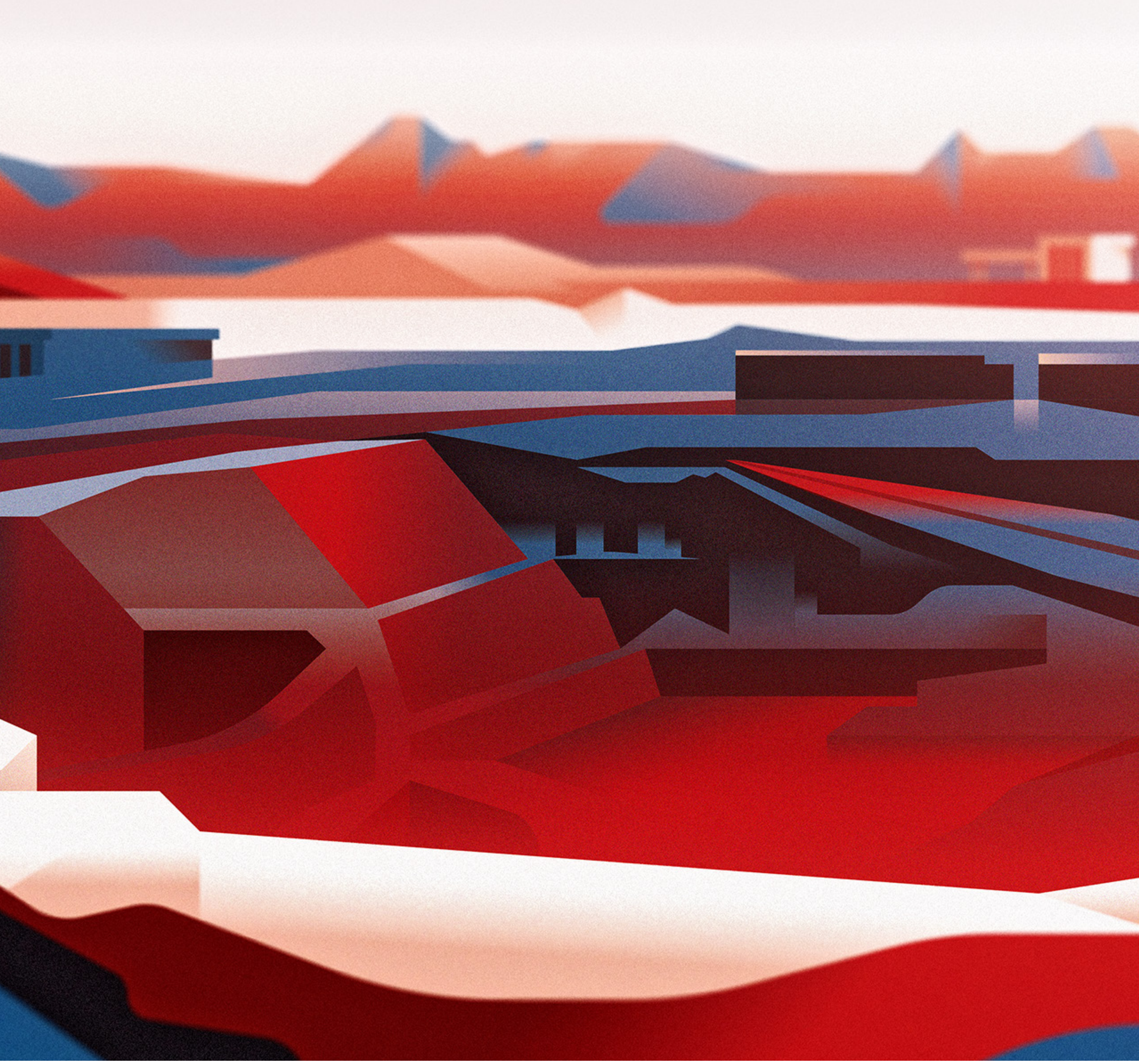

01.26.2023

Rare Earths for America's Future

DANIEL OBERHAUS

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EXECUTIVE SUMMARY

There are few materials that are quite as important for America's future security and economic prosperity as rare earth elements (REEs). These 17 metallic elements are essential inputs for weapon systems, clean energy technologies, and consumer electronics, yet for the past 20 years the United States has been almost entirely reliant on China for sourcing these critical materials. Today, the U.S. produces just 15% of the world's REEs and exports 100% of mined material abroad — primarily to China — for separation and refining. China, by contrast, mines about 60% of all REEs produced globally and has increased domestic production of REEs by 60% over the last five years alone. The national security implications of China's dominance of the rare earth supply chain are obvious, but viable solutions to securing America's rare earth supply are not.

This policy paper provides an overview of the past, present, and future of the REE industry in the United States. Its primary goal is to establish a framework for a sustainable domestic REE industry through streamlined permitting, tax reform, and high-impact R&D. It considers how to mitigate the environmental impact of REE mining, the challenges and opportunities for REE manufacturing and recycling, the hype and hope for unconventional REE sources, and concludes with four recommendations for a U.S. REE strategy, namely:

1. **Introduce tax incentives for domestic REE producers**
2. **Establish a federal coordinating body for REE mine permitting**
3. **Establish a federal REE recycling program**
4. **Prioritize federal support for REE alternatives**

Although these are not the only pathways to securing a domestic rare earths supply, we believe that these policies are the most feasible and effective solutions available to policymakers today. When it comes to establishing a robust American rare earths industry, time is of the essence. As we'll explore throughout this paper, China's dominance of this sector has been wielded for political leverage in the past with disastrous economic consequences that were felt across the globe. This may very well happen again in the future, but the stakes will be even higher given the increasingly central role that rare earths play in our daily lives. The key to avoiding this scenario will be decisive action designed to support the domestic rare earths industry at every step in the value chain from basic research and mining to processing and manufacturing. America was once the global leader in rare earth production and processing, and it can regain its leadership position once again through the intelligent policy decisions we make today.

INTRODUCTION

Over the past 50 years, rare earth elements (REEs) have become an indispensable part of our daily lives. Prized for their unmatched magnetic and conductive properties, the 17 metallic elements that fall under the REE umbrella (see Appendix A) are used in cars, lights, computers, fiber optic cables, phones, televisions, wind turbines, solar panels, as well as for more esoteric purposes such as anti-counterfeit features on banknotes, satellites, and the guidance systems in missiles. It is no exaggeration to say that modern life would not be possible without REEs, yet at present the United States does not have anywhere close to the production and processing capacity it needs to meet its growing REE demands. Instead, the U.S. is almost entirely reliant on an REE supply chain that is dominated by Chinese producers and processors. Even with the recent rare earth discovery in Sweden, it could take years to see the full impact of the new mineral source, and it likely would not fully alleviate the world's reliance on Chinese REEs. The growing awareness of America's vulnerability to REE supply shocks that can affect several aspects of our national security has underscored the importance of crafting a strategy that will ensure a sustainable supply of these critical elements well into the future.

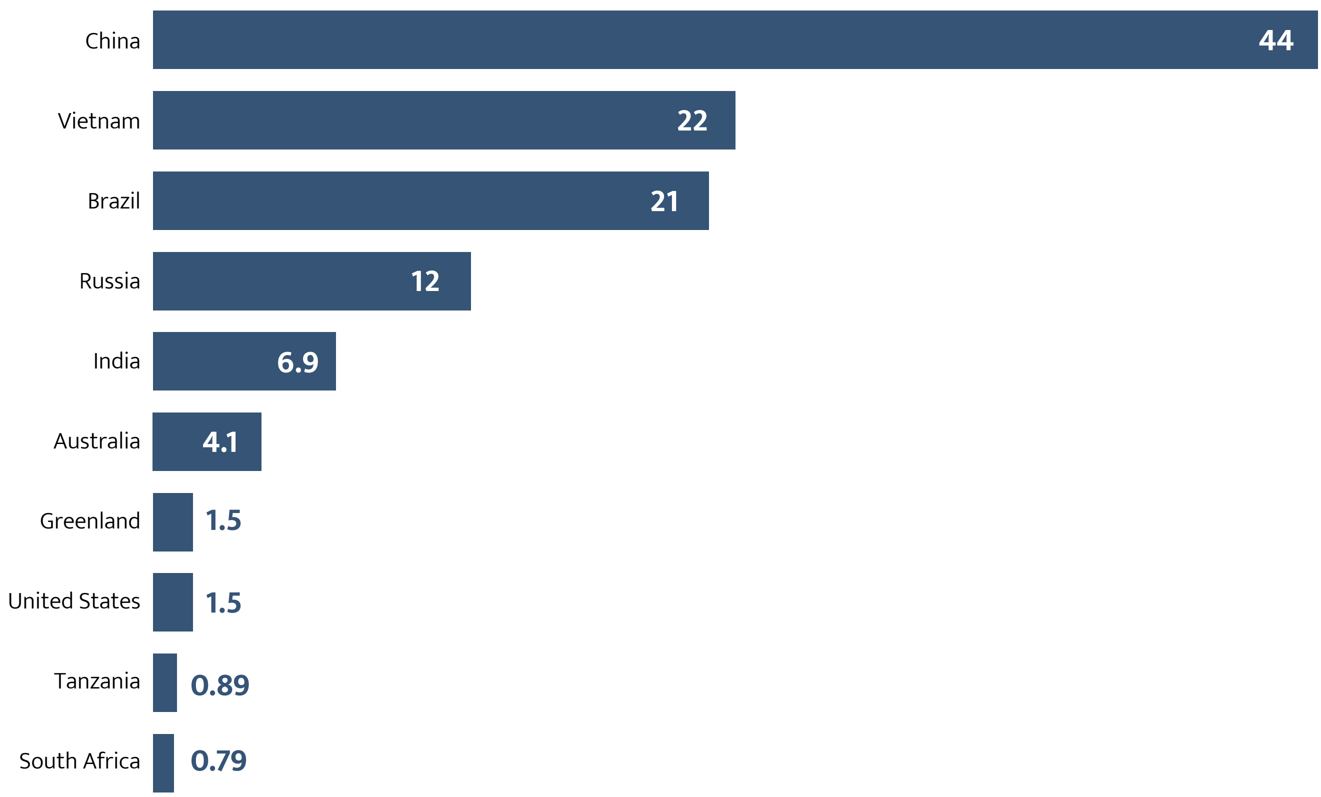
TABLE 1: THE RARE EARTHS LIFE CYCLE

CYCLE STAGE	CYCLE STAGE DESCRIPTION
REE Mining/ Production	REE mining (also referred to as REE production) involves the extraction of REEs from the earth. REEs are typically extracted from conventional open pit mines, but deeper deposits can also be reached with underground mines. REEs are never found in their pure elemental form; instead, they are always part of a mineral ore — most frequently monazite or bastnaesite. China is by far the world's largest REE producer and mines about 4 times more REEs than the U.S. annually.
REE Separation, Refining, and Processing	REE separation and refining (sometimes referred to as REE processing) refers to a multi-step process to extract the elemental rare earths from the mineral ore. There are a variety of techniques used to process REE minerals, but they typically involve crushing the mineral ore, creating an REE concentrate, and purifying the REE concentrate into a rare earth oxide using leaching and other processes. Various processing methods are discussed in greater detail below. Although multiple REE processing facilities are under construction in the U.S. and some REE concentrates are produced domestically, today 100% of the REEs produced in the U.S. are exported abroad — primarily to China — for separation and refining.
REE Manufacturing	Manufacturers use rare earth oxide powders to manufacture a variety of consumer electronics and other products. Processed REEs are rarely used on their own in the manufacturing process; instead, they are usually used as "doping" agents to enhance desirable qualities (such as magnetism) in other materials. Manufacturing that uses REEs occurs both domestically and abroad.
REE Recycling	REE recycling is the catchall term for processes that can extract relatively small quantities of rare earths from consumer electronics and other products. At present, the domestic REE recycling industry is still in its infancy. Most REE recycling processes are still being investigated in laboratory settings and only a handful of small scale REE recycling operations exist in the United States and globally.

Until the mid-1980s, the United States was the world leader in the production of REEs. At its peak, the U.S. supplied 33% of the world's REE demand — most of it from a single mine in California called Mountain Pass.[1] But beginning in the late 1980s, America's domestic production of REEs began a long and precipitous decline from which it has never recovered. The decline in U.S. REE production coincided with the birth of the digital era, which created a surge in demand for these materials that are used in computers and consumer gadgets. Concerns about the environmental impact of REEs production and processing pushed the industry to China, which quickly became the world's leading supplier of rare earths and their end products, such as high-performance magnets.

In 2002, the last active REE mine in the U.S. ceased production and by 2010, China controlled 95% of global REE production.[2] Over the past few years, the United States has once again started producing rare earths at the Mountain Pass mine in California, but China still controls the majority of global REE production.[3] In 2019, for example, China produced an estimated 132,000 metric tons of rare earths while the United States produced 26,000 tons of ores and compounds.[4] Of the limited quantities of REEs that are produced in the U.S., at the time of writing all of this mined material is shipped abroad — primarily to China — for processing. As a result of this lack of processing capacity, in 2019 100% of all REEs consumed in the U.S. were imported and the estimated value of these REE compounds and metals was $170million.[5]

FIGURE 1: GLOBAL REE RESERVES BY COUNTRY



SOURCE: USGS 'RARE EARTHS 2021'

The extreme concentration of REE production and processing in China is fraught with significant geopolitical, economic, and environmental risks. The world experienced the impact of China's dominance of the REE supply chain in September 2010, when China's military halted a routine shipment of REEs to Japan in response to Japan's detention of the captain of a Chinese fishing vessel.[6] China's blockade on REE exports to Japan came on the heels of two years of intentionally reduced production in the country, and between 2008 and 2011 the prices of some of these elements increased by as much as 2000%.[7] (See Fig. 2) The production of REEs in China has resulted in substantial environmental harm as a result of the preponderance of illegal mining operations and unsustainable mining practices at state-sanctioned projects. This was the primary reason cited by Chinese officials for introducing production limits.[8] Nevertheless, the perception that China was manipulating the market for these REEs led the U.S., Japan, and the European Union to file a WTO suit against China to relax its production controls.

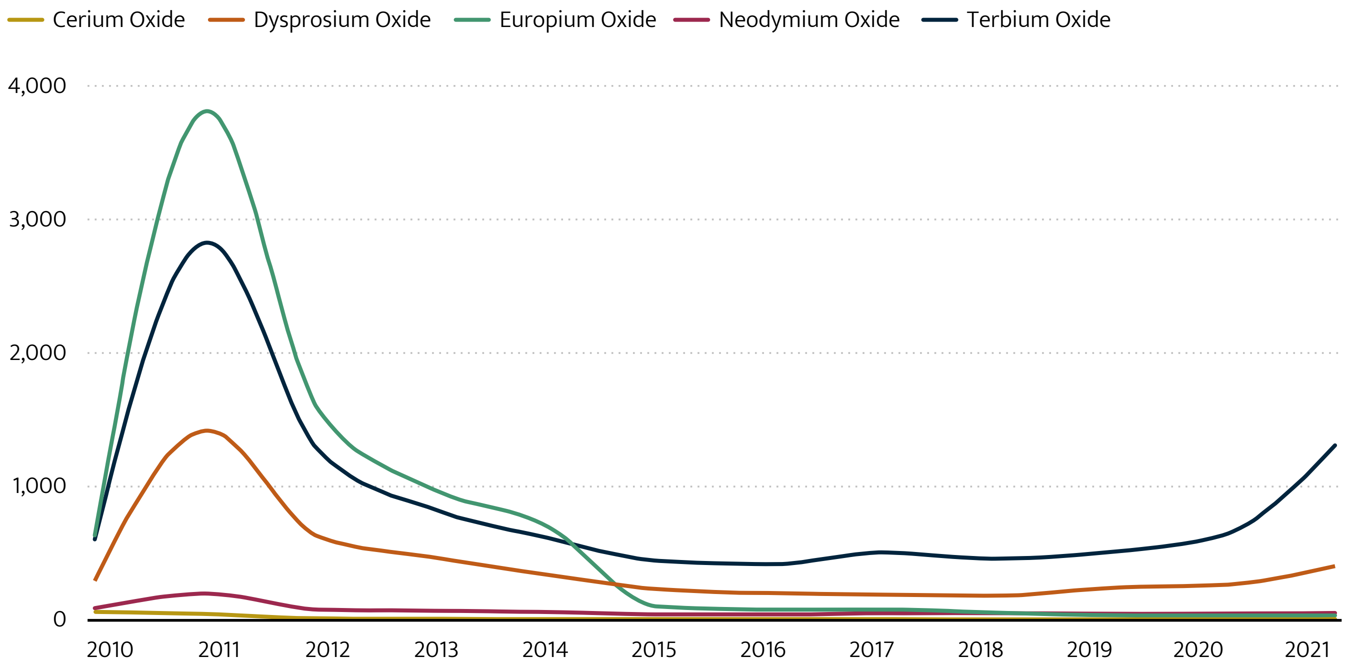
Despite America's efforts, the prices of REEs have steadily risen over the past decade and especially during the past two years as a result of the global pandemic.[9] Still, current estimates suggest that there are enough REEs in the world's mineable deposits to sustain production at current levels for another century.[10] However these estimates are subject to large assumptions about the growth of digitalization and electrification in the global economy, which will be the largest driver of REE demand in the coming decades. As of 2020, four countries — China, Brazil, Vietnam, and Russia — control approximately 83% of mineable REE reserves, with the bulk of these reserves concentrated in China. India, Australia, Greenland, Tanzania, South Africa, and the U.S. together account for another 13% of global deposits. In sum, 95% of all known mineable REE deposits are concentrated in just 10 countries in a markedly skewed distribution.[11] Given that the United States is home to just 3% of known mineable REE deposits, it is critically important for the country to explore alternatives to terrestrial mining for REEs, including their recovery from e-waste, industrial waste, deep sea and deep space deposits, and other unconventional sources.

The REE industry is dynamic and constantly evolving. As such, a full discussion of all emerging REE mining, processing, and recovery methods is beyond the scope of this paper. (Note: This paper will use the terms mining/production and refining/processing interchangeably.) While we have endeavored to give the reader the broadest possible overview of the domestic REE sector, there will inevitably be unintentional omissions. The same is true for the specific REEs covered in this report. The incredible diversity of qualities and applications of individual rare earths defies a comprehensive treatment in such a limited space. As such, we have decided to focus on policies that will help secure the most in-demand and commercially REEs, which are typically "light rare earths". These REEs include lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, and gadolinium. Of particular importance are praseodymium and neodymium due to their use in high performance magnets found in electric vehicle motors, computer hard drives, and a number of other consumer products. Except where it is necessary to highlight specific elements, this paper will default to the generic term rare earth elements (REEs) for the sake of clarity, although these elements may elsewhere be referred to as rare earth metals (REMs) or rare earth oxides (REOs) depending on the context.

BACKGROUND ON THE PRODUCTION, PROCESSING, AND USE OF RARE EARTHS

The term "rare earth element" is a misnomer. In fact, REEs account for 17% of all naturally occurring elements on Earth.[12] With the exception of promethium, of which only a few dozen grams exist on our planet, all of the rare earth elements are more common than silver, gold, and platinum.[13] Thus the challenge with procuring a sustainable supply of REEs is not so much their lack of abundance, but their relative inaccessibility. They are typically dispersed in such small concentrations in the Earth's crust that recovering them is difficult or impossible to achieve economically.

FIGURE 2: REE PRICES ($/KG)
THE AVERAGE PRICES FOR REOS AT YEAR END FROM 2010-2021



SOURCE: USGS
NOTE: AVERAGE PRICES FOR 2021 ARE ESTIMATED
NOTE: THE PRICE SPIKE SEEN IN 2010-2011 WAS THE RESULT OF CHINA'S EXPORT RESTRICTIONS ON RARE EARTHS AT A TIME WHEN IT CONTROLLED ROUGHLY 95% OF GLOBAL PRODUCTION FOR KEY REES.

REEs are found in a wide variety of geological contexts, although never in their pure elemental state.[14] Instead, they are typically found in small concentrations in mineral ores. In the U.S., the primary REE-containing mineral ores are bastnasite, monazite, and loparite.[15] The type of mineral ore that contains the REEs plays an important role in the extraction process, as discussed below. Today, there are more than 850 known REE deposits around the globe, of which less than 200 have been developed.[16] The U.S. Geological Survey has identified 23 hardrock deposits in the United States that are estimated to contain 13 million metric tons of REEs. (To put this in perspective, China is estimated to have 44 million metric tons of REE reserves).[17] America's REE deposits are spread across 14 states, with the majority of hardrock deposits located west of the Mississippi river.[18]

At present, nearly all REEs are produced through conventional mining processes and less than 1% of REEs are recycled.[19] There are two main "flavors" of REE deposits that determine the type of extraction processes used: hardrock deposits and placer deposits, which are found in the sediments of river beds or near large bodies of water. Hardrock mines have historically been the main source of REEs in the United States and are typically developed as either open pit or subterranean mines. These REE mines use the same fundamental exploration and extraction techniques as other metal mines that produce resources like copper, silver, and gold.

The REE production cycle has four main stages: exploration, development, extraction, and processing.[20] The exploration for REE deposits can involve both passive and active techniques. Passive techniques include sampling water, rock, and soil, remote sensing with satellites, and geophysical sensing techniques such as magnetometry or radiometric spectrometry. These passive exploration processes tend to have little to no environmental impact.[21] Active exploration techniques tend to involve a limited drilling program to quantify the size and composition of an REE deposit. The goal of these drilling activities is to collect core samples for mineral analysis and confirm certain attributes of a geophysical model of the resource such as rock hardness. A typical drill site is a few hundred square feet and the environmental impact of the drilling activities will strongly depend on the size and accessibility of the resource, as well as local geologic characteristics.

If exploratory activities confirm the presence of a substantial REE deposit, the organization conducting the exploration will move into the development phase. This stage involves a substantial environmental impact review conducted by the Environmental Protection Agency, the application for permits from state and federal regulators, and the creation of a feasibility study that outlines the scope of the project and the economics of its development. During this phase, the resource developer must demonstrate that the mine will not result in the degradation of wildlife habitats, air quality, water quality, and other environmental factors beyond limits established through state and federal regulations. The resource developer must also demonstrate that the mine can be developed economically in order to attract requisite investment in the project.

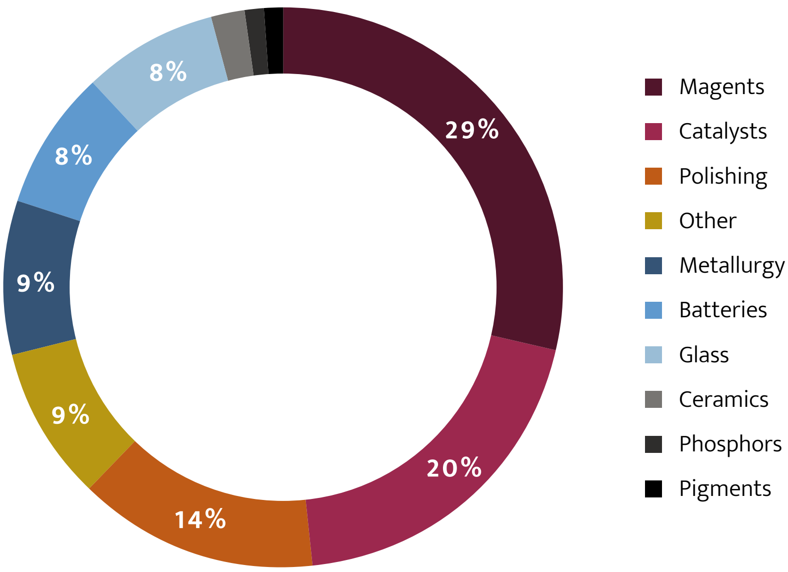
When a mine has secured its necessary permits, completed its environmental impact studies, and released its feasibility study, the resource developer is ready to begin extraction of the REE-bearing mineral ores. This process is similar to other metal ore mines and typically involves blasting rock and creating either an open pit or subterranean mine. One important difference between hardrock REE mines and other metal mines is that REE developers must be particularly careful about how they handle waste material due to the relatively high co-occurrence of REEs and radioactive elements like thorium and uranium.[22]

Once extraction is underway at an REE mine, the developer can begin processing the mineral ore to extract rare earth elements. The exact processing methods will depend on the characteristics of the mineral ore in the deposit, but in general the first step in this process involves crushing the mineral ore producing a rare earth concentrate using flotation, magnetic, or gravimetric processes.[23] After this stage, the REE material will exist in much higher concentrations, which allows for more efficient separation into its final elemental form.

While several separation processes exist to extract elemental rare earths from concentrates, the most common method is known as hydrometallurgy.[24] This is a catch-all term for solvent extraction processes that effectively "dissolve" the REE concentrate in a liquid and then leverage unique characteristics of the REE to extract a relatively pure element from the solution. For example, a common technique used in the REE industry today is known as "sulfuric acid baking," which involves converting the concentrated rare earths into sulfates through a reaction with sulfuric acid at high temperatures. The rare earth sulfates are then dissolved in a water leaching process, impurities are removed with lime, and individual rare earths are extracted in a solvent leaching process.[25] A common alternative technique is known as pyrometallurgy, which uses extreme heat to extract elemental rare earths. The most common pyrometallurgical technique in use today is known as oxidative roasting, which involves heating rare earths in an oxygen rich environment before subjecting them to a hydrochloric acid leaching process to produce elemental rare earths.[26]

After an REE has been separated into its elemental form, it is ready to be sold. The primary use cases for REEs in order of demand are: magnets, catalysts, polishing, metallurgy, batteries, glass, ceramics, phosphors, and pigments. Notably, magnets and catalysts alone account for a combined 50% of total REE demand.[27] Regardless of their end use case, REEs aren't typically used on their own. Instead, they are most commonly used in metal alloys where they are mixed with materials like iron or nickel to make them stronger or lighter. This process is known as doping and is why REEs are commonly referred to as metallic "vitamins."[28] While REEs may not be directly used in many applications, they can still account for a significant portion of the metallic content in many devices. For example, a typical wind turbine will require around 500 pounds of REEs per megawatt and an EV motor will contain around 2 pounds REEs.[29]

FIGURE 3: REE END USES - RARE EARTH ELEMENTS GROUPED BY END USE CASES



SOURCE: GOVERNMENT OF CANADA

THE CURRENT STATUS OF RARE EARTH PRODUCTION AND POLICY IN THE U.S.

While the United States has abundant REE reserves on the order of about 13 million metric tons, America accounts for a small fraction of global REE production and processing. Over the past decade, REE production has been dominated by China, which currently produces around 58% of the world's rare earths and controls around 85% of global REE refining capacity.[30] The United States, by contrast, produces about 15% of global REEs and has effectively no domestic refining capacity.

All of America's REEs that have been produced over the last decades have come from a single source: the Mountain Pass mine in California's San Bernardino County. This project started producing REEs in 1952 under the direction of the Molybdenum Corporation of America and at its peak in the 1980s, it met 100% of America's REE demands and accounted for 33% of global REE supply. The mine continued operations until 2002, when it ceased mining operations due to the weak prices for REEs that resulted from China flooding the global market. Since it first opened, the mine has seen a parade of owners, including the Chevron Corporation, Unocal, Molycorp, and most recently MP Materials, which acquired the mine in the summer of 2017 following Molycorp's bankruptcy. MP Materials restarted mining operations the same year it acquired the project.

At present, the Mountain Pass project remains the only active large-scale REE mine in the United States, but there are several other projects that are in various stages of development. While policymakers have been sounding the alarm about a looming REE shortage and a worrisome dependence on China for these critical minerals for more than a decade,[31] it wasn't until relatively recently that the U.S. federal government started allocating substantial resources to securing America's REE supply. In this section we will examine some of these initiatives as well as the main federal regulations that dictate the feasibility of new mining projects.

FEDERAL INVESTMENT IN REE PROJECTS

American REE developers enjoyed a substantial tailwind during the Trump Administration, which made the domestic development of strategic minerals a key pillar of its policy agenda. In December 2017, President Donald Trump signed an executive order directing several department heads of the federal government, including the Secretary of Commerce, Secretaries of Defense, and the Interior, Agriculture, and Energy, and the United States Trade Representative to "ensure [the] secure and reliable supplies of critical minerals," which includes REEs.[32] The final report found that for 31 of the 35 critical minerals identified in the report, the United States imports more than half of its annual consumption, and is completely dependent on imports to supply its demand for 14 of those minerals. In 2020, President Trump issued a follow-on executive order that invoked the Defense Production Act and instructed the Department of the Interior to direct funds to expanding the production of REEs and other critical minerals in the United States.[33]

In Congress, the Chairman of the U.S. Senate Energy Committee, Senator Joe Manchin (D-W. Va.) has emerged as one of the most vocal proponents of domestic REE Production. Shortly after President Joe Biden invoked the Defense Production Act to secure REEs and other critical minerals in March 2022,[34] Senator Manchin convened a Senate Energy and Natural Resources Committee on critical mineral supply chains.[35] Senator Manchin underscored his position that "more action is going to be necessary to get supply chains — including mining, processing, manufacturing and more — where they need to be domestically to keep up with the growing demand for these critical minerals instead of increasing our reliance on China." This is in line with a number of bills that have been introduced to the West Virginia legislature in 2022 that aim to spur the development of REE production in the state.[36]

While REE developers were already working on establishing new mines prior to Trump and Biden's executive orders, their issuance — coupled with increasing support from Congressmen in states like West Virginia and Texas — have given new life to the REE industry by both providing federal funding and streamlined permitting for REE R&D and commercialization efforts. A timeline of some of the most notable federal funding initiatives can be found in Table 2.

While these programs are a start, they still pale in comparison to investments being made into REE research and production abroad, such as Russia's 2020 announcement committing $1.5 billion to production projects in the country.[37] With some notable exceptions, such as the DOD's $28 million commitment to the Urban Mining Company, private REE developers in the United States have received relatively little federal funding to develop new projects so far compared to the state support seen in countries like Russia and China. As of June 2022, the U.S. DOD has allocated more than $200 million in contracts to companies working on America's REE supply chain.[38]

TABLE 2: U.S. FEDERAL FUNDING FOR REE INITIATIVES 2020-2022

DATE	AWARDING AGENCY	AMOUNT ($MM)	RECIPIENTS	FUNDING USE
July 2020	Department of Defense	**$28.8**	Urban Mining Company	Neodymium Permanent Magnets[39]
August 2020	Department of Energy	**$20**	DoE National Laboratories	Basic Research on REE supply[40]
September 2020	Department of Defense	**$122**	Various	REEs from coal and coal byproducts[41]
November 2020	Department of Defense	**$13**	MP Materials, TDA Magnetics, Urban Mining Company	REEs processing, REE magnets, REE stockpiling[42]
January 2021	Department of Energy	**$28.35**	Various	REEs from coal and alternative sources[43]
February 2021	Department of Defense	**$30.4**	Lynas Corporation	REE separation facility[44]
April 2021	Department of Energy	**$19**	Various	REEs from waste, regional resource characterization, technology development [45]
February 2022	Department of Defense	**$35**	MP Materials	REEs processing facility at Mountain Pass, CA[46]
February 2022	Department of Energy	**$140**	TBD	Design, construction, and operation of commercial REE extraction and separation from unconventional resources[47]
June 2022	Department of Defense	**$120**	Lynas Corporation	Construction of heavy rare earths separation plant[48]

REE MINES CURRENTLY UNDER DEVELOPMENT

Notably, the federal funding for REE initiatives has focused on supporting processing capacity and alternative sources of REEs, rather than supporting the development of new mines. While building a domestic processing capacity is essential for securing a sustainable REE supply chain in the U.S. given that all REE processing currently occurs abroad, these efforts need to be matched with increased production of REEs as well. There is a lot of work to be done in this area as can be seen from a brief overview of current mining efforts underway in the U.S.:

- **Mountain Pass (California):** The Mountain Pass mine in California began operations in 1952 and remains the United States' only operating rare earths mine. In 2021, Mountain Pass produced 42,400 tons of rare earth oxides contained in concentrate that was exported and separated outside of the U.S. The ore at Mountain Pass contains 15 of the 17 rare earths, although like most REE mines the primary rare earths mined at the facility are neodymium, praseodymium, cerium, and lanthanum. (Less than 2% of the rare earths in the ore at Mountain Pass are the 11 heavy rare earths.) The mine is operated by MP Materials, which plans to establish light and heavy rare earths refining facilities on site.

- **Bokan Mountain (Alaska):** The Bokan Mountain project has been under development by Ucore since 2012.[49] It aims to produce a total of 24,300 tons of rare earth oxides over its 11-year lifespan. The Bokan deposit contains 16 rare earth elements in various concentrations with significant concentrations of dysprosium, yttrium, and terbium.[50] Bokan boasts the highest grade of heavy rare earth resource in the United States. Ucore has planned further exploration studies in the summer of 2022 on the path to a prefeasibility study. In the meantime, Ucore is developing a proprietary REE extraction technology for a processing facility nearby the proposed mine site that expects to begin a commercial scale demonstration in 2022.[51]
- **Bear Lodge (Wyoming):** Bear Lodge is an REE deposit that has been under development by Rare Element Resources since 2010. In 2016, the project received a draft environmental impact statement from the U.S. Forest Service that recommended the project proceed, but tumbling REE prices put the project on hold. Rare Element Resources has since recommenced the permitting process. The project will produce a variety of rare earths with a particular focus on neodymium and praseodymium. In late 2021, General Atomics, which owns 48% of Rare Element Resources, received $21.9 million in funding from the U.S. DOE to pay for half the cost of building a demonstration processing facility near the planned mine site that is expected to be operational in 2023.[52]
- **Elk Creek (Nebraska):** The Elk Creek Project is under development by NioCorp and aims to produce a variety of critical minerals and rare earths. A feasibility study released in 2022 revealed that the Elk Creek site contains various amounts of all rare earth elements, but the primary focus will be on developing four magnetic REE oxides, namely: neodymium, praseodymium, dysprosium, and terbium.[53] In addition to these REOs, NioCorp also intends to produce critical minerals including niobium, scandium, and titanium. The mine has an estimated life of 36 years and 632 kilo tonnes of indicated rare earth oxides.[54]
- **Round Top (Texas):** The Round Top project is under development by the Texas Mineral Resources Corporation, which has been exploring the deposit for more than a decade. In 2013, TMRC issued a preliminary economic assessment of the project based on an extensive drilling program. The economically exploitable rare earths at the project include scandium, yttrium, praseodymium, neodymium, samarium, terbium, dysprosium, and lutetium. It recently entered into a joint venture agreement with USA Rare Earth to further develop the project with a near term goal of producing a feasibility study. In 2020, TMRC opened a pilot metallurgical plant in Colorado.[55]

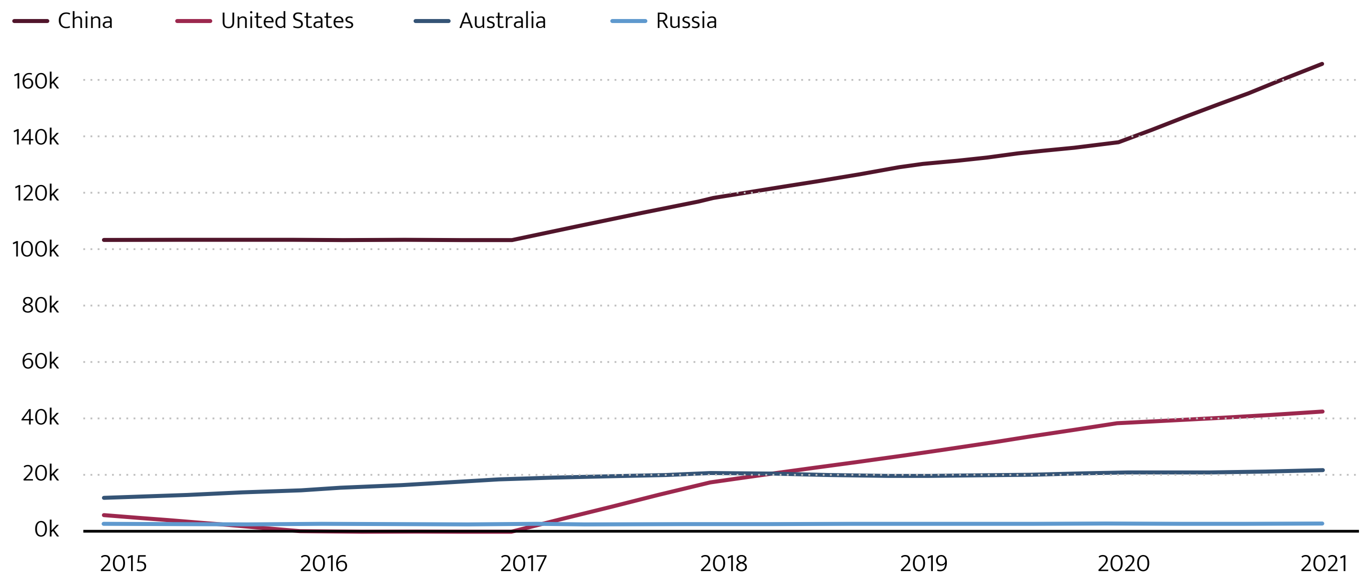
PERMITTING NEW MINES

In most respects, the regulation of REE mines is similar to the regulation of hardrock mines for other metals and minerals. Permitting new mines is a years-long process that typically requires mine operators to seek approval from a multitude of regulatory agencies at the federal, state, and local levels.[56] Generally speaking, federal law is mostly concerned with aspects of mineral ownership, operations, and environmental oversight, while state and local governments have authority over aspects of mining such as reclamation bonding, water rights, and permits for certain operations like truck haulage.[57]

At the federal level, a new REE mine can expect to engage several agencies, including the Bureau of Land Management (BLM), U.S. Forest Service (FS), U.S. Fish and Wildlife Service (FWS), Bureau of Indian Affairs (BIA), Bureau of Reclamation (BR), the Office of Surface Mining (OSM), the Department of Energy (DOE), and the Environmental Protection Agency (EPA).[58]

A notable difference between REE projects and other open pit hardrock mines is that some new REE mines will also be subject to oversight from the Nuclear Regulatory Commission (NRC) given the usual colocation of REE minerals and radioactive materials such as uranium and thorium, which produces waste classified as "Technologically Enhanced Naturally Occurring Radioactive Material".[59] The primary statute governing hardrock is the General Mining Law of 1872, a gold rush-era law that concerns the transfer of rights to mine minerals and metals on federal land and is administered by the BLM.[60] In addition to the General Mining Law of 1872, new REE mines must also comply with a number of other acts that are largely focused on limiting the environmental impact of a project including the Federal Land Policy and Management Act, the Clean Water Act, the Clean Air Act, the Endangered Species Act, the Wilderness Act, the National Historic Preservation Act, and the National Environmental Policy Act.[61,62,63]

FIGURE 4: ESTIMATED REE PRODUCTION BY COUNTRY



SOURCE: USGS
NOTE: THE INCREASE IN U.S. PRODUCTION STARTING IN 2017 IS ALMOST ENTIRELY ATTRIBUTED TO RESTARTING MINING OPERATIONS AT CALIFORNIA'S MOUNTAIN PASS MINE, WHICH REMAINS THE ONLY LARGE SCALE REE MINING OPERATION IN THE U.S.

The fact that new REE mines must comply with dozens of federal, state, and local regulations creates a significant drag on new project development. The complex regulatory environment exposes project developers to frivolous lawsuits that can delay the permitting process by months or years, but even in the absence of litigation many federal agencies simply do not have enough dedicated staff to field permit applications in a timely manner. There is also a notable lack of coordination between the various agencies, which results in substantial–but as yet unquantified–redundancies in the permitting process. For example, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) — better known as the Superfund law — allows the BLM, USFS, and state agencies to each require that mining companies demonstrate that they have the financial resources for reclamation of the mining project.[64]

On average, it takes about two years for a hardrock mine to receive permits in the U.S., but it is not uncommon for the permitting process to take more than a decade.[65] However, the actual length of time that it takes to permit an REE mine is unknown, given that the most recent new permit for this kind of project was granted in 1950 and permitting laws have changed substantially since then.[66] Several estimates, including from the U.S. DOE, suggest that the typical permitting time for a new REE mine is between 7 and 10 years.[67] According to a recent study by Argonne National Laboratory on REE supply chain risks, "the decision points that would make somebody want to open or close a mine ... largely comes down to a lot of regulatory elements."[68] As such, policies designed to streamline the permitting process for new mines is one of the most effective tools the U.S. has at its disposal for boosting REE production.

ADDRESSING THE ENVIRONMENTAL COST OF DOMESTIC RARE EARTH PRODUCTION

One of the biggest criticisms leveled against domestic REE production is the observation that such projects come with steep environmental costs. Any hardrock mining project will have negative environmental externalities that can include the production of acidic waste water, toxic gasses, large volumes of dust, and biodiversity loss. While this is also true of REE mines, these projects have gained a reputation for being particularly destructive because they also result in the production of low level radioactive waste and use relatively large amounts of water and energy compared to other mining projects.[69] The problem with this perception of REE is that it is largely based on China's mining experience, which until very recently was subject to hardly any environmental oversights. Moreover, these criticisms also fail to take into account new mining technologies and practices that can substantially reduce the negative environmental impact of REE mines. In fact, an increase in domestic REE production can have a massively positive effect on the environment by shifting mining away from international jurisdictions with little to no environmental protections.[70]

LESSONS FROM CHINA

The Chinese REE industry began to develop in the mid-1980s and expanded dramatically throughout the 1990s and early 2000s. Until quite recently, the extraction of REEs in China was largely unregulated, which resulted in a proliferation of small-scale illegal REE mines. One common method for extracting REEs at these Chinese mines used leaching ponds where acids and other chemicals are used to separate REEs from ore. The waste water from this process was then typically collected in plastic-lined pools for storage. Yet due to the lack of environmental regulations, these pools were often simply abandoned despite containing significant concentrations of toxic and radioactive chemicals. Today, it is not uncommon to see dozens or hundreds of these waste water pools dotting the hills in China's primary mining provinces such as Jiangxi and Guangdong where they are, in the words of one recent report, "just one landslide or barrier failure away from a spill of their contaminated contents into waterways or groundwater."[71]

In 2012, China's State Council issued a report on the "increasingly significant" environmental issues associated with REE production, which it described as having "severely damaged surface vegetation, caused soil erosion, pollution, and acidification, and reduced or even eliminated food crop output."[72] In fact, the year prior to this report, a product quality inspection initiative carried out by China's General Administration of Quality Supervision found that 19 out of 85 tea products examined contained excessive levels of toxic REEs.[73] The report marked the beginning of an intensive effort by the Chinese government to crack down on illegal REE mines and impose stricter environmental standards on sanctioned REE projects. The result of these efforts has been a significant consolidation of REE mining and processing companies into a handful of state corporations, which simplifies the process of ensuring compliance with environmental standards.[74]

Decades of REE production has taken a toll on China's environment and resulted in expensive cleanup and reclamation projects that the Chinese government has estimated will cost at least $5.5B.[75] Overexploitation of China's minerals has also severely impacted its reserves of REEs, which once accounted for approximately two-thirds of the world's reserves, but now accounts for less than half of global reserves.[76] China first took steps to address both the environmental and economic challenges posed by its largely unregulated REE industry in 2006 by decreasing its REE exports.[77] This marked the beginning of a period of instability and rapidly rising prices in the global REE markets that culminated in actions by the United States, Japan, and Europe through the World Trade Organization in 2012 that sought to remove China's export quotas for these critical minerals.[78, 79]

China's export controls on REEs must be considered in the broader context of its attempts to put its REE industry on sustainable footing which included restructuring its domestic REE industry and implementing more rigorous environmental standards. In 2011, China's Ministry of Land and Resources announced its intention to establish three rare earth production districts in the North, South, and West of the country. This decision had the effect of concentrating REE production into a handful of state corporations, which allowed China to limit price wars between smaller producers in the country and limiting oversupply of REEs in the global market.[80] That same year, China's Ministry of Ecology and Environment enacted Emission Standards of Pollutants in Rare Earth Industry, a statute designed to limit the amount of pollutants produced by REE miners.[81]

After a decade of China's reform initiatives for its REE industry, it is instructive to look at the economic impact of its environmental policies. Broadly speaking, China has attempted to improve the sustainability of its REE industry through economic policies (e.g., production quotas, resource taxes, and export duties), as well as explicitly environmental regulations that limit pollutants and set standards for mine reclamation.[82] Conventional wisdom suggests that greater regulation will undermine the competitiveness of an REE producer by imposing additional costs such as buying pollution abatement equipment and implementing new processes to ensure compliance with the regulations. On this view, the cost of enhanced environmental regulation should cause REE exports to fall as producers move to jurisdictions with less stringent environmental oversight to maintain their competitiveness in the global market. Indeed, over the past few years China has increasingly been importing heavy rare earths from Myanmar, where environmental regulations on mining are much less stringent.[83]

But recent research suggests that this conventional view of the economic effects of environmental regulations on REE production is misleading. In fact, based on REE export data from China to 17 countries, enhanced environmental regulations have actually promoted REE exports and improved productivity overall.[84] A potential explanation for this is the existence of so-called "innovation offsets," which are industry innovations that arise from stricter environmental regulation and can offset the cost of these regulations to firms.[85] Over the past two decades, an abundance of research has supported the theory of innovation offsets in industries such as manufacturing, energy, and agriculture.[86,87,88] For example, a study of U.S. oil refineries found that refineries subject to increasingly stringent and costly pollution abatement regulations saw a sharp increase in productivity compared to oil refineries that weren't subject to those regulations as a result of new technologies and processes that were adopted to comply with air quality standards.[89] China's recent experience of moving from a largely unregulated to a highly regulated REE industry suggests that it is both possible and economically desirable to enhance environmental regulations for REE production and processing. In short, stricter environmental regulations needn't undermine the competitiveness of a domestic REE industry and can drive innovation that makes producers more competitive in global markets.

LESSONS FROM MOUNTAIN PASS, CALIFORNIA

The Mountain Pass mine in southern California offers a useful counterpoint to the Chinese experience in REE production. Whereas China's REE industry consisted of thousands of illegal small-scale mines that operated in the absence of any environmental regulations for decades, the United States has only ever had a single large-scale REE mine that has always been subject to strict environmental oversight. The stark difference between the Chinese and American REE industries can provide a better understanding of the impact of environmental regulations on domestic REE production and how the United States can foster a more robust REE industry while maintaining strong environmental safeguards.

The Mountain Pass mine opened in 1952 and was operated by Molybdenum Corporation of America (later acquired by Chevron) until 2002, when it ceased mining operations due to competition from Chinese suppliers and environmental restrictions. In 2008, the mine was acquired by Molycorp Minerals, which resumed mining and processing activities until its bankruptcy in 2015.

Today, the mine is owned and operated by MP Materials, which resumed mining and processing activities in 2018. In 2021, MP Materials produced 42,400 tons of rare earth concentrates — the highest level of production in the mine's 70-year history — which accounts for about 15% of the rare earths consumed globally. In February 2022, MP Materials also received a $35 million contract from the U.S. DOD to fund the construction of a heavy-rare earth processing facility on site at Mountain Pass. The heavy rare earths processing capacity will complement MP Materials' efforts to build a light rare earth separation facility, which will begin operation in 2023, with support from the U.S. DOD.[90] The primary materials produced at the mine will be Neodymium-Praseodymium Oxide (a key input into high performance magnets) as well as cerium and lanthanum carbonate. With the completion of its heavy rare earth separation facility, MP Materials also plans to produce 11 heavy rare earth elements, both from Mountain Pass ore and, in the future, third party feedstock. Finally, MP Materials is also constructing a manufacturing facility near Fort Worth, Texas, which will begin producing rare earth alloys using materials from the Mountain Pass mine for General Motors in 2023 and finished magnets for GM products by 2025. Thus, MP Materials will likely represent the first organization that can supply an end-to-end source of REE products in the U.S.

While Mountain Pass is relatively benign in terms of its environmental impact, it has experienced several mishaps over its lifetime before being acquired by MP Materials. The most notable incidents occurred between 1984 and 1998, when a pipeline carrying waste water from the mine to evaporation ponds resulted in dozens of spills that leaked hundreds of thousands of gallons of waste water containing radioactive materials into the surrounding desert. An investigation into these accidents resulted in the termination of chemical processing at the mine and forced the mine's operator to pay $1.4 million in fines and settlements.[91] (This pipeline is no longer active.) Since taking over the mine in 2017, MP Materials has introduced a number of environmental controls including recycling 95% of the water used on site and using dry tailings, which store waste materials from the mining process as a concrete-like material that eliminates the risk posed by tailing dams that can leak toxic liquids into the local environment.

The reforms implemented by MP Materials after acquiring Mountain Pass from Molycorp weren't limited to mining, however. Some of the most important improvements involved overhauling the way that REEs recovered from Mountain Pass are processed. In particular, Molycorp removed a step in the process flow, oxidative roasting, which heated ore in oxygen-rich environments to remove impurities. Oxidative roasting is a well-established practice that has been in use for more than half-a-century, yet seems to have been abandoned by Molycorp to maximize the production of cerium, one of the lower-value REEs found at Mountain Pass. Instead of using this well-established process, Molycorp opted for a highly complicated multi-stage leaching and cracking process, which resulted in unsustainable operating costs and low levels of recovery of high-value neodymium-praseodymium oxide.

MP Materials is currently wrapping up the second stage of its process optimization plan, which it intends to conclude by late 2022. This will involve the reintroduction of the oxidative roasting process, recommissioning separation and extraction circuits, and upgrading the product finishing assets at the site. By reintroducing the oxidative roasting process, MP Materials is able to optimize production costs by selectively rejecting cerium, a low value rare earth, rather than subject it to the cost and reagent-intensive separation and refining process. The company has also implemented a new reagent scheme to enhance recovery and lower temperatures. Taken together, the reforms implemented by MP Materials at Mountain Pass will make the mine and its processing facilities both environmentally and economically sustainable.

RARE EARTHS RECYCLING: CHALLENGES AND OPPORTUNITIES

The challenges posed by permitting and funding new REE projects in the United States has led to a growing interest in alternative sources of these critical minerals. One of the most promising directions for alternative sources of REEs is recycling these minerals from e-waste such as used consumer electronics and spent EV components. E-waste is a significant problem in the United States with 7 million tons being generated each year, only a small fraction of which is recycled.[92] As such, recovering REEs from this waste stream can not only contribute to America's REE supply, but simultaneously alleviate the challenges posed by e-waste. At present, it is estimated that around 17% of the world's REEs are recycled.[93] Nevertheless, projections suggest that recycling could provide a substantial source of domestic REEs by 2050. A recent report from the U.S. National Renewable Energy Laboratory found that recycling hard drives alone — which depend on rare earths for their permanent magnets — could result in up to 107,000 metric tons of recovered REEs, which is double the total amount of REEs produced in the U.S. last year.[94]

The methods for recycling e-waste depend on both the type of rare earth being recycled and the product that it is being extracted from. The primary challenges associated with recycling rare earths from e-waste include sourcing the feedstock in an economically viable manner and the technical difficulties with separating REEs from end products. Rare earth recycling programs are still in their early days, but there are a number of efforts underway to advance these recovery processes in both the public and private sector. While these initiatives cannot be expected to recover enough REEs to meet the demand in the U.S. for the foreseeable future, the exponential growth in digital technologies — and green energy technologies in particular — suggest that e-waste recycling can become an important source of domestic REEs in the future provided these initiatives receive adequate support.

PUBLIC SECTOR INITIATIVES

Much of the fundamental work on recycling REEs from e-waste has been led by researchers in the U.S. DOD, DoE, and several academic institutions in the United States. These efforts have been focused on developing techniques for extracting the limited amount of REEs in e-waste such that the recovered materials can serve as raw feedstock for future products that require rare earths. One of the biggest challenges in these research efforts is overcoming the substantial cost associated with purifying the chemical mixtures obtained from consumer devices.[95]

In 2017, researchers at the University of Pennsylvania succeeded in developing an organic compound that was capable of selectively binding to rare earths. The unique properties of this organic compound allowed the research team to efficiently separate rare earths from other materials found in electronic devices in a single filtration step. Importantly, this process was optimized for two of the most common pairs of rare earth compounds — neodymium/dysprosium and europium/yttrium — which are typically found in permanent magnets and fluorescent light bulbs, respectively. The simplified extraction method not only reduces the cost of recovering rare earths from e-waste, its reliance on an organic compound also means that the extraction occurs in an environmentally sustainable compound that generates minimal toxic waste byproducts.[96]

More recently, a group of researchers at Penn State developed a new nanotechnology platform that leverages plant cellulose — found in both paper and cotton — to selectively bind to neodymium ions and separate them from other ions in a solution.[97] This process uses negatively charged cellulose nanoparticles to bind with the positively charged neodymium ions, which results in particles of this rare earth aggregating into larger pieces of neodymium that can be reused in other products. Unlike the acidic solutions used in most contemporary REE recycling processes, the process developed by the Penn State researchers uses an inexpensive renewable resource — plant cellulose — that doesn't depend on harsh acidic solutions. This process also holds the promise of extracting REEs from other waste streams such as industrial wastewater and mining tailings. This makes the solution both cost effective and clean, and a promising pathway toward sustainable REE recycling at scale.

While initiatives like the above provide a promising foundation for the future of REE recovery from e-waste, any practical solution must be capable of extracting REEs in a low-volume context. By contrast, today most REE recovery programs rely on processing e-waste in massive quantities to achieve economic viability. The problem with this approach, however, is that it requires collecting large quantities of e-waste and at present there are not well-developed networks for collecting e-waste and delivering it to specialized recycling centers. Overcoming this challenge will require novel extraction processes that are economically viable even in low-volume contexts. This allows for hyper-local recovery of REEs, which can drive down the cost of extraction while simultaneously encouraging e-waste recycling by consumers.

In 2022, DARPA launched its Recycling at the Point of Disposal program, which is providing funding to three universities — Iowa State, Arizona State, and MIT — plus the National Institute of Standards and Technology to develop low-volume REE recycling platforms that can handle e-waste from the DOD in a distributed manner.[98] If these teams are successful, their hardware will be capable of recovering REEs that would otherwise have been lost using sourcing critical minerals it depends on. conventional recovery methods. Furthermore, they are tasked with developing a process that can extract these REEs without generating toxic byproducts. At the end of the program, each team will demonstrate their hardware and successful projects can be scaled up to assist the DOD with sourcing critical minerals it depends on.

PRIVATE SECTOR INITIATIVES

Despite the flurry of research on REE recycling in the public sector, the commercial market for REE recycling is far less developed. Recent data suggests that the global market for REE recycling is currently $248 million and is expected to reach $422 million by 2026. While this 11.6% CAGR is notable and points to a rapidly expanding industry, it is still just a small fraction of the roughly $9 billion global REE market.[99] Nevertheless, several American companies are pursuing REE recycling today and are laying the foundation for a circular REE economy. This section will briefly highlight their approaches and progress:

- **TdVib,** an Iowa-based materials company, recently signed a license agreement for a technology that is capable of extracting REEs from high-powered magnets in e-waste. The technology was developed at the Critical Materials Institute, a DoE Innovation Hub led by the Ames Laboratory, and works by selectively dissolving REE-laden magnets in a solution that leaves non-REE materials undissolved. This water-based solution avoids the need for acids that can create toxic byproducts and simplifies the process of extracting REEs from shredded hard drives. Importantly, the process of commercializing this technology has resulted in a substantial improvement in its efficiency. Whereas researchers were able to achieve a leaching efficiency of REEs extracted from shredded e-waste of about 70% in the lab, TdVib has reportedly boosted this recovery efficiency to 90% by scaling up the process at its facilities.[100]
- **Nth Cycle,** an early-stage venture backed startup based in Massachusetts, has developed a process for extracting REEs from e-waste and mine tailings using electricity. Nth Cycle's process is based on a technique developed by researchers at Yale University that uses carbon nanotube filters to separate elements found in e-waste. By applying electricity at different voltages, Nth Cycle is effectively able to tune its device to separate out different elements based on how they respond to different voltage levels. While conceptually similar to a technique known as electrowinning that is commonly used in recycling common metals like copper, Nth Cycle's reliance on carbon nanotubes means its process can work at much smaller scales and still recover REEs even if they exist in minute concentrations in the e-waste.[101]
- **REEcycle** is a Texas-based metal recycling startup that has developed a technique for recovering REEs from high-powered permanent magnets that are found in hard drives, wind turbine motors, EVs, and other electronics. REEcycle spun out of work done by students at the University of Houston, who won the 2014 U.S. DoE Clean Energy Business Plan Competition and started REEcycle shortly thereafter.[102] REEcycle's proprietary solvent takes crushed permanent magnets that have had their nickel coating removed and selectively dissolves and crystalizes the REEs contained in the magnets. The solvent works at low pressures and relatively low temperatures, which is key to the sustainability of the process. To date, REEcycle has been supported entirely by $1.2 million in grants provided by the National Science Foundation, which it is using to construct its first demonstration plant facility.[103]

- **Noveon Magnetics** is a Texas-based manufacturer that recycles end-of-life permanent magnets and uses the resulting REEs from the recycling to manufacture new neodymium magnets in its facility. Noveon claims to be the only manufacturer of this type of magnet in the United States and is the only magnet manufacturer that can rely exclusively on recycled rare earth feedstock for its magnets. While little has been published about Noveon's recycling process, it claims to be able to extract rare earths from spent magnets without first shredding those materials and has reportedly achieved 95% recycling efficiency through its process.

The proliferation of early-stage REE e-waste recycling startups bodes well for the future of this industry in the U.S., but their success is far from guaranteed. It is highly likely that the United States will depend on recycled REEs to meet its demand in the coming decades, but it is less certain whether the REE recycling economy will mature quickly enough to support these companies. The cleantech investment boom in the early part of the last decade offers a cautionary tale. While investors threw a tremendous amount of capital at clean energy startups the market ultimately wasn't ready to support their products. Indeed, one of the casualties of the cleantech boom and bust was Blue Oak Materials, an REE e-waste recycling startup that raised $36 million from high-profile investors but has since shuttered its operations. In order to ensure that there is a mature ecosystem of REE recyclers available to meet domestic critical mineral needs, it is important for the U.S. to adopt policies that both support entrepreneurs in this sector while also establishing policies that incentivize recycling and the use of recovered REEs in end products.

UNCONVENTIONAL SOURCES OF RARE EARTHS

In addition to recycling REEs from e-waste, there are a multitude of efforts underway that are exploring unconventional sources of rare earths. While most of these pathways are still in the early stages of research, they represent promising potential sources of domestic REE production in the future. These efforts can be broken into three primary categories: REEs sourced from industrial waste such as coal and fly ash; REEs sourced from unconventional locations such as the seafloor and lunar surface; and alternatives to REEs that attempt to replace rare earths with materials that have comparable properties. This section will provide a brief overview of the status of each pathway and current challenges.

COAL WASTE / FLY ASH

Arguably the most prominent alternative source of REEs are rare earths sourced from the residue leftover from burned coal — fly ash — and other coal byproducts such as acid mine waste. Coal typically contains relatively low concentrations of REEs, but when coal is combusted it can concentrate these minerals in the ash by up to a factor of 10 compared to coal.[104] At present, most research efforts in this area are focused on characterizing coal waste sources to understand which have the highest concentrations of REEs and developing technologies to extract REEs from coal waste products. A variety of techniques are being explored such as using chemical processing or jolts of electricity to separate the valuable REEs from the glassy matrix that contains them in coal ash.[105] Other research groups are examining ways to extract REEs from waste ore generated in the process of coal mining as well as acid mine drainage, the highly acidic water that often seeps from mines and represents one of the most serious environmental threats from mining activity.

The National Energy Technology Laboratory (NETL) has been exploring the potential of extracting REEs from coal since 2010 and began partnering with researchers at West Virginia University in 2016 to further develop the technology. Since then, NETL has awarded more than 30 grants to universities focused on developing methods to extract REEs from coal waste, including opening a pilot scale REE extraction facility in partnership with WVU to advance the technology toward commercialization.[106] This pathway for REE production came to national prominence in 2019 when U.S. Senators Joe Manchin (D-W. Va.), Shelley Moore Capito (R-W.Va.), and Lisa Murkowski (R-Alaska), introduced a bill called the Rare Earth Element Advanced Coal Technologies Act (REEACT), which would support the development of technologies that can extract rare earths from coal and coal byproducts with an annual appropriation of $23 million for the DoE through 2027.[107]

While the REEACT bill did not pass in Congress, it was rolled into the Energy Act of 2020 mandated an assessment of the feasibility of economically recovering REEs from coal and coal byproducts.[108] In February 2022, the DOE launched a $140M program to establish a commercial-scale plant to extract rare earths from coal waste and in May, the Department of Energy released its assessment of this pathway to REE production, which found that there are (a) substantial quantities of REE in coal waste and byproducts to support large-scale pilot facilities to assess commercial opportunities; (b) it is technically feasible to produce high quality REEs from low-grade coal waste resources; and (c) it is possible to recover REEs from coal and coal byproducts in an environmentally sustainable manner.[109, 110] Based on the progress outlined in this report on both resource characterization and technology development, the DOE claimed that it has created the conditions to enable "large-scale pilot projects for producing hundreds of metric tons of mixed rare earths" by 2025.

While the work by the DOE confirms that there are sufficient quantities of REEs in coal waste and byproducts to justify extraction efforts and that it is also technically feasible to extract REEs from coal waste, it is still unclear whether this REE production method can be carried out economically. Many forms of coal waste typically have very low concentrations of REEs on the order of several hundred parts per million. To put this in perspective, the REEs produced at the Mountain Pass mine in California are pulled from high-grade ore where rare earths are present in concentrations of around 80,000 ppm.

Many industry observers have concluded that while it may be technically feasible to extract REEs from coal waste, doing so economically will require either a substantial increase in the market price of REEs or substantial government incentives for this pathway to REE production to improve its economics.[111] It will also be important for policymakers to consider the secondary benefits of this REE production pathway, such as supporting the economy in former coal regions such as West Virginia that have taken a serious hit as coal production has declined in the United States. Extracting REEs from coal waste in these regions could provide a serious economic benefit as well as help them deal with the environmental damage from decades of coal mining.[112]

REE ALTERNATIVES

A second pathway for addressing the United States' REE demands seeks to develop alternative materials that are substitutes for legacy materials that include REEs.[113] Generally speaking, the push to identify alternatives for rare earths has largely focused on replacing REE-based magnets (which may include neodymium, praseodymium, and/or dysprosium) given these magnets critical role in technologies such as wind turbines, hard drives, EVs, and consumer electronics.[114]

The hunt for alternatives to REE magnets began in earnest in 2011 following a surge in REE prices that resulted from China's export controls, which alerted policymakers to their almost total dependence on China's rare earths industry. That year, ARPA-E launched its Rare Earth Alternatives in Critical Technologies (REACT) program, which funded 14 projects exploring REE alternatives at American universities and national labs with a total of $31.6 million in grants.[115] The REACT program underscores the critical role that federal funding must play in creating a pathway to commercialization for REE alternatives.

Prior to REACT, it was highly uncertain whether REE-free alternatives to neodymium magnets could be developed that had both comparable performance and superior economics. It was a research program that required scientists and engineers to explore a vast problem space in materials science that was riddled with dead ends. It was the kind of basic R&D that was unlikely to be undertaken by private companies at their own expense until a stronger foundation had been laid by researchers at universities and government labs. REACT, in short, acted as a technology accelerator for a variety of early-stage magnetic material candidates.

ARPA-E primarily focuses on high-risk, high-reward research projects and unsurprisingly, many of the REACT projects failed to produce viable pathways to commercial REE alternatives. A notable exception is the Minneapolis-based startup Niron Magnetics, a company that is working to commercialize REE-free magnets that grew out of a REACT-funded project at the University of Minnesota exploring synthesis pathways for iron nitride.[116] Among the many REE-free magnet candidates that have been considered in academic studies, iron nitride stands out as having the highest magnetization of any known substance and being made from common, relatively inexpensive materials. As such, it represents a promising alternative for neodymium magnets that are used in a wide variety of applications including consumer electronics, electric vehicles, and wind turbines.

As a result of the funding provided to the University of Minnesota researchers through REACT, they were able to spin off their research into Niron Magnetics to explore pathways to commercialization. The basic R&D work done with support from the REACT gave investors the confidence to continue to support the development of iron nitride magnets with private funding. It still took 7 years after the REACT program ended to identify an ideal synthesis pathway for producing iron nitride, which the company achieved in 2019. Since then, Niron Magnetics has focused on developing processes to turn its iron nitride powder into commercial-grade magnets and is currently working on developing its first prototyping production facility for REE-free magnets.

At present, iron nitride permanent magnets of the type being developed by Niron Magnetics are arguably the most advanced REE-alternative on the pathway to commercialization. While REE-free magnets are unlikely to replace all REE magnets, research has shown that they compare favorably to REE magnets along a number of key performance metrics such as magnetic flux. (In fact, iron nitride has a theoretical maximum magnetic flux that is 50% higher than neodymium magnets, making it the most magnetic substance ever created—though work to capture its full potential in a commercial product is still ongoing.)

Aside from its performance, iron nitride also has the potential to avoid many of the negative externalities associated with REE mining and processing by virtue of the fact that it is made from iron that can potentially be sourced from recycled steel and ammonia, two inputs with relatively low environmental impact. Recent life cycle analysis of REEs and REE alternatives by researchers at the University of Purdue has indicated that iron nitride can reduce key water contamination metrics and greenhouse gas emissions by about 95% and 75% respectively relative to REE magnets.[117]

Accelerating the adoption of REE alternatives will require close coordination between manufacturers, federal funding agencies, and material producers. One important barrier to their adoption, for example, is that any new magnetic material requires redesigning for the devices that use them to optimize for the magnet's unique set of properties. To make this innovation possible, it will be important for policymakers to create incentives for REE development and commercialization. Federal agencies such as the DOE and DOD will need to focus on existing funding streams dedicated to supply chain security and environmentally sustainable innovation to the development and scaleup of promising REE-alternatives given the substantial risk, time, expertise, and capital costs associated with their development and manufacturing. Further, any incentives for domestic, traditional REE mining and processing (e.g., tax incentives and funding opportunities) must also be made available to domestic rare earth alternatives, to avoid unintentionally reducing the relative competitiveness of domestic innovations.

FRONTIER REE RESOURCES

Sourcing REEs from coal waste and developing alternatives to REEs are the most highly developed unconventional solutions pathways to securing a domestic supply of these critical minerals and the production of technologies that depend on them. However, there are also several alternative pathways in comparatively early stages of development that may also prove to be an important source of REEs in the future, but are unlikely to contribute substantially to the domestic REE supply in the coming decade. The three most promising "frontier REE resources" are biomining, lunar mining, and deep sea mining.

Biomining

Biomining is an umbrella term for techniques that leverage microorganisms to extract metals and minerals of interest from ore. Biomining works by using a natural property of some bacteria that are capable of selectively ingesting certain metals and minerals. These microbes are effectively leaching metals from an ore body as a byproduct of their natural functioning. This means that it is possible to create large cultures of microbes that feed on ores and then convert these vats of microbes into saleable metals. Biomining has already been used to extract commercial amounts of precious and industrial metals such as gold and copper from ore. This process not only limits the amount of toxic chemicals that need to be used in extractive processes, it also allows for the extraction of desirable metals and minerals from low grade ore bodies that would be uneconomic to exploit using more conventional methods. In 2021, DARPA launched its Environmental Microbes as a BioEngineering Resource (EMBER) program to explore pathways for biomining REEs.[118] The four-year program will focus on two primary technical challenges: bioengineering microbes and biomolecules to selectively bind to REEs in harsh environments such as geothermal fluids and developing biomining workflows to purify REEs from real source material.[119] The ultimate goal of the program is to establish a pilot-scale REE biomining demonstration.

Lunar Mining

The idea of mining REEs on the lunar surface was first given broad public attention when it was raised by former NASA administrator Jim Bridenstine in 2019, who predicted that REE mining would occur on the moon before the end of the century.[120] The interest in mining the moon for REEs has gained traction due to (1) the declining cost of space access resulting from the maturation of reusable launch vehicles developed by American companies such as SpaceX and Blue Origin and (2) NASA's mandate to establish a permanent presence on the lunar surface through its Artemis program.

There are a number of important unresolved questions about mining REEs on the moon that remain to be addressed, particularly the quality and quantity of rare earth deposits on the lunar surface. While past research has proven that REEs are present in trace amounts in lunar soil, the concentration levels of these critical minerals on the moon is still unknown, but estimated to be significantly lower than concentrations on Earth.[121] Our best estimates of lunar REE concentrations come from traces detected in samples of lunar meteorites and lunar regolith returned by the Apollo missions.[122] It is difficult to determine the true abundance of REEs on the moon based on these limited samples and substantially more surveying must be done before a conclusion can be made as to the abundance of rare earths on the moon.

A second challenge is the unfavorable economics of off-world mining. Although launch costs have fallen precipitously over the past decade due to the advent of reusable orbital-class rockets, it still costs on the order of $10,000 to send a kilogram of payload to the moon. SpaceX's next generation Starship rocket, which has been selected by NASA to deliver astronauts to the lunar surface, is expected to significantly lower the cost of lunar access, but even with this massive rocket in the mix, it will be difficult to justify the exorbitant cost of lunar mining operations for the foreseeable future. The economic challenges associated with deep space mining efforts are readily seen in the high-profile failures of two domestic asteroid mining companies — Planetary Resources and Deep Space Industries — which have effectively shuttered operations after being acquired and shifting their focus away from mining initiatives.[123, 124]

Deep Sea Mining

To date, all of the world's rare earth elements have been sourced through surface mining, generally in the form of an open pit mine. Current estimates suggest there are 120 million tons of REE reserves on land — with just 1.8 million tons of reserves in the U.S. — which is likely sufficient to meet global demand for REEs through at least another century.[125] Still, the abundance of REE deposits on land pales in comparison to the vast troves of REEs on the ocean floor that are pumped to the surface through hydrothermal vents. Current estimates suggest there may be as much as 100 billion tons of REEs in the mud on the bottom of the Pacific Ocean.[126] Indeed, one study identified a 1-square kilometer hotspot near Hawaii that may contain 25,000 metric tons of rare earth elements. This is equivalent to roughly 60% of the annual output of the Mountain Pass Mine in California.[127]

The abundance of deep sea REE deposits is alluring, but exploiting these minerals is rife with technological, economic, geopolitical, and environmental complications. While the concentrations of REEs identified in the mud around Hawaii are comparable to the concentrations of some operating mines in China, they are significantly harder to access, which may make recovery uneconomical. In terms of technology, recovering REEs from the ocean floor requires sophisticated robots, but at present nearly all of these robots are under development by foreign companies.[128] On the geopolitical front, the regulation of deep sea mining is controlled by the United Nations' International Seabed Authority, which is expected to vote on seabed mining regulations established by the ISA in 2023. Yet because the U.S. has not ratified the UN Convention on the Law of the Sea, a prerequisite to participate in ISA, it will not be part of the negotiations leading up to the vote.[129] Finally, deep sea mining is likely to have a substantial negative impact on the marine environment due to sediment raised from mining activities that can destroy seabed ecosystems well beyond the boundaries where the mining actually occurs. Given how little is known about deep ocean ecosystems, many oceanographic researchers are urging that more research needs to be done on the impacts of deep sea mining before these activities are allowed to commence.[130]

A FRAMEWORK FOR A SUSTAINABLE REE PRODUCTION STRATEGY IN THE U.S.

Over the past four decades, the United States has lost its position as the world's predominant supplier of REEs as a result of underinvestment in new domestic REE mines, processing capacity, and R&D activities. It is imperative for the United States to establish a new national framework for securing a domestic supply of these critical minerals given their increasing strategic and economic importance. While the U.S. has sufficient REE deposits to meet its needs through at least the end of the century, efforts to tap into this supply of critical minerals have been hamstrung by extremely inefficient permitting processes and insufficient economic incentives. In order to overcome these barriers to a robust domestic supply of REEs, the following four policies are recommended:

1. **Reform Tax Incentives for Domestic REE Producers at Each Juncture in the Supply Chain**
   Arguably the primary reason that the United States lost its lead as the world's primary producer of REEs is because its single mine in California could not compete with the cheap supply of REEs from Chinese producers flooding the global markets in the early 2000s. While elevated prices of REEs have reduced some of the economic challenges with developing REE projects in the United States, in order to create a truly competitive domestic REE industry policy makers should consider strong tax incentives for producers. Tax credits should be oriented both toward the production of raw materials as well as products made with REEs. A model of this type of legislation is the Rare Earth Magnet Manufacturing Production Tax Credit Act introduced

into the House of Representatives in 2021, which would provide a $20/kg tax credit for neodymium magnets produced in the US, which could grow to a $30/kg tax credit if those magnets are made with REEs sourced from domestic mines.[131] While tax credits for finished REE products are important, the US also needs to incentivize new rare earths production, which means it should establish tax credits for operators at each juncture in the US supply chain (e.g., credits for the production of refined REEs.) These kinds of tax credits have been shown to be powerful tools in other sectors like clean energy, where production credits have played a major role in increasing America's supply of wind and solar power, and can play a similar role in fostering the creation of a substantial domestic REE industry.

2. **Establish a Federal Coordinating Body for REE Mine Permitting**
   One of the most significant impediments to new REE mines in the United States is the long permitting timelines that require developers to interface with dozens of state and federal regulatory agencies. While these permitting activities are necessary to prevent unnecessary environmental degradation resulting from mining activities, there is a significant opportunity for policy makers to streamline the permitting process. The most effective pathway for accomplishing this would be to establish a federal coordinating body that works with state-level permitting boards to eliminate duplicative permitting requirements and expedite the permit review process through close collaboration across all relevant state, federal, and local agencies. Establishing this coordinating body should be accompanied by Congressional legislation that removes the need for developers to comply with duplicative environmental impact assessments. At present, an REE developer will typically have to complete an EIS to comply with NEPA and several states also have the authority to request that developers furnish a nearly identical EIS under the State Environmental Policy Act (SEPA), which can add several months or even years to the permitting process. In addition to eliminating many duplicative permitting steps, the federal coordinating body would ensure that all participating agencies are on the same page when it comes to assessing a new project. Today, many of the relevant permitting agencies are understaffed and lack insights into the actions of other agencies, which results in unnecessary delays due to a lack of coordination. A federal coordinating body will help developers understand which agencies they need to talk to and when, while ensuring these agencies address new permit applications in a timely manner.

3. **Establish a Federal REE Recycling Program**
   While recycled REEs will not be a substantial source of critical minerals in the near future, as products that use REEs continue to proliferate–largely driven by mass electrification and the clean energy transition–they will likely become an important source of REES in the coming decades. The United States should prepare for this future today by establishing a federal program designed to increase the number of consumer electronics that make their way into the recycling ecosystem. There are many models that this recycling program could follow, such as deposit programs for beverage containers coupled with

ordinances requiring consumers to recycle products containing REEs. One example is legislation proposed in 2020 through the Clean Economy Jobs and Innovation Act, which would require the DOE to establish a research program for recycling REEs specifically from energy storage systems.[132] A broader federally led program will help REE recycling overcome its "chicken-and-egg" problem where recyclers are disincentivized to pursue REE recycling due to a lack of feedstock and profitability, yet consumers lack the knowledge about which items to recycle or convenient method for recycling them. By working with states to establish a comprehensive national REE recycling program, the federal government can proactively prepare for the growing end-of-life supply of REEs in the coming decades and ensure that these REEs contribute to a closed-loop ecosystem.

4. **Prioritize Federal Support for REE Alternatives**

   Over the past few years, the Department of Defense and the Department of Energy have launched a number of programs aimed at supporting R&D on unconventional sources of rare earths. One of the most well-funded pathways is research on extracting rare earths from coal waste products such as fly ash and acid mine drainage. While coal waste is a promising potential source of REEs, the concentrations of critical minerals in this waste are so low that it is unlikely to supply more than a small fraction of the United States' REE needs. Moreover, given that America is phasing out coal, supplies of REEs that rely on coal waste cannot be relied on for the long term. Instead, the United States should prioritize funding projects that seek alternatives to REEs. This may be in the form of novel materials that have similar properties to REEs or new designs for systems that remove the need for REEs. When it comes to unconventional sources of REEs, this is the highest impact use of federal R&D dollars given that it can spur technological innovation in areas such as consumer electronics, transportation, and defense systems while simultaneously limiting our reliance on an inherently limited supply of rare earths. There are a variety of pathways for spurring research on REE alternatives, yet we recommend that any program include the establishment of innovation prizes led by national laboratories. In the past, this approach has been fruitfully used to encourage innovation in a variety of domains and should be considered as an important tool for encouraging research on REE alternatives.[133]

CONCLUSION

Our analysis of the current state of the REE supply chain in the United States suggests that if the aforementioned policies were implemented, it would substantially alleviate strains on the domestic supply of REEs. To date, policy discussions around securing a domestic REE supply have focused on increasing mining of REEs and establishing processing facilities in the United States. While these are certainly critical components, it is clear that there must be comparable federal investment and policies focused on supporting other areas of the REE value chain. In particular, the U.S. must support more basic research on REE alternatives and unconventional REE sources while establishing incentives for manufacturers to embrace domestically produced REEs.

The importance of REEs to a wide variety of national priorities, especially defense and the clean energy transition, encourages policy makers to act with urgency to secure a domestic supply of these materials. The long timelines associated with standing up new REE production and processing capacities means that even if action were taken today, it will likely be several years before the full extent of these policies are felt in the United States. In the meantime, the U.S. will be almost entirely dependent on China and other foreign suppliers for its critical mineral needs. This is a bipartisan policy issue that is fully within the capabilities of the United States to address and it has been neglected for far too long.

ABOUT THE AUTHOR

Daniel Oberhaus is a science writer based in Brooklyn, New York. He was previously a staff writer at Wired magazine covering space exploration and the future of energy. His first book, Extraterrestrial Languages, is about the art and science of interstellar communication and was published by MIT Press in 2019.

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APPENDIX A: TABLES AND DATA

TABLE 3: THE RARE EARTH ELEMENTS

ELEMENT NUMBER	RARE EARTH ELEMENT	USE CASES
21	**Scandium**	Aluminum alloys, lighting, alloys for the aerospace industry
39	**Ytrium**	Lasers, red phosphors, cancer drugs, ceramics, fuel efficiency, microwave communications for satellites, color televisions, computer monitors, temperature sensors, targeting and weapons systems
57	**Lanthanum**	Refinery catalyst, camera lenses, lighter flints, batteries, catalysts for petroleum refining, electric car batteries, digital cameras, video cameras, x-ray films
58	**Cerium**	Car catalytic converters, glass polishing agent, lighter flints, catalyst, polishing, metal alloys, lens polishes, silicon microprocessors, disk drives
59	**Praseodynium**	Magnets, lighter flints, greenish-yellow glass and ceramics, corrosion resistance in magnets
60	**Neodymium**	Magnets, lasers, violet glass and ceramics, fluid fracking catalyst, magnets used in laptops, guidance and control systems for DOD
61	**Prometheum**	Luminous paint, pacemaker batteries, fluid fracking catalyst
62	**Samarium**	Magnets, cancer therapy, nuclear reactor control rods, high temperature magnets
63	**Europium**	Red phosphors for lighting and color displays, LCD displays, fluorescent lighting
64	**Gadolinium**	Refractive glass, MRI contrast agent, nuclear reactor shielding
65	**Terbium**	Green phosphors for lighting, magnetostrictive alloys
66	**Dysprosium**	Stabilizing additive in magnets, lasers, commercial lighting, hard drives
67	**Holmium**	Lasers, magnets
68	**Erbium**	Lasers, fiber optics, nuclear reactor control rods
69	**Thulium**	Portable X-ray source, light filaments, lasers, production of surgical lasers used to treat neurological and prostate conditions and because it shines blue under ultraviolet light
70	**Ytterbium**	Lasers, chemical reducing agent, stainless steel additive, cancer therapy
71	**Lutetium**	PET scan detectors, refractive glass, refinery catalyst

NOTE: THE 17 RARE EARTH ELEMENTS, THEIR ATOMIC NUMBERS, AND PRIMARY USE CASES. LANTHANIDE SERIES ELEMENTS ARE HIGHLIGHTED IN GRAY.

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The future can be a better, more vibrant place, but we will need significant technological breakthroughs to get there. To solve climate change, cure diseases, prevent future pandemics, and improve living standards across the globe we need continued scientific advancement and technological improvements. The United States is particularly well-positioned to drive these advancements because we are on the frontier of knowledge ourselves. Even small changes to the way we govern and incentivize science and technology can have long-run consequences for the U.S. and for the world.

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