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14. ABSTRACT

Once dominant in the industry, the U.S. is now dependent upon China for Rare Earth Elements (REE), a key component in commercial and military technology. As the global demand for REEs increase exponentially, beyond their natural abundance, it is imperative that the U.S. find stable and sustainable sources in order to secure the future of U.S. national security. U.S. and Allied investment in REE recycling would provide a means for long-term access to these vital resources by exploiting the existing and untapped above-ground stores of REEs trapped in current trash disposal systems.

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MASTER OF MILITARY STUDIES

TITLE:

THE ESSENTIAL ROLE OF RECYCLING IN DECREASING AMERICA'S DEPENDENCE ON FOREIGN SOURCES OF RARE EARTH MINERALS

AUTHOR:

MAJOR MARGARET MCCORD, USAF

AY 2020-21

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Date: ____

Executive Summary

Title: The Essential Role of Recycling in Decreasing America's Dependence on Foreign Sources of Rare Earth Minerals

Author: Major Margaret McCord, United States Air Force

Thesis: U.S. investment in REE recycling creates a foundation for long term access and stability that is vital for national security in this age of great power competition with China and an exponentially growing global demand for REEs.

Discussion: The U.S. made Rare Earth Elements accessible to the world, enabling technological leaps due to their unique electromagnetic properties. In the 1980s, market forces started to shift away from U.S. dominance in the industry, and by 2015 the U.S. was reliant upon China for 80% of its Rare Earth Elements (REE). Such reliance creates a national security concern because REEs are critical to not only U.S. commercial industry but also defense. Weapon systems such as the F-35, precision guided munitions, and the Aegis destroyer all require REEs to function. As the global demand for REEs increases exponentially, it is imperative that the U.S. find stable and sustainable sources in order to secure the future of U.S. national security.

Conclusion: U.S. enduring REE access hinges upon its ability to recycle the existing and untapped above ground stores of REEs found in various waste streams. It is incumbent upon policy makers to take actions to make recycling a key component in long-term US REE security.

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THE OPINIONS AND CONCLUSIONS EXPRESSED HEREIN ARE THOSE OF THE INDIVIDUAL STUDENT AUTHOR AND DO NOT NECESSARILY REPRESENT THE VIEWS OF EITHER THE MARINE CORPS COMMAND AND STAFF COLLEGE OR ANY OTHER GOVERNMENTAL AGENCY. REFERENCES TO THIS STUDY SHOULD INCLUDE THE FOREGOING STATEMENT.

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Preface

The current situation regarding Rare Earth Elements provides a poignant example of the need for better, more sustainable sources for raw materials that are fundamental to our technological future. Hopefully, the lessons learned and efforts taken to reinforce sustainable, domestic rare earth element supply will subsequently enhance the recycling of all major components of modern technology and usher in a new paradigm for material management.

I would like to acknowledge the efforts of my research advisors, Dr. Jorge Benitez, Lt Col David Preston, and the numerous Command and Staff College faculty as well as technical advisors and thank them for their guidance in strengthening this work. Finally, I owe a debt of gratitude to my family for making all of this possible.

I. Introduction

The term *rare earth elements* (REEs) refer to the 15 lanthanide elements in addition to yttrium (Yt) and scandium (Sc), because of their similar chemical characteristics[1]. These 17 elements are further broken down into Light REEs (LREEs) and Heavy REEs (HREEs), based on their atomic number[2]. REEs have become increasingly significant to a wide range of commercial (Figure 1) and military technologies because of their high magnetic strength, unique luminescent and electrochemical properties[3].

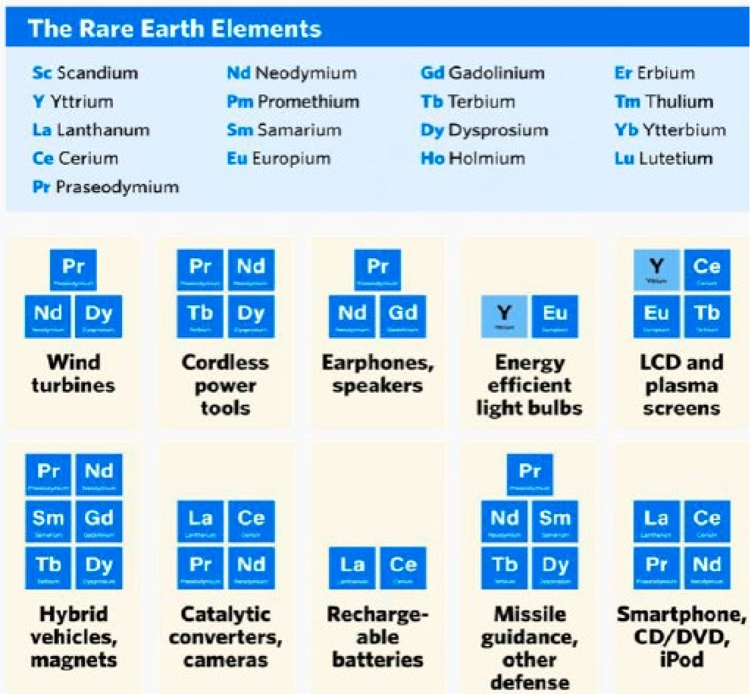

Figure 1. Common Commercial Applications for REEs[4]

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[1] US Department of Energy, *Critical Materials Rare Earths Supply Chain: A Situational White Paper (*Washington, DC: Office of Energy Efficiency & Renewable Energy, Apr 2020), 10.
[2] DOE, 10.
[3] Raeanna Carrell, "Putting the "Us" Back in the U.S. Defense Industrial Base: The Case of Rare Earths," *Journal of Public and Environmental Affairs* 1, no. 1 (2020), 2.
[4] Raeanna Carrell, 2.

Originally thought to be rare, REEs are actually fairly abundant in the earth's crust (Figure 2), and have been found within 19 states in the U.S., though typically in low concentrations[5].

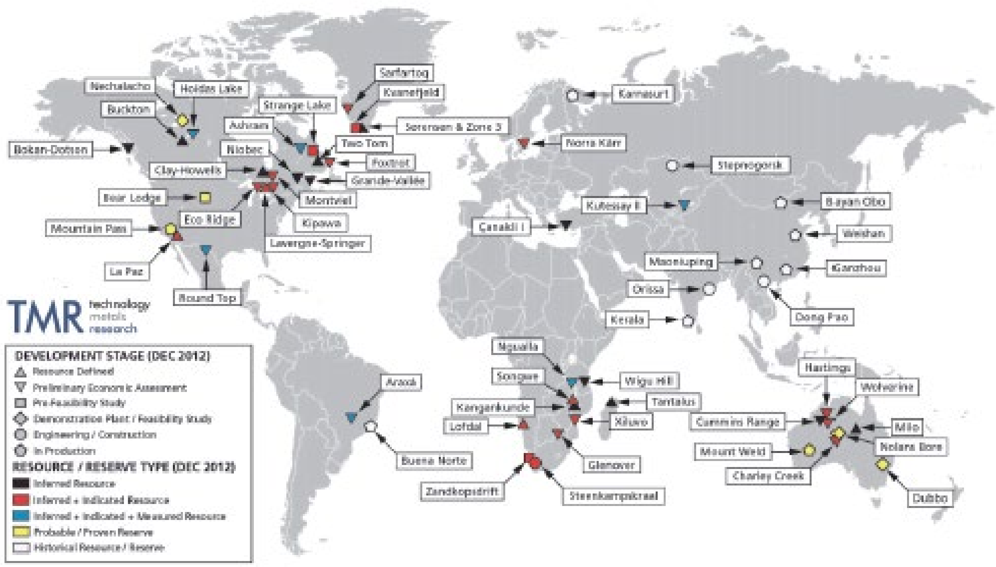

Figure 2. Global Distribution of REE Deposits[6]

Because of the challenge in separating out the individual REEs, there was little demand for them prior to WWII. An efficient process of separation was discovered and developed in 1947 at Ames Laboratory, initially considered the hub of all rare-earth developments, and the first U.S. REE mine was opened in 1949[7]. REE Processing (Figure 3) is still complex when compared to other minerals[8]. While the REE separation step varies slightly depending on the

[5] DOE, 11.
[6] David L. An, "Critical Rare Earths, National Security, and U.S.-China Interactions, A Portfolio Approach to Dysprosium Policy Design," RAND Graduate Dissertation (Santa Monica, CA: Sept, 2014), 16.
[7] Joanne Abel Goldman, "The U.S. Rare Earth Industry: Its Growth and Decline," *Journal of Policy History* 26, no. 2 (2014), 144, https://search.ebscohost.com/login.aspx?direct=true&db=a9h&AN=121179845&site=ehost-live.
[8] Cindy Hurst, "China's Rare Earth Elements Industry: What Can the West Learn?" Institute for the Analysis of Global Security (Washington, DC: March, 2010), 5.

type of rock (Bastnaesite, Monazite, Xenotime), it generally takes 10 days after the ore is out of the ground for the REE oxides to be produced[9].

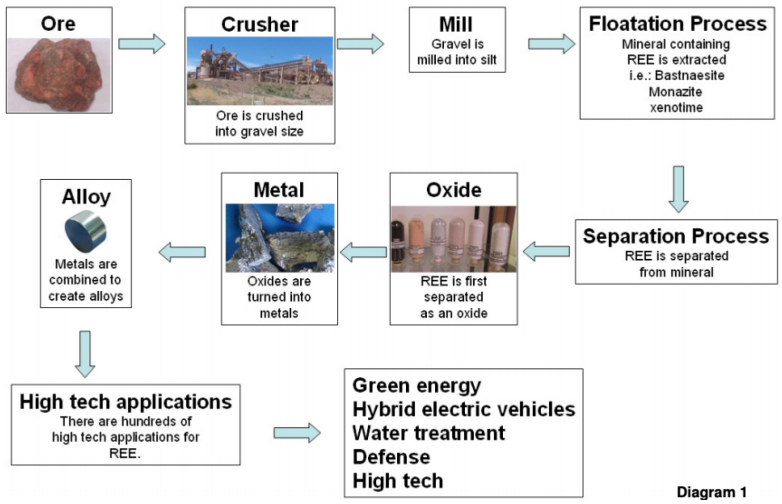

Figure 3. REE Processing Steps[10]

Since 1947, REEs have been critical in solving technological challenges and enhancing existing industries such as ceramics, lighting, atomic energy, and petroleum refinement[11]. REEs have enabled technology to become smaller, lighter, more efficient, more environmentally-friendly, as well as more thermally durable, with the greatest demand (roughly 60% domestically) for their use as stabilizers in fluid cracking catalysts (FCCs)[12] and in the field of permanent magnets (roughly 31% of the global consumption in 2016)[13]. The green energy sector is particularly reliant upon REEs due to their heavy use in semiconductors[14] and the high-performance permanent magnets required for hybrid/electric vehicle motors as well as the direct-

[9] Hurst, 5.
[10] Cindy Hurst, 5.
[11] Goldman, 145.
[12] Brandon S. Tracy, An Overview of Rare Earth Elements and Related Issues for Congress (Washington, DC: Congressional Research Service, Nov 2020), 1.
[13] Carrell, 2.
[14] Goldman, 145.

drive generators used to store wind energy[15]. Semiconductors, the flat material upon which microchips are built, are foundational to nearly all electronic devices as they host the integrated set of circuits required for operation[16]. These microchips can be designed for a variety of functions, such as memory chips, graphic processing units, program logic microprocessors, etc. By exposing semiconductors to substances such as REEs, the conductivity of the material can be manipulated in various ways to enhance their performance[17], increase efficiency, and reduce operating costs[18]. The Biden administration has set ambitious goals that will increase both the demand and relevancy of sustainable REE procurement. This includes developing a carbon pollution-free power sector by 2035, a net-zero economy by 2050, and creating jobs in manufacturing and engineering that will simultaneously accelerate federal projects in an environmentally friendly, sustainable manner[19].

REEs are not only critical to commercial industry; current defense applications (Figure 4 & 5) rely on them for equipment such as jet engines, satellites, communication systems, missile

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[15] D.D. Imholte, R.T. Nguyen, A. Iver, A. Vedanatam, M. Brown, B. Smith, C. Anderson, B. O'Kelley, John W Collins, *An assessment of U.S. rare earth availability for supporting U.S. wind energy growth targets* (Idaho Falls, ID: Idaho National Laboratory, Feb 2018), 2, http://www.inl.gov.

[16] Investopedia, The Main Types of Chips Produced by Semiconductor Companies, (May 2020), https://www.investopedia.com/ask/answers/042115/what-are-main-types-chips-produced-semiconductor-companies.asp

[17] Gernot S. Pomrenke, Paul B. Klein, and Dietrich W. Langer, *Rare Earth Doped Semiconductors, Materials Research Society Symposium Proceedings* 301, (1993), 3. https://apps.dtic.mil/dtic/tr/fulltext/u2/a277517.pdf.

[18] Olivia Smith, *Why Semiconductors are Necessary for Clean Energy Practices*, (Jan 2020), https://medium.com/@oliviasmith8019/why-semiconductors-are-necessary-for-clean-energy-practices-d952ded61c54

[19] The White House, *FACT SHEET: President Biden Takes Executive Actions to Tackle the Climate Crisis at Home and Abroad, Create Jobs, and Restore Scientific Integrity Across Federal Government*, January 2021, Statements and Releases, https://www.whitehouse.gov/briefing-room/statements-releases/2021/01/27/fact-sheet-president-biden-takes-executive-actions-to-tackle-the-climate-crisis-at-home-and-abroad-create-jobs-and-restore-scientific-integrity-across-federal-government/.

guidance systems, antimissile defense systems, laser systems, night vision goggles, and optical lenses[20].

Figure 4. REE Applications in Electronic Warfare, Targeting & Weapons Systems, and Guidance & Control Systems[21]

Specifically, weapons systems such as the Virginia-class fast attack submarine, DDG 51 Aegis destroyer, and the F-35 Joint Strike Fighter rely on REEs to function[22]. Potentially even more relevant to national security is the significance of REEs to developing technologies such as directed-energy weapons[23], miniaturization, nanotechnology, and operations in space[24]. In spite of their significance to the economy and national defense, global market forces have reduced U.S. domestic production to one active REE mine with no ability to separate and process REEs from the mined concentrates at a commercial scale[25]. While there have been numerous attempts to bolster U.S. REE production,[26] the enduring supply/demand imbalance can only truly be rectified by a strategy that involves REE recycling. As the global demand for REEs continues to

[20] Government Accountability Office, *Rare Earth Materials: Developing A Comprehensive Approach Could Help DOD Better Manage National Security Risks in the Supply Chain* (Washington, DC: Government Accountability Office, Feb 2016), 6, 16-161.
[21] Bert Chapman, "The Geopolitics of Rare Earth Elements: Emerging Challenge for U.S. National Security and Economics," *Journal of Self-Governance and Management Economics* 6, no. 2 (2018), 77.
[22] Chapman, 50.
[23] James Kennedy, "China Solidifies Dominance in Rare Earth Processing." *National Defense*, (Mar 2019) 19.
[24] Sarah Kramer and Dave Mosher, "Here's How Much Money It Actually Costs to Launch Stuff into Space," Business Insider, Jul. 20, 2016, 1, http://www.businessinsider.com/spacex-rocket-cargo-price-byweight-2016-6 (accessed December 30, 2016).
[25] DOE, 7.
[26] Chapman, 81.

exponentially grow, recycling affords the long term REE access and stability that will continue to be vital to U.S. national security, especially in this period of great power competition.

REE	Technology	Function	Examples
Nd, Pr, Sm, Dy, Tb	Permanet Magnet	Guidance and Control Electric Motors and Actuators, Stealth/Noise Cancellation	Smart Bombs, Joint Direct Attack Munition (JDAM), Joint Air to Ground Missile (JAGM), Cruise Missiles, Unmanned Aerial Vehicles (UAVs), AIM-9x, AIM-120 AMRAAM, Helicopter Acoustic Signature Reduction (NdFeB plus Terfenol-D)
		Electric Drive Motors	Zumwalt DDG 1000, Joint Strike Fighter (JSF), Hub Mounted Electric Traction Drive, Integrated Starter Generator, Combat Hybrid Power System (CHPS)
Y, Eu, Tb	Amplification of Energy and Resolution	Targeting, Detection, Countermeasures	Nd-doped Yttrium Aluminium Garnet (YAG) Laser for targeting and underwater mine detection (e.g. Magic Lantern), Laser Targeting (Air- and Ground-based), Counter-Improved Explosive Device (IED) (e.g. Laser Avenger), SaberShot Photonic Disrupter
Nd, Y, La, Lu, Eu	Amplification, Enhanced Resolution of Signals	Communications, Radar, Sonar, Radiation and Chemical Detection	Sonar Transducers, Radar, Enhanced Radiation Detection, Multipurpose Integrated Chemical Agent Alarm (MICAD), Microwave Amplification for Satellite Communication, High-Capacity Fiber Optics
Ce, La	Displays and Optics	Enhanced Battlefield Displays	Driver's Vision Enhancer (DVE), Avionics Displays
Various	Energy Storage, Density Amplification, Capacitance	Electronic Warfare and Directed Energy Weapons	Jamming Devices, Electromagnetic Railgun, Ni Metal Hydride Battery, Area Denial System (e.g. Long Range Acoustic Device or LRAD)

Figure 5. Examples of Rare Earth Applications in U.S. Military Systems[27]

II. America's Dangerous Dependence on China for Rare Earth Elements

Between 2015 and 2018, 80% of U.S. REEs were imported from China, and much of the remaining 20% of imported REEs were derived from Chinese raw materials[28]. In the last decade, the U.S. Government has become increasingly aware of U.S. deficiencies surrounding REEs. For example, the Department of Defense (DOD) produces the *Annual Industrial Capabilities Report to Congress* and biennial *Strategic and Critical Materials Report on Stockpile Requirements* to communicate the status of critical materials, with REEs appearing in both reports[29]. In 2017, President Trump signed Executive Order 13817, directing the Department of the Interior (DOI), in conjunction with other federal agencies, to create and maintain a list of

[27] David L. An, "Critical Rare Earths, National Security, and U.S.-China Interactions, A Portfolio Approach to Dysprosium Policy Design," RAND Graduate Dissertation (Santa Monica, CA: Sept, 2014), 53.
[28] Tracy, 1.
[29] GAO, 7.

mineral commodities that are vital to the U.S. economy and national security[30]. Rare earths were included on DOI's most recent list of *Critical Mineral Resources*[31]. In 2016, the U.S. Government Accounting Office conducted an assessment of all DOD reports and pertinent legislation on the subject between 2011 and 2015. The GAO concluded that U.S. national security depends on REEs, that the U.S. process for prioritizing and ensuring access is flawed, and that the U.S. is nearly completely reliant upon its peer competitor, China, for its REE supply[32].

The REE industry in the U.S. started out with heavy government investment through direct research and development, grants, public-private partnerships, tax incentives, and supportive public policies, but by the late '60s, the industry had transitioned almost completely to the private sector, with much of the government involvement replaced by more restrictive environmental policies as understanding of the radioactive hazards developed[33]. This procurement shift from U.S. government to domestic private industry to the global market was followed shortly by China's emergence into the REE sphere[34]. Once fully up and running, China's producers were less constrained by safety and environmental regulations, and by the '80s were able to undersell the rest of the international REE market[35]. To withstand the depressed market and stabilize prices domestically, China nationalized most of its REE industries[36]. By following a hands-off approach and turning a blind eye to China's manipulation of market forces, the U.S let domestic rare earth mining and processing atrophy and "dropped the rare

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[30] Klaus J. Schulz, et al., *Critical Mineral Resources of the United States-An Introduction.* Professional Paper 1802-A (Reston, VA: U.S. Geological Survey, 2017), 1.
[31] Tracy, 1.
[32] DOE, 7.
[33] Goldman, 145.
[34] Goldman, 145.
[35] Goldman, 151.
[36] Goldman, 151.

earth ball."[37] When China gained a monopoly over the REE market, the U.S. lost not only access to its own domestic REE reserves, but also the technical experts, specialized equipment, and intellectual patents needed to successfully rejoin the industry.[38] The 2008 recession and subsequent 2011-2015 defense drawdown further diminished the resiliency of the U.S. industrial base, concerning REE and other critical materials[39]. China's heavy government support for its REE industries is a long term commitment and likely to keep them in a dominant position for the foreseeable future[40].

The dangers of being reliant upon China were exemplified by its punitive actions toward Japan in 2010[41]. During a dispute over fishing territories, Japan arrested a Chinese fisherman that had violated Japanese territorial waters[42]. In retaliation, China cut off all REE exports until Japan released the Chinese ship captain without prosecution[43]. Had Japan held fast to its claims, the impact on their technology-heavy industries would have been disastrous[44]. The REE market has also been influenced by the increasing tensions between the U.S. and China. In August of 2017, President Trump ordered an investigation into Chinese trade policies, leading to a spike in Chinese REE export prices[45]. Then again in 2019, during another period of increased tensions, export prices soared (Figure 6) following President Xi's visit to a Chinese REE processing firm,

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[37] Goldman, 140.
[38] Goldman, 139.
[39] Jeffrey A. Green, "Industrial Base Gears Up for Great Power Conflict." *National Defense*, (Jan 2019) 18-19, https://www.nationaldefensemagazine.org/articles/2019/1/24/viewpoint-industrial-base-gears-up-for-great-power-conflict.
[40] Marc Humphries, Critical Minerals and U.S. Public Policy (Washington, DC: Congressional Research Service, June, 2019), 44).
[41] Goldman, 140.
[42] Goldman, 140.
[43] Goldman, 140.
[44] Green, 18-19.
[45] Reuters Staff, "Explainer: China's rare earth supplies could be vital bargaining chip in U.S. trade war." *Reuters, Aerospace and Defense* (May 2019), 7, https://www.reuters.com/article/us-usa-china-rareearth-explainer/explainer-chinas-rare-earth-supplies-could-be-vital-bargaining-chip-in-u-s-trade-war-idUSKCN1T00EK.

with the price of Nd up 25%[46]. More recently, the COVID-19 pandemic's disruption of Chinese REE refinery output has highlighted the U.S.'s vulnerable position[47]. As the now limited supply of Chinese REEs are being prioritized for Chinese consumption, U.S. automakers are having to halt production for weeks[48].

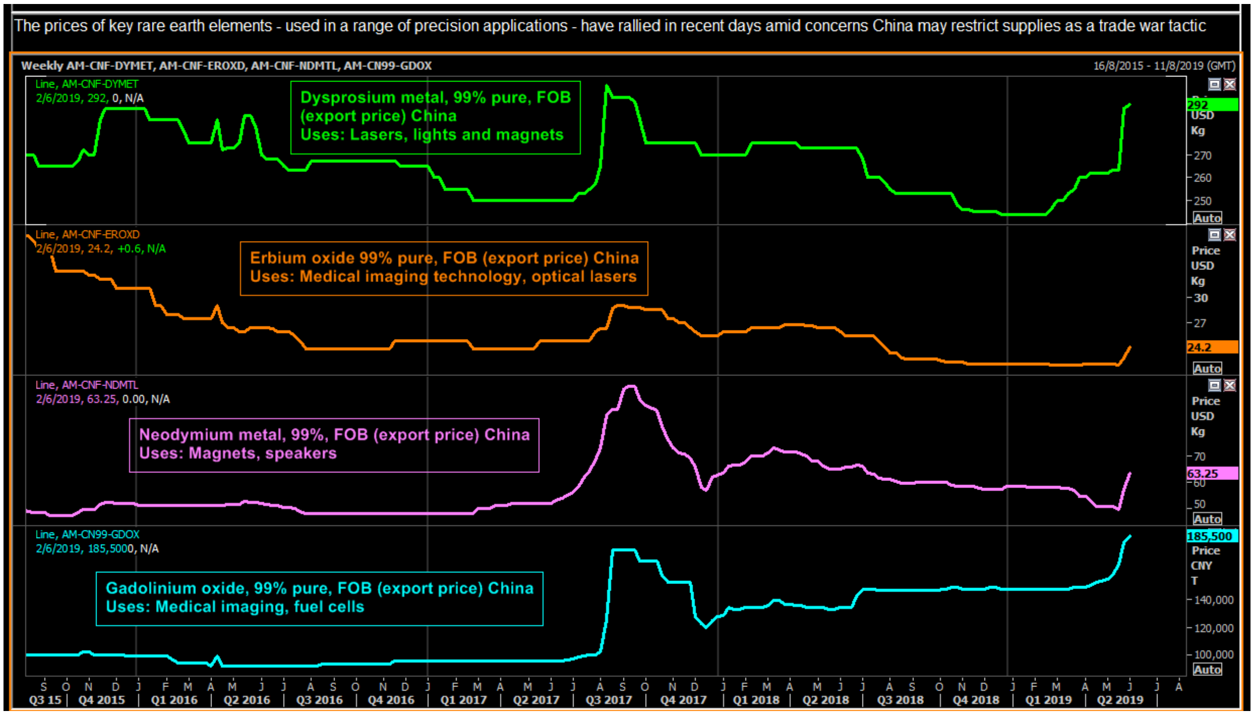

Figure 6. REE export prices surge as China rattles saber in the ongoing trade war with the U.S. [49]

Beyond price volatility, analysts are concerned that if the U.S. and China move from competition into conflict, the U.S. would only be able to sustain a fight for a limited amount of time before the lack of REE access crippled its ability to manufacture replacement parts or reserves of expendable resources[50]. This constraint would be acutely felt in the air-to-air fight,

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[46] Reuters Staff, 7.
[47] Bade, 4.
[48] Bade, 4.
[49] Reuters Staff, 3.
[50] Chapman, 61.

where the number of air-to-air missiles needed to defeat China's large aircraft inventory is likely greater than current stockpiles[51].

In spite of a robust understanding of the significance of REEs and the factors that led to U.S. international dependence, the problem persists. The *2019 Industrial Capabilities Report to Congress* highlighted some of the most recent steps that have been taken to mitigate the risk to critical REE supply chains, such as President Trump's use of the Defense Production Act to initiate, maintain, expand, and restore domestic capabilities related to REE production, separation, and processing[52]. While this is certainly a step in the right direction, it is insufficient and fails to solve the enduring dilemma of REE demand exceeding available resources because it lacks sufficient consideration of REE recycling.

Regaining domestic REE availability is not as simple as opening up old mines and processing facilities. The GAO's 2016 report estimated that it would take 15 years to rebuild the REE supply chain in the U.S., assuming the necessary infrastructure and patents could be acquired[53]. The Mountain Pass Mine was the world's primary source of REEs between 1965 and 1985 and is the only remaining U.S. producer of REEs[54]. After reopening for a second time in 2018 and producing 8.8% of the global REEs, the U.S. was still required to import 100% of the REE it consumed because of a gap in domestic processing facilities[55]. Analysts speculate that even if the Mountain Pass mine can continue contributing 5% of the global REE market, it will struggle without government intervention[56]. With China filing more rare earth patents than all other countries combined, it appears China's dominance in the REE mining and processing

[51] Chapman, 61.
[52] US Department of Defense, *FY19 Industrial Capabilities Report to Congress* (Washington, DC: Office of the Undersecretary of Defense for Acquisition and Sustainment, Jun 2020), 95.
[53] GAO, 13.
[54] Carrell,4.
[55] Tracy, 1.
[56] Carrell, 4.

realm, as reflected through their commitment to research and development, will be long lasting[57]. Finally, the quality of remaining REE ore deposits is declining, creating larger water and energy requirements for mining operations[58].

There are also clear environmental and health risks associated with the REE mining and processing industry, and these risks drive strict U.S. environmental and occupational safety standards that impede further domestic production of REEs[59]. Both Bastnaesite and Monazite, the two main types of rock in which REEs are found, naturally contain the radioactive compounds thorium and uranium[60]. Years of minimal environmental regulation and enforcement have resulted in over 10 million tons of radioactive wastewater being dumped into a now toxic lake surrounding the Chinese REE mine in Batou. Roughly 60,000 cubic meters of sulphuric and hydrofluoric acid are released for every one ton of rare earth produced; leading to ruined water supplies, agriculture, and medical issues[61]. In spite of plans to open a REE processing facility in Texas,[62] the U.S. REE mining and processing industries will always struggle to compete with Chinese REE producers and prices as long as they continue to have such lax environmental and safety standards.

In 2014, concern over U.S. reliance on strategic competitors spurred congressional action and the acquisition of REEs as part of the National Defense Stockpile[63]. The DOD is increasing

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[57] Marc Humphries, Critical Minerals and U.S. Public Policy (Washington, DC: Congressional Research Service, June, 2019), 44).
[58] Pieter van Exter, Sybren Bosch, Branco Schipper, Benjamin Sprecher, and Rene Kleijn, Metal demand for renewable electricity generation in the Netherlands, (Amsterdam, Netherlands: Metabolic, 2018), 4, https://www.metabolic.nl/publication/metal-demand-for-renewable-electricity-generation-in-the-netherlands/.
[59] Kyung Rim, Kwon Koo and Jung Park, "Toxicological Evaluations of Rare Earths and Their Health Impacts to Workers: A Literature Review," *Journal of Safety and Health at Work*, no. 4 (2013) 21, http://dx.doi.org/10.5491/SHAW.2013.4.1.12.
[60] DOE, 9.
[61] An, 27.
[62] Reuters Staff, 6.
[63] Humphries, 2.

domestic stockpiles of critical materials through the 2021 Annual Materials Plan[64] which is set to acquire various quantities of seven REEs, while also working with allies to create a shared National Technology and Industrial Base to leverage the collective capabilities of several nations[65]. While essential for guaranteeing a certain level of immediate resource security, stockpiling and renewed domestic mining will not be enough to address the growing global imbalance between supply and demand of these finite resources, especially considering that 38% of all global REE reserves are found in China (Figure 7) [66].

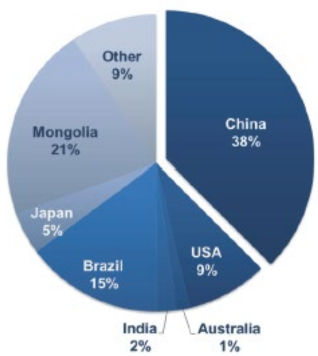

Figure 7. 2013 Global REE Reserves

III. Improved Recycling is Necessary to Help Provide the US with Long Term Access to Strategic Minerals

The global demand for minerals continues to reach new record highs as the increasing average standard of living merges with rising concentrations of REEs required for each new piece of technology[67]. Global demand for certain REEs is projected to grow between 700-

[64] Strategic Materials, *Annual Materials Plan for FY 2021* (Washington, DC: Defense Logistics Agency, 2021).
[65] Carrell, 5-6.
[66] Reuters Staff, 5.
[67] Schulz, 7-8.

2600% over the next 25 years, well exceeding the natural abundance found in ores[68]. By 2025, even the availability of raw Chinese REEs is expected to dwindle when China becomes the world's leading *importer* of REEs, as part of their shift to manufacturing finished products and the expanse of their green energy sector[69]. Only two strategies address this ultimate REE balance concern: innovation in REE recycling and REE replacement technology[70]. Unfortunately, REE substitutions are not always available without a loss in performance, if at all[71]. For example, substituting either REE neodymium or dysprosium in NdFeB "Neo" permanent magnets would render such a loss in performance that the battery would no longer be suitable for use in motors or certain military radar systems[72]. Additionally, when considering certain defense applications specifically, substitutions have not sufficiently demonstrated the required high heat tolerances afforded by REEs[73]. And so, while substitution must continue to be considered, the best chance at obtaining a sufficient quantity of REEs for the US military and economy, in the long run, requires a strategy inclusive of REE recycling. In fact, REE recycling would directly contribute to the resilient, diverse, and secure supply chain that President Biden has declared as necessary to U.S. economic prosperity and national security[74]. Growing the U.S. REE recycling industry requires two simultaneous efforts: increase the scope and effectiveness of US recycling operations as well as improve availability and access to the above-ground REE

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[68] R. Gueroult, J.M. Rax, and N. J. Fisch, "Opportunities for plasma separation techniques in rare earth elements recycling," *Plasma Physics* (Oct 2017), 1.

[69] Urban Mining Company: How A U.S. Company Uses Unconventional Resources to Meet a Strategic Defense Need, *Small Business Innovation Research-Domestic Capability for Magnet Production, Topic # DLA 161-003* (Washington, DC: DLA Strategic Materials, 2018), 2.

[70] R. Gueroult, J.M. Rax, and N. J. Fisch, 1.

[71] GAO, 22, 24 & 27.

[72] H.M. Bandara, et al., " Rare Earth Recycling: Forecast of Recoverable Nd from Shredder Scrap and Influence of Recycling Rates on Price Volatility," *Journal of Sustainable Metallurgy*, no. 1 (May 2015) 179.

[73] Carrell, 6.

[74] The White House, *Executive Order on America's Supply Chains*, February 2021, Presidential Actions, https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/.

sources. For the U.S. to be successful, both efforts will require much more support from the federal government and close coordination with allied countries.

An assessment of the sales from a single hybrid electric vehicle company indicates that over the next 10 years, enough end-of-life waste will be made available to supply the DoD's Neo magnet demand for 50 years[75]. The EU-funded QUMEC[76] project estimates that in Europe, current reserves of all REEs above ground (in waste products) could meet half of the annual demand with efficient recovery and recycling processes, resulting in roughly an 80% reduction in energy and greenhouse gas emissions when compared to traditional mining and ore processing[77]. As these above-ground alternative sources continue to grow, the earth's REE deposits are being transformed from underground ores of monazite or bastnasite to waste electrical and electronic equipment (WEEE) in landfills and scrap yards, making the ability to efficiently and effectively 'mine' these alternative sources critical to future REE access. Currently, roughly 80% of the end-of-life products in the EU that contain Nd are already being recycled for general purposes, but existing sorting and separation processes aren't designed to recover the REE materials, which ultimately get discarded[78]. If the REE separation process was developed, it is estimated that existing waste streams could meet approximately 60% of the current European Nd demand[79]. Additional estimates indicate that with the proliferation of hybrid vehicles and wind turbines, there will be as much as 460 tons of Dy available for recycling by 2030[80], highlighting the fact that investment into these recovery pathways needs to begin now to facilitate access to those

[75] Urban Mining Co.
[76] QUMEC stands for Quantifying urban mines in Europe and related implications for the metal-energy-climate change nexus.
[77] European Commission, Rare metals have huge potential for recycling in Europe, Research and Innovation (European Union, 2020), http://ec.europa.eu/research/infocentre/article_en.cfm?artid=51685, 1.
[78] European Commission, 2.
[79] European Commission, 2.
[80] An, 141.

future reserves. But some above-ground sources of REE could already be meeting demand. The EU estimates that if recycling facilities and processes were currently in place, they could meet 100% of their demand for Europium through recycling[81]. The EU is not alone in this struggle, recycling programs in the U.S. are anemic, with most states limiting collection to a narrow section of electronics[82].

One 2015 study forecast that by 2034, 42% of the total projected demand for Neodymium (Nd) will be recovered from ferrous scrap such as electric vehicle motors; but to have a stabilizing impact on REE availability, the recycling rate would need to exceed 50%, requiring recovery from additional waste streams[83]. The U.S. military, accounting for 9% of the global REE demand[84], needs to be an active participant in REE recycling of end-use products. Furthermore, one of the central challenges to REE recycling is that each individual element needs to be available in sufficient quantities and at relatively frequent intervals in order to supply demands and support constant recycling operations[85]. By including military waste in the recycling process, it bolsters the quantity of available REEs and ensures REEs used almost exclusively by the U.S. military are retained and reclaimed. Though previously rejected due to economic concerns and faced with a different threat environment, the DoD in 2012 identified the five applications (Figure 8) that hold the greatest REE recycling potential.[86] But unfortunately,

[81] European Commission, 2.
[82] An, 145.
[83] H.M. Bandara, 186-187.
[84] Reuters Staff, "Explainer: China's rare earth supplies could be vital bargaining chip in U.S. trade war." *Reuters, Aerospace and Defense* (May 2019), 3, https://www.reuters.com/article/us-usa-china-rareearth-explainer/explainer-chinas-rare-earth-supplies-could-be-vital-bargaining-chip-in-u-s-trade-war-idUSKCN1T00EK.
[85] An, 138.
[86] US Department of Defense, *Diversification of Supply Chain and Reclamation Activities Related to Rare Earths* (Washington, DC: Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, Feb 2014), 10.

no DoD-wide program to recover REEs from these applications exist, nor has this list been updated to reflect advances in REE recovery technology.

Product Type	Rare Earth	Potential Annual Amount (MT)
Fluorescent Lamps	Yttrium oxide	58
	Europium oxide	4
	Erbium oxide	3
Nickel Metal Hydride Batteries	Lanthanum	3.5 to 5
	Neodymium	3.5 to 5
Neodymium Magnets from Computers and Other Electronic Components	Neodymium	3.5
	Praseodymium	1
	Dysprosium	0.25
	Gadolinium	0.1
	Terbium	0.01
Thermal Barrier Coatings	Yttrium oxide	5
Automotive Catalytic Converters	Cerium oxide	20

Figure 8. 2012 Estimate of Rare Earths Theoretically Recoverable from DoD Applications[87]

The DoD is not new to the recapture of critical materials from waste. As part of the DLA's Strategic Material Recovery and Recycling Program (SMRRP), military bases send old aircraft engine parts (Figure 9) to DLA so super alloys can be stripped, saving the DoD money and reinforcing the domestic supply[88]. DLA's Precious Metals Recovery Program (PMRP) ensures that any unusable DoD property containing gold, silver, platinum, palladium, rhodium, iridium, osmium, or ruthenium is processed in a way that recovers those materials[89]. The program starts early on in the life cycle of most components with a Precious Metals Indicator Code (PMIC) assigned to the National Stock Number (NSN) of any component that contains precious metal[90]. DLA then offers these recovered precious metals at a stable and competitive

[87] US Department of Defense, 10.
[88] Dianne Ryder, "DLA Strategic Materials Partners with Research and Development," *Defense Logistics Agency* (October 2018), 2, https://www.dla.mil/AboutDLA/News/NewsArticleView/Article/1674904/dla-st/.
[89] *Defense Logistics Agency Website*. "Department of Defense (DoD) Precious Metal Recovery Program (PMRP)," accessed March 1, 2021, https://www.dla.mil/DispositionServices/Offers/Disposal/HazardousWaste/PreciousMetals/.
[90] *Defense Logistics Agency Website*.

price for future projects[91]. Both the SMRRP and PMRP provide excellent templates for how the DoD can improve its ability to reclaim REEs from its waste streams, with REE identification being a logical first step. To facilitate that effort, devices such as portable X-ray fluorescence analyzers, traditionally used in assessing geological samples, are proving to be useful at detecting the presence of some REEs in electronic devices[92].

Figure 9. Tinker AFB, Oklahoma, sends excess used engine parts to DLA's Strategic Materials Depot in Hammond Indiana, where Super alloys are then stripped from the parts.[93]

Europe provides another example of how to stop throwing away valuable amounts of REEs. In recognition of the changing nature of global REE reserves, and to reduce reliance upon China, the European Union (EU) has developed an effective method of recovering Nd from

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[91] *Defense Logistics Agency Website*.
[92] Chris Calam, "Rare Earth Element Metals Recycling: Is There Hope After All? (Part 1)," ThermoFisher Scientific (September 2016), https://www.thermofisher.com/blog/metals/rare-earth-element-metals-recycling-is-there-hope-after-all-part-1/.
[93] Ryder, 2.

WEEE. It has developed a three-step process of oxidation, selective extraction, and precipitation that allows for a cost-effective recovery of over 90% of the Nd[94]. Other efforts have found that Nd and Dy can be effectively recovered from old Neo magnets by using hydrogen to extract the REEs from waste hard disk drives (HDDs) in the form of a powder which can then be reformed into new magnets for a fraction of the energy required in primary magnet production[95]. There are also now methods of recycling Europium (Eu), Terbium (Tb), and Yttrium (Y) from flat screens, as well as Yt and Eu from cathode ray tube equipment and fluorescent lamps[96]. In addition to chemical and high-temperature processes for separating REEs from waste streams, there have been breakthroughs in the use of plasma mass filters, which can efficiently separate REEs from metals like iron but also contaminants, which could result in higher quality results across the REE recycling spectrum[97]. Due to the large quantities of REEs used (roughly 20,000 tons of REEs being used in 2008 alone), recovery of Lanthanum (La) and Cerium (Ce) from spent FCCs and fluid cracking slag provides a great opportunity, and recycling strategies have been developed that would enable the user to adjust purity levels based on current economic viability and recycling objectives, with recovery rates as high as 84%[98]. A user can choose to produce high-quality La and Ce distinctly for any number of applications or a large amount of La Ce mischmetal that is easier to produce and still has direct use in the petrochemical industry.

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[94] S. Peelman, J. Sietsma and Y. Yang, "Recovery of Neodymium as (Na, Nd)(SO4)2 from the Ferrous Fraction of a General WEEE Shredder Stream," *Journal of Sustainable Metallurgy*, no 4 (Mar 2018) 276.

[95] A. Walton, et al., "The use of hydrogen to separate and recycle neodymium-iron-boron-type magnets from electronic waste," *Journal of Cleaner Production*, no. 104 (May 2015) 236.

[96] Xin Song, Moon-Hwan Chang, and Michael Pecht, "Rare-Earth Elements in Lighting and Optical Applications and Their Recycling," J*ournal of the Minerals, Metals & Materials Society* 65, No. 10 (Aug 2013) 1280-1281.

[97] R. Gueroult, J.M. Rax, and N. J. Fisch, 8.

[98] S. Maryam Sadeghi, Joao Jesus and Helena Soares, "Recycling spent fluid cracking catalysts for rare earth metal recovery – a review," Journal of Recycling and Sustainable Development 11, (Nov 2018) 50.

When it comes to moving out of research and development into operations, forward-thinking members of private industry have led the charge[99]. For example, Japanese-based Hitachi, Mitsui Metal Mini Co., and Kosaka Smelting and Refining have developed the process and equipment necessary to effectively extract REEs from hard drives, motors, air conditioners, NiMH batteries, and more[100]. Companies in Nebraska and Belgium have set up facilities to recover the REEs which make up 20% of fluorescent lightbulbs[101],[102]. In the U.S., Apple's Material Recovery Lab has used machine learning to improve REE recovery from old iPhones, enabling the iPhone 12's battery and camera to be made of 100% recycled REEs[103]. Apple's efforts haven't only benefited REE consumption. Liam, the iPhone disassembly robot can take a phone apart in 6 seconds to recover gold, silver, copper, tin, tungsten, and cobalt, in addition to the REEs[104]. The recovered gold alone was valued at just under $40 million[105]. While significant progress has been made in the REE recovery and recycling realm, further research and development are needed to ensure access to the full spectrum of REEs, as well as to enable recovery from a wide range of source material as REEs are used in an increasing number of applications.

As advances in REE recycling take place internationally and across commercial industries, they create an opportunity for the U.S. to leverage its foreign allies and domestic industrial partners to form a robust, diverse, and stable supply chain across the REE spectrum

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99 An, 141.
100 An, 141-142.
101 Reuters Staff, 7.
102 An, 142.
103 Dimitris Mavrokefalidis, "Apple launches new iPhone model made using 'recycled rare earth materials'," Energy Live News, Efficiency & Environment, Technology (Oct 2020), https://www.energylivenews.com/2020/10/14/apple-launches-new-iphone-model-made-using-recycled-rare-earth-materials/.
104 Calam.
105 Calam.

while sharing the initial investment costs. Along these lines, The Defense Logistics Agency (DLA) has begun to successfully seize these opportunities through Small Business Innovation Research (SBIR) programs that aim to grow domestic REE recycling capability[106]. Between 2016 and 2017, DLA awarded about one million dollars to the emerging Urban Mining Company, enabling them to develop, optimize, and upscale a highly effective method of recovering REE alloy from domestic end-of-life devices and reprocess them into superior Neo magnets (Figure 10)[107]. Not only do the new magnets possess higher magnetic flux, higher coercivity, increased resistivity, and better thermal stability, but 100% of waste materials are utilized so there is zero output to landfills[108]. Tapping into the current 600,000 tons of available NdFeB material, UMC claims to offer a closed-loop solution where a customer's waste stream can support their future consumption[109].

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[106] Ryder, 4.
[107] Urban Mining Company: How A U.S. Company Uses Unconventional Resources to Meet a Strategic Defense Need, *Small Business Innovation Research-Domestic Capability for Magnet Production, Topic # DLA 161-003* (Washington, DC: DLA Strategic Materials, 2018), 2.
[108] Urban Mining Co., Technology.
[109] Urban Mining Co., Technology.

Figure 10. Urban Mining Company's closed-loop Neo magnet recycling process[110]

Because of the high quantities of REE's required, a circular economy based on recycling is viewed as key to the success of the renewable energy industry[111]. Up to 4600 metric tons of NdFeB will be required to meet the U.S. targets[112] for wind energy alone; a goal that U.S. REE production capacity cannot meet with domestic mining alone[113].

In 2020, the DoD granted the Urban Mining Company $28.8 million in Defense Production Act Title III funds to safeguard essential domestic industrial resources during the COVID-19 pandemic[114]. While most U.S. government subsidized research to this point has been focused on REE substitution rather than recycling[115], programs such as the SBIR offer hope of growing a domestic REE recycling industry. However, for the REE recycling industry to

[110] Urban Mining Co., Technology.
[111] Pieter van Exter, Sybren Bosch, Branco Schipper, Benjamin Sprecher, and Rene Kleijn, Metal demand for renewable electricity generation in the Netherlands, (Amsterdam, Netherlands: Metabolic, 2018), 4, https://www.metabolic.nl/publication/metal-demand-for-renewable-electricity-generation-in-the-netherlands/.
[112] DOE's goal is wind power supplying 10% of national end-use electricity demand by 2020, 20% by 2030
[113] Imholte, D.D. et al., 2.
[114] Colin Staub, "Rare earth recycler draws $28.8 million in federal funding.' E-Scrap News (September 2020), 3, https://resource-recycling.com/e-scrap/author/colinstaub/.
[115] An, 113.

succeed, it will require sufficient access to WEEE streams. Leaving WEEE management to the state level has resulted in fifteen states that have no WEEE legislation and the U.S. trailing behind the European Union in terms of WEEE recycling rates[116]. Without support in the forms of policy and economic incentives, the majority of WEEE, in particular, will continue to end up in the trash[117].

Yet another reason for strong U.S. government engagement and support in WEEE management, is to ensure long-term access to the full range of REEs for technological development as well as Research and Development, regardless of current marketability. There are distinct variations in significance and use of REEs (Figure 11) between various industrial sectors, between the U.S. and the rest of the world, between commercial and military sectors[118].

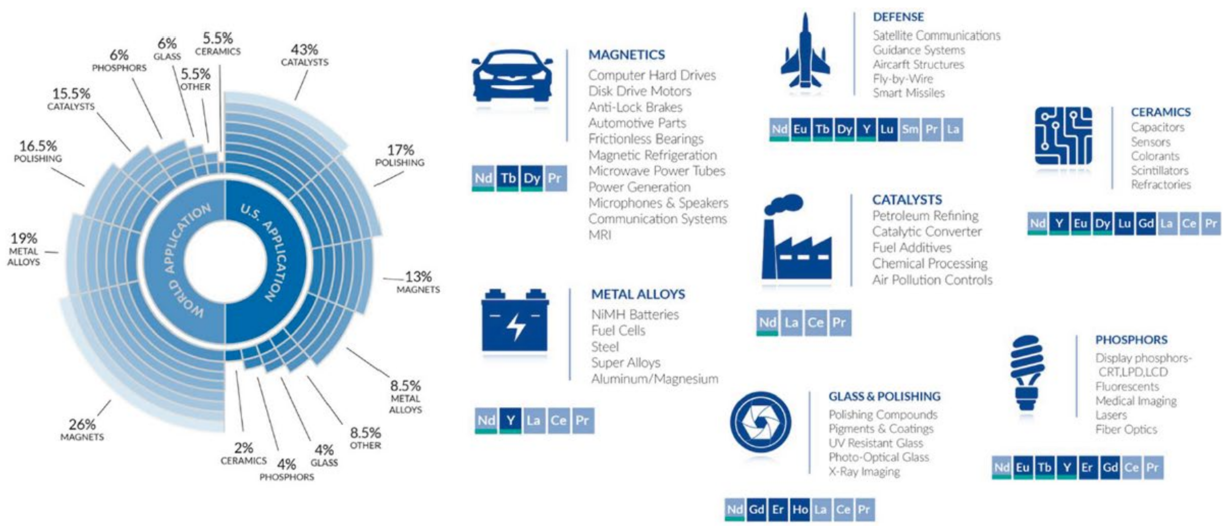

Figure 11. Overview of REE Demand[119]

[116] Brook Larmer, "E-Waste Offers an Economic Opportunity as Well as Toxicity." The New York Times Magazine (Jul 2018), 1, https://www.nytimes.com/2018/07/05/magazine/e-waste-offers-an-economic-opportunity-as-well-as-toxicity.html.
[117] Larmer, 1.
[118] Tracy, 8.
[119] Tracy, 8.

Current REE prices range widely and do not necessarily reflect the significance to national security. For example, in 2018 the per kilogram cost of Tb was valued at $455 while La was only $2, yet the defense sector relies much more on La[120], and thus it is afforded the highest acquisition ceiling out of all the REEs on the 2021 Annual Materials Plan[121]. Therefore, in addition to successfully passing some of the recently proposed legislation (Figure 12) that promotes REE research and development, technical training, and strategic forecasting[122], U.S. policy will also need to ensure economic incentives sufficiently support REE recycling during market variability to prevent market forces from targeting only highly lucrative minerals or undervaluing minerals disproportionately needed for military technology.

Legislation	Description	Sponsor / Introduction Date	Status
S. 1600, Critical Minerals Policy Act of 2013	S. 1600, the Critical Minerals Policy Act of 2013, was introduced on October 29, 2013, and referred to the Energy and Natural Resources Committee. The bill would require the Secretary of Interior and the Secretary of Energy to amend current policies, including "facilitate the reestablishment of domestic, critical mineral designation, assessment, production, manufacturing, recycling, analysis, forecasting, workforce, education, research, and international capabilities in the United States."	Sen. Murkowski, Lisa [R-AK]	1/28/2014 - Committee on Energy and Natural Resources. Hearings held
H.R. 761, National Strategic and Critical Minerals Production Act of 2013	H.R. 761, the National Strategic and Critical Minerals Production Act of 2013 was introduced on February 15, 2013, and referred to the Committee on Natural Resources on July 8, 2013, (H.Rept.113-138). The bill would require both the Secretary of the Interior and the Secretary of Agriculture to more efficiently develop domestic sources of the minerals and materials of strategic and critical importance to U.S. economic and national security, and manufacturing competitiveness.	Rep. Bishop, Rob [R-UT-1]	9/18/2013 - The bill passed in a recorded vote, 246-178. 9/19/2013 - Referred to the Senate Energy and Natural Resources Committee.
H.R. 1063, National Strategic and Critical Minerals Policy Act of 2013	H.R. 1063, the National Strategic and Critical Minerals Policy Act of 2013, was introduced on March 12, 2013. The bill would require the Secretary of the Interior to conduct an assessment of the current and future demands for the minerals critical to United States manufacturing, agricultural competitiveness, economic and national security.	Rep. Lamborn, Doug [R-CO-5]	3/15/2013 - Referred to the Subcommittee on Energy and Mineral Resources. 5/15/2013 - Ordered to be reported by Unanimous Consent.
H.R. 981, RARE Act of 2013	H.R. 981, the RARE Act of 2013, was introduced on March 6, 2013, referred to the Subcommittee on Energy and Mineral Resources on March 7, 2013. The bill would require the Secretary of Interior to conduct an assessment of current global rare earth element resources and the potential future global supply.	Rep. Johnson, Henry C. "Hank," Jr. [D-GA-4]	5/15/2013 - Ordered to be reported by Unanimous Consent.

Figure 12. Recently Proposed U.S. House and Senate Bills Pertaining to REEs[123]

[120] Tracy, 1.
[121] Strategic Materials, *Annual Materials Plan for FY 2021* (Washington, DC: Defense Logistics Agency, 2021).
[122] Marc Humphries, Critical Minerals and U.S. Public Policy (Washington, DC: Congressional Research Service, June, 2019), 51).
[123] An, 112.

IV. Conclusion

In 2014 the DoD provided an assessment on current REE risk mitigation efforts and rejected a strategy of REE recycling due to technological and economic hurdles[124]. Since that assessment was made, the U.S. has entered into an era of great power competition and increased global tension, naming China as its strategic competitor[125]. With China serving as the primary source for U.S. REEs, it is incumbent upon policy makers to take actions to reduce hurdles to recycling and support this key component of long-term REE security. U.S. enduring REE access hinges upon its ability to recycle the existing and untapped above-ground stores of REEs found in various waste streams. To cultivate domestic REE recycling capability will require support from the U.S. government through supportive policies, incentives, and investment in research and development (Figure 13). The U.S. will also need to coordinate with global allies to strengthen access to diverse REE sources and recycling technology. REEs are vital to U.S. national security due to their role as a force multiplier in current and emerging technology within both the commercial and governmental sectors.

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124 US Department of Defense, *Diversification of Supply Chain and Reclamation Activities Related to Rare Earths* (Washington, DC: Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, Feb 2014), 3.

125 US Department of Defense, *Summary of the National Defense Strategy of The United States of America* (Washington, DC: Office of the Secretary of Defense, 2018), 3.

	Improve access and exploitation of above ground REE stores/waste streams	Increase efficiency and efficacy of REE recovery and recycling processes
Diplomatic	Collaborate with allies and industry to exploit advances in AI technology to develop a robust global waste sorting and processing capacity to increase access to the strategic materials, especially REEs, in most common waste streams.	Coordinate with allies to maximize research and development efforts across the spectrum of REE recovery and recycling in a timely manner. Offer allies an alternative source of REEs from U.S. recycling, to decrease dependency on China.
Information	Conduct a patriotic appeal to consumers and municipalities to bring awareness to the value that REE-containing waste products have to national defense to encourage recycling of these products.	Increase federal funding for research and development to continue to improve the quality and efficiency of REEs recovered from waste material. Share relevant patents with U.S. and allied industry partners.
Military	Identify DoD equipment containing REEs and contract commercial sorting and processing to ensure military-essential REEs are recovered at the end of the life cycle.	Ensure REE are recovered from DoD's waste materials and made available to follow on recycling by U.S. commercial or defense industry.
Economic	Provide economic incentives to encourage the recycling of REE-rich equipment and divert critical materials from landfills.	Provide economic incentives for using U.S.-recycled REEs in commercial and government products.

Figure 13. Summary of Recommendations

Fortunately, this vulnerability is receiving more U.S. government attention and support due to President Biden's recent Executive Order on America's Supply Chains, in which he charges the Secretary of Commerce to identify risks and solutions in semiconductor manufacturing, the Secretary of Energy to identify risks and solutions for the high-capacity battery industry, and the Secretary of Defense to identify risks and solutions for the supply chains of critical and strategic materials such as REEs[126]. As part of strengthening U.S. supply chains for these three REE-intensive industries, the Executive Order also focuses on close cooperation with allies and partners in order to withstand potential international emergencies and form a robust international supply chain capacity[127]. This executive order is a good first step but needs to be backed up swiftly with a comprehensive domestic and international REE strategy supported by enduring bipartisan legislation and funding. Every day the REE balance problem gets worse and the Biden administration's goals of becoming a world leader in green energy and

[126] The White House, *Executive Order on America's Supply Chains*, February 2021, Presidential Actions, https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/.

[127] The White House, *Executive Order on America's Supply Chains*, February 2021, Presidential Actions, https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/.

electric vehicle production will only accelerate this REE timeline, so REE security must be prioritized to ensure the success of these objectives and the security of the American people.

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