Rare Earth Permanent Magnets

Supply Chain Deep Dive Assessment

U.S. Department of Energy Response to Executive Order 14017, "America's Supply Chains"

February 24, 2022

(This page intentionally left blank)

About the Supply Chain Review for the Energy Sector Industrial Base

The report "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition" lays out the challenges and opportunities faced by the United States in the energy supply chain as well as the federal government plans to address these challenges and opportunities. It is accompanied by several issue-specific deep dive assessments, including this one, in response to Executive Order 14017 "America's Supply Chains," which directs the Secretary of Energy to submit a report on supply chains for the energy sector industrial base. The Executive Order is helping the federal government to build more secure and diverse U.S. supply chains, including energy supply chains.

To combat the climate crisis and avoid the most severe impacts of climate change, the United States is committed to achieving a 50 to 52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution by 2030, creating a carbon pollution-free power sector by 2035, and achieving net zero emissions economy-wide by no later than 2050. The U.S. Department of Energy (DOE) recognizes that a secure, resilient supply chain will be critical in harnessing emissions outcomes and capturing the economic opportunity inherent in the energy sector transition. Potential vulnerabilities and risks to the energy sector industrial base must be addressed throughout every stage of this transition.

The DOE energy supply chain strategy report summarizes the key elements of the energy supply chain as well as the strategies the U.S. government is starting to employ to address them. Additionally, it describes recommendations for Congressional action. DOE has identified technologies and crosscutting topics for analysis in the one-year time frame set by the Executive Order. Along with the policy strategy report, DOE is releasing 11 deep dive assessment documents, including this one, covering the following technology sectors:

- carbon capture materials,
- electric grid including transformers and high voltage direct current (HVDC),
- energy storage,
- fuel cells and electrolyzers,
- hydropower including pumped storage hydropower (PSH),
- neodymium magnets,
- nuclear energy,
- platinum group metals and other catalysts,
- semiconductors,
- solar photovoltaics (PV), and
- wind.

DOE is also releasing two deep dive assessments on the following crosscutting topics:

- commercialization and competitiveness, and
- cybersecurity and digital components.

More information can be found at www.energy.gov/policy/supplychains.

Acknowledgments

The U.S. Department of Energy (DOE) acknowledges all stakeholders that contributed input used in the development of this report – including but not limited to federal agencies, state and local governments, U.S. industry, national laboratories, researchers, academia, non-governmental organizations, and other experts and individuals. DOE also issued a request for information (RFI) to the public on energy sector supply chains and received comments that were used to inform this report. The authors appreciate input and guidance from Dr. Tsisilile Igogo, a detailee at the DOE's Office of Policy from the National Renewable Energy Laboratory, who coordinated the agency's energy supply chain reviews.

Principal Authors
Smith, Braeton J., Principal Energy Economist, Argonne National Laboratory
Riddle, Matthew E., Assistant Energy Scientist, Argonne National Laboratory
Earlam, Matthew R., Materials Process Engineer, Argonne National Laboratory
Iloeje, Chukwunwike, Energy Systems Scientist, Argonne National Laboratory
Diamond, David, Senior Analyst, Advanced Manufacturing Office, DOE Office of Energy Efficiency and Renewable Energy [Detailee from U.S. Geological Survey]

Contributors
Bauer, Diana, Acting Deputy Director, Advanced Manufacturing Office, DOE Office of Energy Efficiency and Renewable Energy
Hyde, Iain, Director, National Preparedness Analytics Center, Argonne National Laboratory
Graziano, Diane J., Chemical Engineer, Argonne National Laboratory
Kaiser, Autumn, Geographic Information Systems Analyst, Argonne National Laboratory
Keavney, Dava, Senior Program Analyst, Advanced Manufacturing Office, DOE Office of Energy Efficiency and Renewable Energy
Khazdozian, Helena, Technology Manager, Advanced Manufacturing Office, DOE Office of Energy Efficiency and Renewable Energy
Nguyen, Ruby T., System Dynamics and Modeling Group Lead, Idaho National Laboratory
Price, Paige, Technology Transfer and Intellectual Asset Management Specialist, Idaho National Laboratory

Reviewers
Hovanec, Christopher, Technology Manager, Advanced Manufacturing Office, DOE Office of Energy Efficiency and Renewable Energy
Gabriel, Brian, Industrial Analyst, Defense Logistics Agency
Granite, Evan, DOE Office of Fossil Energy and Carbon Management
Lamke, Ryan, International Relations Specialist, Office of International Affairs
Onda, Chikara, Senior Fellow, DOE Office of Policy
Ring, Matthew, Attorney-Advisor, DOE Office of the General Counsel
Tusing, Richard, Senior Advisor, National Renewable Energy Laboratory
Zevin, Avi, Deputy General Counsel for Energy Policy, DOE Office of the General Counsel

Document Editors
Jandeska, Kathryn, Technical Editor, Argonne National Laboratory
Salinas, Lorenza, Desktop Publishing Coordinator, Argonne National Laboratory

Nomenclature or List of Acronyms

EO 14017	Executive Order on America's Supply Chains
AISI	American Iron and Steel Institute
AMO	Advanced Manufacturing Office
B	boron
Ce	cerium
CMI	critical materials institute
CO	carbon monoxide
CO2	carbon dioxide
CR	concentration ratio
CVD	chemical vapor deposition
DFIG	doubly-fed induction generator
DLA	Defense Logistics Agency
DOC	Department of Commerce
DOE	Department of Energy
DPA	Defense Production Act
Dy	dysprosium
DyFe	ferrodysprosium
EIA	Energy Information Administration
EPA	Environmental Protection Agency
Er	erbium
ESIB	Energy Sector Industrial Base
Eu	europium
EV	electric vehicle
Fe	iron
FeN	iron-nitride

FeNi	iron-nickel
GBD	grain boundary diffusion
Gd	gadolinium
GDP	gross domestic product
GM	General Motors
HCl	hydrochloric acid
HEV	hybrid electric vehicle
HHI	Herfindahl-Hirschman Index
Ho	holmium
HRE	heavy rare earth
IEA	International Energy Agency
IIJA	Infrastructure Investment and Jobs Act
IP	intellectual property
ITC	International Trade Commission
kt	thousands of tonnes
La	lanthanum
LAMP	Lynas advanced materials plant
LRE	light rare earth
Lt	lutetium
MGOe	mega-gauss-oersteds
MW	megawatt
NaOH	sodium hydroxide
NASA	National Aeronautics and Space Administration
Nd	neodymium
NdFeB	neodymium iron boron
NdPr	didymium
NdPrF3	didymium fluoride

NiMH	nickel-metal hydride
NSF	National Science Foundation
NSTC	National Science and Technology Council
OEM	original equipment manufacturer
PMSG	permanent magnet synchronous generators
Pr	praseodymium
R&D	research and development
RDD&D	research, development, demonstration and deployment
RE	rare earth
SBIR	small business innovation research
Sm	samarium
SmCo	samarium cobalt
SmFeN	samarium-iron-nitride
STTR	small business technology transfer
Tb	terbium
Tm	thulium
TO	thermal oxidizers
USGS	United States Geological Survey
VIM	vacuum induction furnace
Yb	ytterbium

Executive Summary

In February 2021, President Biden signed the "Executive Order on America's Supply Chains" (EO 14017), directing executive agencies to evaluate the resilience and security of the nation's critical supply chains and to craft strategies for the industrial bases that underpin America's economic and national security. Sec. 3(b) of EO 14017. As part of the one-year response to EO 14017, the U.S. Department of Energy (DOE), through the DOE national laboratories, conducted evaluations of the supply chains that encompass the Energy Sector Industrial Base, with a particular focus on technologies required to decarbonize the U.S. by 2050.

This report focuses on the supply chain for rare earth permanent magnets, specifically sintered neodymium-iron-boron (NdFeB) magnets, used in clean energy technologies. Sintered NdFeB magnets are the strongest magnets commercially available and provide a host of benefits to wide-ranging applications in consumer and industrial electronics, especially in advanced motor and drive systems. Within the Energy Sector Industrial Base, and clean energy in particular, NdFeB magnets are key intermediate components of permanent magnet synchronous (direct drive) generators in wind turbines (especially for offshore turbines) and electric synchronous traction motors for propulsion systems in battery and hybrid electric vehicles.

Under aggressive decarbonization scenarios, such as those striving toward net-zero carbon emissions by 2050, demand for rare earth magnets is expected to grow rapidly, both domestically and globally. This demand poses a significant and undeniable challenge to U.S. decarbonization goals because rare earth magnets (and the rare earth materials they contain) are characterized by substantial market volatility and geopolitical sensitivity. Markets for rare earths are opaque as they are produced as byproducts and often sold via contractual relationships. Nearly all supply chain stages are concentrated in China and the chemistry associated with processing rare earths is challenging, expensive, and hazardous. Furthermore, substitution is difficult throughout the supply chain due to the unique characteristics and technical advantages of rare earth magnets.

The U.S. government has been actively engaged in promoting U.S. production and building a more resilient supply chain. In 2021, the U.S. Secretary of Commerce launched an investigation of the effects of imports of NdFeB magnets on National Security to evaluate whether Section 232 of the Trade Expansion Act of 1962 is applicable for addressing the issues in the supply chain. The federal government is also executing projects under Title III of the Defense Production Act (DPA), which has been authorized for use to support rare earth and sintered NdFeB magnet production. DOE has also directed research funding and provided industry support to rare earth and NdFeB magnet projects. However, significant challenges still exist to develop and sustain a resilient rare earth magnet supply chain.

This report characterizes the sintered NdFeB supply chain as having four primary stages. These include:

1. Raw materials production, including mining and concentration from primary sources, recycling from secondary sources, and processing from unconventional sources, such as mine tailings and coal byproducts.
2. Processed materials production, which includes rare earth oxide separation and metal refining.
3. Alloy-making and magnet manufacturing.
4. Use of magnets in downstream end-products.

Figure ES1 shows how the supply chain for magnets is highly concentrated in China, especially as it moves further down the supply chain from mining, to separation, to metal refining, and to magnet manufacturing.[1]

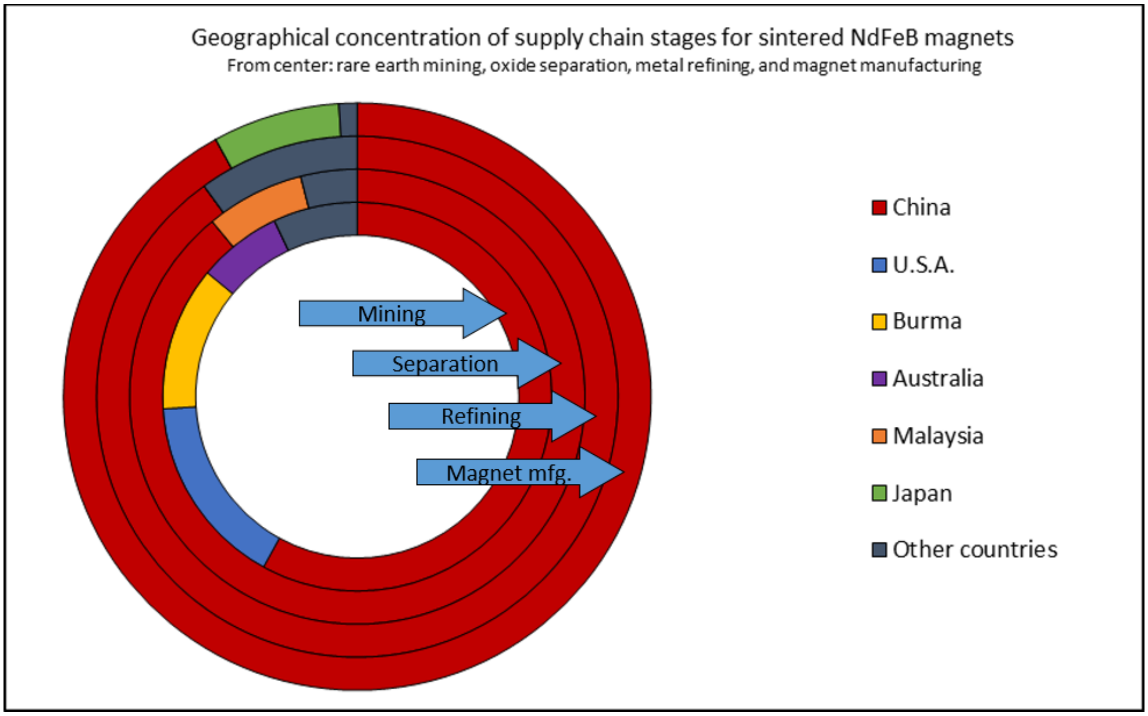

Figure ES1. Geographical concentration of supply chain stages for sintered NdFeB magnets, 2019

Several factors determine U.S. resilience and competitiveness in the rare earth magnet supply chain, including geographical concentration, geopolitical sensitivity of trade partners, net import reliance, price volatility, substitutability throughout the supply chain, and other factors. While improving in recent years due to a number of domestic and international projects that increase domestic production capacity and the diversity of foreign supply sources, the supply chain of rare earth (RE) elements and magnets is still not resilient. U.S. manufacturers continue to struggle to be competitive, particularly in the midstream stages of the supply chain. The United States currently has limited domestic production capacity for the sintered neodymium magnets used in wind turbines and electric vehicles, while China dominates each of the major stages in the supply chain. Even more significantly, this concentration of production in China increases at every downstream stage, rising from a 58% share of annual global rare earth mining in 2020 to a 92% share of annual global magnet production, the stage with the highest added value. Therefore, establishing a resilient domestic magnet manufacturing industry will require restoring U.S. competitiveness in multiple stages of the supply chain. This report discusses these issues in detail and describes several ongoing efforts by U.S. and foreign firms that may improve the resilience of the U.S. supply chain, as well as lessons learned from past efforts.

[1] Note the figure includes stages 1 through 3 from raw materials production through magnet manufacturing, but does not include stage 4, the use of magnets in downstream products; the middle two concentric circles together encompass the processed materials stage.

This discussion leads to a number of vulnerabilities facing U.S. efforts to decarbonize the Energy Sector Industrial Base. These include:

- The instability of the global market for RE elements.
- Reliance on China for raw material and magnet production (in particular, reliance on Chinese firms that can influence global markets through production decisions and that can be influenced by the Chinese government them through policy decisions).
- Reliance on scarce materials from mines and processes that rely on environmentally hazardous extractive techniques (including carbon-intensive practices).
- Aggressive pursuit of intellectual property by foreign firms for common magnet manufacturing practices that restricts U.S. firms from competing.
- Large, expected increases in demand due to the increased deployment of offshore wind turbines and battery and hybrid electric vehicles.

These vulnerabilities lead to some opportunities for the United States. In particular:

- The United States possesses significant sources of rare earths, both conventional and unconventional, and is already one of the leading producers outside of China of concentrate from mines; projects are currently underway to add a similar amount of domestic separation capacity.
- Technological improvements in processing unconventional sources and process intensification and scale-up in RE separation and metal refining may create opportunities for more competitive domestic metal refining and expanded separation beyond the existing projects.
- Research, development, demonstration, and deployment (RDD&D) in magnet recycling techniques and support for recycling companies could allow U.S. suppliers to establish technological advantages and help fill a key supply chain gap.
- New investments in RDD&D along the supply chain to allow substitution away from vulnerable materials and products can make producers that use those technologies less vulnerable to supply chain disruptions.

Find the policy strategies to address the vulnerabilities and opportunities covered in this deep dive assessment, as well as assessments on other energy topics, in the Department of Energy 1-year supply chain report: "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition."

For more information, visit www.energy.gov/policy/supplychains.

Table of Contents

About the Supply Chain Review for the Energy Sector Industrial Base....iii
Acknowledgments....iv
Nomenclature or List of Acronyms....v
Executive Summary....viii
1 Introduction....1
2 Supply Chain Mapping....2
2.1 Supply Chain Overview....2
2.1.1 Overview of Supply Chain Segments....3
2.2 Supply Chain Segments....4
2.2.1 Raw Materials Production....4
2.2.2 Processed Materials Production....9
2.2.3 Magnet Alloy and Magnet Manufacturing....13
2.2.4 Major Uses of NdFeB Magnets....17
2.2.5 Recycling....19
3 Supply Chain Risk Assessment....23
3.1 Risk Factors....23
3.2 Current U.S. Risk Factors and Resilience....25
3.2.1 Assessment of risk factors....25
3.2.2 Resilience....36
3.3 U.S. Competitiveness....39
3.3.1 Raw Materials....40
3.3.2 Processed Materials....41
3.3.3 Magnet Alloys and Magnets....42
3.3.4 Recycling....45
3.4 Key Vulnerabilities and Causes....45
3.4.1 Rare Earth Element Market Instability....45
3.4.2 Reliance on China for Raw Materials and Magnets....46
3.4.3 Reliance on Potentially Environmentally Hazardous Processes....46
3.4.4 Reliance on a Small Pool of Knowledgeable Workers....46
3.4.5 Intellectual Property Constraints....46
3.4.6 Vulnerabilities Faced by New Domestic Suppliers....47
3.4.7 Large Expected Increases in Demand....47
4 Key U.S. Opportunities and Challenges....48
4.1 Opportunities....48
4.2 Challenges to Realizing Opportunities....49
5 Conclusions....51
References....52

Appendix A: Additional Technical Information....64
Appendix B: Assessment Table....67

List of Figures

Figure ES1. Geographical concentration of supply chain stages for sintered NdFeB magnets, 2019 ix

Figure 1. Supply chain stages for rare earth element magnets 4

Figure 2. Raw materials supply chain for NdFeB magnets.. 5

Figure 3. Geographic concentration of rare earth mine production, 2020 6

Figure 4. Processed material supply chain for NdFeB magnets... 10

Figure 5. Geographic concentration of rare earth oxide separation, 2020 11

Figure 6. Geographic concentration of rare earth metal refining, 2020 13

Figure 7. The magnet manufacturing stage of NdFeB magnet supply chain.. 14

Figure 8. Sintered magnet manufacturing process steps and typical process yields 15

Figure 9. Geographic concentration of sintered NdFeB magnet manufacturing, 2020...................................... 16

Figure 10. The component and final product manufacturing stage of NdFeB magnet supply chain................... 18

Figure 11. Magnet recycling stage of NdFeB magnet supply chain 20

Figure 12. Representative magnet recycling pathways.. 21

Figure 13. Geographical concentration of supply chain stages for sintered NdFeB magnets, 2019.................... 27

Figure 14. Projected global NdFeB demand by application under aggressive decarbonization scenarios 31

Figure 15. Projected U.S. domestic NdFeB demand by application under aggressive decarbonization scenarios.. 32

Figure 16. Projected global embedded Nd, Pr, and Dy in magnet demand under aggressive decarbonization scenarios.. 33

Figure 17. Projected U.S. and global embedded Nd, Pr, and Dy in magnet demand under aggressive decarbonization scenarios.. 34

Figure 18. Relative Scale of Essential Civilian Shortfall for NdFeB magnets identified in the 2021 Report on Stockpile Requirements.. 38

Figure 19. NdFeB Patent Applications Origin by Jurisdiction 44

Figure 20. Top applicants for NdFeB magnet patents (firms).. 44

List of Tables

Table 1. Coatings used on NdFeB permanent magnets 9

Table 2. Maximum operating temperature and associated Dy content of NdFeB magnet grades 15

Table 3. 2020 share of magnets contained in demand for selected NdFeB magnet applications 17

Table 4. Maximum operating temperature, associated Dy content, and example applications of NdFeB magnet grades 18

Table 5. Geographical concentration of production for various supply chain steps for sintered NdFeB magnets, 2020 26

Table 6. Market concentration and geopolitical sensitivity 27

Table 7. Current and prospective U.S. domestic projects related to NdFeB magnets 29

Table 8. 2020 sources for demand growth estimates for selected NdFeB magnet applications 30

Table 9. Expected magnets contained in global demand for selected NdFeB magnet applications, thousands of tonnes 31

Table 10. Expected magnets contained in U.S. demand for selected NdFeB magnet applications, thousands of tons (kt) 32

Table 11. Volatility measures for rare earth oxides 34

Table 12. Cell cost for Argonne NdPr production analysis 42

Table B1. Assessment Table 67

1 Introduction

Decarbonizing the economy by 2050 will require radical transformations to the U.S. Energy Sector Industrial Base (ESIB), including in the manufacture of renewable electricity generation technologies and zero-emissions vehicles. While the technologies to achieve these goals are available, they currently rely on raw materials characterized by opaque and volatile global markets and their supply chains are often concentrated in geopolitically sensitive areas. Furthermore, midstream stages of supply chains, such as material processing and the manufacturing of components, are also concentrated in foreign countries with complicated geopolitical relationships with the United States. This report focusses on the supply chain for rare earth permanent magnets.

Rare earth (RE) permanent magnets – specifically, neodymium-iron-boron (NdFeB) magnets – are the strongest magnets commercially available and provide a host of benefits to existing and emerging technologies, including clean energy and defense technologies, consumer electronics, power tools, sensors, machines, and many other technologies. [1-3] In particular, RE magnets enable the use of technologies that improve the efficiency and simplicity of electrical machines. [4] Within the energy sector, they are necessary components of direct drive and hybrid generators in wind turbines and of traction motors in electric and hybrid-electric vehicles. These technologies enable the construction of higher-capacity, more efficient wind turbines with reduced maintenance costs and the manufacturing of more efficient, more powerful, and lighter-weight motors in electric vehicles (EVs).

Given the importance of NdFeB magnets to clean energy, national security, and economic prosperity, the U.S. government has been actively engaged in encouraging and incentivizing U.S. production and improving the resilience of the NdFeB magnet supply chain. In 2021, the U.S. Secretary of Commerce launched an investigation of the effects of imports of NdFeB magnets on National Security to evaluate whether Section 232 of the Trade Expansion Act of 1962 is applicable for addressing the issues in the supply chain. The federal government is also executing projects under Title III of the Defense Production Act (DPA), which is dedicated to ensuring the timely availability of essential domestic industrial resources to support national defense and homeland security requirements, and which has been authorized for use to support the production of rare earth elements and sintered NdFeB magnets. As of publication of this report, the DPA Title III program has active agreements with industry to re-establish domestic production capacity for rare earth element separation and production of NdFeB magnets, with additional actions possible in the future. DOE has also directed RDD&D funding to help secure the domestic supply chain of critical materials that are used to build clean energy technologies, including $30 million announced in 2021 for 13 national lab and university-led research projects. The National Science and Technology Council (NSTC) committee on Homeland and National Security works across multiple agencies to implement the Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals published by the Department of Commerce (DOC) in 2019.

This report provides an overview of the NdFeB magnet supply chain, its vulnerabilities, and opportunities to improve the resilience of the supply chain in the United States. It provides a complete mapping of the NdFeB magnet supply chain from the extraction of raw materials to the production of sintered magnets and discussion of each step in the supply chain. It also discusses the current supply chain risk facing the United States, the current competitiveness of the U.S. supply chain, and potential opportunities for enhancing supply chain resilience. This analysis serves as a basis for highlighting several vulnerabilities (and their causes) in the RE magnet supply chain associated with decarbonizing the ESIB.

The report is organized as follows. First, it discusses the mapping of the RE magnet supply chain from raw materials production through major end uses and recycling. It then discusses risk and resilience factors and provides information on the current status of developments within the supply chain in the United States. The report then discusses key vulnerabilities affecting the supply chain as identified by the analysis and notes some potential opportunities.

2 Supply Chain Mapping

This section discusses the supply chain for producing rare earth permanent magnets and the various production and manufacturing steps required. It also discusses their use in components and final products within the Energy Sector Industrial Base (i.e., wind turbines and EVs) and various approaches to magnet recycling and product recovery.

2.1 Supply Chain Overview

The intended use of a permanent magnet in a final product dictates the optimization of three key magnet properties that have an influence on which elements are needed and in what quantities. These properties are the coercivity (or resistance to demagnetization); the maximum energy product (a measure of the magnetic energy that can be stored in the material dependent upon its coercivity and magnetization); and the maximum operating temperature. In most applications, a trade-off is made between these desired properties, the final weight of the product, and the cost.

Two types of rare earth magnets exist: NdFeB magnets (the focus of this report) and samarium cobalt (SmCo) magnets. SmCo magnets are more resistant to demagnetization at higher temperatures than NdFeB magnets and are thus more suitable for high-temperature applications where weight is not a concern. The higher maximum energy product of NdFeB at temperatures up to about 180 degrees Celsius allows manufacturers to reduce the size and weight of components (or achieve higher efficiency out of components of the same size). [1, 5] Further, NdFeB magnets are produced as both bonded and sintered magnets. Both bonded and sintered magnets rely on the light REs neodymium (Nd) and praseodymium (Pr), while heavy REs such as dysprosium (Dy) and terbium (Tb) are used primarily in sintered magnets to improve their resistance to demagnetization at temperatures above 120 degrees C. [1] Because bonded magnets generally have lower-energy products and tend to be brittle, both direct-drive generators and traction motors have relied on sintered NdFeB magnets. [6-8] Approximately 93% of the current market for NdFeB magnets is for sintered magnets. [9]

In the context of permanent magnets, a number of existing bottlenecks and challenges may inhibit U.S. decarbonization goals. The overwhelming majority of global RE mine production, separation capacity, metal and alloy manufacturing, and magnet manufacturing are dominated by China, and all existing domestic RE mine production (by companies such as MP Materials and Chemours) requires separation and further refining overseas due to a lack of existing domestic separation, alloy making, or metal refining for RE materials. [10, 11] While Nd, Pr, and didymium (unseparated NdPr) are now being produced outside China, access to heavy REs (HREs) is still constrained. And with the exception of some emergent sintered magnet capacity from Urban Mining Company (which produces magnets from recycled feedstock), existing RE magnet manufacturing in the United States is mostly limited to SmCo magnets. Projects are under development at several stages of the supply chain to address many of these bottlenecks, but challenges remain to develop the supply chain further and to ensure that these projects are successful.

2.1.1 Overview of Supply Chain Segments

Magnets are an intermediate product used in various subcomponents for a range of finished products (end uses); accordingly, the supply chain for NdFeB magnets includes segments both upstream of magnet manufacturing, such as raw materials production, and downstream, such as manufacturing of direct drive generators for wind turbines.

Materials used in NdFeB magnets include the light RE metals neodymium (Nd) and praseodymium (Pr), the heavy REs dysprosium (Dy) and sometimes terbium (Tb), as well as iron (Fe) and boron (B). Additional elements are sometimes included as well, including copper, cobalt, niobium, and cerium. [12] According to rough calculation based on standard magnet composition and current material prices, the RE metal inputs are estimated to account for over 90 percent of material costs and are more likely to be subject to supply disruptions than other material inputs to NdFeB magnet production. Therefore, for raw materials, this report focuses on RE element supply chains and also considers equipment and labor costs.

The main supply chain segments for NdFeB magnets, including downstream segments as well as recovery for the recycling of magnets and embedded materials, are

1. Raw materials production, which includes the mining and processing of RE elements and other materials as well as production of materials from secondary and unconventional sources.
2. Processed materials production, which includes the separation of individual REs into oxides and RE metal refining.
3. Sintered magnet manufacturing, which includes both metal alloying and magnet making processes.
4. Manufacturing of components for final uses and final products.
5. End-of-life product recovery and magnet remanufacturing.

Figure 1 illustrates the production steps associated with each supply chain stage. The remaining sub-sections of Section 3 discuss each stage in greater detail.

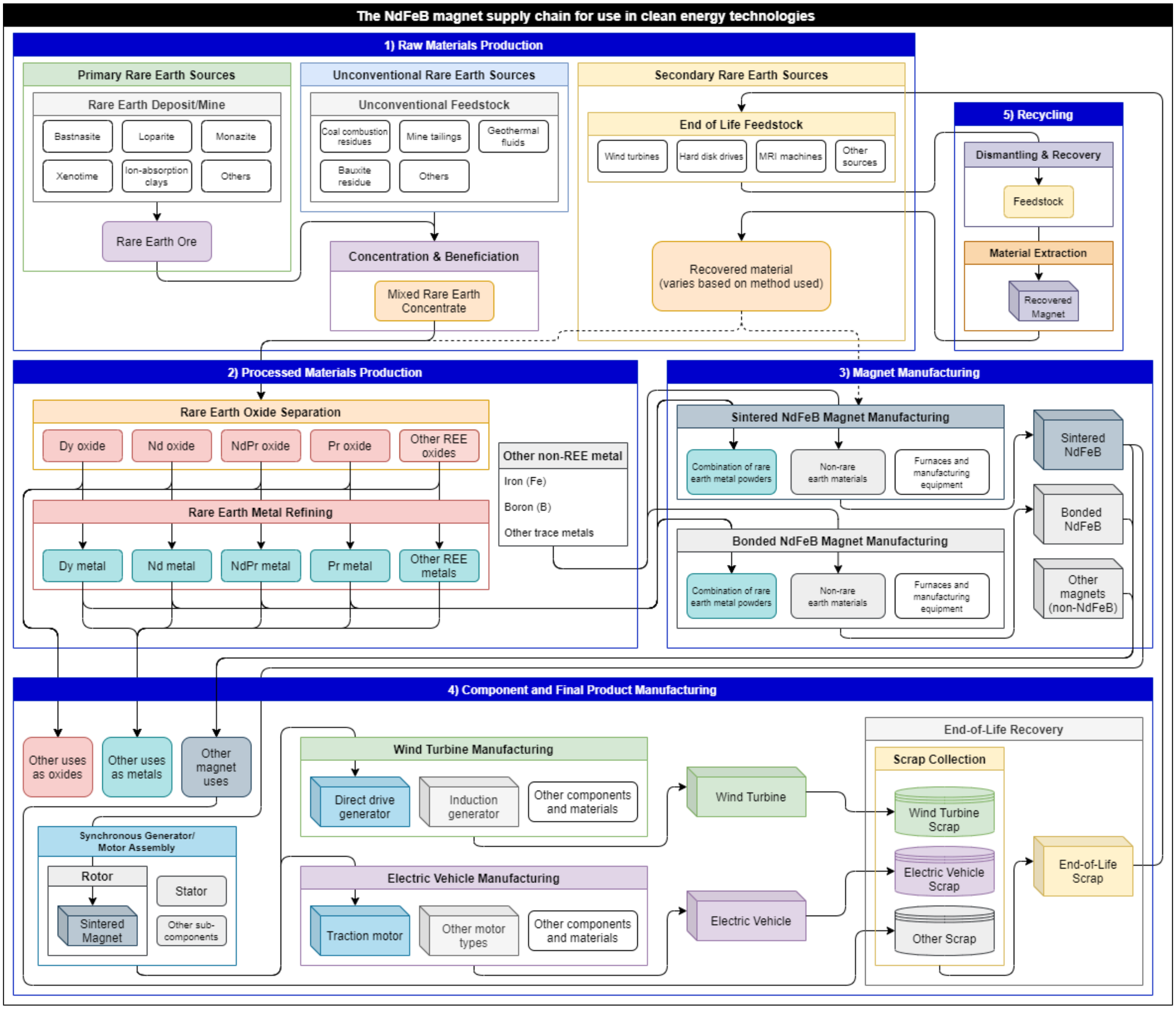

Figure 1. Supply chain stages for rare earth element magnets

2.2 Supply Chain Segments

2.2.1 Raw Materials Production

Raw materials production includes the production of materials from primary sources (mining), secondary sources (recycled material), and unconventional sources as well as the concentration and beneficiation of mine products into a mixed rare earth concentrate. Figure 2 shows the portion of Figure 1 covered in this section of the report, including the different types of resources and production stages covered. Due to the significance of RE metals in NdFeB manufacturing, this section focuses more intently upon the mining and concentration of these materials, but also discusses production of high-purity iron, boron, and materials used in magnet coatings. Sintered NdFeB magnets are composed of roughly 30% RE material, 69% iron, and 1% boron by weight.

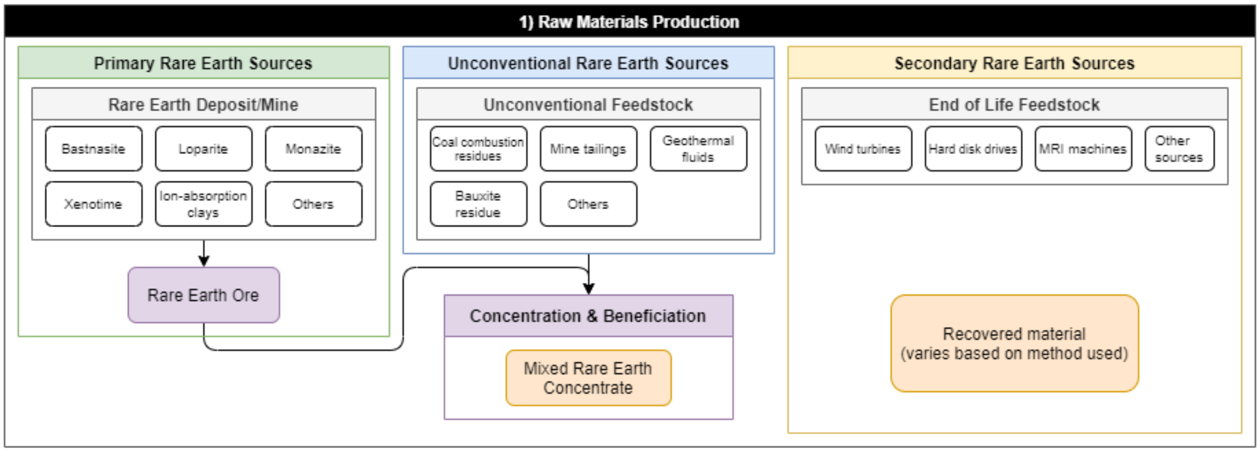

Figure 2. Raw materials supply chain for NdFeB magnets

2.2.1.1 Rare Earth Elements

2.2.1.1.1 Primary Sources of Rare Earth Elements – Mining and Processing

RE elements include the lanthanide elements (which comprise the chemical elements with atomic numbers from 57 to 71), scandium, and yttrium. REs are chemically similar and are often present in the same mineral deposits. They are divided into two groups based on their atomic weights, which also determines their occurrence in nature. Light REs (LREs) include the elements cerium (Ce), lanthanum (La), praseodymium (Pr), neodymium (Nd), and samarium (Sm). Heavy REs (HRE)s include the elements europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lt). NdFeB magnets require a combination of LREs and HREs, namely Nd, Pr, and either Dy or Tb.

Most rare earths are currently produced through the mining of primary ores. As REs are found in the same deposits, they are produced as co-products, with some deposits containing primarily LREs and other containing more HREs. Ores are mined and then beneficiated using some combination of gravity, magnetic, electrostatic, and flotation separation to remove excess material and increase the concentration of rare earth metals. [13]

2.2.1.1.2 Current and Planned Mining

Figure 3 shows global RE mining production by country in 2020, based on United States Geological Survey (USGS) data. [14] The majority of the world's RE production occurs in China, followed by the United States, Burma, and Australia, with smaller amounts coming from Madagascar, Russia, India, and Brazil. The largest single source of REs in the world is the Bayan Obo mine in the Inner Mongolia autonomous region in China. It is a combined rare earth, iron, and niobium mine with rare earths contained both in independent minerals such as bastnäsite (a LRE fluorocarbonate) and monazite (a mixed rare earth phosphate) as well as in iron oxide minerals, which are mined primarily for the iron with rare earths as a byproduct. [15] China also produces LREs from several other sources, primarily in Sichuan province. The majority of HREs come from a variety of small mines in South China and Burma that produce REs from ionic clays. Concentrates from the mines in Burma are sent to China for further processing. Outside of China and the United States, the largest producer of LREs is Lynas's Mount Weld mine in Australia, a carbonatite deposit containing multiple rare earth-containing minerals. [16]

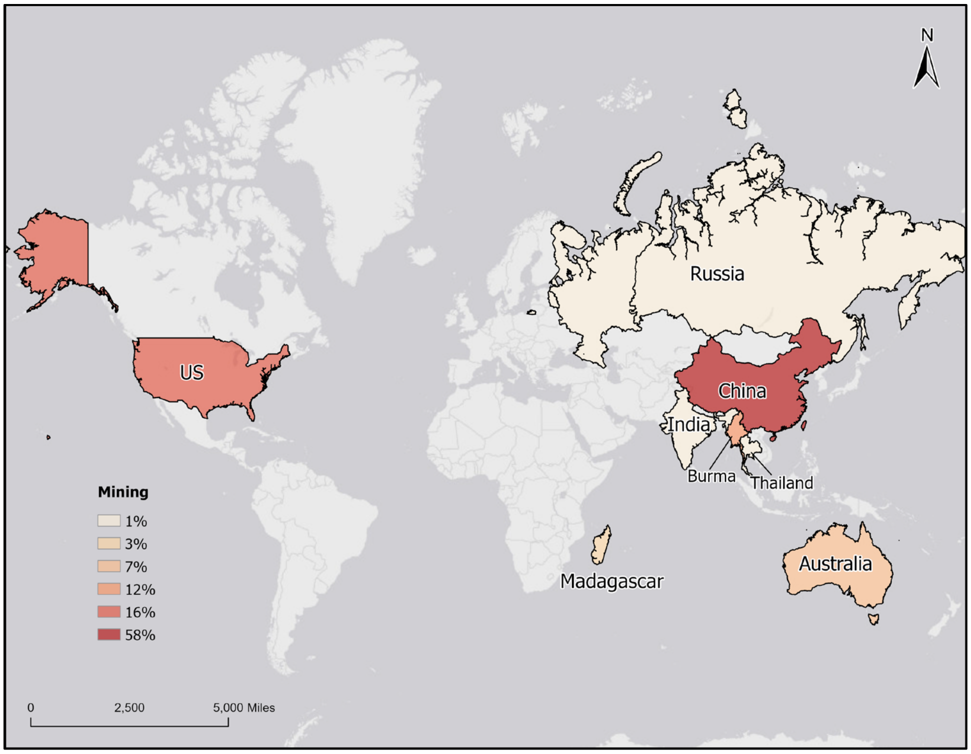

Figure 3. Geographic concentration of rare earth mine production, 2020 [14]

The two RE-containing mineral ores currently extracted in the United States are bastnäsite and monazite. The highest-grade bastnäsite ore deposit in the world is located at Mountain Pass, California, and has been exploited since the 1950s. The mine and mill have been operated by a number of oil and mining companies and are currently operated by MP Materials who bought the property out of bankruptcy proceedings for former owner Molycorp. [10] This ore body has large amounts of Ce, La, Nd, and Pr and small amounts of Sm, but does not contain a significant amount of HREs. The ratio Ce/La/Nd/Pr is about 52/30/12/4. [17] The Ce and La are in excess supply worldwide, which keeps these prices low and makes it hard to sell all the Ce and La produced. As a result, the cost of the mining and milling operation must be borne primarily by the sale of Nd and Pr. USGS estimates that total rare earth oxide production from Mountain Pass mine was 26,000 tonnes/year in 2019, [14] and MP materials reported producing 38,500 tonnes/year in 2020, [10] enough to produce about 13% of current world Nd+Pr, but just 0.6% of the world's Dy.

Monazite is found in heavy mineral sands in the southeastern United States, which historically have been mined for titanium and zirconium with monazite largely treated as a waste product until recently due to the presence of radioactive materials such as thorium in the monazite. Through a recent deal between Chemours and Energy Fuels, Chemours now separates rutile, zircon, and monazite sands in Georgia and sends the byproduct monazite to a plant in Utah owned by Energy Fuels to produce a mixed rare earth carbonate. [18, 19] Energy Fuels is primarily a uranium producer and is able to handle the radioactive thorium and uranium from the monazite. [20] Monazites are generally rich in Ce and La with some Nd and Pr and smaller amounts of HREs. The monazite produced in the southeast United States is typically about 55% rare earth content, with about 22% of that NdPr oxide. [18] Planned shipments from Chemours to Energy Fuels of 2500 tonnes monazite per year would be enough to generate about 0.7% of world Nd/Pr oxide production. [21] Energy Fuels aims to increase production to 15,000 tonnes monazite/year with additional monazite from other locations, which could increase Nd/Pr production to about 4% of current world production. [11]

A wide range of projects at various stages of development aim to add rare earth mining capacity throughout the world. Technology Metals Research identified 58 resource deposits with a formally characterized rare earth resource as of November 2015. [22] Deposits from this list in the United States include Round Top, Bear Lodge, Bokan Mountain, and La Paz, though this is not a comprehensive list of all potential ore bodies in the United States. Other advanced projects outside the United States include Nechalacho in Canada, Browns Range in Australia, Araxa in Brazil, and Penco in Chile. Many projects have found it challenging to acquire the necessary funding to develop these resources, but some have reached advanced stages of development.

Of particular interest are projects with high concentrations of HREs, since HRE mining and processing is currently limited to the ionic clays in China and Burma. Ionic clays also are being developed in Chile; however, current plans do not include separation facilities and at planned production rates, they would still make up only about 2% of world Dy production. [23] Potential sources for HREs exist in other types of deposits throughout the world, such as a rhyolite ore at Round Top in Texas, Browns Range in Australia, and Bokan Mountain in Alaska. However, extracting REs from these ores is more difficult than from ionic clays, and has thus far not been established at a commercial scale.

USA Rare Earths hopes to develop Round Top in Texas, which could produce about 8% of current world Dy oxide supply if developed at the scale proposed in its 2019 preliminary economic assessment. [24] If successful, this could fill a gap in the U.S. supply chain, as existing bastnäsite and monazite deposits have smaller shares of heavy rare earths. The domestic companies and projects mentioned in this section do not necessarily represent an exhaustive list, as new players in the industry are constantly emerging.

2.2.1.1.3 Secondary Sources of Rare Earth Elements

Secondary sources are made up of scrap from end-of-life products that contain RE elements. Currently little production of REs from secondary sources occurs worldwide, but REs could potentially be extracted from a variety of end-of-life products. Historical (and near-future) end-use demands determine the availability of REs from secondary sources. Current and potential secondary sources of REs span a number of end-use categories (such as alloys in batteries and scrap metal, catalysts, phosphors, ceramics, glass, and permanent magnets); however, many of these applications contain lower-value rare earths (such as Ce and La) that are unlikely to be economical to recover. [25] By end-use category, permanent magnets and catalysts dominate demand at 33% and 32%, respectively. [26] As Nd and Pr are the primary elements of interest for use in magnets, [25, 26] spent magnets are by far the largest potential source of materials needed for NdFeB magnets. Magnet recycling is discussed further in Section 2.2.5

2.2.1.1.4 Unconventional Sources of Rare Earth Elements

In addition to mining and secondary production, REs can be extracted from unconventional sources, such as byproducts of mining or other upstream processes. Unconventional sources under consideration for RE recovery include coal and the clays and shales above and below the coal seams, coal ash from coal-fired power plants, [27, 28] geothermal fluids used for energy production, [29] mine tailings, [30] acid mine drainage, [31] and red mud (bauxite residue) generated from the production of alumina. [32] One advantage of unconventional sources is that they could potentially be developed more quickly than mining projects, though REs occur in vastly smaller concentrations in these sources.

One of the more promising unconventional sources of REs is coal ash, a combustion byproduct collected from coal burned at coal-fired power plants. Because coal ash contains small concentrations of toxic metals that can impose significant negative environmental and health impacts if not contained, most industrialized nations regulate its collection and storage. Coal ash has been reclaimed for beneficial uses in concrete and cement, asphalt and pavement, and other construction and industrial products. In 2010, an estimated 42 percent of the total coal ash produced in the United States was reclaimed for use, with the remainder stored in on-site repositories. [33] A recent study evaluating the potential of U.S. coal mines as domestic rare earth sources found that bituminous coal from the Appalachian region has the highest potential for economic RE recovery, with the most promising samples in the eastern Kentucky area. [34]

In recent years, published research has focused on evaluating the RE content of coal ash from power plants around the world, and several processes for extracting REs as an intermediate step between coal-fired power plants and cement plants have been developed and evaluated. Some of these processes show potential to improve the quality of coal ash for its use in cement, as in the case of Battelle's acid digestion process. [27] Other potential coal ash processes include the use of biosorption, [30] supercritical carbon dioxide, [35] novel membrane separation, [36] and sequential extraction followed by hydrothermal treatment. [37] The DOE has recently funded development of four pilot-scale projects for the recovery of rare earths and critical materials from coal and coal byproducts.

While currently no industrial scale production of rare earths takes place from unconventional sources, a number of domestic projects are under development. MP Materials has received DOE funding with the University of Kentucky for a feasibility study to produce rare earths oxides and metals from coal byproducts. [38] Phoenix Tailings aims to produce rare earths from mine tailings such as bauxite residue, or red mud. [39] These companies and projects do not comprise an exhaustive list, as new projects are announced regularly with varying degrees of readiness.

2.2.1.2 Iron

NdFeB magnets consist of about 69% iron, 1% boron, and 30% rare earth metals (Nd, Pr, Dy) with small additions of Co, Al, Tb, and Ho. The iron used is an American Iron and Steel Institute (AISI) 1001 steel, which Induction Iron used to provide to magnet producers in the United States when magnets were being manufactured domestically. Currently there is very little domestic production of this very low carbon steel; rather, it is now imported from Germany and sometimes from Brazil and other locations. However, there are U.S. companies that could produce the material if domestic demand were greater. Electrolytic iron, produced by electrorefining low carbon steel in an aqueous solution, could also be used. Electrolytic iron is more expensive than 1001 steel, since remelt consolidation must be used in magnet production. Electrolytic iron is being produced in the United States, as well as in China, India, and the United Kingdom.

2.2.1.3 Boron

The boron in NdFeB magnets is supplied in the form of ferroboron, a reagent that is easy to obtain and has been produced in the United States. It occurs as borate mineral, such as borax. The ore is converted to boric acid, then reduced in an electric arc furnace with carbon steel, aluminum, and iron ore to produce ferroboron. While the United States has active boron mining, it does not currently produce ferroboron (according to 2017 data) and must rely on imports. [40] The domestic production of boric acid reached about 250,000 tonnes in 2020. Supply of ferroboron could potentially be produced from these materials. Ferroboron is produced in China, India, and Turkey.

Ferroboron is typically composed of roughly 17 to 20% boron, with iron accounting for the remaining 80 to 83%. Total ferroboron used in 2017 in the United States was about 665 tonnes. [40]

2.2.1.4 Other Raw Materials

Magnets are sensitive to water vapor, and if left unprotected with a coating the magnet will corrode. Water vapor and oxygen in the air will convert the rare earth metal fraction to an oxide. Various coatings are applied to the surface of NdFeB magnets to prevent corrosion. The most common coating is a nickel-copper-nickel tri-layer, applied in three separate layers through electrolytic processes. The solutions used in the plating process contain phosphorous, some of which may end up in the coating. Non-magnetized preforms are used, with magnetization occurring after the plating is complete. Table 1 shows various coatings used and their thicknesses. There appear to be no restrictions on the domestic industry to apply these coatings.

Table 1. Coatings used on NdFeB permanent magnets [41]

Coating type	Thickness	Comment
Ni-Cu-Ni	12 micron	Most common coating, may contain phosphorous
Gold-coating, Ni-Cu-Ni-Au	12 micron of Ni-Cu-Ni, 0.5 micron Au	Gold coating wears rapidly
Chrome, Ni-Cu-Ni-Cr	15 micron	
Copper, Ni-Cu	10 micron	
Epoxy resin, Ni-Cu-Ni	10 micron	Can easily wear, small scratches will lead to corrosion of magnet
Zinc	4 micron	Leads black marks when handled
Teflon	25 -250 micron	Can easily be damaged
Silver, Ni-Cu-Ni-Ag	12 micron, silver 0.5 micron	Silver added to improve appearance
ABS (plastic)	800 micron	
Xylan	15-30 micron	
Parylene	30 micron	Applied by chemical vapor deposition (CVD)
Nickel	10 micron	May contain phosphorous
Al	4-10 micron	CVD application

2.2.2 Processed Materials Production

Processed materials production includes RE separation to separate individual rare earths from concentrates, generally in oxide form, and metal refining to convert rare earth oxides to metals. These steps, illustrated in Figure 4, are often associated with the midstream portion of the NdFeB magnet supply chain.

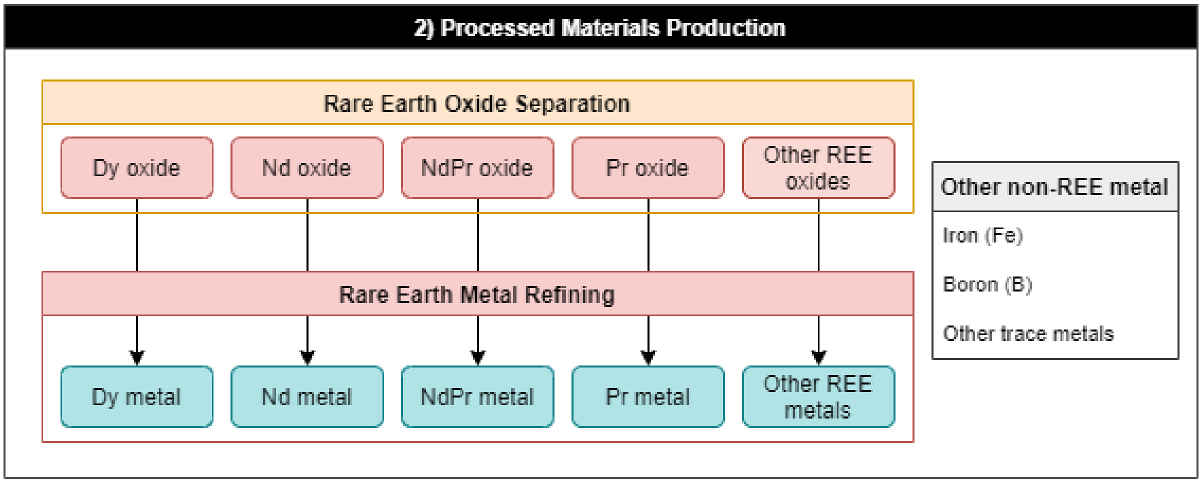

Figure 4. Processed material supply chain for NdFeB magnets

2.2.2.1 Rare Earth Element Separation

While a variety of rare earth deposits exists, in all of them many different rare earths are combined, as well as with other minerals. Because of the chemical similarity of different rare earth elements, separating them from each other is particularly challenging. NdFeB magnets require a combination of rare earths, especially Nd, Pr, and Dy, with the proportions of each rare earth influencing magnet properties. Nd and Pr are particularly difficult to separate, due to similar chemical properties. As a result, they are often used in magnets unseparated as didymium (NdPr alloy), sometimes combined with separated Nd to get the desired Nd to Pr ratio in a magnet. Mixed rare earth oxides and mischmetals, an alloy containing multiple unseparated rare earths, are also used in applications such as nickel-metal hydride (NiMH) batteries, alloys, and ceramics, but are not suitable for most NdFeB magnets.

The primary process currently used for separation is solvent extraction. The extraction process is engineered for each type of concentrate as the ratios of Ce/La/Nd/Pr in each ore body is different. The concentrates of bastnäsite require high-temperature cracking with sulfuric acid or other reagents to render the mineral amiable to dissolution. Similar processing on monazite is necessary. Before entering the solvent extraction trains, Ce is generally removed from brines through oxidation. Solvent extraction trains potentially use hundreds of mixer/settlers, each of which consists of a mixing chamber where a solvent is mixed with the feed solution, and a settling chamber where lighter and heavier materials are separated by gravity. The process initially separates light rare earths such as Nd and Pr from heavy rare earths such as Dy and Tb before performing additional separations. The process consumes large amounts of acid, caustic, and water. Treating wastewater and purchases of solvents are key drivers of costs, so technologies to recycle solvents from the wastewater can play an important role in cost reduction and improved environmental performance. [42] Ongoing research is being conducted to develop extracting reagents that do not require as much acid and caustic to use in the mixer/settler/stripping units. During ore processing, small amounts of uranium and thorium also must be separated from the rare earth streams, which leads to additional challenges dealing with radioactive materials. Additional details on the solvent extraction process are described in Appendix A.

2.2.2.1.1 Current and Planned Separation

Figure 5 shows global RE separation by country based on author estimates of known industry partnerships. For example, since most of the product of Mount Weld mine in Australia goes to Malaysia for separation, we assume that Malaysia's share of separation is the same as Australia's share of mine production. Similarly, mine production from the United States, Burma, and Madagascar is assumed to be separated in China. Despite just under 60 percent of total RE mine production occurring in China, the country controls almost 90 percent of RE separation.

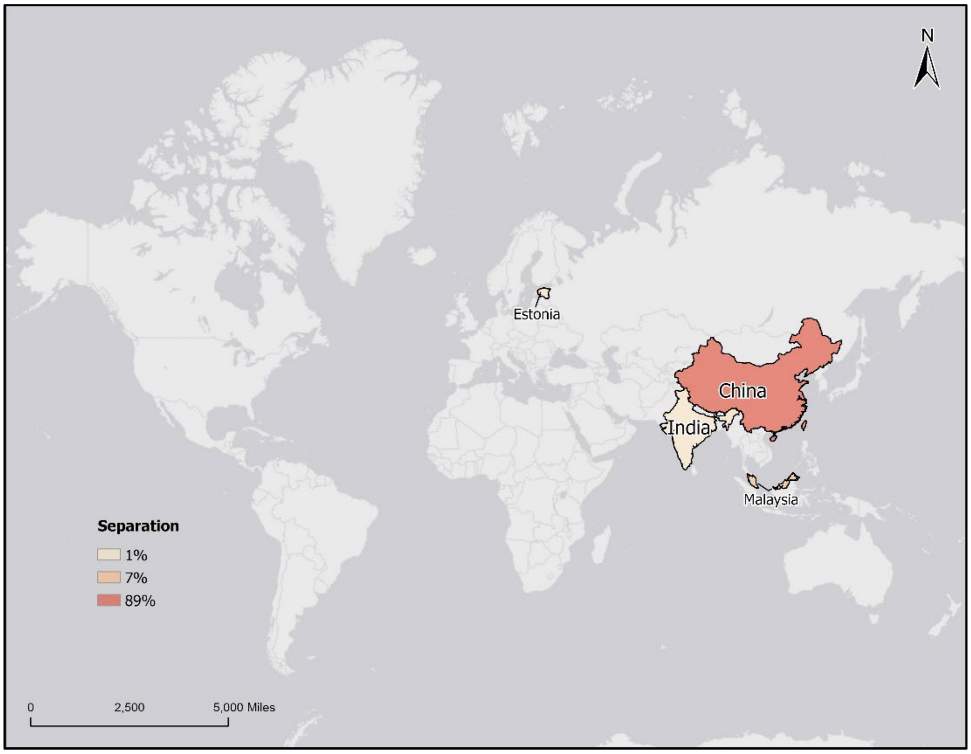

Figure 5. Geographic concentration of rare earth oxide separation, 2020

China's share of heavy rare earth separation is even higher, near 100%. Most of these separated HREs come from ionic clay minerals found in China and Burma. Of the rare earth ores mined in the United States, the bastnäsite found in Mountain Pass mine is not rich in Dy, while monazite sands may have some Dy. Improvements can be made in the current practice to recover Dy from mineral sands. When the fraction of HREs is much smaller than the fraction of LREs, it may not be economical to separate small quantities of HREs into individual rare earths. None of the Dy mined in the United States is currently separated domestically, and the rare earth products from Lynas's separation facility in Malaysia do not include separated heavy rare earths. [43] Light and heavy rare earth separation capacity also exists at a Solvay facility in France (though it is not clear whether it is currently producing) as well as some idle capacity to separate heavy rare earths in Japan. [44]

MP Materials produces primarily light RE elements, such as Nd and Pr, from the Mountain Pass mine in California. They currently send the concentrate to China for separation of rare earth oxides, but have raised funding (including through an award under the DPA Title III program) to finish rebuilding their domestic separation processing facilities, originally built by Molycorp, with the goal to begin production in 2022. [10, 45] If it processes all of its current production of concentrates, this could represent about 12% of current global rare earth production. [45] MP Materials has also stated its intentions to establish a complete domestic supply chain from mining through magnet production. [10]

Energy Fuels recently began producing a mixed rare earth carbonate from monazite separated by Chemours. Energy Fuels has an agreement with Neo Performance Materials, a company headquartered in Canada, to export rare earth carbonate to Estonia for separation in its Silmet facility. [21] While this doesn't increase U.S. RE separation, it does improve global diversity. The company has also studied costs of separating rare earth oxides and refining them into metals and has announced plans to develop separation operations in the future. [11]

Lynas is planning a separation facility in Texas through its subsidiary Lynas USA LLC, with support from the DPA Title III program, which would be able to separate both light and heavy REs. [46, 47] The scale of the planned heavy rare earth separating facility is not yet clear, but if it processes all of the heavy REs currently produced from Lynas' Mount Weld mine, this would generate about 2% of current world Dy oxide production, and would be the most significant source of separated heavy REs outside of China. With the addition of the light rare earth processing facility, it was estimated that, between its plants in Texas and Malaysia, Lynas would be able to produce about 25% of the world's separated rare earth oxide. [46]

USA Rare Earths, which owns the Round Top deposit in Texas, has reportedly made progress in developing a separation facility in Colorado. [24, 48] If successful, this facility could provide an additional source of separated heavy REs such as Dy, sourced from a domestic resource with high concentrations of heavy REs.

General Atomics has received DOE funding for a demonstration facility to process and separate light REs from stockpiles of mined material from the Bear Lodge mine in Wyoming. [49] Roughly 90 tonnes of RE oxides, including 20 tonnes of Nd/Pr oxides, would be produced from this demonstration plant over the course of a year, which would be about 0.1% of current world production. [49] If both Bear Lodge mining and General Atomics separation were expanded to the level planned in a 2014 pre-feasibility study for Bear Lodge, production could increase to about 4% of current world Nd/Pr production. [22, 38] The companies and projects mentioned in this section do not necessarily represent an exhaustive list, as new projects and deals are constantly announced with varying degrees of readiness.

2.2.2.2 Rare Earth Element Metal Refining

Rare earth oxides or chlorides separated from rare earth ores must be refined into metals in order to be used in magnets. The metals most commonly used in magnet production are didymium (NdPr), a mix of Nd and Pr, pure Nd, and ferrodysprosium (DyFe), with Tb metal used less frequently. The most commonly used processes for refining metals are electrowinning and sodium reduction.

Electrowinning converts rare earth oxides to metals or alloys using an electrowinning cell, which consists of a set number of anodes and cathodes. Each metal or alloy produced requires a specific electrolyte composition. All of the electrolytes are composed of solutions of lithium fluoride and the rare earth fluoride of the metal of interest. The electrolytes are typically 80-90% rare earth fluoride, with the balance lithium fluoride. The electrolyte can make up nearly half of the initial capital costs of metal refining. Details of the electrowinning process and key challenges in its design are described in Appendix A.

Rare earths can also be refined into metals using sodium reduction, in which sodium metal is used to reduce anhydrous rare earth chloride salts. This process is a metallothermic reduction similar to the Hunter process for production of titanium. Challenges include the production of anhydrous chloride, as rare earth chlorides are deliquescent, acquiring the sodium metal, which is imported, and the separation of the byproduct sodium chloride from the rare earth metal.

2.2.2.2.1 Current and Planned Refining

Rare earth metal refining currently occurs largely in China and a handful of Southeast Asian countries, with smaller amounts in Estonia and the United Kingdom, with no current metal refining in the United States. Vietnam Rare Earths JSC operates a plant in Vietnam; [50] metal refining likely is occurring in Thailand; and the state-owned rare earth company in Laos may be in production. Silmet in Estonia (owned by Canada-based Neo Performance Materials) and Less Common Metals in the United Kingdom also have limited metal refining capability. [51, 52] While no reliable information is available on the amount of metal refining that occurs in different locations, our estimates of the geographic concentration of global RE metal refining in 2020, based on consultation with experts, are shown in Figure 6.

While no metal refining is currently occurring in the United States, potential remains for metal to be refined domestically if the economics improved. Likely some idle metal refining capacity exists, including in old Mitsubishi furnaces in Ohio. MP materials has announced plans to build out its supply chain from mining through magnet manufacturing, including metal refining. [10] Energy Fuels, which is currently processing monazite in its Utah facility, has also studied fully separating and refining rare earth metals. [11] As with the other sections, these companies and projects do not necessarily represent an exhaustive list.

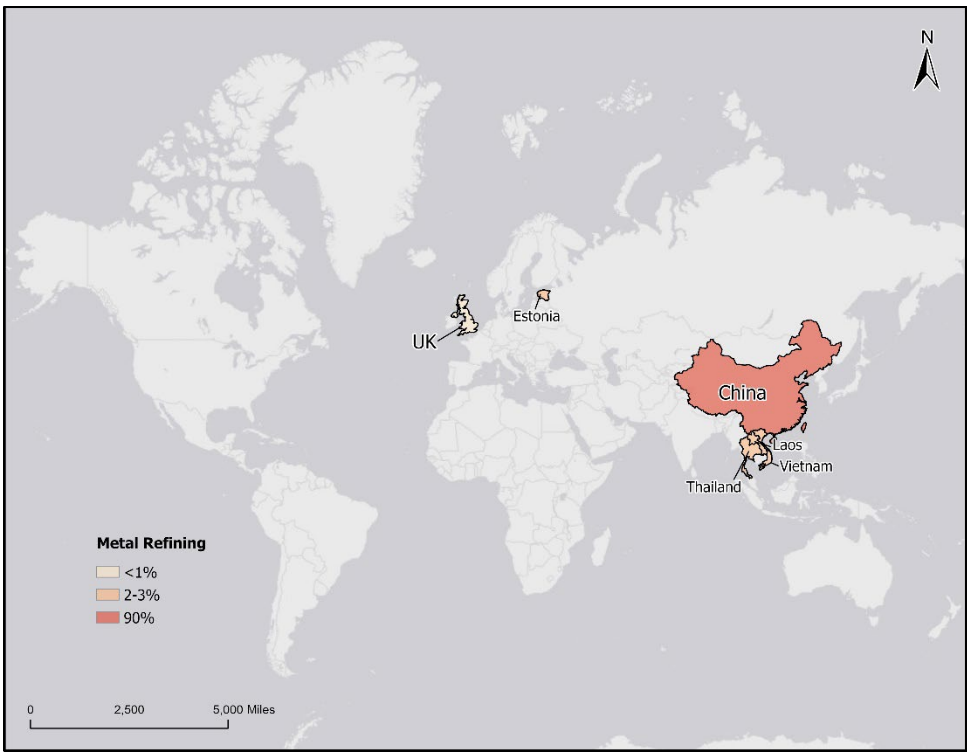

Figure 6. Geographic concentration of rare earth metal refining, 2020

2.2.3 Magnet Alloy and Magnet Manufacturing

Magnets are produced from alloys or powders that combine rare earth metals such as Nd and Pr with iron and boron. The alloys used in the production of NdFeB magnets are grouped into two classes—those used for bonded magnets where plastic resins are used to bind the magnetic particles together, and those used in sintered magnets. Bonded magnets are typically favored in applications that require complex shapes, while sintered magnets are typically used in harsher, higher-temperature conditions. [1] Sintered NdFeB magnets can have small additions (0.5 to 11 percent) of Dy or Tb that improve the high-temperature resistance to demagnetization, but adds cost to the magnet as dysprosium has consistently been one of the most expensive rare earth elements over the past decade. The magnets can also have additions of cobalt, aluminum, and other transition metals. The total RE fraction is about 30 percent, with the balance iron and boron. Figure 7 shows the magnet manufacturing portion of the supply chain diagram from Figure 1.

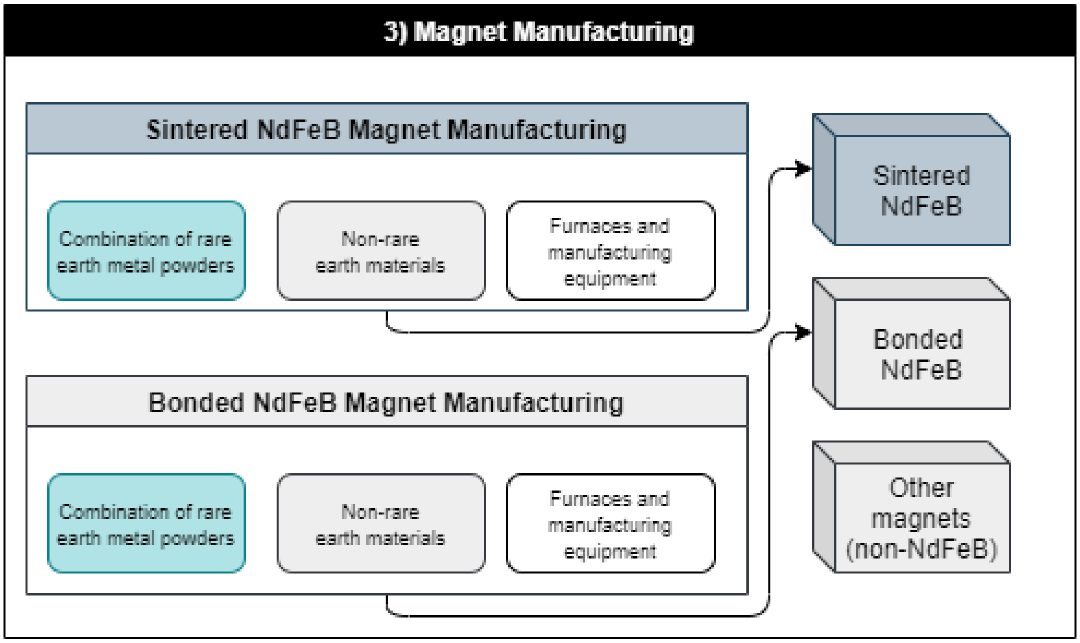

Figure 7. The magnet manufacturing stage of NdFeB magnet supply chain

Sintered magnets tend to follow a powder metallurgy route. [1] Magnet alloys can be produced by induction melting the metals, followed by strip casting, where molten metals are poured on the outer surface of a cooled metal cylinder while the cylinder is rotated to produce a directionally solidified microstructure of the alloy with a small grains size. This may be followed by hydrogen decrepitation to reduce the grain size further, producing a strip that is then jet milled using autogenous milling of the alloy into a powder with small grains that can be used for magnet production. [1] These powders are pyrophoric, or prone to igniting when exposed to air, making them difficult to ship. The alloys could be produced by a separate melt step in a different location than the casting step; however, this increases the cost of the material as more energy is necessary to melt it a second time before casting. The formation of the powder in the jet-milling step is important as the shape of the grains controls the microstructure of the magnet that defines its key performance parameters. The powder is then aligned and pressed in a magnetic field, followed by sintering at 1,000-1,100°C. [1]

Once formed, the sintered magnets are machined to the desired shape and coated with a metal film of nickel (5-10 microns) to protect the magnet from corrosion. After plating, the magnet is magnetized in a high magnetic field to align the magnetization of the grains in the magnet. Figure 8 summarizes the magnet manufacturing steps, with typical first-time process yield by mass. This figure provides more detail about the “Sintered NdFeB Magnet Manufacturing” box in Figure 7. The largest material losses occur in the machining step, depending on the final size and shape of the magnet.

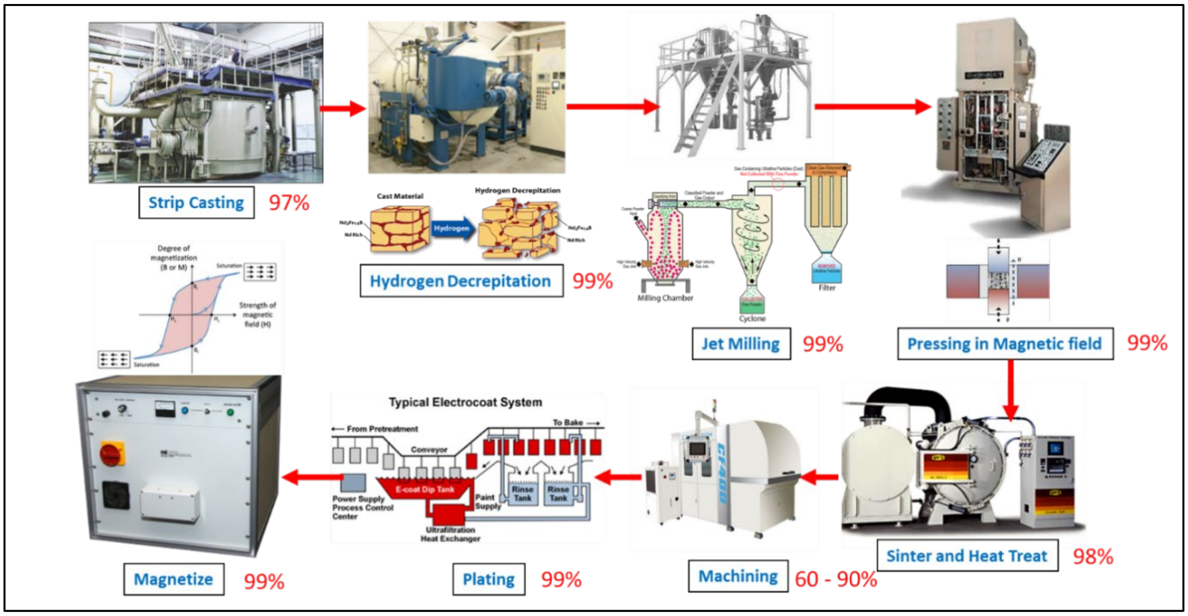

Figure 8. Sintered magnet manufacturing process steps and typical process yields [53]

Sintered NdFeB grades typically range between 35 and 52 mega-gauss-oersteds (MGOe), a measure of their maximum energy product. They are typically referred to as their energy product proceeded by an "N" (e.g., "N35," "N42," etc.) followed by a suffix that denotes their maximum recommended operating temperature. To operate at higher temperatures, some of the Nd/Pr is replaced with HRE (either Dy or Tb). Table 2 shows NdFeB suffix grades with their maximum operating temperature and estimated Dy and Nd/Pr contents. For example, a "N42AH" magnet (or "42AH," for short) would have an energy product of 42 MGOe and a max operating temperature of 220 °C, while an "N52" magnet would have energy product of 52 MGOe and max operating temperature of 80 °C.

Table 2. Maximum operating temperature and associated Dy content of NdFeB magnet grades

Suffix	No suffix	M	H	SH	UH	EH	AH
Max operating temp. (°C) [54]	80	100	120	150	180	200	220
Approx. Dy content (wt. %) [55]	<0.5%	1.4%	2.8%	4.2%	6.5%	8.5% - 11%	8.5% - 11%
Approx. Nd+Pr content (wt. %)[2]	29.5%	28.6%	27.2%	25.8%	24.5%	19% - 21.5%	19% - 21.5%

Manufacturers have made widespread efforts to economize on HREs in NdFeB through better manufacturing processes such as grain boundary diffusion (GBD) and the dual alloy process, which combines NdPr metal with ferro-dysprosium (DyFe). Through these processes, Dy contents for a given grade can be reduced below the levels shown in Table 2.

[2] Author calculation based on assumption of 30% total RE content.

Toyota developed a magnet that did not require HREs, while also reducing the Nd content [56] though it is not currently being used in their HEVs due to lower performance. Other efforts have included strategies such as altering machines to use different grades of magnets with lower HRE content and improving manufacturing efficiency via methods such as near-net-shape manufacturing and waste reduction. [8] However, barriers exist to widespread implementation of efficient manufacturing methods that economize on HREs due to existing patents and intellectual property.

2.2.3.1 Current and Planned Magnet Manufacturing

The major producers of NdFeB magnets, alloys, and powders are China (92%), Japan (7%), Vietnam (1%), Germany (<1%) and a few other countries with relatively limited capacity. [12] Outside of China, major manufacturers of alloys and powders include Hitachi Metals (a Japanese company being purchased by U.S. investment company Bain Capital), Shin-Etsu Chemical (Japan), TDK (Japan), Vacuumschmelze (a German company owned by U.S. private equity firm Apollo) and its subsidiary Neorem (Finland), Neo Performance Materials (Canada), Less Common Metals (UK), and possibly Magneti (Slovenia). [12, 57] Many of these companies manufacture magnets in facilities in other countries. For example, Hitachi, [58] Shin Etsu, [59] TDK, [60] and Vacuumschmelze [61] produce some magnets in China; Shin Etsu produces magnets in Vietnam via Shin Etsu Magnetic Materials Vietnam; and Neo Performance Materials (formerly Magnequench) produces powders for bonded magnets in China and Thailand. Figure 9 shows the geographic concentration of global sintered NdFeB manufacturing in 2020, based on estimates from Adamas Intelligence. [12]

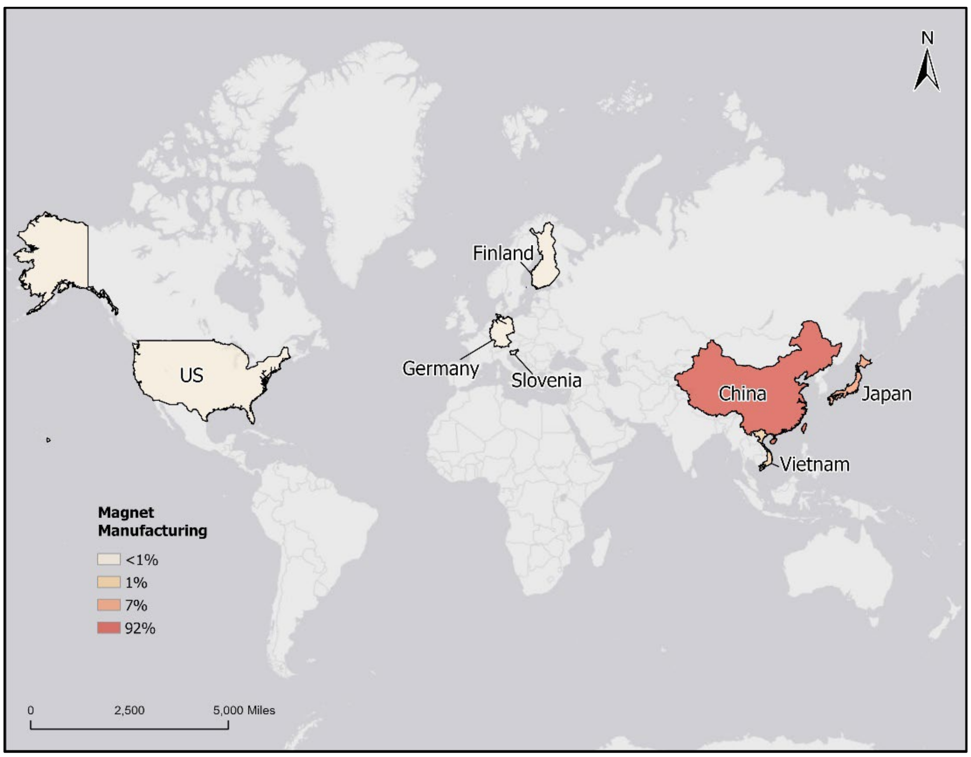

Figure 9. Geographic concentration of sintered NdFeB magnet manufacturing, 2020

The lone domestic producer, Urban Mining Company, manufactures sintered NdFeB magnets from recycled material and has received funding from the DPA Title III program. [45] While their current and planned production level is not publicly available, an article from 2019 states that they were initially targeting

250 tonnes/year at the time, with a plant with capacity of 1000-2000 tonnes/year, and plans to expand production. [62] A company representative stated in 2020 that they handle about 2000 tons/year of NdFeB magnets. [63]

MP Materials recently announced plans to construct a magnet production facility in Fort Worth, Texas, to supply NdFeB magnets to General Motors (GM) for use in its vehicles. The facility would produce 1000 tonnes of NdFeB magnets per year, or about 1% of current worldwide production, with initial production starting in 2023. [64] Vacuumschmelze also announced plans to produce magnets for GM vehicles in the United States, though the planned size of the plant is not yet clear. [65] Quadrant also recently announced plans to begin producing magnets in the U.S., with initial target production capacity of 1,500-2,000 tonnes/year in 2024. [66] USA Rare Earths has also purchased magnet production equipment from a facility in North Carolina originally owned by Hitachi. [67] As with other sections, the companies and projects mentioned in this section do not necessarily represent an exhaustive list.

2.2.4 Major Uses of NdFeB Magnets

2.2.4.1 General Uses

Rare earth magnets have many uses across a broad spectrum of applications, including wind turbines, electric vehicle drives, hard disk drives, cell phones, loudspeakers, industrial motors, non-drivetrain motors in vehicles, power tools, and electric bikes. Many of these products use permanent magnet motors and drives, which are low maintenance and power dense, and have been found to use about 2% less energy than an efficient induction motor in a variable speed application. [5]

As shown in Table 3, consumer electronics and industrial motors make up the largest share of current NdFeB magnet demand, but wind turbine and vehicle demand represent significant and growing segments of the market. Each application requires different magnet grades, shown in Table 4. Vehicle drives operate at high temperatures and therefore require high coercivity magnets, while hard disk drives and loudspeakers require magnets with very little if any Dy as they do not operate at high temperatures. [68]

Table 3. 2020 share of magnets contained in demand for selected NdFeB magnet applications [69]

Application	Percent share of U.S. demand, 2020	Percent share of global demand, 2020
Offshore wind turbines	0	14
Electric vehicles	11	6
Consumer electronics (hard disk drives, cell phones, loudspeakers, other)	45	29
Industrial motors	30	30
Non-drivetrain motors in vehicles	9	8
Other sintered magnets (includes electric bikes)	1	5
Bonded magnets	4	7

Table 4. Maximum operating temperature, associated Dy content, and example applications of NdFeB magnet grades

Grade suffix	Max operating temp. (°C) [54]	Approx. Dy content (wt. %) [55]	Approx. Nd+Pr content (wt. %) [3]	Example spplications
No suffix	80	<0.5%	29.5%	Toys, games, advertising, etc.
M	100	1.4%	28.6%	Hard disk drives, CD/DVD, MRI machines, sensors, refrigeration, etc.
H	120	2.8%	27.2%	Gauges, hysteresis clutch, magnetic separation, etc.
SH	150	4.2%	25.8%	**Wind power generators**, electric bicycles, energy storage systems, magnetic braking, industrial motors, general automotive applications, etc.
UH	180	6.5%	24.5%	Commercial and industrial generators, wave guides, undulators, etc.
EHz/AH	200/220	8.5% - 11%	19% - 21.5%	**Hybrid and electric traction drives**, high temp. motors and generators, etc.

This report focuses on the two types of demand that are part of the Energy Sector Industrial Base: wind turbine and electric vehicle manufacturing. Figure 10 shows the key steps in the wind turbine and electric vehicle manufacturing stages of the supply chain.

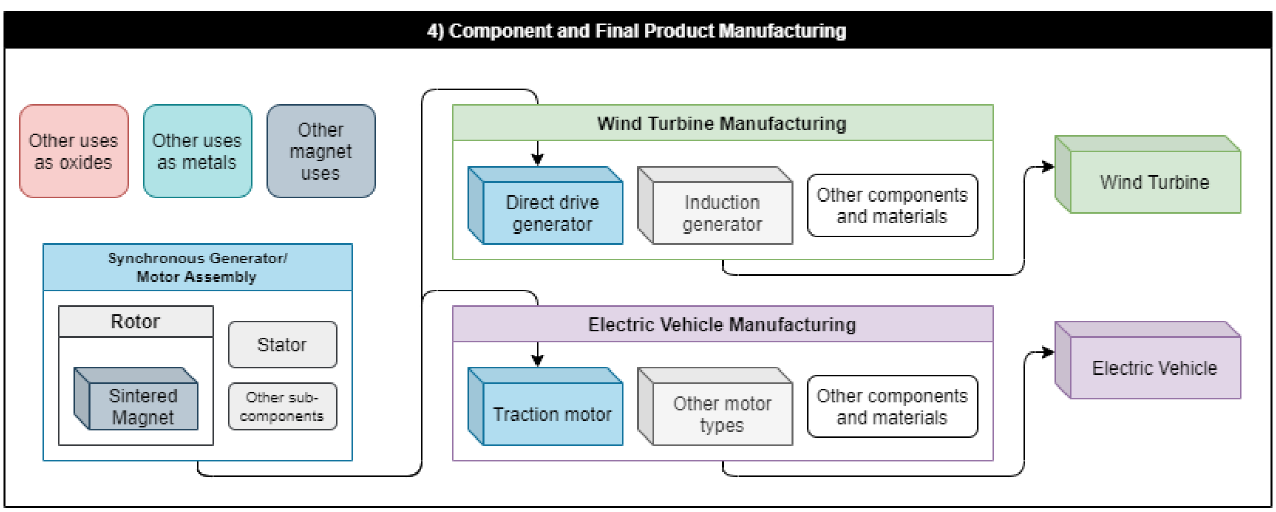

Figure 10. The component and final product manufacturing stage of NdFeB magnet supply chain

[3] Author calculation based on assumption of 30% total RE content.

2.2.4.2 Wind Turbines

Within wind turbines, NdFeB magnets are used in permanent magnet synchronous generators (PMSG), also referred to as direct drive generators. Not all wind turbine systems require rare earth magnets. In fact, the most common generator system, the doubly-fed induction generator (DFIG), is an asynchronous generator with gears that contains no rare earth magnets. Other permanent magnet-free generators include externally excited synchronous generators, squirrel-cage induction generators, and other asynchronous generators. [6]

PMSGs are preferred for offshore wind applications for a variety of reasons, including reduced maintenance costs, overall generator efficiency, and overall generator weight (which allows for the construction of larger, higher-capacity wind turbines). The size of the permanent magnet is typically 2.7-3.2 tonnes per MW of wind turbine capacity. [70] They typically rely on SH grade magnets, though there is some potential to substitute grades depending on the generator design. [8, 55]

2.2.4.3 Electric Vehicles

Within EVs, NdFeB magnets are used in electric synchronous traction motors for propulsion systems in battery and hybrid electric vehicles. As with wind turbines, a variety of other electric propulsion systems are available; however, synchronous motors are preferred as they allow for a lighter and more compact design, higher efficiency (due to the lack of an external power system to produce a magnetic field), and higher torque. [7] It is estimated that between 90% and 100% of battery and hybrid electric vehicles will have synchronous traction motors with NdFeB magnets by 2025. [71] Each electric vehicle motor typically requires 1-2 kg of permanent magnet material. [72] In general, traction drive motors operate at high temperatures and require EH and AH grade magnets. [55]

NdFeB magnets also have other general uses in automotive applications outside of EV motors in uses such as audio speakers, electronic sensors, transmissions, and power steering. These applications require relatively small amounts of magnets, however, and demand is negligible compared to use in traction motors. [7]

2.2.5 Recycling

The majority of the rare earth recycling that occurs today is of swarf, the residue from cutting magnets during magnet manufacturing. [12] Recycling of end-of-life magnets into new magnets or separated rare earth elements currently is done only at a small scale, but a variety of different methods have been developed that show promise for expanded use in the future. The type and complexity of recycling process for rare earth magnets will depend on the composition, the target products, whether it is sintered or resin bonded, and the type of protective coating. In general, the recycling process for magnet-containing end-of-life products occurs in two steps: the magnet recovery step (where magnets are separated from the products they are inside of) and the rare earth recovery step (where rare earth elements are separated from the rest of the magnet). The supply chain steps are shown in Figure 11.

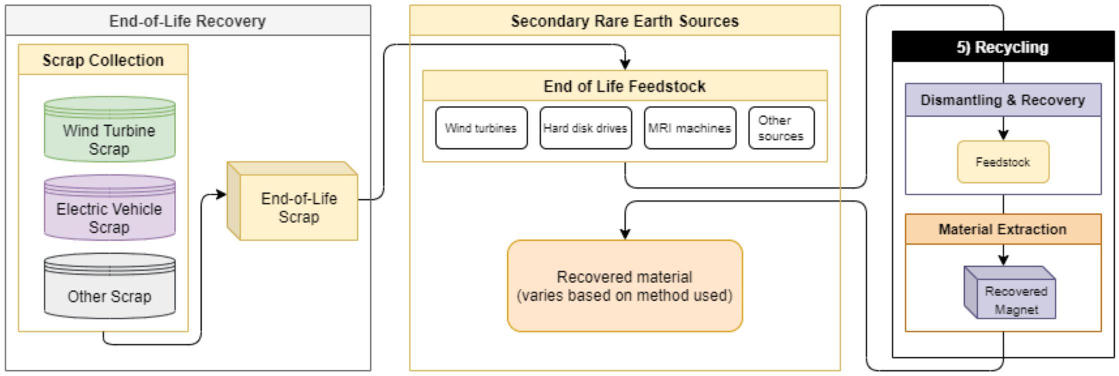

Figure 11. Magnet recycling stage of NdFeB magnet supply chain

2.2.5.1 Magnet Recovery

Figure 12 illustrates a typical approach for recovering magnets from end-of-life products. The primary steps include dismantling,[73-75] sorting (which can be manual or automated[76] to separate the magnet component from the rest of the materials), demagnetization, and recovery for the magnet scrap, accompanied by a parallel physico-mechanical process to recover and separate other materials and components. Alternatively, the product can be crushed or shredded, followed by a combination of separation steps, such as magnetic and electrostatic separation, screening, surface abrasion, and chemical etching to remove protective film. The downside of this approach is the potential for entrainment and chemical corrosion of the underlying magnet.[77-79] Hydrogenation processes use hydrogen at atmospheric pressure to split the NdFeB magnet into a demagnetized powdered alloy form that can be re-formed into a magnet via sintering or resin bonding after eliminating the hydrogen.[80] Direct plasma heating can also recover the magnet material.[81] This approach is flexible and can easily handling coatings and adhesives, making it suitable for both sintered and bonded magnets, although the recycled product has lower magnetic properties.

2.2.5.2 Rare Earth Recovery

Once the magnet material is liberated, the individual rare earths and metals can be recovered via three primary routes: hydrometallurgical, pyrometallurgical, and direct electrochemical. In practice, the recovery process generally involves some combination of the different pathways. These pathways are similar to what obtains in the primary extraction and recovery, except that recycling is generally less complex because of fewer species and order of magnitude higher starting concentrations.

Hydrometallurgy is widely used in primary processing of REs and is suitable for recycling. As shown in Figure 12, the first step in hydrometallurgy is acid leaching to dissolve the magnet or feed materials into an aqueous solution, followed by separation via direct selective (fractional) precipitation, or via solvent-based techniques like liquid-liquid extraction and ion-exchange, followed by selective precipitation.[82-84] In general, the hydrometallurgical process yields RE salts or oxides, which can be delivered as is, or electrowon to create RE alloys. Some processes use a sulfuric acid baking process to convert the RE to a sulfate form.

Pyrometallurgy is a core pathway for primary RE processing, and is equally suitable for magnet material recycling. This basic working mechanism is to use elevated temperatures to selectively transition and concentrate the REs in the magnet into a different phase for easy separation from non-rare earth components.[78] Pyrometallurgical routes for RE recovery can be broadly classified into roasting and melt processing.[78, 80, 85] Roasting creates a product that facilitates selective downstream separation.[78] In melt processing, the rare earths are selectively extracted from the magnet scrap using either molten metal, molten salt, or molten oxide slag.[86-88]

The **electrochemical** recovery route is an emerging technology for material recovery from magnetic scrap. Explored options include molten salt electrolysis process,[78,80] selective electrochemical leaching,[89,90] and in situ electrochemical oxidation combined with precipitation.[89,91]

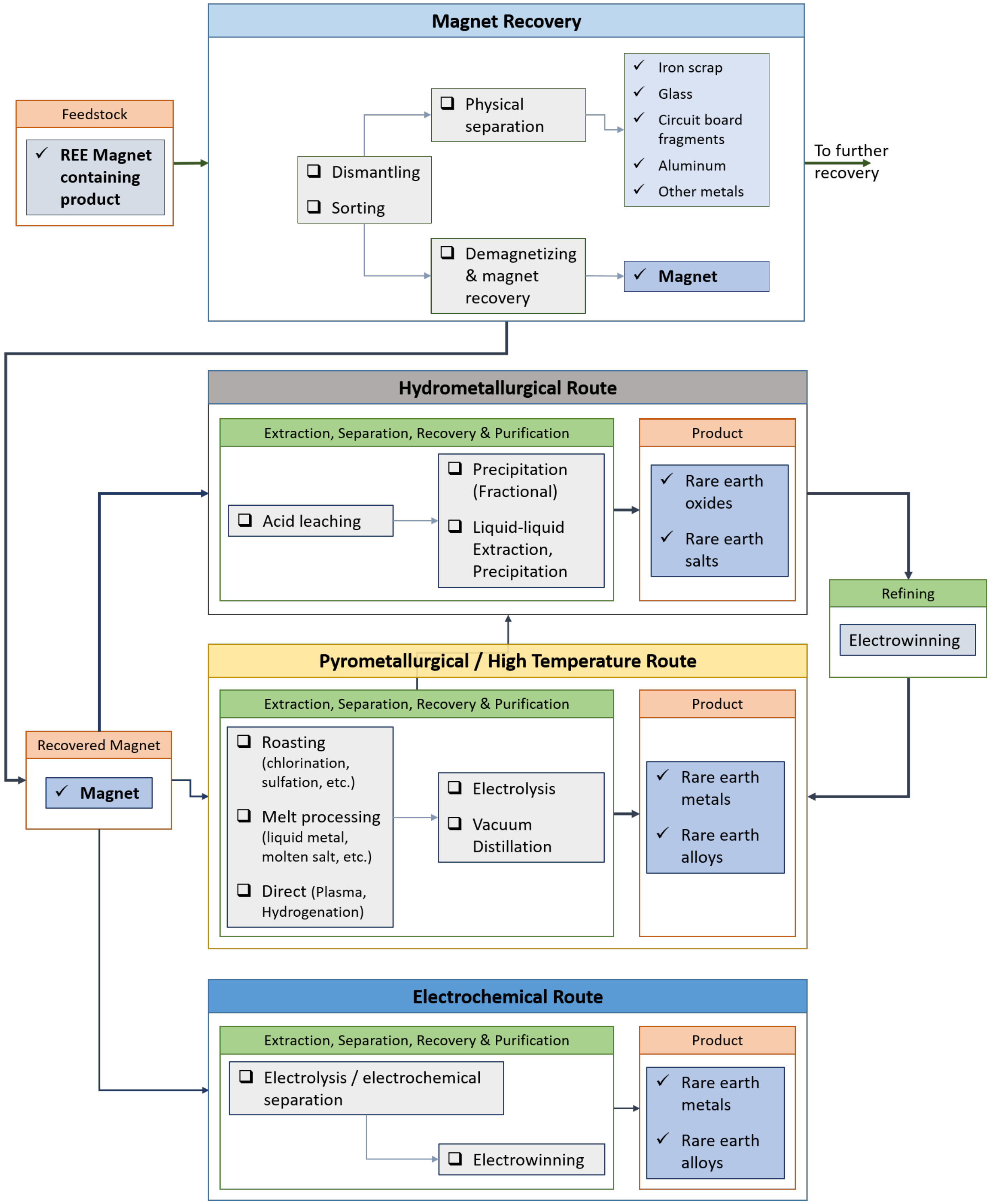

Figure 12. Representative magnet recycling pathways

2.2.5.3 Swarf Recycling

As shown in Figure 8, material losses are associated with the magnet manufacturing process. This material is usually recycled at the point of generation. [78] Magnet cuttings or swarf are generated at the point of production, where the machining used to shape the magnet generates solid wastes. These can contain some machine cutting fluids and magnetic powder (the cutting is performed before magnetization). They can be recycled internally by acid digestion and separation of the iron and boron from the REs. There are several chemical compositions used in magnet production and chemical separation can be used. This reports as a yield loss in magnet production.

The volume of the swarf recycling stream in 2020 is estimated as 9% of the NdFeB magnets produced globally. [12] Swarf recycling is generally performed near the magnet production facilities where it is generated, so the geographic distribution of magnet swarf recycling is similar to the geographic distribution of magnet production. [12]

2.2.5.4 Current and Planned End-of-life Magnet Recycling

Limited information is available about the geographic distribution of end-of-life magnet recycling, as it is a nascent market that has not been well studied. Only small quantities of end-of-life magnets are recycled anywhere in the world, including in China. One of the few companies actively recycling end-of-life magnets is Urban Mining Company in San Marcos, Texas, which uses a hydrogenation process to directly manufacture new magnets from recycled products. The company has received $28 million from the DPA Title III program. [63] As discussed in section 2.2.3.1, while current production from the company is not publicly available, an article from 2019 stated that they were initially targeting 250 tonnes/year at the time, with a plant with capacity of 1000-2000 tonnes/year and plans to expand production. [62] A company representative stated in 2020 that they handle about 2000 tons/year of NdFeB magnets. [63] HyProMag in the UK has also developed a recycling process using a similar method. [92] The advantage of this method is that it can break up magnets while still in place, and it does not use acids to dissolve the magnet. Rare Resource Recycling Inc. received small business innovation research (SBIR) phases I and II funding in 2015 and 2017, totaling about $900,000 to scale their magnet recycling process based on metal-organic frameworks, but discontinued operations in 2021. [93] In 2016 Momentum Technologies licensed a technology for automated dismantling, sorting, and magnet recovery from end-of-life products developed at Oak Ridge National Laboratory and are currently now applying their technology to lithium- ion battery recycling. [94, 95] DOE's Advanced Manufacturing Office also announced Phase II SBIR funding to Pioneer Astronautics, a Colorado-based company using green chemistry to recycle Dy from magnets, and Small Business Technology Transfer (STTR) Phase II funding to TdVib, L.L.C., an Iowa-based company developing non-toxic rare earth element recycling techniques. [96]

American Resources Corporation (U.S.) plans to separate rare earths from recycled magnets. [97] Established magnet production companies such as Hitachi have also developed recycling capabilities, [75] but it is not clear if they are conducting recycling operations. DOE's Critical Materials Institute (CMI) also performs research on magnet recycling, including the recovery of magnet materials from used hard drives. [98] As with other sections of this report, the companies and processes in this section do not necessarily provide an exhaustive list of current efforts.

3 Supply Chain Risk Assessment

This section reviews several supply risk and resilience factors in order to identify and assess current vulnerabilities in the rare earth magnet supply chain in the United States. It begins with an overview of some important factors, assesses each supply chain stage for its domestic resilience and competitiveness within the United States, and highlights potential opportunities for improving supply chain resilience. The principal observations from this assessment include Chinese dominance, limited production capacity among U.S. economic allies, and a corresponding lack of domestic U.S. capacity in each of the key supply chain stages. The United States currently has limited domestic production capacity for the sintered neodymium magnets used in many critical technologies including wind turbines and electric vehicles, while China dominates all of the major stages in the supply chain. This includes rare earth mining, separation and processing of individual rare earth oxides, metal refining, and magnet production. Even more significantly, this concentration of production in China increases at every downstream stage, rising from a 58% share of annual global rare earth mining in 2020 to a 92% share of annual global magnet production, the stage with the highest added value. Therefore, establishing a resilient domestic magnet manufacturing industry will require restoring U.S. competitiveness in multiple stages of the supply chain.

3.1 Risk Factors

Supply chain risk is one of the key components of material criticality. [99] While focusing primarily on the riskiness of raw materials supply chains, these metrics can also be extended to downstream stages of supply chains. Common metrics cited by material criticality in assessments of supply risk include [72, 100, 101]

- Market and geographical concentration of production.
- Geopolitical sensitivity of supply.
- Net import reliance.
- Number of domestic suppliers and capacity.
- Demand growth rate.
- Price/market volatility.
- Substitutability of materials and technologies.
- Competing demand.
- Environmental and workplace safety compliance/conditions.

Market concentration refers to the extent to which an industry or supply chain segment is controlled by a small number of firms or countries. Highly concentrated industries are those where a single (or a few) actor(s) may directly affect market outcomes, such as by restricting supply to raise prices, or by oversupplying the market to lower prices below a profitable level for competitors. Such markets are not competitive. Market concentration can be measured both at the firm and country level by metrics such as the concentration ratio (CR), a measure of the share of production of the top firms in an industry, or the Herfindahl-Hirschman Index (HHI), the sum of shares raised to the second power of all firms in an industry.

Geopolitical sensitivity of supply refers to the strength of a producing nation's relationship with the United States, political stability, strength of institutions, labor rights issues, and other factors that may determine the stability of supply coming from a given country. Countries with geopolitical sensitivities may be those with an acrimonious relationship with the United States, political rivals, or simply nations with unsafe or unstable working conditions for laborers. Geopolitical sensitivity increases the risk of a potential supply disruption, particularly when coupled with high market concentration.

Net import reliance refers the dependence of a country on imports of a good to meet domestic consumption. [102, 103] It is measured by the share of total apparent consumption that is provided by imports, with higher values indicating more dependence on imported goods. While a high net import reliance does not in itself imply a higher supply chain risk, it may imply more risk if trade partners are also associated with high market concentration and geopolitical sensitivity.

Similarly, **the number of domestic suppliers and domestic capacity** is correlated with the risk from the risk factors mentioned above. A larger number of domestic suppliers could make the domestic industry more resilient to disruptions and firms less susceptible to downturns in the business cycle. Similarly, more domestic capacity implies a lower net import reliance, and a lower chance that a supply chain is concentrated in geopolitically sensitive regions. Conversely, if a large share of domestic capacity is controlled by a single firm, then that firm can impose barriers to entry for new firms. It may also mean the domestic supply chain is less resilient in the case of a market downturn where the firm must cease operations.

Demand growth rate refers to the rate at which global demand for a good is expected to grow over time. Demand growth for materials and intermediate products depends not only on the demand for final products, but also on the substitution choices of suppliers further downstream on the supply chain. Rapid demand growth may imply additional supply chain risk, as production capacity may fall behind demand if the growth is not fully anticipated soon enough for new capacity to be built.

Price and market volatility describes fluctuations in the price and supply/demand balance of a commodity. High volatility increases the cost and riskiness of doing business, as low prices may disincentivize new investments or make production unprofitable for producers, while high prices may make producers operating on the margin unprofitable. For example, if the costs of raw materials make up a significant share of the total cost of a product, significant increases in the cost of raw materials could make production of the product unprofitable. Price volatility is highly correlated with the measures discussed above.

Substitutability refers to the ability of firms and individuals to alter their production and consumption patterns in response to price changes or other market shocks. [104] With regard to supply chains, substitution possibilities apply broadly throughout different stages in the supply chain. For example, substitutions can occur between raw materials, components, or even end uses. [8, 105] A lack of substitutability is detrimental to resilience, whereas a material or technology with many available substitutes is likely to be more resilient.

Competing demand refers to demand from other sources for a necessary intermediate product that inhibits the ability of a sector to procure the desired amount of the product at a cost-effective price, if it is available at all. If there is greater competing demand for a commodity or product, then there is more supply risk associated with its use in the manufacturing of a specific good. In theory, the use with the higher willingness (or ability) to pay (based on a variety of economic factors) would crowd out the ability of uses with a lower willingness to pay to procure the product. Similarly, uses that represent a small portion of demand may face greater risk from competing demand.

Environmental compliance and workplace safety conditions refer to potential environmental damage and occupational safety and health practices that could result in unsteady supply. For example, producers that have a poor record of adherence to environmental policies have a greater likelihood of being shut down or penalized with fees (increasing costs), and those with poor safety records may face labor shortages or boycotts.

Each of these factors, as well as several others, play a role in determining the supply risk at each stage of a supply chain. The information and indicators discussed in this section were used to qualitatively assess the NdFeB supply chain for various questions related to developing a domestic supply chain. See Table A1 in Appendix B for a summary of key these key factors across the stages of the supply chain.

3.2 Current U.S. Risk Factors and Resilience

3.2.1 Assessment of risk factors

3.2.1.1 Market Concentration

The current U.S. supply chain for NdFeB magnets for use in wind turbines and electric vehicles is improving but is not sufficiently robust to supply chain disruptions. China accounted for nearly 60 percent of total RE mining production in 2020, representing a significant decrease compared to 2012, when it controlled over 90 percent of global production. [14, 106] While the mine production of RE elements has diversified since 2012, China still accounts for an estimated 89 percent of total RE separation capacity, an estimated 90 percent of total metal refining capacity, and approximately 92 percent of global sintered NdFeB magnet manufacturing. The United States, by comparison, accounted for about 16 percent of total RE mine production in 2020 (up from less than 1 percent in 2012), but still is not separating rare earths or refining them into metals, and produces less than 1% of the world's NdFeB magnets, although there are plans to add domestic capacity in each of these areas. Table 5 and Figure 13 show the geographical market concentration of the main supply chain steps for sintered NdFeB magnets by country.

One way of measuring the level of geographic concentration of production is the Herfindahl–Hirschman index (HHI), which ranges from a value near zero if there are a large number of countries producing equal amounts of a product, to 10,000 if all production is done in the same country. Table 6 shows the HHI at each stage of the supply chain using the shares from Table 5. The value increases from 3826 to 8514 as the supply chain stage progresses from mining to magnet production.

In addition to the amount of concentration, it is also useful to assess the geopolitical sensitivity of the countries where production takes place. Table 6 shows the weighted average of the World Bank's Regulatory Quality Indicator ranking for producing countries at different stages of the supply chain, weighted by the amount of production. [107] The index ranking ranges from 1 for the lowest regulatory quality to 99 for the highest. The weighted average value is the highest for mining and the lowest for metal refining. Index ranking ranges from 1 for the lowest regulatory quality to 99 for the highest. The weighted average value is the highest for mining and the lowest for metal refining.

In addition to the geographic concentration of production, a relatively small number of individual firms operate at most stages of the supply chain. Even at the mining stage, where there is the least geographic concentration, two firms, Lynas and MP Materials make up a large share of production outside of China and Burma. This concentration may make the supply chain less resilient to disruptions should one of them cease to exist. Meanwhile, China has pursued a policy of consolidating production into a small number of state-owned companies, which may serve to further increase pricing power. Three of the six companies currently holding rare earth production quotas in the process of being consolidated, [108] leaving just four rare earth producers in China, with possible plans to eventually consolidate into two large companies, one in the north and one in the south. [109] The southern company would likely control nearly all production of HREs in the country. An unknown amount of Chinese production is also done illegally, so that it is not subject to Chinese production quotas or efforts to consolidate. [110]

Table 5. Geographical concentration of production for various supply chain steps for sintered NdFeB magnets, 2020

Country	Mining[4]	Separation[5]	Metal refining[6]	Magnet alloy manufacturing[7]
China	58%	89%	90%	92%
U.S.A.	16%	-	-	<1%
Burma	12%	-	-	-
Australia	7%	-	-	-
Madagascar	3%		-	-
India	1%	1%	-	-
Russia	1%	-	-	-
Thailand	1%	-	~3%	-[8]
Malaysia	-	7%	-	-
Estonia	-	1%	~2%	-
Japan	-	-	-	7%
Vietnam	-	-	~3%	1%
Laos	-	-	~2%	-
Germany	-	-	-	<1%
Slovenia	-	-	-	<1%
Finland	--	-	-	<1%
U.K.	-	-	<1%	-
Other countries	1%	2%	<1%	<1%

[4] See Gambogi (2021) for estimated 2020 rare earth mine output by country [14]
[5] Calculated based on current understanding of where concentrate from specific producers is separated (for example, output from Lynas' Mount Weld mine in Australia is separated at its LAMP facility in Malaysia and HREs mined in Burma are transported to China for further processing).
[6] Current hypothesis based on expert consultation.
[7] Adamas Intelligence [12]
[8] For 2019, Thailand accounted for ~8% of bonded NdFeB powders. [12] Neo Magnequench (subsidiary of Neo Performance Materials) manufactures bonded magnetic powders at their facility in Korat, Thailand.

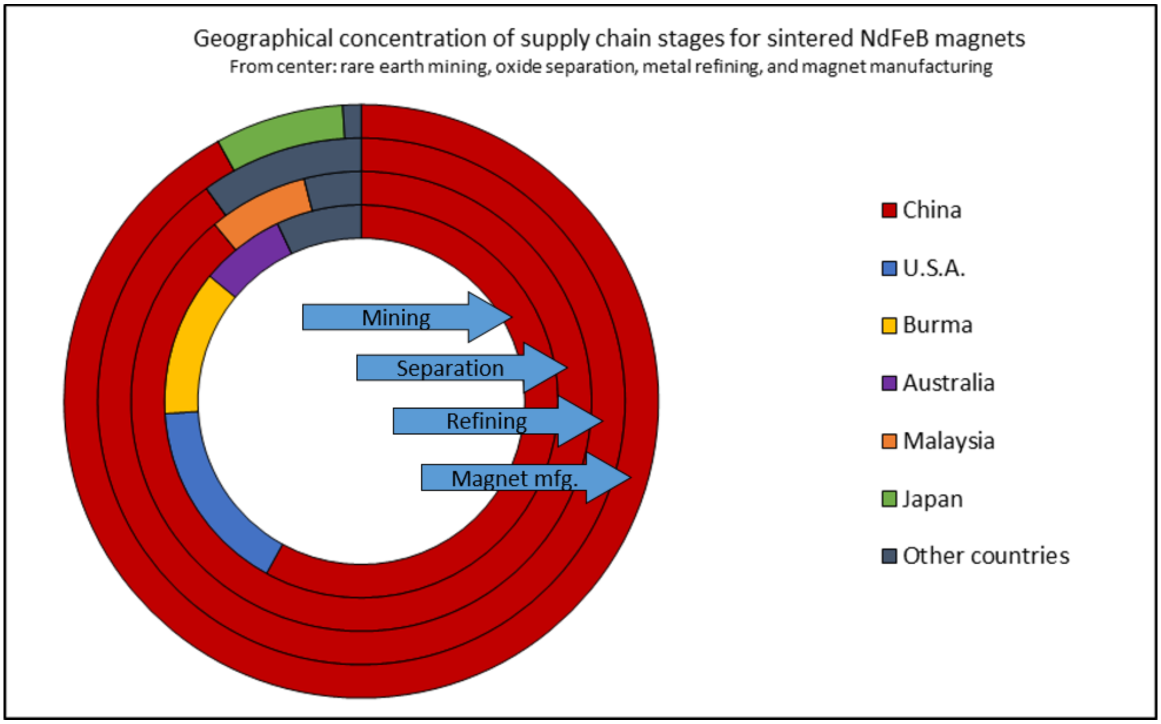

Figure 13. Geographical concentration of supply chain stages for sintered NdFeB magnets, 2019

Table 6. Market concentration and geopolitical sensitivity

	Mining	Separation	Metal Refining	Magnet Mfg.
HHI – country concentration of operating mining or manufacturing facilities (Monopoly = 10,000)	3826	7976	8200	8514
Geopolitical sensitivity (based on weighted avg. World Bank Regulatory Quality index; highest = 99.0, lowest = 1.0)	64.04	51.12	45.00	47.58

14

3.2.1.1.1 Vertical Integration

Vertical integration across stages of a supply chain may be able to help with a firm's competitiveness by making it less reliant on other companies for demand and material supply. On the other hand, a market dominated by vertically integrated companies may be less flexible than separate companies at each stage of the supply chain, and it may be more difficult for new entrants to be able to acquire intermediate products.

China has a significant amount of vertical integration: rare earths from the Bayan Obo mine in Inner Mongolia are separated, refined, and used to manufacture automotive magnets not far from the mine. Shenghe Resources mines, separates rare earth oxides, and produces rare earth metals and alloys. [111]

Outside of China, mining and initial processing facilities are normally co-located and -owned, though the level of processing done at that stage may vary. Separation facilities can be vertically integrated with mines or independent separation facilities can exist, though the processing needed to separate rare earths may vary depending on the source material. For example, Lynas owns the Mount Weld mine and processing facility in Australia and the Lynas Advanced Materials Plant in Malaysia for separating the concentrates into Nd/Pr oxides and other separated REs. [112] MP Materials owns the Mountain Pass mine, but currently sends a rare earth concentrate to China to be separated. MP Materials has plans to become more vertically integrated with their expected re-opening of separation facilities and planned expansion into metal refining and magnet production. [10]

3.2.1.2 Domestic Suppliers and Capacity

As discussed in Section 2, the United States currently has limited manufacturing capability throughout the supply chain. Recently some improvements in diversity of supply have taken place, particularly at the mining stage, and new projects under development could further improve this diversity. Several U.S. companies have limited current production, but have expertise and potential to expand. In addition, a number of projects are under development that could improve U.S. resilience. However, there is no guarantee that these new projects will reach completion without further support. This is one of the reasons that the DOC has evoked a Section 232 Trade Investigation on NdFeB magnets.

Table 7 lists major ongoing domestic projects, which vary in their size and level of advancement. Projects that have funding secured or have a specific agreement with the U.S. government or with a buyer are listed as “planned”, while potential projects that have not yet demonstrated publicly that they have risen to this level are listed as “reported”.

Table 7. Current and prospective U.S. domestic projects related to NdFeB magnets

Company/ Project	Location	HQ	Mining	Concen -tration	Sepa- ration	Metal refining	Magnet mfg.	Recycling/ Unconven- tional
MP Materials (Mountain Pass) [10, 38, 64]	Mountain Pass, CA	Las Vegas, NV	Current	Current	Planned	Reported	Planned	Reported
Southern Ionic Minerals (Chemours) [18]	Offerman, GA	Wilmington, DE	Current	-	-	-	-	-
Rare Element Resources (Bear Lodge) [49]	Bear Lodge, WY	Vancouver, BC	Planned	-	-	-	-	-
USA Rare Earths (Round Top) [24, 48, 67]	Sierra Blanca, TX	Tampa, FL	Reported	Reported	Reported	-	Reported	Reported
Energy Fuels [11, 18]	White Mesa, UT	Lakewood, CO	-	Current	Reported	Reported	-	-
General Atomics [49]	WY	San Diego, CA	-	Planned	Planned	-	-	-
Phoenix Tailings [39]	Unclear	Woburn, MA	-	Reported	Reported	Reported	-	Reported
Lynas USA / Blue Line [46, 47]	Hondo, TX	San Antonio, TX	-	-	Planned	-	-	-
Urban Mining Co. [63]	San Marcos, TX	San Marcos, TX	-	-	-	-	Current	Current
Vacuumschmelze [65]	Unclear	Hanau, Germany	-	-	-	-	Planned	-
Quadrant [66]	Louisville, KY	San Diego, CA	-	-	-	-	Reported	-

Taken together, these projects could help fill some important gaps in U.S. supply chains for rare earth magnets and magnet materials. At the rare earth mining and separation stage, projects underway could increase the U.S. role in world markets and help fill some (but not all) of the gap in world supply needed to meet projected demand growth. The production of HREs is being pursued, but at less advanced stages of development. Less progress has been made on the metal refining and alloy and magnet production stages of the supply chain, with most projects underway either small-scale or in earlier stages of development.

3.2.1.3 Demand Growth Rate

Rapid demand growth in EV and offshore wind turbine demand could lead to additional challenges, as shortages could be faced if supply doesn't increase fast enough to meet this demand. This report assesses potential rare earth magnet demand growth under scenarios aimed at achieving net zero carbon emissions by 2050.

This analysis assumes that the major uses of RE magnets in the ESIB primarily consists of use by direct drive wind turbines and traction motors in EVs and that other uses grow at rates that follow expected GDP growth. Direct-drive generators that use NdFeB magnets are assumed to be primarily used in offshore wind turbines, and all offshore wind turbines are assumed to use direct-drive generators, and thus demand for magnets in turbines is driven by demand for offshore wind turbines. Further, this analysis assumes that demand growth for offshore wind energy is consistent with the projections estimated by Lantz et al.[70] that conceptualize a path forward for wind energy through 2050 under the assumption that the United States has 30GW of installed offshore wind power capacity by 2030. Lantz et. al. estimate that offshore wind capacity in the United States could vary between 77GW and 255GW by 2050 if the 2030 target is reached, with approximately 110GW available if continued growth is consistent with the 30GW by 2030 scenario. This scenario represents an increase in cumulative demand for permanent magnets to nearly 81,000 tonnes by 2030 and 337,000 tonnes by 2050. Global offshore wind turbine demand is estimated to be consistent with International Energy Agency's (IEA) Net Zero by 2050 report. [113] Magnet use per megawatt (MW) of wind turbine production of 2.7 tonnes/MW in 2030 and 3.2 tonnes/MW in 2050 from Lantz et al.[70] is used to estimate permanent magnet requirements.

The portion of new U.S. vehicle sales that are EVs, including battery and fuel cell EVs, are assumed to follow Larson et al.'s E+ scenario with rapid electrification of transportation, [114] while global EV shares of new sales are assumed to follow IEA's Net Zero by 2050 report. The projected total number of sales of different sizes of vehicles is taken from Argonne National Laboratory's VISION model, and total global vehicle sales are estimated based on the U.S. Energy Information Administration (EIA)'s projections of the size of the global vehicle fleet. [115, 116] Approximately 90% of battery and fuel cell EVs are assumed to use traction drive motors that require permanent magnets, [117] and this analysis assumes that they will continue to do so through 2050. Average magnet weight per vehicle is assumed to be in the middle of the range from DOE's 2011 Critical Materials Strategy. [72]

Projected demands through 2030 for magnets in products that are not part of the Energy Sector Industrial Base (ESIB) are taken from Argonne National Laboratory's Global Critical Materials (GCMat) model, which compiles data from a variety of sources (see Riddle et al. [69] for documentation of these sources). Demand growth from 2030 through 2050 for these products is assumed to follow projected GDP growth. The key sources for these demand growth assumptions are summarized in Table 8.

Table 8. 2020 sources for demand growth estimates for selected NdFeB magnet applications

Application	Part of Energy Sector Industrial Base?	U.S. demand growth, 2020-2030	U.S. demand growth, 2030-2050	Global demand growth, 2020-2030	Global demand growth, 2030-2050
Offshore wind turbines	Yes	Lantz et al.[70]	Lantz et al.[70]	IEA [113]	IEA [113]
Electric vehicles	Yes	Larson et al.[114]	Larson et al.[114]	IEA [113]	IEA [113]
All other uses	No	Sources documented in Riddle et al.[69]	GDP growth	Sources documented in Riddle et al.[69]	GDP growth

Table 9 and Figure 14 show the results for global growth; Table 10 and Figure 15 show anticipated domestic growth. Total global demand growth for magnets could be rapid in the net zero by 2050 scenarios, with average annual growth rates calculated to be 12.5 percent through 2030 and 6.3 percent through 2050. Domestic demand for products containing permanent magnets is estimated to grow somewhat less rapidly, with 8.7 percent average annual growth rate through 2030 and 5.0 percent through 2050. Significant growth in magnet manufacturing would be needed to meet this demand. Since the majority of Nd, Pr, and Dy are used in permanent magnets, significant growth in production of those rare earth materials would also be needed.

Table 9. Expected magnets contained in global demand for selected NdFeB magnet applications, thousands of tonnes (kt)

Application	Part of Energy Sector Industrial Base??	Demand in 2020		Projected Demand in 2030 (high growth)		Projected demand in 2050 (high growth)	
		Amount (kt)	Share	Amount (kt)	Share	Amount (kt)	Share
Offshore wind turbines	Yes	16.9	14.2%	139.2	36.0%	273.7	36.3%
Electric vehicles	Yes	7.3	6.1%	114.1	29.5%	266	35.3%
Consumer electronics (hard disk drives, cell phones, loudspeakers, other)	No	35.1	29.4%	41	10.6%	65.4	8.7%
Industrial motors	No	36.0	30.2%	53.7	13.9%	85.7	11.4%
Non-drivetrain motors in vehicles	No	9.4	7.9%	18.3	4.7%	29.3	3.9%
Other sintered magnets (power tools, electric bikes)	No	6.5	5.5%	9.6	2.5%	15.3	2.0%
Bonded magnets	No	8.0	6.7%	11.1	2.9%	17.7	2.3%
Total	-	119.2	100.0%	387	100.0%	753.2	100.0%

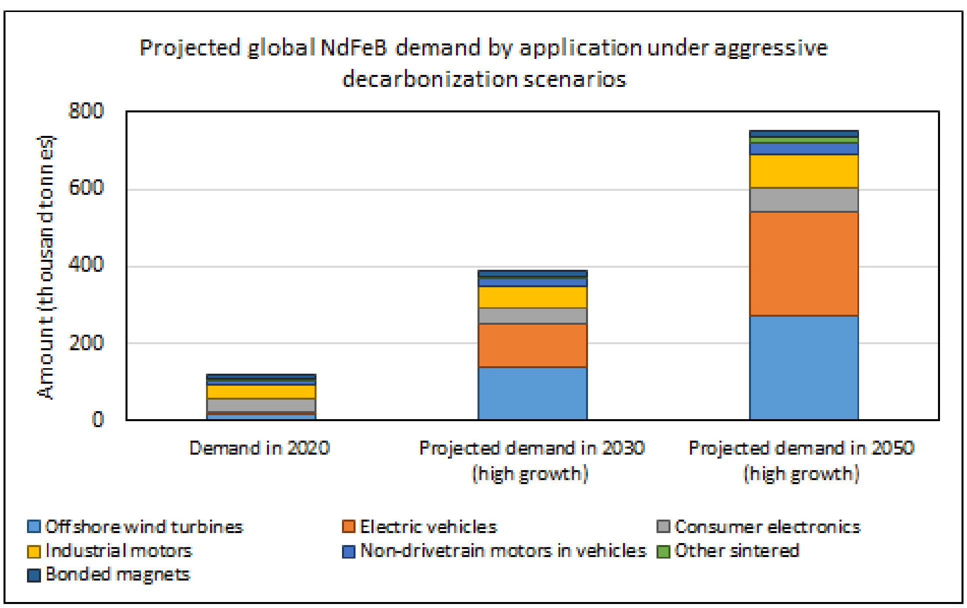

Figure 15. Projected global NdFeB demand by application under aggressive decarbonization scenarios

Table 10. Expected magnets contained in U.S. demand for selected NdFeB magnet applications, thousands of tonnes (kt)

Application	Part of Energy Sector Industrial Base?	Demand in 2020		Projected Demand in 2030 (high growth)		Projected demand in 2050 (high growth)	
		Amount (kt)	Share	Amount (kt)	Share	Amount (kt)	Share
Offshore wind turbines	Yes	0	0.0%	10.1	27.3%	19	27.7%
Electric vehicles	Yes	1.8	11.2%	10.2	27.6%	23.1	33.7%
Consumer electronics (hard disk drives, cell phones, loudspeakers, other)	No	7.2	44.7%	7.4	20.0%	11.8	17.2%
Industrial motors	No	4.9	30.4%	5.9	15.9%	9.5	13.8%
Non-drivetrain motors in vehicles	No	1.5	9.3%	2.4	6.5%	3.9	5.7%
Other sintered magnets (power tools, electric bikes)	No	0.1	0.6%	0.1	0.3%	0.2	0.3%
Bonded magnets	No	0.6	3.7%	0.8	2.2%	1.3	1.9%
Total	-	16.1	100.0%	37	100.0%	68.6	100.0%

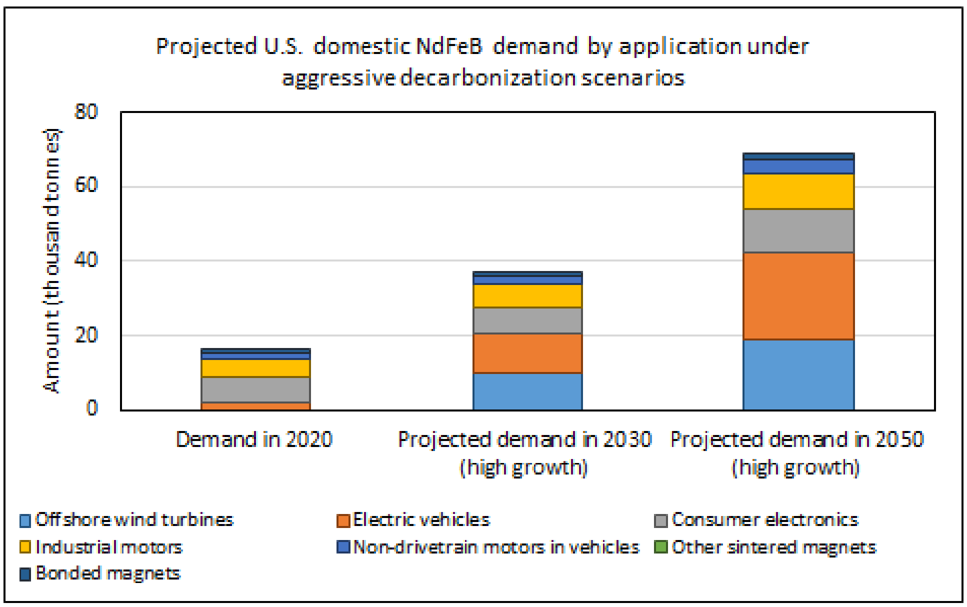

Figure 16. Projected U.S. domestic NdFeB demand by application under aggressive decarbonization scenarios

Based on the typical magnet grades by end use and their associated material contents (as shown in Table 2 in Section 2), demand for Dy is expected to grow more rapidly in these aggressive decarbonization scenarios than demand for Nd and Pr. Domestic embedded Nd and Pr demand (that is, the Nd and Pr needed to meet domestic demand for magnet-containing products) is estimated to grow by 114 percent by 2030 and 293 percent by 2050 (relative to 2020 demand), while domestic embedded Dy demand is estimated to grow by 243 percent and 594 percent, respectively. This represents domestic embedded demand of 9.2kt for Nd and Pr by 2030 (up from 4.3kt in 2020) and of 1.9kt for Dy (up from 0.6kt). Figure 16 shows the estimated relative growth in global demand for the materials between 2020 and 2050 under the high growth scenario. Note that this analysis is based on simple calculation assuming current technology with no substitution, and does not consider the impact of prices or availability on technology deployment.

Based on the same calculations, the United States will also demand a relatively smaller share of global embedded demand for Nd, Pr, and Dy in both 2030 and 2050 relative to 2020. While U.S. and global demand are expected to grow, because U.S. demand for magnets is expected to grow at a slightly slower rate, the United States is expected to account for approximately 9.5 percent of global demand for Nd, Pr, and Dy by 2030, relative to 13.5 percent in 2020. Figure 17 shows how U.S. embedded demand is expected to grow relative to global demand.

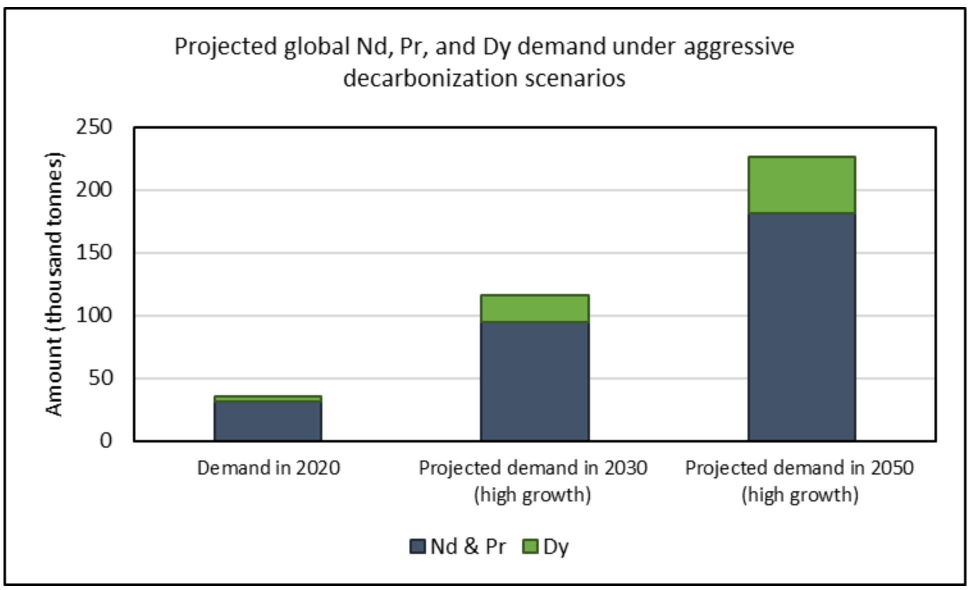

Figure 17. Projected global embedded Nd, Pr, and Dy in magnet demand under aggressive decarbonization scenarios

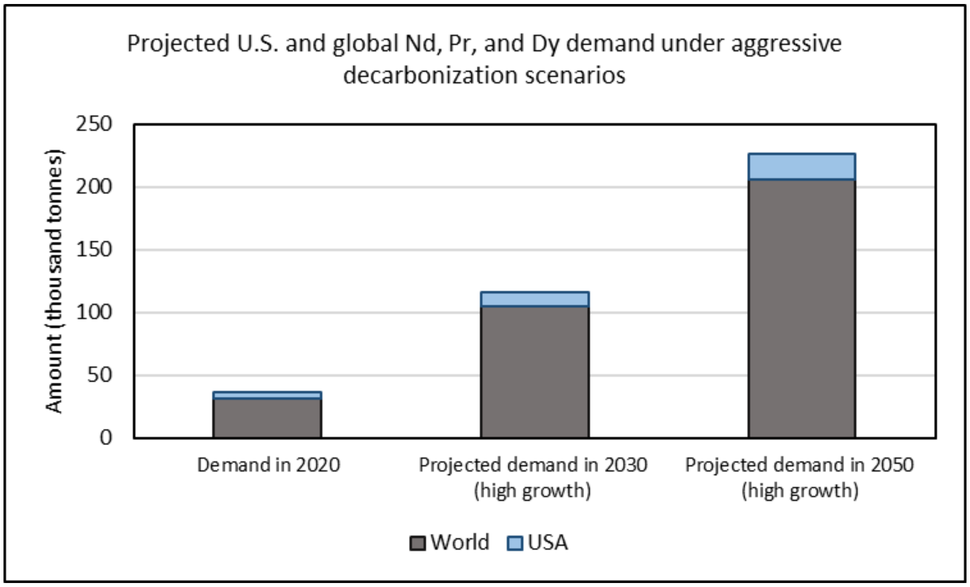

Figure 18. Projected U.S. and global embedded Nd, Pr, and Dy in magnet demand under aggressive decarbonization scenarios

3.2.1.4 Price and Market Volatility

Rare earth oxide and metal prices showed high volatility from 2010 through 2012, as NdPr oxide prices rose to more than 11 times January 2010 levels, and Dy oxide prices increased to more than 18 times January 2010 levels and then fell back down significantly. Since the beginning of 2020, NdPr oxide prices have again risen by 243%, and Dy oxide prices by 88%. However, between those periods, prices were relatively stable, without large month-to-month swings in price. Table 11 shows price volatility measures for Nd, Pr, Dy and Tb oxides, calculated by using prices from Argus Metal Pages. [118] Price volatility is calculated as the standard deviation of changes in the natural log of monthly average prices between January 2010 to June 2020, following the same approach as Redlinger and Eggert. [119] Month-to-month volatility was found to be lower than the average of 30 materials studied in Redlinger and Eggert; however, the potential for large price swings still exists for rare earth metals.

Table 11. Volatility measures for rare earth oxides

Indicator	Neodymium oxide	Praseodymium oxide	Dysprosium oxide	Terbium oxide
Price volatility	0.10	0.09	0.13	0.14

3.2.1.5 Substitutes

The availability of substitutes across the supply chain is another important consideration for the current resilience of the U.S. NdFeB magnets supply chain. Supply chains with readily available substitutes are more resilient than those without. Substitution in magnets can occur at the elemental level by replacing certain elements with others or through improvements in technological processes, at the grade (or magnet) level by redesigning system architectures, or at the system level by meeting an end use in an entirely different way. [8] For example, Dy and Tb can be substituted as HREs within a specific magnet grade; total HRE content can be halved by the use of processes such as the grain boundary diffusion (GBD) process; direct-drive generators in wind turbines can be designed such that they operate at lower temperatures, requiring magnets with a reduced HRE content; or alternate technologies that do not use magnets can be used to generate renewable electricity (such as solar panels or wind turbines that use induction generators in place of magnets).

Reducing the HRE content of a given NdFeB magnet grade is difficult, but technologies such as GBD allow manufacturers to reduce HRE content while maintaining enhanced stability at higher temperatures. This process is more pertinent to smaller magnets, [54] however, and is subject to intellectual property constraints. Still, some companies, such as Toyota, have developed NdFeB-based magnets with high coercivity with low or no Dy content. [56] Grade substitution is one possible strategy for wind turbine and EV manufacturers to economize on HREs in the medium term and has been performed in the past; however, substitution between different magnet types (i.e., using an alternative to NdFeB) is difficult and unlikely with current technology as no other magnets are available with energy product similar to NdFeB. [8] Weaker magnets are not suitable for use in wind turbines or EVs due to the need to minimize weight in vehicles for greater efficiency, and significant engineering challenges exist to including heavier magnets at the top of direct-drive wind turbines. At the system level, wind turbines with induction generators and gearboxes are commonly used, but are not ideal for large offshore wind turbines due to higher maintenance costs and lower capacity. Despite these challenges, evidence suggests that magnet manufacturers could continue to reduce the HRE content of magnets used in clean energy applications in the medium term under elevated HRE prices. [120] For example, if prices were to double due to a persistent supply disruption, experts estimate that the HRE content of certain NdFeB magnets could be reduced by about 43 percent. [120]

In addition to the development of GBD and other efforts to reduce the HRE content of NdFeB, current R&D efforts by CMI and similar groups have focused on developing substitutes for NdFeB magnets. Much of this research has focused on developing so-called “gap” magnets with an energy product between approximately 10 and 25 MGOe that fill a commercial gap between ferrite magnets and existing NdFeB magnets, potentially reducing demand for NdFeB magnets in some end uses. [121, 122] Such research has involved, for example, substituting a portion of the Nd/Pr in the NdFeB system with Ce or La, which are more abundant and less expensive to obtain. [123] Efforts are taking place to improve and further develop other magnet systems that target the gap magnet space, such as samarium-cobalt (SmCo), iron-nickel (FeNi), samarium-iron-nitride (SmFeN), and iron-nitride (FeN) magnets. Furthermore, improvements in techniques to manufacture magnets closer to their final shape (for example, through improvements in near-net-shape manufacturing and additive manufacturing for bonded magnets) can reduce the waste generated from cutting and machining magnets from blocks to their final dimensions. [124]

3.2.1.6 Competing Demand

As discussed in Section 3.2.1.3, NdFeB magnets have a variety of downstream uses other than wind turbines and electric vehicles. These other uses include consumer electronics (hard disk drives, cell phones, loudspeakers, etc.), industrial motors, non-drivetrain motors in vehicles, power tools, electric bikes, and certain defense technologies. Users with a higher willingness to pay could potentially crowd out users that operate closer to their margin. That is, at high material prices, magnets may make up a larger portion of the total manufacturing costs for certain downstream uses where alternate technologies exist. For wind turbines manufacturers, for example, the existence of technologies that do not rely on magnets limits their ability to pass increased costs through to end users. Growth in demand for consumer electronics and industrial motors could provide challenges to wind turbine and electric vehicle manufacturers whose demand is expected to grow far more rapidly under aggressive decarbonization scenarios. The continued development of gap magnets, as discussed in Section 3.2.1.5, could alleviate this risk.

3.2.1.7 Environmental Issues and Illegal Supply

A notable portion of RE mining in China is performed illegally at artisanal mines. Because illegal mining is not tracked, however, estimates vary widely. Some researchers estimate that illegal mining accounts for up to 25 percent of China's total RE mineral output, which could translate to 16 percent of LRE supply and up to 65 percent of HRE supply. [125] Illegal miners pay little attention to environmental standards and cause environmental damage through their mining and processing actions (in-situ leaching, for example), allowing them to maintain low internal prices due to their market power. [126] While lower prices may benefit downstream users of REs globally, they also make it more difficult for mining projects in countries with stricter environmental regulations to compete. Increased environmental standards in China may actually encourage increased supply from illegal mining, which some researchers argue may improve supply chain resilience. [127, 128] China has attempted to crack down on illegal mining in the past. [110] Successfully stopping illegal production could cause prices to rise, making global projects potentially more profitable while also improving local environmental conditions; however, ending illegal production could lead to further supply restrictions in a market that is already subject to considerable disruptions.

3.2.2 Resilience

A resilient supply chain for clean energy technologies minimizes disruptive impacts arising from market disturbances and external events and is free from undue influence from any single actor. It is competitive, not concentrated in ownership or location in any specific geographic region, and has redundancies. As such, a resilient supply chain for the intermediate components used in clean energy technologies is also required, particularly for ones that are difficult to substitute.

Markets can experience a variety of disruptions, ranging from national emergencies to loss of production capacity to new technology developments. A resilient supply chain will be able to adapt in the face of these disruptions and continue to supply needed goods to consumers.

Resilience can be supported by an innovation ecosystem that is responsive to change. Better availability of market data and information can allow market participants to recognize potential challenges early and adapt their behavior in response. Redundant production capacity with a diversity of ownership and geographic location of production can reduce impacts if one company or production facility is shut down. Diversity of feedstocks and production techniques can provide the flexibility to adapt to the current market conditions. For example, the capability to produce using substitutes can allow a shift to the use of new materials if one material becomes unavailable. A skilled workforce that innovates quickly can reduce the time needed to respond to changing conditions. Material stockpiles or inventories held by private companies can also provide continued supply of needed products while the supply chain adjusts.

The U.S. government is taking action through multiple agencies to improve the resilience of the rare earth magnet supply chain. The Strategic and Critical Materials Stock Piling Act (50 U.S.C. 98 et seq.) requires that the Secretary of Defense biennially assess strategic and critical material requirements for military, industrial, and essential civilian applications under the context of a National Emergency scenario. The Defense Logistics Agency (DLA) Strategic Materials office performs the assessment with significant input from the military, the United States Geological Survey, the Department of Commerce, the Department of Energy, and industry. The analyses have generally led to the same conclusion for many strategic and critical materials, such as rare earth elements: the essential civilian sectors of the U.S. economy bear the brunt of risk and vulnerability related to potential supply disruptions of strategic and critical materials. Several reasons exist for this general finding, including that requirements for essential civilian applications (such as production of automobiles and energy) dwarf military requirements and that military production will be prioritized during times of shortages under the authorities of Title I of the Defense Production Act (50 U.S.C. §4531-4534, as amended).

NdFeB requirements were assessed in the 2021 Report on Stockpile Requirements. The quantified findings of the assessment are restricted, but Figure 18 helps shed some light on key facts for NdFeB magnets required for essential civilian and military applications. First, annual military and essential civilian requirements are shown as the dark blue and gray bars, respectively. Essential civilian requirements are significantly greater than military requirements. Second, the dashed lines show the capacity of modern large- and moderate-scale NdFeB production facilities. Military requirements are significantly less than capacity of even a moderate-scale NdFeB magnet plant. Third, the essential civilian shortfall is shown as a red line. The scale of this shortfall significantly exceeds annual military requirements and the capacity of a moderate-scale NdFeB plant. Last, U.S. essential civilian demand is on the order of scale of a large, modern NdFeB plant. No such plant currently exists in the United States.

It should be noted that these results do not capture the projected future growth of the market over the next decade. Other caveats and assumptions are in play, including the ability of U.S. industry to utilize substitutes and source materials from friendly nations.

Several conclusions on options for mitigating the essential civilian shortfall can also be derived from Figure 18. First, military requirements are insufficient to sustain the level of production that the country will require in the event of a national emergency. Sustaining sufficient domestic production would require that the essential civilian sector, such as the automotive industry, purchase from new and emerging domestic sources. Given that China is considered the lowest-cost producer, the essential civilian sector will need to be willing to pay a premium to ensure the resiliency of their supply chain by helping sustain these facilities. Second, the magnitude of the shortfall is significant in scale compared to the total U.S. market, so stockpiling is likely not the best solution. The stockpile would need to cover all grades and requirements of the civilian sector and be at the scale of roughly half a year's production of a large-scale NdFeB facility. This is both technically and monetarily challenging. The ideal solution is a more diverse commercial industrial base supported by procurement from the largest NdFeB consumers, such as the automotive sector.

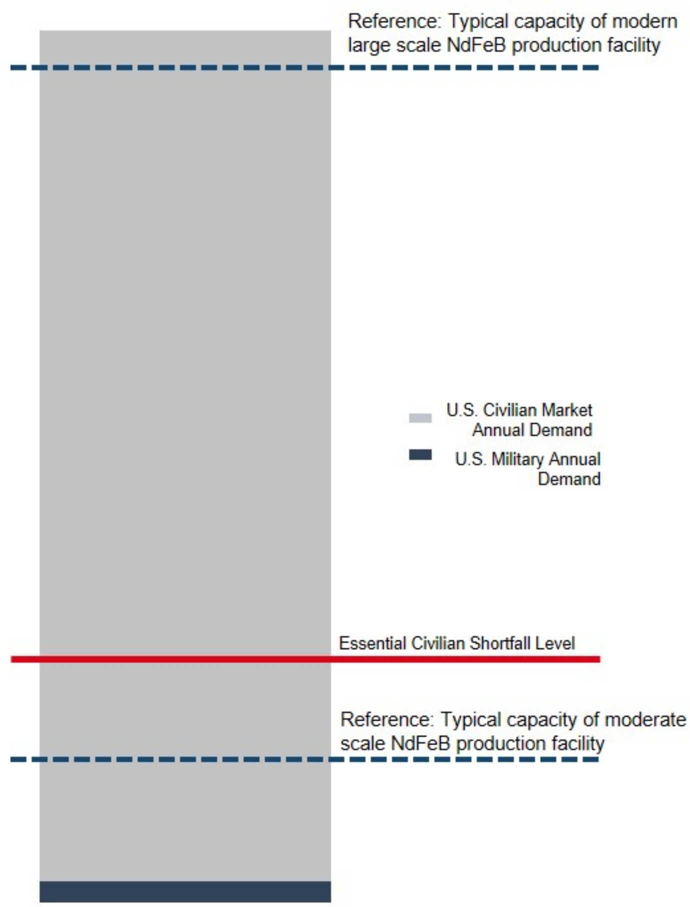

Figure 18. Relative Scale of Essential Civilian Shortfall for NdFeB magnets identified in the 2021 Report on Stockpile Requirements

The U.S. government has engaged with researchers and industry through a variety of methods to build supply chain capabilities and the innovation environment to support a more resilient supply chain. MP Materials, Lynas, Urban Mining Company, and TDA Magnetics have all received government funding under the Defense Production Act, Title III, as part of a strategy to strengthen the domestic rare earth supply chain, with additional funding possible in the future. [45, 46]

DOE also supports RDD&D to expand the technical knowledge and research capabilities needed to support supply chain resilience. In 2021, DOE announced $30 million to help secure the domestic supply chain of critical materials that are used to build clean energy technologies through 13 national lab and university-led research projects. DOE is also standing up new programs that address critical materials availability in response to the Infrastructure Investment and Jobs Act (IIJA) of 2021. For example, the IIJA establishes a new rare earth elements demonstration program. DOE also works with other agencies in addressing supply chain risks related to materials. For example, DOE plays a leadership role in the National Science and Technology Council (NSTC) committee on Homeland and National Security tasked with implementing the Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals published by DOC in 2019. DOE collaborates and coordinates with other executive branch agencies, including the Departments of Defense, Commerce, Interior, Homeland Security, Education, State, Justice, Agriculture, and Transportation; Environmental Protection Agency (EPA); National Aeronautics and Space Administration (NASA);

International Trade Commission; and National Science Foundation (NSF). DOE plays a key role in United States' bilateral critical minerals partnerships with Canada and Australia and continues to work with other agencies developing partnerships with the European Union to diversify supply chains.

3.3 U.S. Competitiveness

Chinese companies occupy a dominant position throughout the global rare earth magnet supply chain, while Japanese, European, Australian, and Canadian companies play more minor roles. Several U.S. companies also participate in the supply chain, and many are attempting to increase their production or expand to new areas. However, these companies face a number of challenges to be competitive with established global producers, especially those in China.

Some key factors that can influence the competitiveness of U.S. companies across the supply chain include labor costs, material costs and availability, equipment costs, transportation costs, subsidies, and other government support received by competitors, permitting and environmental regulations, possession of intellectual property, and technical challenges.

Labor costs are significantly lower in many countries than in the United States: an important consideration, given the value of maintaining robust labor standards and competitive wages for American workers. Labor costs in China range from 18% to 50% of U.S. labor costs, depending on the skill level required for the work, with lower disparities for more skilled work. [129] In the magnet supply chain, processes are not particularly labor intensive and labor cost differences are likely to be on the higher end of this range, so higher labor costs do not preclude U.S. producers from being competitive; however, labor costs can contribute to higher domestic costs at upstream and midstream stages of the supply chain. Labor costs may be higher for metal refining than for other supply chain stages due to the need to use relatively small cells to avoid major loss of material if a batch does not meet specifications.

Material costs and availability may also vary by region and may depend on where materials are produced. Because most of the supply chain is located in China, material availability and prices may be more stable for Chinese producers. Rare earth oxide and metal prices were significantly lower in China from 2010 to 2015, [118] and while reported price differences have since equalized, these prices do not account for transportation costs or tariffs. In addition, the potential exists for significantly higher prices outside of China in the future in the event of disruptions to supply. [130]

Large, vertically integrated companies may have competitive advantages over smaller companies. Vertical integration can help reduce reliance on other companies for demand and material supply and can allow the company to capture the value added from multiple parts of the value chain. Large-scale producers can also benefit from economies of scale that may reduce costs per unit of product.

Transportation may be a deterrent to the development of one stage of the supply chain if domestic production capability at other stages of the supply chain does not exist. On the other hand, if domestic demand and suppliers do exist, high transportation costs could help domestic suppliers be competitive at meeting domestic demand.

Government support or subsidies to key industries in other countries can present a challenge for domestic producers to be competitive if they do not receive similar support. Permitting processes and environmental regulations also pose a challenge to producers, especially if they are stricter or more difficult to navigate than in other countries.

In particular, China has historically engaged in policies that support the competitiveness of its mining and manufacturing sectors relative to other countries, especially for RE mining and downstream industries. This has included restrictive export policies such as export quotas, [110] production quotas, and forced consolidation of production, [110] stockpiling of rare earths when demand is low, [131] support for handling of radioactive thorium byproducts from the state-owned China National Nuclear Corporation, [132] capital for project expansions, [133] and direct subsidies and awards for projects to develop new products. [134]

Initially, Chinese policies promoted economic growth and capitalized on China's rich endowment of RE resources by encouraging the development of downstream activities (such as magnet manufacturing) that would create more value added than mining. [110] Under tightened export policies, manufacturers in China benefited more than foreign producers from lower raw materials costs. These tight RE export policies have also been motivated by balancing the objectives of economic growth and sustainable development. [110] Shen et al. [110] provide an overview of RE policy in China from 1975 to the present, which includes periods of promoting upstream raw material production for export, restrictions on production and foreign investment, restrictions on exports coupled with promotion of downstream industries, and more recent consolidation of the RE industry.

Patents held by foreign companies can also pose a barrier to new entrants to a market, as discussed in Section 3.3.3. It can be challenging for a new producer to gain the needed technical knowledge and experience to compete with an existing producer. On the other hand, technological capability could also be an area of competitive advantage for U.S. producers if they can overcome initial hurdles, especially if newly developed techniques improve methods currently in use.

3.3.1 Raw Materials

3.3.1.1 Rare Earth Mining and Processing

Rare earth mining is driven by the quality of mineral deposits and other sources of rare earth materials, the costs of developing and mining the resource and meeting permitting requirements, and the location of processing facilities or the costs of building new facilities. Rare earth resources exist throughout the world with large proven reserves in such countries as China, Vietnam, Brazil, and Russia. [14] Resources differ in the ore grade, the composition of different rare earths in the ore, the type of mineral, and the difficulty of processing it.

The United States has several high-quality ore deposits, which has helped it become the largest miner of rare earths outside of China. Mountain Pass mine has one of the highest ratios of rare earths to total ore body, but the quantities of high-value rare earths such as Nd, Pr, and Dy are relatively low. Quantities of radioactive materials such as thorium in the ore can also be a challenge for mines to handle safely, particularly in monazite deposits. Deposits such as Round Top and Bokan Mountain contain large proportions of valuable heavy rare earths, but extracting REs from these ores is more difficult than from ionic clays.

A key factor limiting the development of mines outside China is the location of processing facilities. Shipping mine concentrates overseas for separation increases costs. Adding more downstream production facilities (such as the planned opening of MP Materials' separation facility, along with refining and magnet production facilities to provide a market for separated products) could help improve the economics of domestic mining.

3.3.2 Processed Materials

3.3.2.1 Rare Earth Oxide Separation

While about 58% of global mine production comes from China, it is estimated that about 89% of rare earth separation occurs in China and no separation is currently done in the United States. Separation costs depend on the ore being processed, so proximity to a good source of ore is important. Other key operating costs include the purchase of reagents used in the solvent extraction process and the costs of disposal of unused materials and wastewater. Separating heavy rare earths domestically comes with particular challenges due to the small quantities of heavy rare earths currently produced in the United States, as rare earth separation may not be economical at small scales.

Technological developments may influence costs and environmental performance as well. A separation facility constructed by Molycorp to process material from Mountain Pass mine attempted to reduce costs of both wastewater treatment and new purchases of reagents through a chlor-alkali facility to recycle the reagents hydrochloric acid (HCl), sodium hydroxide (NaOH), and bleach from wastewater streams. [42] However, the chlor-alkali facility ran into operational difficulties delaying full ramp-up of production, and processing was shut down when Molycorp went bankrupt. [135] Current owners MP Materials claims to have overcome any operational challenges faced by the previous owners and aims to restart U.S. separation of rare earths by 2022. [10]

Since treatment of wastewater and disposal of mine tailings are key cost drivers, environmental regulations and their level of enforcement play an important role in determining separation costs and the risks of being shut down if regulations change or are found to have been violated. Lynas's processing facility in Malaysia, for example, has at times been at threat of being shut down due to government concerns with their onsite storage of low-level radioactive waste. [136] The Chinese government has made efforts to increase environmental standards for rare earth processing facilities, but the standards are likely still lower than those in the United States and may not be as strictly enforced, helping to reduce processing costs in China. [128]

Another key factor that can influence a company's ability to compete with producers from China is its ability to establish offtake agreements with buyers offering a guaranteed source of demand. For example, Lynas has an agreement to sell its didymium oxide to be used by Japanese magnet makers, with support from the Japanese government, which has an interest in diversifying its supply of rare earth outside of China. [137]

3.3.2.2 Rare Earth Metal Refining

While the exact shares are not clear, the majority of metal refining occurs in China, with smaller amounts likely being done in Vietnam, Thailand, and Laos along with some in Estonia and in the United Kingdom.

With DOE funding, Argonne National Laboratory conducted an analysis for a corporate sponsor to understand the costs of producing didymium (NdPr) using electrowinning. From the work a 3000 Amp cell was designed. The cell cost is shown in Table 12.

This design uses 275 kg of electrolyte, with 87% didymium fluoride/13% lithium fluoride composition. At average 2105-2018 prices, the estimated cost of the electrolyte for a cell is $50,000. This costs more than the wear items in the cell, the furnace, cathode, and turn dish. Errors in the operation of the cell when starting, such as bath composition swings or oxyfluoride formation, are expensive to fix if the bath is changed out and the company does not have a process to recondition the electrolyte. The total up-front cost of a cell line designed to produce 1000 tons per year of NdPr is estimated to be about $8.6 million, including the cost of 25 cells, electrolytes for each cell and additional equipment and engineering costs. This does not include costs of the building, which were not estimated but could increase capital costs significantly. At a cost of capital of 5%, yearly capital payments would be $.0.43 per kg of metal refined on top of the costs of the building. Operating costs include the cost of the rare earth oxide feed, graphite, equipment repair and maintenance, power and analytical costs. Graphite used is estimated to cost $4.20 per kg of metal refined. Repair and maintenance costs are estimated at $0.53/kg and power costs are estimated at $0.39/kg. Numerical estimates for analytical costs needed to ensure the product meets specifications are not available but are also significant. These costs can be reduced by melting the metals in an induction furnace, but this could more than triple the costs.

Table 12. Cell cost for Argonne NdPr production analysis

Item	Count	Unit cost
Graphite crucible	1	2,380
Tungsten turn dish	1	6,100
Tungsten cathode	1	4,650
Safety can	1	5,107
Feeder	1	4,058
Lid	1	1,200
Furnace	1	40,000
Power supply (AC to DC)	1	58,580
Total		122,000
Delivery	5%	6100
Tax, use tax	7%	8540
Installation	20%	24,400
Total		$161,400

The price of NdPr metal from China averaged $4/kg more than the cost of the 1.18 kg of NdPr oxide needed to produce 1 kg of NdPr metal in 2019. [118] Adding the cost of graphite on its own raises the cost of producing metals using published prices above the published price of the metal, while capital and other operating costs raise costs further above market prices.

Based on this analysis, a domestic company is unlikely to be able to operate successfully buying oxides and selling metals on the open market. However, it may still be cost-effective for a company to produce its own metal if it also produces its own oxides and magnets, or has local suppliers and buyers for each. While transportation costs are not readily available, it is likely that it could cost less to refine metals domestically rather than pay to transport oxides to an overseas metal refiner and transport the metals back to the United States.

3.3.3 Magnet Alloys and Magnets

China's dominance in the upstream portion of the supply chain has also contributed to its dominance in magnet manufacturing. NdFeB alloys and powders are commonly produced close to where magnets are produced due to challenges transporting magnet powders. The particle size used in magnet production is less than 10 microns. The powders are reactive with water and air and liable to spontaneously ignite, making them difficult to handle and transport (they must be shipped over land). Using a larger particle size would mitigate some of the handling issues, but the powder would then have to be further ground for magnet use, requiring some processing at the manufacturing site.

Magnet production in China is made up of a large number of small producers, but the number of large magnet producers has grown in recent years. Adamas estimates that there were 160 different Chinese magnet producers in 2019, with ten companies that produced 5000 tonnes of magnets or more, up from four companies in 2015. [12] Several companies have produced NdFeB magnets in the United States in the past, but have since shut down U.S. operations due to challenges competing with China. These challenges extend back to the 1990s, when a 1996 USITC case from 1996 determined that Chinese companies skirted IP rights when exporting magnets to the U.S. market. [138]

The advantages of producing in China has also been made evident by the fact that established magnet producers, such as Hitachi, [58] Shin Etsu, TDK,[60] and Vacuumschmelze, [61] have recently established production facilities in China. The availability and stability of supply of rare earth metals in China has been a key driver of this shift. Reduced export quotas and a temporary cut-off of shipments of rare earths from China to Japan, as well as the resulting price differentials between REs for Chinese and non-Chinese buyers, led producers from outside China to be concerned about the stability of RE metal supplies. China also manufactures equipment to manufacture magnets that is about one-third to one-half the cost of Western equipment.[9]

Japan's position as the second-largest magnet manufacturer stems from its significant expertise in magnet production, as shown in their U.S. and foreign patent applications. U.S. and foreign patents owned by Japanese companies such as Hitachi have helped to keep Chinese magnet producers from flooding the Japanese domestic markets. A total of 1,413 published patent applications filed between 2001 and 2021 are related to NdFeB magnets. Figure 19 shows the country in which the earliest application was filed for each technology: 60.5 percent of original filings were in Japan, 9.7 percent of original filings were in China, and only 5.7 percent of original filings were in the United States.

[9] Conversation with industry experts.

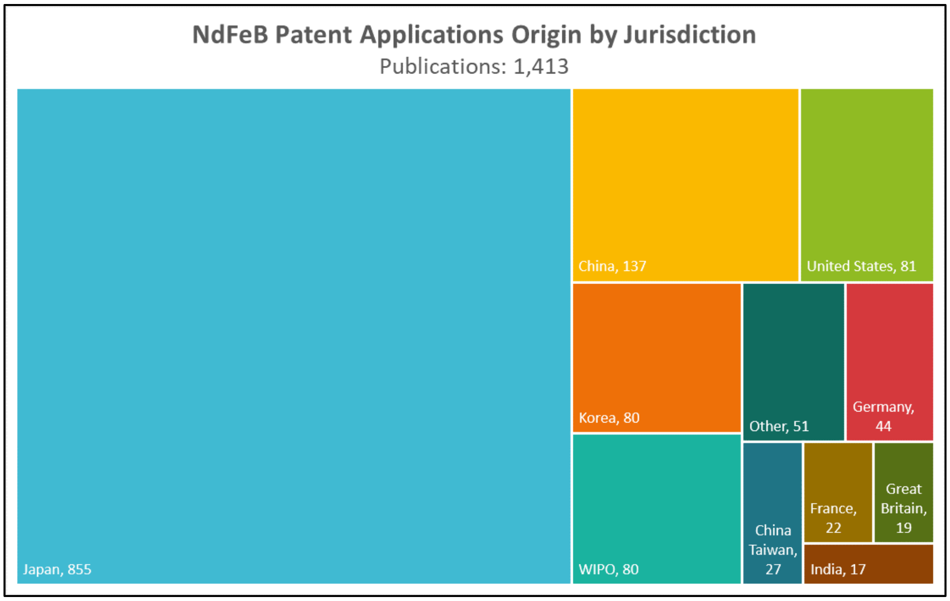

Figure 19. NdFeB Patent Applications Origin by Jurisdiction

The leading assignees for patent applications related to NdFeB magnets are shown in Figure 20. A total of 1,413 published patent applications were evaluated. Shin-Etsu Chemicals Company has the most patent applications in this area.

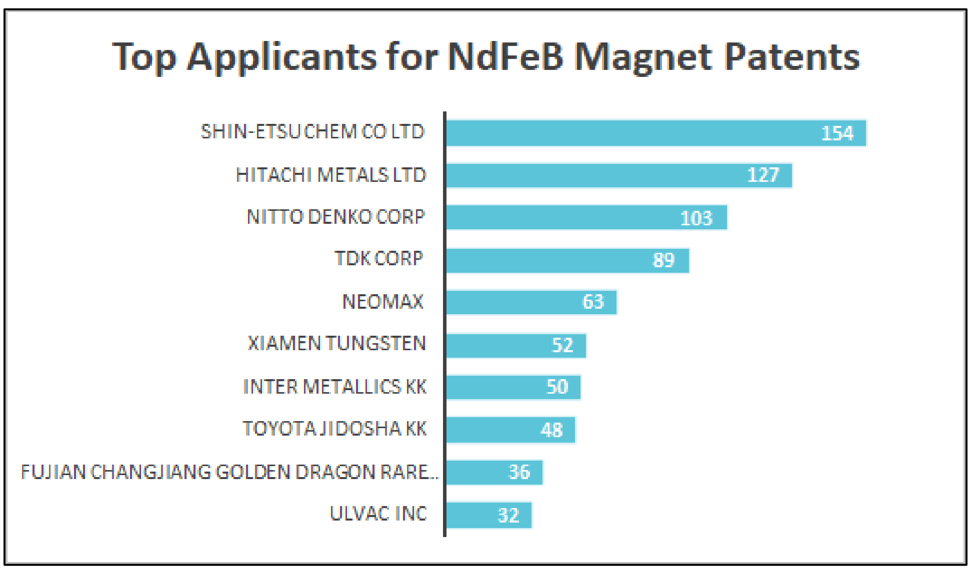

Figure 20. Top applicants for NdFeB magnet patents (firms)

Patents have also provided a significant barrier to entry for new magnet producers. Hitachi holds patents covering the standard techniques for producing sintered magnets, making it difficult for new magnet producers without a Hitachi license. [139] Four Hitachi patents were the subject of a 2012 complaint to the International Trade Commission (ITC); those were set to expire in 2021 and 2022, which may make it easier for new magnet companies in the future, although other relevant patents may have longer expiration dates. [140]

3.3.4 Recycling

To be competitive, recycling must compete with existing producers. Costs can be high to collect end-of-life products containing magnets and to separate magnets from those products.

One way to reduce costs relative to conventional techniques is to reproduce magnets without separating into individual elements. However, this approach leads to additional challenges, such as collecting enough end-of-life magnets of uniform composition or innovating a method that deals with different compositions. Magnet compositions are not known in advance as they are not labeled. The resulting magnet may have different properties than standard magnets, and markets need to be established with buyers willing to buy recycled magnets.

3.4 Key Vulnerabilities and Causes

Various issues describe the current resilience and competitiveness of the NdFeB magnet supply chain. Several vulnerabilities associated with the supply chain present weaknesses that, if left unresolved, could hinder the success of certain technology pathways, the ability of the United States to meet its climate and decarbonization goals, and potentially future U.S. prosperity and economic growth. Based on the factors discussed in this section, U.S. vulnerabilities in the NdFeB magnet supply chain to achieve decarbonization and climate goals include

- Rare earth element market instability.
- Reliance on China for raw material and magnets.
- Reliance on potentially environmentally hazardous processes.
- Reliance on a small pool of knowledgeable workers.
- Intellectual property constraints.
- Vulnerabilities faced by new domestic suppliers.
- Large expected increases in demand.

Of these vulnerabilities, the most crucial for the United States to address is the reliance on China for raw materials and magnets due to a lack of midstream capabilities for rare earth metal refining and sintered magnet manufacturing. Because refining and magnet manufacturing operations are still highly concentrated in foreign countries, current efforts to diversify raw material production domestically may not improve the resilience of the overall supply chain if those raw materials must be exported for further processing.

These vulnerabilities and their root causes are discussed in more detail below.

3.4.1 Rare Earth Element Market Instability

The global market for rare earth elements has historically been plagued by excessive price volatility and market uncertainty. Market volatility makes investments in technology and manufacturing less attractive as firms may have difficulty operating profitably. This volatility is a symptom of the small and highly concentrated market for REs and magnets (as compared with major commodities like iron or copper), for which nearly all upstream and midstream supply chain stages are concentrated in countries in geopolitical competition with the United States (namely China). A lack of easily substitutable materials and technologies also inhibits the ability of material and magnet users to respond quickly to high price environments, while technological substitutions that eventually occur under sufficiently high prices can lead to swings in demand and reduced performance. Many wind turbines do not use rare earth magnets, but the maintenance and efficiency benefits of permanent magnet generators for offshore wind turbines is substantial. EVs can use alternative drivetrains that do not rely on magnets, but trade-offs are involved with other components (such as batteries) that may require additional critical materials. [141]

3.4.2 Reliance on China for Raw Materials and Magnets

As discussed, there is limited (though increasing) production of raw materials (both from primary and secondary sources) required for magnet production outside of China, particularly for HREs required for sintered magnets for use in higher-temperature applications. Chinese companies have also acquired ownership stakes in a number of companies that operate outside China. [141]

As shown in Figure 13, little rare earth separation and metal refining capacity exists outside of China, with very limited to no current U.S. domestic capability. Despite some emerging capacity from some recycled magnets from companies such as Urban Mining Company, there is also relatively little domestic sintered NdFeB magnet manufacturing capacity. At the same time, however, there is currently limited domestic manufacturing of intermediate components that use magnets directly.

Due to this geographical concentration of nearly all upstream and midstream NdFeB supply chain stages in China, U.S. decarbonization goals are reliant on both Chinese firms and the Chinese government. Firms can exert control over international and U.S. domestic markets for raw materials, metals, magnets, and components through market manipulations like restricting output to increase prices and price dumping to lower prices to discourage investment or make competing firms outside of China less profitable. The Chinese government influences markets through various policies and regulations, such as economic and trade policy (e.g., export quotas, subsidies, tariffs, exchange rate targeting, etc.), economic and trade regulation (e.g., trade embargoes, price controls, etc.), and environmental regulations (e.g., permitting, emission standards, clean water standards, etc.).

3.4.3 Reliance on Potentially Environmentally Hazardous Processes

In addition to the vulnerabilities discussed above, the reliance on scarce materials from mines and processes that rely on environmentally hazardous extractive techniques could potentially work against environmental stewardship goals (both domestic and abroad) if not properly handled. Rare earth mining has led to environmental damage in the past (for example, Mountain Pass mine was closed in 2002 after being fined for allowing lead from mine tailings to enter storm water). Solvent extraction used to separate rare earths creates wastewater that must be treated before it can be released into the environment. Rare earth mining practices have improved since Mountain Pass was shut down, but additional process improvements may be able to further reduce environmental impacts. Extraction of rare earths, iron, and other magnet materials is also carbon-intensive relative to magnet-to-magnet recycling. [142] Recycling of magnets, technologies that require smaller magnets or use fewer materials, and process improvements may all be able to reduce these environmental impacts.

3.4.4 Reliance on a Small Pool of Knowledgeable Workers

The United States also faces a potential training gap in workforce skills and educational requirements relative to the extractive and metallurgical industries, due to the recent lack of domestic production that has led to a limited pool of experienced workers. A related issue is the learning required by firms to successfully separate and refine RE products and manufacture magnets at scale, which can be expensive, time intensive, and costly.

3.4.5 Intellectual Property Constraints

Aggressive pursuit of intellectual property by foreign firms for common magnet manufacturing practices restricts U.S. firms from competing. Existing intellectual property in the United States and abroad to manufacture magnets by companies such as Hitachi and Shin Etsu serves as a barrier to entry for unlicensed firms wishing to use existing magnet manufacturing technologies that reduce reliance on HREs.

3.4.6 Vulnerabilities Faced by New Domestic Suppliers

As new domestic production is established, these producers will face challenges to remain competitive. Magnet producers may face a lack of demand for magnets directly from intermediate component and original equipment manufacturers (OEMs). Rare earth producers may face a lack of demand for co-produced REs such as cerium and lanthanum, reducing profitability. If producers fail to address environmental challenges with the production process, negative environmental impacts may result. Price dumping by foreign producers may also lower product prices, making it harder to compete.

3.4.7 Large Expected Increases in Demand

Expected increases in deployment of offshore wind turbines and battery and hybrid electric vehicles is likely to drive rapid demand growth for NdFeB magnets. This will strain existing supply chains for magnets and rare earth products, potentially exacerbating any existing vulnerabilities.

4 Key U.S. Opportunities and Challenges

Given the vulnerabilities discussed in the previous section, the United States has a number of timely opportunities available. This section discusses these opportunities and the challenges they face.

4.1 Opportunities

Potential opportunities exist throughout the RE magnet supply chain for additional domestic manufacturing. Growing the RE magnet supply chain in the United States is an opportunity to promote well-paying manufacturing and technology jobs in the United States as well as an opportunity to stabilize supply for a key component of wind turbine and electric vehicle manufacturing, thereby encouraging more domestic downstream production.

Increase demand for offshore wind turbines and electric vehicles. Increasing demand for downstream clean energy applications could lead to significant increases in demand throughout the magnet supply chain. To best support domestic industries and minimize risks to disruptions to supply, a complete domestic supply chain is optimal, from rare earth mining and processing, to separation, metal refining, magnet manufacturing, and through production of direct drive offshore wind turbines and electric vehicle traction motors.

Fill gaps in the supply chain at the metal refining, magnet alloy, and magnet manufacturing stages by incentivizing domestic production across the supply chain. This opportunity pertains especially to HRE oxide mining and separation. The United States has an opportunity to fill these gaps as demand grows. Currently, no metal refining takes place in the United States, and most refining outside of China is done by a few companies operating in southeast Asia. The only NdFeB magnet production that occurs in the United States is performed on a small scale that does not match demand. Leveraging mechanisms within DOE and coordinating with DOD and DOC on actions stemming from the DPA TIII and 232 investigation could lead to mutually beneficial resilience enhancements in defense, commercial, and clean energy supply chains.

Improve existing technologies for process intensification and scale-up in RE separation and metal refining. Such technological improvements may also create opportunities for more competitive domestic production in these areas. Progress on the mining and separation stages of the domestic supply chain will also enable domestic metal refiners to have a more readily available source of materials without relying on Chinese suppliers. The combination of increasing demand and increasing domestic supply creates a more conducive environment for U.S. metal refining and magnet manufacturing industries to be successful. Rapid demand growth is also likely to create opportunities for new producers to meet any demand that is in excess of Chinese production levels.

Capitalize on the United States' world-class rare earth resources. The United States possesses significant sources of rare earths, and already produces a significant amount of concentrate from mines. Projects are currently underway to add domestic separation capacity as well. These projects would make the United States one of the largest miners and separators of rare earth minerals outside China.

Foster a diverse global supply chain with strong trade relationships. A more diverse global supply chain with good trade relationships with suppliers would also help reduce supply risks by filling in gaps where domestic supply is not available and by providing more diversity of stable supply. This can also be accomplished through encouraging investments by American firms in operations in countries outside of China through the U.S. International Development Finance Corporation, for example.

Improve existing magnet recycling technologies and processes. Magnet recycling technologies are less mature than conventional processes, creating an opportunity for U.S. producers to take the lead in developing new technologies. Increased magnet recycling would also reduce the reliance on environmentally hazardous extraction techniques. The United States has existing magnet recycling capacity through firms such as Urban Mining Company, and opportunities may exist to expand this capability using technologies that separate REs out of recycled magnets as well as technologies that generate new magnets from the recycling process more directly. Proper labeling of manufactured magnets would also facilitate direct magnet to magnet recycling capabilities by reducing the burden on would-be recyclers. Given expected increases in demand for magnets, however, recycling is unlikely sufficient to produce magnets at the magnitude needed to support clean energy supply chains.

Develop and improve technologies that facilitate substitutions away from (or reductions in) vulnerable materials and products. For example, the development and manufacturing of technologies that allow the use of NdFeB magnets without HREs such as Dy, which are less available outside China, could be used in conjunction with new domestic separation and refining of LREs to allow wind turbines and EVs to be produced with domestically sourced rare earths. New substitution methods, such as the continued development and commercialization of gap magnets or technologies that use fewer magnets, can also allow companies to avoid intellectual property (IP) constraints associated with conventional production methods. Yield loss can be avoided through such technologies as additive manufacturing. Material discovery and optimization can play a role in reducing U.S. reliance on HREs. Reduced material use would also reduce environmental degradation associated with rare earth mining and processing.

Develop and foster a workforce with required skills in mining, mineral processing, and metal and magnet manufacturing. A training gap exists, particularly in the mineral processing and magnet manufacturing sectors, and may be due, in part, to a lack of interest relating to a negative perception of the extractive industries. Promoting a vision for a workforce to support sustainable mining, coupled with strong environmental stewardship practices across the supply chain, could begin to alleviate this challenge.

The development of a domestic supply chain could provide additional stability in a risky market. Having rare earth supplies shut down could lead to production delays, or worse, an inability to build technologies to decarbonize the U.S. economy. Having contracts between domestic companies could benefit both – provide a stable source of materials for the buyer, perhaps at a somewhat higher price, and a stable source of revenues for the seller.

4.2 Challenges to Realizing Opportunities

Current efforts are underway to help realize these opportunities. The geographic concentration of nearly all upstream supply chain stages in China is being partially addressed by new U.S. production capabilities that are planned or under development, many with the support of the U.S. government, including through the DPA Title III, as well as new production in other countries that could help reduce geographic concentration. The lack of reliable substitute materials and technologies is being addressed through RDD&D on material substitution in magnets supported by DOE's CMI, some improvements in wind turbine design, and improvements in magnet manufacturing processes. [8] The Department of Commerce investigation into the effects of imports of NdFeB magnets on National Security may also lead to additional actions to correct market imbalances. However, it will not be easy to establish a domestic supply chain, as significant challenges exist to competing with existing producers, especially those in China.

Chinese producers have advantages in the level of environmental regulation, the scale of their operations, labor costs, and integrated supply chains. They also have sustained support from the Chinese government, which has used a variety of methods to support their industry. Chinese dominance in the upstream stages of the supply chain (i.e., rare earth mining, separation, and processing) has also contributed to their even greater dominance in magnet manufacturing. China also has significant excess capacity, allowing existing producers to ramp up production and drive down prices, undercutting new competitors.

Some of these advantages could be reduced as China increases its levels of environmental regulations and additional supply chain development in the United States helps improve domestic availability of materials, but it is likely that ongoing efforts by the U.S. government will be needed to offset the advantages enjoyed by Chinese producers.

Complex production processes such as those in the magnet supply chain require some trial and error to perfect. New firms entering the market will need to have sufficient funding to navigate this phase. Magnet producers will need to learn how to control the microstructure of the magnets, metal refiners may face challenges controlling the electrolyte composition, and oxide separators may need to master recycling of reagents to keep costs low. If a new company has sufficient funding to navigate this initial stage, there is still no guarantee that U.S. producers would still be competitive with Chinese producers.

There are additional challenges for domestic magnet recyclers. The recycling processes for NdFeB are still under development. It does not appear that recycling will close the gap between the demand for magnets and RE metals available until about 2050 when half the supply might be produced from recycled magnets [78]. The cost of retrieving the small magnets used in some applications is too high compared with the value of the magnet, or the REs in the magnet. Much of the REs in the magnets enters the steelmaking process when articles are recycled. This makes it difficult to acquire sufficient supplies of recycled magnets that can be recycled cost-effectively.

Companies that recycle magnets directly without separating out individual REs, also face a distinct set of challenges. Not all magnets have the same chemistry, even for the same grade of magnet, and it is difficult to know the composition of a magnet acquired at end-of-life, making it difficult to predict the magnet properties that result from blending different recycled magnets and produce a uniform product for buyers. As a result, finding end users interested in recycled magnetic materials can be a challenge. It would be easier to follow the direct magnet recycling model if the composition of existing magnets were known. Labeling to help recyclers know the composition of magnets, or product stewardship with magnet producers recycling their own magnets, could help with this.

A challenge for policy makers is that efforts to reduce dependence on NdFeB magnets or on RE metals may discourage investments in the manufacturing supply chain. For example, research and development (R&D) efforts focused on developing substitute magnets could make the supply chain more resilient; however, if successful, those efforts decrease the demand for NdFeB magnets, thus increasing investment risks for NdFeB magnet manufacturing and raw materials production.

5 Conclusions

Rare earth magnets, particularly NdFeB magnets, play a key role in the U.S. economy, including key energy technologies such as wind turbines and electric vehicle motors. Due to their high energy density, these powerful permanent magnets are used in highly efficient and low-weight electrical motors and generators, providing key advantages compared to alternative technologies. However, these magnets—as well as the rare earth compounds, metals, and alloys used to produce them—come largely from China, with limited production in the United States.

Due to the significance of the rare earth magnet supply chain, efforts have been made by various government agencies to support the development of a more resilient supply chain and encourage additional domestic production. Domestic rare earth mining has increased in recent years, and new domestic separation of rare earth concentrated into individual rare earths is expected in the near future. Potential new domestic metal refining and magnet production are also being planned, though this new production is a little farther away.

While these developments are promising, they may not be sufficient to eliminate vulnerabilities and build a resilient supply chain, especially given expected growth in demand. Resilience can continue to be improved with additional diversity of supply through expanded domestic production at all supply chain stages by a variety of producers using multiple material sources and production techniques, and through partnerships with international suppliers. It can also be supported by a knowledgeable workforce with the technological capability to allow rapid responses to changing environments. In addition, new domestic suppliers may need sustained support to compete with foreign producers, especially those from China. The successful development of a more resilient supply chain for rare earth magnets could help enable sustained expansion of efficient clean technology deployment.

Recommended policy actions to address the vulnerabilities and opportunities covered in this report may be found in the Department of Energy 1-year supply chain review policy strategies report, "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition." For more information, visit www.energy.gov/policy/supplychains.

References

[1] David Brown, Bao-Min Ma, and Zhongmin Chen. Developments in the processing and properties of NdFeB-type permanent magnets. *Journal of Magnetism and Magnetic Materials*, 248(3):432–440, 2002.

[2] Leena Grandell, Antti Lehtil, Mari Kivinen, Tiina Koljonen, Susanna Kihlman, and Laura S. Lauri. Role of critical metals in the future markets of clean energy technologies. *Renewable Energy*, 95:53–62, 2016.

[3] Valerie Bailey Grasso. Rare earth elements in national defense: Background, oversight issues, and options for Congress. Report 7-5700, Congressional Research Service, September 2013.

[4] A.S. McDonald, M.A. Mueller, and H. Polinder. Structural mass in direct-drive permanent magnet electrical generators. *IET Renewable Power Generation*, 2:3–15(12), March 2008.

[5] Alex Newkirk, Prakash Rao, and Paul Sheaffer. U.S. industrial and commercial motor system market assessment report volume 2: Advanced motors and drives supply chain review. Technical Report LBNL-2001418, Lawrence Berkeley National Laboratory, 6 2021.

[6] Claudiu C. Pavel, Roberto Lacal-Arantegui, Alain Marmier, Doris Schűler, Evangelos Tzimas, Matthias Buchert, Wolfgang Jenseit, and Darina Blagoeva. Substitution strategies for reducing the use of rare earths in wind turbines. *Resources Policy*, 52:349–357, 2017.

[7] Claudiu C. Pavel, Christian Thiel, Stefanie Degreif, Darina Blagoeva, Matthias Buchert, Doris Schűler, and Evangelos Tzimas. Role of substitution in mitigating the supply pressure of rare earths in electric road transport applications. *Sustainable Materials and Technologies*, 12:62–72, 2017.

[8] Braeton J. Smith and Roderick G. Eggert. Costs, substitution, and material use: The case of rare earth magnets. *Environmental Science & Technology*, 52(6):3803–3811, 2018. PMID: 29499609.

[9] John Ormerod. Bonded magnets: Material and process update. Conference Presentation; Motion Control and Motor Association Technical Conference; Accessed November 15, 2021 at http://nebula.wsimg.com/00791b2521e0d9fb30b5b6d11ea15b2b?AccessKeyId=2F01719A5C29B88E2C21&disposition=0&alloworigin=1, 2015.

[10] MP Materials. About: Our story. https://mpmaterials.com/about/#history, November 2021.

[11] Energy Fuels. Energy fuels engages leading consultant to support development of rare earth separation at White Mesa Mill in Utah. Press release; accessed November 15, 2021 at https://www.energyfuels.com/2021-04-27-Energy-Fuels-Engages-Leading-Consultant-to-Support-Development-of-Rare-Earth-Separation-at-White-Mesa-Mill-in-Utah, April 2021.

[12] Adamas Intelligence. Rare earth magnet market outlook to 2030. Market Report, August 2020.

[13] Adam Jordens, Ying Ping Cheng, and Kristian E. Waters. A review of the beneficiation of rare earth element bearing minerals. *Minerals Engineering*, 41:97–114, 2013.

[14] Joe Gambogi. Rare earths. 2021 mineral commodity summaries, U.S. Geological Survey, 2021.

[15] K. Bisaka, I.C. Thobadi, and C. Pawlik. Extraction of rare earths from iron-rich rare earth deposits. *Journal of the Southern African Institute of Mining and Metallurgy*, 117:731 – 739, 08 2017.

[16] Lynas Rare Earths. Mt Weld, Western Australia. Company website accessed January 21, 2022 at https://lynasrareearths.com/about-us/locations/mt-weld-western-australia/.

[17] Edward S Shedd, JD Marchant, and Morton Min Wong. *Electrowinning misch metal from a treated bastnasite concentrate*, volume 7398. US Department of the Interior, Bureau of Mines, 1970.

[18] Energy Fuels. Energy fuels set to enter commercial rare earth business in q1-2021, producing materials that make many clean energy and advanced technologies possible. Webcast, December 15, 2020. News release, December 2020.

[19] Chemours. Zircon sands. Company website accessed January 21, 2022 at https://www.chemours.com/en/brands-and-products/chemours-minerals/products/zircon-sands.

[20] Energy Fuels. Company website. Accessed January 21, 2022 at https://www.energyfuels.com/.

[21] Energy Fuels. Neo performance materials and energy fuels announce joint launch of U.S.-European rare earth production initiative. Press release; accessed November 15, 2021 at https://www.energyfuels.com/2021-03-01-Neo-Performance-Materials-and-Energy-Fuels-Announce-Joint-Launch-of-U-S-European-Rare-Earth-Production-Initiative, March 2021.

[22] Technology Metals Research. TMR advanced rare-earth projects index. TMR website; accessed November 15, 2021 at https://www.techmetalsresearch.net/metrics-indices/tmr-advanced-rare-earth-projects-index/, 2015.

[23] Cecilia Jamasmie. Hochschild to spin off Chilean rare earths project. Mining.com, Oct 20, 2021; Accessed November 15, 2021 at https://www.mining.com/hochschild-to-spin-off-chilean-rare-earths-project/ accessed 11/4/2021, 2021.

[24] Deepak Malhotra, Thomas Matthews, Donald Hulse, and Christopher Emmanuel. Ni 43-101 preliminary economic assessment round top project. Technical report, Gustavson Associates, 2019.

[25] Rajesh Kumar Jyothi, Thriveni Thenepalli, Ji Whan Ahn, Pankaj Kumar Parhi, Kyeong Woo Chung, and Jin-Young Lee. Review of rare earth elements recovery from secondary resources for clean energy technologies: Grand opportunities to create wealth from waste. *Journal of Cleaner Production*, 267:122048, 2020.

[26] Ryan Castilloux. Rare earth market outlook: Supply, demand, and pricing from 2016 through 2025. Market Report, 2016.

[27] Richard Peterson, Michael Heinrichs, Darwin Argumedo, Rachid Taha, Slawomir Winecki, Kathryn Johnson, Ann Lane, and Daniel Riordan. Recovery of rare earth elements from coal and coal byproducts via a closed loop leaching process: Final report. Technical report, National Energy Technology Laboratory, 8 2017.

[28] Ross K. Taggart, James C. Hower, Gary S. Dwyer, and Heileen Hsu-Kim. Trends in the rare earth element content of U.S.-based coal combustion fly ashes. *Environmental Science & Technology*, 50(11):5919–5926, 2016. PMID: 27228215.

[29] Bernard P. McGrail, Praveen K. Thallapally, Jian Liu, and Satish K. Nune. Magnetic partitioning nanofluid for rare earth extraction from geothermal fluids. Technical report, Pacific Northwest National Laboratory, 8 2017.

[30] Hongyue Jin, Dan M. Park, Mayank Gupta, Aaron W. Brewer, Lewis Ho, Suzanne L. Singer, William L. Bourcier, Sam Woods, David W. Reed, Laura N. Lammers, John W. Sutherland, and Yongqin Jiao. Techno-economic assessment for integrating biosorption into rare earth recovery process. *ACS Sustainable Chemistry & Engineering*, 5(11):10148–10155, 2017.

[31] Behzad Vaziri Hassas, Mohammad Rezaee, and Sarma V. Pisupati. Precipitation of rare earth elements from acid mine drainage by CO2 mineralization process. *Chemical Engineering Journal*, 399:125716, 2020.

[32] Chenna Rao Borra, Bart Blanpain, Yiannis Pontikes, Koen Binnemans, and Tom Van Gerven. Comparative analysis of processes for recovery of rare earths from bauxite residue. *JOM*, 68(11):2958–2962, November 2016.

[33] Craid Heidrich, Hans-Joachim Feuerborn, and Anne Weir. Coal combustion products: A global perspective. In *2013 World of Coal Ash (WOCA) Conference Proceedings*, April 2013.

[34] Ronghong Lin, Yee Soong, and Evan J. Granite. Evaluation of trace elements in U.S. coals using the USGS COALQUAL database version 3.0. part i: Rare earth elements and yttrium (rey). *International Journal of Coal Geology*, 192:1–13, 2018.

[35] Saptarshi Das, Gabrielle Gaustad, Ashok Sekar, and Eric Williams. Techno-economic analysis of supercritical extraction of rare earth elements from coal ash. *Journal of Cleaner Production*, 189:539–551, 2018.

[36] Zachary Hendren, Young Chul Choi, Helen Hsu-Kim, James C. Hower, Desiree Plata, and Mark Wiesner. Preliminary techno-economic evaluation of a novel membrane based separation and recovery process for rare earth elements from coal combustion residues. In *2017 World of Coal Ash (WOCA) Conference, Lexington, KY*, May 2017.

[37] Ronghong Lin, Mengling Stuckman, Bret H. Howard, Tracy L. Bank, Elliot A. Roth, Megan K. Macala, Christina Lopano, Yee Soong, and Evan J. Granite. Application of sequential extraction and hydrothermal treatment for characterization and enrichment of rare earth elements from coal fly ash. *Fuel*, 232:124–133, 2018.

[38] MP Materials. MP Materials receives department of energy award. Press release, accessed November 15, 2021 at https://www.mpmaterials.com/ MPMaterialsReceivesDepartmentofEnergyAward_5.13.2021FINAL.pdf, May 2021.

[39] Phoenix Tailings. Company website. Accessed January 21, 2022 at https://www.phoenixtailings.com.

[40] Amanda Brioche. Boron. Mineral Commodity Summaries 2021, U.S. Geological Survey, 2021.

[41] Supermagnete. FAQ: Which magnet coatings are there? https://www.supermagnete.de/eng/faq/Which-magnet-coatings-are-there, November 2021.

[42] Scott Honan and Douglas D Daugherty. Molycorp project phoenix water and reagent recycling with clean power. *Responsible Mining: Case Studies in Managing Social & Environmental Risks in the Developed World*, 347, 2015.

[43] Lynas Rare Earths. Lynas Malaysia, Kuantan, Malaysia. Company website accessed January 21, 2022 at https://lynasrareearths.com/about-us/locations/kuantan-malaysia/

[44] Solvay. Rare earths. Company website accessed January 21, 2022 at https://www.solvay.com/en/solutions-market/mining/solvent-extraction/rare-earths

[45] U.S. Department of Defense. DOD announces rare earth element award to strengthen domestic industrial base. Press release accessed December 2, 2021 https://www.defense.gov/News/Releases/Release/Article/2488672/dod-announces-rare-earth-element-award-to-strengthen-domestic-industrial-base/, February 2021.

[46] U.S. Department of Defense. Dod announces rare earth element award to strengthen domestic industrial base. Press Release, accessed Dec 2, 2021 https://www.defense.gov/News/Releases/Release/Article/2488672/dod-announces-rare-earth-element-award-to-strengthen-domestic-industrial-base/, February 2021.

[47] Caroline Messecar. US selects Lynas to design heavy rare earth plant. Argus Media, accessed December 2, 2021 at https://www.argusmedia.com/en/news/2098582-us-selects-lynas-to-design-heavy-rare-earth-plant, April 2020.

[48] USA Rare Earth LLC. Update: USA rare earth reports significant progress at its Round Top Mountain heavy rare earth / lithium / critical minerals project in Texas and at its critical minerals processing facility in Colorado. GlobeNewswire, August 2, 2021; Accessed November 15, 2021 at https://www.globenewswire.com/news-release/2021/08/02/2272958/0/en/UPDATE-USA-Rare-Earth-Reports-Significant-Progress-at-Its-Round-Top-Mountain-Heavy-Rare-Earth-Lithium-Critical-Minerals-Project-in-Texas-and-at-Its-Critical-Minerals-Processing-Fac.html, August 2021.

[49] Shane Lasley. Rare earth project reemerges in Wyoming. Metal Tech News, October 13, 2021. Accessed November 15, 2021 at https://www.metaltechnews.com/story/2021/10/13/tech-metals/rare-earths-project-reemerges-in-wyoming/735.html, October 2021.

[50] Vietnam Rare Earth JSC. About us. Company website accessed January 21, 2022 at http://vtre.vn/about-us.html

[51] Silmae. NPM Silmet. Company website accessed January 21, 2022 at https://www.sillamae.ee/web/eng/molycorp-silmet

[52] SCALE Project. Less Common Metals. Project website accessed January 21, 2022 at http://scale-project.eu/partners/less-common-metals/

[53] John Ormerod. Rare earth magnets: hidden but essential. Presentation to ASM International, Los Angeles Chapter, October 27, 2020.

[54] Arnold Magnetic Technologies. Available neo grades. Company website, https://www.arnoldmagnetics.com/products/neodymium-iron-boron-magnets/, accessed November 15, 2021.

[55] Steve Constantinides. The important role of dysprosium in modern permanent magnets. Technical Report Rev. 150903a, Arnold Magnetic Technologies, 2017.

[56] Toyota Motor Corporation. Toyota develops new magnet for electric motors aiming to reduce use of critical rare-earth element by up to 50%. Press release, February 2018.

[57] Magneti Ljubljana d.d. Company website. Accessed January 21, 2022 at https://www.magneti.si/en/

[58] Hitachi Metals, Ltd. Notice Concerning Establishment of Neodymium-Iron-Boron Magnet Joint Venture (Subsidiary Transfer) in China https://www.hitachi-metals.co.jp/e/ir/ir-news/20160902en.pdf. Public Notice, September 2, 2016, Accessed January 21, 2022 at https://www.hitachi-metals.co.jp/e/ir/ir-news/20160902en.pdf, 2016.

[59] Shin-Etsu. Shin-Etsu Chemical to set up a base in China to manufacture magnet alloys for rare earth magnets. News release, March 22, 2012, accessed January 21, 2022 at https://www.shinetsu.co.jp/en/news/news-release/shin-etsu-chemical-to-set-up-a-base-in-china-to-manufacture-magnet-alloys-for-rare-earth-magnets/, 2012.

[60] Nikkei Asia. TDK to make magnets for hybrids in China. Nikkei Asia, June 6, 2014, Accessed January 21, 2022 at https://asia.nikkei.com/Business/TDK-to-make-magnets-for-hybrids-in-China, 2014.

[61] KPMG. Exhibit 99.1 Audited consolidated financial statements of VAC Holding GmbH (in Euros) as of and for the years ended December 31, 2010 and 2009. Independent Auditors Report, October 12, 2011, Accessed January 21, 2022 at https://www.sec.gov/Archives/edgar/data/899723/000119312511272915/d242370dex991.htm, 2011.

[62] Magnetics Business and Technology. Urban mining progressed in pioneering effort to scale up rare-earth magnet production from recycled magnets. Website, Accessed November 15, 2021 at https://magneticsmag.com/urban-mining-progresses-in-pioneering-effort-to-scale-up-rare-earth-magnet-production-from-recycled-magnets/., October 2019.

[63] Colin Staub. Rare earth recycler draws 28 million in federal funding. Accessed November 15, 2021 *at* https://resource-recycling.com/recycling/2020/09/15/rare-earth-recycler-draws-28-million-in-federal-funding/

[64] MP Materials. MP Materials to build U.S. magnet factory, enters long-term supply agreement with General Motors. Press release, accessed December 9, 2021 at https://mpmaterials.com/articles/mp-materials-to-build-us-magnet-factory-enters-long-term-supply-agreement-with-general-motors, December 2021.

[65] Vacuumshmelze. Announcement from General Motors and VACUUMSCHMELZE. VAC News, Press release, December 9, 2021, Accessed January 21, 2022 at https://www.vacuumschmelze.com/Newsroom/announcement-from-general-motors-and-vacuumschmelze-n2195, 2021.

[66] Argus Media. Correction: Quadrant plans Kentucky RE magnet plant, February 4, 2022, Accessed February 14, 2022 at https://www.argusmedia.com/en/news/2297061-correction-quadrant-plans-kentucky-re-magnet-plant, 2022

[67] Mike Millikin. USA rare earth acquires US rare earth permanent magnet manufacturing capability from Hitachi; mine-to-magnet. Green Car Congress, 15 April 2020; Accessed November 15, 2021 at https://www.greencarcongress.com/2020/04/20200415-rareearth.html, April 2020.

[68] Steve Constantinides. The demand for rare earth materials in permanent magnets. Presentation at the 51st Annual Conference of Metallurgists, Niagara Falls, NY, September 2012. Accessed November 15, 2012 at https://www.arnoldmagnetics.com/wp-content/uploads/2017/10/Demand-for-rare-earth-materials-in-permanent-magnets-Constantinides-COM-2012-psn-hi-res.pdf., September 2012.

[69] Matthew E. Riddle, Eric Tatara, Charles M. Olson, Diane J. Graziano, Braeton J. Smith, and Allison Bennett Irion. Argonne's global critical materials agent-based model (GCMat). Technical report ANL-20/25 159423, Argonne National Laboratory, 4 2020.

[70] Eric Lantz, Garrett Barter, Patrick Gilman, David Keyser, Trieu Mai, Melinda Marquis, Matthew Mowers, Matt Shields, Paul Spitsen, and Jeremy Stefek. Power sector, supply chain, jobs, and emissions implications of 30 gigawatts of offshore wind power by 2030. Technical report NREL/TP-5000-80031, National Renewable Energy Laboratory, 8 2021.

[71] Pavel C., Marmier A., Alves Dias P., Blagoeva D., Tzimas E., Schűler D., Schleicher T., Jenseit W., Degreif S., and Buchert M. Substitution of critical raw materials in low-carbon technologies: lighting, wind turbines and electric vehicles. Scientific analysis or review LD-NA-28152-EN-C (print),LD-NA-28152-EN-N (online), 2016.

[72] U.S. Department of Energy. Critical Materials Strategy 2011. Technical report, U.S. Department of Energy, 2011.

[73] Takashi Nakamura. *How to Recover Minor Rare Metals from E-Scrap*, 37–44. Springer International Publishing, Cham, 2016.

[74] Y. Tanaka, S. Tsujioka, Y. Eryu, T. Nemoto, and T. Takada. Resource recycling for sustainable industrial development. *Hitachi Review*, 60(6), 2011.

[75] Y. Hiroshige, Baba, K., and T. Nemoto. Rare-earth magnet recycling. *Hitachi Review*, 62(8), 2013.

[76] A. Conner-Simons. Robots that can sort recycling. MIT News, accessed November 15, 2021 at https://news.mit.edu/2019/mit-robots-can-sort-recycling-0416, 2019.

[77] Komal Habib, Keshav Parajuly, and Henrik Wenzel. Tracking the flow of resources in electronic waste - the case of end-of-life computer hard disk drives. *Environmental Science & Technology*, 49(20):12441–12449, 2015. PMID: 26351732.

[78] Yongxiang Yang, Allan Walton, Richard Sheridan, Konrad Güth, Roland Gauß, Oliver Gutfleisch, Matthias Buchert, Britt-Marie Steenari, Tom Van Gerven, Peter Tom Jones, and Koen Binnemans. REE recovery from end-of-life NdFeB permanent magnet scrap: A critical review. *Journal of Sustainable Metallurgy*, 3(1):122–149, March 2017.

[79] Brett Carlson. *Recycling of neodymium-iron-boride magnet waste by selective sulfation roasting.* PhD thesis, Colorado School of Mines, 2018.

[80] Muhamad Firdaus, M. Akbar Rhamdhani, Yvonne Durandet, W. John Rankin, and Kathie McGregor. Review of high-temperature recovery of rare earth (Nd/Dy) from magnet waste. *Journal of Sustainable Metallurgy*, 2(4):276–295, December 2016.

[81] Renaud Gueroult, Jean-Marcel Rax, and Nathaniel J. Fisch. Opportunities for plasma separation techniques in rare earth elements recycling. *Journal of Cleaner Production*, 182:1060–1069, 2018.

[82] Clifford G. Brown and Leonard G. Sherrington. Solvent extraction used in industrial separation of rare earths. *Journal of Chemical Technology and Biotechnology*, 29(4):193–209, 1979.

[83] Manis Kumar Jha, Archana Kumari, Rekha Panda, Jyothi Rajesh Kumar, Kyoungkeun Yoo, and Jin Young Lee. Review on hydrometallurgical recovery of rare earth metals. *Hydrometallurgy*, 165:2–26, 2016. SI: IC-LGO 2015.

[84] Feng Xie, Ting An Zhang, David Dreisinger, and Fiona Doyle. A critical review on solvent extraction of rare earths from aqueous solutions. *Minerals Engineering*, 56:10–28, 2014.

[85] Koen Binnemans, Peter Tom Jones, Bart Blanpain, Tom Van Gerven, Yongxiang Yang, Allan Walton, and Matthias Buchert. Recycling of rare earths: a critical review. *Journal of Cleaner Production*, 51:1–22, 2013.

[86] Bradley R. Nakanishi, Guillaume Lambotte, and Antoine Allanore. *Ultra High Temperature Rare Earth Metal Extraction by Electrolysis*, 177–183. Springer International Publishing, Cham, 2016.

[87] Y. Xu, L. S. Chumbley, and F. C. Laabs. Liquid metal extraction of Nd from NdFeB magnet scrap. *Journal of Materials Research*, 15(11):2296–2304, November 2000.

[88] Sakae Shirayama and Toru H. Okabe. Selective extraction and recovery of Nd and Dy from Nd-Fe-B magnet scrap by utilizing molten MgCl2. *Metallurgical and Materials Transactions B*, 49(3):1067–1077, June 2018.

[89] Prakash Venkatesan, Tom Vander Hoogerstraete, Tom Hennebel, Koen Binnemans, Jilt Sietsma, and Yongxiang Yang. Selective electrochemical extraction of REES from NdFeB magnet waste at room temperature. *Green Chem.*, 20:1065–1073, 2018.

[90] Irina Makarova, Ekaterina Soboleva, Maria Osipenko, Irina Kurilo, Markku Laatikainen, and Eveliina Repo. Electrochemical leaching of rare-earth elements from spent NdFeB magnets. *Hydrometallurgy*, 192:105264, 2020.

[91] Yujian Zhou, Stephen Schulz, Leonard F. Lindoy, Hao Du, Shili Zheng, Marco Wenzel, and Jan J. Weigand. Separation and recovery of rare earths by in situ selective electrochemical oxidation and extraction from spent fluid catalytic cracking (fcc) catalysts. *Hydrometallurgy*, 194:105300, 2020.

[92] HyProMag. Company website. Accessed January 21, 2022 at https://hypromag.com/.

[93] Small Business Innovation Research. Rare Resource Recycling Inc. Website, accessed November 15, 2021 at https://www.sbir.gov/sbc/rare-resource-recycling-inc.

[94] U.S. Department of Energy, Advanced Manufacturing Office. Small Business Innovation Research (SBIR). Website accessed January 21, 2022 at https://www.energy.gov/eere/amo/small-business-innovation-research-sbir, 2021

[95] Momentum Technologies. Company website. accessed January 21, 2022 at https://www.momentum.technology/

[96] U.S. Department of Energy, Advanced Manufacturing Office. Small Business Innovation Research (SBIR). Website accessed January 21, 2022 at https://www.energy.gov/eere/amo/small-business-innovation-research-sbir, 2021.

[97] AP News. American resources corporation receives final permit approval for its first rare earth and critical element purification and isolation facility. Press release, accessed December 9, 2021 at https://apnews.com/press-release/Accesswire/technology-business-c297ce00e5d6d94dabd46f3507ca3502, November 2021.

[98] EurekAlert! Rare-earth magnet recycling tech wins innovation award. News release, August 28, 2018; Accessed November 15, 2021 at https://www.eurekalert.org/news-releases/854799, August 2018.

[99] Lorenz Erdmann and Thomas E. Graedel. Criticality of non-fuel minerals: A review of major approaches and analyses. *Environmental Science & Technology*, 45(18):7620–7630, 2011. PMID: 21834560.

[100] T. E. Graedel, E. M. Harper, N. T. Nassar, Philip Nuss, and Barbara K. Reck. Criticality of metals and metalloids. *Proceedings of the National Academy of Sciences*, 112(14):4257–4262, 2015.

[101] Nedal T. Nassar, Jamie Brainard, Andrew Gulley, Ross Manley, Grecia Matos, Graham Lederer, Laurence R. Bird, David Pineault, Elisa Alonso, Joseph Gambogi, and Steven M. Fortier. Evaluating the mineral commodity supply risk of the U.S. manufacturing sector. *Science Advances*, 6(8), 2020.

[102] J. Brainard, Robert G. Sinclair, Kevin Stone, E. Sangine, and Steven M. Fortier. North American net import reliance of mineral materials in 2014 for advanced technologies. *Mining Engineering*, 70(7), 2018.

[103] Andrew L. Gulley, Nedal T. Nassar, and Sean Xun. China, the United States, and competition for resources that enable emerging technologies. *Proceedings of the National Academy of Sciences*, 115(16):4111–4115, 2018.

[104] Braeton J. Smith and Roderick G. Eggert. Multifaceted material substitution: The case of NdFeB magnets, 2010–2015. *JOM*, 68(7):1964–1971, July 2016.

[105] Benjamin Sprecher, Ichiro Daigo, Wouter Spekkink, Matthijs Vos, Rene Kleijn, Shinsuke Murakami, and Gert Jan Kramer. Novel indicators for the quantification of resilience in critical material supply chains, with a 2010 rare earth crisis case study. *Environmental Science & Technology*, 51(7):3860–3870, 2017. PMID: 28257181.

[106] Joe Gambogi. Rare earths. 2014 mineral commodity summaries, U.S. Geological Survey, 2014.

[107] World Bank. Regulatory quality index. Trade and Competitiveness Data, Accessed January 21, 2022 at https://tcdata360.worldbank.org/indicators/51ada6ba, 2020.

[108] Keith Zhai. China to create new state-owned rare-earths giant. Wall Street Journal, December 3, 2021, Accessed January 21, 2022 at https://www.wsj.com/articles/china-set-to-create-new-state-owned-rare-earths-giant-11638545586, 2021.

[109] Bloomberg News. China to form two rare earth giants to strengthen pricing power. Mining.com; Accessed Nov 15, 2021 at https://www.mining.com/web/china-to-form-two-rare-earth-giants-to-strengthen-pricing-power/, September 2021.

[110] Yuzhou Shen, Ruthann Moomy, and Roderick G. Eggert. China's public policies toward rare earths, 1975-2018. *Mineral Economics*, 2020.

[111] Jack Lifton. Lifton comments on the "significant signing" of Tantalus Rare Earths off-take agreement with Shenghe Resources. Investor Intel, February 9, 2015; Accessed November 15, 2021 at https://investorintel.com/markets/technology-metals/technology-metals-intel/lifton-comments-significant-signing-tantalus-rare-earths-shenghe-resources-rare-earth-industry/, February 2015.

[112] Lynas Rare Earths. Company website accessed January 21, 2022 at https://lynasrareearths.com/

[113] International Energy Agency. Net zero by 2050: A roadmap for the global energy sector. Report 4th revision, International Energy Agency, October 2021.

[114] E. Larson, C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, R. Socolow, EJ Baik, R. Birdsey, R. Duke, R. Jones, B. Haley, E. Leslie, K. Paustian, and A. Swan. Net-zero America: Potential pathways, infrastructure, and impacts. Technical report, Princeton University, December 2020.

[115] M Singh, A Vyas, and E Steiner. VISION model: Description of model used to estimate the impact of highway vehicle technologies and fuels on energy use and carbon emissions to 2050. Technical report, Argonne National Laboratory, 2 2004.

[116] Michael Dwyer. EIA projects global conventional vehicle fleet will peak in 2038. Today in Energy, October 2021.

[117] Roskill Information Services Ltd. *Rare Earths: Outlook to 2029*. 19th ed., 2018.

[118] Argus Metal Prices. Accessed June 8, 2020 at https://www.argusmedia.com/en/metals/argus-metal-prices, 2020.

[119] Michael Redlinger and Roderick Eggert. Volatility of by-product metal and mineral prices. *Resources Policy*, 47:69–77, Elsevier, 2016.

[120] Braeton James Smith. *Three Essays on Substitution in Clean Energy Applications*. PhD thesis, Colorado School of Mines, 2018.

[121] J.M.D. Coey. Permanent magnets: Plugging the gap. *Scripta Materialia*, 67(6):524–529, 2012. Viewpoint Set No. 51: Magnetic Materials for Energy.

[122] Li Yin, Rinkle Juneja, Lucas Lindsay, Tribhuwan Pandey, and David S. Parker. Semihard iron-based permanent-magnet materials. *Phys. Rev. Applied*, 15:024012, Feb 2021.

[123] M. Hussain, L.Z. Zhao, C. Zhang, D.L. Jiao, X.C. Zhong, and Z.W. Liu. Composition-dependent magnetic properties of melt-spun la or/and ce substituted nanocomposite NdFeB alloys. *Physica B: Condensed Matter*, 483:69–74, 2016.

[124] Ling Li, Brian Post, Vlastimil Kunc, Amy M. Elliott, and M. Parans Paranthaman. Additive manufacturing of near-net-shape bonded magnets: Prospects and challenges. *Scripta Materialia*, 135:100–104, 2017.

[125] Ruby Thuy Nguyen and D. Devin Imholte. China's rare earth supply chain: Illegal production, and response to new cerium demand. *JOM*, 68(7):1948–1956, July 2016.

[126] Daniel J. Packey and Dudley Kingsnorth. The impact of unregulated ionic clay rare earth mining in China. *Resources Policy*, 48:112–116, 2016.

[127] Maxwell Brown and Roderick Eggert. Simulating producer responses to selected Chinese rare earth policies. *Resources Policy*, 55:31 – 48, 2018.

[128] Nabeel A. Mancheri, Benjamin Sprecher, Gwendolyn Bailey, Jianping Ge, and Arnold Tukker. Effect of Chinese policies on rare earth supply chain resilience. *Resources, Conservation and Recycling*, 142:101 – 112, 2019.

[129] Donald Chung, Emma Elgqvist, and Shriram Santhanagopalan. Automotive lithium-ion battery (LIB) supply chain and U.S. competitiveness considerations. Technical Report NREL/PR-6A50-63354, National Renewable Energy Laboratory, 2015.

[130] Matthew E. Riddle, Eric Tatara, Charles Olson, Braeton J. Smith, Allison Bennett Irion, Braden Harker, David Pineault, Elisa Alonso, and Diane J. Graziano. Agent-based modeling of supply disruptions in the global rare earths market. *Resources, Conservation and Recycling*, 164:105193, 2021.

[131] Chris Gill. China cuts rare earth exports by 43% in Sept, builds stockpile. Asia Financial, October 14, 2020, Accessed January 21, 2022 at https://www.asiafinancial.com/china-cuts-rare-earth-exports-by-43-in-sept-builds-stockpile, 2020.

[132] World Nuclear News. New Chinese JV for rare earth minerals from Greenland. WNN, January 23, 2019, Accessed January 21, 2022 at https://www.world-nuclear-news.org/Articles/New-Chinese-JV-for-rare-earth-minerals-from, 2019.

[133] Argus Media. China's ZKSH to form re magnets JV. Argus Media, July 10, 2020, accessed January 21, 2022 at https://www.argusmedia.com/en/news/2122039-chinas-zksh-to-form-re-magnets-jv?backToResults=true, 2020.

[134] Mary Hui. China's rare earth hub is rolling out massive subsidies to fix the industry's Achilles heel. Quartz, July 15, 2021, accessed January 21, 2022 at https://qz.com/2031940/chinas-rare-earth-hub-baotou-introduces-massive-subsidies/, July 2021.

[135] Molycorp. Second amended disclosure statement for debtors second amended joint plan of reorganization. Exhibit 99.1, https://www.sec.gov/Archives/edgar/data/1489137/000110465916120339/a16-11036_1ex99d1.htm, 2016.

[136] YAO-HUA LAW. Radioactive waste standoff could slash high tech's supply of rare earth elements. Science, News, April 1, 2019, Accessed January 21, 2022 at https://www.science.org/content/article/radioactive-waste-standoff-could-slash-high-tech-s-supply-rare-earth-elements, 2019.

[137] Japan Oil, Gas and Metals Corporation. Sojitz and JOGMEC enter into definitive agreements with Lynas including availability agreement to secure supply of rare earths products to Japanese market. Press release, March 30, 2011, accessed January 21, 2022 at https://www.jogmec.go.jp/english/news/release/release0069.html, 2011.

[138] U.S. International Trade Commission. Certain neodymium-iron-boron magnets, magnet alloys, and articles containing the same. Publication 2964, U.S. U.S. International Trade Commission, https://www.usitc.gov/publications/337/pub2964.pdf, 1996.

[139] U.S. Department of Energy. Critical materials rare earths supply chain: A situational white paper. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, https://www.energy.gov/sites/prod/files/2020/04/f73/Critical%20Materials%20Supply%20Chain%20White%20Paper%20April%202020.pdf, 2020.

[140] Walter T. Benecki. Hitachi Metals, ltd. – the magnet industry newsmaker. Magnetics Magazine, Accessed December 9, 2021 at https://www.waltbenecki.com/uploads/hitachi_in_the_news.pdf, 2021.

[141] Mary Hui. The U.S. is taking steps toward breaking China's rare earths monopoly. Quartz, February 5, 2021; Accessed November 15, 2021 at https://qz.com/1969069/the-us-takes-steps-to-break-chinas-rare-earths-monopoly/, February 2021.

[142] Hongyue Jin, Peter Afiuny, Timothy McIntyre, Yuehwern Yih, and John W. Sutherland. Comparative life cycle assessment of NdFeB magnets: Virgin production versus magnet-to-magnet recycling. *Procedia CIRP*, 48:45–50, 2016. The 23rd CIRP Conference on Life Cycle Engineering.

[143] E. Morrice and M.M. Wong. Fused-salt electrowinning and electrorefining of rare-earth and yttrium metals. *Minerals Science and Engineering*, 11(3):125–136, 1979.

[144] Remacor. Mischmetal production 1000 tpy facility. Report, West Pittsburg, PA,, 1994.

[145] I.S. Hirschhorn. Commercial production of rare earth metals by fused salt electrolysis. *JOM*, 20(3):19–22, 1968.

[146] Edward Morrice and Thomas A. Henrie. *Electrowinning high-purity neodymium, praseodymium, and didymium metals from their oxides*, vol. 6957. U.S. Department of the Interior, Bureau of Mines, 1967.

[147] B. Porter, E.S. Shedd, C. Wyche, J.D. Marchant, and R.G. Knickerbocker. Higher purity ingot cerium from molten salts. *JOM*, 12(10):798–801, 1960.

[148] H Vogel and B Friedrich. Development and research trends of the neodymium electrolysis–a literature review. In *Proceedings of the 8th European metallurgical conference, Duesseldorf*, 2015.

[149] Liu Zhongxing, Wu Yongfu, and Zhang Hailing. Rare earth electrolysis cell. CN201305647Y, 2008.

[150] Xiaoling Guo, Jilt Sietsma, and Yongxiang Yang. Solubility of rare earth oxides in molten fluorides. *ERES2014*, 149–155, 2014.

[151] Anthony Lazarus and Peter Boyle. Environmental effects reports for didymium pilot plant. Technical Report AS140190, Environ Australia Pty Ltd, June 2013.

[152] Hanno Vogel, Benedikt Flerus, Felix Stoffner, and Bernd Friedrich. Reducing greenhouse gas emission from the neodymium oxide electrolysis. Part i: analysis of the anodic gas formation. *Journal of Sustainable Metallurgy*, 3(1):99–107, 2017.

[153] Hanno Vogel and Bernd Friedrich. An estimation of PFC emission by rare earth electrolysis. In *TMS Annual Meeting & Exhibition*, 1507–1517. Springer, 2018.

[154] Bofeng Cai, Helin Liu, Fan Kou, Youming Yang, Bo Yao, Xiping Chen, David S Wong, Lizhi Zhang, Jianzhong Li, Guochun Kuang, et al. Estimating perfluorocarbon emission factors for industrial rare earth metal electrolysis. *Resources, Conservation and Recycling*, 136:315–323, 2018.

[155] Vasilis Fthenakis. Options for abating greenhouse gases from exhaust streams. Technical report, Brookhaven National Laboratory, Upton, NY, 2001.

Appendix A: Additional Technical Information

Separation (Solvent extraction)

The primary process currently used for separation is solvent extraction. The exact process is engineered for each type of concentrate being processed, but common steps include high-temperature cracking with sulfuric acid or other reagents, removal of Ce from brines through oxidation, followed by the solvent extraction trains themselves. These trains consist of potentially hundreds of mixer/settlers, each of which consists of a mixing chamber where a solvent is mixed with the feed solution, and a settling chamber where lighter and heavier materials are separated by gravity. They initially separate light rare earths such as Nd and Pr from heavy rare earths such as Dy and Tb before performing additional separations.

The organic phase of the solvent extraction system that is widely used is based on a mixture of kerosene and Di-2-ethylhexyl phosphoric acid or 2-ethylhexyl phosphonic acid mono-ethylhexyl ester. Oxalic acid is used to separate the RE chloride salts from the solution. These processes consume large amounts of acid, caustic, and water. Ongoing research is underway to develop extracting reagents that do not require as much acid and caustic in the mixer/settler/stripping units.

In processing the ore, the small amounts of uranium and thorium must be separated from the rare earth streams. The solvent extraction trains have long resistance times with potentially hundreds of mixer/settlers. The separation of Nd from Pr can take 30 mixer settlers. In some applications, the cost of Nd-Pr separation is not justified for a small gain in magnet performance, and didymium (NdPr) metal is used in magnet fabrication. For applications that require a Nd:Pr ratio different from the typical 3:1 of didymium, separated Nd or Pr oxide can be used to increase or decrease the Pr content.

The solvent extraction trains used in the separation process are designed to take advantage of the fact that Ce can be removed from the brines by oxidation to produce an insoluble ceric oxide. This removes a significant fraction of the REs process stream, reducing the size of the equipment if solvent extraction alone was used for separation. Promethium is not naturally occurring, and as a result the hydrometallurgical process has a natural gap between the light and heavy rare earths where they can be separated.

Metal refining (electrowinning)

The first rare earth metal refining was done in Germany in the 1940s and then in the U.K. and the United States. [143] This early metal refining produced mischmetal, an alloy containing an unseparated mixture of REs, which was used largely for lighters and for inoculants for ductile iron production. Historically, mischmetal was produced in large amounts in the United States by Ronson and REMACOR. [144, 145] The U.S. Bureau of Mines developed the oxide feed/fluoride electrolyte process, also known as electrowinning, demonstrating small-scale production of Nd and Pr and larger-scale production of mischmetal and Ce using the same method. [146, 147] This process then was scaled to larger cells in China. [148] Some cells have reached 10kA in size. [149]

Electrowinning is done using an electrowinning cell, which consists of a set number of anodes and cathodes, and an electrolyte, which varies depending on the metal or alloy being produced. Typically, a graphite anode and tungsten cathode are used. All of the electrolytes are composed of solutions of lithium fluoride and the rare earth fluoride of the metal of interest. The electrolytes are typically 80-90% rare earth fluoride, with the balance lithium fluoride. Electrowinning cells operate on a similar principle as a Hall-Héroult cell. The rare earth oxide feed is added to the electrolyte.

The cost of the electrolyte is high: spot prices of didymium fluoride ($NdPrF_3$) in September 2021 were found at \$735/kg. The density of the electrolyte is about 4.7 g/cm^3, so an estimated 3kA cell would require about 260 kg of didymium fluoride (at a cost of \$190,000) to start the cell, with bath replacement estimated as about 2% per month. Such a cell could produce about 38 tonnes per year of metal, requiring about 44.7 tonnes of oxide. The cost of the cell is about \$110,000. Given these costs, without an internal supply of rare earth fluoride, a smelter would have difficulty operating cost-effectively.

To produce ferrodysprosium (DyFe), which is used as input into NdFeB magnet production, a consumable iron cathode is used. The dysprosium alloys with the iron from the cathode to form a eutectic at about 80/20% Dy/Fe. Dysprosium fluoride is used as the electrolyte. The cost of the electrolyte is much higher as dysprosium fluoride is about three times the cost of didymium fluoride. Cell size is similar to the didymium cell. This process uses consumable cathodes produced from low carbon steel.

The solubility of the oxide varies with the RE metal produced, with highest solubility of about 4% in Nd oxide electrolysis. [150]

The composition potential for the oxide is lower than the fluoride. As a result, the cell reactions can be written as shown below. This process uses a graphite (C) anode, and produces carbon monoxide (CO) and carbon dioxide (CO_2) at the anode.

$$RE_2O_3 + 3C = 2RE + 2CO_{(g)}$$

$$RE_2O_3 + 1.5C = 2RE + 1.5CO_{2(g)}$$

The electrolytic process consumes graphite, the theoretical minimum of 0.09 to 0.12 kg C/kg Nd. The actual wear rates are about 0.2 to 0.4 kg C/kg Nd. [151] This shows that cost of production outside the cost of the oxide is governed by this expense. Typical cost of graphite is about \$20/kg, which results in a cost of \$4-\$8/kg Nd. The supply of graphite also has to be available, sometimes this material has a long lead time (estimate from SGL Graphite suggests a nine-month lead time) and only certain grades will not add contamination from the ash in the graphite when used in the cell. The CO produced from these reactions has to be treated before release, and this adds a capital cost to the process. The CO can be converted to CO_2 by thermal oxidation.

The limiting current density of about 1A/cm^2, and the solubility of the oxide helps describe the size of the cell [152]. The electrolyte volume is defined by how fast the operator is comfortable in the depilation of oxide of the bath.

A key challenge in rare earth metal refining is that in some conditions, the anode effect can lead to a reaction, shown below, which consumes valuable electrolyte and generates tetrafluoromethane, a greenhouse gas with 6200 times the potency of CO_2, and other perfluorocarbons (PFCs). The limited solubility of the oxide in the electrolyte can result in the anode effect if the current density on the anode is too high or the supply of oxide in the bath is depleted. The anode effect in the Hall-Héroult cell results in rapid rise in cell voltage and arching in the cell. Anodes and cathodes in the Hall-Heroult cell are operated on current control, and the anodes are horizontal. In the anode effect the gas trapped carries an electrical arc causing a large increase in cell voltage drop.

$$4REF_3 + 3C = 3RE + 3CF_{4(g)}$$

The emissions of tetrafluoromethane (CF_4) from electrolysis has been estimated over a range, from 26.6 g/ton NdPr to 29.5 g/ton with 3.1 g/t of C_2F_6. [153, 154] Emissions in the production of DyFe are reported much higher, in the 111 g/ton range.

To avoid the anode effect and emissions of PFCs, a dedicated power supply under voltage control (fixed voltage, not current) operates each electrowinning cell. The cell voltage or applied voltage is controlled to operate below the formation of tetrafluoromethane. This is not the most cost-effective method of supply of DC power; however, it is necessary. Using one power source to operate several cells and not produce tetrafluoromethane has not been demonstrated, Permitting the emission of PFC from cell electrolysis, or the development of a dry scrubbing method (a thermal oxidizer) to convert the CF_4 before emission might be necessary. Commercial thermal oxidizers (TO) developed for the plasma etching industry are designed to destroy CF_4. [155]

Appendix B: Assessment Table

Table B1. Assessment Table

Component	SC segment/ process	Sub-segment/ product	Significant domestic suppliers	Significant domestic demand	Projected significant domestic demand	Significant global market	Projected significant global demand	Cost competitive among US suppliers	Cost competitive between US suppliers vs. global suppliers	Is foreign supply diversified?	Is foreign supply from reliable trade partners?	Is there sufficient effort to address environ-mental concerns?	Is there sufficient effort to address human rights concerns?	Does it make sense to build a domestic capability for this product/ component?
Raw materials	Mining and processing	Rare earth ore	Yes	No	Maybe	Maybe	Yes	Maybe	Maybe	No	No	Maybe	Maybe	Maybe
		Iron ore	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
		Borate ore	Yes	Yes	Maybe	Maybe	Maybe	Maybe	Yes	Yes	Yes	Maybe	Maybe	No
	Processing	Rare earth concentrate	Yes	No	Maybe	No	Maybe	N/A	Maybe	No	Maybe	Maybe	Maybe	Maybe
	Separation (rare earths only)	Nd oxide	No	No	Maybe	Maybe	Yes	N/A	No	No	Maybe	Maybe	Maybe	Maybe
		NdPr oxide	No	No	Maybe	Maybe	Yes	N/A	No	No	Maybe	Maybe	Maybe	Maybe
		Dy oxide	No	No	Maybe	No	Maybe	N/A	No	No	No	Maybe	Maybe	Maybe
Processed materials	Metal refining and alloying	Nd metal	No	No	Maybe	Maybe	Maybe	N/A	No	No	No	Maybe	Maybe	Maybe
		NdPr metal	No	No	Maybe	Maybe	Maybe	N/A	No	No	No	Maybe	Maybe	Maybe
		DyFe alloy	No	No	Maybe	No	Maybe	N/A	No	No	No	Maybe	Maybe	Maybe
		NdFeB alloy	No	No	Maybe	Maybe	Maybe	Maybe	No	No	No	Maybe	Maybe	Maybe
		Boron	Yes	Maybe	Maybe	Yes	Maybe	Maybe	Maybe	Yes	Yes	Maybe	Maybe	Maybe
		High purity Fe	No	No	Maybe	Yes	Yes	Yes	Yes	Yes	Yes	Maybe	Maybe	Maybe
	Secondary materials recovery	Magnet materials recovered from scrap	No	No	Yes	Maybe	Yes	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe
Magnet manufacturing		Sintered NdFeB magnet	No	Yes	Yes	Maybe	Yes	Maybe	No	No	No	Maybe	Maybe	Maybe
Component manufacturing		Direct drive generator	No	No	Yes	Maybe	Yes	Maybe	Maybe	Maybe	Yes	Maybe	Maybe	Maybe
		Traction motor	Maybe	Yes	Yes	Yes	Yes	Maybe	Maybe	Maybe	Yes	Maybe	Maybe	Maybe
End product		Direct drive/ offshore wind turbine manufacturing	No	Maybe	Yes	Maybe	Yes	No	Maybe	Maybe	Yes	Maybe	Maybe	Yes
		EV manufacturing	Yes	Maybe	Yes	Yes	Yes	Yes	Yes	Maybe	Yes	Maybe	Maybe	Maybe
End-of-life product collection		Scrap containing NdFeB material	Maybe	Maybe	Yes	Maybe	Yes	Maybe	No	Maybe	Maybe	Maybe	Maybe	Yes
		NdFeB material recovered for re-use	Maybe	Maybe	Yes	Maybe	Yes	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe	Yes

U.S. DEPARTMENT OF ENERGY

For more information, visit:
energy.gov/policy/supplychains

DOE/OP-0008 ▪ February 2022