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Cost Effectiveness Analysis of Rare Earth Element Supply Chain Policy

December 2024

CPT James A. Reynolds, USA

Thesis Advisors: Dr. Robert F. Mortlock, Professor
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Department of Defense Management

Naval Postgraduate School

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ABSTRACT

The purpose of the research is to investigate and analyze the cost-effectiveness of alternative sources of rare earth elements (REM) in preparation for and in the early stages of a conflict in East Asia. This research explores the criticality of REM, their sources, and the factors that would inhibit their use during an East Asian conflict. This research is conducted by analyzing open-source scholarly, professional, and technical written research. Additionally, this topic is explored through analysis, policy, and law. This study employs cost-effectiveness analysis to explore the viability of three courses of action available to mitigate this shortage. After investigating these subjects at length, this research concludes that the current viability of supply chains that mine, transport, and process these materials would no longer be viable or reliable during conflict. This research further concludes that full-scale domestic production at all stages is the most cost-effective investment for this scenario. Additionally, this work highlights limitations and makes recommendations as well as suggests areas for future study.

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ABOUT THE AUTHOR

Captain James Reynolds is a United States contracting officer. He was commissioned by Army ROTC at the SUNY College of Brockport in 2015 where he received his Bachelor of Science. After completing his education at the Naval Post Graduate School, he will be joining the 928th Contracting Command at Fort Riley Kansas. Captain Reynolds is married to his wife of 7 years Ivana, and they have two boys Eric and Edward. Captain Reynolds is passionate about spending time with his family who love to travel and spend time in the outdoors.

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LIST OF ACRONYMS AND ABBREVIATIONS

AP	Acidification water/air
AGI	American Geological Institute
BPMPI	Best Practice Mineral Potential Index
CC	Corruption Control
CEA	Cost-Effectiveness Analysis
CERP	Centre for Economic Policy Research
EPA	Environmental Protection Agency
EPFW	Eutrophication Fresh Water
EPM	Eutrophication Marine
GCI	Global Cyber Index
IAI	Industrial Attractiveness Index
MOE	Measure of Effectiveness
MOP	Measure of Performance
NPV	Net Present Value
PPI	Policy Perception Index
REE	Rare Earth Elements
REM	Rare Earth Elements
REO	Rare Earth Oxides
USGS	U.S. Geological Survey
WGI	World Governance Index
WTO	World Trade Organization
USBLS	US Bureau of Labor Statistics

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I. INTRODUCTION

A conflict with China would sever the United States (U.S.) from its leading supplier of rare earth elements (REE), a material vital to the Department of Defense. This research is focused on addressing an imminent threat to national security. It seeks to answer the following research question: How will the Department of Defense adequately source sufficient quantities of REE during a conflict with China in a cost-effective manner?

A. RESEARCH PURPOSE

The United States' ability to access REE also known as rare earth minerals (REM), is central to maintaining its technological military advantage. The United States has relied heavily on technological superiority to win wars throughout its history (Scharre, 2024). An inability to acquire these resources would have significant negative consequences for the United States' ability to defend itself and project its influence globally.

In an age of advanced computers and electronics, the list of critical materials has increased. The United States currently relies on international trade to acquire the resources needed to fulfill these requirements. Recognizing the severity of the consequences that would arise should the United States be unable to source these materials, this research investigates the financial feasibility of implementing alternate sources and supply chains.

This subject is much discussed in Washington and has frequently been written about in scholarly circles, and yet no clear direction for addressing this seismic issue has yet been settled upon (Morrison & Tang 2012). This research effort also seeks to explore the challenges to implementation as well as the relative strengths and weaknesses of alternative options. This research seeks to identify the most cost-effective strategy of replacing China as the primary source of rare earth minerals. This research examines sources of minerals and the ability to separate and refine them. This research does not examine the costs of production facilities to produce additional finished goods. Research on this topic is restricted to open-source, unclassified materials.

B. IMPORTANCE OF RESEARCH

REMs are vital to consumers, the green energy industry, and the defense industry. Cell phones, telecommunications, missiles, and aircraft all require REE to function (U.S. Geological Survey [USGS], 2014). According to former Australian Deputy Prime Minister Kim Beazley, over 3,000 different U.S. weapons systems require REE (Zhang, 2024). China holds a near-perfect monopoly on these critical resources in both extraction and refinement (Baskaran, 2024). Should the United States enter into conflict with China without a national reserve or mature alternative markets, the ability to manufacture cutting-edge and essential components would be jeopardized.

Unlike the War on Terror, war with China would place stresses on U.S. national security and industrial base infrastructure not seen in the 21st century. The war in Ukraine, which began in 2022, provides the world with a stark reminder that conflicts between industrialized nation-states are bloody and protracted affairs. While only two armed combatants take to the battlefield, the war in Ukraine is a global conflict. Nations from all over the world have taken sides by providing economic, logistical, information, and military-industrial base support (Ng & Ma, 2024). A war between the United States and China would stress these factors to their breaking point unless substantial efforts to prepare are undertaken.

C. ORGANIZATION OF REPORT

This research is comprised of five chapters. Chapter I introduces key issues, states the purpose of the research, and explores all relevant background information required for the reader to understand the history, challenges, and perspectives of relevant stakeholders. Chapter II reviews expert analysis of technical, political, and economic issues pertaining to this topic. Chapter III explains the methodology employed in this research. Chapter IV presents the analysis and supporting data, as well as addresses the research question. Chapter V concludes by summarizing key points and making recommendations for further research.

D. BACKGROUND

According to the U.S. Geological Survey (USGS), REE are small granule substances found in sediments around the world. This list includes yttrium, praseodymium, scandium, lanthanum, cerium, dysprosium, terbium, samarium, neodymium, europium, erbium, thulium, gadolinium, holmium, lutetium, ytterbium, and promethium (USGS, 2014). They are typically metallic and pliable, appearing like discoloration in sediments, as REM do not form clusters or nuggets like gold or other elements (USGS, 2014). First discovered in the 18th century, their name is derived from the fact that these elements were often found in deposits containing much sought-after mineral substances like petrochemicals (Wall, 2014).

Contrary to their name, these elements are not actually rare and can be found all over the globe. These elements are found in vast quantities in China, Australia, Brazil, and the United States (Pecharsky & Gschneidner, 2023). Often discovered in fluorocarbon deposits, these elements have been discovered frequently by accident while pit mining for other substances (Pecharsky & Gschneidner, 2023). Where REEs are mined as a by-product, there are typically lucrative additional resources being harvested (Pecharsky & Gschneidner, 2023). The central issues limiting the full exploitation of these resources are the logistics, cost, and environmental considerations of harvesting and processing (Wall, 2014).

Mining REE requires the use of chemical fluids, which cause the sediment to separate, allowing for the residue deposits to be isolated and collected Nayar (2021). According to Jaya Nayar (2021), writing for the *Harvard International Review*, these processes produce a myriad of hazardous ecological side effects:

> Both methods produce mountains of toxic waste, with high risk of environmental and health hazards. For every ton of rare earth produced, the mining process yields 13kg of dust, 9,600-12,000 cubic meters of waste gas, 75 cubic meters of wastewater, and one ton of radioactive residue.

The next step in the process is separation (Pecharsky & Gschneidner, 2024). Processing REEs is complex and dangerous. The U.S. Environmental Protection Agency (EPA, 2021) stated that the reason processing REE is so challenging is that they are often extracted in combination with two radioactive elements, uranium and thorium. The relative lack of environmental restrictions imposed by governments in developing economies is often less restrictive with regard to isolation and waste containment (Department of State, 2021).

While financially and environmentally costly to mine and process, these elements are vital to produce numerous commercial and defense technologies. For example, they are used in electronic screens, from televisions to touch screens found in cell phones [AGI], 2023). These elements are instrumental in glass and cameras, and in the auto industry they are found inside catalytic converters, power steering, and various other applications (American Geoscience Institute [AGI], 2023). Computers utilize the magnetic application of these technologies to provide superior attraction/repulsive qualities for superior performance in disc drives (American Geoscience Institute [AGI], 2023). The military applications of these technologies are widespread and of equal magnitude; REEs are indispensable to the production of guided missiles, aircraft engines, and the computers used in tanks and sonar systems, to name only a few (Parman, 2019).

To explore the subject of life with diminished or no access to REEs, one need not explore the hypothetical but merely analyze recent trade events. In 2014, China—which controls 70% to 90% of the world's REEs (Andrews-Speed & Hove, 2023)—demonstrated its control by reducing its exports. This resulted in the United States, Japan, and the European Union collectively appealing to the World Trade Organization and generating claim DS431 (World Trade Organization, 2015). Earlier, in 2010, China had flexed its muscles by refusing to supply any REE to Japan for 2 months due to a maritime dispute (World Trade Organization, 2015). While the Centre for Economic Policy Research (CEPR) suggested this reduction was more likely due to the unpredictable nature of Chinese exports, the fact remains that China has the market power and record of approaching political issues with economic restrictions. According to *The Economist*, China has been reducing raw exports since 2017 and increasing the exports of finished goods using REE ("Rare Earths Give China Leverage," 2019). U.S. defense manufacturers require unfinished materials in construction. Further reduction or total cessation of imports could be catastrophic. This research investigates some of the available mitigation options crisis but the solutions explored are not exhaustive. There are a number of nations where these resources may be found where the United States could seek to develop enhanced capabilities and trade agreements. However, investigating all of these options would detract from the depth of detail. Adding possible alternative nations for future research is a recommendation to future researchers.

Discussed in this work are three alternative courses of action to secure resources should conflict preclude China as a source. These options include Australian mining, separation, refinement, and production; U.S. mining, separation, refinement, and production; and U.S. recycling mining, separation, refinement, and production.

For the purposes of this research, Australia was chosen to replace China in its role as the primary supplier of finished REE materials. The decision to select one nation as opposed to a network of cooperating nations was made for two reasons. First, in this scenario, it is assumed that the movement of goods between nations in East and Southeast Asia is severely disrupted. Not only would maritime warfare inhibit the movement of goods by ship, but a kinetic war with China is assumed to become regional and disrupt all industrial components in society in such nations as Malaysia, Korea, Japan, Vietnam, and so forth. Second, to collect the level of detailed data required to analyze this problem, all attention was focused on one partner nation. Australia was chosen for several reasons. Possessing an abundance of natural resources relevant to this work, with strong political, economic, and defense ties to the United States, Australia is a logical source of REEs (U.S. Embassy and Consulates Australia, 2024). Additionally, Australia's geographic positioning makes trans-Pacific traffic more realistic than, for example, industrial-scale cargo movements from Malaysia.

The next course of action (COA) investigated in this research is domestic production. This means the elements are mined, separated, refined, and processed into end products inside the continental United States. The United States is home to a tremendous concentration of REEs; however, the exploitation of these resources has experienced several serious challenges over the years (Green, 2019). The largest REE mine in the United States was the Mountain Pass facility in California (Gilmore, 2022). According to Jeffery Green, writing for *Defense News*, Mountain Pass mine went from the world's dominant supplier of REE raw materials to being financially insolvent in 2 decades because of the rise of China mining. The cost of doing business in America, specifically regarding adherence to environmental protection laws, meant that China could underprice U.S. efforts (Green, 2019).

While large deposits of REE are present in the United States, recycling remains a compelling option for the resourcing of these materials (Gosen, 2019). One issue mentioned previously is the sizable economic and environmental impact and the political implications of recommending large-scale mining in the United States. REE mining typically involves open pit mining or a technique similar to hydrofracking (Haque et al., 2014). These processes produce large amounts of hazardous waste and can threaten groundwater. Given the United States' 21st century relationship with these topics, developing additional mining and processing capacity may be viewed as a political nonstarter and receive little support. Citing French investigative journalists in *The Guardian* newspaper, the story of Baotou Mongolia encapsulates concerns about the impacts of REE mining (Bontron, 2012). These descriptions help to shape public perception and concern about mining (Ali, 2014).

It is undeniable that REEs are vital to both national security and the civilian economy. China's control of the industry presents a real threat to both of these interests. The Federal Government has stated plainly that it intends to tackle this issue directly. Several options are available to resolve this problem however a primary strategic line of effort has not been selected. That is to say that to date, the government's strategy is to diversify but comparative economic research has not been released. The literature review of this research will focus on the work that has been done to identify solutions to this problem.

Resolving this issue presents a number of challenges involving the use of financial resources, the environment, and international relationships. These issues will be explored in depth in the literature review.

II. LITERATURE REVIEW

Upon entering office as president of the United States, President Biden issued Executive Order (E.O.) 14017, *America's Supply Chains*, which instructed several governmental agencies to conduct a review of the United States' supply chain infrastructure. This order resulted in a report titled, *Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth*. This report was then cited in a fact sheet released in February 2022, titled, *Securing a Made in America Supply Chain for Critical Elements*.

In the fact sheet, the White House stressed the importance of REE, the nation's dependence on foreign nations, and the need to achieve domestic capacity as a matter of national security (The White House, 2022). This document continued by listing investments and policy efforts being made to address these deficiencies. Investments included ramping up production domestically at Mountain Pass mine in California as well as developing new markets with allies and partners.

In *Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth*, the Departments of Commerce, Energy, Defense, and Health and Human Services made a series of recommendations. The report lays out the necessity to achieve supply independence not only for the good of the economy but also for national security, stating that Department of Defense stockpiles are anticipated to be depleted in 2024 (The White House, 2021, p. 188).

Unlike the recommendations made regarding semiconductors, electric vehicle batteries, and labor initiatives, no monetary recommendations were made about investing in REM infrastructure. The document discussed the creation of updated standards for mineral extraction and processing as well as the need to identify more domestic sources. The report also recommended that the import of neodymium be investigated.

> **Evaluate whether to initiate a Section 232 investigation on imports of neodymium magnets:** Neodymium (NdFeB) permanent magnets play a key role in motors and other devices, and are important to both defense and civilian industrial uses. Yet the U.S. is heavily dependent on imports for this critical product. We recommend that the Department of Commerce

> evaluate whether to initiate an investigation into neodymium permanent magnets under Section 232 of the Trade Expansion Act of 1962. (The White House, 2021, p. 16)

Section 232 of the Trade Expansion Act of 1962 permits the president to impose trade restrictions on materials deemed to be a threat to national security (Congressional Research Service [CRS], 2022). Additionally, recommendations were made to increase domestic production through both traditional mining and recycling. Investing in allies and partners through information, equipment, and expertise sharing, as well as grants and loans was recommended (Congressional Research Service [CRS], 2022 p. 202)

This research is largely inspired by and seeks to further the work of Bernkopf et al. (2021) in their thesis titled *Analysis of Rare Earth Element Supply Chain Resilience During a Major Conflict*. This thesis project centered on evaluating rare earth supply chains and considered the volume of material, speed, and security of transport (Bernkopf et al., 2021, p. v). The authors imagined a scenario where a conflict with China would disrupt the supply of REEs and evaluated courses of action based on current conditions. They concluded that mining, processing, and manufacturing materials outside of the United States would be superior to a domestic approach (Bernkopf et al., 2021, p. xxi). Their conclusion involved several critical assumptions about the location of critical material development sites, and their evaluation of security was based on computer modeling (Bernkopf et al., 2021, p. xviii).

This research varies from that piece in that, firstly, it seeks to determine a future policy, not actions to take should a conflict arise tomorrow. Second, it examines results through a cost-effective approach. Finally, it assumes a more pessimistic outlook about maritime movement security.

The need for reliable sources of critical elements is clear, but the criteria on where to seek alternative sources is less clear. This research takes the perspective of national security as its highest priority but acknowledges that economic, environmental, legal, and diplomatic factors are also vitally important. The decision to compare Australia to the United States as a course of action (COA) was addressed previously but can be more fully understood considering the research performed by (Jaroni et al. 2019). In their 2019 paper, Jaroni et al. looked at the financial feasibility of alternative sourcing of rare earths from China. Regarding sheer capacity, three obvious candidates emerge. The United States, whose mines include Mountain Pass, Bear Lodge, and Bokan Mountain is estimated to have a 29.3 metric ton (mt)/year production capacity (Jaroni et al. 2019). Australia is evaluated to have a 34 mt/year production capacity between Mount Weld, Nolans, and Browns Range mines (Jaroni et al. 2019). The third option was South Africa, which produces an estimated 22 mt/year from their Steenkampskraal and Zandkopsdrift facilities (Jaroni et al. 2019). South Africa was excluded from consideration in this research due to its involvement with Brazil, Russia, India, China, South Africa, Iran, Egypt, Ethiopia, and the United Arab Emirates (BRICS; Reuters, 2024). Ultimately, Jaroni et al. concluded that given global economic circumstances (as of time of writing in 2019) that only the Australian mining projects would produce a positive net present value. While the work of Jaroni et al. is valuable, the scenario presented in this thesis includes assumptions that inherently impact the application of these findings.

Policy-makers and researchers have explored alternatives apart from mining, such as recycling. Less than 1% of REE are being recycled as of 2011 (Balaram, 2019). Recycling REE poses unique challenges. The central issues described by Amato et al. (2019) were economic. It is less costly to purchase these refined or processed goods than it is to develop the industrial infrastructure to recycle them. This research, however, is focused on the national security perspective and not a profit-driven perspective.

Patil et al. (2022) discussed the viability of recycling and the reasons for its current underdeveloped state, citing the high expense of capability development, the low maturity of required techniques, and the low expectancy of profitability given current market conditions. However, given expectations for limited or temporarily no international access during a global war with a peer adversary, it can be argued that these market conditions would promote diversification.

Amato et al. (2019) investigated the environmental and economic impacts of increased REE recycling and concluded that it is pound for pound more environmentally friendly than mining and that the recycling of fluorescent powders, fluid catalytic cracking (FFC) catalysts, and permanent magnets can be done in a net economically positive manner. One of the central issues identified in recycling not only by Amato et al., but additionally by Haque et al. (2014), is the difficulty of collecting devices that contain these materials.

Finally, Qiu and Suh (2019) discussed economic limitations on the subject, which explains private-sector reluctance to participate in increased REE recycling initiatives. They claim that recycling rare earth oxides (REO), as used in lighting, does not become profitable until pricing reaches three times 2018 levels.

Policymakers have several viable options for replacing China as its primary source of REE. Domestic sources are plentiful, and allied countries also contain REE in abundance. Recycling REEs remains an attractive option as the technology has evolved rapidly in recent years with the profitability improving over time. Previous research into this question has endorsed offshoring to a network of international partners. The methodology chapter of this research will quantify and measure the relative strengths and weaknesses of three courses of action identified in this chapter.

III. METHODOLOGY

The following chapter explains the techniques employed to answer the research question and provides examples to illustrate the methods employed.

A. CLARIFICATION ON MEASURES OF EFFECTIVENESS AND PERFORMANCE

Measures of effectiveness inform researchers about how successful something is at obtaining a goal. The environmental impact measure (Measure of Effectiveness [MOE] 1) examines the impediments that a policy might face because of the ecological consequences of each COA. Next, MOE 2 is security, which contains the two sub-MOEs internal and external security. In this research, security describes both threats from an adversary as well as threats to internal disruption and delay for social and industrial reasons. MOE 3, productivity contains two sub-MOEs, capacity and maturity. Capacity examines the feasibility of each COA and therefore informs on the amount of investment needed to meet requirements. Industrial maturity allows for an analysis of the level of investment required to meet minimum standards as well as inform policymakers about how much time is required for a COA to be viable. Each sub-MOE contains areas for data measurement and comparison called measures of performance (MOP). Figure 1 depicts how the sub-MOE capacity, maturity, internal and external security feed into the scores of environmental impact, security, and productivity. In Figure 1 the weight or significance given to a sub-MOE or MOE indicates the level of priority it has. The example of internal security (W 1/2) and external security (W 1/2) indicates that internal and external security are equally valued in determining the total value of the security MOE.

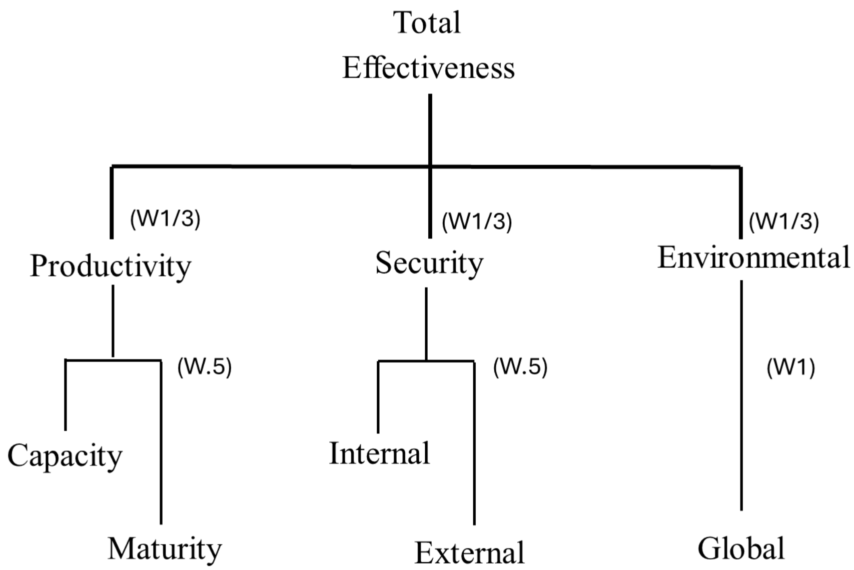


Figure 1. MOE Hierarchy

1. Sub-MOE: Global Environmental impact

The first MOE addresses the environmental impact and the political implications of industrial mining and recycling. This measure largely focuses on increases in ecological toxicities that can harm plants and animals in the environment. Additionally, global challenges like certain greenhouse gases have been included. It is worth noting that while the environmental impact of industrial mining is most relevant to the domestic COA it is also worth considering when analyzing all other courses of action. If U.S. policymakers are taking threats to the environment seriously, then the global impact of mining, refining, and transportation remains relevant regardless of where they occur on Earth. Measures of Performance (MOP) for environmental impact include CO2 emitted, particulate matter generated, ecotoxicity, fresh/salt water effects, and acidification. This MOE is the only category in this research without more than one sub-MOE.

2. Sub-MOE: External Security

In a great power conflict, there is a progression in hostility. This research assumes that prior to conflict, competition would increase steadily. In preparation for a major war, it can likewise be assumed that China would cease to supply critical goods and materials. The scenario involves the possibility of enemy interdiction of supply routes. MOP for this Sub-MOE include competitive status, transportation disruption, supply vulnerability (threat), and global cyber security index score,

3. Sub-MOE: Internal Security

In addition to the external threat caused by an adversary, this research looks at internal threats to production. MOP associated with internal security includes labor stability, supply vulnerability (access), legal political challenges, and corruption.

4. Sub-MOE: Production Capacity

The focus of this MOE is assessing the capacity of each part of the production process across each COA. This MOE informs much of the data on what investments would be needed to meet requirements. As was mentioned previously, the world is more reliant on China for separation and refinement of REEs than it is for mining (Department of Energy, 2022). The United States and Australia have an abundance of REE deposits but extracting them is less than half of the battle (Gosen, 2019). Transforming them into refined materials with applications for advanced technologies is an entirely distinct challenge. MOP for production capacity includes mining capacity, separating capacity, refining capacity, and alloy manufacturing capacity.

5. Sub-MOE: Industrial Maturity

This MOE examines COAs' other industrial factors, which help to understand timelines, investment requirements, and social challenges. The MOPs for this MOE include production capacity value, active labor pool in the sector, Policy Perception Index (PPI), Best Practice Mineral Potential Index (BPMPI), and Industrial Attractiveness Index (IAI). PPI, BPMPI, and IAI are all measures taken by the Fraser Institute, a Canadian nonprofit that explores and examines international policy regarding the mining industry (Fraser Institute,2024).

B. COST-EFFECTIVENESS

The approach used in this research is known as cost-effectiveness analysis (CEA). This method compares courses of action in order to determine which provides the best balance of both cost and effectiveness. This method is employed when objective numerical values of effectiveness are not available (Kaplan, 2022).

To conduct a cost-effectiveness analysis, this research must translate qualitative information into quantitative data. This process is conducted sequentially in several steps. First, MOEs are selected. In this research, the MOEs are environmental impact, security, capacity, and maturity. To attach numerical values to these MOEs, each MOE is broken down into MOPs. These measures of performance are inherently quantifiable. For this research, tables are generated for each MOE, which contains their related MOPs. Once all MOP data is populated, ranking relative performances is possible, and each COA can be compared quantifiably. Plotting this data on a value function graph permits comparison of the different MOEs with unequal numbers of MOPs.

After a table is fully populated with data and results are ranked, those ranks are plotted in a value function chart to normalize results. An example of ranking would be that if COA 1, U.S. domestic production, produced the least pollution for each of the five measures related to the environmental MOE, it would be ranked first (best performance) in each category. Adding up each ranked score would produce a cumulative ranked score of 5. If Australia were ranked last (worst performance), then this COA's cumulative ranked score would be 20. The graph used to produce a value function score would have the maximum value of the x-axis as 20, which reflects the potential of a COA finishing in fourth place in each of the five measures, and a minimum x value of 5, which reflects the potential for a COA to finish in first place in each of the five measures. The lowest possible Y value is 0 and the highest is 1.

The cumulative ranked score provides a coordinate on the x-axis. To find the corresponding Y value, three algebraic equations are employed. First is the equation for slope, as seen in Figure 2. The second formula applied is the point-slope formula shown in Figure 3. The final step at finding the Y coordinate is applying the equation of a line (Figure 4).

$$m = \frac{y2 - y^1}{x_2 - x_1}$$

Figure 2. Slope Equation

$$y - y1 = m(x\text{-}x1)$$

Figure 3. Point–Slope Formula

$$y = -\frac{y}{x} x + y$$

Figure 4. Equation for a Line

For visualization purposes, a line is drawn vertically from this point on the x-axis until it meets a diagonal line drawn between (0.1) and (20, 0) for this example. The point at which this vertical line meets the diagonal running between (0,1) and (20, 0) is the point at which a horizontal line will be drawn to the y-axis. Where this line intersects the y-axis is our value function score. See the example graph in Figure 5.

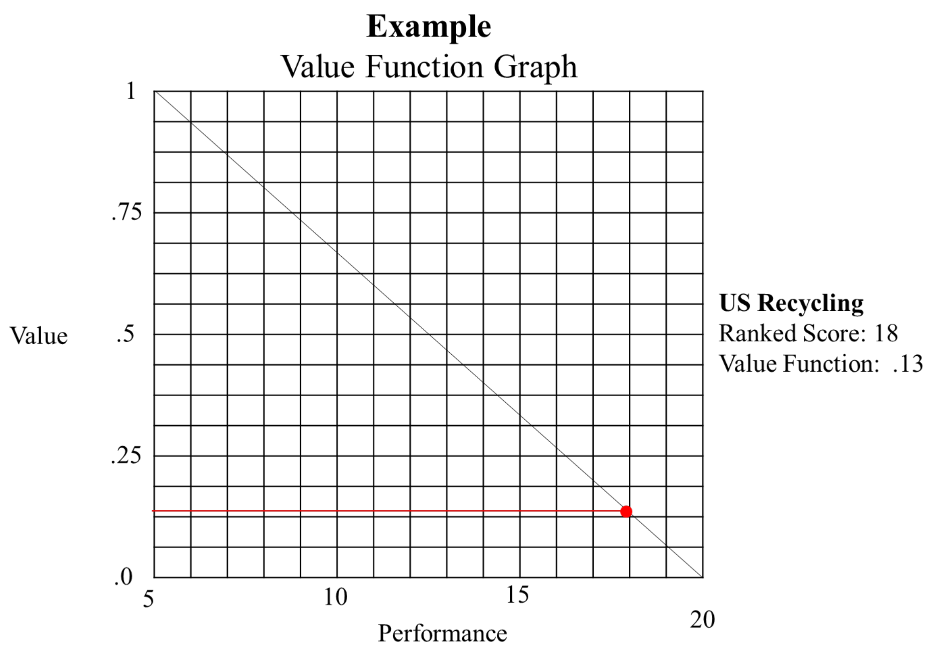


Figure 5. Example Value Function Graph

Once this process has been completed for all MOEs, the results are combined into a hierarchy for visualization purposes. Figure 6 is an example of an MOE hierarchy.

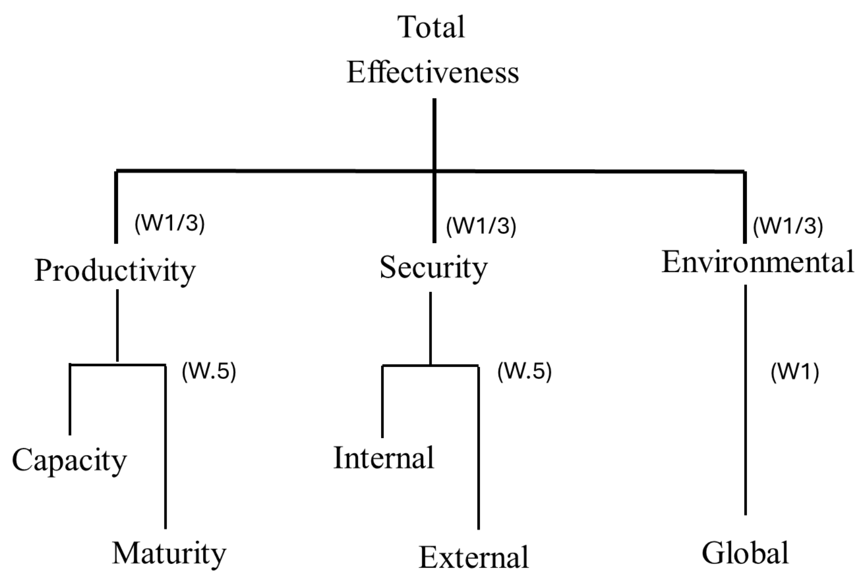


Figure 6. MOE hierarchy

C. COSTS

Parametric data is employed to justify the estimated costs to implement each COA. Parametric estimation employs known costs from related historical projects (PMBOK, 2008). Cost and performance are then plotted in a graph where performance is the x-axis, and cost is the y-axis. Results between COAs are then compared, and recommendations can be made for policy. The possibility of joint ventures and their impact on costs is investigated in Chapter V. Historical examples from the industry of the U.S. collaborating with foreign nations and private companies is employed to extrapolate potential alternative cost scenarios.

IV. RESULTS AND DATA

This chapter introduces the raw data collected to assess the MOPs for all courses of action and the baseline COA. Raw data from tables is then normalized across MOP and presented in hierarchy figures. The chapter include two cost models, one with and one without foreign/industry cooperation. Finally, results are presented with their associated costs.

A. ENVIRONMENTAL DATA

Table 2 contains the summation of data obtained about the respective environmental impacts of mining (or recovering) rare earth minerals from the various COAs. Table 1 lists the definitions as key terms in MOPs. While this research is aimed at exploring alternatives to sourcing minerals from China, China was included for comparative purposes and is referred to as the baseline COA. The MOPs for this MOE are listed under the "Hazards" banner and run along the top row. All scores provided reflect the amount of waste produced while generating 1 kg of neodymium. This measure is used as a stand-in for the pollution generated by all REEs.

Table 1. Descriptions of MOEs

Measures of Performance	Descriptions
CO2	Carbon Dioxide, a green house gas largely responsible for mechanism of global warming.
Particulate Matter	Referring to any solid matter released into the air, or solid matter. Frequently containing microscopic radioactive particles.
Ecotoxicity	Stresses inflicted on an ecosystem as a result of chemical or industrial activity
EPFW: Eutrophication Fresh Water	Process where runoff of chemical agent promotes rapid plant growth which over consumes oxygen and kills plant life in a body of fresh water.
EPM: Eutrophication Marine	Process where runoff of chemical agent promotes rapid plant growth which over consumes oxygen and kills plant life in a body of salt water.
AP: Acidification of water supply/air	Lowering of PH levels in water which present a hazard to life. Air Acidification refers to the precipitation containing PH concentrations.

Note. Adapted from Zapp et al. (2022), Accardo et al. (2024).

Table 2. Environmental Hazards MOPs

Hazard / Method	CO2	Particulate Matter	Ecotoxicity	EPFW	EPM	AP	Rank Total	VF Score
China	98kg 4	0.4kg 3	0.5 PE 4	0.04kg 4	0.28kg 4	0.7kg 4	23	0.056
USA Mining	61kg 1	0.5kg 4	0.25 PE 1	0.02kg 2	0.02kg 1	0.2kg 1	10	0.78
AUS	72kg 2	0.3kg 2	0.3 PE 3	0.03kg 3	0.04kg 3	0.5kg 2	15	0.53
Recycling	81.34kg 3	0.2Kg 1	.295 PE 2	0.016 1	0.0252kg 2	0.56kg 3	12	0.67

Note. The number in the bottom right of each cell indicates ranking, high number low score, low number high score. Adapted from Zapp et al. (2022), Accardo et al. (2024).

B. EXTERNAL SECURITY

Table 4 contains the summation of data obtained about the respective external security impacts on sourcing minerals from the various COAs. Table 3 contains definitions and explanations of key terms. External security specifically refers to threats resulting from adversary actions. The MOPs for this MOE are listed under the "Hazards" banner and run along the top row.

Table 3. Descriptions of MOEs

Measures of Performance	Descriptions
Competitive Status	Informs the level of cooperation assumed, and amount of control US policy makers have.
Transportation Disruption (NM)	Distance in NM from source to US port. Relevant to enemy opportunities for interdiction.
Supply Vulnerability	Reliance on international raw materials, information or expertise.
GCI: Global Cyber Index	Score of nations cyber security force protection levels (100 best -0 worst)

Note. Adapted from The competitive status column is assumed by the scenario. Distance in NM from Sydney to Los Angeles from (Prokerala,2024). Supply vulnerability assumed by scenario. GCI score (European Commission, 2024)

Table 4. External Security MOPs

Hazard / Method	Competitive Status	Transpo. Disruption (NM)	Supply vulnerability	GCI	Rank Total	VF Score
China	Adversary 4	NA 4	H 4	92.5 4	16 4	0
USA Mining	Self 1	NA 1	L 1	100 1	4 1	1
AUS	Ally 2	6521.66 2	M 2	97.5 2	10 3	0.5
Recycling	Self 1	NA 1	M 2	100 1	5 2	0.916

Note. The number in the bottom right of each cell indicates ranking, high number low score, low number high score. Adapted from The competitive status column is assumed by the scenario. Distance in NM from Sydney to Los Angeles from (Prokerala,2024). Supply vulnerability assumed by scenario. GCI score (European Commission, 2024)

C. INTERNAL SECURITY

Table 6 contains the summation of data obtained about the respective internal security impacts on sourcing minerals from the various COAs. Table 5 lists definitions and explanations of key terms. Internal security specifically refers to threats resulting from conditions within the nation or industry represented. The MOPs for this MOE are listed under the "Hazards" banner and run along the top row. Corruption is addressed in this MOE, as it suggests inefficiency and can present a threat to the operation of the state's efforts.

Table 5. Descriptions of MOEs

Measures of Performance	Descriptions
Labor stability	Labor stability refers to the likelihood of strikes or other disruptive events obtained from historical data.
Supply vulnerability	Refers to the assessed regularity of access to essential industrial inputs.
Legal/Political Challenges	Refers to the assessed probability of encountering political or legal challenges of implementation.
WGI/CC	The World Banks "World Governance Index/Corruption Control Score Which ranks nations 0(low) – 100(high)

Note. Adapted from Labor stability U.S. Bureau of Labor Statistics (USBLS, 2024), and (Australian Bureau of Statistics, 2024). Supply vulnerability assumed by scenario. Legal political challenges from Grist.org (Stone,2024) and Fraser Institute (Mejia, J., & Aliakbari, E. 2024). WCI/ CC is from World Bank (World Bank, 2024).

Table 6. Internal Security MOP

Hazard / Method	Labor stability	Supply vulnerability	Legal/ Political challenge	WGI/CC	Rank Score	VF Score
China	H 1	H 4	H 4	55.19 4	13	.25
USA Mining	M 2	L 1	M 2	82.55 2	7	.75
AUS	H 1	L 1	L 1	95.28 1	4	1
Recycling	M 2	M 2	L 1	82.55 2	7	.75

Note. The number in the bottom right of each cell indicates ranking, high number low score, low number high score. Adapted from Labor stability U.S. Bureau of Labor Statistics (USBLS, 2024), and (Australian Bureau of Statistics, 2024). Supply vulnerability assumed by scenario. Legal political challenges from Grist.org (Stone,2024) and Fraser Institute (Mejia, J., & Aliakbari, E. 2024). WCI/CC is from World Bank (World Bank, 2024).

D. PRODUCTION CAPACITY

Table 8 contains the summation of data obtained about the respective production capacities from the various COAs. Table 7 lists definitions and explanations of key terms. The MOPs for this MOE are listed under the "Hazards'" banner and run along the top row. Under the mining MOP, the numerator for China, COA 1, and COA 2 refers to the percentage of total global production. The denominator refers to the approximate need based on average annual imports. Of note, no reliable data exist about the percentage of finished products the United States consumes per year, only the quantity imported. The decision to use this figure as a reference point was made based on the assumption that critical defense components are manufactured primarily domestically (i.e., those components found in major weapon systems).

In order to provide data on recycling capacity in such a way that it could be compared, mining quantities were used based on material present in circulation available for recycling to indicate the potential for mineral production.

Table 7. Description of MOE

Measures of Performance	Descriptions
Mining	Raw materials extracted from nature.
Separating	Removal of superfluous matter from raw product
Refining	Purification of separated materials into condition ready for alloy processing.
Allow Manufacturing	Combination of various pure elements into a material usable in manufacturing.

Note. Adapted from Recycling data from (Balde et al.,2024). U.S. and Australian data from the (U.S. Department of Energy, 2024). Chinese data from (USGS, 2024).

Table 8. Production Capacity MOP

Hazard / Method	Mining	Separating	Refining	Alloy Manufacturing	Rank Total	VF Score
China	58% 1	89% 1	90% 1	92% 1	4	1
USA Mining	16% / +560% 2	0% 3	0% 2	<1% / 35% 2	9	.58
AUS	7% / +240% 3	0% 3	0% 2	0% 3	11	.42
Recycling	NA / +43% 4	0% / +43% 2	0% 2	0% 3	11	.42

Note. The number in the bottom right of each cell indicates ranking, high number low score, low number high score. The numerator in the first column indicates the percent of the global market, denominator indicates the percent of the annual import average. Recycling figures derived from e-waste generated annually in the United States as a stand-in for raw material quantities. Adapted from Recycling data from (Balde et al.,2024). U.S. and Australian data from the (U.S. Department of Energy, 2024). Chinese data from (USGS, 2024).

E. INDUSTRIAL MATURITY

Table 10 compares the industrial maturity of different COAs' industrial capacity, and Table 9 lists definitions and explanations of key terms. This information is intended to inform policymakers of factors other than facilities that require consideration prior to capital investment. The MOPs for this MOE are listed under the "Hazards" banner and run along the top row. MOP PPI, BMPI, and IAI were available exclusively for mining activities. In order to provide comparative approximations for mining, assumptions were made about policy perceptions and research on perceptions in the market.

Table 9. Description of MOP

Measures of Performance	Descriptions
Production Capacity Value	Annual value of exports in millions of US dollars.
Active Labor Pool	Removal of superfluous matter from raw product
PPI: Policy Perception Index	Purification of separated materials into condition ready for alloy processing.
BPMPI: Best Practices Mineral Potential Index	Extent to which industry employs latest and most efficient techniques.
IAI: Industry Attractiveness Index national average	Measure of appeal to investors.
Fraser Institute Scores	0 Worst – 100 Best

Note: Adapted from: PPI, BPMI, IAI from (Fraser Institute,2024). Production capacity value from (OEC,2024) Innovation News Network (Trotter,2024), recycling assumed based on global positioning, report by (Markets and Markets, 2024). Labor Pool reflects total mining industry data from (IBIS World,2024) (Statista, 2024), and USGS.

Table 10. Industrial Maturity MOP

Hazard / Method	Production Capacity Value	Active Labor Pool	PPI	BPMPI	IAI	Rank Total	VF Score
China	679 1	3.5m 1	15% 4	23% 4	19% 4	10 1	.67
USA Mining	577 2	556k 2	79.82% 2	72.97% 1	75.71% 1	8 1	.8
AUS	367 3	219k 3	75.02% 3	70.56% 2	72.34% 2	13 2	.53
Recycling	30 4	23k 4	100% 1	50% 3	50% 3	15 3	.33

Note. The number in the bottom right of each cell indicates ranking, high number low score, low number high score. Adapted from PPI, BPMI, IAI from (Fraser Institute,2024). Production capacity value from (OEC,2024) Innovation News Network (Trotter,2024), recycling assumed based on global positioning, report by (Markets and Markets, 2024). Labor Pool reflects total mining industry data from (IBIS World,2024) (Statista, 2024), and USGS.

F. VALUE FUNCTION PERFORMANCE DISCUSSION

1. Baseline: China

Table 11. Base Line Cumulative Performance

Base Line: China							
MOP	Objective Scores	Weght	Weighted Score	Sum	Weight	Weighted Score	Total
Environment	0.056	1	0.056	0.056	0.33	0.018	0.335
External Security	0	0.5	0	0.125	0.33	0.041	
Internal Security	0.25	0.5	0.125				
Maturity	0.67	0.5	0.335	0.835	0.33	0.276	
Production Capacity	1	0.5	0.5				

Note: Table 11 displays the COAs performance by sub-MOE resulting in a cumulative MOE score found in the far-right column.

a. *Environmental Summary of Results*

Chinese industrial processes related to mining and refining REE had the most deleterious effects on the environment of all available COAs. Of the six MOPs, China ranked last (most environmentally destructive) in all but one category. China's ranked score was 23 out of a total of 24. A score of 24 would only be available to a COA in this MOE that received a last place ranking in each of the six MOPs. Therefore, China's VF score is very low, at .052. This result is not surprising to researchers given China's well-documented lack of environmental protection standards, as was discussed in previous chapters.

b. *External Security Summary of Results*

Unlike other MOEs, where it is worthwhile to consider the current levels of service received by China, measures of security automatically result in the lowest possible ranked scores with a 16/16 based on the underlying scenario. Due to China's role in the scenario as a hostile state actor, it received the lowest possible ranked scores, which likewise resulted in the maximum possible VF results. Reflecting their ranked score, China's VF score is 0/1.

c. *Internal Security Summary of Results*

As with external security, China automatically received the lowest possible ranked scores in each category given its status as hostile in this scenario. China received the worst rank in supply vulnerability and political challenges because of their role in the scenario. As a point of comparison for capability, however, China did outperform both U.S. COAs with labor stability. As a result of their role in the scenario and high corruption, China received a cumulative ranked score of 13 and therefore a VF score of .25/1, placing them firmly in last place.

d. *Production Capacity Summary of Results*

As has been repeated throughout this thesis, China has the largest contribution to all stages of REE production. While calculating the exact quantities produced by China that end up in the United States is not possible at this time, providing the levels of market share they currently own informs the key issues identified in this paper. China received a cumulative ranked score of 4. By achieving the highest possible ranked score of 4/16, China received a VF score of 1/1.

i. Industrial Maturity Summary of Results

China dominates the production capacity value and size of the active labor pool. However, China's standards, procedures, and policies result in poor performances in all MOPs which inform industry attractiveness and health. China received a cumulative ranked score of 10/20.China received a .67/1 VF performance score.

2. COA 1 U.S. Mining

Table 12. COA 1 Cumulative Performance

COA 1: US Domestic Production							
MOP	Objective Scores	Weights	Weighted Score	Sum	Weight	Weighted Score	Total
Environmental	0.78	1	0.78	0.78	0.33	0.257	0.77
External Security	1	0.5	0.5	0.875	0.33	0.289	
Internal Security	0.75	0.5	0.375				
Maturity	0.8	0.5	0.4	0.68	0.33	0.224	
Production Capacity	0.58	0.5	0.29				

Note: Table 12 displays the COAs performance by sub-MOE resulting in a cumulative MOE score found in the far-right column.

a. Environmental Summary of Results

COA 1 performed well in CO_2 emissions, ecotoxicity, and acidification—placing first in each respective category. Of potential concern for this COA is its incongruously high particulate matter discharge rate. Regarding the environmental impact MOE, U.S.-based mining received a cumulative ranked score of 10 and received an accompanying .791/1 VF result. These scores placed domestic mining as the most environmentally sound COA examined in this research.

b. External Security Summary of Results

This COA received the highest possible ranked score with a first-place finish in each of the four categories, resulting in a 4/16. As with COA 3, this COA has the advantage of not relying on international agreements or long-distance maritime transportation. The factors that ultimately differentiated it from COA 3 are explored in subsequent data points. With the achievement of the maximum ranked score of 4/16, COA 1 received a VF score of 1/1.

c. *Internal Security Summary of Results*

COA 1 received a cumulative ranked score of 7/16. Critically, areas in which COA did not perform optimally are areas in which a series of assumptions had to be made based on historical trends, namely labor stability. A VF score of .75/1 was achieved.

d. *Production Capacity Summary of Results*

With the reopening of the Mountain Pass Mine facility, the United States is currently outproducing both alternatives in this research. At the time of writing, a separation/refinement facility has opened; however, no data is available about its performance. COA 1 received a ranked score of 9/16. With a superior or equal score to both alternative COAs, COA 1 received a VF score of .58/1.

e. *Industrial Maturity Summary of Results*

With the recent return to operations for Mountain Pass Mine, the United States fares poorly in production capacity value and was edged out slightly with regards to active labor force by COA 2. However, results obtained from the Fraser Institute regarding the attractiveness of mining as an industry surpass those of COA 2, albeit marginally. COA 1 scored 8/20. With the same ranked score as China, COA 1 received a .8/1.

3. COA 2 Australia

Table 13. COA 2 Cumulative Performance

COA 2: Australia							
MOP	Objective Scores	Weights	Weighted Score	Sum	Weight	Weighted Score	Total
Environmental	0.53	1	0.53	0.53	0.33	0.175	0.58
External Security	0.5	0.5	0.25	0.75	0.33	0.248	
Internal Security	1	0.5	0.5				
Maturity	0.53	0.5	0.265	0.475	0.33	0.157	
Production Capacity	0.42	0.5	0.21				

Note: Table 13 displays the COAs performance by sub-MOE resulting in a cumulative MOE score found in the far-right column.

a. Environmental Summary of Results

Australia's environmental performance reflects an industrial capacity with far greater controls than China's but not as strict as those found in the United States. Australia's CO_2 emissions are lower than two other COAs, but the primary environmental concern this research suggests is waste runoff into water supplies. Receiving a cumulative ranked score of 15 and a VF score of .531, this COA represents a significant improvement over the baseline. In selecting for further investment by policymakers, further research will be required to understand and mitigate water-based ecological hazard threats.

b. External Security Summary of Results

Australia performed well in all areas of security; however, its ranked score was ultimately hindered by its distance, relationship, and inferior cybersecurity to the U.S.-based COA. COA 2 received a cumulative ranked score of 10/16. Of note is the nuanced difference between distance and supply vulnerability, which vulnerability speaks to likelihood of interdiction as well as any factors that would subject the supply to disruptions (e.g., market forces, etc.). Distance informs more than just opportunities for enemy contact. It also addresses all factors that can affect international maritime shipping, the intentional and natural. Australia received a VF score of .5/1.

c. Internal Security Summary of Results

Ranking in first place for cumulative MOP results, Australia received a 4/16. No significant political, legal or labor hurdles were suggested in the data obtained, and Australia outranked the United States on the World Bank's corruption index.

Australia received the maximum available score for this MOE, which resulted in a perfect VF score of 1/1.

d. Production Capacity Summary of Results

With Australia's lack of separating, refining, and alloying capabilities, it finished with a cumulative ranked score of 11. Australia received a VF score of .42. These results highlight specific absences that would require significant investment.

e. Industrial Maturity Summary of Results

COA 2 received a cumulative ranked score of 12. Australia was marginally outperformed by COA 1 was MOP referencing policy and practices that make Australia an attractive market to expand into. It is conceivable that these elements could be affected by policy negotiation. Following a ranked score of 11, COA 2 received a VF score of .6.

4. COA 3 U.S. Recycling

Table 14. COA 3 Cumulative Performance

COA 3: US Recycling							
MOP	Objective Scores	Weights	Weighted Score	Sum	Weight	Weighted Score	Total
Environmental	0.67	1	0.67	0.67	0.33	0.221	0.62
External Security	0.92	0.5	0.46	0.835	0.33	0.276	
Internal Security	0.75	0.5	0.375				
Maturity	0.33	0.5	0.165	0.375	0.33	0.124	
Production Capacity	0.42	0.5	0.21				

Note: Table 14 displays the COAs performance by sub-MOE resulting in a cumulative MOE score found in the far-right column.

a. Environmental Summary of Results

With an overall second-best score against measured COAs presented in this research, recycling performed highly in all categories bar CO2 emissions. Of note, the data indicates the amount of various hazardous by-products to mine 1 kg of neodymium. In MOEs where this neodymium is mined, further steps would be required to separate, refine, alloy and so forth, until the mineral is usable in product production. Unlike mining, recycling begins by rendering down materials and then moves to separation and refinement. Separation and refining are both energy-intensive processes that are not reflected in data for mining COA. It is important to acknowledge these processes' distinctions, and while no further data is available at this time to elucidate this matter, it is rational to assume that recycling's true results would be superior to all alternatives when measured one step of the process at a time.

With a combined ranked score of 12, the recycling COA finishes just behind the domestic mining COA with regard to total environmental impact. The worst MOP for this COA was CO_2 emissions, which can be explained by the energy requirements needed in separation and refinement, which are not included in mining COA. Overall, recycling received a .679/1 VF score, ranking higher than both Australian mining and the Chinese baseline.

b. *External Security Summary of Results*

COA 3 received a ranked score of 5, finishing one point shy of first place with COA 1. The only differentiating factor separating the two COAs is the unknown pertaining to the ability to source all varieties of material domestically. This research was unable to obtain verifiable data pertaining to the quantities and quality of raw materials required for recycling. This forces the assumption that importing raw materials for recycling is highly probable and, therefore, materials will need to move internationally before being recycled. Further research on this topic is recommended in the conclusion. The resultant VF score for the provided is .916/1. This result could improve if future data reveal that no external sourcing is required for recyclable goods.

c. *Internal Security Summary of Results*

COA 3 received an identical cumulative ranked score as COA 1 of 7/16. The performances in each MOP, however, were not identical. While labor stability was assumed to be identical between COAs, as this MOP could only be analyzed on national-level historical inference, supply vulnerability was not the same. In the context of internal security, supply vulnerability looks at how effectively sources within a nation or industry can be relied on to deliver materials consistently. This differs from supply vulnerability in an external context because that measures reliance on factors outside of the control of the United States, like markets. In the internal security context, recycling received a lower score because the ability of the industry to collect electronics in the quantities needed is unknown. Additionally, COA 3 did outperform COA 1 regarding anticipated legal or political challenges, based on the assumption that recycling is perceived as less of a threat to the environment at the sociopolitical level. As with COA 1, COA 3 received a .75/1.

d. *Production Capacity Summary of Results*

As was described previously, the figures used in this COA refer to the waste-containing viable REE materials for recycling; it does not reflect current extraction numbers. At the time of writing, private sector companies in the industry are in the beginning stages of adding further manufacturing capabilities, but no data is available for comparison. COA 3 received a cumulative ranked score of 11. As with COA 2's performance, COA 3 received a VF score of .42. As further data emerge pertaining to refining and alloy manufacturing, this result is expected to improve.

e. Industrial Maturity Summary of Results

With the least currently realized capital potential, COA 3 finished last in both production capacity value and active labor pool. However, due to statements provided in national-level policy documents, it is assumed that recycling would be viewed favorably by policymakers, explaining the PPI evaluation of 100%. BPMI and IAI were assumed based on e-waste scores and recent growth in the industry internationally. This resulted in a cumulative ranked score of 15/20. COA 3 received a VF score of .33, reflecting the low maturity of the industry.

G. HIERARCHY OF PERFORMANCE RESULTS

1. Base Line China

With the cumulative performance scores applied from Table 11, the baseline course of action scores are displayed in the hierarchy (Figure 7). This visualization illustrates the contributions of sub-MOEs to the three primary MOEs. The weights provided below indicate that productivity, security, and environmental impact are all preferred equally. Due to facts assumed by the research scenario China performed particularly poorly in the Security MOE.

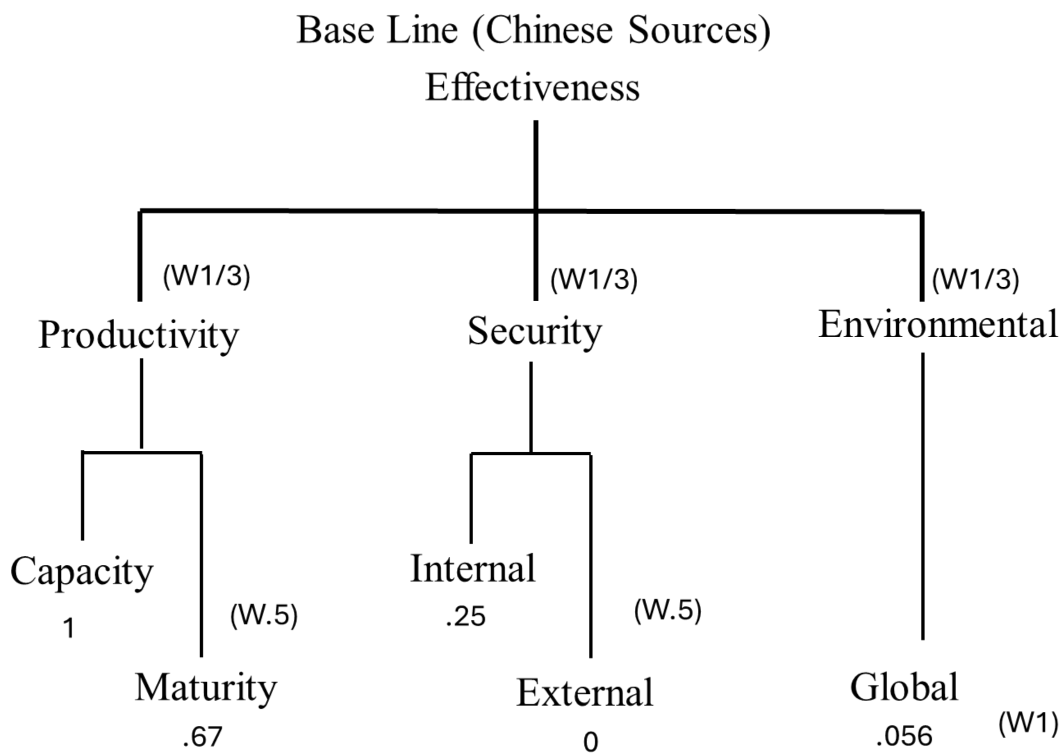


Figure 7. Base Line Chinese Performance Hierarchy

2. COA 1 U.S. Mining

With the cumulative performance scores applied from Table 12, COA 1 scores are displayed in the hierarchy (Figure 8). This visualization illustrates the contributions of sub-MOEs to the three primary MOEs. The weights provided below indicate that productivity, security, and environmental impact are all preferred equally. COA 1 performed well in the Environmental and Security MOE.

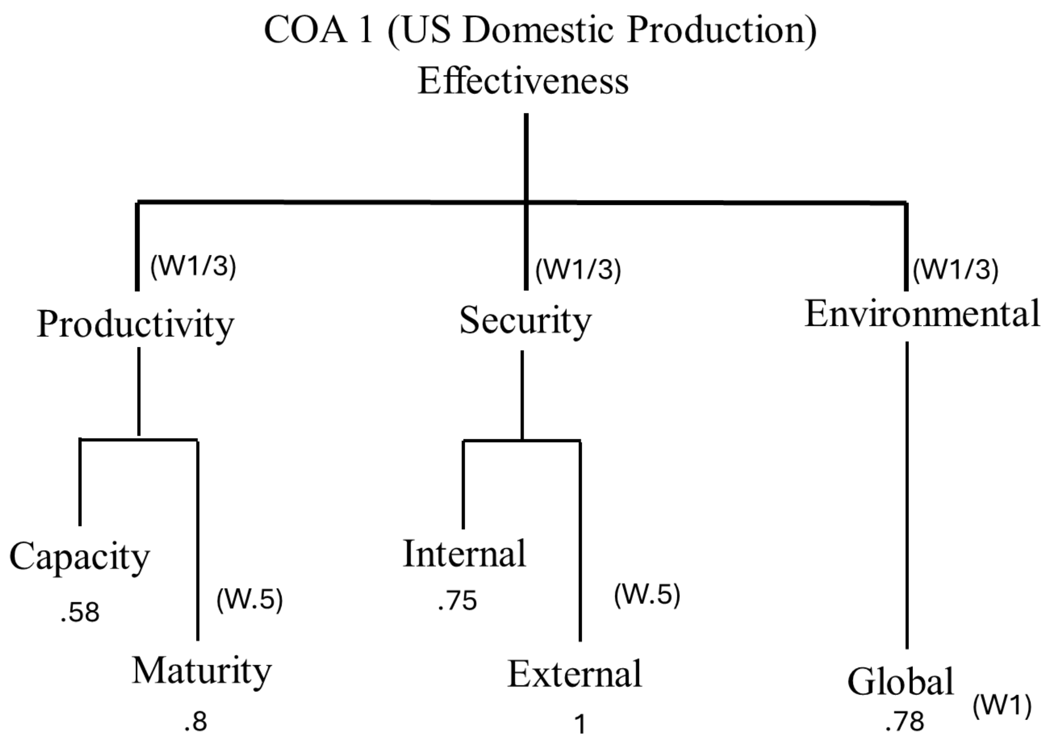


Figure 8. COA 1 U.S. Mining Performance Hierarchy

3. COA 2 Australia

With the cumulative performance scores applied from Table 13, COA 2 scores are displayed in the hierarchy (Figure 9). This visualization illustrates the contributions of sub-MOEs to the three primary MOEs. The weights provided below indicate that productivity, security, and environmental impact are all preferred equally. COA 2 performed well in the Internal Security MOP.

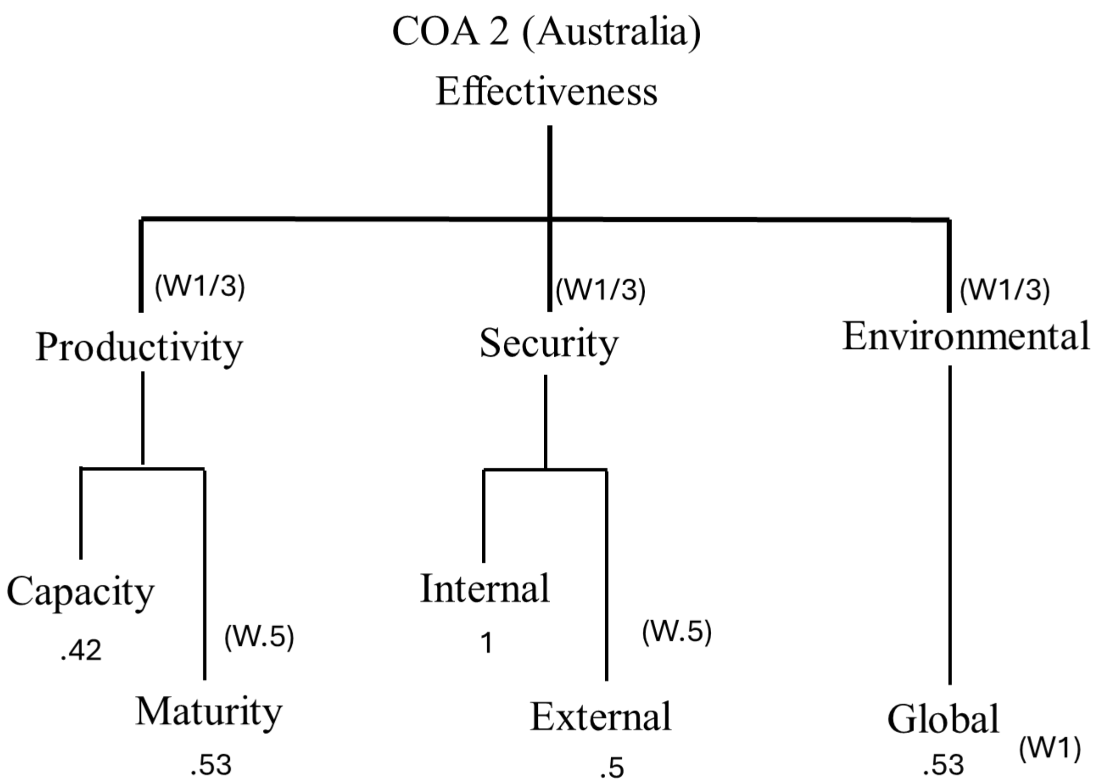


Figure 9. COA 2 Australia Performance Hierarchy

4. COA 3 U.S. Recycling

With the cumulative performance scores applied from Table 14, COA 3 scores are displayed in the hierarchy (Figure 10). This visualization illustrates the contributions of sub-MOEs to the three primary MOEs. The weights provided below indicate that productivity, security, and environmental impact are all preferred equally. COA 3 performed well in the Security MOE but underperformed in the Productivity MOE compared to COA 1.

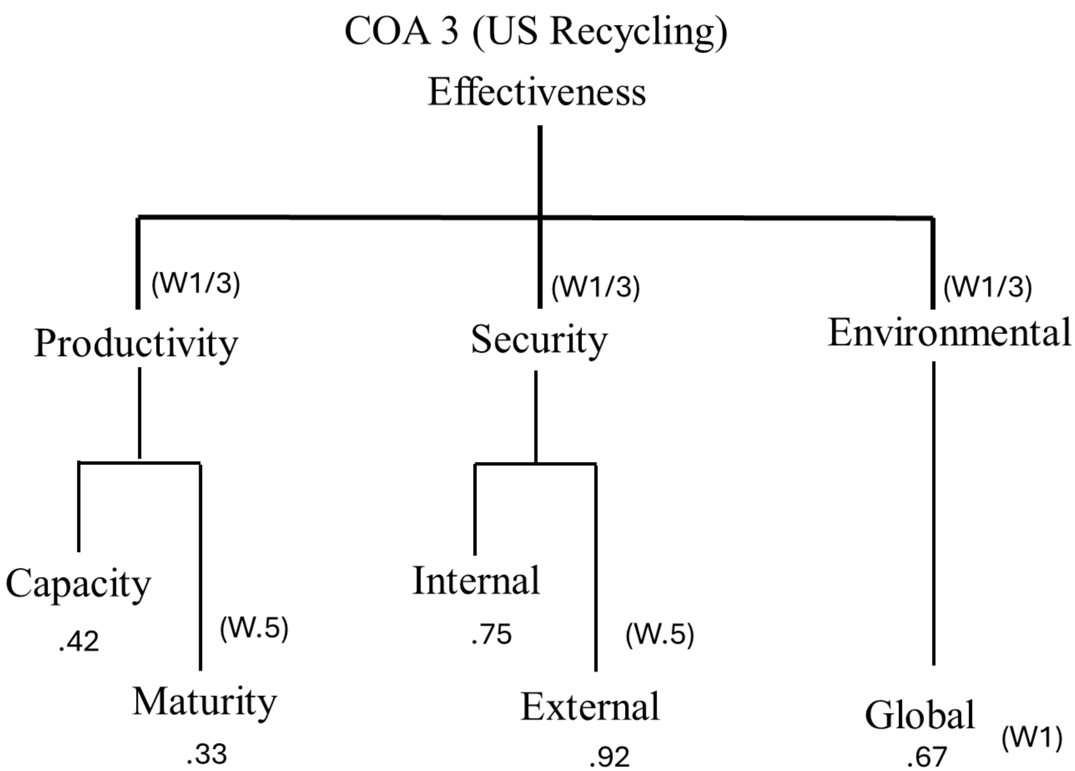


Figure 10. COA 3 U.S. Recycling Performance Hierarchy

H. COMPARATIVE ANALYSIS

Table 15 displays the results of each COA unweighted. The column titled "weight" allows for normalization across measures. The far-right column titled "total" indicates the course of actions score out of the highest possible score of 1, with higher scores being superior to lower scores.

Table 15. COA Comparison

Base Line: China							
MOP	Objective Scores	Weght	Weighted Score	Sum	Weight	Weighted Score	Total
Environment	0.056	1	0.056	0.056	0.33	0.018	0.335
External Security	0	0.5	0	0.125	0.33		
Internal Security	0.25	0.5	0.125			0.041	
Maturity	0.67	0.5	0.335	0.835	0.33		
Production Capacity	1	0.5	0.5			0.276	

COA 1: US Domestic Production							
MOP	Objective Scores	Weights	Weighted Score	Sum	Weight	Weighted Score	Total
Environmental	0.78	1	0.78	0.78	0.33	0.257	0.77
External Security	1	0.5	0.5	0.875	0.33	0.289	
Internal Security	0.75	0.5	0.375				
Maturity	0.8	0.5	0.4	0.68	0.33	0.224	
Production Capacity	0.58	0.5	0.29				

COA 2: Australia							
MOP	Objective Scores	Weights	Weighted Score	Sum	Weight	Weighted Score	Total
Environmental	0.53	1	0.53	0.53	0.33	0.175	0.58
External Security	0.5	0.5	0.25	0.75	0.33	0.248	
Internal Security	1	0.5	0.5				
Maturity	0.53	0.5	0.265	0.475	0.33	0.157	
Production Capacity	0.42	0.5	0.21				

COA 3: US Recycling							
MOP	Objective Scores	Weights	Weighted Score	Sum	Weight	Weighted Score	Total
Environmental	0.67	1	0.67	0.67	0.33	0.221	0.62
External Security	0.92	0.5	0.46	0.835	0.33	0.276	
Internal Security	0.75	0.5	0.375				
Maturity	0.33	0.5	0.165	0.375	0.33	0.124	
Production Capacity	0.42	0.5	0.21				

I. COST-EFFECTIVENESS

1. Costs

Estimating the exact quantities of REE needed by the DoD is challenging. The actual amounts required to conduct full-scale military operations are unknown or classified. Likewise, the total amount of REE required annually for civil use in green technology and commercial goods is also speculative. Matt Sloustcher, a representative of MP Materials, told the news magazine *National Defense* that the DoD consumes around 5% of total U.S. needs annually (Easley, 2023). According to the USGS, the U.S. imported 8,800 metric tons of REE in 2023(USGS, 2024). However, most REE that enter the country are assumed to do so inside of finished goods.

This research assumes that the DoD would consume half of all 2023 REE imports in a high-intensity conflict annually. Therefore, this research estimates the cost to build the necessary facilities to produce 4,400 mt per year (USGS, 2024). In order to estimate the cost of developing the facilities required, parametric estimates call on the cost of MP Corp's recent additions. MP invested an estimated $235 million to build facilities capable of separating and refining 1,000 mt per year of REE (Easley, 2023). $200 million went toward a refinement facility (Easley, 2023) and $35 million went to a separating facility (Stone, 2023). This research does not investigate the enhancement of the finished goods industry. Therefore, the cost of developing sufficient U.S. mining-based facilities is 3.4 times this figure. In Australia, 4.4 times this figure is used, and no sources of Australia having separation or refining capabilities were found. Parametric data for recycling facilities capable of production at the necessary scale were obtained from the Solvay-Orbia joint venture, which promises to produce 5 million EV batteries a year (Solvay, 2023). This project is reported to cost $850 million (Solvay, 2023). Final costs are COA 1 at $782 million, COA 2 at $1.012 billion, and COA 3 at $850 million. Presented in Figure 11 are results assuming the U.S. government pays total costs.

2. Discussion

Presented in Figure 11 are results assuming the U.S. government pays total costs. Given the data in an unweighted environment, where the U.S. Government seeks to establish an alternative source of refined REE U.S. domestic mining (COA 1) dominates COA 2 and COA3. This result assumes no joint ventures with foreign governments or venture capitalists. Alternative cost and investment models are examined subsequently.

3. Unweighted Cost Effectiveness Results

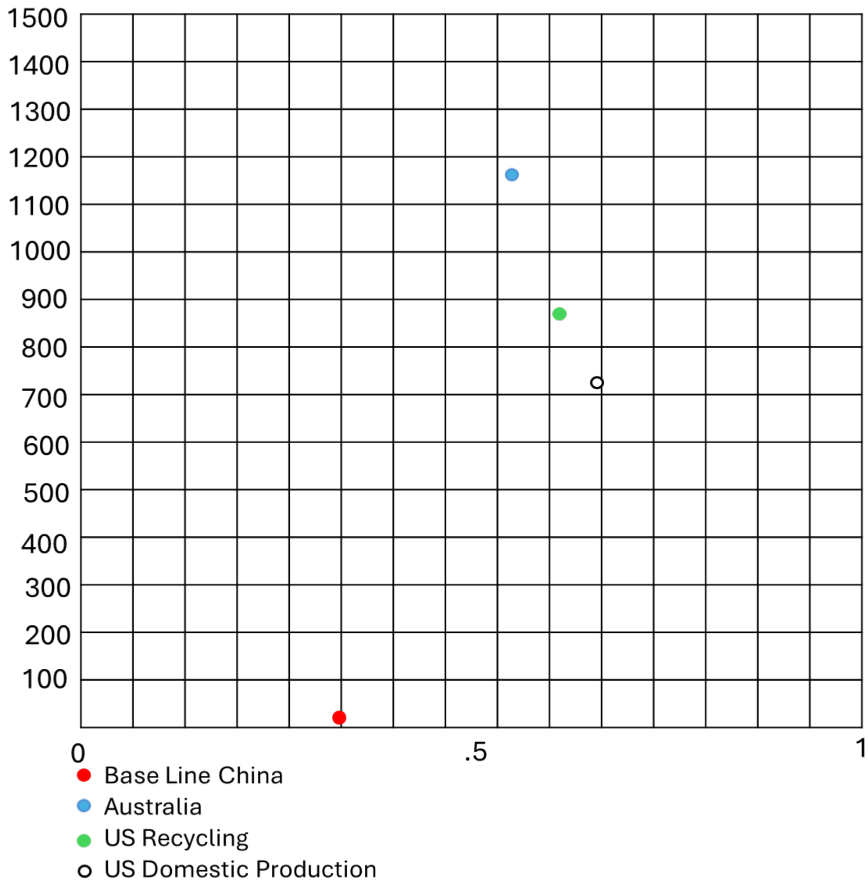


Figure 11. Cost Effectiveness

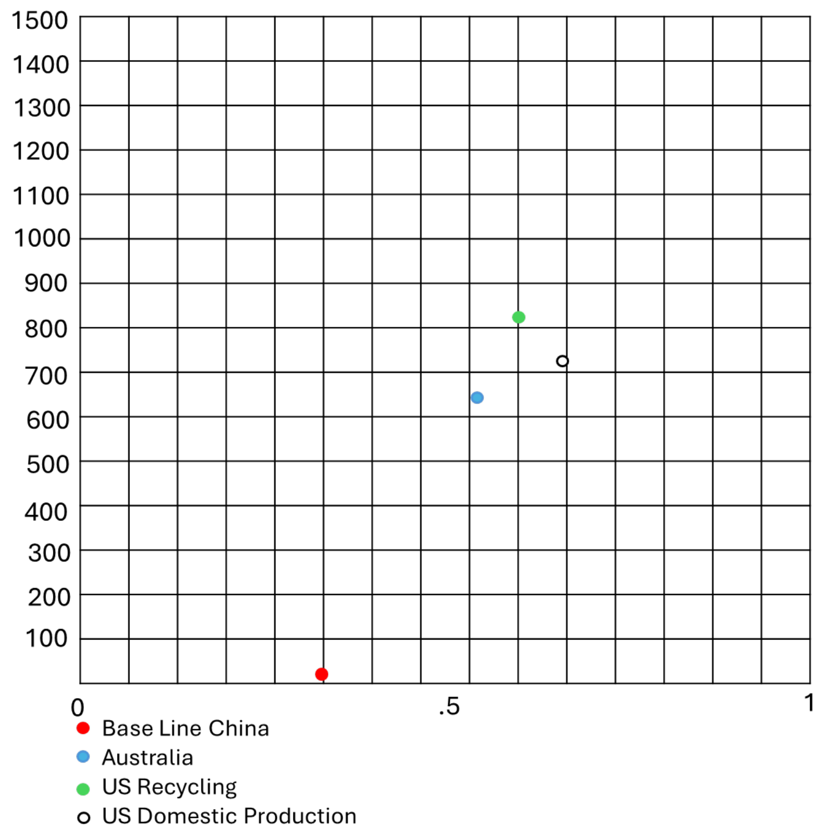
4. Discussion

An alternate model of costs is described in Figure 12 which promotes COA 2 as competitive with COA 1. This model assumes cooperative agreements between the U.S., Australia, and the Australian mining industry, where the DoD secures rites to resources in exchange for upfront investment. The investment shown accounts for 50% of the total estimated cost. The DoD has developed relationships with Australian rare earth mining companies such as Lynas Corp. DoD invested 258 million dollars in a Lynas Corp rare earth separating facility in 2023 (Lynas, 2023). The existence of this relationship suggests the possibility of greater cooperation in the future.

The price of developing the necessary rare earth recycling facilities was estimated to decrease in accordance with a two hundred and fifty million dollar investment, commiserate with those awarded to Mountain Pass and Lynas Corp (Easley, 2023: Stone, 2023).

5. Alternative Investment Model

Figure 12 depicts an alternative scenario where performance remains the same but the costs to COA 2 and COA 3 are reduced in accordance with investments already made for COA 1. While this strategy may not dramatically impact which COA 1's superiority it does highlight the potential to be strategically impactful for other reasons such as alliance strengthening. Additionally, these costs are offset in accordance with historical financing precedence established by the U.S. government.



Note: The adjusted costs reflected in this model represent a fifty percent cost partnership with the Australian mining industry/government and an investment in U.S. recycling commiserate with capital invested in U.S. mining at MP Corp (Easly, 2022).

Figure 12. Alternative Investment Model

V. CONCLUSION

A. RESULTS

The results of this research support the use of mines located in the continental United States as the most cost-effective sources of REEs. All three sources investigated in this research appear to be viable options for the future with regard to their capacity. The amount of time to fully develop the supply chain as well as their respective costs vary. The research question was, *Which of the three methods for replacing China as a source of REE would be the most cost-effective?* This research is important because it informs the effective and efficient use of valuable state resources to ensure a supply chain exists for a commodity vital to national defense. The MOEs that were taken into consideration were the environment, the security of the sources, and the productivity of the source. Sub-MOEs that were investigated included environmental impact, internal security, external security, production capacity, and industrial maturity. MOEs that were used to evaluate the courses of action include

- CO2 emissions
- Particulate matter emissions
- Freshwater toxification
- Saltwater toxification
- Acidification
- Ecotoxicity
- Competitive status
- Transportation in nautical miles
- Supply vulnerability (threat)
- Global cyber index performance
- Labor stability
- Supply vulnerability (access)
- Legal/political challenge
- Corruption control score
- Mining capacity
- Refining capacity
- Allow manufacturing capacity
- Production capacity value

- Active labor pool
- Policy perception index score
- Best practices mineral potential index
- Industrial attractiveness score

COA 1 outperformed its competitors comprehensively with the exception of the base-line China's current production MOP. While China will likely remain dominant in production, for the purposes of this research the production capacity of COA 1 is assessed as sufficient to replace it. This research indicated that both COA 2 and COA 3 have the potential to be viable and cost-effective alternatives based on their capacities, and the precedence of cost-sharing initiatives. Finally, the results of this research clearly indicate that the United States need not be dependent on foreign sources of critical resources for national security.

B. CONCLUSION

The U.S. is currently positioned precariously with regard to its rare earth supply chain. Critical minerals are currently being mined, refined, or employed by China to such an extent that hostilities or loss of trade access would severely impact national security in the U.S. The U.S. has the capacity to develop alternative supply chain sources, each with unique costs and benefits. The results of this research support the onshoring of mining and producing goods using these resources. The time and money required to bring this supply chain up to full functionality is significant. However, the consequences of being unprepared are likely more severe. Armed with data senior decision-makers are more prepared to allocate time, money, and attention in order to resolve this imminent threat.

C. RECOMMENDATIONS

Based on the data obtained in the course of this research it is recommended that the United States select as its primary focus of investment domestic mining and production of rare earth minerals for use in the defense industry.

D. OPPORTUNITIES FOR FURTHER RESEARCH

This research assumed that the pursuit of each COA—domestic mining, investing in Australian sources, and recycling within the United States—were mutually exclusive options. That is to say that this research did not investigate the potential blending of two or all three COAs as with a linear programming problem. Due to the sparsity of data about various individual minerals within the family of REE, neodymium was frequently used as a proxy for all minerals. However, with enhanced data access, a blended solution may become more attractive.

Lastly, this research considered only the procurement of raw materials that were refined to the point that they could be used industrially to produce finished goods. This research did not address the need to produce or acquire more facilities that manufacture finished goods. Investigating the limitations of U.S. defense contractors to domestically manufacture those goods is recommended and could prove useful to policy makers.

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