrease the HHI, but alone could not reduce the HHI to low risk. Goodman's 2023 working paper, "Method of Estimating Global Supply Chain Risk," identifies a country's level and concentration of import dependence as additional risk factors in supply chain risk analysis. Applying Goodman's analysis

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[1] NdFeB magnets are sometimes referred to as "neodymium" or NIB magnets. See Magnet Shop, "Neodymium Magnets," accessed March 28, 2024.

[2] Permanent magnets are magnets made from materials that create a constant magnetic field. These magnets differ from electromagnets, which require an electric current to create the magnetic field and can be switched on and off.

[3] Even if the supply chain concentration is domestic, a shock can still create sourcing issues.

[4] In 2010, China banned REE exports to Japan, amid rising political tensions between the two countries following a maritime dispute. Rachman, "Japan Might Have an Answer to Chinese Rare-Earth Threats," August 15, 2023.

[5] The regulations enter into force October 1, 2024. Reuters, "China Issues Rare Earth Regulations," June 29, 2024.

[6] USDOE, *Rare Earth Permanent Magnets: Supply Chain Deep Dive Assessment*, February 24, 2022.

[7] USDOE, *Rare Earth Permanent Magnets: Supply Chain Deep Dive Assessment*, February 24, 2022, 27. Generally, values less than 1,500 indicate a competitive market (low risk), values between 1,500–2,500 indicate moderate concentration (moderate risk), and values greater than 2,500 mean an industry is highly concentrated (high risk). Goodman, "A Method of Estimating Global Supply Chain Risk and Predicting the Impacts of Regional Disruptions," January 2023, 5.

method to the U.S. NdFeB magnet supply chain yields a high risk value for imports from China of 7,944.[8] This assessment shows that both increased U.S. domestic production and import diversification are needed to reduce import dependence on China and associated supply chain risk.

The United States, among other countries, has undertaken initiatives to reduce supply chain reliance on China.[9] These initiatives include efforts to expand domestic mine production, separation, and refining capacity; collaboration with trading partners to support diversified supply chains (i.e., friendshoring); and the development of technologies to recover REEs and recycle REE-containing products—particularly NdFeB magnets—from electronic waste (e-waste). This paper focuses on the prospects of the latter effort—secondary REE and NdFeB magnet production through e-waste recycling as a pathway to lower NdFeB magnet supply chain risk. The risk analysis presented further contextualizes potential impacts of increased domestic and foreign secondary production and import diversification to supply chain security.

The paper also examines the accompanying environmental benefits from increased secondary production from e-waste. Increasingly, environmental externalities and regulations are viewed as a form of supply chain risk.[10] As secondary REE and NdFeB magnet production displace primary REE production and e-waste disposal, environmental damages associated with REE mining and e-waste decrease. With stricter environmental regulations—including those surrounding international e-waste trade and disposal—the environmental benefits associated with lowering supply chain risk may give further incentive for policymakers to advance domestic initiatives on secondary REE and NdFeB magnet production.

The paper first presents an overview of current REE supply chains, with a focus on NdFeB magnets as a critical intermediate product. The next section details emerging REE recovery technologies for NdFeB magnets and the economic viability of secondary production given current U.S. production of e-waste and recycling capacity. Background on the environmental costs of primary REE production and e-waste disposal practices follows. The paper next presents potential impacts of increased secondary NdFeB magnet production on trade flows, supply chain security, and the environment. Analysis of potential impacts indicates that secondary production of REEs and NdFeB magnets can yield various environmental benefits and significantly reduce domestic supply chain risks. Further research is needed to accurately quantify these impacts.

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[8] Risk measure is based on data from 2023. Calculations are provided in appendix A. Authors note that one limitation of this risk methodology in assessing NdFeB magnet supply chains is that a large share of imports of these products are embedded in finished products. Thus, the exact level of import dependence and concentration cannot fully be captured.

[9] Van Veen and Melton, "REE Supply Chains Pt. II," June 2021; See also, USDOC, *Effect of Imports of NdFeB Permanent Magnets on the National Security*, February 2023; and White House, "Executive Order on America's Supply Chains," February 24, 2021.

[10] Hsieh, Chen, and Huang, "Investigating the Role of Supply Chain Environmental Risk," January 2023; CDP, "Environmental Supply Chain Risks," February 9, 2021.

Overview of REEs and Current Supply Chains

Uses and Production Process

REEs are a group of 17 metallic elements with similar physical and chemical properties, including fluorescence, magnetism, and high electrical conductivity. Elements classified as REEs include the 15 elements classified as the "lanthanides," as well as scandium and yttrium.[11] REEs are critical inputs into many modern technologies, including electronics, batteries, fuel cells, catalysts, and fiber optics.[12] Despite their moniker, REEs are more prevalent in the earth's crust than many other elements (e.g., iridium). However, they are often found in low-concentration, mixed deposits that are difficult to separate, making extraction and refinement challenging and costly. In addition, the low concentrations of REEs within ores can require extensive mining and refining processes that generate significant waste volumes and cause major disruptions to the environment. Despite the environmental costs posed by mining and processing, demand for REEs has continued to increase in recent years in part because they are used in green technologies such as wind turbines and electric vehicles. Table 1 lists commonly consumed REEs and their major downstream uses.

Table 1 Selected commonly used rare earth elements and their major downstream uses

Element	Major uses
Lanthanum (La)	Fluid catalytic cracking (petroleum refining), battery alloys (for items such as hybrid vehicles, cell phones, and laptops), glass polishing, glass additives (for cameras, telescope lenses, optical glasses, and infrared absorbing glass), and electrolyzers.
Cerium (Ce)	Glass polishing, glass additives, fluid catalytic cracking, automotive catalytic converters, metallurgy, battery alloys.
Praseodymium (Pr)	Magnets (for items such as electric motors, wind turbine generators, and consumer electronics), metallurgy, glass polishing, ceramics, battery alloys.
Neodymium (Nd)	Magnets (for items such as cell phones, medical equipment, electric vehicle motors, wind turbines, and audio systems), metallurgy, battery alloys.
Samarium (Sm)	Battery alloys, magnets (for items such as power generators, motors, and refrigerators), catalysts, fuel cells.
Yttrium (Y)	Phosphors (for television screens and other electronic displays, and LED lighting), ceramics, and electrolyzers.

Sources: Longlast, "Rare Earth Mining," 2013; The Breakthrough Institute, "Are There Enough Critical Minerals for Hydrogen Electrolyzers?" February 27, 2024.

The production process for REEs begins at an open-pit mine with the extraction of ores, typically containing less than 10 percent REEs by weight.[13] Several stages of physical processing and chemical separation transform the ores into more highly concentrated rare earth oxides (REOs). Most commercial end uses require these oxides to have at least 99 percent purity. The pure REOs are further refined into the metallic form of REEs and are typically alloyed with other metals such as iron. The makeup of the

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[11] The 15 lanthanide elements are lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu).

[12] For additional information on specific REEs and their common uses, see Ogasa, "Rare Earth Elements' Hidden Properties Make Modern Technologies," January 16, 2023; Longlast, "Rare-Earth Mining," 2013.

[13] Gschneidner, Jr. and Pecharsky, "Rare-Earth Element: Uses, Properties, & Facts," accessed May 24, 2023.

metal alloys depends on specific end uses.[14] For example, neodymium alloyed with iron and boron through a powder metallurgy process yields sintered NdFeB magnets, which are the strongest permanent magnets. Globally, NdFeB magnets are the most used rare earth magnet.[15]

Current Supply Chains

Global Production and Refinement

China has dominated production of REEs since the early 1990s.[16] Before China's dominance, the Mountain Pass mine in California was the world's largest—and for many decades the only significant—source of REEs.[17] As low-priced imports from China flooded the U.S. market, however, the Mountain Pass mine reduced production and eventually ceased mining altogether in 2002.[18] By 2002, China supplied nearly 90 percent of global REE production and continued to provide between 80 and 98 percent until 2018.[19] In an effort to reduce the ever-growing dependence on REEs from China, the Mountain Pass mine briefly reopened in 2012 but was shuttered again from 2015 to 2017.[20]

Since its most recent reopening in 2018, the Mountain Pass mine, which continues to be the only U.S. source of mined REEs, has quickly increased production each year.[21] U.S. production increased from 14,000 metric tons (mt) in 2018 to 43,000 mt in 2023 (about 12 percent of global production).[22] Meanwhile, other REE deposit-rich countries—such as Australia, Burma, and Thailand—have also increased production of REEs, as the United States and other countries continue initiatives to reduce reliance on China. Despite these efforts, China still contributed more than two-thirds (69 percent) of global mine production in 2023.[23]

Even as REE mining increases and diversifies globally, China largely controls the next stages of the value chain. The country is one of few with existing capacity to separate and refine REEs and produce valuable intermediate products, such as NdFeB magnets (figure 1). As a result, countries with increasing REE mining capacity still must export their production to China for mid- and downstream processing. A 2023

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[14] For further details on production processes, see Longlast, "Rare-Earth Mining," 2013.

[15] *Stanford Magnets*, "A Brief Introduction to Neodymium Magnets (NdFeB)," September 4, 2020.

[16] Hedrick, "Minerals Yearbook 1994: Rare Earths," 1994.

[17] Bradsher, "Challenging China in Rare Earth Mining," April 22, 2010.

[18] The mine was initially closed because of environmental issues; news sources covering the closure indicate that competition from China made its reopening unviable.

[19] China's significant REE reserves, low labor costs, and lenient environmental regulations attributed to its dominance in REE mining and NdFeB production. USGS, "Mineral Commodity Summaries: Rare Earths," 1996–2024; Reuters, "China's Rare Earth Dominance in Focus," December 21, 2023; China Power Project, "Does China Pose a Threat?," July 17, 2020; Politico, "China Dominates the Rare Earths Market," December 14, 2022.

[20] This reopening was driven in part by the conflict in the South China Sea in 2010. For more information see: Rachman, "Japan Might Have an Answer," August 15, 2023.

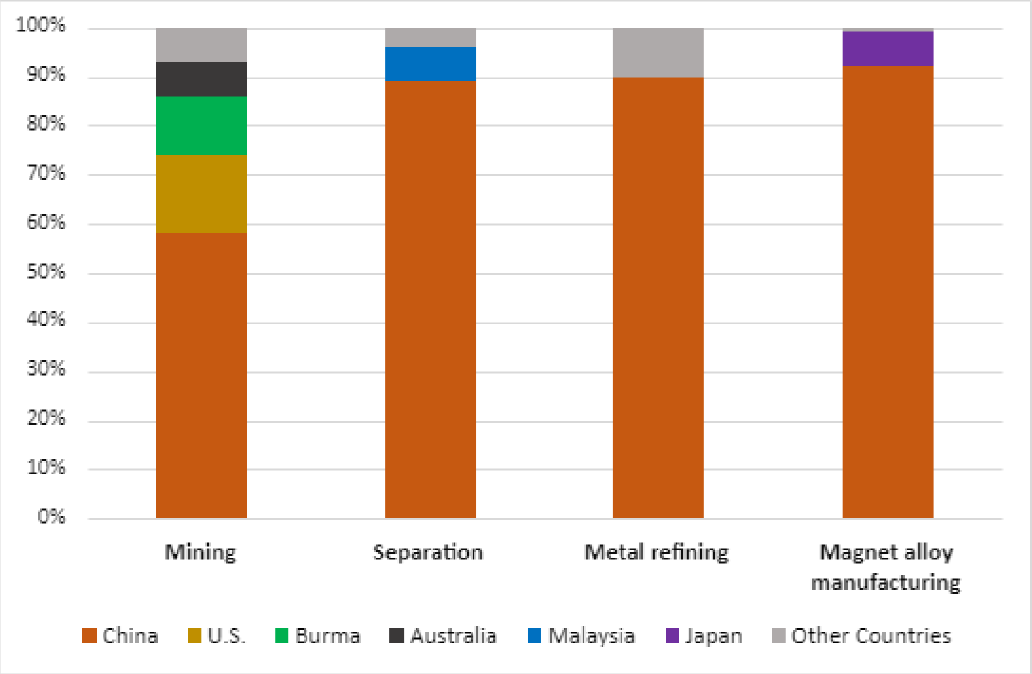
[21] Recent policy initiatives and funding by the U.S. government, including approximately $45 million in contributions from the Department of Defense, have helped to encourage this increase in production. See USDOD, "DOD Awards $35 Million to MP Materials," February 22, 2022 and USDOD, "DOD Announces Rare Earth Element Awards," November 17, 2020.

[22] Today, the Mountain Pass mine produces 9 of the 17 REEs (including neodymium), some of which are produced in the form of mixed concentrates. MP Materials, "What We Do," accessed April 2, 2024; USGS, "Mineral Commodity Summaries: Rare Earths," 2019–24.

[23] USGS, "Mineral Commodity Summaries: Rare Earths," 2024.

report by the U.S. Department of Commerce (USDOC) found that the United States recorded no NdFeB magnet production between 2017 and 2022 and is nearly “one hundred percent dependent on imports [of NdFeB magnets] to meet defense and commercial requirements,” with three-quarters of those imports from China.[24]

Figure 1 Geographical concentration of supply chain stages for sintered NdFeB magnets



Source: Adapted from USDOE, *Rare Earth Permanent Magnets: Supply Chain Deep Dive Assessment*,” February 24, 2022, 25.

Trade Flows

Exports

Despite China’s dominance in production, the United States briefly surpassed China as the world’s largest global exporter of REEs from 2019 to 2022. China recouped its place as largest global exporter in 2023.[25] In 2023, the United States supplied 29.0 percent of global exports and China supplied 44.6 percent. More than 99 percent of U.S. exports of REEs from 2019 to 2023 were of unrefined ores or oxides (table 2). This majority is attributable to the lack of separation and refining capacity in the United States. The lack of capacity is further demonstrated by the 95 percent of U.S. REE exports by volume sent to China—the country with the largest capacity for separation and refining.[26]

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[24] USDOC, *Effect of Imports of NdFeB Magnets*, February 2023, 7, 59.

[25] Ranking is on the basis of both value and volume of global imports. S&P Global Trade Atlas, HS subheadings 2805.30, 2846.10, and 2846.90, accessed February 29, 2024.

[26] USITC DataWeb/Census, Domestic Exports, HS subheadings 2805.30, 2846.10, and 2846.90, accessed March 5, 2024. Data do not include exports of ferrocerium alloys.

Table 2 U.S. exports of rare earth elements by form 2019–23
In metric tons (mt), and thousand dollars ($1,000); REO = rare earth oxide; REE = rare earth element.

Product	2019	2020	2021	2022	2023
Unrefined rare earth ores and REOs (mt)	46,521	63,993	76,173	76,387	33,759
Rare earth metals (mt)	84	29	19	21	50
All REEs (mt)	**46,605**	**64,022**	**76,192**	**76,408**	**33,809**
Unrefined rare earth ores and REOs ($)	83,362	118,415	309,912	581,028	362,550
Rare earth metals ($)	1,620	2,321	1,388	1,715	2,955
All REEs ($)	**84,982**	**120,736**	**311,299**	**582,743**	**365,505**

Source: USITC DataWeb/Census, Domestic exports, *Harmonized Commodity Description and Coding System* (HS) subheadings 2805.30, 2846.10, and 2846.90, accessed March 5, 2024.

Notes: Unrefined rare earth ores and rare earth oxides are exported under HS subheadings 2846.10 and 2846.90. Rare earth metals are exported under HS subheading 2805.30. Data do not include exports of ferrocerium alloys under HS subheading 3606.90, a basket category, which also includes non-rare earth products. Ferrocerium alloys likely account for a very small share of global exports of rare earths.

Beyond REEs, intermediate products—specifically certain fabricated inputs—are traded. For example, although the United States does not currently have any NdFeB magnet production capacity,[27] a small volume of U.S. NdFeB magnet exports was reported during the period of 2019–23 (table 3). Although the USDOC report on NdFeB magnets suggests that these exports are largely driven by magnet finishers and fabricators rather than producers, the U.S. Geological Survey (USGS) noted in 2022 that some recycling from e-waste already occurs, which could be an additional source of these exports (see section below on “E-Waste and Secondary Sourcing Opportunities”).[28]

Table 3 U.S. exports of NdFeB magnets, 2018–22
In number, kilograms, and thousand dollars; n.a. = not available.

Units	2018	2019	2020	2021	2022	2023
Magnet count	1,461,905	2,796,595	5,172,735	12,276,108	3,441,167	4,244,966
Kilograms	n.a.	n.a.	n.a.	8,907,619	646,492	745,318
Thousand dollars	9,426	11,155	10,804	11,978	10,979	14,632

Source: USITC DataWeb/Census, Domestic exports, HS statistical reporting number 8505.11.0070, accessed March 5, 2024.

Note: Data on NdFeB magnet exports in kilograms were not available before 2021.

Imports

The United States is the third-largest global importer of REEs behind China and Japan.[29] Because both China and Japan have some REE processing capacity, they are likely processing and then re-exporting

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[27] USDOC, *Effect of Imports of NdFeB Magnets*, February 2023, 58.

[28] USDOC, *Effect of Imports of NdFeB Magnets*, February 2023, 45; USGS, “Mineral Commodity Summaries: Rare Earths,” 2022, accessed November 11, 2023.

[29] Statistics based on both value and volume of global imports. S&P Global Trade Atlas, HS subheadings 2805.30, 2846.10, and 2846.90, accessed February 29, 2024.

some of what they import. Although U.S. REE imports, similar to exports, primarily constitute unrefined ores and oxides (table 4), researchers indicate that imports of further processed products (e.g., rare earth metals) are likely to be embedded in intermediate or finished products.[30] Similarly, although U.S. imports of NdFeB magnets are quite large (table 5), these numbers are also likely understated because imports are embedded in intermediate or finished products.

Table 4 U.S. imports of rare earth elements by form, 2019–23

In metric tons (mt) and thousand dollars ($); REO = rare earth oxide; REE = rare earth element.

Product	2019	2020	2021	2022	2023
Unrefined rare earth ores and REOs (mt)	20,185	10,608	12,006	16,481	14,588
Rare earth metals (mt)	519	303	487	406	400
All REEs (mt)	**20,704**	**10,911**	**12,493**	**16,887**	**14,988**
Unrefined rare earth ores and REOs ($)	145,626	96,044	133,113	184,386	160,809
Rare earth metals ($)	8,191	8,838	17,257	17,687	21,990
All REEs ($)	**153,818**	**104,882**	**150,369**	**202,073**	**182,780**

Source: USITC DataWeb/Census, Imports for consumption, HTS subheadings 2805.30, 2846.10, 2846.90, accessed March 5, 2024.

Note: Data do not include imports of ferrcerium alloys.

Table 5 U.S. imports of NdFeB magnets 2019–23

In number, kilograms, and thousand dollars; n.a. = not available.

Units	2019	2020	2021	2022	2023
Magnet count (no.)	323,174,931	283,065,006	320,089,077	330,372,785	339,389,816
Kilograms (kg)	n.a.	n.a.	7,667,483	5,757,954	6,100,236
Dollars ($)	152,484	141,054	235,847	336,127	304,432

Source: USITC DataWeb/Census, Imports for consumption, HTS statistical reporting number 8505.11.0070, March 5, 2024.

Note: Data on NdFeB magnet exports in kilograms were not available before 2021.

E-Waste Recovery and Secondary Sourcing Opportunities for REE and NdFeB Magnets Supply

E-waste describes electronic and electrical equipment that has reached its end-of-life (EOL) in its primary function or is otherwise obsolete, defunct, or discarded. The most thought of form of e-waste is consumer electronics, such as mobile phones, computers, and televisions. E-waste also includes larger components such as electric vehicle batteries and wind turbine generators, all of which contain REEs. E-waste is the fastest-growing post-consumer waste stream globally, driven by technological innovations

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[30] USGS, "Mineral Commodity Summaries: Rare Earths," 2023; Gagarin, Hannah and Roderick G. Eggert, "Measuring Trade Flows of Sintered NdFeB Magnets and Li-ion Batteries: Reported vs Embedded U.S. Imports," *Mineral Economics,* June 27, 2023.

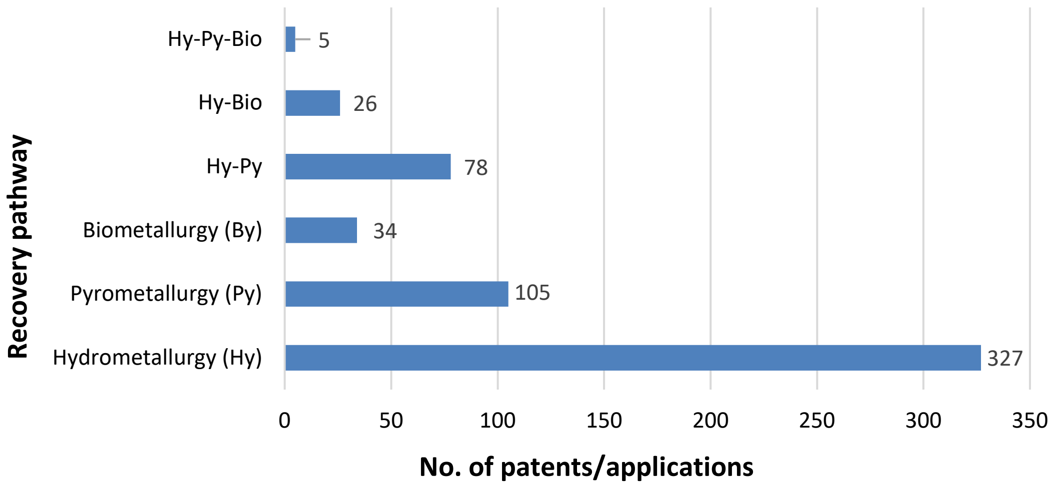
in the electronics sector, the increasing demand for electronics in developing economies, and the decreasing lifespan of electronics.[31]

After China imposed domestic export restrictions on REEs in 2009, leading to global supply chain issues, research initiatives related to REE recovery from various e-waste accelerated globally.[32] This section reviews the state of innovation in REE recovery methods from e-waste, with emphasis on the recovery of neodymium from EOL NdFeB magnets.

Overview of Recovery Methods

Research to isolate and retrieve REEs from e-waste is ongoing, but several REE recovery methods are increasingly applied. A 2023 analysis of patent technologies for REE recovery from e-waste identified six of the most common pathways (figure 2).

Figure 2 Technology landscape for REE recovery from e-waste



Source: Reconstructed from Barbieri, “Searching Patent Information on the Recovery of Rare Earth Metals,” April 26, 2023, 11.

Hydrometallurgy and pyrometallurgy are covered most extensively in the literature as commercially established methods for metals recovery—in part because the process steps are like those in primary metals production (i.e., straight from the ore). In applications to reclaim REEs from magnets in e-waste, both methods have high recovery rates for a range of magnet compositions.[33] Biometallurgical methods have emerged as an environmentally efficient alternative to conventional routes and may become increasingly economically viable. From 2014 to 2022, more than 50 publications detailed

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[31] From 2000 to 2010, the average lifespan of large electronics and electrical devices decreased from eight years to two years, while the average lifespan of mobile phones decreased from four years to nine months. Municipal solid waste is another form of post-consumer waste. Işıldar et al., “Biotechnological Strategies . . . Recovery of Critical Raw Materials,” January 2019, 468; Ramprasad et al., “Sustainable Recovery of Rare Earth Elements,” August 2022, 2.

[32] Işıldar et al., “Biotechnological Strategies . . . Recovery of Critical Raw Materials,” January 2019, 46; Ambaye et al., “Emerging Technologies . . . Recovery of Rare Earth Elements,” October 2020, 2.

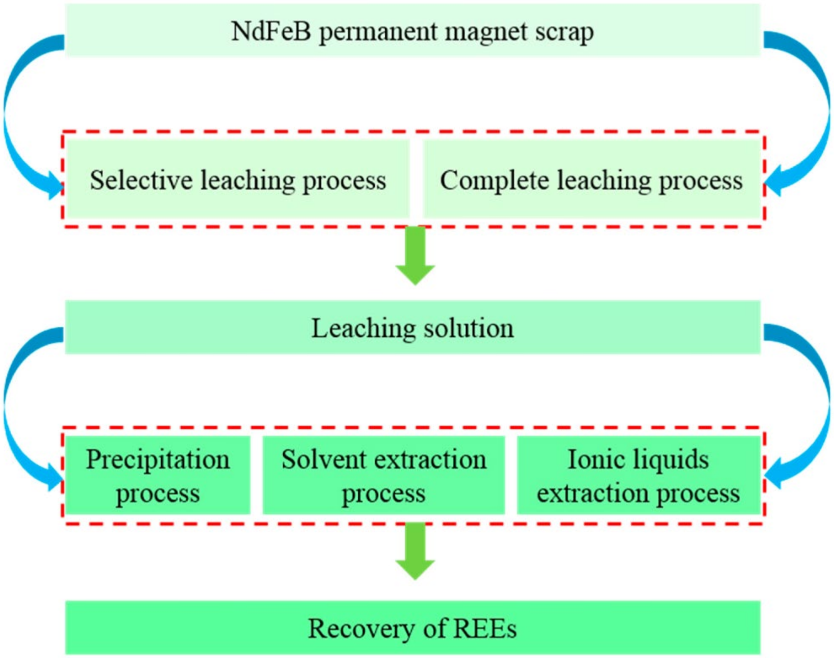
[33] The recovery rate is the proportion of valuable material obtained in the processing of a primary ore or EOL material. Zhang et al., “Hydrometallurgical Recovery of Rare Earth Elements,” June 2020, 2–3.

biometallurgical patent applications for REE recovery.[34] Researchers are also developing novel methods for REE recovery in NdFeB magnets, including hydrogen processing of magnetic scrap (HPMS), described in detail below. The profiled methods here are not exhaustive, and within each overarching method the process steps vary depending on the e-waste source, desired form, and type of recovered REE.

Hydrometallurgy

Hydrometallurgy is a process that recovers targeted metals from ore or spent material through water-based steps in three stages: leaching, extraction and purification, and recovery (figure 3).[35] In the hydrometallurgical recovery process for neodymium, the final product comes in the form of a mixed oxide, a rare earth salt mixture, or a pure rare earth oxide (REO) or salt.[36] Generally, hydrometallurgical processes recover REEs at a high rate from a wide variety of waste compositions.[37] This recovery route is currently favored in part because it uses the same processing steps as those for primary REE extraction from ores, allowing primary producers to integrate secondary production more smoothly than alternative recovery routes.[38]

Figure 3 Schematic process diagram of REE recovery via hydrometallurgy
NdFeB = neodymium iron boron



Source: Zhang et al., "Hydrometallurgical Recovery of Rare Earth Elements," June 2020, 9.

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[34] Barbieri, "Searching Patent Information . . . Recovery of Rare Earth Metals," April 26, 2023, 13.
[35] TES, "The Difference Between Hydrometallurgy and Pyrometallurgy," May 2, 2023.
[36] Periyapperuma et al., "Analysis of Sustainable Methods to Recover Neodymium," September 2021, 2.
[37] Periyapperuma et al., "Analysis of Sustainable Methods to Recover Neodymium," September 2021, 2; Zhang et al., "Hydrometallurgical Recovery of Rare Earth Elements," June 2020, 3.
[38] Zhang et al., "Hydrometallurgical Recovery of Rare Earth Elements," June 2020, 3.

Hydrometallurgy is the most common method to extract REEs, both in primary and secondary recovery.[39] REE recovery from EOL NdFeB magnets and batteries via hydrometallurgy typically first involves crushing the spent product into a powder. Once crushed, the material is leached: dissolved in water with agents like acid at high temperatures. Leaching the crushed powder yields a highly concentrated REE liquid to be further processed.[40] Type of acid, temperature, and pulp density—or the solid-to-liquid ratio applied in the process—affect the recovery efficiency of leaching. For example, higher temperature and optimized pulp density can yield a 98.1 percent recovery efficiency of neodymium from spent NdFeB magnets.[41] The final recovered product after leaching is REO mixtures. The separation of multiple rare earth metals mixed in the resulting leachate is one result of extraction or selective precipitation, which is a disadvantage to this process. Either extraction or selective precipitation can result in the separation of multiple rare earth metals mixed in the resulting leachate—one disadvantage to this process. Solvent extraction—the main alternative to precipitation—can separate individual REEs while maintaining high purity but requires more complex steps and increases chemical use and waste generation.[42]

Pyrometallurgy

REEs are also recovered from e-waste through various pyrometallurgical routes. Pyrometallurgy uses heat-based extraction and purification for metals recovery.[43] Thermal processing is easier to scale and uses less water and fewer chemicals than hydrometallurgy but requires a much higher energy intensity. Because of its high energy intensity, heat-based processing is generally applied to high-grade wastes such as NdFeB magnets, nickel-metal hydride (NiMH) batteries, printed circuit boards, and lamp fluorescent powder.[44] Pyrometallurgy typically involves three main steps: roasting, smelting, and refining. Roasting heats REE compounds to create gas; smelting reduces—or separates—metals at high temperatures (ranging from 500°C to 1,000°C) in furnaces; and refining uses various furnaces and electrolytic processes to further sort metals according to their composition.[45]

Molten salt electrolysis is a common pyrometallurgical approach for neodymium recovery from NdFeB magnets. Spent NdFeB magnets chemically react with fluoride- and chloride-based salts before being heated at 700°C, yielding a dense neodymium deposit of 99.78 percent purity.[46] Molten salt electrolysis can, however, produce harmful gas byproducts (e.g., chlorine or bromine). Alternative halide salts (i.e.,

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[39] Owusu-Fordjour and Yang, "Bioleaching of Rare Earth Elements," October 2023, 1.

[40] Brião, da Silva, and Vieira, "Absorption Potential for the Concentration and Recovery of Rare Earth Metals," December 20, 2022, 4.

[41] In studies of REE recovery from Ni-MH batteries (rechargeable batteries), the use of hydrochloric acid has increased efficiency to about 99.9 percent in the leaching step. Periyapperuma et al., "Analysis of Sustainable Methods to Recover Neodymium," September 2021, 2.

[42] Periyapperuma et al., "Analysis of Sustainable Methods to Recover Neodymium," September 2021, 2.

[43] TES, "The Difference Between Hydrometallurgy and Pyrometallurgy," May 2, 2023.

[44] NiMH batteries are common household rechargeable batteries. Ramprasad et al., "Sustainable Recovery of Rare Earth Elements from Electronic Waste," August 2022, 6.

[45] TES, "The Difference Between Hydrometallurgy and Pyrometallurgy," May 2, 2023.

[46] Periyapperuma et al., "Analysis of Sustainable Methods to Recover Neodymium," September 2021, 2.

those substituted for traditional molten salt electrolysis) can reduce these byproducts and the temperature required to recover neodymium from NdFeB magnets.[47]

Bioprocess and Biometallurgy

REE recovery through bioprocesses—sometimes referred to as biomining or biorecovery—is becoming a viable, sustainable alternative to hydrometallurgy and pyrometallurgy. Historically, bioprocesses have helped extract REEs from primary sources, such as monazite ores, but are increasingly being applied to e-waste.[48] Bioprocesses used in REE recovery include bioleaching, biosorption, bioprecipitation, and bioreduction.[49] Bioleaching, similar to the leaching process in hydrometallurgy, uses microorganisms to dissolve minerals in aqueous media.[50] Unlike in hydrometallurgy, microorganisms in bioleaching recover REEs at higher rates in e-waste with lower REE concentrations because high concentrations can cause the microorganisms to suffer from heavy metal toxicity.[51] Typically, using multiple microbial strains in a bioprocess is preferred to using a pure culture because of the complexity of minerals in the waste material.[52] Microorganisms (i.e., fungi, bacteria, and archaea) produce certain acids and enzymes that facilitate a symbiotic interaction—the dissolution of mineral particles and growth of the microorganisms from use of those minerals.[53]

Like chemical processes, REE recovery rates from bioprocesses are affected by physical and chemical factors, including oxygen levels, temperature, pulp density, acidity, and metal toxicity.[54] These factors affect growth of microorganisms, which relies on nutritional inputs (e.g., sucrose and glucose) and the microbes' ability to interact with metals. In forward-looking systems of sustainable waste recovery, researchers suggest that using organic waste applications—food, sewage, and agricultural residue—may simultaneously minimize operational costs for microbial growth while using two waste streams for resource recovery.[55]

Other Recovery Technologies for Permanent Magnets

Established metal recovery methods have gained renewed attention for their potential applications to REE recovery from e-waste; other novel methods are specifically designed to recover REEs from spent NdFeB magnets. Research and development funding for innovations in magnet-to-magnet recycling has accelerated given the value and increasing volume of this e-waste stream.

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[47] Periyapperuma et al., "Analysis of Sustainable Methods to Recover Neodymium," September 2021, 2.

[48] Dev et al., "Biological Recovery of Rare-Earth Elements from Electronic Waste," October 2020, 12.

[49] Işıldar et al., "Biotechnological Strategies for the Recovery of Valuable and Critical Raw Materials," January 2019, 475–476; Vo et al., "Biomining for Sustainable Recovery of Rare Earth Elements from Mining Waste," January 2024.

[50] Owusu-Fordjour and Yang, "Bioleaching of Rare Earth Elements," October 2023, 2.

[51] Dev et al., "Biological Recovery of Rare-Earth Elements," October 2020, 12.

[52] Kinnunen and Hedrich, "Biotechnological Strategies to Recover Value from Waste," October 2023, 3.

[53] Owusu-Fordjour and Yang, "Bioleaching of Rare Earth Elements," October 2023, 2.

[54] Dev et al., "Biological Recovery of Rare-Earth Elements," October 2020, 10.

[55] Studies at Idaho National Laboratory (INL) suggested bioleaching with potato waste rather than refined glucose as a nutrient source for microorganisms reduced costs by 17 percent. Mirkouei, Amin, "Low Emission Rare Earth Metals Manufacturing," May 29, 2024; Dev et al., "Biological Recovery of Rare-Earth Elements," October 2020, 12.

One recovery approach gaining attention for REEs is hydrogenation, a process that exposes the metals to hydrogen gas. In hydrogenation, the hydrogen gas diffuses through the metals' grain boundaries, causing fracturing and separation.[56] For permanent magnets, the hydrogen decrepitation process is used for both primary and secondary production.[57] Typically, the permanent magnets in discarded hard disk drives—a common e-waste that contains REEs in addition to other critical minerals—are disassembled, demagnetized, and decoated before the hydrogenation process. The chemical and metallurgical composition of permanent magnets leaves them vulnerable to exposure to hydrogen gas, which collapses the magnet's structure and converts it to powder form for further processing. The resulting powder is highly demagnetized relative to the output from mechanical crushing in conventional recovery methods—an efficiency advantage of hydrogen decrepitation.[58]

Another developing method for magnet-to-magnet recycling is hydrogen processing of magnetic scrap (HPMS), which occurs in two main stages: the collection and transformation of EOL magnets to powder, and production of new NdFeB magnets with recovered powder.[59] The EOL magnet separates when exposed to hydrogen at atmospheric pressure and room temperature—requiring no additional energy input to separate the magnet. The resulting powder is demagnetized, facilitating easy collection.[60] The hydrogen exposure facilitates the mechanical separation of the nickel coating, eliminating the need for additional process steps and other chemical or energy inputs. Finally, the HPMS process yields NdFeB alloy powder with high enough purity to be directly reprocessed into new permanent magnets.[61]

Advancements and Tradeoffs in Pathways for REE Recovery from NdFeB Magnets

Both hydrometallurgy and pyrometallurgy have high REE recovery rates and use relatively simple production steps that mirror established practice for primary NdFeB magnets production. However, these conventional routes are resource inefficient, requiring high levels of energy, water, and chemical inputs, and produce significant waste byproducts. The potential to lower secondary production costs through input resource efficiency has encouraged development of alternative recovery pathways, such as biorecovery and HPMS.

Bioprocesses' relative efficiency and performance in lower-concentrated e-waste gives the recovery pathway a key techno-economic advantage over other secondary recovery methods.[62] Bioleaching is already used commercially for metals recovery from mining waste and known as a more feasible recovery method for low-value (i.e., less concentrated) ores compared to conventional mining and process techniques.[63] In comparisons of bioprocesses versus chemical leaching to extract REEs from

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[56] Grain boundaries refer to the material composition of the metal. Habibzadeh, Kucuker, and Gökelma, "Parameters of Recycling NdFeB Magnets," May 23, 2023, 17435.

[57] Habibzadeh, Kucuker, and Gökelma, "Parameters of Recycling NdFeB Magnets," May 23, 2023, 17435.

[58] Habibzadeh, Kucuker, and Gökelma, "Parameters of Recycling NdFeB Magnets," May 23, 2023, 17435.

[59] Habibzadeh, Kucuker, and Gökelma, "Parameters of Recycling NdFeB Magnets," May 23, 2023, 4.

[60] *Magnetics*, "HyProMag H2-Enabled Magnet Recycling Ventures," January 11, 2023.

[61] *Magnetics*, "HyProMag H2-Enabled Magnet Recycling Ventures," January 11, 2023.

[62] A techno-economic assessment analyzes the economic performance of an industrial process. Dev et al., "Biological Recovery of Rare-Earth Elements," October 2020, 12.

[63] Owusu-Fordjour and Yang, "Bioleaching of Rare Earth Elements," October 2023, 2.

low-grade wastes, such as the extraction of praseodymium (Pr) from low-grade magnets, only biological extraction was shown to yield complete recovery.[64]

Currently, biorecovery applications in e-waste remain at the laboratory stage.[65] Nevertheless, biorecovery methods for REEs may be on the brink of commercial scale. The economic potential for REE recovery from bioprocesses depends on optimization of the physical and chemical factors noted above to both support microbial growth and maintain high recovery rates at a low cost. One assessment of REE bioleaching from e-waste in petroleum refineries estimated capital and maintenance costs and revenue for a bioleaching facility that could process nearly 18,000 mt of catalyst waste. Estimates indicated the bioleaching plant could yield a marginal profit.[66] A limiting factor for profitability in bioprocesses is time consumption—certain forms of recovery can take months to years to complete.[67]

HPMS provides several economic and environmental advantages for recovering permanent magnets. Compared to primary production using ores, HPMS can reduce production costs by 53 percent, energy consumption by 45 percent, and carbon dioxide (CO_2) emissions by 11 mt per mt of recycled NdFeB magnet.[68] The University of Birmingham patented an HPMS process and exclusively licensed it to HyProMag Limited, a company established to commercialize the process. Its German subsidiary HyProMag GmbH received grants from the European Regional Development Fund and the German Ministry of Economic Affairs to establish a production-scale facility to recover and produce NdFeB magnets, alloy pellets, and powders using the patented HPMS process.[69] Initial commercial production and sales at HyProMag's UK and Germany operations are slated for 2025.[70]

Table 6 highlights several innovations in REE recovery from e-waste in the past decade, most of which focus on neodymium recovery from NdFeB magnets. The types of recovery, common e-waste sources, recovery forms, and demonstrated recovery rates are shown.

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[64] Dev et al., "Biological Recovery of Rare-Earth Elements," October 2020, 12.

[65] Kinnunen and Hedrich, "Biotechnological Strategies to Recover Value from Waste," October 2023.

[66] Thompson et al., "Techno-Economic and Life Cycle Analysis for Bioleaching," February 5, 2018.

[67] Kinnunen and Hedrich, "Biotechnological Strategies to Recover Value from Waste," October 2023.

[68] Habibzadeh, Kucuker, and Gökelma, "Parameters of Recycling NdFeB Magnets," May 23, 2023, 4.

[69] *Magnetics*, "HyProMag H2-Enabled Magnet Recycling Ventures," January 11, 2023; Mining Technology, "HyProMag secures grants for rare earth recycling plant in Germany," November 24, 2022.

[70] Bulbulia, Tasneem, "Mkango's HyProMag subsidiary continues to progress," August 30, 2024.

Table 6 Emerging pathways for REE recovery from e-waste
Nd = neodymium; Pr = praseodymium; Dy = dysprosium; REE = rare earth element.
In percentages;

Method type	Process	REEs	Recovery form	Types of e-waste	Highest reported recovery rate
Hydrometallurgy	Membrane-assisted solvent extraction	Nd, Pr, Dy	REE oxides	Hard disk drives, other sources of permanent magnets	> 99.5
Hydrogenation	Hydrogen processing of magnet scrap (HPMS)	Nd, Pr, Dy, Tb	Direct alloy powder	Sources of permanent magnets	90
Electrical dissolution	Enhanced dissolution in organic (citric) acid	Nd, Pr, Dy	Nd, Pr, Dy oxides	Sources of permanent magnets	99.9
Bioprocess	Bioleaching with nanoengineered cellulose	Nd	Nd^{3+} containing compound	Computers, printed circuit boards, other sources of permanent magnets	88.1
Bioprocess	Biosorption using dried green algae	Nd	Leachate solution	Sources of permanent magnets	99.9

Sources: ORNL, “Electronic Waste is Mined,” August 14, 2019; Magnetics, “HyProMag H2-Enabled Magnet Recycling Ventures Coming Onstream,” January 11, 2023; Habibzadeh, Kucuker, and Gökelma, “Review on the Parameters of Recycling NdFeB Magnets,” May 23, 2023; Kucuker, et al., “Biosorption of Neodymium (Nd) Using Microalgae,” June 15, 2016; Wamea et al., “Nanoengineering Cellulose for the Selective Removal of Neodymium,” January 15, 2022; Kumari et al., “Electrochemical Treatment of Spent NdFeB Magnet,” August 2021, 1.
Notes: The research institutions involved in the development of these processes include government, private industry, and academia. Hard disk drives are the hardware component of electronics (e.g., computers) that store data.

Different forms of e-waste are suited for different recovery routes, and often multiple methods are applied to yield a production-ready input from a spent material. E-waste availability, economic viability, and resource efficiency are key factors considered in each recovery method, informing a techno-economic perspective of the potential for secondary production of NdFeB magnets from e-waste.

U.S. Production of E-Waste and Recycling Capacity

The viability of secondary REE and NdFeB magnets production as an alternative to primary production requires sufficient e-waste supply and enough recoverable REEs within that waste. The United States produced 7.2 million mt of e-waste in 2019, generating about 12 percent of total global e-waste production that year.[71] Concentrations of REEs in e-waste vary depending on the product, with one recent estimate suggesting that NdFeB magnets comprised up to 26.7 percent of e-waste, by weight.[72] Based on the above U.S. e-waste production figures, this estimated concentration yields a recovery potential of approximately 1.8 mt of NdFeB magnets. Successful REE recovery, however, relies heavily on the efficiency of the reclamation processes and recycling. For example, one 2023 analysis found that

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[71] U.S. e-waste production is up from 6.9 million mt in 2019. Forti et al., “The Global E-Waste Monitor 2020,” 2020, 72. Baldé et al., “The Global E-Waste Monitor 2024,” 2024, 68.
[72] Although the paper says that most bulk e-waste would not typically be as concentrated. Brewer, Dror, and Berkowitz, “Electronic Waste . . . Rare Earth Element Pollution,” January 1, 2022.

NdFeB magnets recovery from e-waste could supply between 12 percent and 70 percent of U.S. electric vehicle demand by 2050, depending on these factors.[73]

In 2019, only 15 percent U.S. e-waste production was collected for recycling.[74] As of 2024, despite no federal laws governing the collection or recycling of e-waste, 25 states and the District of Columbia have some type of legislation on e-waste regulation in place.[75] The laws in these states are estimated to cover 75–80 percent of the U.S. population. Most states that have implemented laws use an "extended producer responsibility" approach, meaning producers of electronic products are responsible for instituting recycling programs in that state to sell their product.[76] Despite the coverage that legislation provides at the state level, U.S. collection rates remain low, in part, because of high costs and decreasing profit margins.

Internationally, the Basel Convention prohibits the transboundary movement of certain types of hazardous e-waste. These restrictions include REE-heavy e-waste products such as certain batteries and cathode-ray tubes.[77] As of early 2024, most countries have ratified the convention, though the United States remains an exception and continues to export a large volume of e-waste to Asian countries. Many recipient countries are parties to the convention but allow informal or illegal import markets to circumvent the rules.[78] In recent years, China and other countries have started to crack down on these informal markets and more seriously limit imports of e-waste.[79] If those efforts are successful, the United States will have fewer export options and may be pressured toward a domestic solution for e-waste disposal, potentially leading to increased domestic recycling and secondary supply.

Economic Viability of Recovery from E-Waste

About $57 billion of valuable metals in e-waste are unrecovered annually.[80] The potential market for REE recovery is immense but currently only 1–2 percent of REEs produced globally are recovered through recycling processes.[81] These rates indicate that nearly the entire secondary source stream for REE inputs is untapped, and this stream may be able to alleviate reliance on primary production as projected demand for REEs increases. For example, annual demand growth for NdFeB magnets is an

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[73] Maani et al., "Estimating Potentially Recoverable Nd from End-of-Life (EoL) Products," March 2023, 1, 3.

[74] Reinsch and Hokayem, "A Canary in an Urban Mine," July 29, 2021; Global E-Waste Statistics Partnership, "United States of America, 2019 E-Waste Statistics," 2019.

[75] Forti et al., "The Global E-Waste Monitor 2020," 2020; Global E-Waste Statistics Partnership, "United States of America, 2019 E-Waste Statistics," 2019; Electronic Recycling Coordination Clearinghouse, "Map of States with Legislation," accessed February 5, 2024.

[76] For example, Virginia's Computer Recovery and Recycling Act requires computer and computer equipment manufacturers selling in Virginia to file a recovery/recycling plan to sell its products within the state. Programs must be of no cost to the consumer. Virginia DEQ, "Computer & Electronics Recycling," accessed May 26, 2023.

[77] UNEP, "Basel Convention," accessed February 5, 2024.

[78] Eco-Business, "Defusing Southeast Asia's E-Waste Time-Bomb," August 2019.

[79] Larmer, "E-Waste Offers an Economic Opportunity as Well as Toxicity," July 5, 2018; The Malaysian Reserve, "Cross-Border E-Waste to Get Prior Approval Before Being Carried Out," December 15, 2022

[80] Ghimire and Ariya, "E-Wastes," September 2020.

[81] Zhang et al., "Hydrometallurgical Recovery of Rare Earth Elements," June 2020, 5; Patil et al., "Separation and Recycling Potential of Rare Earth Elements," March 2022, 1.

estimated 12.5 percent, with peak global demand expected by 2035.[82] By 2050, demand for neodymium and dysprosium are projected to exceed extraction volumes by 9 and 35 times, respectively. [83] Key factors that limit economic viability of REE recovery from e-waste are the challenges associated with technological separation for smaller forms of e-waste, insufficient infrastructure for large-scale e-waste collection, and lack of regulatory incentives.[84] As such, the purchase of REEs from primary production sources remains less expensive than the purchase of REEs reprocessed from e-waste.[85]

Higher concentrations of targeted metals in both ore and e-waste tend to increase the economic viability of primary extraction and secondary recovery.[86] The economic viability of secondary recovery methods is especially favored because e-waste contains higher concentrations of REEs than those present in ores.[87] The e-waste thought to have the greatest economic potential for REE recovery is phosphors (used in fluorescent and LED lights), NdFeB magnets, and NiMH batteries.[88] Recovery of neodymium from NdFeB magnets is extensively covered in literature as one of the most viable pathways for REE recovery from e-waste, in part, because of the high REE concentration in NdFeB magnet residue compared to other spent materials.[89]

Recovery Solutions for the REE Balance Problem

One key inefficiency in REE primary production is the extraction and overproduction of low-value rare earths—such as lanthanum and cerium—present in ores sought for higher-value rare earths like neodymium and dysprosium. Typically, to extract one unit of neodymium, two equivalent units of cerium and one equivalent unit of lanthanum must be extracted.[90] This is known as the "balance problem" in REE mining. Overproduction of these lower-value REEs causes market distortions and uneven pricing dynamics.[91] Secondary recovery of high-value REEs from e-waste can reduce the volume of overproduction of low-value REEs from primary mining.

This balance problem has in part led to the establishment of national strategies and frameworks to encourage a circular economy approach—using waste as an input stream.[92] Regardless of incentives,

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[82] Ramprasad et al., "Sustainable Recovery of Rare Earth Elements," August 2022, 4; Brião, da Silva, and Vieira, "Absorption Potential . . . Recovery of Rare Earth Metals," December 20, 2022.

[83] Ramprasad et al., "Sustainable Recovery of Rare Earth Elements," August 2022, 4; Brião, da Silva, and Vieira, "Absorption Potential . . . Recovery of Rare Earth Metals," December 20, 2022.

[84] Patil et al., "Separation and Recycling Potential of Rare Earth Elements," March 2022

[85] This is especially the case in small-scale products with REEs, which require more processing steps to separate the desired material. Brião, da Silva, and Vieira, "Absorption Potential . . . Recovery of Rare Earth Metals," December 20, 2022.

[86] As noted above, bioprocessing is an exception as higher metal concentrations can harm microorganisms.

[87] For example, REE concentration in LF phosphor powder is roughly 15 times higher than in primary ore. Shahabuddin et al., "A Review . . . Opportunities of Electronic Waste," April 1, 2023; Ramprasad et al., "Sustainable Recovery . . . Electronic Waste," August 2022, 2; Giese, "E-Waste Mining and the Transition," April 14, 2022.

[88] Patil et al., "Separation and Recycling Potential of Rare Earth Elements," March 2022, 2.

[89] For example, REEs make up 32 percent of the content in NdFeB magnet scraps from hard disk drives, 65–70 percent of which is neodymium. Zhang et al., "Hydrometallurgical Recovery of Rare Earth Elements," June 2020, 5; Patil et al., "Separation and Recycling . . . Rare Earth Elements," March 2022; Sagrillo Pimassoni et al., "The Recovery of Rare Earth Elements from Waste," October 1, 2023; Brião, da Silva, and Vieira, "Adsorption Potential . . . Recovery of Rare Earth Metals," December 20, 2022.

[90] Patil et al., "Separation and Recycling Potential of Rare Earth Elements," March 2022, 2.

[91] Patil et al., "Separation and Recycling Potential of Rare Earth Elements," March 2022, 2.

[92] European Commission, "Waste from Electric and Electronic Equipment," accessed February 13, 2024.

the marginal cost differentials in primary versus secondary REE production will converge as demand for REEs and the volume of e-waste increase, recovery technologies scale, primary deposits deplete, and environmental costs become market integrated. The next section details environmental costs associated with primary mining and e-waste disposal, both of which are displaced by secondary NdFeB magnet production.

Environmental Impacts of REE Production and E-Waste Disposal

Beyond reducing supply chain risks, increased domestic secondary REE production and import diversification away from China can provide cost savings through improved environmental outcomes. Secondary REE production reduces environmental damages by displacing both primary REE production and e-waste disposal. This section details environmental impacts associated with primary REE production and e-waste disposal and provides estimates of environmental and human health costs associated with both flows.

REE Mining and Primary Production Pathways

The environmental costs from mining rare earth metals are extensive. Greenhouse gas (GHG) emissions from REE mining carry a social cost, while hazardous waste byproducts generated during mining operations cause health and environmental damages to local communities.[93] Every metric ton of mined REEs generates an estimated 2,000 tons of toxic waste, which can include radioactive thorium and uranium residues that contaminate the air, water, and soil.[94] From 2010 to 2020, a 94 percent increase in GHG emissions associated with REE mining accompanied an 80 percent increase in production, and annual REE mining emissions are expected to reach 169,500 mt of CO_2 equivalent by 2030.[95] The largest GHG emitter in REE mining by far is China, with 57.6 percent of the global share, followed by the United States, Burma, and Australia.[96]

Because most primary production of REEs occurs in China, many studies focus on environmental damages from REE mining are focused on that country.[97] Within China, the Bayan-Obo mine—the world's largest REE mine—is the subject of several environmental impact analyses. The mining operations include a tailing pond with 70,000 mt of thorium, a radioactive element.[98] This tailing pond lacks proper lining, which allows radioactive waste to leach into the groundwater and surrounding soil.[99] Mine workers' exposure to toxic chemicals and the development of "cancer villages" situated close to

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[93] The social cost of carbon (SCC) is a monetary estimate of the damage caused by each marginal ton of carbon emissions. Asdourian and Wessel, "What is the social cost of carbon?" Brookings Institute, March 14, 2023.

[94] Nayar, "The Complicated Legacy of Rare Earth Mining," August 12, 2021.

[95] Golroudbary et al., "Global Environmental Cost of Using Rare Earth Elements," August 2022, 7; Statista, "Mine Production of Rare Earth Elements Worldwide," February 6, 2024.

[96] Golroudbary et al., "Global Environmental Cost of Using Rare Earth Elements," August 2022, 7.

[97] Zhang et al., "Allocating Environmental Costs of China's Rare Earth Production to Global Consumption," July 20, 2022; Zapp et al., "Environmental Impacts of Rare Earth Production," March 1, 2022; Lee and Wen, "Rare Earths from Mines to Metals," 2017.

[98] Tailing ponds are temporary storage sites for waste material from ore extraction.

[99] Nayar, "The Complicated Legacy of Rare Earth Mining," August 12, 2021; Su, "The Hidden Costs of China's Rare-Earth Trade," July 29, 2019.

mines have led to increased scrutiny of regulations at Bayan-Obo and other REE mines. Reports indicate that China's government has estimated environmental damages of $5.5 billion from illegal mining practices at REE mines.[100]

One environmental impact analysis of China's REE production allocated environmental costs from primary production based on global REE consumption.[101] Associated life-cycle impact categories that carried monetary damage estimates included abiotic resource depletion[102] (79.6 percent of cost), global warming (8.2 percent), acidification (5.7 percent), respiratory ailments from dust (3.6 percent), toxicity to humans (2.0 percent), photochemical oxidation, eutrophication, and ecotoxicity.[103] Total environmental costs of China's rare earth production were an estimated $7.2 billion in 2015, of which $5.4 billion could be attributed to exports of REEs.[104] In 2015, exports to Eastern Asia—mostly Japan and the Republic of Korea (South Korea)—made up the largest share, followed closely by North America.

Several life-cycle assessments (LCAs) compare the environmental impacts of REE recovery methods for e-waste relative to primary REE production. LCAs quantify environmental impacts associated with the life of a product from extraction to disposal (commonly referred to as "cradle-to-grave"). One LCA estimated that NdFeB magnet-to-magnet recycling reduced environmental impacts from 64 percent to 96 percent relative to primary permanent magnet production.[105] Another LCA of primary NdFeB production versus production via hydrogen decrepitation estimated emissions savings of 18–33 percent along with reduced environmental impacts associated with resource use, freshwater ecotoxicity, and marine eutrophication.[106] Finally, in a comparison of neodymium recovery from hard disk drives via hydrometallurgy versus primary NdFeB magnet production, the secondary production method performed better both environmentally and economically. The neodymium recovery route reduced environmental impacts relative to primary production by up to 65 percent for eight environmental impact categories; while the unit production cost was reduced by 53.5 percent.[107]

E-Waste Generation and Disposal

Heavy metals in e-waste—including REEs—harm human health and the environment and are typically released as pollutants during the (often informal) e-waste dismantling process.[108] The human health and environmental impacts from ever-growing e-waste production are enormous: Though e-waste occupies only 2 percent of the global waste stream by volume, it accounts for 70 percent of reported toxic and

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[100] Nayar, "The Complicated Legacy of Rare Earth Mining," August 12, 2021; Su, "The Hidden Costs of China's Rare-Earth Trade," July 29, 2019.

[101] Zhang (2022) focuses on rare earth oxides, though what is included in this category is not explicitly stated.

[102] Abiotic resources are nonliving resources. Beyond capital costs of production, current extraction (depletion) of finite resources carries an economic opportunity cost. Broadly, this cost signifies the difference in foregone future revenue and current revenue from one ton of REE extracted today. In other words, it's the cost associated with depleting a resource at a suboptimal point in time.

[103] The final three categories each represented less than 1 percent of total cost. Zhang et al., "Environmental Impacts of Hazardous Waste, and Management Strategies," February 2022, 3.

[104] Zhang et al., "Environmental Impacts of Hazardous Waste, and Management Strategies," February 2022, 5.

[105] Jin et al., "Life Cycle Assessment of Neodymium-Iron-Boron Magnet-to-Magnet Recycling," February 27, 2018, 1.

[106] Accardo, Costantino, and Spessa, "LCA of Recycled (NdDy)FeB Permanent Magnets," January 2024.

[107] Karal et al., "Hydrometallurgical Recovery of Neodymium," March 15, 2021.

[108] Liu et al., "A Global Perspective on E-Waste Recycling," March 2023, 10.

hazardous chemicals in the environment.[109] The diversion of e-waste streams from disposal carries additional environmental benefits.

People are exposed to e-waste by various pathways, including food and water intake, and inhalation of, or direct skin contact from particles. Workers directly handling e-waste are at the greatest risk of immediate exposure and subsequent health issues. However, studies have also shown long-term impacts to surrounding communities, including the bioaccumulation of heavy metal toxins and carcinogens in staples like eggs and rice and more widespread contamination of drinking water sources.[110] The distribution of these e-waste damages poses an environmental justice issue at the global level. Historically, most e-waste was exported from Europe and the United States to developing economies—such as China, India, Mexico, Brazil, Ghana, and Nigeria—and handled manually in poor communities, leading to increased rates of cancer and respiratory issues within those communities (see box A).[111] As economies develop, their own e-waste generation also increases, compounding the severity of exposure.

Box A Two Major E-Waste Sites, Agbogbloshie and Guiyu: Effects on Human Health

Guiyu, China, and Agbogbloshie, Ghana, are historically two of the largest and most infamous e-waste dump sites in the world.

A rural village in the Guangdong Province of China, Guiyu at one time received up to 70 percent of the world's e-waste.[a] Guiyu's government statistics reportedly indicate that more than 80 percent of families, including children, engaged in informal e-waste recycling.[b] A study published in 2007 found that about 80 percent of children in the village had elevated blood lead levels.[c] Another study estimated that informal e-waste processing caused 637 premature deaths in the population, mostly as a result of lead poisoning.[d]

The 20-acre Agbogbloshie scrapyard, on the outskirts of Accra, Ghana, has been considered the most toxic place in the world.[e] Agbogbloshie was shut down suddenly by the government in 2021 reportedly because of negative publicity. An estimated 8,000 workers in the scrapyard handled hazardous e-waste manually and burned waste to separate valuable metals, inhaling toxic fumes.[f] Most workers were men in their twenties, many of whom migrated from poorer regions and viewed scrap recovery as a promising economic opportunity. A health study of 142 otherwise asymptomatic e-waste workers in Agbogbloshie found exposure to high particulate matter concentrations from e-waste burning led to lower respiratory function and increased risk for asthma and chronic obstructive pulmonary disease.[g]

[a] Li and Achal, "Environmental and Health Impacts Due to E-Waste Disposal," October 1, 2020.
[b] Wang, Qian, and Liu, "Understanding Environmental Pollutions of Informal E-Waste," April 2020.
[c] Huo et al., "Elevated Blood Lead Levels of Children in Guiyu," July 2007.
[d] Boardman, Geng, and Lam, "The Social Cost of Informal Electronic Waste Processing," March 2020.
[e] Goutier, "E-Waste in Ghana," August 7, 2014.
[f] Akese, "Agbogbloshie: A Year after the Violent Demolition," July 21, 2022.
[g] Amoabeng Nti et al., "Effect of Particulate Matter Exposure on Respiratory Health," April 27, 2020.

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[109] Abalansa et al., "Electronic Waste, an Environmental Problem," January 2021.

[110] Liu et al., "A Global Perspective on E-Waste Recycling," March 2023; Khattak, "The Environmental Impact of E-Waste," March 13, 2023.

[111] Abalansa et al., "Electronic Waste, an Environmental Problem," January 2021.

Secondary NdFeB Magnet Production: Potential Impacts on Supply Chains and New Sourcing Opportunities

Estimates of e-waste recycling and volumes of NdFeB magnets and other rare earth containing e-waste with recovery potential vary significantly. Thus, it is difficult to predict the potential effects of increased REE recovery from e-waste on overall domestic production and subsequent impacts on trade and the environment. In addition, the U.S. government has called for reducing imports of REEs and NdFeB magnets from China and increasing domestic production capacity but has not set specific targets for the value or volume of these changes. Further analyses can provide information to better set targets.

Goodman's supply chain risk methodology (detailed further in appendix A) identifies the basic changes—increased domestic production or reduced imports—needed for the supply chain risk to be reduced from "high" to "moderate" or "low." The current HHI for NdFeB magnets indicates high supply chain risk at 8,514. To decrease the HHI, the United States could increase domestic production, thereby reducing the geographic concentration of production and reducing import reliance. Table 7 highlights a few of these efforts.

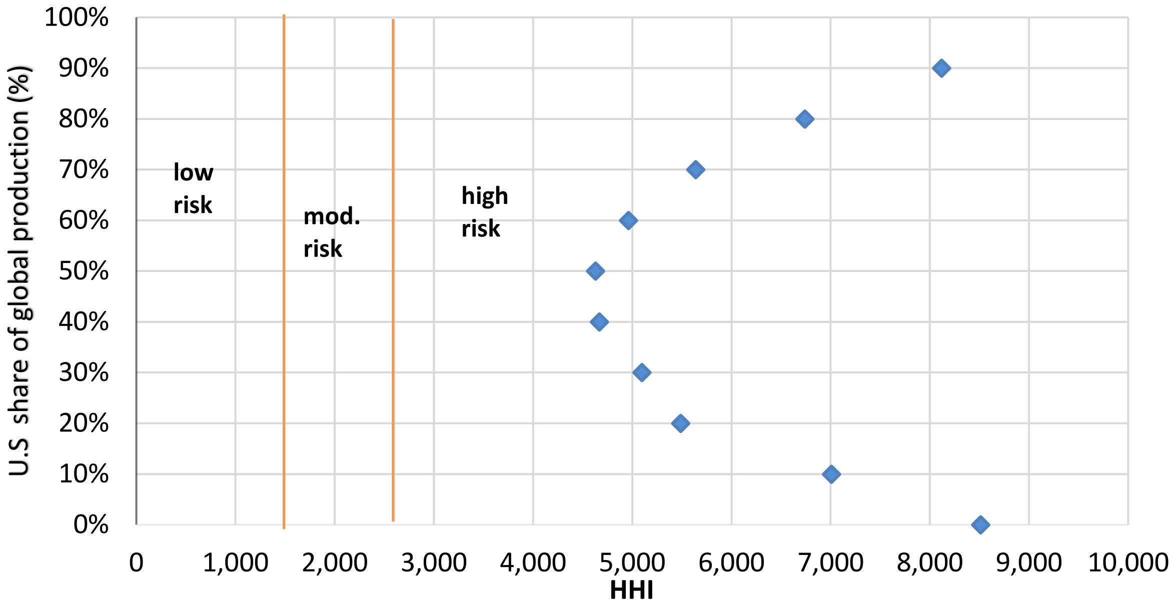
Table 7 Domestic initiatives to recover REEs from e-waste

Organization	Method type	Details
USDOE	Hydrometallurgy	Scientists at USDOE's Oak Ridge National Laboratory and licensees Momentum Technologies began piloting an industrial scale recycling process in August 2022. The recycling process uses membrane-assisted solvent extraction. The process has been demonstrated to yield a 95 percent rare earth recovery rate.
USDOE	Hydrometallurgy	Another USDOE project, led by a team at the Critical Materials Institute at Ames Laboratory, has developed a process for extracting rare earths from e-waste using an acid-free dissolution process. The project was licensed for commercial use by TdVib LLC, a company based in Iowa, in early 2022.
HyProMag	Hydrogenation	European firm HyProMag has recently announced 50 percent completion of a feasibility study for a magnet recycling plant in Forth Worth, Texas. Like other HyProMag plants, it will use HPMS to recover alloy powder from permanent magnets. The first magnet production is targeted for 2026.
Penn State	Bioprocess	Researchers at Penn State Bhave developed a process of bioleaching with nanoengineered plant cellulose to extract neodymium from e-waste. The process has not yet been scaled for commercial use.

Sources: ORNL, Electronic Waste is Mined," August 14, 2019; Sustainable Electronics, "ORNL Scientists Scale Up Process to Reclaim Rare Earths," August 5, 2022; Ames National Laboratory, "Green Rare Earth Recycling Goes Commercial," February 25, 2022; Magnetics, "HyProMag H2-Enabled Magnet Recycling Ventures Coming Onstream," January 11, 2023; AccessWire, "Mid-Project Update for HyProMag USA," July 15, 2024; Penn State, "Mussels Inspire Eco-Friendly Way to Extract Critical Rare Earth Elements," August 9, 2023.

Unfortunately, increasing domestic production without any changes to foreign production would not allow the HHI to fall enough to reach moderate risk (figure 4). The HHI's limited effect on the supply chain risk is due to its formula—the same level of risk is assigned to any highly concentrated sourcing.[112] Consequently, if production becomes too concentrated within the United States, the HHI would reflect the same level of risk it does when production is concentrated in China.

Figure 4 Impact of increasing domestic production of NdFeB magnets on the HHI



Source: Calculated by authors.

Note: Generally, values less than 1,500 indicate a competitive market (low risk), values between 1,500–2,500 indicate moderate concentration (moderate risk), and values greater than 2,500 mean an industry is highly concentrated (high risk).

While overreliance on domestic production carries risk, other supply chain risk calculation methodologies tend to assign greater relative risk to imports than to domestic production.[113] This approach seems more appropriate, given that shipping or other transportation disruptions, as well as supply disruptions from political and other external conflicts, are less likely to occur domestically. Moreover, an increase in domestic production is only one way the United States could reduce its supply chain risk.[114] Another strategy to reduce risk, in the case of NdFeB magnets, is the diversification of sourcing away from China to other sources. In 2023, China supplied 93.3 percent of U.S. imports of NdFeB magnets. Other notable suppliers included Germany (accounting for 2.4 percent), the Philippines (1.2 percent), and Japan (0.8 percent).[115] In the context of recovered or recycled NdFeB magnets and data on available e-waste and current recycling efforts, both Europe and Asia (non-China) have the potential to become suppliers for the United States (table 8).

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[112] Note that this is true for a country-level HHI. A firm-level HHI, which is not explored in this paper, would yield different results.

[113] As is the case in Goodman, "A Method of Estimating Global Supply Chain Risk," January 2023.

[114] Goodman, "A Method of Estimating Global Supply Chain Risk," January 2023.

[115] USITC DataWeb/Census, Imports for consumption, HTS subheading 8505.11.0070, accessed March 5, 2024.

Table 8 Global e-waste annual production, recycling, and availability by region

Mmt = million metric ton; REE = rare earth element.

Country/region	E-Waste production volume (Mmt)	Percent collected for proper recycling (%)	Available e-waste for REE recovery (Mmt)
Americas	14	30	4.3
United States	7.2	15	1.1
Europe	13	42.8	5.6
Asia	30	11.9	3.6
Africa	3.5	0.7	0.03
Oceania	0.71	41.4	0.29
World Total	**62**	**22.3**	**13.8**

Source: Baldé et al., “The Global E-Waste Monitor 2024,” 2024; Reinsch and Hokayem, “A Canary in an Urban Mine,” July 29, 2021; The Global E-Waste Statistics Partnership “United States of America, 2019 E-Waste Statistics,” 2019.

Note: Available e-waste for REE recovery is based on the volume of e-waste that has been collected for recycling. Percent collected for proper recycling in the United States is based on older data and may be understated. Numbers may not add exactly due to rounding.

Europe’s Potential

Europe has the highest e-waste recycling rate of any global region, at 42.8 percent. Europe’s production volume means about 5.6 million mt of e-waste are available annually for REE recovery. Europe’s success in e-waste recycling is largely attributed to a longstanding culture of recycling and various laws that facilitate recycling. Within the European Union (EU), the Waste Electrical and Electronic Equipment (WEEE) Directive requires the separate collection and proper treatment of e-waste and sets targets for its collection, recovery, and recycling.[116] Many non-EU European countries, such as Switzerland and Iceland, have similar laws.[117]

In November 2023, the EU reached a provisional agreement on a European Critical Raw Materials Act aimed at reducing risk in the EU supply chain for 34 critical raw materials, including REEs. Among its goals, the proposed act would set targets to increase recycling of these materials by 15 percent.[118] The REEProduce Project, which has been largely funded by the EU, is designed to help meet this goal by establishing an industrial scale rare earth recycling program. This program would allow REEs to be recovered in the EU at 25 percent less than the cost of sourcing primary REEs from China.[119] Similarly, the EU-funded Sustainable Recovery, Reprocessing and Reuse of Rare Earth Magnets in a European Circular Economy (SUSMAGPRO) project “aims to develop a recycling supply chain for rare earth magnets in Europe” by effectively reusing rare earth materials across industries.[120]

The Netherlands may be particularly well suited to increase NdFeB magnet production via recycling. A 2020 report on Dutch e-waste flows indicates that the Netherlands e-waste recycling rate is nearly 75 percent.[121] This high rate is likely due to ambitious sustainability goals, such as the Dutch government’s

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[116] “Waste from Electrical and Electronic Equipment (WEEE),” accessed February 13, 2024.

[117] Forti et al., “The Global E-Waste Monitor 2020,” 2020.

[118] “Council and Parliament Strike Provisional Deal,” November 13, 2023.

[119] REEProduce EU, “FAQs & Glossary,” accessed February 29, 2024.

[120] “About SUSMAGPRO,” accessed March 1, 2024.

[121] Though 25 percent is not “compliantly” recycled. Baldé et al., “The Dutch WEEE Flows 2020,” 2020.

goal of a 50-percent reduction in the use of primary raw materials by 2030.[122] Although currently no commercial-scale REE recycling appears to be underway, several research initiatives are ongoing. Notably, two Dutch universities have partnered with a consortium of European firms and research groups to establish Valomag, an EU-sponsored initiative to develop technologies for recycling EOL permanent magnets, including NdFeB magnets.[123]

In Germany, several recycling methods are used to produce NdFeB magnets. German company Heraeus has partnered with the Fraunhofer Institute to use pyrometallurgical processes to recycle NdFeB magnets.[124] Meanwhile, as noted in the section on "Other Recovery Technologies," an NdFeB magnet recycling plant in Germany is expected to come online some time in 2024.[125] In its first phase, the facility, owned by HyProMag, is expecting to produce a total of 100 mt of NdFeB magnets, alloy pellets, and powders annually.

Meanwhile, a HyProMag pilot program in England successfully produced 3,000 NdFeB magnets in 2023 and is expected to upgrade to commercial production in 2024. Its initial production target is 20 mt per year with plans to scale up to a minimum of 100 mt. The company is evaluating the potential to scale production to 1,000 mt per year.[126] Other initiatives for recovering REEs and NdFeB magnets are underway in Belgium, France, Slovenia, and Sweden.[127]

Asia's Potential (Outside of China)

Asia is the largest e-waste producer of any global region and has an e-waste recycling rate of 11.9 percent. Based on its production volume, Asia has about 3.6 million mt of e-waste available for REE recycling annually (table 8). Many (especially developing) countries in Asia do not yet have national legislation on handling e-waste, but their governments are prioritizing efforts to establish such legislation. Meanwhile, countries such as South Korea and Japan have long-standing histories of e-waste regulation.[128] Japanese firms have also been working on technologies to extract REEs from e-waste as far back as 2009.[129] Now, Japan is hoping to share and deploy its technologies across Asia. In August 2023, Japan and the Association of Southeast Asian Nations (ASEAN) announced a collaboration to build e-waste recycling capacity in Southeast Asia, in order to diversify supply chains for copper and rare

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[122] This goal was announced by the Netherlands government in 2016. Government of the Netherlands, "Circular Dutch Economy by 2050," accessed March 7, 2024.

[123] Valomag, "Valorisation of Magnets," accessed March 1, 2024.

[124] Heraeus Remloy, "Recycling Neodymium Magnets," accessed March 4, 2024.

[125] Mining Technology. "HyProMag H2-Enabled Magnet Recycling Ventures," January 11, 2023.

[126] Globe Newswire, "First Production of Recycled Magnets at Tyseley Energy Park," December 12, 2023.

[127] Carter, "Belgium Leads the Way," August 9, 2023; Solvay, "Solvay to Develop Major Hub," September 16, 2022; MagREEsource, "REEngineering Magnets," accessed March 4, 2024; Susmagpro, "About SUSMAGPRO," accessed March 1, 2024.

[128] Panasonic, "Japanese Home Appliance Recycling Law," accessed March 5, 2024; UNESCAP, *Policy Brief: Toward Sustainable E-Waste Management in Asia and the Pacific*, June 2021, 14–15; Chung and Murakami-Suzuki, "A Comparative Study of E-Waste Recycling Systems," 2008.

[129] Tabuchi, "Japan Recycles Rare Earth Minerals from Used Electronics," October 4, 2010.

metals.[130] Finally, Thailand and India are also making efforts to recover REEs from NdFeB magnets and other e-waste.[131]

Potential Impacts of a Shift in Import Sourcing on U.S. Supply Chains

Increased efforts to recover REEs and NdFeB magnets from e-waste recycling across Europe and Asia (outside of China) could also benefit U.S. supply chains. As secondary production of REEs reaches commercial levels abroad, the United States can begin importing from these new sources. Asia (not including China) currently accounts for 8 percent of global NdFeB magnet manufacturing; Europe accounts for less than 1 percent.[132]

Applying Goodman's supply chain risk model to global trade of NdFeB magnets, a 10 percent increase in production in Europe and Asia (not including China) would yield an estimated 25 percent increase in U.S. imports from each source. An increase in diversified imports at this scale would reduce the U.S. risk factor for imports from China by 35 percent to 5,133 (though the resulting HHI is still considered high risk; see appendix A for calculations).[133] An increase in domestic production accompanying this shift in imports would yield an even greater reduction in risk. The example demonstrates the significant impact a relatively small shift in imports could have on supply chain risk.

Potential Environmental Benefits from REE Import Diversification and Increased Domestic Secondary REE Production

Increased secondary NdFeB magnet production in the United States and other foreign sources can yield additional environmental benefits. Previous analyses of the environmental and social damages of rare earth mining and e-waste disposal in China provide unit cost estimates associated with primary REE production and informally disposed e-waste. The life-cycle impact assessment of REE mining in China detailed in the Environmental Impacts section of this paper estimated an environmental cost of \$81,000/mt of REO produced from China.[134] This cost stems from 2015 data and includes damages from abiotic resource depletion, global warming, acidification, and harm to human health. Adjusted to 2023 dollars, the environmental cost associated with REE production in China is \$104,490 per metric ton. Applied to the 10,982 mt of REEs imported to the United States from China in 2023, this cost calculation

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[130] *Japan Times*, "ASEAN to Cooperate on Recycling Rare Metals," August 23, 2023.

[131] *Nation Thailand*, "Thai Scientists Create Recycling Tools," September 12, 2020; *Times of India*, "Project on Rare Earth Extraction from Aluminium Waste," September 5, 2023.

[132] USDOE, *Rare Earth Permanent Magnets: Supply Chain Deep Dive Assessment*, February 24, 2022, 26.

[133] As noted above, the United States currently sources about 2.4 percent of its NdFeB magnet imports from Europe via Germany and about 2 percent of its imports from Asia (not including China) via the Philippines and Japan.

[134] Abiotic resource depletion is a major component of the \$81/kilogram cost estimate. The impacts of this factor may vary from 2015 to 2023, but the cost estimates reported in Zhang (2022) did not vary much from 2010 to 2015, ranging from \$79 to \$83 per kilogram.

results in an estimated $1.15 billion in environmental damages annually.[135] Diversifying imports away from China to sources with more stringent environmental regulations, such as the United States or Europe, could reduce annual environmental damages associated with imports.

As noted in table 8 (global e-waste availability), the United States produced 7.2 million mt of e-waste in 2019, of which 15 percent was collected to recycle, creating about one million mt of e-waste available for REE recovery. In developing economies and low-income regions, up to 82.6 percent of e-waste is illegally handled and informally processed.[136] One assessment of human health damages developed a monetary estimate of health costs per unit of e-waste informally processed using observational data in Guiyu, China, where 70 percent of the world's e-waste was once destined (see box A).[137] In 2023 dollars, 1 mt of informally processed e-waste yields $513 in human health damages. Should the United States capitalize on its one million mt of annual e-waste available for proper REE recycling that may otherwise be disposed improperly in China, environmental benefits in the form of reduced human health damages could reach up to $513 million.[138]

Social cost savings associated with carbon emissions abatement can also accrue through diversion of e-waste disposal. The Waste Electrical and Electronic Equipment Forum estimates that each metric ton of e-waste recycled prevents 2 mt of carbon dioxide emissions.[139] Applying the current social cost of carbon of $51/mt used in U.S. damage assessments, developing secondary production capacity to use the one million mt of e-waste available domestically for REE recycling could yield an additional $102 million in social cost savings.[140] In total, certain annual avoidable environmental and health damages associated with primary REE extraction and improper e-waste disposal in the U.S. supply chain for NdFeB magnets reach upwards of $1.77 billion.

Conclusion

U.S. policymakers have demonstrated growing concern about the concentration of REE supply chains, especially in China, in part, because of overreliance and vulnerability to supply disruptions. At the same time, global efforts to combat climate change have drawn a more critical review of the negative effects these supply chains can have on the environment and its workers. The secondary sourcing and production of these products from e-waste has the potential to reduce, but not eliminate, these risks. Several methods of secondary sourcing and recovery are in development at the laboratory scale. The ultimate success of these recovery methods is highly dependent on infrastructure for proper e-waste disposal and collection, technological capacity for separation, and regulatory incentives to encourage this development.

If these methods are adopted widely, secondary recovery could significantly reduce supply chain risk by allowing for increased NdFeB magnet production in the United States, Europe, and Asia. Secondary

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[135] Zhang (2022) focuses on rare earth oxides, though what is included in this category is not explicitly stated. In keeping with the production categories established in this paper, we use imports of "unrefined rare earth ores and oxides" under HTS subheadings 2846.10 and 2846.90. USITC DataWeb/Census, Imports for consumption, accessed March 8, 2024.

[136] Waste Management World, "14th October: International E-Waste Day," October 13, 2022.

[137] Boardman, Geng, and Lam, "The Social Cost of Informal Electronic Waste Processing," March 2020.

[138] Boardman, Geng, and Lam, "The Social Cost of Informal Electronic Waste Processing," March 2020.

[139] Rosane, "This Year's E-Waste to Outweigh Great Wall of China," October 18, 2021.

[140] Mindock, "Biden 'Social Cost of Carbon' Climate Risk Measure Upheld," October 21, 2022.

recovery methods could also yield environmental benefits by reducing damages caused by rare earth mining and improper e-waste disposal (especially in China). Unfortunately, data on e-waste collection and recovery rates of the various secondary production processes are limited, as are data on global trade and production of REEs and NdFeB magnets. To quantify potential impacts of secondary recovery more accurately on supply chains and the environment, more centralized and far-reaching data collection efforts are needed.

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Appendix A: Risk Factor Methods

The assessment of baseline and scenario U.S. supply chain risks for neodymium iron boron (NdFeB) magnets is adapted from the approach developed by Goodman (2023).[141] Detailed below, the main adjustment to Goodman's methods is an estimation of U.S. import dependence on China using import's share of apparent consumption, rather than total net trade.

Market concentration is a key factor in supply chain risk assessment. The Herfindahl-Hirschman index (HHI) is a measure of geographic concentration of production. Equation 1 calculates the HHI as the sum of the squares of production share by country, where *s* is the share (in percentage points) of global production of commodity *c* in country *i*, for all *n* producing countries:

$$(1)\ HHI = \sum_{i=1}^{n} s_{i,c}^{2}$$

The HHI can range from close to zero—where the number of equal-size producers is infinite—to 10,000, which represents 100 percent of global production concentrated in a single country. Generally, HHI values less than 1,500 indicate a competitive market and values greater than 2,500 indicate a highly concentrated industry.[142] Table A-1 presents the estimated concentration of NdFeB magnet production in 2020.

Table A-1 Estimation of global concentration of permanent magnet production

NdFeB = neodymium iron boron; HHI = Herfindahl-Hirschman Index.

Country	Share of global NdFeB magnet production (%)	HHI
China	92	8,464
Japan	7	49
Vietnam	1	1
Total	**100**	**8,514**

Source: U.S. Department of Energy, *Rare Earth Permanent Magnets,* February 24, 2022, 26.

In estimating U.S. import dependence, Goodman (2023) first calculates the ratio of U.S. imports from a given source to all U.S. imports, where $\mathrm{I}_{i,US,c}$ represents imports to the United States from country *i* for commodity *c*:

$$(2a)\ \frac{\mathrm{I}_{i,US,c}}{\sum_{i=1}^{n} \mathrm{I}_{i,US,c}}$$

2023 trade data on NdFeB magnets are applied to term 2a, calculating U.S. imports from China relative to all U.S. imports (in kilograms):[143]

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[141] Goodman, "A Method of Estimating Global Supply Chain Risk," January 2023.

[142] Goodman, "A Method of Estimating Global Supply Chain Risk," January 2023, 5.

[143] USITC DataWeb/Census, Imports for consumption, HTS subheading 8505.11.0070, accessed March 5, 2024.

$$(2b)\ \frac{5{,}693{,}994}{6{,}100{,}236} = .933$$

In 2023, 93.3 percent of U.S. imports of NdFeB magnets came from China. The second component used in the estimation of U.S. import dependence is the imports share of apparent consumption, where apparent consumption is defined as the total of imports ($\mathrm{I}_{US,c}$) and domestic production ($P_{US,c}$), less exports ($\mathrm{E}_{US,c}$). Imports share of apparent consumption is then:

$$(3)\ \frac{\sum_{i=1}^{n} \mathrm{I}_{i,US,c}}{(\sum_{i=1}^{n} \mathrm{I}_{i,US,c} + P_{US,c} - \sum_{i=1}^{n} \mathrm{E}_{i,US,c})}$$

In the baseline risk calculation, the lack of current domestic production of NdFeB magnets is used to imply imports account for 100 percent of apparent consumption. The U.S. import dependence on China for NdFeB magnets is then 0.933. This factor is used in the final risk calculation in combination with the HHI measure of global concentration from table A-1 to arrive within the high-risk category:

$$(4a) \sum_{i=1}^{n} s_{i,c}^{2} \left(\frac{\mathrm{I}_{i,US,c}}{\sum_{i=1}^{n} \mathrm{I}_{i,US,c}}\right)\left(\frac{\sum_{i=1}^{n} \mathrm{I}_{i,US,c}}{(\sum_{i=1}^{n} \mathrm{I}_{i,US,c} + P_{US,c} - \sum_{i=1}^{n} \mathrm{E}_{i,US,c})}\right)$$

$$(4b)\ 8{,}514 * (0.933)(1) = 7{,}944$$

In the import diversification scenario, secondary permanent magnet production via e-waste recovery in Europe and Asia (outside of China) increases by 10 percent, resulting in a 25 percent increase in U.S. imports from each source. The new HHI is calculated below in table A-2.

Table A-2 Estimation of global concentration of permanent magnet production, given 10 percentage point increase in production in Asia (outside of China) and Europe

NdFeB = neodymium iron boron; HHI = Herfindahl-Hirschman Index.

Source	Share of global NdFeB magnet production (%)	HHI
China	72	5,166
Asia (outside of China)	18	323
Europe	10	103
Total	**100**	**5,592**

Source: U.S. Department of Energy, *Rare Earth Permanent Magnets,* February 24, 2022.

Note: Magnet production changes are based on previous production estimates provided. Asia outside of China previously accounted for 8 percent of global production via Japan and Vietnam. Europe previously accounted for zero production.

The 25 percent increase in European and Asian imports is derived by multiplying current imports from those sources (based on 2023 trade data) by 1.25 (see table A-3).

Table A-3 Estimation of U.S. imports given 25 percent increase in imports from Asia (outside of China)
In metric tons (mt) and percentage (%).

Source	U.S. imports for consumption (mt)	Share of U.S. imports (%)	U.S. imports given a 25% increase from Europe and Asia (outside of China) (mt)	Share of U.S. imports given 25% increase from Europe and Asia (outside of China) (%)
China	5,693,994	93.3	5,693,994	91.8
Asia (outside of China)	180,415	3.0	225,519	3.6
Europe	217,194	3.6	271,493	4.4
Rest of world	8,633	0.1	8,633	0.1
Total	6,100,236	100.0	6,199,639	100.0

Source: U.S. Department of Energy, *Rare Earth Permanent Magnets,* February 24, 2022.

The share of U.S. imports from China is now 0.918. Because we are not changing domestic production, import dependence remains at 1.0. Our new calculation for imports from China is as follows:

$$(4c)\ 5592 * (0.918)(1) = 5133.$$