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Dissertation

Critical Rare Earths, National Security, and U.S.-China Interactions

A Portfolio Approach to Dysprosium Policy Design

David L. An

RAND CORPORATION

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This document was submitted as a dissertation in September 2014 in partial fulfillment of the requirements of the doctoral degree in public policy analysis at the Pardee RAND Graduate School. The faculty committee that supervised and approved the dissertation consisted of Brian Chow (Chair), Charles Wolf, Jr., and Deborah Elms.

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Dedication

For my father, who modeled a life defined by the rarest mix of virtues: fierce love, unbounded grace, profound gratitude, and unrelenting perseverance. Love you dad.

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Abstract

In recent decades, China has become the world's principal source of rare earths extraction, processing, and manufacturing of its derivative goods. China's monopoly is partly a result of its rich geological endowment, particularly of the "heavy" rare earths that are increasingly valuable in green energy and military technology applications. The country's rapid industry consolidation, however, has been abetted by unfair policies such as export restrictions that subsidized domestic producers. Furthermore, Beijing has indicated a tight-fisted disposition, intent on reserving its rare earths for domestic consumers and preferring that trade partners "find their own sources." This dissertation examines how the U.S. can pursue a portfolio of policies to reduce American vulnerability to the supply disruption of one critical heavy rare earth, dysprosium. Intended primary for U.S. policy makers, the study first provides a consolidated narrative of the interplay of politics, economics, and geology of rare earths in general and dysprosium in particular. It then systematically evaluates the effectiveness and costs of a roster of new and incumbent policies. A new strategic planning framework leverages mixed-integer linear programming to concoct policy portfolios that maximize U.S. resiliency to dysprosium supply disruptions at given budget levels. This enables a trade-off analysis comparing the portfolios' vulnerability reduction effectiveness against their costs. This analysis culminates with a recommendation of the portfolio that balances fiscal feasibility with acceptable vulnerability reduction. The hope is that the method and research findings will also serve as a generalizable template for mitigating the criticality of other vulnerable rare earths and materials.

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Abbreviations and Acronyms

AlNiCo	Aluminum Nickel Cobalt
AESA	Active Electronically Scanned Array
AREPI	Advanced Rare-Earth Projects Index
ARPA-E	The Advanced Research Projects Agency-Energy
AVIC	Aviation Industry Corporation
BGS	British Geological Survey
BIS	Bureau of Industry and Security
CAGR	Compounded Annual Growth Rate
CBO	Congressional Budget Office
CFL	Compact Fluorescent Lamps
CHPS	Combat Hybrid Power System
CMI	Critical Materials Institute
CRL	Commercial Readiness Level
CREE	Critical Rare Earth Element
CRI	Comprehensive Recycling Initiative
CS_k	Criticality score of policy for a given scenario k
$CS_{R\&D}$	Criticality score of R&D project
DLA	Defense Logistics Agency
DMEA	Defense Microelectronics Activity
DoC	Department of Commerce
DoD	Department of Defense
DoE	Department of Energy
DSB	Dispute Settlement Body
EA	Export Administration
EAA	Export Administration Act of 1979
EAR	Export Administration Regulations
EC	European Commission
EE	Export Enforcement
EERE	Office of Energy Efficiency and Renewable Energy
EMCD	Export Management and Compliance Division
EOL	End of Life
EPA	Environmental Protection Agency
EPCA	Energy Policy and Conservation Act
EPEAT	Electronic Product Environmental Assessment Tool
ETBC	Electronics TakeBack Coalition
EU	European Union
FCC	Fluid Cracking Catalyst
FP7	7th Framework Programme for Research and Innovation
FY	Fiscal Year
GATT	General Agreement on Tariffs and Trade
GM	General Motors
GMEL	Greenland Minerals and Energy Limited
GW	Gigawatt
HH	High Demand and High Supply Capacity
HREE	Heavy Rare Earth Element
HREO	Heavy Rare Earth Oxide
IEA	International Energy Agency
IED	Improved Explosive Device

JDAM	Joint Direct Attack Munition
JOGMEC	Japan Oil, Gas, and Metals National Corporation
JORC	Joint Ore Reserves Committee
JSF	Joint Strike Fighter
JV	Joint Venture
KIIT	Korea Institute of Industrial Technology
KORES	Korea Resources Corporation
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
LL	Low Demand and Low Supply Capacity Case
LRAD	Long Range Acoustic Device
LREE	Light Rare Earth Element
LREO	Light Rare Earth Oxide
MCS	Mineral Commodities Summary
METI	Ministry of Economy, Trade, and Industry
MEXT	Ministry of Education, Culture, Sports, Science, and Technology
MICAD	Multipurpose Integrated Chemical Agent Database
MIT	Massachusetts Institute of Technology
MLR	Ministry of Land and Resources
MoU	Memorandum of Understanding
MRI	Magnetic Resonance Imaging
MW	Megawatt
NASA	National Aeronautics and Space Administration
NDAA	National Defense Authorization Act
NdFeB	Neodymium-Iron-Boron
NDRC	National Development and Reform Commission
NDS	National Defense Stockpile
NEDO	New Energy and Industrial Technology Development Organization
NI	National Instrument
NiMH	Nickel Metal Hydride Batteries
NIMS	National Institute for Materials Science
NPMR	National Plan for Mineral Resources
NPV	Net Present Value
NRC	National Research Council
OEA	Office of Enforcement Analysis
OEE	Office Export Enforcement
OExS	Office of Exporter Services
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
PRC	People's Republic of China
PV	Present Value
RCRA	Resource Conservation and Recovery Act
R&D	Research and Development
$R\&D^3$	Research and Development Degree of Difficulty
REACT	Rare Earth Alternatives in Critical Technologies for Energy
REE	Rare Earth Element
REM	Rare Earth Metals
REO	Rare Earth Oxides
RMSP	Rare Metals Stockpiling Program
SBMR	State Bureau of Material Reserves
S.I	Optimistic Scenario

S.II	Pessimistic Scenario
S.III	Worst Case Scenario
SmCo	Samarium Cobalt
SMSP	Strategic Materials Security Program
SOE	State-Owned Enterprises
SOFC	Solid Oxide Fuel Cells
SX	Solvent Extraction
T_k	Threshold sum ex-post criticality score for a scenario k
TMR	Technology Metals Research
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
UN	United Nations
U.S.	United States
USDOA	United States Department of Agriculture
USFS	United States Forest Service
USGS	United States Geological Survey
USML	United States Munitions List
USMMA	United States Magnetic Materials Association
USTR	United States Trade Representative
VAT	Value-Added Tax
WEEE	Waste of Electrical and Electronic Equipment
WTO	World Trade Organization
XA_k	*Ex-Ante* criticality score for a given scenario k
YAG	Yttrium-Aluminum-Garnet

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The impetus for this research topic originates from my work with Richard Silberglitt on RAND's critical materials project through which I gained familiarity with literature and data on minerals and the commodities trade. The fascinating tutorial on complex dynamic system with Raffaele Vardavas was instrumental in helping me understand and model the stochasticity of commodity economics as well as getting me started on the R learning curve. Instructions from Thomas Light and Paul Heaton helped establish and explore the early microeconomic theory and empirical framework of the study, respectively. I had the great pleasure of exploring the game theoretic potentials for this research thanks to the course taught by Fabian Duarte and Jeremy Burke.

To thank the members of the dissertation committee would be an understatement. Under their cultivation, I have learned to complete a research that aims to "Be the Answer" through "Objective Analysis, Practical Solutions," to quote the PRGS and RAND mottos, respectively.

Deborah Elms filled a critical vacuum in the committee, yielding her significant expertise on the trade dimensions of the research, a policy area that is outside RAND's traditional research domain. I particularly thank her for consistently pushing back on structural clarity and for pulling me back from the needle to see the branch, from the branch to the tree, and from the tree to forest. Her guidance allowed me to confidently answer the two toughest questions a doctoral student could face, "What is your dissertation about?" and "How is that relevant?"

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Executive Summary

Research Introduction

This dissertation serves as a "one-stop shopping" destination for the U.S. policy planner seeking to understand the complex political, economic, and technical dynamics governing rare earths in general and dysprosium in particular and to identify a comprehensive solution for increasing American resilience to dysprosium supply disruptions. The study leverages qualitative and quantitative data and methods to provide a systematic explication, diagnosis, and treatment of the dysprosium supply challenge. In particular, it presents a framework for maximizing dysprosium criticality reduction under budget constraints using an optimization model.

The first step is to understand the unique political, economic, and technical dynamics that define the criticality of a material such as dysprosium. This establishes the empirical and qualitative foundations for understanding why a given material is "critical" and equally importantly, what role policies can have in reducing the criticality. Next, a roster of policy options is considered (derived from literature and additionally synthesized by the author) that can address the drivers of dysprosium criticality. The study then utilizes a linear programming model to determine which policy combination (portfolio) maximizes American resilience to dysprosium supply disruptions for a series of budget levels up to $3 billion.

The result is a cost-effectiveness trade-off curve and the identification of unique optimal portfolios of policies that reduce dysprosium criticality. There are three practical planning benefits of this approach for the policy planner. First, the planner is able to select and assemble policy options that can best reduce dysprosium criticality (vulnerability to supply disruption), given an allocated budget. Secondly, if budgetary pressures call for additional cost saving measures, the planner has an indication of how much savings are possible, and if budgets are cut involuntarily, how much those cuts will affect dysprosium criticality reduction effectiveness. Lastly, if the optimized portfolio at a given budget level does not sufficiently decrease dysprosium criticality, the planner has an analytical framework for justifying additional funding to meet required dysprosium criticality reduction levels. At the very least, senior decision makers can be forewarned of the potential consequences of budget reductions on dysprosium criticality or vulnerability to supply disruption.

Finally, three "Sweet Spot" Portfolios are identified for three different ranges of portfolio implementation budgets (low, moderate, and high). Not only do these Sweet Spot portfolios yield the highest effectiveness for their given budgets, they also provide the policy planner with superior value for money.

Dysprosium Supply Risk – Politics, Economics, and Geology

China rose to become the leading rare earths producer today through strategic investment in the industry spanning the decades. Eager to capitalize on its abundant geological reserves and to exploit its unique properties, Beijing has sought to develop mining capacities, invest in scientific research, and in the last decade, consolidate lucrative global midstream and downstream rare earth production facilities within its borders. This consolidation is now largely complete, with greater than 90 percent of upstream and midstream capacities and at least 75 percent of downstream NdFeB magnet capacity currently residing within China. In particular, China has a monopoly of valuable heavy rare earths, including dysprosium, at least for the near term.

Beijing's strategy for capturing the global rare earth value chain was two-fold. First, China's rise as an upstream monopolist was abetted by its geological endowment of large and easy to excavate (read less costly) deposits, particularly of heavy rare earths which include dysprosium. Secondly, to capture the midstream and downstream capacities, Beijing instituted export restriction measures that created a two-price system—a domestic price that effectively subsidized Chinese suppliers and an international market price that was much higher. This created financial pressures that forced foreign rare earth processors and manufacturers to either close down or relocate their business to China to take advantage of lower rare earth ore prices. It was not until 2009, however, with Beijing's drastic cuts in export quotas and the concomitant rise in prices afterwards that rare earths gained the attention of policy makers worldwide. In the years since, the U.S. along with the Japanese and European governments among others, have prevailed against Beijing's export barriers on critical materials and rare earths in two successive suits before the WTO.

Undergirding the political and economic fracas of rare earths is a non-human factor: the abundant presence of rare earths within China's political borders. The abundance is not merely in terms of quantity (just less than half of the world's reserve) but also in valuable heavy rare earths in the form of ion-adsorption which are significantly easier to extract than heavy rare earths found in other deposits around the world. The triumvirate of rare earths quantity, elemental distribution, and quality gives China a natural (pun not intended) advantage in the political economy of rare earths.

Dysprosium Material Importance: The NdFeB Permanent Magnet

By far, the most significant use of dysprosium is in small quantities in the manufacture of NdFeB (Neodymium-Iron-Boron) permanent magnets. These magnets have superior overall qualities in terms of power (magnetism), coercivity (resistance to heat and de-magnetization), and efficiency (smaller amounts that still yield superlative performances which allow for miniaturization) than all its predecessors, such as the SmCo (Samarium-Cobalt) and iron magnets. Permanent magnets are used in hard drives, autos, smart phones, and medical devices as well as in next generation wind turbines and advanced military weapons systems. With greater demand for technology goods that shrink in size without sacrificing performance, dysprosium-laced permanent magnets play an increasingly important role in the modern economy.

Dysprosium, the Most Critical Rare Earth

This study heavily relies on the critical materials framework established by NRC (2008) and Bauer et al. (2011) which introduced the criticality matrix. According to this matrix, the more important a material is to society and the more risk there is of a supply disruption for that material, the more critical or vulnerable the material. Dysprosium ranks high in both dimensions (Bauer et al. 2011). Criticality is manifested in part by shortfalls, the difference between available supply and demand. A range of potential shortfalls is possible in the decades ahead. In the best case, the shortfalls will be limited if demand requirements are stable and supply capacities grow steadily outside of China. In the hypothetical worst case, however, the shortfall can be very acute.

While China is the dominant rare earths producer, it is increasingly also a net importer as well, especially of the heavy/critical rare earths (including dysprosium) as its technology manufacturing base matures. Meeting shortfall demand by opening up Chinese rare earths trade thus may not improve American supply of dysprosium given China's own voracious demand for the material.

U.S. Policy Options for Increasing Resiliency

Ten policy choices recommended by U.S. government agency reports, legislators, or otherwise synthesized by the author are classified along four Policy Areas (Supply Chain Development, Functional Substitute R&D, Trade Restrictions, and Contingency Plans). Policy Area 1 seeks the revitalization of the U.S. rare earth supply chain (from upstream extraction, midstream separation and processing, to downstream manufacturing); Policy Area 2 includes the research and development (R&D) of substitutes; Policy Area 3 leverages U.S. trade power to either shield and nurture American rare earths suppliers from Chinese rent-seeking, or to impose costs on Beijing to deter it from pursuing such policies; and finally, Policy Area 4 is the stockpiling of dysprosium by the Department of Defense (DoD) either through the National Defense Stockpile (NDS) or via contracts with private sector suppliers to maintain a buffer stock inventory.

Each policy option was qualitatively evaluated on its ability to reduce criticality of one or more sub-dimensions of the criticality matrix by the end of the FY 2029 and interpreted into a 4-point integer scale based on the NRC (2008) and Bauer et al. (2011) studies. The exception is the NDS, which is selected as a necessary "insurance" policy for meeting military and essential civilian needs for four years during a contingency event such as a major conflict or homeland attack. The policy implementation costs for the fifteen fiscal year planning period (FY 2015 to FY 2029) were also estimated.

Three Sweet Spot Optimal Portfolios for Three Budget Ranges

The study applies a linear programming model to calculate how much dysprosium criticality reduction can be achieved under various budget levels ranging from zero to $3 billion. This analysis yields a trade-off curve that exhibits diminishing marginal criticality reductions with each additional dollar increase in the budget. In addition, a dozen unique policy portfolios are identified that are optimal for different ranges of budget. Of these, three are identified as what are called "Sweet Spot" Portfolios because they reduce U.S. dysprosium vulnerability to specified criticality ranges at the lowest cost possible:

Portfolio 3 offers the highest per dollar vulnerability reduction value amongst all the portfolios. The downside, however, is that this portfolio may not be resilient enough to shield the U.S. from critical shortfalls in the worst of cases. Thus, Portfolio 3 would be the selected option if the policy maker is merely interested in the best value without consideration of the robustness of the portfolio against worst case scenarios. It consists of investments in three policy options. First is U.S. domestic mining permitting reforms. Second is R&D on functional substitutes. Third is export restrictions on raw materials that China is import-dependent on in order to compel Beijing to dismantle its export restrictions as well as to deter it from manipulating global supplies henceforth.[1] Portfolio 3's actual implementation cost is $102 million. With the NDS contingency insurance of $62 million, the total cost is $164 million.

Portfolio 5 is the Sweet Spot Portfolio for a budget between $431 million to approximately $2 billion. It is designed to sufficiently decrease U.S. dysprosium vulnerability so that the U.S. would not experience acute shortages even in the worst case scenario. It includes Portfolio 3's three policy options plus two more policies—the Comprehensive Recycling Initiative (CRI) that invests in both cost-effective dysprosium recycling technology R&D and legislation to increase collection rates of e-wastes that contain

[1] Portfolio 3 selects export restrictions as the default policy. However, the policy maker can also select import restrictions as a viable alternative for a slightly higher budget ($6.4 million). *Regardless of which policy is selected, however, these policies are not assumed to be automatically executed because of their high potential for political and economic blowback.* Thus, the funds are allocated as reserves in case the U.S. policy maker later decides that either of the policies is implemented after serious deliberation about the merits of their effectiveness in increasing supply resiliency.

dysprosium; and R&D investment in better rare earths midstream (separation and processing) technologies that can improve the competitiveness of U.S. rare earth suppliers. The actual portfolio cost is $431 million, with the total rising to $493 million after the NDS contingency plan.

Portfolios 11/12 would achieve the maximum reduction in American dysprosium vulnerability with the full set of policy options at the lowest possible budget. However, the cost would be approximately $2.7 billion for the implementation of all possible policies (including the NDS contingency plan).[2] Portfolios 11/12 include a DoD accreditation regime to incentivize U.S. and qualified countries' rare earth suppliers to become certified trusted sources of dysprosium and derivative products for the U.S. military. It also includes expanding the DoD's pre-existing Trusted Foundry program to include government-owned dysprosium (and other critical rare earths) midstream and downstream capacities to meet DoD requirements.

All three Sweet Sport Portfolios are optimal for their budgets and achieve their relative policy objectives. Portfolio 3 returns maximum value proposition albeit with high uncertainty regarding reductions in vulnerability. Portfolio 5 provides a more robust outcome against uncertain futures but requires a larger budget than Portfolio 3. Portfolios 11 and 12 achieve the maximum possible vulnerability reduction for the policy maker. Given the constrained federal budget environment, however, Portfolios 11 and 12 are politically untenable. Thus, Portfolios 3 and 5 represent the more serious contenders for adaptation. Between the two, the decision maker must weigh the prospect of comparatively higher reductions in dysprosium criticality offered by Portfolio 5 (at a higher cost) against the budget-friendly but less robust option offered by Portfolio 3. This study recommends that the policy maker implement Portfolio 5 given its ability to shore up the resiliency of the U.S. dysprosium supply chain regardless of future scenarios and to do so in a fiscally responsible manner.

[2] Portfolio 11 and 12 are interchangeable because the only difference between the two is which of the two versions of the trade restriction options are selected.

Chapter 1 – Introduction

"So, are rare earth minerals actually rare? Not really."
- Charles Homans

Introduction

The objective of this dissertation is to examine how the U.S. can pursue policies to secure a more reliable supply chain of one highly critical rare earth element (CREE), dysprosium, and to seek technical solutions that reduce heavy reliance on its use. The primary audience for this research is the U.S. policymaking community. Thus, a complementary research objective is to assist the U.S. policy maker to best utilize public resources to reduce the likelihood of dysprosium supply shortfall, and should a shortfall occur, its magnitude in a cost-effective manner.

This introductory chapter will present the dissertation's core research findings, explicate the relevance of the research to the U.S. policymaking audience, highlight the study's research contributions and practical policymaking utility, establish the case for dysprosium "criticality," and why it is the rare earth element (REE) that has been chosen for this study. Finally, it provides a research roadmap to assist the reader navigate the chapters as they build the case for why and how the U.S. policy maker should and can cost-effectively decrease American vulnerability to dysprosium supply disruptions.

Research Findings

The Policy Challenge

The growth in Sino-American trade relations over the past decades has wrought great economic benefits for both countries by allowing each to fully exploit its comparative advantages. One of China's natural comparative advantages is its rich geological endowment of rare earth elements, particularly of the so-called "heavy" rare earth elements (HREEs) including dysprosium, that are increasingly valuable in green energy and military technology applications. In recent decades, China has become the principal source of rare earths extraction, processing, and manufacturing of its derivative goods to global consumers, including the U.S.

Such economic interdependence, however, is premised on the reliability and willingness of the supplier to export its goods to its trading partners. Recent Chinese policies have cast heavy doubt on both accounts. China's rare earths industry integration has been propelled by beggar-thy-neighbor policies designed to hasten advanced Chinese rare earths production capacities. Beijing's principal policy tool for achieving this goal has been through export restrictions (via quotas and tariffs) on rare earth ores. These measures have created a two-tiered price system whereby international rare earth prices are significantly higher than China's domestic prices. This creates price pressures for foreign firms to relocate to China, consolidating China's monopoly of the rare earth supply chain. Furthermore, with China's rare earths demand expected to soar as the economy expands, Beijing is intent on reserving its rare earths for its own domestic consumption. In sum, "Chinese rare earths for Chinese consumption" is Beijing's resounding mantra.

The intersection of China's near monopoly of the global rare earths supply chain, Beijing's desire to preserve production for its own market, and the sensitive application of rare earths in U.S. military

systems and green energy production necessitates a strong, coherent, and cost-effective policy response from the United States government.

Policy Solution

The American policy maker has a range of technical, political, and economic policy options available to redress these concerns. Ten policy options are broadly categorized under four Policy Areas summarized in Table 1.1. Policy Area 1 seeks the revitalization of the U.S. rare earth supply chain (from upstream extraction, midstream separation and processing, to downstream manufacturing); Policy Area 2 includes the research and development (R&D) of substitutes; Policy Area 3 leverages U.S. trade power to shield and nurture American rare earths suppliers from Chinese rent-seeking or to impose costs on Beijing to deter said policies; and Policy Area 4 is the stockpiling of dysprosium by the Department of Defense (DoD) either through the National Defense Stockpile (NDS) or via contracts with private sector suppliers to maintain a buffer stock inventory.[3]

TABLE 1.1 – POLICY AREAS AND POLICY OPTIONS

Policy Area	Policy Option
1	1.1 Domestic Upstream Production
	1.2 Midstream R&D Separation and Processing
	1.3 DoD Downstream Accreditation
	1.4 DoD Trusted Foundry
	1.5 Comprehensive Recycling Initiative (CRI)
2	2.1 Functional Substitute R&D
3	3.1 Export Restriction
	3.2 Import Restriction
4	4.1 Traditional Stockpiling
	4.2 Buffer Stockpile

This dissertation finds that there are three different policy portfolios for three respective budget ranges that can minimize American vulnerability to supply risks of dysprosium in a cost-effective manner. These three portfolios—Portfolios 3, 5 and 11/12—are referred to as "Sweet Spot" Portfolios because they maximize vulnerability (criticality) reduction for a given budget while also capturing large value for money. Regardless of which portfolio the policy maker selects, the assumption is that the U.S. government will continue to politically engage Beijing in the World Trade Organization (WTO) and pursue DoD stockpiling of critical materials (including select rare earths) as statutorily required. It would also continue to consult, cooperate, and coordinate with other countries on critical material matters, including rare earths.

[3] A couple of unique policy option attributes should be noted upfront which are extrapolated later. First, the two Policy Area 3 trade restriction options (export restriction and import restriction) are mutually exclusive. As explained in Chapter 6, the import restriction is designed to keep Chinese rare earths out while the export restriction is designed to keep pressure on China to continue supplying the U.S. and other trade partners with its rare earths. Second, one of the two Policy Area 4 contingency plan options are always chosen as an insurance policy against the worst possible outcome (in practice, it is always the NDS option due to its cost advantage).

Portfolio 3 is comprised of three "core" policies[4]: reforms to U.S. mining permitting delays (which will support domestic upstream production), research and development (R&D) funding for substitute technologies that do not rely on dysprosium (functional substitutes), and American export restrictions on raw materials for which China is import-dependent on to coerce and/or deter Beijing from manipulating dysprosium (and other rare earths) supplies. In addition, the study recommends that the Department of Defense (DoD) retains a dysprosium stockpile as an insurance against serious national contingencies that could result in severe dysprosium shortfalls. This portfolio emphasizes maximize per dollar value for the American public but may not be robust enough to sufficiently reduce U.S. dysprosium supply vulnerability in the most extreme cases. Portfolio 3 is the most cost-effective choice for total federal program appropriations of $430 million or less. The actual implementation cost for the three policies plus stockpiling over the planning period from Fiscal Year (FY) 2015 to Fiscal Year 2029 is an estimated $164 million. Any spending beyond $164 million yields diminishing reduction in dysprosium vulnerability (diminishing marginal returns).

These three core policies plus the stockpiling plan are always selected no matter the budget level. They have the highest effectiveness to cost ratios which offers the policy maker the greatest bang for the buck.

Portfolio 5 is comprised of the three portfolios in Portfolio 3 plus two additional policies: first, a Comprehensive Recycling Initiative (CRI) that increases the recycling rate of electronic consumer waste and the recovery of minute traces of dysprosium contained within them; and second, R&D investment into next generation cost-effective rare earth separation and processing techniques that can help make American rare earth production more competitive. This portfolio is designed to sufficiently reduce American vulnerability to dysprosium supply disruptions such that the U.S. would not experience drastic shortages even in the most pessimistic future scenario. Portfolio 5 is optimal and offers the highest value for appropriated budgets between $431 million and approximately $2 billion (inclusive).[5] The actual implementation cost—which includes the DoD stockpile—is estimated at $493 million.

Portfolios 11 and 12[6] are comprised of the same five policies in Portfolio 5 but with two additional policies: first, investment in a DoD accreditation program that certifies the origins and qualities of dysprosium and its derivative goods that are used by the U.S. defense industrial base; and second, the inclusion of a separate DoD rare earths processing and rare earth magnet manufacturing capacity as an extension of the pre-existing DoD Trusted Foundry program for semiconductors. This portfolio achieves the maximum reduction in U.S. vulnerability with the given set of policy tools. Portfolios 11 and 12 are the optimal high-value portfolios for budgets greater than $2 billion. The actual costs, again including the DoD stockpile, is an estimated $2.7 billion.

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[4] Core policies are selected no matter the budget level. They have the highest effectiveness to cost ratios which offers the policy maker the greatest bang for the buck.

[5] "Optimal" policy portfolios maximize the reduction of dysprosium criticality (which is equivalent to maximizing the reduction of American vulnerability to dysprosium supply disruptions) subject to an allotted fiscal budget. "High value" policy portfolios are those that provide the greatest decrease in dysprosium with each additional dollar of budget increase. In microeconomics, this is referred to as marginal returns.

[6] Portfolios 11 and 12 are identical except in whether the policy maker selects export restrictions (Portfolio 11) or import restrictions (Portfolio 12). Import restrictions prohibit the U.S. importation of Chinese rare earths in order to help the revitalization of a domestic U.S. rare earth industry. Export restrictions are punitive and are designed to impose a cost on China by curbing exports of raw materials that China is import-dependent via quotas or tariffs. Import and export restrictions are mutually exclusive options (explained in Chapter 6) with minor differences in cost and effectiveness ratings. For these reasons, Portfolios 11 and 12 are simply considered variations of a single portfolio.

These three Sweet Spot Portfolios achieve two important policy objectives.[7]

First, Sweet Spot Portfolios are designed to maximize reductions to U.S. dysprosium supply vulnerability (maximize criticality reduction) at a given level of federal budget in the long term, specifically by the end of FY 2029. This means that for an appropriated program budget, the policy maker knows what the best combinations of policy options will help reduce American vulnerability.

Second, they capture the greatest value for money for the U.S. taxpayer. This means that Sweet Spot Portfolios return a high dysprosium criticality reductions for every dollar spent (this is known as marginal returns). Any additional money spent returns inferior rates of criticality reduction. Any smaller dollar amount means that the policy maker is foregoing proportionally large increases in criticality reduction even if spending increased by only a small amount.

This research's primary audience is the U.S. policymaking community although rare earths stakeholders in industry and academia may also find it relevant. The Sweet Spot Portfolios and the method for identifying them should be of strong policy interest during this time of U.S. budget austerity since the results ensure that limited fiscal resources are deployed for maximum effect and value. With this in mind, this research recommends that the U.S. policy maker advocate moving towards the implementation of Portfolio 11/12 which offers the greatest optimal risk reduction to American vulnerability to dysprosium supply disruption. However, given the hefty cost, an acceptable fallback choice is Portfolio 5. Portfolio 3, which is the least costly option, should only be advocated as an alternative to inaction.

Policy Relevance

Reducing dysprosium criticality is a costly proposition, so why should the U.S. policy maker be interested in rare earths in the first place?

Rare earths are crucial for the manufacture of many products such as personal electronics, wind turbines, hybrid cars, petroleum refining, solar cells, and advanced weapons systems. Rare earths comprise 17 separate elements on the periodic table that share similar chemical properties and are often found together when extracted from mines. A subgroup of elements referred to as critical rare earth elements have been found to be both high in importance to society but also prone to supply disruptions (Hatch 2011 and Bauer et al. 2011). Of the CREEs, dysprosium is the single highest critical element which makes it a suitable candidate for a case study generalizable to less restrictive rare earths elements.

Dysprosium is an important additive for increasing the performance of permanent magnets that have crucial functions in next-generation wind turbines and military systems. Historically, dysprosium has only been mined in China, which has been keen on preserving its limited reserves for domestic

[7] Export and import restrictions policies—mutually exclusive options, with at least one which is selected in all three policy portfolios—are very cost-effective. However, they are "volatile" policies because their political and economic outcomes are difficult to ascertain. Much of their effectiveness relies on legal standing of the measures, the reaction from China, and the collateral economic effects of these measures on domestic and foreign stakeholders. As a result these measures can just as easily backfire or negate any positive outcomes. A second point is that the differences in these two policies' costs and effectiveness are negligible. Thus while the linear programming model selects export restrictions as the default policy option for Portfolios 3 and 5, they can be substituted with import restrictions for an additional $6.4 million and a small decrease in effectiveness.

consumption. Since 2010, the Chinese government drastically reduced export quotas and hiked up export tariffs that have limited rare earths availability in the global market. These events point to the fact that dysprosium and rare earths writ large sit on the nexus of three powerful policy narratives: geopolitics, the environment, and development economics (Wübbeke 2013).

Geopolitically speaking, China's unique status as the monopoly producer of rare earths and other valuable minerals such as tungsten, molybdenum, magnesium, and antimony, its sharp curtailment of allowable exports of these materials to the world market, and finally its apparent willingness to use its market power as political leverage (as it allegedly did in September 2010 over maritime disputes with Japan), have raised concerns about China's reliability as a supplier of these technology metals.

Environmentally, dysprosium and other rare earths have important clean energy applications, such as wind turbines and electrical vehicles. Ironically, however, rare earths production and processing is energy-intensive, highly reliant on toxic chemicals, and can produce radioactive byproducts, mostly from thorium. Insufficient environmental oversights have and continue to lead to environmental degradation, as is the case with China.

Lastly, Beijing's export restrictions—ostensibly to support Chinese producers to move up and capture the rare earth value chain—touches on a long-running debate between the balance of free trade on one hand and the desire for developing economies to become less reliant on cheap raw materials exports and move up the economic value chain on the other.

The controversy of Chinese rare earths in general (and dysprosium in particular) touches on geopolitical, economic, and technology policy dimensions directly affecting public and private stakeholders in the U.S. green technology, military, and mining industries. How successfully and cost-effectively the U.S. policymaking community addresses supply risks of valuable commodities such as dysprosium can form the basis of a strategic framework for addressing other critical elements, rare earths or otherwise. This dissertation introduces just such a planning framework using dysprosium as an example.

Research Contribution

This study contributes to the policy research field in three ways: a consolidated narrative of dysprosium criticality, a new strategic planning framework for reducing material criticality, and recommendations of the aforementioned sweet spot policy portfolios that reduce dysprosium criticality cost-effectively and efficiently using the said planning framework.

Contribution 1 – Consolidated Dysprosium Narrative

Rare earths, let alone dysprosium, are obscure elements that occupy a small but important niche in modern technology industries. They enable technological improvements (e.g., smaller, faster, stronger, and clearer) that provide that vital competitive edge for businesses, energy efficiency, and military systems. This dissertation explores the complex interplay of politics, economics, and geology that make many of the rare earths, and particularly dysprosium, critical. This dissertation offers a consolidated narrative of these dynamics to explain what rare earths are, why they are important, why dysprosium in

particular is highly critical, and what can be done to reduce American vulnerability to dysprosium supply disruptions.

Contribution 2 – New Criticality Reduction Planning Framework

U.S. government planning for supply security is covered by the Budget Control Act of 2011 which mandates curtailed federal fiscal spending through FY 2021. The contemporary policy maker must plan under tightened fiscal constraints. The new policy planning framework introduced in this study will assist U.S. policy makers to achieve the best possible dysprosium criticality reduction under on-going budget austerity through a combination of qualitative metrics and quantitative optimization model.

First, the study gathers a roster of policy options (derived from literature and additionally synthesized by the author) that can reduce dysprosium criticality. The policy options are consistently assessed for their implementation costs between FY 2015 to FY 2029 and their effectiveness in reducing the criticality of dysprosium. A policy's effectiveness is evaluated along two dimensions: *material importance* and *supply risk*. For example, some policies can reduce the importance of dysprosium through research of substitutes and reduce demand (*material importance*). Others can encourage the expansion of dysprosium mining supply capacity outside of China through regulatory reforms or economic incentives (*supply risk*). All the policy options are evaluated on a 1 to 4 qualitative criticality risk metric (1 = low risk, 2 = medium-low risk, 3 = medium-high risk, and 4 = high risk). *Thus, the goal of each policy is to reduce the criticality risk by lowering the metric score to the lowest value possible*. The policies' implementation costs are estimated for the 15 year planning period (FY 2015-FY 2029).

Next, the synthesized scores are applied as criticality reduction coefficients in a linear programming model. Technically speaking, the model's objective function maximizes criticality reduction subject to budgetary constraints that increase in $10 million increments. In non-technical terms, this means that the policy options are selected and assembled into policy portfolios (policy packages) for maximum effectiveness in reducing American vulnerability to dysprosium supply disruptions for a given level of budget allowance. This calculation at various budgets results in a cost-effectiveness trade-off curve plotting an increasing budget against diminishing but positive marginal returns in criticality reduction (effectiveness). The calculation also finds the optimal portfolio of policy choices that maximizes criticality or vulnerability reduction at a given budget level.

Contribution 3 – Sweet Spot Portfolios for Dysprosium Criticality Reduction

The third major contribution of this research is the introduction of the three so-called Sweet Spot Portfolios—derived using the optimization method described above—which the U.S. policy maker should aim to implement. Not only do these Sweet Spot Portfolios yield the highest effectiveness for their given budgets, but they also provide the policy planner with superior value for money, meaning that although their absolute costs may be marginally higher than other portfolios in the respective budget ranges, their effectiveness increases substantially for each additional dollar investment.

Practical Policy Planning Benefits

The cost-effectiveness trade-off curve is particularly useful for senior U.S. decision makers at a time of budget austerity. For example, proposed budgets can be evaluated on their expected impact on criticality reduction and whether the decision maker's policy objectives can be met. Even if the budget were not adjustable, this framework will still allow the decision maker to make an informed decision knowing the expected impact (perhaps a dire one) of the budget. Alternatively, the policy planner will be able to

assess whether a minor budget increase from the original allocation can lead to a disproportionally higher gain in criticality reduction, thereby capturing superior value for money.

To sum up the policy planning benefits, the systematic evaluation of the cost-effectiveness of policy portfolios aids policy makers in three ways when planning for dysprosium supply strategy. First, the U.S. decision maker can know exactly which policy options should be selected to best meet reduction objectives at a specific funding level. Second, the policy maker has an idea if a certain level of funding is sufficient enough to reduce dysprosium criticality by a desired margin. Depending on the budget appropriation, it is possible to identify potential cost savings or if funding is decremented, what the consequences on dysprosium criticality will be. Thirdly, if prospective funding falls below the necessary budget amount, the policy maker can make an analytically justified case for adequate funding or at the least forewarn senior decision makers about consequences of the reduced budget.

Dysprosium Criticality

Among the seventeen elements that comprise the rare earth elements, dysprosium is considered the most "critical." However, because dysprosium mining, economics, and policies are inextricably linked with other rare earths, the study first conducts a qualitative review of the rare earths political economy (Chapter 2) and geology (Chapter 3) before re-focusing on dysprosium shortfall projections (Chapter 4) and a quantitative cost-effective assessment of U.S. policy options and portfolios (Chapters 5 and 6). This section reviews the concept of criticality and why dysprosium is considered the most critical element.

Criticality Defined

The rare earth elements have similar chemical characteristics but their differences are significant enough to affect large variances in geological bounty and technological applications. This translates to differences in the economic and strategic valuation of these minerals which, in turn, impact the criticality of each REE. While scientific and industry insiders involved in the rare earth sector have long understood this importance nuance, policy circles have traditionally not, treating rare earths as a single convenient entity. As noted by one industry observer:

> In wider discussion of the rare-earth sector in general [REEs] are discussed in over-simplified, monolithic terms, ignoring the nuances and supply and demand characteristics of each individual metal (Hatch 2011).

In recent years, however, there has been a greater appreciation of the subtle but important differences not only between light rare earth elements (LREEs) and HREEs, but of the granular details of each element in policy planning. Much of this is due to high profile studies by the European Commission (EC), U.S. Department of Energy (DoE), the U.S. National Research Council (NRC), and joint research by the American Physical Society (APS) and Material Research Society (MRS). Similarly, the DoD's biannual report on strategic and critical materials evaluates the U.S. military's material needs of REEs on an individual basis (DoD 2013a).[8] The studies established that while some rare earths are clearly facing

[8] With exception to the DoD study (2013), the others focus on critical rare earths for the commercial and clean energy industries (understandably since the overwhelming proportion of rare earths needs are in the commercial rather than the military sector).

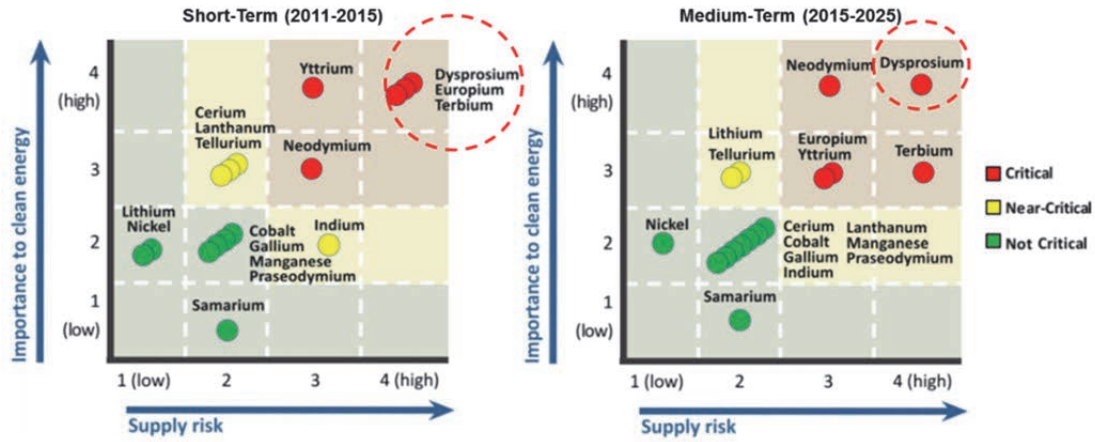
supply shortages now and likely into the future, other rare earths do not face similar problems. The most influential work, by Bauer et al. (2011), finds five rare earths—the HREEs yttrium, dysprosium, europium, and terbium and one LREE neodymium—as the most critical in both short-term (2011-2016) and medium-term (2016-2026). These five rare earths have since been colloquially referred to as "critical rare earths" or CREEs in the industry (Bauer et al. 2011, Hatch 2011, and Lifton 2012).[9]

Dysprosium Is Most Critical

This study adopts dysprosium as the candidate REE for a case study on how the American policy maker can plan and implement a national critical materials strategy. Dysprosium is an ideal element for two reasons. First, it is of great importance for clean energy and national security applications as an additive to NdFeB (Neodymium-Iron-Boron) permanent magnets (as is discussed in Chapter 3 and reviewed again in Chapter 5) and is therefore of keen policy interest. Secondly, unlike less critical materials such as LREEs where the ready availability of substitutes or abundant mining from non-Chinese sources means shortages are unlikely or can be adequately addressed, dysprosium is recognized as a particularly tough challenge. Thus multiple policy options—political and scientific—must be pursued and evaluated.

Policy and industry literature confirm the policy puzzle presented by dysprosium. Of the CREEs, only dysprosium ranked highly for both supply risk and importance in the short-term and medium-term (see Figure 1.1) (Bauer et al. 2011). DoD (2013a) also identifies dysprosium as one of the top elements that would be in shortage during a national contingency (the other elements are the HREEs erbium, terbium, thulium, yttrium, and the LREE scandium).[10] Alonso et al. (2012) come to the same conclusion. In the absence of alternative technologies, substitutes, or effective recycling schemes, the proportional share of dysprosium demand vis-à-vis other rare earths could increase from 1 percent to nearly 8 percent by 2035 (Figure 1.2). Expressed in terms of tonnes of dysprosium oxide demand, this increase represents a 2,600 percent jump from current demand levels. Lifton (2012) points out that dysprosium is particularly problematic because unlike LREEs and other HREEs, it has never been mined outside of China.

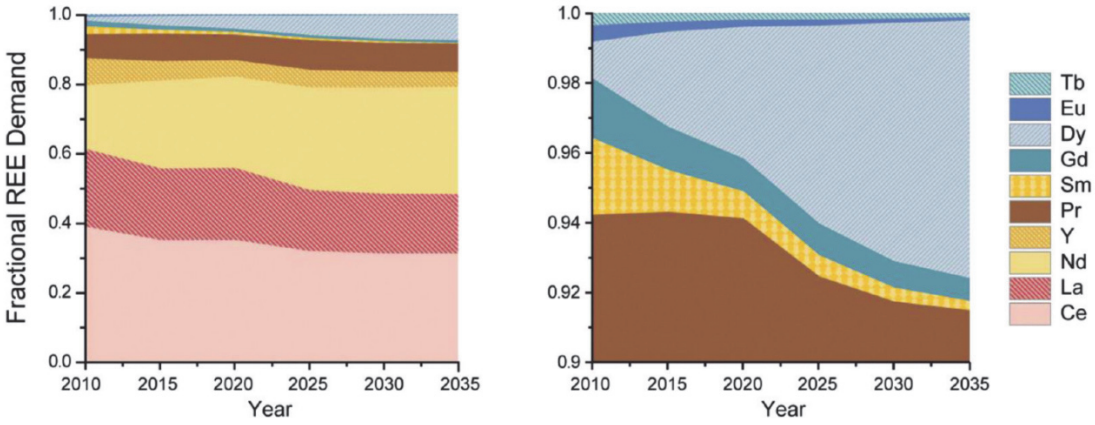
FIGURE 1.1 – DYSPROSIUM IS THE MOST CRITICAL ELEMENT IN THE MEDIUM-TERM



Source: Bauer et al. (2011)

[9] Neodymium, the fifth critical REE, is an LREE but its importance and high demand for production of permanent magnets qualifies it as a critical DoE element.
[10] Three HREEs overlap between the DoE and DoD's respective short lists— dysprosium, terbium, and yttrium.

FIGURE 1.2 – ALONSO ET AL. (2012) PROJECTED REES DEMAND DISTRIBUTION[11]



Source: Alonso et al. (2012)

Dysprosium Technical Factoid

Dysprosium, which derives from the Greek word *dusprositos* meaning "difficult to approach," was discovered by accident in 1886 by a French chemist. Attempting to process a holmium sample via several challenging separation processes, Paul Émile Lecoq de Boisbaudran stumbled across dysprosium, thus earning the new elements its name. Dysprosium is silvery and malleable and can be cleaved easily with a knife. Dysprosium has a melting point of 1407 °C while dysprosium oxide—usually found as a light pink powder—has a melting point of 2340 °C (InvestorIntel 2014).

Dysprosium is found in xenotime and monazite ores. Xenotimes, which are rare, typically have higher dysprosium oxide at about 8 to 9 percent of total rare earth oxide (REO) content. Monazites, which are more abundant, typically have about 0.2 to 0.9 percent dysprosium oxide enrichment levels.

Roadmap of Research Chapters

This dissertation identified three Sweet Spot Portfolios that can optimally reduce dysprosium criticality by the end of FY 2029 for the best value on behalf of the American public—Portfolios 3, 5, and 11/12. In order to arrive at these findings, however, the study employed a mix of qualitative and quantitative sources and methods. This section provides an overview, a roadmap, of the chapters in this dissertation and how they complement one another in building the case that the Sweet Spot Portfolios deliver on their purported benefits to the American policy maker. The first half of the dissertation progresses by establishing the "policy challenge" of dysprosium. The second half then analyzes the "policy solution," i.e., how the U.S. policy maker can meet the said challenge.

[11] Right hand side figure is a zoom of the left hand side figure's *y* axis from 0.9 to 1.0.

The Policy Challenge – Chapters 2, 3, and 4

The policy challenge chapters (Chapter 2, 3, and 4) take a retrospective, contemporary, and prospective examination, respectively, of why dysprosium (and rare earths writ large) presents a difficult policy puzzle. They examine why rare earths and dysprosium in particular are important, how rare earths production has become a Chinese monopoly, why it is difficult to challenge that monopoly, and what the range of dysprosium shortfall projections could be like in by 2030.

Chapter 2 studies the political economy of the rare earths sector followed by Chapter 3, where the geological and scientific underpinnings of rare earths discussed in detail. Chapter 4 transitions away from the past and present and into the future: it projects supply capacity and demand requirements in the coming decades to understand dysprosium market drivers and the range of possible dysprosium shortfalls.

The Policy Solutions – Chapters 5, 6, and 7

The policy solutions chapters (Chapters 5, 6, and 7) discuss the method for analyzing how to reduce dysprosium criticality, examine the costs and effectiveness of available policy options, and then calculate what the optimal and high value policy portfolios are, respectively. They introduce the combined qualitative and quantitative criticality reduction methodology applied in the new strategic planning framework, conduct an in-depth survey and assessment of policy options that can reduce dysprosium criticality, and apply the quantitative linear programming methodology to calculate, identify, and check the robustness of Sweet Spot Portfolios.

Chapter 5 reviews the technical framework for portfolio optimization which undergirds Chapters 6 and Chapter 7. It discusses U.S. policy objectives regarding dysprosium and the concept of "criticality." The general approach to calculating policy implementation costs and for assessing the effectiveness of policies in reducing said criticality is also explained. Finally, the chapter explains the process for optimizing the combination of different policy options into an integrated policy portfolio that is most cost-effective against three potential future scenarios.

Chapter 6 conducts a review of the contributory effectiveness and monetary costs of various policy options that have been implemented by the government, suggested in the literature, and devised over the course of this research. The review formulates the data into consistent effectiveness and cost bases that can be analyzed for dysprosium supply security planning. Chapter 7 applies linear programming to analyze the optimal combination of policy options to cost-effectively meet U.S. policy objectives in the FY 2015 to FY 2029 timeframe.

Finally, Chapter 8 will provide a summary conclusion to this research.[12]

Chapter Summary

Dysprosium is considered the most critical rare earth element due to its increasing importance to vital technology sectors yet its high susceptibility to supply disruptions. Much of the risk arises from China's

[12] In the report, numbers are not rounded to significant figures so that readers can more easily replicate, match, and check the calculations. They are rounded, however, in the final analysis and summary in Chapters 7 and 8.

monopoly of the entire production chain and its policies that increasingly discourage exports to the global market. These trends pose a difficult challenge for American policy makers.

This dissertation introduces a new strategic policy planning framework designed to analyze how American vulnerability to dysprosium supply disruptions can be reduced within the fiscal constraints of the current period of austerity. Using this method, the study recommends that the U.S. policy community adopts Portfolio 11/12 to optimally and cost-effectively reduce dysprosium criticality. Given budgetary realities, however, Portfolio 5 offers a respectable alternative. Portfolio 3, the least expensive option, should be implemented only as a last resort.

While the research findings are most applicable to dysprosium, they have important implications for other critical rare earths. The hope is that the methods applied, research findings, and policy recommendations on dysprosium will serve as a generalizable template for mitigating the criticality of other rare earths and materials that are similarly important but supply-constrained.

Chapter 2 – The Politics and Economics of Rare Earth Elements

"The Middle East has oil, and China has rare earths."
– Deng Xiaoping

Introduction

Next to the energy market, no other mineral has been so intertwined with geopolitics in recent years as rare earths. This is because China emerged as the world's dominant producer of all things rare earths—from ores all the way up the value chain to high performance magnets that are critical to improving performances of green energy technologies and advanced weapons systems. Of course, China has been the world's de facto manufacturing base for a generation so the consolidation of yet another industry in China is not necessarily an issue. The cause for concern, however, rises from China's reluctance to openly trade its rare earths in the global market as it seek to conserve and reserve its supply for domestic consumption. Beijing's message is simple, "Go find your own rare earths."

From mining and extraction to alloys, metals, magnets, and semi-manufactured components, China has in the last two decades emerged as the world's one-stop source of rare earth goods. On one hand, this development should not come as a surprise given China's large reserves. On the other hand, this outcome was not a given for two reasons. First, other countries also have significant rare earth reserves, including the U.S. and Mongolia. In fact, the U.S. was the world's single largest producer until the 1980s. Secondly, unlike primary metals like copper or iron ore, rare earths are high technology specialty metals that require advanced know-how to properly separate and purify (process) the rare earths. This sort of specialty skill was previously found only in Japan, the U.S., and some European countries.

How did China surpass these countries to become the principal integrated rare earth supplier?

This chapter traces China's policies that have led to its rare earth ascendency. The following chapter (Chapter 3) explores the applications of rare earths and their physical and geological properties that undergird the political and economic dynamics discussed here. The research finds two principal reasons that drove China's success. The first is China's fortuitous geological endowment. Its reserves are not only the world's largest, but also have greater shares of particularly valuable rare earths called heavy rare earths. What is more, these HREEs are embedded in ion-adsorption deposits which happen to be the easiest to extract rare earths from (these and other technical and geological properties are discussed in detail in Chapter 3). These attributes contribute to significant cost advantages for Chinese rare earth miners. Poor environmental regulations also enable miners to produce at lower costs.

The second factor to China's success is Beijing's focused attempt in the last two decades to increase its separation and processing capacities (midstream) and manufacturing capacities (downstream) at the expense of U.S. and Japanese capacities. Beijing has achieved this through attempted acquisitions of U.S. firms and through de facto subsidies that induce U.S. and Japanese midstream and downstream firms to relocate to China. Such inducements were enabled through China's restrictions of rare earth exports to the rest of world which had the effect of increasing global rare earth prices while decreasing Chinese domestic prices (thus the subsidy effect).

This chapter will also review the environmental costs of China's rapid rise to rare earth sovereignty as well as the negative impact it has had on the U.S. rare earth supply chain. It will cap with an overview of policy responses from key rare earth consuming countries (an extensive review of American policy responses and potential options are conducted separately in Chapter 6).

China's Path to Rare Earth Dominance

China's rare earth monopoly is a fairly recent phenomenon that has taken shape over the last couple decades. In the years leading up to the 1940s, the primary rare earths suppliers were India and Brazil. Australian and Malaysian mines soon became principal suppliers in the following decades until the American Mountain Pass mine become the dominant supplier starting the 1980s. China's resurgence began in earnest in the 1980s, coinciding with its economic reforms started in the 1970s (Walters, Lusty, and Hill 2011).

Two simple reasons explain China's dominant position in the global REEs supply. The first is its geological endowment. China has large reserves, including the vast majority of known ion adsorption clay deposits which are known to be much easier (and thus less costly) to process than other forms of rare earths-bearing deposits. Secondly, perhaps most importantly, Beijing has actively fostered the growth of the REEs industry for decades, culminating in its successful global consolidation today.

China's Geological Endowment

Despite its name, rare earth elements are not necessarily "rare." According to the latest estimates, in 2013 there was an estimated 147 million tonnes of rare earth oxides in the earth's crust that qualified as "reserves," defined as those rare earth elements that could be "economically extracted or produced" (USGS 2014a and Currie 2013b).[13,14] Based on global consumption levels from 2013, this is equivalent to more than 1,300 years' worth of reserves. The global rare earth resource level, which includes the reserves plus those resources not yet deemed economical for extraction, is far greater.

Just around 38 percent of the world's REEs reserve is in China (Figure 2.1). Mongolia's reserves account for 21 percent of world reserves, Brazil holds about 15 percent, the U.S 9 percent, and Japan about 5 percent.[15] Next is India (2 percent) and Australia (1 percent). Additional reserves of various quantities are held across the globe, including in Finland, Greenland, Kyrgyzstan, Madagascar, Malawi, Mozambique, South Africa, South Korea, Sweden, Turkey, Vietnam, and others, collectively comprising 31 percent of global reserves (USGS 2013). Figure 2.2 exhibits the global distribution of rare earth deposits by deposit status and reserve/resource type.[16]

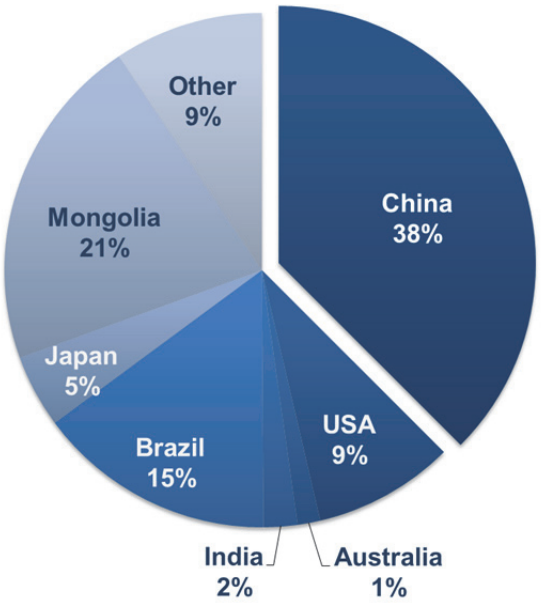
[13] Full definition of mineral reserves according to the USGS reads, "That part of the reserve base which could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials; thus, terms such as "extractable reserves" and "recoverable reserves" are redundant and are not a part of this classification system" (USGS 2013).

[14] In addition, there was 540,000 tonnes of yttrium oxide in 2012 which the USGS reported separately from the REEs estimates (USGS 2013).

[15] An estimated 6.8 million tonnes of rare earths were found on the Pacific seabed within Japan's exclusive economic zone in 2012 (Currie 2013b).

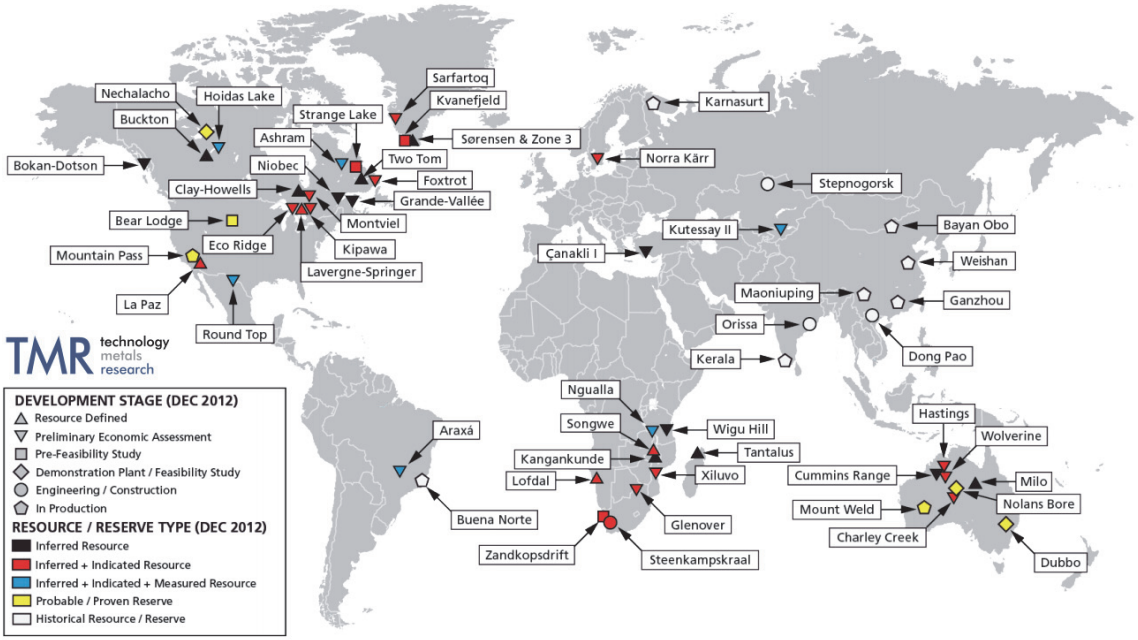
[16] The country of Mongolia has significant rare earth reserves. Because of its landlocked status, however, and its poor transportation infrastructure, there has been little development or interest in Mongolian reserves until recent years. Like the Bayan Obo mine (the world's largest rare earth mine in China's Inner Mongolia) however, Mongolian rare earths are believed to be overwhelmingly comprised of less valuable (and less critical) light rare earths (Sullivan 2011; Feary 2012; and Humber and Kate 2011). Nonetheless, it is possible that future explorations could identify economic reserves of heavy rare earths in the future.

FIGURE 2.1 – 2013 REES GLOBAL RESERVES (147 MILLION TONNES)



Data: USGS (2014a) and Currie (2013b)

FIGURE 2.2 – GLOBAL DISTRIBUTION OF REES DEPOSITS



Source: Hatch (2013c)

It is clear that REEs are not unique to China. However, it has two advantages that have made it a rare earths powerhouse. First is simply the scale of its reserve. As shown in Figure 2.3, China's rare earths deposits are scattered throughout the country with the northern areas rich in LREEs and the southern

regions with greater concentrations of HREEs (Tyrer and Sykes 2013). To appreciate the scale of China's clout, consider the fact that Bayan Obo—the single largest known rare earth deposit— in northern China has reserves of about 2.8 million tonnes of REO, which is greater than Australia's entire reserve of about 2.1 million tonnes (Kanazawa and Kamitani 2006). Secondly, its distribution of REEs in the southern regions is far more valuable due to their higher concentration of HREEs in its minerals (Walters, Lusty, and Hill 2011). These high-value HREEs are expensive to process and separate in general, but China's unique geology has endowed it with HREE-rich ion-adsorption deposits which are the easiest (and thus least expensive) to process.

FIGURE 2.3 – CHINA'S RARE EARTHS MINING DEPOSITS

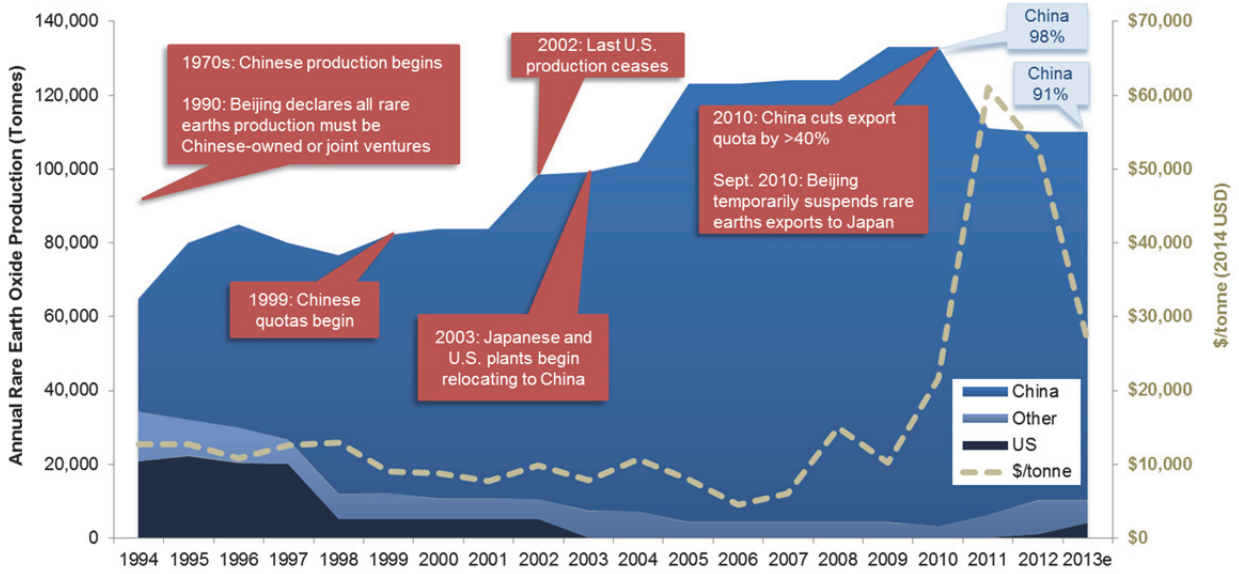
Source: Wübbeke (2013)

Beijing's Push on Rare Earths Industry Development

China has become the world's dominant rare earths producers within the last two decades. Endowed with large, lucrative, and easy-to-mine deposits, Chinese mining (upstream) production has also been abetted by laxer environmental control laws and cheaper labor compared to Western countries. These factors compound China's significant comparative advantage in rare earths mining vis-à-vis foreign deposits. As

a result, China's share of global supply rose from less than 50 percent in 1994 to a peak of 98 percent of global supply in 2010 (Figure 2.4).[17] According to the latest estimate, Chinese production was approximately 100,000 tonnes in 2013 (USGS 2014a). Having consolidated upstream capacity, China has in recent years been seeking to expand its midstream and downstream rare earth capacities—which have traditionally been located in Japan, the U.S., and Europe— in order to more fully capture the economic value of its rare earth production.

FIGURE 2.4 – REO PRODUCTION 1994 TO 2013



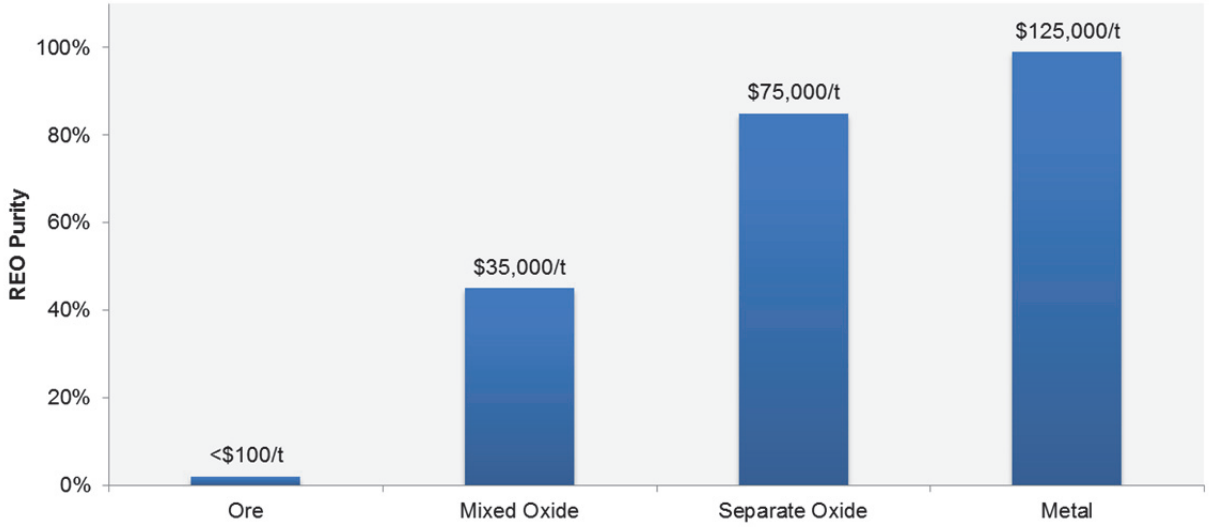
Data: USGS, various.

Vertical Integration of the Chinese Rare Earths Industry

Beijing has sought to build a vertically integrated rare earth industry that captures the full value of rare earths-derived manufacturing and for good reason (Nicoletopoulos 2011). For common metals, most of their economic values are readily captured upon ore extraction. For example, about 75 percent of copper and over 90 percent of gold and silver market values are reflected in raw ores. In contrast, less than half of rare earth values are captured during the mining stage (Tyrer and Sykes 2013). Hayes-Labruto et al. (2013) estimate that while raw rare earth ores are worth less than $100 per tonne, its value rises substantially with greater purification, particularly when processed into separate oxides. When fully purified into rare earths metal, the value rises more than a thousand fold to $125,000 per tonne (Figure 2.5).

[17] As depicted in Figure 2.4, rare earth prices reached an all-time high in 2011 but have subsequently leveled off. The price increase was fueled by China's dramatic cuts in rare earths export quotas starting in 2010 and by concerns of critical shortages for non-Chinese consumers. The prices began dropping in late 2011, however, as signs of rare earths production outside of China, particularly in Australia and the U.S eased some of the shortfall concerns. More interestingly, we will see in Chapter 6 that because much of the world's midstream and downstream rare earths consumers have been compelled to move from Japan, Europe, and the U.S. to China to take advantage of lower rare prices, Chinese export figures actually fell *below* quota levels in recent years.

FIGURE 2.5 – VALUE OF RARE EARTHS ACROSS THE VALUE CHAIN



Data: Hayes-Labruto et al. (2013)

To increase vitality of indigenous midstream and downstream production of rare earths-based alloys, powders, and magnets, Beijing adopted two strategies. In the first case, Beijing created a two-tiered pricing system that heavily favored domestic production of rare earths. Export quotas and duties inflated domestic supply (whilst decreasing international supply). This deflated domestic rare earths prices while increasing the prices in the international market. This incentivized foreign processing and manufacturing capacities to relocate to China to take advantage of lower input prices. According to Silberglitt et al. (2013):

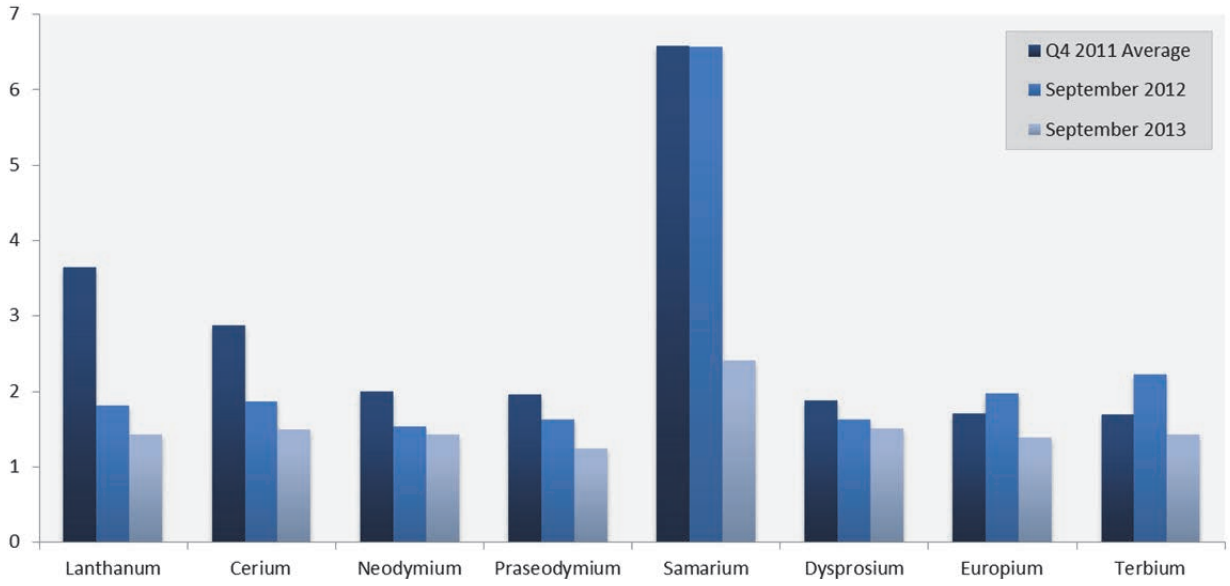
> The export restrictions have resulted in a two-tier pricing system for certain materials of which China is the dominant producer, including its rare earth metals, allowing China's domestic manufacturers to pay a lower price than the export price. By undercutting the market price, China's actions have both discouraged the continuation of manufacturing in the United States and provided motivation for moving U.S. manufacturing operations specifically to China.

Beijing has largely equivocated against the charge that China's export restrictions were a de facto subsidy to consolidate global rare earth manufacturing capacities within its border. In its 2012 White Paper on rare earths, the State Council portrayed the migration of rare earths manufacturers to China as an example of the country's friendly investment environment for foreigners: "China has been actively creating a fair and open environment for foreign investment, encouraging foreign investment in…high-end application development and equipment manufacturing in the rare-earth industry [emphasis added]" (Government of the People's Republic of China 2012).[18] But the facts speak for themselves. Recent trends show that the

[18] This is certainly true for foreign investments in midstream and downstream capacities where China has traditionally lagged and has been aggressively seeking to develop. By enticing Japanese and Western firms to relocate to China and indigenize, Beijing has been able to accelerate China's consolidation of global rare processing and manufacturing capacities and technologies within its borders. In contrast, foreign ownership is tightly regulated for upstream capacities. In 1991 China's State Council classified rare earths as a "protected" and "strategic" resource which prohibited direct foreign investment in China's REE mining and

price of exported Chinese rare earth oxides (Free on Board or FOB price) was anywhere from 168 percent to 650 percent higher than China's domestic prices, depending on the specific rare earth element (Figure 2.6). While the ratios of FOB to domestic prices have generally decreased since 2011, the discrepancy still persists with foreign consumers paying an average 54 percent premium over Chinese consumers in September 2013.

FIGURE 2.6 – RATIO OF FOB CHINA AVERAGE PRICE TO CHINA'S DOMESTIC PRICE



Data: Lynas Corporation (2013) and Silberglitt et al. (2013)

The second strategy to boost its midstream and downstream capacity has been to acquire foreign firms and transplant them back to China. This strategy was employed in 1995 with Magnequench, a unit of General Motors (GM) that produced NdFeB permanent magnets using a "rapidly solidified" magnet patent developed by GM engineers. According to the acquisition terms, the Chinese state investors, Beijing San Huan New Materials High-Tech Inc. and China National Non-Ferrous Metals Import and Export Corporation, agreed to keep Magnequench in operation at its original location in Anderson, Indiana. However, in 2001 on the day after the expiration of the agreement, the entire staff was laid off and the equipment shipped off to Tianjian, China and with it, the U.S. lost the sole manufacturing capacity for NdFeB magnets (Hurst 2010b). Inconveniently for the DoD, Magnequench was the sole source supplier for manufacturing of U.S. Hellfire missiles (Buchanan 2008).[19] Magnequench subsequently merged with a Toronto-based Canadian company, AMR Technologies, Inc., forming a new company, Neo Material Technologies, Inc. (Neo) in 2005. In 2012, Neo was acquired by the U.S. rare

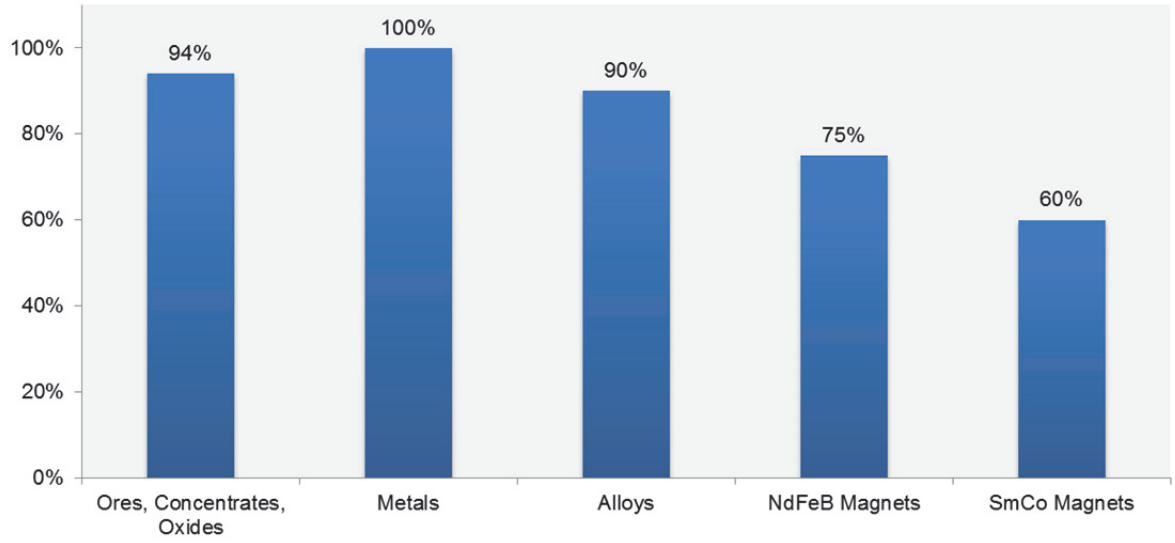
extraction (upstream) segment. Any upstream foreign investment required a joint venture agreement with Chinese producers (Hurst 2010b).

[19] The acquisition was approved by the Committee on Foreign Investment in the United States (CFIUS) which oversees and approves foreign acquisitions of U.S. companies that have national security implications. Much of the lessons learned from the Magnequench saga were incorporated into Foreign Investment and National Security Act of 2007 (FINSA) which revised the CFIUS review process.

earths producer Molycorp, Inc. but the NdFeB manufacturing plant remains to this day in Tianjin (Areddy 2012 and Grieb et al. 2008).[20]

Through implicit subsidies and acquisitions, China's consolidation seems to have been a *fait accompli* by 2010 (Bauer et al. 2011). According to data synthesized by Green (2012), China not only produced virtually all the rare earth ores and oxides, but also the processed metals and alloys, all the way down the manufacturing stream to NdFeB magnets (75 percent of the market) and its closest alternative, SmCo magnets (60 percent) (see Figure 2.7). The vertical integration is also evident in the changing composition of its rare earth goods export. Between 2006 and 2010, the volume of NdFeB permanent magnet exports from China essentially doubled (Wübbeke 2013). Similarly, the relative proportion of exported permanent magnets to rare earth ores has increased rapidly in the past decade, rising more than six-fold between 2000 and 2012 (Figure 2.8). The more than doubling of the ratio from 2010 to 2011 is witness to the effect of the expatriation of Japanese and U.S. permanent magnet manufacturers to China and the export of their finished goods from China back to their former home countries in subsequent years.

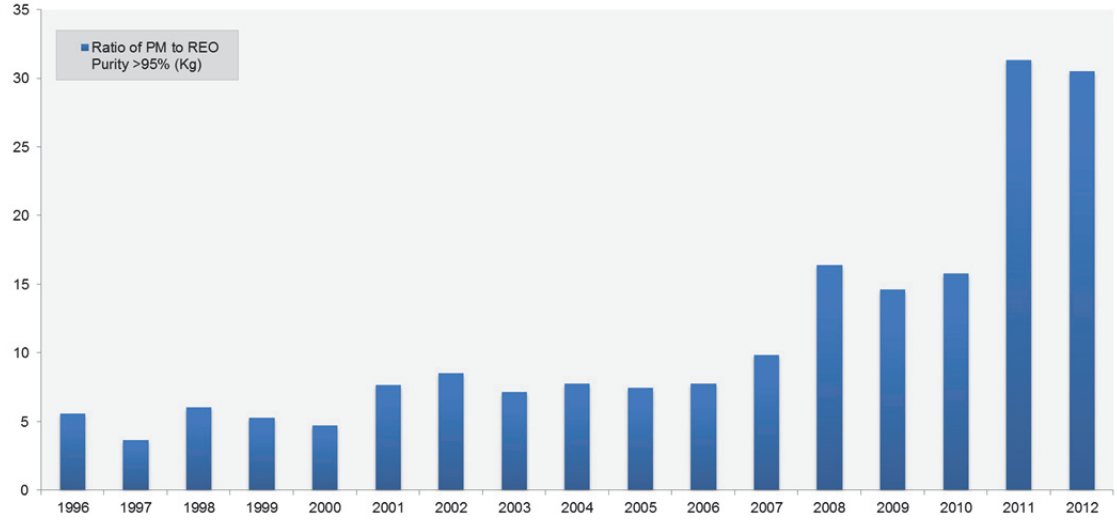
FIGURE 2.7 – CHINA'S SHARE OF THE RARE EARTH SUPPLY CHAIN[21]



Data: Green (2012) and Green (2011)

[20] Rare earths are used in a variety of applications depending on the specific rare earths in question. This research focuses on dysprosium whose primary use is as an important additive in NdFeB permanent magnets. For this reason, the discussion on the downstream manufacturing sector principally revolves around the rare earths permanent magnet industry.
[21] Cross reference the concomitant rise in the value of rare earths products as it moves down the value china in Figure 2.5.

FIGURE 2.8 – RATIO OF CHINA'S PERMANENT MAGNET EXPORTS TO ORE EXPORTS[22]



Data: UN Comtrade

A concrete testament to the exodus of U.S. magnet manufacturing to China is manifested by the sharp drop in the number of permanent magnet makers from around 20 in the 1990s to half that figure as of July 2013. Table 3.3 lists the producers that have either remained in the U.S. and those that have either run out of business or relocated abroad in the last two decades. While the market is constantly in flux, as of July 2013, there was only one indigenous American NdFeB magnet producer that was still operational, Thomas & Skinner, which did not exist in the 1990s (in fact none of the original American NdFeB magnet manufacturers—Magnequench, IG Technologies, and Crucible Magnetics—have survived). Going against the tide, Hitachi Metals, Ltd. (HML), Japanese subsidiary, established a sintered NdFeB magnet plant in China Grove, North Carolina to supply permanent magnets to U.S. electric auto makers (Benecki 2013). The production capacity is estimated at about 480 tonnes per annum (Richardson et al. 2012).

The capacity reductions are not just limited to NdFeB magnets—similar decline was apparent for SmCo, AlNiCo, and iron (ferrite) magnets manufacturers whose numbers have dwindled by almost half by mid-2013 to two SmCo producers, three AlNiCo[23] producers, and two ferrite producers (Richardson et al. 2012 and Benecki 2013). Even for SmCo magnets, however, the U.S. is still largely dependent on China for samarium, a light rare earth, and is also heavily dependent on China, Russia, Finland, and Norway for cobalt (USGS 2013). The dramatic emigration is not unique to the U.S. Japanese auto firms Honda, Nissan, and Toyota have relocated electric motor manufacturing for electric vehicles to China in 2011. Showa Denko and Hitachi Magnetics have also moved proportions of its magnet manufacturing capacities to China (Green 2011).[24]

[22] Note: HS Code 280530 for rare earths and 850511 for permanent magnets.
[23] Not a rare earth magnet.
[24] Under U.S. regulations, AlNiCo and SmCo magnets[24] are covered under the Berry Amendment (now codified under Title 10 U.S.C. 2533) which requires preferential U.S. acquisition of American sourced materials for DoD procurement. They are also covered under the subsequent Specialty Metals Clause which requires metals incorporated into defense products be melted in the U.S. or in another "qualifying country" (Adams 2013, Richardson et al. 2012, and DoD 2009). Qualifying countries are Australia,

TABLE 2.1 – THE EMIGRATION OF U.S. PERMANENT MAGNET MANUFACTURING

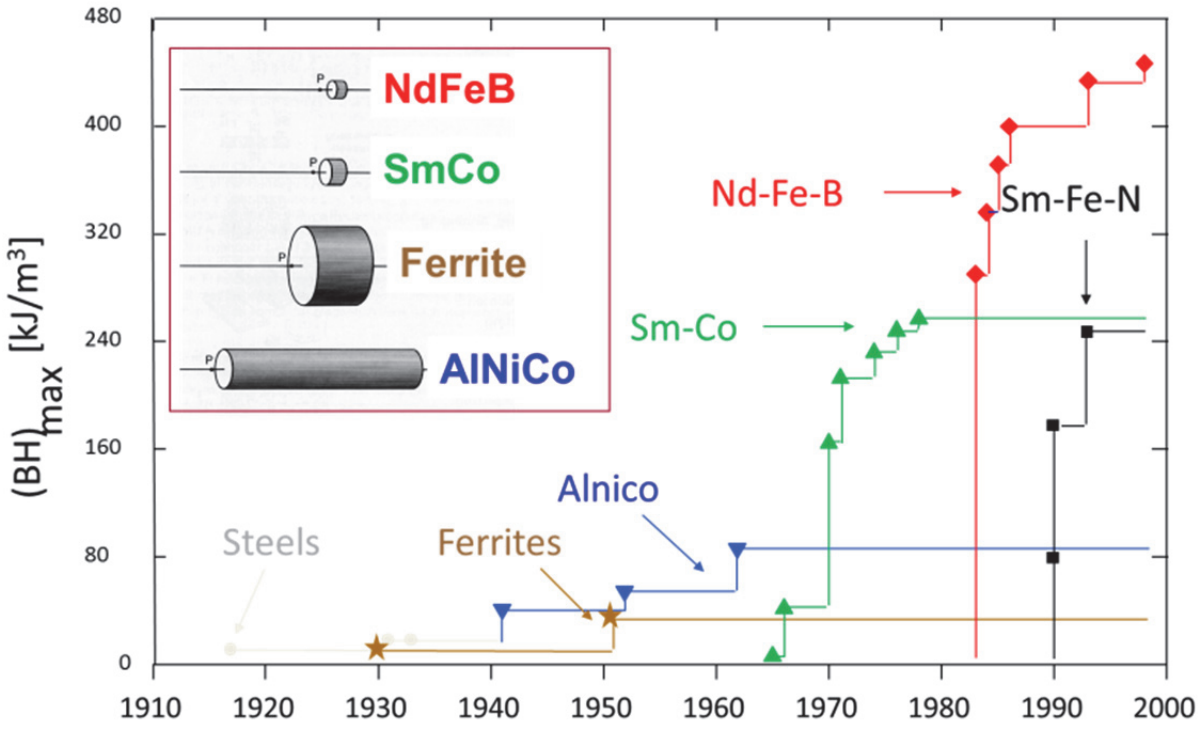
U.S.-based Producer	1990s				July 2013			
	NdFeB	SmCo	AlNiCo	Ferrite	NdFeB	SmCo	AlNiCo	Ferrite
Hitachi Metals, Ltd.	✓	✓	✓	✓	✓			✓
Arnold Magnetic Technologies		✓	✓	✓		✓	✓	✓
Electron Energy Corporation		✓				✓		
Permanent Magnet Co., Inc.			✓				✓	
Thomas & Skinner			✓		✓		✓	
TDK				✓				✓
Crucible Magnetics	✓	✓	✓					
IG Technologies (Ugimag)	✓	✓						
Magnequench	✓							
Sumitok				✓				
General Magnetics				✓				
Kane				✓				
Producer Count	**4**	**5**	**5**	**6**	**2**	**2**	**3**	**2**
Note: Shaded rows denote producers that have maintained or re-established manufacturing in the U.S. between the two periods.								

Data: Richardson et al. (2012), Benecki (2013), and USMMA (2013)

If there is a silver lining, it is that while Chinese manufacturing capacity of permanent magnets has increased substantially in volume, the quality of its magnets still lags behind Japan—a common refrain found in other infant Chinese industry sectors where impressive manufacturing capacity belies technological lag. For example, even though Chinese NdFeB permanent magnets capture the greatest proportion of the market by volume, its capture by value is proportionally less because of Japan's continuing technological edge in quality (Research in China 2010). In particular, HML maintains a substantial lead in cutting-edge NdFeB design thanks to continued R&D over the years. Figure 2.9 shows the evolution of magnet technology over the decades and HML's proprietary sintered NdFeB magnet's clear advantage over rival designs in its magnetic power. Of course, this qualitative edge is overshadowed by Japan's (indeed the world's) historically exclusive reliance on Chinese rare earths—a trend that Tokyo has been working hard to reverse, as discussed later in this chapter.

Belgium, Canada, Denmark, Egypt, Germany, France, Greece, Israel, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom, and Northern Ireland (see DFAR 225.252.7014) (Grasso 2014). NdFeB magnets are not explicitly stated, but they are assumed to be covered under the broad definition of "high performance magnets" in the specialty metal clause.

FIGURE 2.9 – EVOLUTION OF HIGH PERFORMANCE PERMANENT MAGNETS



Source: Gutfleisch (2014)

The Chinese, while prolific and longstanding in rare earth research, are believed to be still catching up on its American and Japanese peers. Su Wenqing, the former director of China Rare Earth Society, stated that although Chinese scientists held nearly two-thirds of rare earth patents between 1998 and 2002, much of it was "low technology content" compared to more advanced Japanese (and American) patents.[25] HML holds nearly 1,000 patents related to rare earth products—100 in the U.S., 300 in China, and the balance in Japan (Bruno 2013)—and it successfully sued Chinese NdFeB magnet makers for patent breaches in 2012 (Benecki 2013). Much to the ire of the Chinese, royalties adversely affect the cost competitiveness of indigenous Chinese NdFeB magnet manufacturing. So when HML contemplated a joint venture in China, Beijing set the now-familiar precondition that HML transfer core NdFeB magnet know-how to the Chinese. HML refused and the venture was scuttled (Wübbeke 2013). HML eventually established its American presence in 2012.

The Next Generation Rare Earths Research and Application

Even if it is not at the vanguard of rare earth research, China has a long and continuing history in rare earth research. It has two publicly funded research laboratories, known as State-Key labs, dedicated to rare earths research that have been in operation for more than five decades. The Rare Earth Materials Chemistry and Applications laboratory is affiliated with Beijing University and focuses on rare earth

[25] This trend seems consistent with China's overall patent quality levels. China's Xinhua news agency reported that, "the quality of [China's] patents is still poor" and that, "China owns very few patents featuring originality and high or core technology" (Xinhua 2014).

separation techniques (Humphries 2013 and Hurst 2010b).[26] Founded in 1987, the Rare Earth Resource Utilization laboratory is another State-Key lab affiliated with Changchun Institute of Applied Chemistry.[27] The Batou Research Institute for Rare Earths was founded in 1963 and is believed to be the largest research center dedicated to rare earths study. The General Research Institute for Nonferrous Metals was founded in 1952 (Humphries 2013; Hurst 2010b). More recently, in October 2000 Shenyang National Laboratory for Materials Science (SYNL), a National Laboratory, was founded with support from the Institute of Metal Research, Chinese Academy of Sciences, the Ministry of Science and Technology, and Chinese Academy of Sciences. SYNL has a dedicated research program on rare earth permanent magnets (SYNL 2014).[28]

The Ministry of Land and Resources' (MLR) 2008-2015 National Plan for Mineral Resources (NPMR) expressively prioritizes China's leadership not only as a rare earth producer but also as a force in rare earth technology research. Rare earths are identified as a key R&D focus in the Outline of the National Program for Long- and Medium-Term Scientific and Technological Development (2006-2020). The program's research focus will be on sustainable extraction technologies and next-generation application of rare earth properties in magnetism, luminescence, hydrogen-storage, catalytic materials, information technology, clean energy, and health care (Government of the People's Republic of China 2012). China's rare earth research also benefits from more broad research funding programs such as Program 863 for National High-Tech R&D and Program 973 for National Basic Research (Hurst 2010a).

These research efforts have led to proliferation of Chinese authored publications on rare earths including the founding of China's own "Journal of Rare Earths" in 2006 by the Chinese Society of Rare Earth. Chinese-authored publications outnumber those authored by American and Japanese peers, although Hayes-Labruto et al. (2013) and Wübbeke (2013) note that Japanese research is considered far more innovative than those by Chinese researchers.

While the scale and particularities of China's research into military applications of rare earths is not fully known, Hurst (2010a) identifies several past and currently known projects that demonstrate China's keen desire to leverage its rare earth abundance for military applications. As early as 1963, Chinese scientists used rare earth ductile iron that greatly increased the kill ratio of its mortar projectiles compared to standard pig iron designs. The Chinese Aviation Industry Corporation (AVIC) is allegedly developing 10 different types of rare earth magnesium alloys. Two examples include the neodymium-based ZM_6 for use in helicopter rear brakes, ribs for fighter jet wings, and rotor plates for high capacity generators and the BM25 which replaced aluminum alloys previously used in attack jets. Hurst (2010a) also notes that the Chinese have been actively researching ways to adopt rare earths in the same military applications that the U.S. military has been using them for, such as applications in lasers, communications, superconductivity, sonar, radiation shielding, and combustibility in munitions among others.

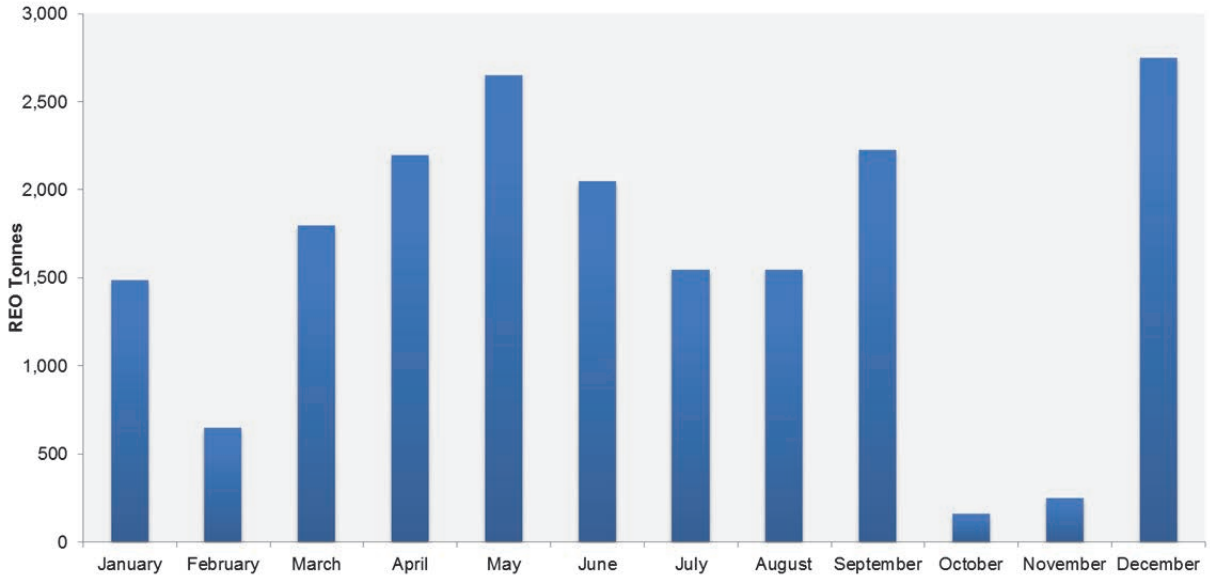
[26] According to the most recent English data available from the Rare Earth Materials Chemistry and Applications Laboratory website, the funding was an estimated $2 million in 2004, in current inflated-adjusted USD (Peking University n.d.).
[27] CAS Key Laboratory of Rare Earth on Advanced Materials and Valuable Utilization of Resources is the full name (Changchun Institute of Applied Chemistry n.d.).
[28] For a list of China's National, State Key, and CAS Key laboratories go to http://english.ucas.ac.cn/Research/Pages/NationalLabs.aspx. In contrast, until recently the only U.S. research institution with sustained study of rare earths has been at the Colorado School of Mines (Grasso 2013).

Rare Earths as a "Geopolitical Lever?"

China is not only the world's largest producer of rare earth ores, but it has also become the largest processor and manufacturer of rare earth goods, particularly of permanent magnets which have wide commercial applications in energy, defense, and consumer electronics and autos. Having consolidated nearly the entirety of the global rare earth value chain within its borders, there have been some concerns of what China could theoretically do with its rare earths monopoly.

To be clear, there is no evidence that Beijing has or intends to use its rare earths as an overt tool of coercion in its foreign policy tool box (a "geopolitical lever"). However, a public discourse in China which called on the Beijing leadership to do so and ambiguous circumstances surrounding the sudden fall in Chinese rare earths exports to Japan coinciding with (on-going) territorial island disputes have raised eyebrows in Washington and Tokyo. For example, when the Obama administration announced a multi-billion dollar arms deal with Taipei in February 2010, the Chinese online media—official and unofficial—exploded in fury, including calls to ban sales of REEs to U.S. firms (Hurst 2010a). In a second instance, in September 2010, a maritime dispute between China and Japan escalated to the point where Beijing allegedly temporarily stopped exports of rare earth minerals to Japan in the following months—materials important for Japan's electronics and automobile industries and for which it depended almost entirely on China for (see Figure 2.10).

FIGURE 2.10 – CHINESE MONTHLY RARE EARTH OXIDE EXPORTS TO JAPAN IN 2010



Data: Morrison and Tang (2012)

Observers differ on whether a technical "embargo" was enacted by Beijing against Japan. *The New York Times* extensively covered the issue. An op-ed piece by Paul Krugman even chimed that China's actions demonstrated that it was "dangerously trigger-happy, willing to wage economic warfare on the slightest provocation" (Krugman 2010). Beijing has maintained that no embargo of any kind was in place with Premier Wen Jiabao declaring that, "We haven't imposed, and will not, impose embargo on the [rare earth] industry…We aim for the world's sustainable development" (as cited in Morrison and Tang 2012). Subsequent media reports, academic analysis, and private conversations provide conflicting views on the

matter. Johnston (2013) maintains that the dip in exports in October and November 2010 to Japan may just have been statistical noise. Others have hypothesized that internal politics were a more likely explanation rather than any concerted effort by Beijing's leadership to delay the shipments (Webster 2011). Whatever Beijing's intention or the extent of its involvement may have been, it has not been helped by Moscow's more blatant use of its natural gas clout as political leverage in Eastern Europe in recent years, actions that are fodder to Western nations increasingly concerned about resource nationalism and its geopolitical implications.[29] Beijing certainly has not been so overt and may not be willing to break so easily from respectable international norms lest it unnecessarily tarnishes the world's growing recognition of China as a global power.

Less publicized but equally wary to U.S. policy makers has been Beijing's willingness to manipulate the market by habitually ceasing and resuming REEs production at its state-owned facilities in order to "protect resources and maintain market stability," which is to say to control market prices (Green 2011). Beijing has demonstrated willingness to use its substantial clout in the commodities market in the past before. In late 2010, it unloaded 200,000 tonnes of aluminum ingots at below market price and blunted a price rally. It has also been accused of using its petroleum strategic reserves to influence the oil markets by the International Energy Agency (Areddy 2011).

Of course, the actual efficacy of any "leverage" (phantom or real) or market manipulation by the Chinese is also a function of the Americans' (and the Japanese and Europeans') own resiliency through the development of alternative sources of supply, substitution, stockpiling measures, and other policies that can minimize, dissuade, or neutralize Chinese influence. Chapter 6 reviews what such options might be while Chapter 7 analyzes which combination of the policies are most cost-effective.

The Cost of Rare Earth Monopoly

China's rise as the world's primary integrated rare earth supplier has yielded economic benefits (and potential geopolitical leverage, however unlikely). But the benefits have come with a large cost basis, environmentally and socially. The environment and public health toll from China's rare earth mining activity is staggering. In Batou, the world's largest rare earth production center in China's Inner Mongolia, vernacular sources report of radioactive tailings —the residue of non-REEs metal concentrates leftover from concentrates—overflowing during heavy rainfall and of high radiation levels in drinking waters and above-average cancer rates in surrounding villages. The estimated environmental damage to China from the rare earth industry is approximately $6 billion (Els 2012).

In China, where environmental regulation has been traditionally an afterthought, just one tonne of rare earth production was believed to have released 60,000 cubic meters of sulphuric and hydrofluoric acid, 200 cubic meters of acidic water, and 1 to 1.4 tonnes of radioactive waste, leading to polluted water supplies, ruined agriculture productivity, and health issues (Hilsum 2009 and China Daily 2010). According to Gibson (2011), more than 10 million tons of wastewater is discharged into a toxic, six-mile-wide "lake" in Batou. Even when radioactive content is minimal and extraction is easy, as is the case with ion adsorption clay deposits in southern China, the aforementioned use of harsh chemicals is believed to exact a high toll.

[29] Moscow has in the past decade used pressure tactics, including threats to cutoff natural gas supply, against its neighboring countries—Ukraine, Georgie, and Belarus—to leverage above-market gas prices (Beehner 2010).

Hurst (2010b) details many of the consequences to the surrounding locality. Tailings often contain radioactive thorium.[30] A single tonne of rare earth production results in 2,000 tonnes of tailing according to one Chinese official's estimate. The radioactive tailings have seeped into local farmlands and the Yellow River whether because they were improperly stored above sea level or because they were transported on open air railway carts across thousands of miles. One Chinese health study links thorium dust exposure to higher carcinogenic mortality rates specifically among rare earth workers (Chen et al. 2004). Kilby (2014) quotes another study that found that rare earth communities had radiation exposure levels above the national average (Shuai 2005).

Environmental damage is compounded by the hundreds of illegal mining enterprises all over China. No firm data are available but a review of vernacular sources by Kilby (2014) quotes local officials reporting smuggled tonnage between 20,000 and 40,000 tonnes a year between 2008 and 2010. The best official estimate comes from a State Council review of discrepancies between reported approved Chinese exports and reported foreign imports of REEs in 2011. By this approximation, illegal exports amounted to between 35 and 56 percent of approved export levels between 2006 and 2008 and 20 percent of approved export levels in 2011 (Government of the People's Republic of China 2012). According to data assembled by Hatch (2011), alleged illegal mining volume was estimated at about 29,700 tonnes in 2010, which is equivalent to more than 33 percent of the approved total production quota of 89,2000 tonnes (Table 2.2). The sprawling black market not only prevents Beijing's efforts to bring the production under its levers to "maintain value" of REEs but it also makes any environmental protection measures difficult to implement.

While China's rare earth producers continue to leach toxic waste into the environment, the demand for rare earths within China (and abroad) is expected to only increase. Chinese demand grew from around 20,000 tonnes in 2002 (Chen 2010) to more than 102,000 tonnes in 2010[31]. By 2015, China is expected to add an additional 60 gigawatts of wind-generated clean energy that would require upwards of 40,000 tonnes of rare earth magnets (Ma 2012). By 2020, installed wind power capacity would reach 100 gigawatts with concomitant increase in demand for REEs. China's growing middle class consumption will also increase demand for personal handheld electronics and electrical vehicles and bikes which all require various amounts of REEs (Hurst 2010b). Chapter 4 will examine global dysprosium demand projections in greater detail.

[30] Thorium has lower radioactivity than uranium and plutonium and is often considered as a "cleaner" alternative to the latter pair for nuclear energy. In the U.S., regulations require specific handling instructions for thorium and other low radiation tailings and requirements for "perpetual surveillance and maintenance of the disposal site" (NRC 2014 and Katusa 2012).
[31] Author's estimation based on China's domestic production, export quota, and world production data from USGS 1994 to 2012a.

TABLE 2.2 – ESTIMATION OF CHINA'S ILLEGAL REES MINING IN 2010

Province/Region	2010
Fujian	1,500
Guangdong	2,000
Guangxi	2,000
Hunan	1,500
Inner Mongolia	50,000
Jiangxi	8,500
Shandong	1,500
Sichuan	22,000
Yunnan	200
Total Production Quota	**89,200**
Actual Production	**118,900**
"Illegal" Production?	**29,700**

Data: Hatch (2011)

Beijing's Seller's Remorse

Politically, there has been a growing sense that China has been squandering a valuable national commodity by selling it under market value. One article provides a narrative of China's rare earth monopoly as an instance of Western plunder, consistent with China's historical victim narrative under the hands of exploitative foreigners. Evoking the concept of *baoweizhan* or "Defense War," China's official news agency Xinhua has put forth titles such as, "China declares 'Rare Earth Defense War'" and "Will it be easy for China to win the 'rare earth defense war?" (Wübbeke 2013). In response to Western and Japanese complaints about export restrictions, the same author retorted that, "developed nations have hardly mentioned the benefits they have won from China's cheap price" and points to how the U.S. has been cautious to protect its own rare earth resources by importing from China while Japan has been squirrelling away imported Chinese rare earths into a strategic stockpile.

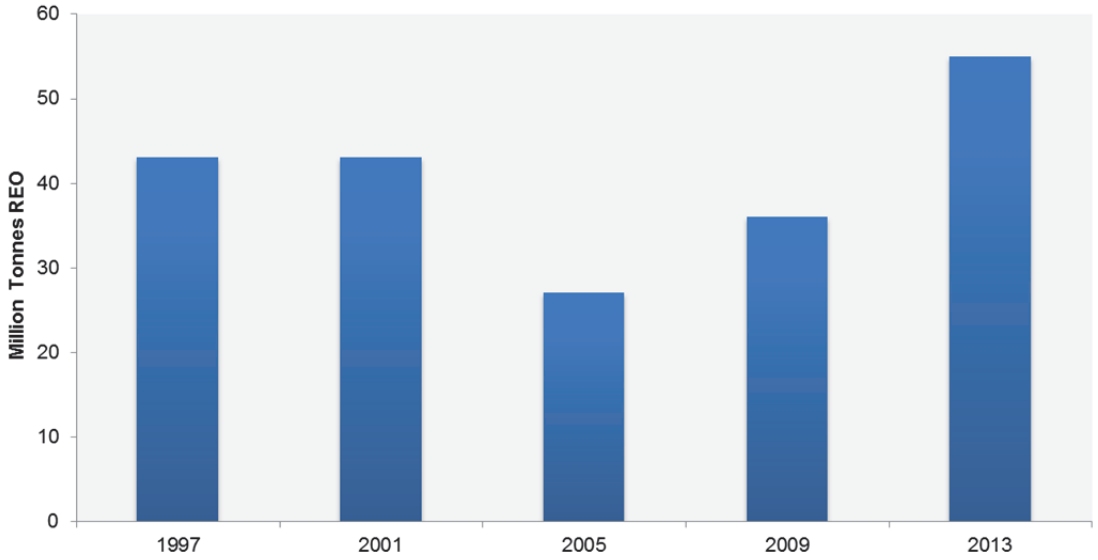
Chinese officials have pointed to its decreasing reserve levels with alarm. At the height of the global commodity boom in 2008, for example, it was found that China's reserve dropped from a decade-long level balance of 43 million tonnes to 27 million tonnes in 2008. In 2010 Premier Wen Jiabao complained that, "China contributes a large proportion of the global rare earth output, far outdoes exceeding its share of the world's total rare earth deposits" (Sina.com 2012 as cited in Wübbeke 2013). The *China Times* wrote that, "The United States and European nations have stopped mining their own rare earth resources and turned to China for supply, leaving China to sustain the high environmental cost of extraction" (Shi 2011). Quipped one Chinese expert, "China had been selling these precious rare-earth metals at dirt-cheap price for 20 years" (People's Daily Online 2009). Rather than the view that China's monopoly was the successful outcome of decades of industrial strategy, the political narrative has instead been couched in terms of wasted opportunities and foreign exploitations.

This victim narrative, however, conveniently omits Beijing's decades of intentional development of its rare earths industry. In fact, the narrative would be more compelling if Beijing were to point to the heavy environmental costs borne by the Chinese, costs which directly translate to savings for U.S. and other foreign consumers. Such a story would more rightly portray an exploitative dimension to the current system. But the fact remains that China's environmental crisis is largely self-inflicted; the greater the environmental damage from rare earths, the greater the imperative to capture profitable downstream margins to recoup the upfront environmental losses. But this uncomfortable reality is politically

inconvenient and untenable, especially for a political brass bedeviled by widespread rural unrest stemming from environmental damage in the last decade. At the height of discontent, the number of formal complaints and mass protests about the environment is believed to have grown roughly 30 percent each year since 2002, topping 230,000 protests nationwide in 2010 alone (Hayes-Labruto et al. 2013).

Two facts undermine Beijing's victim narrative. First, while it is true that China's reserve decreased in 2008, it then moved up to a new *high* not long afterwards. Reserve estimates are dynamic, sensitive to price, demand, technology, and exploration. After dipping to 27 million tonnes, China's reserve estimate climbed to 37 million tonnes in 2009 and all the way to 55 million tonnes last year (USGS 1998b to 2014b) as shown in Figure 2.11.

FIGURE 2.11 – CHINA'S REOS RESERVE ESTIMATE

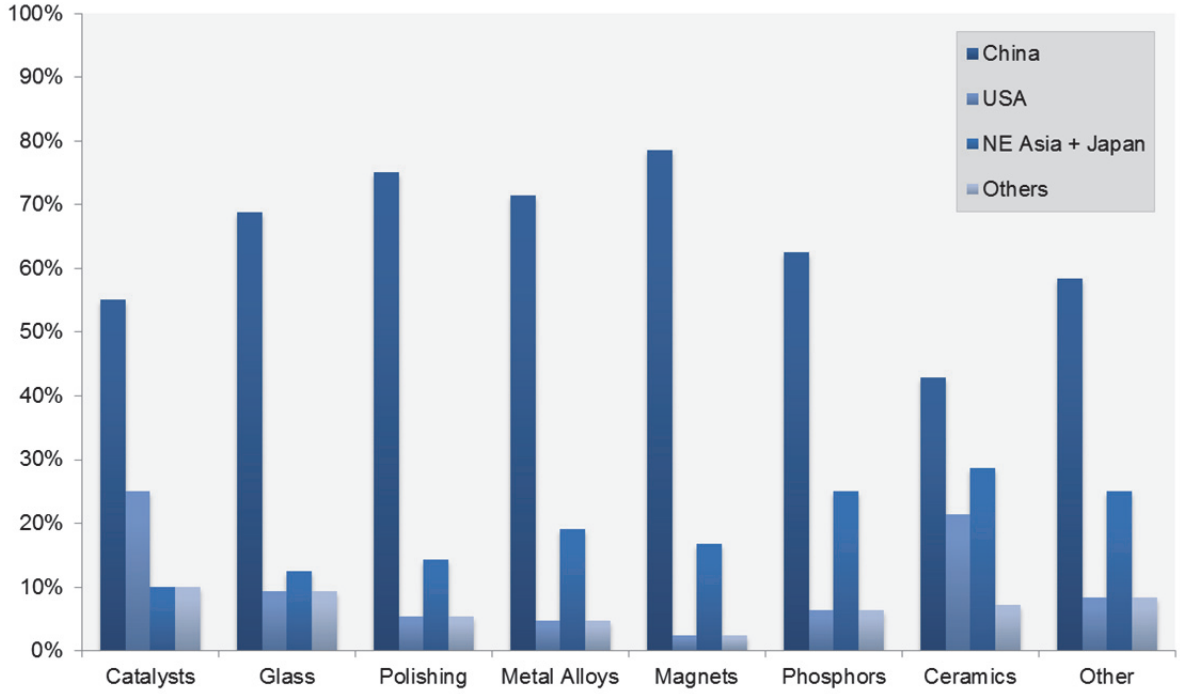


Data: USGS (1998b to 2014b)

Secondly, Beijing's assertion that Japan and the West were plundering Chinese resources for their own consumption at China's expense is largely untrue. It is indeed true that China's rare earth production share (90 percent) is disproportionate to its share of rare earth reserves (37 percent). But it is also true that China is the world's single largest consumer of REOs. According to data by Kingsnorth (2012), Chinese demand for REO applications were all above 50 percent of global demand except for ceramics (Figure 2.12). More specifically, Chinese demand for critical applications in magnets, polishing, and metal alloys ranged between 70 to 79 percent while demand for generally LREE-dependent applications in glass, phosphors, and catalysts ranged between 55 and 69 percent. Put it differently, while China does produce more than 90 percent of rare earths, it also consumes 72 percent of total world production (Tryrer and Sykes 2013). By Beijing's own design, it is producing and consuming its own rare earths, a trend likely to continue in coming years when most of the critical demand for green energy technology will

come from within China's border.[32] Given the toxic effect of China's rare earth industry on the environment, however, it is bitterly ironic they are so crucial for "green" energy development.

FIGURE 2.12 – CHINA IS THE PRIMARY CONSUMER FOR ALL RARE EARTHS APPLICATIONS



Data: Kingsnorth (2012)

China's Controversial Way Forward

Beijing seeks greater efficiency and regulation over the sprawling industry where as much as half of all HREEs and 15 percent of LREEs are believed to have been illegally mined in 2011. It also seeks to minimize the negative environmental externalities associated with rare earth extraction and processing (Nicoletopoulos 2011). To achieve this, the government has responded to the ecological and organizational crises in five ways: environmental protection measures, industry consolidation, export restrictions, acquisition of REEs suppliers abroad, and stockpiling. From the perspective of foreign consumers, however, this policy package could not be seen as more threatening (Hurst 2010b). In response to international criticisms, Beijing's White Paper defended the quota system as a "reasonable quota…that basically satisfies the normal demand of the international market" and that, "China opposes politicizing the rare-earth issue." It then homes into its main message that countries with rare earths

[32] Assuming consumption ratio of light to heavy rare earths remain constant, China can largely meet its own demand. China's domestic reserve of approximately 55 million tonnes is equivalent to between four-and-half and six hundred years' worth of its recent production rate. As we will see, however, the increasing demand for heavy rare earths like dysprosium both in China and abroad means even China may need to rely on foreign sources.

should be "developing their own resources to diversify the supply and expand rare-earth trade in the international market" (Government of the People's Republic of China 2012). In other words, China was closing shop, at least for the moment, until it got its house in order.

This section surveys five distinct policies that China has pursued in recent years to consolidate its gains over the two decades. These include attempts at better environmental protection, consolidation of rare earth disparate capacities into a few large entities, the use of export restrictions to subsidize midstream and downstream suppliers, the acquisition of foreign rare earth production capacities to help meet growing Chinese demand, and the stockpiling of valuable rare earth elements.

Environmental Protection Laws

The State Council vowed that, "China will never develop the rare-earth industry at the expense of its environment." Past environmental controls dating from the 1980s proved ineffectual in preventing the tainting of water supplies from rare earth mining. Despite both the 11th and 12th Five Year Plans (cumulatively covering the decade from 2006 to 2015) targeting cuts in harmful emissions, there has been little manifest change in rare earth operations (Government of the People's Republic of China 2012). The Rare Earth Industry Pollutant Discharge Standards issued by the Ministry of Environmental Protection in July 2009 set new discharge standards for 14 pollutant types and required producers to introduce more sustainable mining and processing methods (Hurst 2010b).[33] Two years later, a new rare earths mining law limited chemical oxygen demand and pollution emissions of ammonia, nitrogen, phosphorus, fluorine, thorium, heavy metals, sulfur dioxide, chlorine gas, and other particles (Government of the People's Republic of China 2012).

Financial incentives are also being used to cajole rare earth producers to conform to sustainable mining practices. In response to recently low rare earth prices that cut into producers' profit margins, the Ministry of Finance announced it would disburse cash payment of about $160 per tonne of rare earth production capacity and $241 per tonne of rare earth processing capacity for enterprises that successfully pass environmental compliance inspections (Xinhua 2012). Separately, a new environmental tax law on rare earths is expected to become law in 2015 (Shen 2014).

It is unclear how effective—if at all—any of these many measures have been in mitigating the corrosive impact of rare earths mining. Even with financial incentives, major companies such as Batou Steel may not find the carrots sweet enough given the relatively diminutive size of the $3 to $4 billion rare earth sector compared to the much larger and profitable $962 billion global iron ore industry. This leaves little incentive to undertake or participate in expensive environmental control laws that have little impact on their bottom lines (Hayes-Labruto et al. 2013). Even if new standards were to be enforced strictly (which is doubtful), the standards themselves are compromised. In the original proposal, the new discharge limits would have set ammonia at no more than 15 mg per liter. However strong pushback from the industry forced a revision to 20 mg per liter before eventually settling at 25 mg per liter—the old limit dating from 1996. Another significant loophole is that the standards would apply only to new mining concessions (not many of which are expected) while incumbent operators—who will continue to remain the dominant market players given Beijing's consolidation effort—are exempt (Wübbeke 2013).

[33] Among others, these include fluoride, phosphorus, carbon, nitrogen, and ammonia nitrogen.

Consolidation

The MLR has worked to consolidate the expansive Chinese rare earths sector in recent years. Driving this change was the belief that consolidation into a handful of large-scale mining conglomerates would enable greater operational efficiency and control over environmental effects associated with rare earth production (Humphries 2013). Beijing largely failed in its goal to assume a "planned, unified control in administration of all related procedures" of the rare earth industry since originally making the pledge in 1991. A second attempt is being made through the 2008-2015 NPMR to empower Beijing to assert "regulation and control, restrictive exploitation, tightened access and comprehensive utilization" of China's sprawling rare earth industry (Government of the People's Republic of China 2012). As part of this renewed effort, Beijing has restricted mining permits, prohibited expansion of production capacity, stepped up inspection and monitoring for compliance and shutting down illegal mining, and sought mergers of production facilities (Government of the People's Republic of China 2012).

First, in order to temper production, tax rates on rare earth ores rose from around ¥0.4 to ¥2 per ton to ¥60 per ton for LREEs and ¥30 per ton for HREEs. Also, according to the Rare Earth Industry Development Plan (2009-2015), rare earth production has been capped between 130,000 and 150,000 tonnes until 2015[34] (Wübbeke 2013). Approximately 20 percent of REO processing capacity was believed to have been slashed in 2012 alone (Hastings Rare Metals Ltd. 2013). Secondly, the government has cracked down on illicit mining, closing down 23 mines and 76 smelters mostly in the southern provinces where illegal mining is most common because of the concentration of the more valuable HREEs (many of the closed operations are believed to have re-emerged, however) (Wübbeke 2013).

Thirdly, part of the challenge to regulatory control has been the wide dispersal of the rare earths industry across 22 provinces and regions. To better manage across the geographic separation, Beijing is consolidating the industry into three large districts (Figure 2.13). The North District includes Inner Mongolia and Shandong, the South District includes Jiangxi, Guandong, Fujian, Hunan, and Guangxi, and West District comprised solely of Sichuan.

Lastly, industry consolidation has also taken place via massive mergers among producers. At the end of 2008, a new state-owned-enterprise (SOE), the Inner Mongolia Batou Steel Rare Earth High-Tech Co., was formed through a consolidated eight-party joint venture valued at over $102 million (Hurst 2010b and Hawes 2011). A similar consolidation took place with the formation of Chinalco Rare Earth Company through a merger of five plants and a trading company in Jiangsu province (Bromby 2011). In Sichuan province, Jiangxi Copper retained all mining rights in Manoniuping (Wübbeke 2013). As a result, between 2006 and 2011, the number of Chinese producers and traders shrank from 47 to 22, while foreign joint ventures shrank from 12 to 9 (Tse 2011)[35].

The efficacy of these massive reforms is yet to be seen. First, despite Beijing's desire to consolidate the industry into two, at most three, large state-owned rare earth enterprises, it has run into fierce opposition from local authorities intent on maintaining their influence over lucrative rare earth industries, particularly in the southern provinces. Writes Wübbeke (2013):

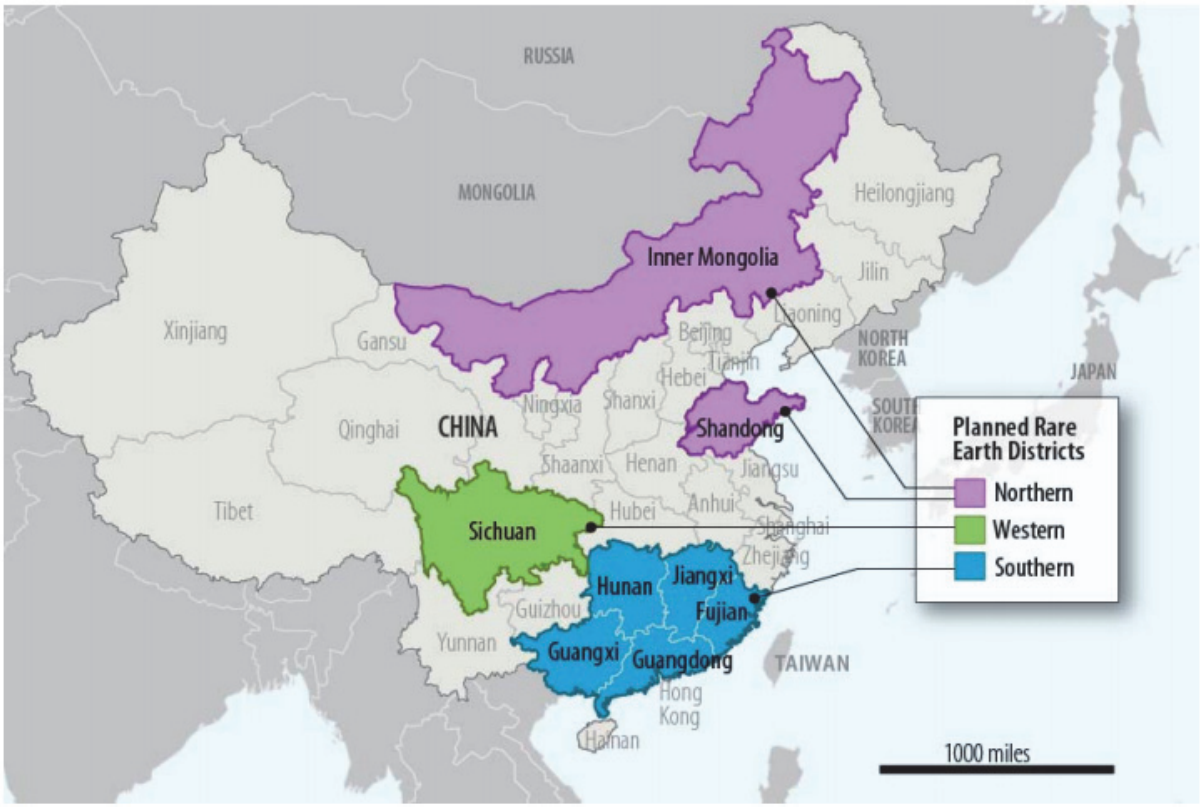
> The central state is trying to involve central government-owned mining enterprises in local mining and processing of REE, such as China Minmetals, Chinalco, and China Nonferrous Metal Industry,

[34] Actual Chinese production between 2009 and 2013 were at or below 130,000 tonnes according to USGS estimates. Chinese production between 2005 and 2008 was at or below 120,000 tonnes (USGS 2007b-2014a).
[35] Mostly Japanese entities with American and European presence.

> and endow them with a strong position in the long run. But many of these enterprises were long unable to obtain local mining licenses, as provincial governments wanted to protect their own companies. Central state companies could become active only in smelting and separation. Minmetals could not break the strong position of Ganzhou Rare Earth Minerals Industry for several years. The provinces of Guangdong and Fujian set up own large provincial REE enterprises. Central government-owned enterprises could obtain mining rights only in Guangxi, Hunan,Yunnan, and Shandong with so far rather marginal production capacities. Although the reorganization increased the degree of concentration, the industry remains fragmented between central, provincial, and some private enterprises.

Secondly, quite ironically, the production restriction measures may have actually *increased* incentives for illegal mining and smuggling due to the inflated market prices abroad caused by supply shortages (Kilby 2014).

FIGURE 2.13 – CHINA'S PROPOSED RARE EARTH REGIONAL DISTRICTS



Source: Morrison and Tang (2012)

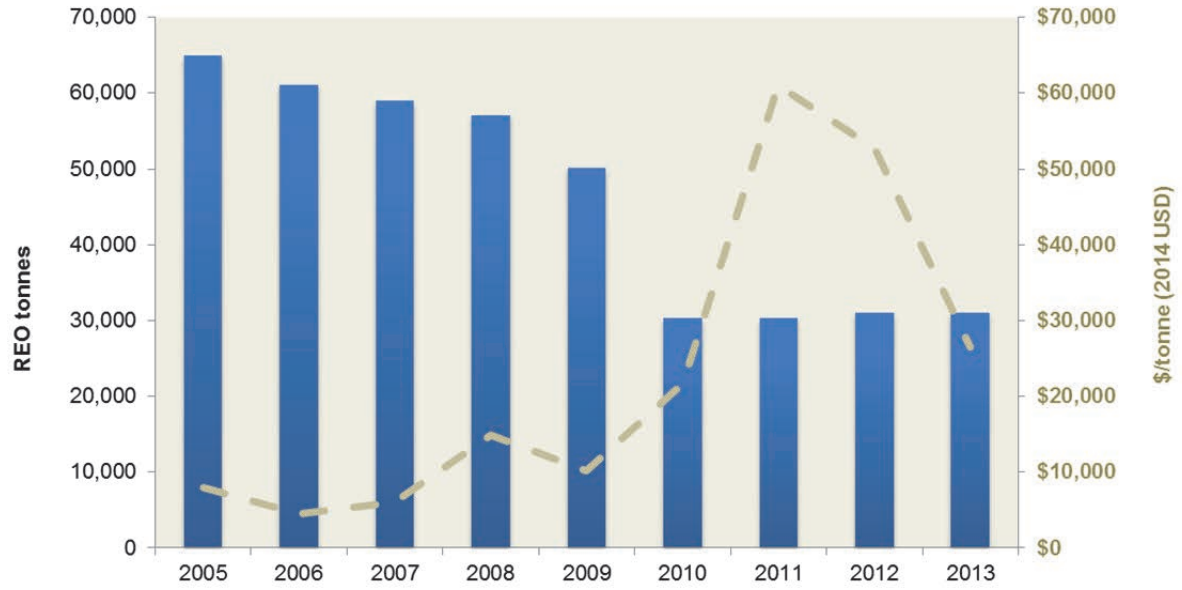
Export Restrictions

China employs export quotas and duties to restrict export of rare earths to the international market. Beijing has defended these measure before the World Trade Organization (WTO) by invoking exemption clauses under GATT Article XX(b) and XX(g) under which WTO signatories could apply "temporary" export quotas and duties for reasons of "resource conservation" and "environmental protection" (WTO 2014a). Elsewhere, Beijing's most public defense was in the form of a June 2012 White Paper titled, "Situation and Policies of China's Rare Earth Industry." It cites China's "excessive exploitation of rare-

earth resources," "severe damage to the ecological environment," "irrational industrial structure," and a "severe divergence between price and value" of rare earths as grounds for changes in its domestic and international rare earth policy (Government of the People's Republic of China 2012).[36]

The Ministry of Commerce sets the annual production quota (which is often exceeded by domestic producers) as well as export quotas. It also establishes the export quota bi-annually with two different quota levels: one for domestic producers and another for joint-ventures with foreign investors whose exports must also be licensed. The quotas are then allocated individually for each firm (Tse 2011). China's quota decreased gradually between 2005 and 2009 from about 65,000 tonnes to 50,145 tonnes. Starting in 2010, however, it was cut by nearly 40 percent to 30,258 at which level it has approximately remained since (Figure 2.14). Not surprisingly, the price rise in 2010 and 2011 was due in large part to the supply shock following these measures.[37]

FIGURE 2.14 – CHINA REO EXPORT QUOTAS



Data: Chinese Ministry of Commerce and USGS[38]

Secondly, the Ministry of Finance imposes export duties on REEs. A 25 percent tariff is levied on exported neodymium, yttrium, europium, dysprosium, terbium, and scandium with the remaining REEs levied a 15 percent tariff (Table 2.3). Since 2007, China has rescinded a refund program for value-added-tax (VAT) on REEs goods on the lower- and mid-tier value chain. It has, however, maintained refunds for exports of REEs goods higher up on the value chain, such as permanent magnets and phosphors. The combined effect of tariffs and VAT refund schemes translates to a 31 percent premium price (before

[36] Export restrictions are not uniquely employed by China and are not always challenged in the WTO. Appendix C provides a brief overview of global usage of commodity export restrictions and the legality thereof.
[37] In 2007, the Ministry of Industry and Information Technology proposed outright bans on the export of raw HREEs ores, specifically dysprosium, terbium, thulium, and yttrium, while permitting exports of processed oxides. This would have given a substantial additional boost to processors of these HREE (Kilby 2014). However, subsequent reports contradict this, saying the bans were never implemented.
[38] Prices from 2005 to 2012 inflated to current 2014 U.S. dollars using data from USGS Historical Statistics (USGS 2014b). Price for 2013 is estimated as a proportion of price decrease in the same time frame from Metal-Pages.com.

transportation and storage costs) of rare earths materials for permanent magnet manufacturers outside of China according to one OECD study (Korinek and Kim 2010).[39]

TABLE 2.3 – CHINESE EXPORT DUTIES ON REES IN 2012

REE	Type	Ore Export Duty	Oxide Export Duty	Chloride Export Duty	Carbonate Export Duty
Cerium	L	25%	15%	NA	NA
Lanthanum	L	25%	15%	25%	15%
Neodymium	L	25%	15%	15%	15%
Praseodymium	L	25%	25%	15%	15%
Dysprosium	H	25%	25%	25%	25%
Terbium	H	25%	25%	25%	25%
Yttrium	H	25%	25%	15%	15%

Data: WTO (2014)

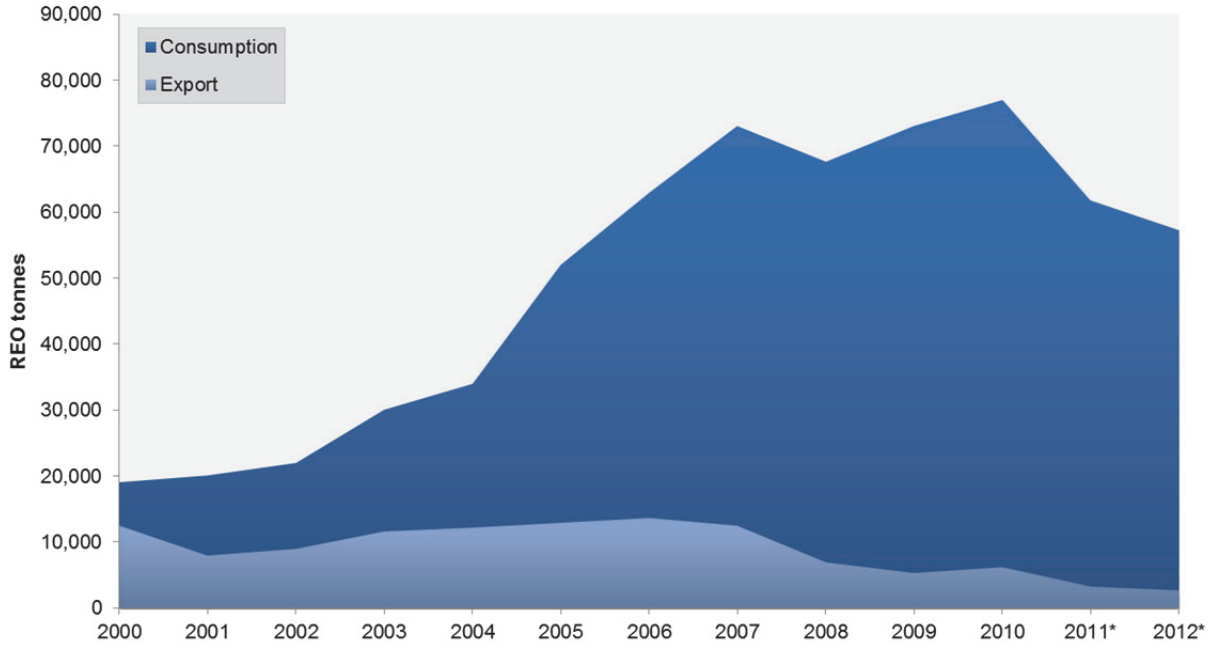
Acquisitions of Rare Earth Supply Capacities Abroad

China has actively sought out foreign sources of rare earths to supplement its growing appetite (Figure 2.15). Its known foreign outreach efforts have been primarily through equity acquisitions of existing rare earths mining interests with varying degrees of success. The highest, most recent profile was in 2005, when China National Offshore Oil Corporation (CNOOC) tendered a $18.5 billion cash offer for U.S. energy company Unocal which owned and previously operated the then-defunct Mountain Pass rare earth mine. While much of the concern was over the impact of the acquisition on energy geopolitics, the acquisition would have had an interesting outcome in the current rare earth competition. Eventually, political pressure and perceived energy security concerns prevented the transaction, paving the way for Chevron's acquisition of Unocal (Kilby 2014 and Hurst 2010b).

In the years since, China has had mixed success elsewhere. Jiangsu Easter China Non-Ferrous Metals Investment Holding Co. acquired 25 percent equity in Arafura Resources Ltd. which operates the Nolan's Bore project in Australia (Arafura 2009). However, an offer to purchase 51.6 percent equity in Lynas Corporation of the Mount Weld fame in Australia was rebuffed by the Australian government (Keenan 2011). Most recently in March 2014, Greenland Minerals and Energy Limited (GMEL) announced that it has signed a Memorandum of Understanding (MoU) with Guangdong Zhujiang Rare Earths Company, a subsidiary of China Non-Ferrous Metal Industry's Foreign Engineering and Construction Co. Ltd. (NFC). The preliminary agreement lays the groundwork for GMEL to export is rare earths to NFC for separation at its facility (GMEL 2014).

[39] In March 2014, the WTO found China's rare earth quotas and taxes to be inconsistent with Beijing's obligations to the Accession Protocols which set conditions for China's formal entry into the WTO as a full member. China has since appealed the ruling and the full resolution of the case may not be concluded for up to another two years. Details on the case are discussed in Chapter 6.

FIGURE 2.15 – CHINESE CONSUMPTION HAS INCREASED THREE-FOLD SINCE 2000[40]



Data: Tse (2011) and UN Comtrade

Stockpile

China's rare earth stockpiling policy is opaque and details are difficult to come by. Still, various sources, including China's own State Council White Paper, point to a public-private national strategic reserve of ten critical materials (Government of the People's Republic of China 2012 and Shi 2011). The ten metals are believed to be rare earths, tungsten, antimony, molybdenum, tin, indium, germanium, gallium, tantalum, and zirconium (China Daily 2010). Managed by the State Bureau of Material Reserves (SBMR), an agency of the National Development and Reform Commission (NDRC), the stockpile was and continues to be used to drive demand for processed aluminum and copper in the wake of weak economic growth following the 2008-2009 global financial crisis. For example, in response to lobbying by domestic smelters, Beijing agreed to purchase upwards of 400,000 tonnes of aluminum ingots and 165,000 tonnes of refined copper cathode at floor prices to pick up slack (Chinamining.org 2011). Consistent with China's observed practice of manipulating commodity market prices through its base metal and petroleum reserves, Beijing may be doing the same with its new rare earth stockpile.

The MLR is believed to be directing the effort with a pilot stockpile plan taking effect in 2010 in conjunction with Batou Steel Rare Earth Hi-Tech Co. (Batou). According to earlier reports, Batou was reported to be stocking 9 percent of its annual production (Yam 2010 and Hurst 2010b). However, because Batou is not a major producer of HREOs, the stockpile is likely comprised of LREOs whose value (strategically and economically) is less critical than HREOs. Perhaps to help build up the HREO

[40] Consumption estimates for 2000 to 2010 from Tse (2011). 2011 and 2012 consumption estimates calculated using the following apparent consumption formulation used by the USGS: Apparent Consumption = Production + Import – Export +/- Stockpile. Trade data sourced from UN Comtrade via the World Bank's WITS interface. 2012 was the last year data was available. China is not known to have begun stockpiling until 2013. Production data from USGS (2002b to 2014a).

reserves, the Ministry of Industry and Information Technology is believed to be offering interest-free loans for suppliers to help stockpile HREOs (Currie 2012b).

One estimate of the final level of the rare earth stockpile is about100,000 tonnes. Batou is believed to have plans to expand the total storage capacity to as high as 200,000 tonnes (Areddy 2011). As part of the inventory buildup, the stockpiling goal for 2013 was 10,000 tonnes (Topf 2013). In April 2014, the SBMR, arranged for the purchase of 13,000 tonnes of REOs into the strategic reserve, purchased at prices 10 percent above the prevailing market rate (Shen 2014). In early April 2014, the SBMR arranged for the purchase of 13,000 tonnes of HREOs into the strategic reserve, purchased at prices 10 percent above the prevailing market rate (Shen 2014 and McLeod 2014).

Is China's Policy of Rationalization Rational?

Beijing's rare earths policy program is rife with contradiction. Its two policy objectives, as currently pursued, are working against each other. Publically, Beijing has stated that its policies are aimed at environmental protection and resource conservation. However, Beijing's overriding objective over the last three decades has been to become the dominant vertical rare earth producer, from extraction to end product integration. So in reality, the concerns over environmental degradation and resource exhaustion have only recently become a policy issue in the *aftermath* of its successful creation of a massive (but poorly regulated) rare earth production base.

It is clear that China wants to consolidate and maintain its lead as a rare earth producer, not merely in terms of production but also in applying them to gain comparative advantage in its commercial and military sectors over its rivals. Yet Chinese leaders need to contend with the toxic effects of the industry as outcry over its negative externalities on the environment and local health mount. Implementation of new environmental control laws and discharge standards aimed specifically at the rare earth industry are steps in the right direction. But because at the end of the day, Beijing's precedent concern is for rare earth industrial supremacy, it chose to enact competing policy measures (such as export restrictions[41] and stockpiling) that *increase* domestic production, not temper it as any well-intentioned conservation planner would do. Beijing is trying to have its cake and eat it too.

Instead, what is happening is that China is paying dearly in terms of health, environmental, and fiscal costs to achieve and maintain a dominant position all across the rare earths supply chain. The truth is that the environmental laws seem to be ineffective, undermined by weak regulatory compliance. The rare earth industry consolidation is only partially successful, stumped by powerful local interests. Meanwhile, export restrictions and production quotas have only *encouraged* illegal mining (which compounds the environmental hazard) while depressing domestic prices. This in turn has compelled Beijing to expend state funds on stockpiles in order to contrive demand so that prices are stabilized! These are the snowballing costs to China as it tries to manufacture a vertical rare earth supply chain. As it happens, these policies also impose costs on its trading partners who are stuck with premium rare earth price tags.

The recent April WTO ruling against Chinese restrictions is unlikely to change the market dynamics. As mentioned, China's 2014 stockpiling goal was 30 percent higher than in 2013 and it is exclusively

[41] As previously discussed, export restrictions deflate domestic prices, which increases consumption demand, leading to greater domestic production.

focused on hard-to-obtain HREOs. According to Chinese analysts, this move was in response to the WTO the ruling: as Beijing prepares for the possibility of having to dismantle the export quotas and duties, it can just as easily maintain the two-tiered price system by increasing stockpiling levels for exclusive domestic consumption, and by imposing higher mining taxes and export licenses fees (a grey area that is not covered explicitly by the GATT framework) (Bloomberg 2014, McLeod 2014a, and Kilby 2014).

Ironically, the only indisputable winners to this convoluted dirigisme may be the foreign rare earth manufacturers who have relocated to China. Welcomed with a red carpet by Beijing, they now access raw REEs at below market value and sell their processed and manufactured products far above equilibrium prices abroad. Meanwhile, the rest of Chinese society subsidizes these market imbalances with their health, land, and cash. To that extent, perhaps China's *baoweizhan* narrative is true after all.

Country Responses to China's Rare Earths Policy

Three responses sum up the global reaction to China's rare earth export restrictions: lawsuit against China through the WTO process, redoubled investment in potential technological solutions to find substitutes technologies and increase recycling capabilities, and increased mining outside of China.

The first response has been a concerted effort by national governments, including the U.S., EU members, Japan, and others to file a complaint with the WTO regarding China's export restrictions. In July 2011 and again in an appeal ruling in January 2012, the WTO favored the U.S., EU, and Mexico in finding that the Chinese restrictions on bauxite, coke, fluorspar, magnesium, manganese, silicon carbide, silicon metal, yellow phosphorus and zinc unfairly gave Chinese buyers a price advantage through a two-tiered pricing system (Barkley 2012). In accordance with the ruling, China removed export restrictions on these materials by January 2013 (WTO 2013). The case was regarded as a "mere prelude to potential litigation on rare earths" according to observers and indeed it was (Lim and Senduk 2013).

Buoyed by the WTO ruling, the Obama administration, joined by Japan and the EU, submitted a second WTO suit against China's restrictions on REEs, tungsten, and molybdenum in June 2012 (EC 2012). Nearly two years later on March 26, 2014, the WTO Dispute Settlement Body (DSB) found that China's export duties and quotas on rare earths, tungsten, and molybdenum were inconsistent with China's binding Accession Protocol. Most notably, the panel found that China's defense under exemptions clauses in Article XX for conservation of natural resources did not apply. The primary reason was that China's participation in the WTO was premised on the Accession Protocols rather than 1994 GATT "permanent" framework and thus it could not invoke the privileges afforded by the latter. Furthermore, the panel argued that even if China were eligible for exemptions under Article XX, the export duties could not be found "necessary to protect human, animal, or plant life or health" as required by Article XX(b) and the export quotas were found to "achieve industrial policy goals rather than conservation" in

conflict with Article XX(g) provisions (WTO 2014a). China appealed the ruling in early June (McLeod 2014b). The WTO appellate body has up to 90 days to respond with a decision (WTO 2014b).[42]

The second response, a mix of private and government initiatives, has been to consider substitutes, work-arounds, and recycling of materials in shortage (reviewed in closer detail in Chapter 6). Private businesses such as Japanese automakers Nissan and Mazda have redesigned their electric vehicles to substantially reduce usage of rare earths metals for which it almost entirely depends on China (King 2012). Honda recently announced that it has created and deployed its own proprietary mass recycling process (Currie 2012a). The Korea Institute of Industrial Technology (KIIT), whose country is also heavily reliant on Chinese rare earths, is funding research at the U.S. Department of Energy's Ames Laboratory to see if rare earth metals can be extracted from scraps using molten extraction (Mick 2012). Separately, the U.S. government established the new $120 million Critical Materials Institute (CMI) at the Ames Laboratory in addition to a bevy of R&D funds specifically for rare earths research under its ARPA-E REACT initiative (Cho 2013).

The third response, primarily a private endeavor responding to incentives from the price hikes, has been to re-start or initiate new mineral production in known deposits outside of China (King 2012). With renewed interest in REEs mining, investors and governments have been actively searching for deposits in both their home countries and abroad. In the U.S., Molycorp purchased the largest known U.S. REEs deposit in Mountain Pass, California from Chevron and restarted production, defunct since 2002 (Molycorp 2011 and Molycorp 2013c). In addition, several exploratory studies are taking place, including the Bear Lodge project in Wyoming by Rare Element Resources Ltd., the Bokan Mountain project by Ucore Rare Metals in Alaska, and the Deep Sands deposit in Utah by the Great Western Metals Group (Molycorp 2010, Ucore 2013, and Hiyate 2010). Japan, South Korea, and Australia have sought production ventures abroad, including Malaysia, Central Asia, and South Africa among others (Herkovitz 2011). Appendix B lists global non-Chinese rare earth projects that are currently active or are in the advanced stages of preparation, which could range anywhere from two to six years or more before production begins.

The following section reviews the policy responses of major consumers of Chinese rare earths other than the U.S. (the U.S. policies are reviewed more in depth in Chapter 6). Japan has been the most active, investing across all five major types of policy investments (investments in development local resources or reforms to encourage development, joint ventures abroad, R&D into substitute and recycling technologies, and stockpiling). China and South Korea have largely focused on investments to increase supply. In contrast, the U.S. and the EU have taken a demand-reduction approach, investing in research to increase recycling. Australia and Canada, two major up and coming rare earth suppliers, have largely maintained the status quo as mining-friendly regions to help capture the upswing in rare earth investors looking for projects. Most countries except Canada and Australia are building rare earth stockpiles (the EU has been deliberating on the issue for some time). See Table 2.4 for the summary. Note that private initiatives are excluded, such as company stockpiles or joint ventures without government support.

[42] According to the WTO, "Parties to a dispute can appeal a panel's ruling. Appeals have to be based on points of law, such as legal interpretation — they cannot re-open factual findings made by the panel. Each appeal is heard by three members of a permanent seven-member Appellate Body comprising persons of recognized authority and unaffiliated with any government." WTO (2014b).

TABLE 2.4 – SUMMARY OF ACTIVE GOVERNMENT POLICY CATEGORIES RELATING TO RARE EARTHS AS OF 2012

Country/Region	% of Global Reserves	Domestic Mining Development	Joint Ventures Abroad	R&D Recycling	R&D Substitution	Stockpile
China	37.4%	✓	✓			✓
United States	8.8%			✓	✓	✓
Japan	4.6%	✓	✓	✓	✓	✓
Australia	1.4%	✓				
Canada	0.6%	✓				
EU	0.2%			✓	✓	*
South Korea	^	✓	✓			✓

* Under discussion; ^ unknown

The European Union

The EU's Raw Materials Initiative, founded in 2008, is the primary program for addressing critical raw material supply challenges. The Raw Materials Initiative has three policy objectives. The first is to work towards international access to raw materials through enforcement of WTO norms, aid to resource-producing economies to promote governance, political risk mitigation, and sustainable mining practices.[43] The second objective seeks to enhance domestic supply through improved mining data and regulatory transparency, reforms to expedite mine permitting, research and development support for mineral extraction, processing, and human capital development. The third objective is to mitigate demand by increasing material recycling and efficiency, research funds to develop work-arounds, substitutes, and prohibition of recyclable waste (European Commission 2008). As follow-up to these initiatives, the EC released a 2010 study identifying fourteen raw materials that were economically important but were at an elevated risk of supply disruption (European Commission, Enterprise, and Industry 2010). A second 2011 study by the EC Joint Research Center on the raw material needs of Europe's clean energy industry identified five metals—tellurium, indium, gallium, and the REEs neodymium, and dysprosium—as particularly vulnerable (European Commission 2011).

Dubbed Horizon 2020 initiative, the EC released a report titled, "A Resource-efficient Europe" that establishes a research and innovation policy framework for guiding Europe towards a comprehensive green resource-efficient economy. Horizon 2020 is due to incorporate and supersede aspects of the EU 7th Framework Programme for Research and Innovation (FP7) which is divided into seven programs that fund research on environmental and energy issues with direct impacts on REE supply and demand management. While the broad mandate of Horizon 2020 has implications for REEs, it does not explicitly target critical materials/REEs supply security as a stand-alone issue (Halme et al. 2012). In February 2014, the EU appointed seven research organizations—Fraunhofer, CEA, VTT, Tenalia, SP, and SINTEF—to focus on neodymium and dysprosium recycling technologies (Clancy 2014).

Member states have taken actions in response to the supply shock, mostly in response to the EU initiative. The Finnish strategy is focused on supply-side growth by encouraging exploration and extraction of critical minerals within labor and eco-friendly norms. The Netherlands has focused on the demand-reduction, promoting on conservation and efficiency measures regarding critical materials. The British

[43] One example of international outreach is a cooperative agreement between the EC and the African Union Commission to improve issues of governance, investment, and geological know-how (Bauer et al. 2011).

and French, like the U.S. government, have commissioned public studies to better understand the context and impact of the critical materials problem. Germany's response has been the most independent and robust, with initiatives pre-dating the EU. Focusing on both state and federal level programs, Germany is pressing on both supply- and demand-side policy frameworks designed to incentivize private sector action towards efficient demand and supply expansion through recycling and substitution (Halme et al. 2012)

Japan

With limited natural resource endowment to supply its expansive and cutting-edge manufacturing base, Japan is particularly vulnerable to raw material disruptions. Japan has relied on as high as 82 percent of its rare earth supply from China (although this number has declined over the last three years to around 62 percent) (Humphries 2013). The Japanese government's response to the REEs supply challenge and the critical raw materials challenge writ large has been to focus on securing reliable supply abroad while tempering demand and increasing efficiency at home. Japan's Ministry of Economy, Trade, and Industry (METI) established four priorities for ensuring supply security in a 2009 report titled "Strategy for Ensuring Stable Supplies of Rare Metals." METI's four objectives are to: (1) secure supply nodes abroad; (2) greater recycling of scrap metals; (3) research into work-arounds; (4) and the establishment of stockpile.

The program implementation and execution responsibilities fall on peer and subsidiary agencies, especially the Japan Oil, Gas, and Metals National Corporation (JOGMEC) and the Japan Bank of International Cooperation (Bauer et al. 2011). Japan is estimated to have budgeted $676 million in fiscal year 2011 for its supply security programs that cover REEs and other critical raw materials, which includes funds for developing foreign sources of REEs and R&D funds for recycling and work-arounds (Maeda 2011). In addition, it has invested $386 million in a research subsidy program for 160 companies (including HML). An additional $1 billion of private research expenditure is expected to be spent thanks to the government's research grants (Maeda and Tsukimori 2011). All in all, both government and private sector expenses in 2011-2012 for material security is estimated to have been around nearly $2 billion (Suga 2011 and Reddall and Gordon 2012).

JOGMEC, an independent government agency tasked with operational functions apart from ministry-level planning functions, in particular assumes responsibilities for much of the METI objectives. JOGMEC's programs fall along five main tasks: (1) the Joint Basic Exploration Scheme which provides financial support of global field surveys; (2) financing of high-risk mining projects; (3) stockpiling of nickel, chromium, manganese, cobalt, tungsten, molybdenum, and vanadium (and possibly REEs) and monitoring of supply levels of indium, platinum, gallium, niobium, tantalum, and strontium; (4) information collection and dissemination of global mineral supply and mining policies and regulations; (5) direct research and development or funding of new exploration, extraction, and recycling methods and techniques (Bauer et al. 2011). As of 2011, JOGMEC had $4 billion in capital (JOGMEC and Sojitz Corporation 2011).

JOGMEC maintains the Rare Metals Stockpiling Program (RMSP). Conceived after the oil crisis of the 1970s, the RMSP was implemented in 1983 with materials stored at a 37,000 cubic meter warehouse facility in Ibaraki Prefecture. According to JOGMEC, RMSP maintains stocks equivalent to 42 days of standard consumption (JOGMEC 2014a and 2014b). It is not clear which rare earth metals are stored at the RMSP facility but industry observers have maintained that Japan does stockpile rare earths. Based on

an estimated annual Japanese consumption of 30,000 tonnes (Maeda and Tsukimori 2011). 42 days of consumption would equal to about 3,450 tonnes.

The New Energy and Industrial Technology Development Organization (NEDO), the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), and the National Institute for Material Science are other government entities that are actively involved in funding research on REEs substitutes and demand mitigation. NEDO ran a one year $81.6 million program focused on rare earth demand reduction and substitute research. A longer term 8 year program, the Rare Metal Substitute Materials Development Project, due to expire in fiscal year 2015, has an estimated $66.5 million annual budget, specifically focusing on dysprosium, terbium, europium, and cerium substitutes in addition to indium, tungsten, and platinum group metals (NEDO 2012). Since 2001, the Japanese government has been running the National Institute for Materials Science (NIMS) which has a budget of $320 million and employs a staff of 1,500 (Halme et al. 2012). A REEs recycling center using collected consumer electronics in Tohoku is expected to be scaled to a national system in 2014 (Smart 2011).

In March 2013, researchers from Tokyo University and the Japan Agency for Marine-Earth Science and Technology confirmed a HREEs-concentrated deposit 5,700 meters below sea level near the island of Minami-Torishima. The estimated deposit is a sizable 6.8 million tonnes[44] and most critically, the deposit is within Japan's undisputed exclusive economic zone and is free of thorium which mitigates both political and extraction costs and risks (Currie 2013b). No information has been made public regarding future production timelines.

In the meantime, Japan's international outreach program has been extensive. Mitsubushi Corporation and Neo Material Technologies Inc. of Canada plan to undertake a joint venture for REEs production at the Brazilian Taboca Pitinga tin mine (Industrial Minerals 2009). In Asia, the Toyota Tsusho Corporation has also made arrangements for a processing facility in India's Orissa state with access to 4,500 tonnes (Walters, Lusty, and Hill 2011). Toyota is also in a joint venture with Sojitz Corporation and the Vietnamese government in Vietnam's Dong Pao project with upwards annual production capacity of 5,000 tonnes of REO (Kingsnorth and Chegwidden 2010).

In Australia, Sojitz Corporation, together with JOGMEC, secured an agreement whereby Lynas Corporation would provision 8,500 tonnes of REEs over a ten year period in exchange for a $250 million investment into Lynas's Mount Weld project. Separately, Northern Minerals of Australia agreed to ship 1,500 tonnes of future HREOs to Sumitomo Corporation from the Browns Range project (Proactive Investors 2013).

In Eurasia, Sumitomo, JOGMEC, and Kazatomprom of Kazakhstan are in a joint venture, the Summit Atom Rare Earth Co. (Sareco), to extract dysprosium from uranium mines in Kazakhstan at an annual rate of about 50 tonnes, or 10 percent of Japan's demand (Fukuyama 2012 and Suleymanov 2010). Sumitomo is also working with Mitsui to consider fast-tracking an investment in the Sakha deposit in Siberia, Russia (Russia Briefing 2011). Japan also signed an exploratory agreement with Mongolia in 2010 (AFP 2010).

[44] Based on Japan's 2011 consumption of 30,000 tonnes, this is equivalent to more than 220 years' equivalent, assuming constant consumption proportions of light and heavy rare earths.

The total Japanese private and public investments in the 2010 to 2012 period alone comes to nearly 20,000 tonnes of near-future non-Chinese REO access, nearly two-thirds of its 2011 demand volume.

South Korea

The execution of South Korea's mineral policy is delegated by the Ministry of Knowledge Economy to the Korea Resources Corporation (KORES), a government-owned enterprise. Formed as a public corporation, KORES is specifically mandated with securing raw materials for South Korea's resource-hungry manufacturing base. Valued at about $2 billion in 2010 and $667 million in capital, KORES seeks investment opportunities abroad for both fuel and non-fuel minerals (KORES 2014).

So far, South Korea's public strategy has focused on supply-side growth with little focus on substitution or recycling development. The exception might be research funded by the Korea Institute of Industrial Technology (KIIT) at the DoE's Ames Laboratory to see if rare earth metals can be extracted from scraps using molten extraction (Mick 2012). Otherwise, Seoul has been most actively supporting exploratory projects both at home and abroad. It commissioned exploratory studies for local sources of rare earths in Hongcheon and Chungju (Park 2011).

Looking abroad, KORES has signed an agreement with Frontier Rare Earths of Luxembourg, which owns a non-operational rare earth project in Zondkopsdrift, South Africa, to form a joint venture for a REEs separation facility (Humphries 2013). According to the agreement, South Korea may have access to upwards of 6,000 tonnes of REOs, which is nearly double its annual demand (Park 2011). KORES's initial 10 percent stake may increase to 50 percent (Frontier Rare Earths 2012). South Korea also signed rare earths exploration agreements with Kyrgyzstan, Uzbekistan, Vietnam, and Australia (Kosich 2011 and Commodity Online 2010).

KORES began stockpiling 60 days' worth of rare earth consumption in 2010 and is expected to complete the inventory by 2014. The inventory would grow from the original 62 tonnes in 2010 to 1,500 tonnes. Other critical metals will also be stored, including chrome, molybdenum, antimony, titanium, tungsten, niobium, and selenium (Park 2011 and Japan Metal Bulletin 2010). In the meantime, South Korean dependence on Chinese REEs decreased from more than 78 percent to 54 percent between 2011 and 2012, shifting instead to Japan to make up the balance (Currie 2013a).

Australia

Because the mining industry is a significant driver of Australia's economy, the Australian government has focused on maximizing production from its known mineral reserves while incentivizing further exploration and development of new deposits. As such, the policy objectives are to promote a favorable investment environment for mining while ensuring sustainable practices. As a result, Australia ranks highly in mining investment environment. Not only does it have the fastest processing time for mining permits, the Australia government permits tax deductions and rebates for costs incurred for exploration and permits rolling over losses/profits between years to decrease tax liabilities (Wyatt and McCurdy 2013). The primary government branch overseeing the mining sector is the Department of Resources, Energy, and Tourism (RET) and its subsidiary agency, Geosciences Australia. The Minerals Down Under National Research Flagship coordinates research and cooperation between the government agencies, the private sector, and the Commonwealth Scientific and Industrial Research Organization (Bauer et al. 2011).

Lynas Corporation, an Australian firm operating the Mount Weld deposit in Australia, was recently green-lit from the Malaysian government to build and operate a REE concentration plant and Advanced Materials Plant in Malaysia (Curtis 2012). Lynas has an agreement with German engineering giant Siemens to provide REEs for its wind turbine generators from Mount Weld (Humphries 2013). Alkane Resources is expected to begin production of yttrium at its Dubbo project in New South Wales at an annual rate of 6,500 tonnes of REO (Alkane Resources 2010). Arafura Resources is believed to begin production at its Nolans Bore project in Northern Territory at end of 2013 at an annual rate of 20,000 tonnes of REO (Arafura 2014a).

Canada

Like Australia, the mining industry plays an important role in Canada's economy. Mining policy planning is established at the federal level by Natural Resources Canada whereas regulatory responsibilities primarily fall on provincial authority. Despite fairly stringent mining and environmental regulations, the Canadian government's intentional focus on regulatory transparency and de-confliction, and the harmonization of jurisdictional responsibilities between the federal and provincial authorities have nonetheless yielded a favorable mining investment climate, ranking ninth in mining permit processing time (Bauer et al. 2011 and Wyatt and McCurdy 2013). Canada maintains a raw materials stockpile equivalent to a fraction (between 0.5 and 4 percent) of annual production for copper, gold, lead, molybdenum, nickel, silver, and zinc (Bauer et al. 2011).

Chapter Summary

The breadth and depth of China's dominance in the rare earths sector is the fruit of a decades-long effort. China's monopoly of rare earths is not merely in the upstream (mining extraction) segment but extends through the midstream (separation and processing) and downstream (manufacturing) segments as well. Today, the vast majority of rare earths are produced in China, purified in China, manufactured into integrated components in China, and increasingly consumed in China.

Despite lingering ambivalence regarding Beijing's desire or intention to use its rare earth advantage as a so-called geopolitical lever, the more immediate problem is China's heavy-handed mercantilist approach to meeting the rising rare earths demand. Rather than opening the productivity of its integrated rare earth supply chain to the global market, Beijing is intent on squirreling away rare earths for domestic consumption through export barriers (presumably for as long as it can within WTO parameters) and mass stockpiling.

This is problematic for American stakeholders because in the wake of China's strenuous consolidation lies the diminished rare earth supply chain capacities of the U.S. and others. No longer is the U.S. merely dependent on China for ores, but it has also become wholly dependent on downstream products. What is more, China is a reluctant supplier and regularly intervenes in the sector to favor Chinese producers and consumers.

The fundamental puzzle for the U.S. policy maker is this: how can the U.S. establish a reliable supply of rare earths when China, the rare earths monopolist by way of shrewd but unfair practices, is reluctant to

trade them? Before proceeding further, however, two important questions must be answered. First, what are rare earths used for that makes them so important? Secondly, if Chinese reserves are 38 percent of the world, why not mine the remaining 62 percent outside of China? These critical questions are answered next in Chapters 3 and 4. Once the importance of rare earths applications are established and the technical challenges of rare earth production are understood in the next two chapters, Chapter 6 will begin to assess what policy options the U.S. policy maker has to reduce American vulnerability to supply disruptions using one heavy rare earth, dysprosium, as an example.

Chapter 3 – Applications and Geological Properties of Rare Earth Elements

"Rare earths have been called the vitamins of industry. They take applications like wind turbines and improve the technology because of their special properties."
– Eric J. Schelter

Introduction

Chapter 2 discussed how China's geological endowment and its strategic policies over the last thirty years have enabled the country to consolidate much of the world's rare earth supply chain in its borders. This chapter explains in greater detail why rare earths are so highly sought after (the applications) and the reason behind their so-called rarity (their physical properties). The following three topics are covered: what applications of rare earths make them so important; what physical properties give rare earths such unique characteristics and why they are so "rare"; and lastly, what the extract and purification (processing) steps for rare earths are.

This exercise serves two purposes. First, they provide a stronger sense of the underlying technical rationale and terminology that are foundational for the following chapters, particularly in Chapter 4's discussion on dysprosium supply and demand projections and Chapter 6's discussion on policy options. Secondly, the technical overview in this chapter gives the reader stronger a sense of why rare earths are valuable and helps resolve the paradoxical notion that rare earths are geologically plentiful yet commercially scarce.

Rare earths used in many industrial applications, whether they be mature industries or cutting edge.[45] Rare earths are typically used as additives in a mix of other materials to help products achieve superior and often superlative performances (e.g., stronger or strongest magnetism, clearer or clearest LED screens, etc.). While the focus of the rest of this research is on one specific element, dysprosium, this chapter conducts an inclusive overview of the applications and properties of other elements because these macro dynamics have a direct bearing on dysprosium as well.

Although rare earths are similar enough in characteristics to be grouped as what are known as lanthanides in the periodic table, their individual compositions are nonetheless sufficiently unique enough to necessitate their separation through expensive and potentially costly chemical processing techniques. The distinction between light rare earths and heavy rare earths originates from differences in the pairing of electrons in the outer most shells. These subtle differences in chemical properties directly translate to geological distributions whereby light rare earths are typically more abundant and easier to extract than heavies which are less abundant and more expensive to extract.

LREEs are fairly abundant and are used in both mature and fast-growth applications. Those elements that are classified as HREEs are much rarer and more expensive and are highly sought after in the fast growing applications. China's southern mines have a proportionally higher ratio of heavy rare earths than are typical. Furthermore, Chinese HREEs are found in ion-adsorption deposits which are the easiest types of deposits to extract rare earths from. These advantages give Chinese miners a significant competitive advantage over producers elsewhere in the world. It is not so much that rare earths are found exclusively in China. But China is uniquely able to extract them at below average costs against which non-Chinese producers cannot easily compete.

[45] Mature applications include uses in fossil fuel catalysts, metallurgy, glass polishing and additives, and phosphors. Fast growth applications include batteries, permanent magnets, defense technologies, and ceramics.

Rare Earth Applications

So-called the "vitamins" of modern industry because of their superlative qualities that significantly improve performance and capacities in manufactured applications, REEs have wide applications in the modern industry and are expected to be in high demand in the coming decades (Hurst 2010a). Koen Binnemans, a rare earth specialist at the University of Leuven in Belgium describes rare earths as, "the pepper and salt in many new technological applications. There are few applications where no other elements can do the job" (Free 2014). More specific to dysprosium, this element has two important properties that make it valuable to modern industry. First, dysprosium is paramagnetic, meaning their magnetism is active only in the presence of an external magnetic field. Second, dysprosium also has strong magnetic anisotropy, meaning its magnetism is easily aligned in one direction while resisting magnetism in the opposite direction (Walters, Lusty, and Hill 2011). These unique properties make dysprosium a critical component in both mature applications and cutting-edge technology.

Commercial usage of REEs forms the bulk of REEs demand. Their primary applications are in the form of catalysts, magnets, metallurgical alloys, phosphors, glass and polishing, ceramics, and defense. Mature industry sectors—defined as those that grow at the rate of the general economy (4 percent or less annual growth)—globally consumed about 60 percent of REEs by volume, primarily for application in catalysts, glass, lighting, and metallurgy. The remaining 40 percent of consumption was used in developing (fast-growth) industry applications (i.e., industries with growth rates higher than the general economic growth rate or greater than 4 percent annual growth), such as use for battery alloys, ceramics, magnets (Bade 2010).

Both mature and developing industry sectors are dependent on light rare earths (the physical properties that distinguish light and heavy rare earths are explicated much greater technical detail in the next section). According to data synthesized by Goonan (2011) on global trends (Table 3.1), LREEs comprised nearly the entire demand for three of four mature industry sectors (catalyst, non-battery metallurgy, and glasses). Phosphors were the only mature sector that was heavily dependent on HREEs, mostly in the form of yttrium. Developing industry sectors (battery alloys, magnets, ceramics, and defense) are also heavy consumers of LREEs but they have a greater reliance than on HREEs than the mature sectors, with exception to phosphors.

Taking a close look at the individual elemental level, some elements are more important to the mature industries than the developing industry and vice versa. For example, the LREEs lanthanum and cerium and HREEs europium, terbium, and others minor HREEs[46] are used in high proportions in mature industries. In contrast, the LREEs praseodymium and neodymium and HREEs samarium, gadolinium, and dysprosium are used almost exclusively by the developing sectors. Yttrium is the one exceptional element that is utilized near parity by both industry sectors (Table 3.2). An explanation of the industry sectors, subsectors, and their use of REEs are as follows.

[46] Holmium, erbium, thulium, ytterbium, lutetium, scandium, and promethium.

TABLE 3.1 – LREES AND HREES CONSUMPTION BY INDUSTRY SECTOR

	Mature Market Sectors %				Developing Market Sectors %			
	Catalysts	Metallurgy (Non-Battery)	Glasses Polishings & Additives	Phosphors	Battery Alloys	Magnets	Defense	Ceramics
LREE	100	100	97	20	97	93	77	47
HREE	0	0	3	80	3	7	23	53

Data: Modified from Goonan (2011)

TABLE 3.2 – INDIVIDUAL REE CONSUMPTION PERCENTAGE BY INDUSTRY SECTOR/SUBSECTOR

	Industry	LREEs %				HREEs, Pm, Sc %						
		La	Ce	Pr	Nd	Sm	Eu	Gd	Y	Tb	Dy	Ho, Er, Tm, Yb, Lu, Pm, Sc
Mature Sector	Catalysts	47	21	2	1	0	0	0	0	0	0	0
	Metallurgy (Non-Battery)	8	14	7	8	0	0	0	0	0	0	0
	Glass Polishing & Additives	20	44	8	2	0	0	0	2	0	0	86
	Phosphors	2	2	0	0	0	100	21	54	73	0	0
	Mature Sector %	**78**	**82**	**17**	**10**	**0**	**100**	**21**	**56**	**73**	**0**	**86**
Developing Sector	Battery Alloys	16	10	5	5	73	0	0	0	0	0	0
	Magnets	0	0	70	76	0	0	69	0	27	100	0
	Defense	4	7	3	5	27	0	10	12	0	0	14
	Ceramics	3	2	5	4	0	0	0	32	0	0	0
	Developing Sector %	**22**	**18**	**83**	**90**	**100**	**0**	**79**	**44**	**27**	**100**	**14**

Data: Goonan (2011)

Major Applications of REEs

Catalysts

There are two applications of REEs in catalysts: fluid cracking catalyst (FCC) used in petroleum refining and automobile catalytic convertors. The fluid cracking process converts heavier crude oils to lighter commercial gasoline and derivatives whereas the automobile catalytic converters are used to reduce emission of pollutants through the exhaust. In both cases, REOs are important secondary elements. In fluid cracking, REOs –primarily lanthanum and cerium—restock ions in the main catalytic element, zeolite. This role helps increase gasoline yields and reduces emissions when processing oil (Bauer et al. 2011). As explained by the DoE,

> The FCC process breaks apart or cracks heavy input streams into primarily gasoline and diesel fuel, but also light hydrocarbon gases, heavy oil, and coke. The heavy crude oil material entering the FCC unit…is heated to about 1,000°F, at which it becomes a gas and flows up a specially designed pip (called a riser) along with a catalyst that helps to break apart the heavy molecules (Bauer et al. 2011).

REOs are used as protective coatings for the actual catalysts, generally palladium and platinum, in automobile catalytic converters. FCC usage comprised 72 percent of REO used with automobile catalytic converters comprising the balance (Goonan 2011).

Glass

REEs are used in glasses for "absorbing ultraviolet light, altering the refractive index, and colorizing or decolorizing. Yttrium is used with garnet to form yttrium-aluminum-garnet (YAG) lasers. Neodymium and other REEs are used as dopants to alter the properties of the YAG lasers" (Goonan, 2011). REEs are also used as glass polishing compounds for making ultra-polished glass surfaces such as in plasma and liquid crystal display (LCD) monitors and wafers for silicon chip production (Tasman Metals Ltd. n.d. and Hatch 2011).

Metallurgy (Non-Battery)

The oldest and most common use of REEs has been in the form of processed alloy known as mischmetal, a pure REO with the same proportional mix of REEs as found naturally on bastnäsite minerals. Because of pyrophoric property, mischmetal has been used as flint in lighters (Walters, Lusty, and Hill 2011). Trace amounts of REEs are alloyed with other metals such as steel, aluminum, and cobalt to (Goonan 2011 and Molycorp 2011) which are then applied in galfan for submarine sonar systems, magnetic refrigeration, and high-impact steel (Lynas 2012). REEs used in metallurgical alloys help prevent cracking and resistance to oxidation (Walters, Lusty, and Hill 2011).

Phosphors

REEs are used in phosphor production in the lighting industry. Energy efficient lighting such as compact fluorescent lamps (CFL) and white light-emitting diode (LED) lights require phosphors. CFLs consume only 25 to 30 percent of traditional incandescent light bulbs while LEDs—which are increasingly used by globally to reduce energy consumption—are not only more efficient than CFLs but also longer lasting (Tasman Metals Ltd. n.d.).

Ceramics

REEs strengthen ceramic structure by enabling higher quality sintering processes. REEs are also used for specialized ceramic functions such as non-conducting microwave material, piezoelectric ceramics that produce electricity if physical pressure is applied, and for use in semiconductor ceramics (Guanming et al. 2007). REEs are crucial for the performance of ceramic capacitors in electronic circuits. The ceramic capacitors are doped with REEs that increase their operational utility and life (Alam, Zuga, and Pecht 2012). REEs are also used for ceramic colorization and in ceramic scintillators[47] with applications in the medical diagnosis and radiography, and industrial inspection (Greskovich and Duclos 1997). A research team at the Massachusetts Institute of Technology (MIT) has found that REE-laced ceramics retain water-resistant (hydrophobic) properties even under excessive abrasion and heat—properties that are extremely useful for longevity and durability of electronic components (Azimi et al. 2012).

Magnets

REEs enable superior magnetic properties, i.e., stronger and more resilient under varying conditions, which make them valuable in electric motors as small as those found in computing hard drives to larger ones used in electric vehicles, and even larger ones used in wind turbine generators. NdFeB magnets are one of several "permanent magnets," so-called because they are the strongest magnets available (InvestorIntel 2014). NdFeB magnets are powerful enough that they are being research for application in nanotechnologies (Hurst 2010a). They are resistant to demagnetization when other magnetic fields are

[47] Scintillators emit light when the material absorbs or hit by charged particles or high-energy photons. For more information go to: http://imagine.gsfc.nasa.gov/docs/science/how_l2/gamma_scintillators.html.

present and also highly resistant to heat (Hatch 2011). These properties enable miniaturization of high capacity motors. Industrial and consumer products that rely on REE magnets for optimal performance include actuators, audio equipment, Magnetic Resonance Imaging devices (MRI), anti-lock brake systems and other automotive parts, communications systems, propulsion systems, frictionless bearings, storage disks, and magnetostrictive alloys (ferromagnets that change shape or dimensions with magnetization) (Goonan 2011 and Tasman Metals Ltd. n.d.).

Because greater magnets generate more electric current in wind generators, NdFeB magnets are highly favored over its alternatives. Furthermore, REE-based magnets in air conditioning units can decrease power consumption by up to 50 percent (Walters, Lusty, and Hill 2011). By one count, there are more than 100 different applications of REEs-bearing permanent elements in a conventional passenger vehicle (Reddall and Gordon 2012). A single automobile may use more than 50 motors for use in steering, seat adjustments, transmission fluid, braking, for example, each of which use traces of REE that make motors more powerful and energy efficient compared to induction motors (Spindell 2013).

Battery Alloys

REEs are used primarily in Nickel Metal Hydride Batteries (NiMH) used in portable batteries in personal electronics and power tools, but most prevalently in hybrid vehicles (Lynas 2012). In particular, lanthanum plays the crucial that enables both the absorption of hydrogen in the cells for energy storage as well as the reverse process that make recharges possible (Hatch 2011).

Defense

Because of their utility in advanced weapons programs, the use and existence of REEs were a national secret in the USSR and was not disclosed until 1993 (Hurst 2010a). Today, REEs continue to have a variety of applications in weapons guidance and control, aircraft materials, lasers, optics and sensors (including sonar transducers that convert electric to sound energy and back), communications/satellite system (Goonan 2011 and Walters, Lusty, and Hill 2011). REEs are used for manufacture of fiber optics where they help data transmission without the use of signal booster stations (Walters, Lusty, and Hill 2011). Other examples of major weapons systems that use REEs include the F-35 Joint Strike Fighter, Global Hawk UAV, defense satellite systems, M1A1 Abrams, and advanced munitions such as the JDAM and Javelin Missile (Greens 2011). Permanent magnets (SmCo but more preferably the NdFeB variants) are used for guiding "smart" ammunitions (Hurst 2010a). NdFeB magnets in conjunction with Terfenol-D speakers are used by "stealth" helicopters to mask the sound of helicopter blades (EWI 2011). Table 3.3 lists the various rare earths and their technological applications in U.S. military systems. Appendix A lists additional examples of defense systems that depend on rare earths.

Other

Gadolinium and europium are used as neutron absorbers while the former is also used as reactor temperature stability agents in the nuclear industry. Cerium and yttrium are often used for pigmentation for consumer products such as paint and sunglasses. REE-based lasers are used for cosmetic, epidermal, and dental procedures. China has also been known to use REEs in fertilizers (Walters, Lusty, and Hill 2011). Molycorp has successfully commercialized a water treatment technology that reduces phosphates that can prevent algae growth (Molycorp 2013a). Today, scandium is produced in only small quantities for research purposes (Thijssen 2011).

TABLE 3.3 – EXAMPLES OF RARE EARTH APPLICATIONS IN U.S. MILITARY SYSTEMS

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

Data: Grasso (2013)

New Applications of REEs

New consumer applications of REEs are on the horizon although not yet ready for commercialization. Gadolinium and neodymium have been identified as plausible magnetic refrigerants whereby household and industrial refrigeration can be achieved by lowering the magnetic field (Walters, Lusty, and Hill 2011). This novel method could potentially reduce up to 15 percent of fossil fuel consumption while minimizing or eliminating the use of hazardous chemicals (Kennedy 2010).

High efficiency fuel cells also exploit REEs properties. Electrolytes synthesized from lanthanum, cerium, and praseodymium carbonates could be used to form solid oxide fuel cells (SOFCs) that produce electricity by oxidizing the fuel elements. The SOFC design is highly promising because they produce electricity with high efficiency but with minimal carbon footprint (Zhu et al. 2008). At least one company, Bloom Energy, has successfully commercialized SOFCs for use in on-site distributed power generation servers (Bloom Energy 2014). REE-based metal-free catalysts for electric (zero emission) automobiles are also a possibility (Hu and Noreus 2003).

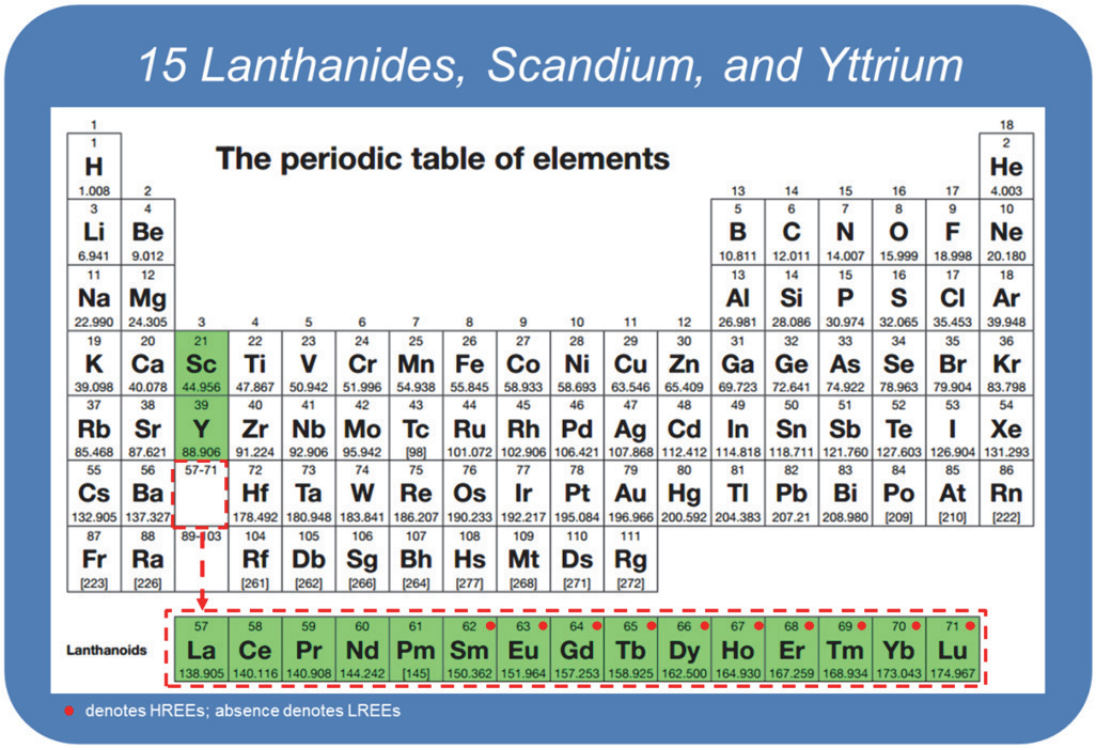
Rare Earth Properties

This next section provides a technical overview of the properties of rare earths. It broadly explores the chemical similarities and differences that translate to the distinction of light and heavy rare earths and the mineralogy of rare earths that dictate how easy or difficult it is to mine them. To start, rare earths are a group of 17 elements on the periodic table that share similar chemical properties. They comprise the 15 lanthanides group of elements (atomic numbers 57 to 71) plus scandium (21) and yttrium (39) (Figure

3.1). Despite their names, REEs are not necessarily rare, geologically speaking, although the yield can range widely for each element in a given geological terrain. "Rare earth elements are not particularly rare in terms of abundance, but for many years remained rarely separated from each other owing to their similar chemical characteristics" (Hurst 2010b and Goonan 2011).

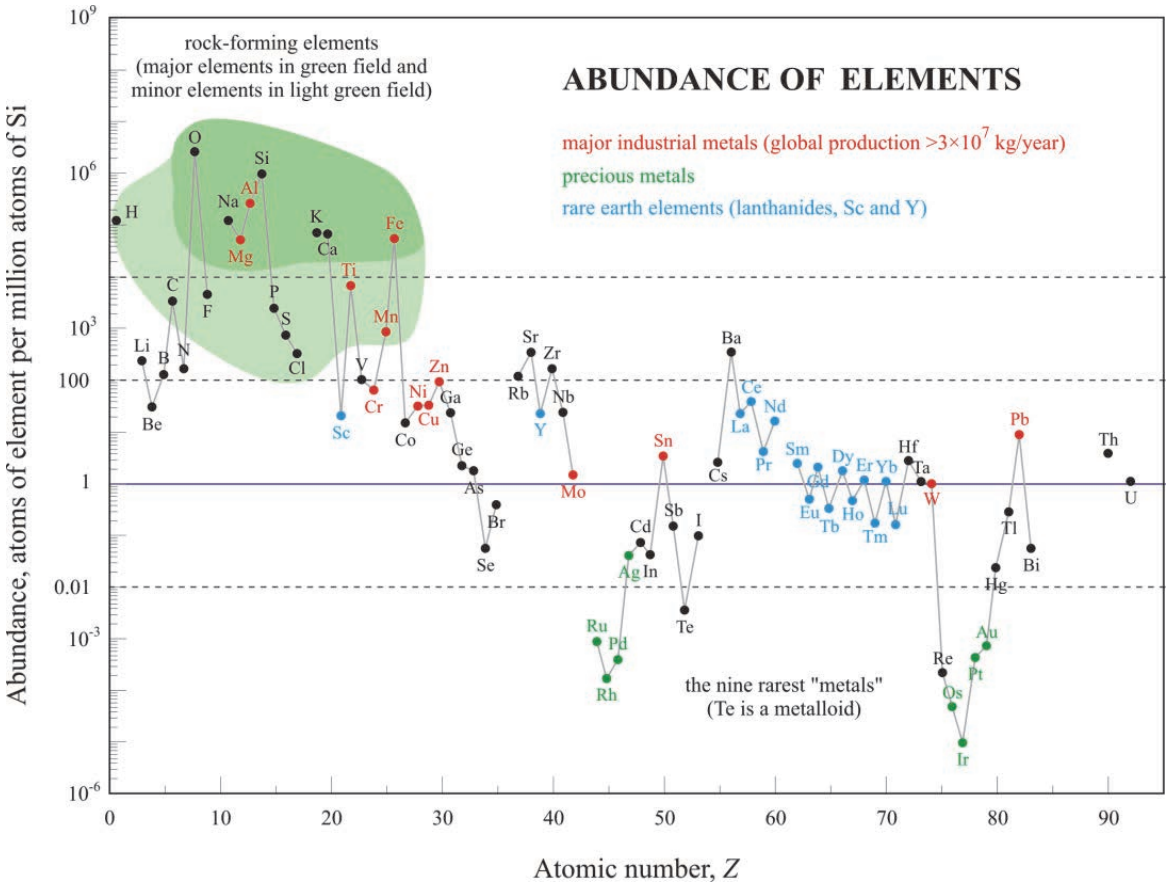
For example, REEs have an overall crustal abundance of 9.2 parts-per-million (ppm), but the most abundant, cerium, is 43 ppm whereas the most rare, thulium, is 0.28 ppm. Contrast this with common metals such as copper's 27 ppm and lead's 11ppm (Taylor and McLennan1985 and Rudnick et al. 2005). Instead the "rarity" of REEs originates from the fact that the lanthanides are exceedingly difficult to separate chemically, making it costly—thus rare—to refine pure metals (Walters, Lusty, and Hill 2011). Figure 3.2 from the U.S. Geological Survey (USGS) shows that the rare earth elements are generally more abundant than many of precious metals (gold, silver rhenium, ruthenium, platinum, palladium, osmium, and iridium).

FIGURE 3.1 – RARE EARTH ELEMENTS



Source: Modified from Hatch (2011)

FIGURE 3.2 – RARE EARTHS ARE NOT NECESSARILY RARE



Source: USGS (2005c)

Light and Heavy Rare Earth Elements

Rare earths are generally classified as either a light rare earth or heavy rare earth based on their atomic weights, with LREEs having lower atomic weights and the HREEs having higher weights. A technical definition of LREEs is that their 4f electron shells[48] are unpaired compared to the paired ones in HREEs.[49] Based on this understanding, LREEs comprise scandium, lanthanum, cerium, praseodymium, neodymium, promethium[50], samarium, europium, and gadolinium. HREEs comprise the remainder: terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, and yttrium (Bleiwas and Gambogi 2013). The Canadian government's National Instrument 43-101 (NI 43-101) and the Australasian Joint Ores Reserves Committee (JORC) classify LREEs and HREEs in similar manner. A technical explanation of the distinction between light and heavy REEs is as follows:

[48] Electron shells are the orbits along which the electrons circle the atomic nucleus. Each shell can carry only a certain range of electrons and each shell needs to be filled before the outer layers are occupied. The shells are identified by its electron shell configuration. In this case, the number 4 in 4f refers to the fourth energy level and the letter f is the sub-shell.

[49] LREEs are described as "unpaired" because they have clockwise electrons but no counter-clockwise electrons. In contrast, HREEs have both clockwise and counter-clockwise electrons, but in different numbers. For each HREE (except lutetium), there are both "unpaired" and "paired" electrons.

[50] Radioactive element (Walters, Lusty, and Hill 2011). Promethium was the last of the REEs discovered and occurs naturally in minute trace amounts. According to one estimate, natural occurrence of promethium on the earth's crust is not greater than 600 grams (see Belli et al. 2007).

> The LREE are defined as lanthanum (Z=57) through gadolinium (Z=64). This is based on the fact that starting with lanthanum, which has no 4f electrons, clockwise spinning electron are added for each lanthanide until gadolinium. Gadolinium has seven clockwise spinning 4f electrons, which creates a very stable, half-filled electron shell. The LREE also have in common increasing unpaired electrons, from 0 to 7. The HREE are defined as terbium (Z=65) through lutetium (Z=71) and also yttrium (Z=39). This is based on the fact that starting with terbium, counter-clockwise spinning electrons are added for each lanthanide until lutetium. All of the HREE therefore differ from the first eight lanthanides in that they have paired electrons. All of the lanthanides have from 0 to 7 unpaired electrons. The defining split at the LREE gadolinium, which has both a stable half-filled 4f shell and 7 unpaired electrons, the following HREE, beginning with terbium, have decreasing unpaired electrons. Terbium has 6 unpaired electrons with the addition of one counter-clockwise electron which creates one electron pair. The number of unpaired electrons then decreases through lutetium, which has no unpaired electrons and a full stable 4f shell with 14 electrons and 7 "paired up" electrons. Yttrium is included in the HREE group based on its similar ionic radius and similar chemical properties. In its trivalent state, which is similar to the other REE, yttrium has an ionic radium of 90 picometers, while holmium has a trivalent ionic radius of 90.1 picometers. Scandium is also trivalent, however, its other properties are not similar enough to classify it as either a LREE or HREE (as cited in Bade 2010).

In contrast, the British Geological Survey (BGS) groups LREEs and HREEs differently, whereby gadolinium is classified as an HREE rather than an LREE (Walters, Lusty, and Hill 2011). Because the division between light and heavy, particularly for those REEs straddling the cutoff point, can be contentious and arbitrary, others further classify REEs into a third category, the so-called medium REEs (MREEs) which include the four mid-weight elements europium, gadolinium, terbium, and dysprosium (Samson and Wood 2004).

The colloquial industry classification differs further in due consideration to the practical economic valuation of the REEs rather the underlying technical properties that undergird the distinction. Industry literature typically defines LREEs to include lanthanum, cerium, praseodymium, neodymium and HREEs to include the elements with atomic numbers 62 to 71 (samarium to lutetium) and yttrium (Hatch 2011). Promethium, an LREE, is also not included among REEs in industry literature because they are not a naturally occurring element that can be extracted through mining but is rather synthetically produced for commercial use as a byproduct of high-yield uranium processing (Knapp et al. 2007). As such, promethium is not part of the conventional REEs mineral extraction supply and demand supply chain and commonly excluded from market analysis. In addition, because scandium is seldom found with other REEs, either light or heavy, it is also excluded altogether. As a result, the REEs listed in industry literature refer to the select 15 elements with a longer list of HREEs (Hatch 2011). Table 3.4 differentiates the various classifications of REEs, LREEs, and HREEs. This research adheres to the industry classification of the light and heavy REEs.

TABLE 3.4 – REE AND HREE CLASSIFICATIONS

Rare Earth Elements		Colloquial Industry Reference	British Geological Survey (BGS)	U.S. Geological Survey (USGS), NI 43-101, JORC
Scandium	Sc		LREEs	LREEs
Lanthanum	La	LREEs		
Cerium	Ce			
Praseodymium	Pr			
Neodymium	Nd			
Promethium	Pm			
Samarium	Sm	HREEs	HREEs	HREEs
Europium	Eu			
Gadolinium	Gd			
Terbium	Tb			
Dysprosium	Dy			
Holmium	Ho			
Erbium	Er			
Thulium	Tm			
Ytterbium	Yb			
Lutetium	Lu			
Yttrium	Y			

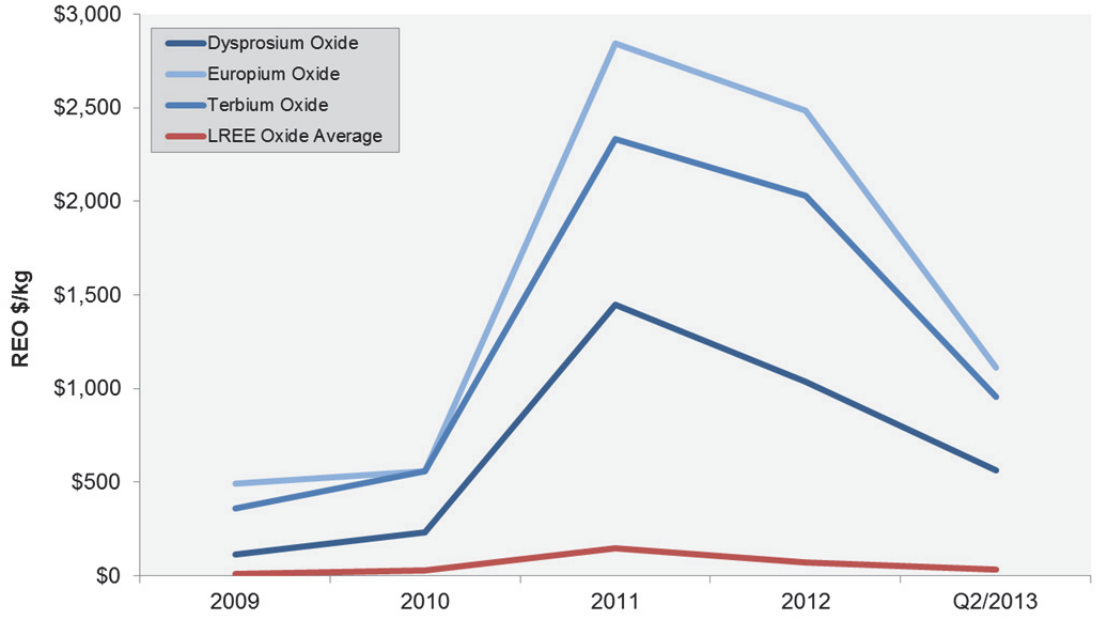
Note: This research adopts the colloquial industr terms in reference to the light and heavy rare earths.

Data: Hatch (2011); Walters, Lusty, and Hill (2011); Bleiwas and Gambogi (2013); and Bade (2010)

The chemical properties have important implications for the distribution and abundance of REEs. First, compared to HREEs, LREEs are found in greater *concentration* because their larger ionic radii keep them separated from other elements. Secondly, by the Oddo-Harkins effects, REEs with even atomic numbers are generally in greater *abundance* than odd-numbered elements. Thirdly, the chemical similarity of the elements results in *multiple* rare earths elements in a given mineral sample and therefore, a broad distribution in the Earth's crust. Finally, elements with higher atomic numbers generally—with a few exceptions—have increasing melting points. For example, the lightest REE, cerium, has a melting point of 798°C whereas lutetium, the heaviest REE, has a melting point more than twice as high at 1663°C (Walters, Lusty, and Hill 2011)

Cumulatively, these characteristics have direct commercial implications. The relative scarcity of heavy rare earths (which includes dysprosium, the element of primary interest of this research) over the lighter variety partially explain the price disparity between the two groups as depicted in Figure 3.3. In recent years, dysprosium oxide prices have been approximately 1,200 percent of light rare earth oxides, while europium and terbium have been around 3,170 percent and 2,600 percent, respectively. The large price differential between heavy and light rare earths is also a reflection of the differing melting points which have a direct impact on feasibility and cost of the refining (purification) process. Higher melting points generally require additional rare earths chemical processing steps which translate to additional costs (Walters, Lusty, and Hill 2011 and Ames Laboratory n.d.). Thus, not only are the heavy rare earths actually rare, they are also more expensive to process in the midstream stage. These two factors combined help to explain the price differential between the heavy and light rare earths.

FIGURE 3.3 – HEAVY RARE EARTHS COST SIGNIFICANTLY MORE THAN LIGHT RARE EARTHS[51]



Data: Lynas Corporation (2013)

Mineralogy

Rare earths are usually found embedded in three types of rock-forming minerals: bastnäsite, monazite, and xenotime.[52] Each formation contains different proportions of LREEs and HREEs: "The chemically similar nature (ionic radii and oxidation states) of the REE means they can substitute for one another in crystal structures. This results in the occurrence of multiple REE[s] within a single mineral and a broad distribution in the Earth's crust" (Walters, Lusty, and Hill 2011). Bastnäsites generally have high concentrations of LREEs, primarily cerium, lanthanum, and neodymium. Monazites contain less lanthanum, more neodymium, thorium (radioactive), and HREEs. Xenotime primarily contains HREEs, such as yttrium, dysprosium, erbium, ytterbium, and holmium (Walters, Lusty, and Hill 2011). In addition to these three most common REEs-bearing minerals, REEs are found in other mineral formations, a selection of which is found in Table 3.5. REE-bearing minerals are found in two major classifications of mineral deposits, classified as primary deposits and secondary deposits.

Primary Deposits

REEs in primary deposits are generally formed over millennia through magmatic consolidation and the rocks often have crystalline textures, the result of a geological process known as igneous. They are also formed through hydrothermal processes, or the formation through the circulation of hot water through the Earth's crust, which is often, but not always, associated with magma flow. One subcategory of igneous rocks is carbonatites which are comprised of at least half of carbonate minerals. When REEs are present in carbonatite igneous rocks, they are almost exclusively LREEs embedded in bastnäsite, allanite, apatite, and monazite. Prominent examples of carbonatite igneous deposits include the Mountain Pass deposit

[51] Dysprosium, europium, and terbium are HREEs. LREEs price average of lanthanum, cerium, neodymium, praseodymium, and samarium oxides. Prices reflect average Free on Board (FOB).
[52] REEs can be found in around 200 different minerals, but the vast majority is found in bastnäsite, monazite, and xenotime.

(California, USA), the Bayan Obo deposit (Inner Mongolia, China), western Sichuan in China, deposits in Kangankunde, Chilwa Island, Songwe, and Tundulu (Chilwa Alkaline Province, Malawi), Okorusu (Namibia), Amba Dongar (India), and Barra do Itapirapua (Brazil) (Walters, Lusty, and Hill 2011).

The second subcategory of igneous rock is alkaline igneous rocks formed from magmatic materials. In particular, perlakaline igneous rocks typically contain low grades of yttrium and other HREEs (Castor and Hedrick 2006).[53] Example of perlakaline igneous rock depsosits include Khibina and Lovozero (Russia), Strange Lake and Thor Lake (Canada), Tamazeght (Morocco), Pilanesberg (South Africa), and Weishan (Shangdong, China) (Walters, Lusty, and Hill 2011).

A third subcategory of primary deposits is non-alkaline igneous iron-REE deposits which often have low grades. Examples are Olympic Dam (Australia), Pea Ridge (Missouri, USA), Kiruna (Sweden), and Bayan Obo (Inner Mongolia, China). A final subcategory of primary deposits contains REEs in only the rarest instances and are found in Rock Canyon Creek (British Columbia, Canada), Hoidas Lake (Saskatchewan, Canada), Snowbird (Montana, USA), Lemhi Pass (Idaho/Montana, USA), and Mary Kathleen (Australia) (Walters, Lusty, and Hill 2011).

Secondary Deposits

In contrast to primary deposits, REEs in secondary deposits are generally formed either through the collection of sediments over time (sedimentary process) or through rocks transformed by temperature and pressure within the Earth's crust (metamorphic processes). Two major types of secondary deposits exist: marine/alluvial placer deposits and residual weathering (lateritic) deposits. Placer deposits are formed through accumulation of heavy minerals transported along river waterways or carried by tides and currents to coasts. As such, placer deposits are generally found on or near coastlines, with monazites being the most common REE-bearing mineral found in them (Walters, Lusty, and Hill 2011). According to one estimate by the USGS, there are an estimated 360 placer deposits with REEs (Orris and Grauch 2002).

There are two major drawbacks to placer deposits for rare earth mining, however. First, monazites are often found in tandem with high concentrations of radioactive thorium, which significantly increases the extraction cost and complexity (Castor and Hedrick 2006). Secondly, placer deposits generally have very low concentration of REE-bearing monazite, comprising no more than 0.1 percent of deposit contents. Exceptions are some Australian placer deposits with up to 1 percent monazite and Indian deposits with 1-2 percent monazite concentrations (Möller1986).[54]

Residual weathering deposits are formed from the accumulation of mineral residues from exposure to the weather. For example, some combination of the disintegration of larger rock formations, leaching of elements, and enrichment of sedentary elements through absorption tend to yield the highest level of rare earth oxides (REOs)[55], especially if an enriched rock is chemically weathered and breaks down into REE-heavy minerals such as calcite, dolomite, and apatite. Examples of residual weathering deposits are the Mount Weld deposit in Australia which has phosphate minerals with REO contents as high as 40 percent and Brazil's Araxa deposit (Lottermoser 1990; Pirajno 2009; and Castor and Hedrick 2006).

[53] Peralkaline igneous rocks are also rich in what are known as high-field strength elements (HFSE) such as zirconium, titanium, yttrium, and niobium.
[54] See Walters, Lusty, and Hill (2011) for details on placer deposits and yield in Australia, Malaysia, Canada, and the U.S. states of Florida, Carolinas, and Idaho.
[55] REOs are rare earth elements purified to at least 99 percent purity. Higher purity commands greater market value.

A recently classified subcategory of residual weathering deposits are ion-adsorption clays (also known as weathered-crust elution-deposited rare earth ore) which are weathered granites enriched with REEs (Chi and Tian 2008). Although weathered granites deposits are small and very low yields of REE content, typically between 0.03-0.35 percent, they tend to have high HREEs distributions and minimal radioactive co-elements which make them highly valuable and economical. Ion-adsorption clays are found in abundance in the southern China provinces of Jiangxi, Guangdon, Hunan, and Fujian (Grauch and Mariano 2008 and Chi and Tian 2008).

Phosphorite and Deep-Sea Mud Deposits

Less researched are phosphorities which are sedimentary rocks with high phosphate and REE content. Potential deposits are believed to exist in the southeastern U.S., from North Carolina extending south to central Florida. The distribution of REEs is unknown except for the existence of yttrium and lanthanum (Long et al. 2010). Phosphorites deposits are also found in southwestern China in the provinces of Zhijin, Hinhua, and Guizhuo (Jie et al. 2006). Another potential source of REEs, one that is abundant but is even less researched than phosphorites, are deep-sea muds on the Pacific seafloor. According samplings, REE content from the South Pacific yielded between 1,000 and 2,230 ppm of REEs, of which 200-430 ppm were HREEs. North Pacific samples were less concentrated but still significant, with REE contents of 400 to 1,000 ppm (Walters, Lusty, and Hill 2011).

TABLE 3.5 – RARE EARTHS-BEARING MINERALS

Mineral	Approximate REO%
Aeschynite-(Ce)	32
Allanite-(Ce)	38
Apatite	19
Bastnäsite-(Ce)	75
Brannerite	9
Britholite-(Ce)	32
Eudialyte	9
Euxenite-(Y)	24
Fergusonite-(Ce)	53
Gadolinite-(Ce)	60
Kainosite-(Y)	38
Loparite	30
Monazite-(Ce)	65
Parisite-(Ce)	61
Xenotime	61
Yttrocerite	53
Huanghoite-(Ce)	39
Cebaite-(Ce)	32
Florencite-(Ce)	32
Synchysite-(Ce)	51
Samarskite-(Y)	24
Knopite	NA

Source: Walters, Lusty, and Hill (2011)

Rare Earth Mining and Processing

An appreciation of the substantial costs and risk associated with rare earth mining and processing explains why rare earths are rare. It is not necessarily the geological paucity but rather the high financial risk and technical finesse to extract and purify these elements that make rare earths so valuable. This section discusses the three typical phases that lead to the successful development of a rare earths mine. It then discusses the steps for separating and processing rare earths into highly purified individual elements.

Mining

With high risks, much higher production costs, and a much smaller market size (a few billion dollars for rare earths compared to major minerals' trillion dollars), major mining companies find rare earths to be a low value proposition (Hayes-Labruto et al. 2013). Filling in the vacuum for rare earths production investment are so-called junior miners (high risk mining venture capital firms) that identify, survey, and certify promising deposits which are then sold to investors who assume capital developments.

The few times major mining firms do produce rare earths are when rare earth ores must necessarily be extracted as a by-product of mining for other minerals. REEs are often the result of "coupled production" of primary metals. Coupled production occurs when certain elements are necessarily produced alongside the desired principal element. Examples include Bayan Obo where REEs production is a coupled product of its massive iron ore extraction operation. The most significant exceptions are the Mountain Pass and Mount Weld projects in the U.S. and Australia, respectively. When REEs are mined, either as a primary production or as necessary by-products, one of four extraction methods is applied. Which technique is used depends on the type of deposit the elements are borne in. Table 3.6 describes the different types of extraction methods.[56]

TABLE 3.6 – REES EXTRACTION METHODS

Extraction Method	Deposit	Description	Example
Open-pit mining	Deposits which are relatively shallow, not more than 100 meters deep from the surface. Hardened rock formation deposits or soft placer deposits.	Digging or use of explosives to reach deposit and then physically moving the ores via truck or conveyer belt for stockpiling or immediate processing. Extraction from dry land-based placer deposits requires little effort other than to collect the sand in bulk and transporting them for processing. Some open-pit mines are combined with underground mines.	Bayan Obo (China), Mountain Pass (USA), Mount Weld (Australia)
Dredge mining	Submerged placer deposits	Floatation vessels with buckets or a suction device to extract REEs-bearing sand for processing.	India
In-situ mining	Ion-adsorption deposits	Developed by China's Jiangxi South Rare Earth Hi-Tech, ammonium sulphate is leached into drilled holes in deposits. This reagent collect	Longnan (China), common in

[56] Coproduction also poses challenges to production planning. As HREEs become more valuable than LREEs, the latter is increasingly considered a by-product of the former's extraction which has led to abundance of cerium and lanthanum. The inability to entirely control production rates plays an important role in the price gulf between LREEs and HREEs. Coupled production is distinct from by-production where production of different elements within a deposit can be controlled according to market conditions. Examples include zinc by-production with indium and germanium and bauxite by-production with gallium (Wellmer and Dalheimer 2012).

		REEs as it travels through the cavity, is collected at the bottom into a tank where it is precipitated using ammonium carbonate, leaving behind REEs. This process is a more environmentally-friendly method than a previous method where heaps of ores were leached en masse.	deposits found in Southern China
Underground mining	Deep and hard formation deposits	Through labor-intensive drilling and explosive blasting, multi-storied horizontal cavities are carved to extract ore which are transported by rail up to the surface. Not unlike traditional coal mining techniques. Some open-pit mines are combined with underground mines.	Elliot Lake (Canada), Lovozero (Russia)

Source: Walters, Lusty, and Hill (2011)

Mining exploration costs can be expensive with frustratingly low success rates. According to one study, the odds that a project with inferred minerals would move to production stage ranges from 1.25 to 10 percent. For projects that have estimated the tonnage of a mineral contained in a deposit, the probability increases to 33 percent. Furthermore, the lead time between discovery and production has historically varied widely. Table 3.7 details the discrete steps and the aspired number of years for those steps which would seem to suggest between eight to fourteen years before production can begin. In reality, lead times for mining projects have historically ranged from five years to nearly half a century (Table 3.8). Finally, price fluctuations "have a significant influence on the willingness of mining companies to take on the investment risk for a new mine" which may delay project financing projects, leading to longer lead times (Wellmer and Dalheimer 2012).

Another source of dissuasion for mining companies is that, unlike major metals, rare earth mining includes an additional step following extraction that requires some base level of elemental separation and purification. Unlike copper, for example, which can be extracted and commercialized with little effort, rare earths typically require extensive physical separation and processing at the basic level to capture greater economic value.[57] Figure 2.5 illustrated the value difference between raw ores and even minimally separated and processed oxides. The junior minors and investors that buy and develop the surveyed deposits follow a fairly familiar path. A breakdown of the rare earth mining development phases sheds light on where the risks lie, the associated costs, and who assumes those risks (and rewards) in the rare earths sector.

Initial Phase

REEs mine discovery takes the form of either greenfield or brownfield projects. The former is the exploration of hitherto unexplored geologies whereas the latter are exploration of potential deposits sitting adjacent to pre-existing mining operations. Explorations are sensitive to mineral price cycles—the higher the prevailing market price, the greater the exploration and vice versa. They tend to be under tight budget and are cursory, with teams moving quickly from location to location based on quick survey results. Rare earth explorations have indeed been rare in the last century until the very recent pickup in activities. Much of the major REEs projects were discovered by accident whilst in search for or production of other minerals (Long et al. 2010). Exploratory surveys are generally funded on a term (e.g., annual or decade, etc.) budgeting basis by funding entities whether they are junior mining interests or public agencies. The costs are also influenced by the geographic scope of the search (global, regional, or local) and the breadth

[57] This physical processing step precedes even the more costly (and sometimes toxic) chemical processing step in the midstream stage.

of elements they are seeking (just rare earths or other minerals both major and minor). Subject to these conditions, budgets can ran anywhere from a hundreds of thousands of dollars to hundreds of millions of dollars (Wilburn and Stanley 2012).

Advanced Phase

Upon initial positive discovery, extensive drilling and mineralogy inference is conducted to size up the deposit. Preliminary environmental and economic feasibility studies are simultaneously started. Depending on the outcome of these studies, mine designs, a pilot processing plant, and a more formal economic feasibility study is pursued. Permit applications are also initiated whilst a formal environmental impact study is also conducted. The second feasibility study results form the basis of securing financial investments (Long et al. 2010). Advanced phases usually progress after an investing entity had acquired the rights from predecessor junior miners that have already explored and surveyed a deposit in the initial phase. While the actual costs vary depending on the location of the reserve and the local infrastructure, the general estimated cost to prove reserves at this stage is generally around $50 million (Bauer et al. 2011).

Final Phase

Assuming financing and regulatory permits and approvals are secured, construction of the mine begins. Initial trial productions are conducted before full capacity is reached, although unanticipated hiccups in the process are common at this stage. Typically, mining companies at each of these stages have expended millions of dollars, either from its own resources, high interest loans, and/or investor equities without any form of revenue from the mining project. The Mountain Pass project required $500 million in pre-production financing since 2008, even though it already had a developed mine and infrastructure and had once been operational for many decades before its 2002 hiatus (Long et al. 2010). The total cost from greenfield projects to final phase costs at least $1 billion. Brownfield projects would cost much less since it would leverage pre-existing infrastructure, with costs ranging from $100 million to $1 billion (Bauer et al. 2011).

TABLE 3.7 – ASPIRATIONAL RARE EARTH MINE DEVELOPMENT SCHEDULE

Stage	Exploration Cycle Stage	Objective	Time Required
1	Grassroots	Conceptual, land acquisition	1 year
2	Target Generation & Drilling	Filtering for drill targets	1-2 years
3	Discovery Delineation	Defining the limits of the discovery - tonnage & grade	1-2 years
4	Infill Drilling	Producing the mineral resource estimate & scoping study	1-2 years
5	Bulk Sample & Metallurgy	Evaluating recoveries and optimal processing method	1 year
6	Prefeasibility	Produce a minable reserve, establish a mining plan and associated costs	1-2 years
7	Permitting, Marketing & Feasibility	Securing approvals, negotiating off-takes, making a production decision	1-2 years
8	Construction	Building the mine	1-3 years
9	Production	Mining cashflow	10-20 years

Source: Avalon Rare Metals (2010)

TABLE 3.8 – SELECTED LEAD TIMES OF GLOBAL MINING PROJECTS

Mine	Country	Commodity	Discovery date	Production start-up	Years to production
Araxa	Brazil	Nb	1955	1961	6
Barro Alto	Brazil	Ni	1969	2010	41
Bulong	Australia	Ni	1971	1999	28
Catalao I	Brazil	Nb	1970	1977	7
Cawse	Australia	Ni, Co	1994	1999	5
Goro	New Caledonia	Ni, Co	1982	2010	28
Murrin Murrin	Australia	Ni, Co	1984	1999	15
Niobec	Canada	Nb	1967	1976	9
Urumu Utsumi	Brazil	U	1971	1981	10
Vermelho	Brazil	Ni	1966	2012	46

Source: Wellmer and Dalheimer (2012)

Processing

Once raw rare earth ores are extracted from the earth, the desired rare earths are separated in what is called a beneficiation process. This allows the individual REEs to be purified to higher concentrates which can then be smelted for specific industrial applications. There are different raw ore processing methods depending on what type of deposit the REEs-bearing mineral was extracted from. Generally, hard rock deposits involve greater effort than placer deposits since the ores must be hauled then crushed and ground before processing and separation can begin. REEs in placer deposits require less effort in the milling stage since they embedded within fine sand.

The two primary methods of beneficiation, physical and chemical, are generally used in conjunction with each other. Physical beneficiation precedes chemical beneficiation which enables higher purification of elements. Depending on the composition of the ore, a series of one or more techniques become necessary to extract pure REE content. Since bastnäsite, monazite, and xenotimes comprise the bulk of rare earth deposits, the beneficiation processes used for these mineral concentrates are used as illustrative examples. Figure 3.4 traces the REEs excavation, processing, and separation steps for bastnäsites from hard rock deposits and monazites and xenotimes from placer deposits.

Hard rock deposits - Bastnäsites

In the case of hard rock deposits such as in Mountain Pass where raw ores have approximately 7 percent REO content, the ores are finely crushed on a mill to about 0.1 millimeters. Then, chemical additives and steam is used to produce slurry with 30 to 35 percent REO content. Using a technique called froth flotation[58] that involves use of chemicals, water, and compressed air, the desired rare earth elements float on froth that forms on the liquid surface. They are then carefully collected, filtered, dried, and cleaned

[58] Walters, Lusty, and Hill (2011) describes froth flotation in greater detail as follows: "Following grinding, water is added to the powdered ore to produce a suspension. Air is blown upwards through the tanks. Chemicals are added which make specific minerals water repellent and cause air bubbles to stick to their surfaces. Consequently, these minerals collect in a froth at the surface and are removed. Reagents used for monazite flotation include fatty acides, hydroxamates, and dicarboxylic acids."

into Bastnäsite concentrates with approximately 60 percent REO content (Walters, Lusty, and Hill 2011). Because other minerals such as barite and calcite have similar flotation properties as REEs, higher purity cannot be achieved through froth flotation alone.

Chemical beneficiation is used to increase REO purity through multiple processes. Which reagents are used, however, depends on the unique mineral content in question. In the case of Mountain Pass bastnäsite, the first step is to use hydrochloric acid which removes strontium and calcium. This increases purity to 70 percent REO. Second, calcination removes carbon dioxide, achieving purity of 85-90 percent REO. Bayan Obo applies a different chemical processes where minerals are baked with sulphuric acid at a high temperature and leached with water to remove impurities (Walters, Lust, and Hill 2011).[59]

Placer deposits – Monazites and xenotimes

Physical beneficiation of REEs from placer deposits can again differ significantly. In most cases, however, gravity separation, magnetic separation, and electrostatic separation are the three principal techniques applied. The gravity technique exploits the density differences of minerals to separate them by feeding the sediment through jigs, spiral and concentrations, and shaking tables. Unwanted gangue material tends to float while the desired minerals, which are denser, tend to sink. The concentrate is then processed further with various combinations of gravity, electrostatic, and magnetic separations that exploit the material structures of the various minerals in the concentrate (Walters, Lust, and Hill 2011).

Following is an illustrative example of how xenotime and monazite concentrates are extracted from dredged sediments. Once concentrates from the preliminary gravity separation is dried, they pass through magnetic separation. The non-magnetic concentrates proceed to electrostatic separation.[60] Here, the non-conductive concentrates undergo a second round separation[61] of magnetic or gravity separation (or both) that separates out the zircon from the concentrate (zircon is slightly magnetic and more dense than REEs). In the final stage, a much more precise gravity separation method is used to separate monazite from xenotime. Higher separation calibration is needed since these two minerals have similar densities. At the end of physical beneficiation, monazites and xenotimes on average contain about 65 and 61 percent REOs, respectively (Walters, Lusty, and Hill 2011).

Alkaline chemical beneficiation is the preferred method for purifying monazite and xenotime. An alternative method using acidic solutions has been used commercially but the use of sulphuric acid caps the purity yield of REOs whereas the other method does not. Furthermore, the alkaline approach, otherwise known as the caustic soda method, is preferred because it enables recovery of phosphate which can be marketed. The process first separates the REEs from phosphate before the thorium is separated (Walters, Lusty, and Hill 2011).

REEs separation

By the end of the chemical beneficiation process, the minerals are purified to at least 80 percent REO purity or greater. However, the various REEs embedded in the minerals need to be separated from each other. As previously noted, because the individual REEs have such similar physical properties, prying

[59] Precipitated as double sulphates, the REEs are then transformed to hydroxides and leached with hydrochloric acid. Russian loparite concentrate is purified through simultaneous application of gaseous chlorination with reagents to remove titanium, niobium, and tantalum. Ammonium sulphate and sulphuric acid is then used to dissolve the REEs-bearing residue. Finally, water and sodium carbonate precipitates the REEs and thorium for capture (Castor and Hedrick 2006).
[60] The magnetic concentrates are ilmenites and are separated.
[61] The conductive concentrates are leucoxenes and are separated.

them apart is difficult. Chemical processing is the most common method of separating and extracting individual REEs. Harsh solvents are necessary because the solubility levels of the REEs are so similar (Bauer et al. 2011).[62]

Ion exchange and solvent extraction (SX) are the two most common methods of separating the REEs. The ion exchange process produces high purity REOs but is more time consuming. As a result, they are used only on a small scale by processors.[63] On the other hand, SX is the preferred method for large scale separation. Because a single round of SX is not enough to separate the REEs in an ore, the process is repeated continuously until the REEs finally do separate.[64] The downside is that SX is best used for LREEs and less effective when separating HREEs (Moore 2000). A third method, fractional precipitation and crystallization, exploits minute differences in the elements' basicity and alkali composition. It was the default method until the 1950s but is no longer used due to its comparatively higher cost and lower efficiency compared to ion exchange and SX methods (Gupta and Krishnamurthy 2005). When purified at greater than 99 percent purity, rare earths are sometimes referred to as rare earth metals (REM). China has by far the highest rare earth purity processing capability, producing concentrates at 99.9999 percent purity. French companies produce at 99.99 percent purity and the Japanese at 99.9 percent purity (Weisenthal 2010). Rare earths used in lighting applications such as europium and yttrium typically require higher purity oxides while nickel metal hydride batteries can tolerate impurities in lanthanum (Frontier Rare Earths 2014).

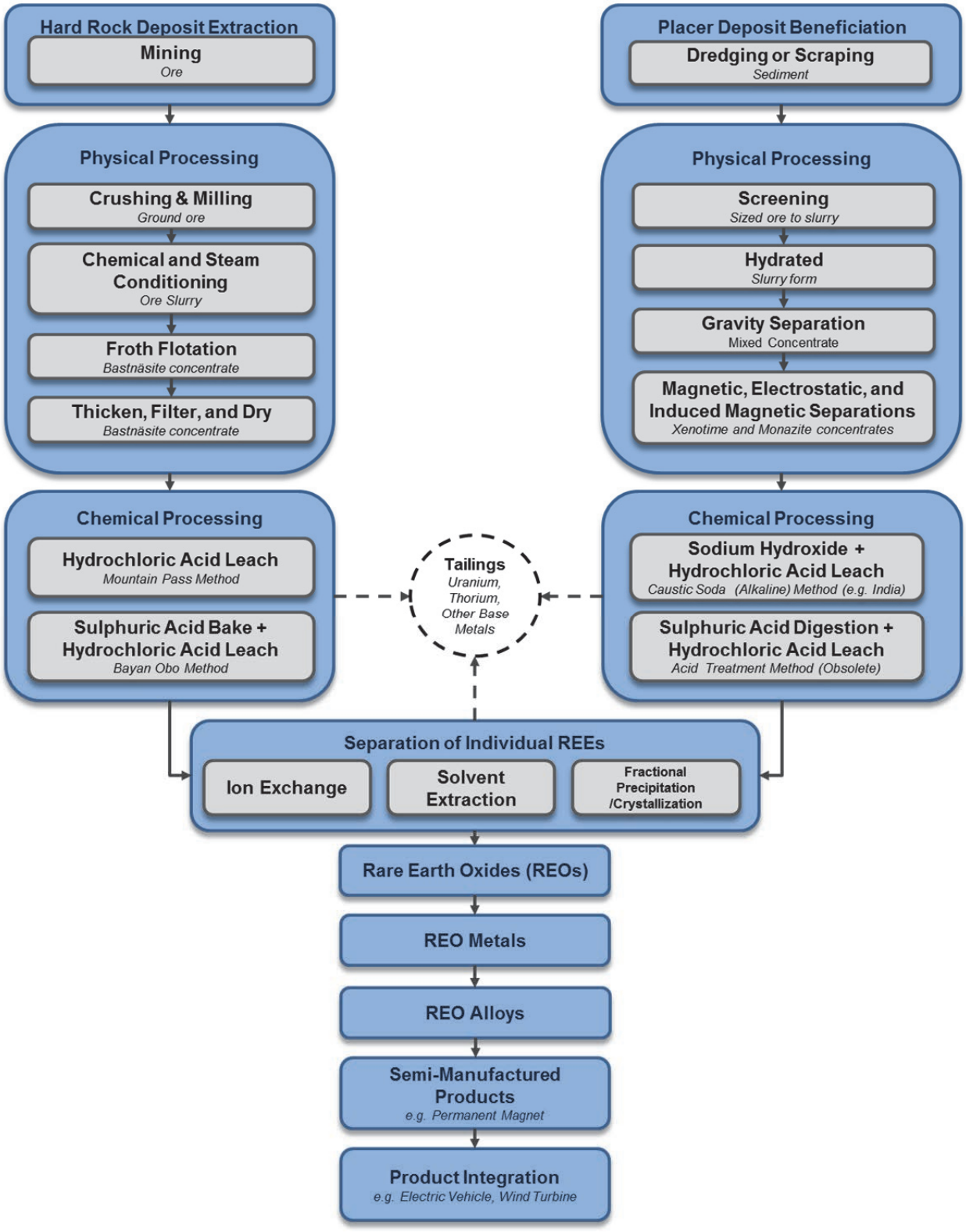
Rare earth processing is resource-intensive in terms of water and energy use. It also requires the use of hazardous chemicals and other toxic by-products. Without proper regulation, enforcement, and care, serious environmental damage can occur from leakage of hazardous waste and radioactive materials. Concern over the latter is a chief reason why many REE production facilities are closed. Malaysian placer deposits with uranium and thorium led to closures in the early part of 2000s while China, Australia, and Europe have banned REEs extraction from sediments with monazites.

[62] Despite the similarities between rare earth elements that lead to their clustering, their properties are nonetheless sufficiently different enough, particularly between the light and heavy variants, to necessitate their separation and purification for industrial needs. Nonetheless, their similarities do enable mutual substitution of one another for some applications, including for NdFeB permanent magnets. As discussed later in Chapter 6, terbium is a viable elemental substitute for dysprosium for these magnets. However, terbium is far rarer and more expensive than even dysprosium, making it a poor substitute.

[63] Walters, Lusty, and Hill (2011) describes that the "ion exchange is a process in which ions are exchanged between a solution and an insoluble (usually resinous) solid. The solution containing the REE is passed over the ion exchange resin. The REE displace the cations [positively charged ion] on the resin surface. This produces an aqueous waste containing the exchanged cations, with a mixture of REE deposited on the resin. Individual REE[s] are then separated using a complexing agent which has different affinities for the various REE[s]."

[64] SX works by separating elements based on differences in solubility of materials when reacted with other materials which do not mix well with each other, typically water and an organic solvent (Walters, Lusty, and Hill 2011).

FIGURE 3.4 – RARE EARTH PROCESSING STEPS FROM EXTRACTION TO PRODUCT INTEGRATION



Data: Vernon (2012); Walters, Lusty, and Hill (2011); and Hurst (2010b)

Chapter Summary

This chapter has demonstrated that rare earths have important uses across key high technology industries in the modern economy. They are particularly important in consumer electronics, green technology, and military systems that are lucrative and sensitive for the U.S., Japan, Europe, and of course China. But as diverse as the applications of rare earths are, so too are the 17 elements that comprise this group of elements. Although colloquially referred to as a single entity, subtle differences in the electron configurations of each element ultimately have significant economic and political implications.

In particular, some elements have unpaired outer electron shells while others are paired. This distinction leads to two general groups of rare earths: light rare earths and heavy rare earths (which include dysprosium, the primary element of interest in this study). The stability of LREEs means they are generally found in greater concentrations in nature and are therefore more "abundant" relative to HREEs which are widely dispersed and not as easily found in concentrations that are economical. In addition, HREEs have higher melting points that make their processing more costly. Compounding the challenge is the fact that HREEs are increasingly in high demand because of their unique properties that are important for superior performance permanent magnets, batteries, ceramics, and military systems.

Thus, taking elemental dispersion, costly extraction and processing, and high demand together, heavy rare earths are significantly more expensive than light rare earths. In the next chapter, Chapter 4, the case of one heavy rare earth, dysprosium, is adopted and further investigated to understand what the shortfall implications of these technical constraints mean for the U.S. policy maker.

Chapter 4 – Dysprosium Supply and Demand Projections

"Dysprosium has emerged as the metal most vital to clean energy industries yet most vulnerable to supply disruptions"
- Dudley Kingsley

Introduction

The preceding chapters provided a retrospective look at the importance of rare earths applications and why dysprosium and other rare earths are principally mined, processed, and manufactured in China. Beijing's policies have focused on developing and vertically integrating the rare earth market, an effort which has been significantly abetted by a favorable geological distribution of large and easy to extract deposits with higher than average grades of highly coveted heavy rare earths, including dysprosium. This is the status today. But what can we expect in the years ahead?

Based on projections analyzed in this chapter, the U.S. policy maker can face a wide range of dysprosium shortfall outcomes. In the Best Case projection, dysprosium shortfall could be minimal if dysprosium demand growth is low and supply capacity growth is high if both Chinese and non-Chinese dysprosium mining increases. In the theoretical Worst Case projection supply capacity would meet less than 20 percent of rising demand by 2020 and less than 5 percent by 2030. A variety of shortfall outcomes are possible within the boundaries of these extreme cases as exemplified in this chapter.

These projections are not predictive. However, they do provide two important insights. The first is that as long as demand for dysprosium remains strong, merely mining more will be unlikely to meet all demand. There is a clear need to pursue additional venues other than extraction—venues which are explored and assessed in Chapter 6.

The second insight is that the projections demonstrate the uncertainty the policy maker faces in terms of how much actual shortfall in dysprosium can be expected. More specifically, the projections clarify the need for the policy maker to plan and invest in policies in the context of a wide spectrum of outcomes. This point establishes the basis for the need for policy planning against various scenarios, which is described in the following chapter, Chapter 5.

Projection Objectives

The following supply capacity and demand requirement projections are not intended to predict or forecast. Rather, it is to illuminate the range of possibilities in global dysprosium production capacities in the coming decades and to flesh out mining supply and demand dynamics specific to dysprosium.[65]

Projections serve a few important purposes.

First, it provides the opportunity to exhibit the uncertainty and difficulty of planning for mining supply capacities into the future. Merely asserting that non-Chinese dysprosium reserves exist can be misleading because it omits the real crux of the challenge, which is to understand whether individual mining projects

[65] Supply capacity refers to the maximum global mining capacity. Demand requirement refers to the quantity of dysprosium required to achieve a policy, social, or economic outcome. For example, in the case of dysprosium, the amount of dysprosium that would be required to install a certain level of wind turbine megawatt (MW) capacity in the pursuit of cleaner energy production would be the demand requirement.

will become operational, if ever. There might be adequate reserves, but it may not be exploited if miners do not develop it within the timeframe of interest.

On the flip side, we may be given to temptation to overstate the level of Chinese monopoly in the REEs domain and underestimate the diversity of non-Chinese supply. Policy choices made in light of past recent events could thus overstate the level of supply insecurity in proceeding years, leading to suboptimal policy investments. Through upper bound supply capacity projections, however, the supply planner may recognize that the diversity of production within the U.S. and other friendly countries in future years.

Secondly, while necessarily pedantic, the demand requirement projections will provide the policy planner with an understanding of demand drivers for dysprosium. Rather than relying on repeated assertions that dysprosium's "demand is growing," a grounds-up analysis of demand drivers provides an opportunity to gain intuition on what is driving growth and at what scale, subject, of course, to projection assumptions.

Lastly, projections help delineate the scope of the supply, demand, and shortfalls (see Dysprosium Shortfall section for a full definition of the shortfall terminology). Projections can illuminate, as will be shown, whether mining can be adequate or whether shortfalls can still exist even in the most optimistic supply projections. The refrain "drill, baby, drill" may be inadequate to satisfy demand. The shortfall projections provide the policy planner to witness why dysprosium is considered the most critical of all elements.

Projection Assumptions

Price Volatility

Theoretical research on mineral market dynamics find that commodity price prediction is extremely challenging precisely because of price volatility. The classic example is the cobweb theorem, which was first presented independently by three European economists—Schultz, Tinbergen, and Ricci—in 1930 (Ezekiel 1938). The theorem states that because production decisions in agriculture and mining take place before actual market prices are observed, producers plan for future quantities based on previous period prices. Exogenous variability that affect either the supply or demand side, such as changes in weather conditions, technology, and consumer demand, results in cyclicality in supply and demand, leading to price volatility (Figure 4.1).

Despite its detractors, most famous among them Samuelson (Dufresne and Vázquez-Abad 2013), the cobweb theory has been refined, embellished, and generalized in part due to its strong intuitive appeal that commodities production such as agricultural produce, livestock, and metals experience time lags. Wellmer and Dalheimer (2012) underwrites this critical link in minerals commodities, noting that, "The feedback control cycle of mineral supply is to all intents and purposes the same as the hog cycle in agriculture or the cobweb theorem." In fact, given that both production lag time and the lag in consumer demand to price changes (delays in both supply and demand), "only the first or, at most, the first two reaction cycles of the cobweb theorem are realized before a new equilibrium is found." Historical mineral

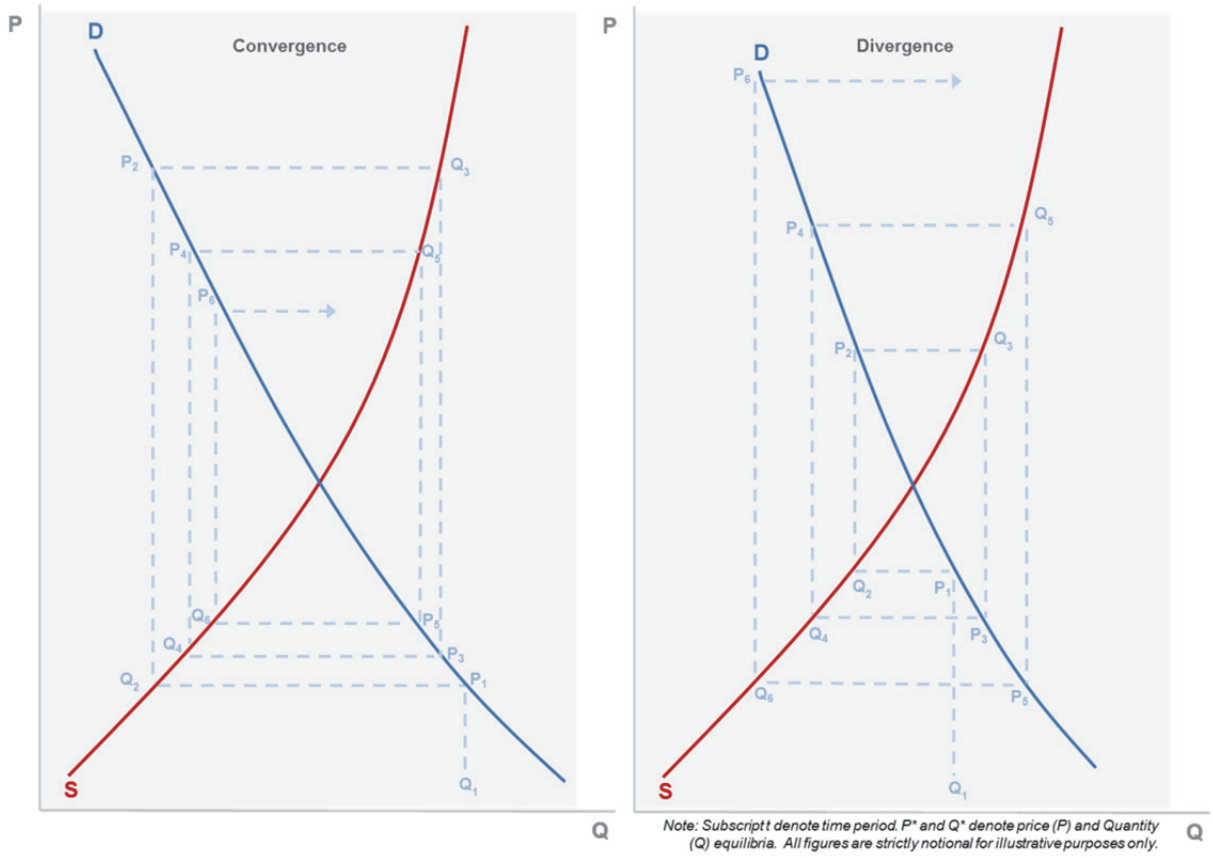
cases include price peaks, collapse, and sustained ebbs for molybdenum, cobalt, and tantalum (Wellmer and Dalheimer 2012).

Figure 4.1 illustrates two cases of a cobweb where the price/quantity spiral inwards and converges to the market equilibrium ("Convergent") and an alternative case where the cobweb spiral outwards away from the equilibrium ("Divergent"). In both of these cases, the underlying intuition is that market prices and supply quantity swing away from the theoretical market equilibrium price and quantity. This uncertainty suggests that demand and supply projections can benefit from assessments on ranges of supply, demand, and shortfall projections rather than precise equilibrium point estimates.

Recent theoretical economic works have expanded the cobweb theory to incorporate the supply lag and a random element, i.e., "stochasticity", in the model. Pryor and Solomon first introduced randomness in observed prices (Pryor and Solomon 1982). Turnovsky examined stochasticity in price forecasting (Tunrovsky 1968). Chiarella's salient work demonstrated chaotic conditions for the model (Chiarella 1988). Chaotic system refers to systems, like the commodities market for example, that are very sensitive to the initial conditions—the starting values used in the mathematical model. Slight changes in these initial numbers, i.e., exogenous shocks to the supply or demand curves—can lead to starkly different and diverse results. This makes predicting the future very difficult if not impossible. This rich and growing niche of academic research uses mathematical modeling to project supply and demand using past data from major minerals such as iron, copper, and zinc. Some prominent works include those by Speirs et al. (2013), van Vuuren et al. (1999), Yerramilli and Sekhar (2006), Guzman et al. (2005), and Cuddington and Zellou (2013). Verhoef et al. (2004) provides an intuitive explanation of the complex and dynamic metal system:

> A change to any of the metallurgical infrastructure's components can shift the relations between the processes elsewhere, resulting in different demands for intermediates and secondary and primary materials but also in changes in the environmental profile or the metals recovery capacity of the system…*As a consequence, the associated metal production and recovery systems typically do not operate at steady state*…Each stage in the life cycle of metals affects the other, and specifications change over time.

FIGURE 4.1 – CONVERGENT AND DIVERGENT COBWEB CASES OF COMMODITY PRICE AND QUANTITY



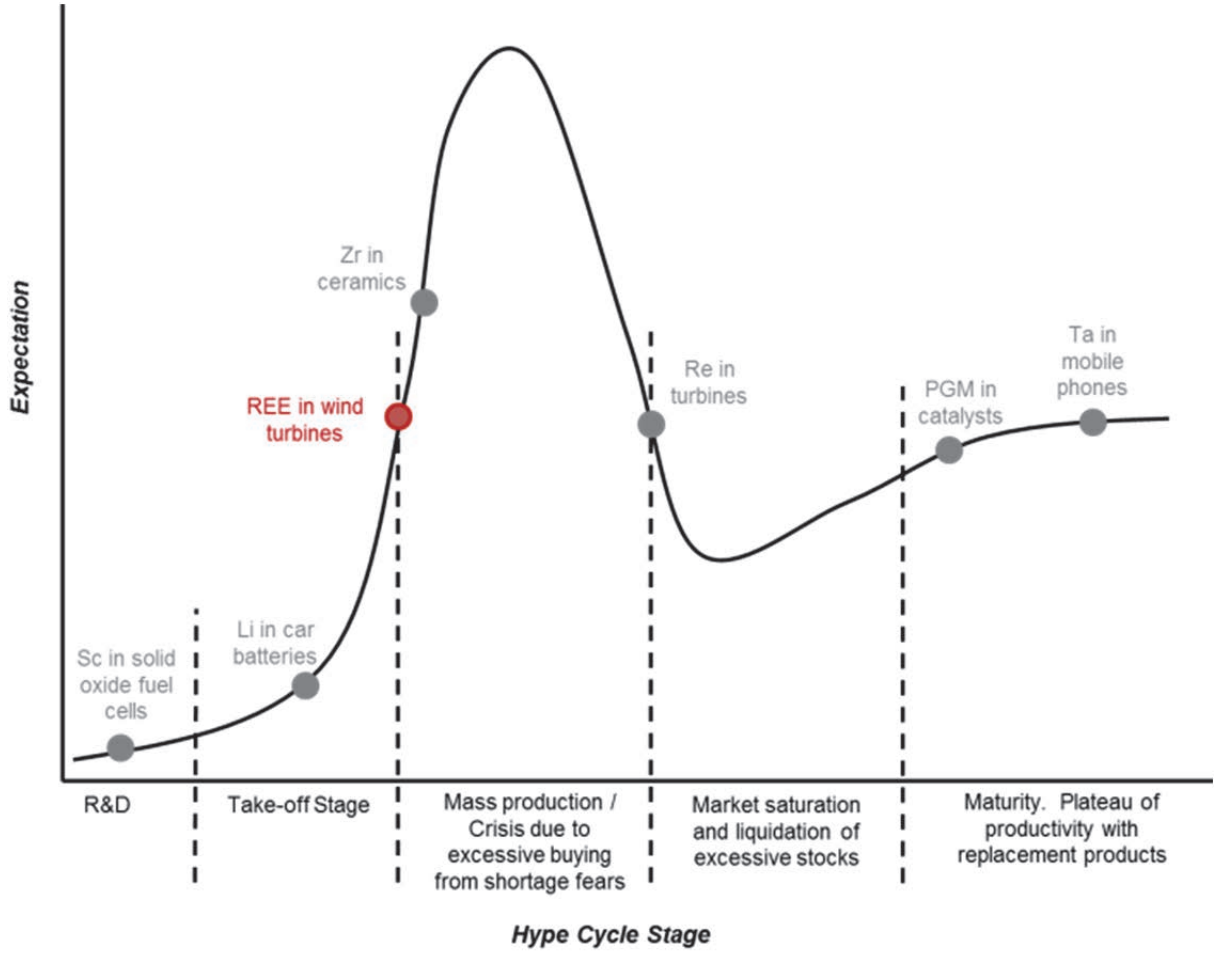
Source: Modified from Ezekiel (1938)

In addition to theoretical mineral economics, we can also expect dysprosium price volatility by looking at its primary driver for demand growth: next generation wind turbines. Work by Wellmer and Dalheimer (2012) posits that rare earth applications in wind turbines are in the early "take-off" stage in the hype cycle framework and can be expected to experience significant market volatility in the coming years. The hype cycle, originally coined by Jackie Fenn at Gartner Inc., traces the evolutionary stages of a new technology and contrasts the stages with the expectation or "hype" surrounding the technology from consumers (Fenn 2008). Hocquard (2010) followed by Wellmer and Dalheimer (2012) adapted the framework to raw materials. In their modification, expectations are interchangeably used with notional price (moving in the same direction on the vertical axis) while the hype cycle stages are modified to better reflect the maturation stages of raw material applications.[66] If true, the peak and nadir of the wind turbine sector is yet to come before the sector recovers and self-corrects onto a more sustainable growth path (Figure 4.2). In short, we can expect even more volatility in the rare earths market, dysprosium included.

[66] Specifically, Hocquard (2010) and Wellmer and Dalheimer (2012) introduce R&D as an initial phase. Fenn's "Technology Trigger" is renamed "Take-off stage," "Peak of inflation" is renamed "Mass production / Crisis," "Trough of disillusionment" is renamed "Market saturation and liquidation," and the original stages of "Slope of enlightenment" and "Plateau of productivity" are combined into "Maturity."

The endemic rare earth price volatility bears itself out in a very practical manner for financial stakeholders in the industry sector. According to Tyrer and Sykes (2013), the discount rate for rare earth mining financial planning ranges from 5 percent to 40 percent. The standard practice is to use 10 percent, which the authors find too optimistic (i.e., too low) given the high uncertainty surrounding their prices. While many financial analysts try to "predict" rare earth prices, Tyrer and Sykes find that such work is often "really no better than guesswork." They quip a mantra all too familiar to rare earth investors:, "With all this technical and economic uncertainty, it is perhaps no surprise that rare earth mine projects are among the most difficult to develop."

FIGURE 4.2 – CONTEMPORARY RAW MATERIALS HYPE CYCLE



Source: Modified from Wellmer and Dalheimer (2012)

Compounded Annual Growth Rate (CAGR)

If price is stochastic, then it makes all the more sense to make projections based on as wide a range of supply and demand inputs as possible. On the basis of this theoretical framework, this chapter's projections estimate the various possible annualized growth rate of supply capacity and demand

requirement each year under different assumptions. Shortfall estimates are then calculated for each based on the combination of different supply capacity and demand requirement change rates.[67]

This study reverts to a simple but useful tool, the compounded annual growth rate (CAGR) equation which has the subtle but crucial advantage of implicitly accounting for volatility. Applied most frequently in financial investment planning, CAGR is used to smooth over volatility when calculating investment returns rates to arrive at a consistent annual investment growth rate figure. The CAGR of dysprosium δ (where δ is either supply or demand in tonnes) between two years, y_1 and y_T, is as follows:[68]

$$CAGR = \left(\frac{\delta_{y_T}}{\delta_{y_1}}\right)^{\frac{1}{y_T - y_1}} - 1$$

Table 4.1 provides the full list of supply capacity and demand requirement projections, their descriptions, and key assumptions. Readers may find it useful to refer to the table when reviewing the various projection combinations in the following sections. Each of these assumptions is discussed in greater detail in sections labeled "Assumptions" under each section on projections.

TABLE 4.1 – SUPPLY AND DEMAND PROJECTION ASSUMPTIONS

Projection Assumptions			
Projection	**Category**	**2010-2020**	**2021-2030**
Demand Requirement - Long Term			
A	Demand - Low	Evolutionary Growth - Historical Rate: 3.7%	
B	Demand - Moderate-High	Evolutionary Growth - Industry Estimated Rate: 13%	
C	Demand - High	Revolutionary Growth: 25%	
Supply Capacity - Short Term			
D	Supply Capacity - High	Optimistic production schedule: mines coming online as announced in latest public estimates and Chinese production grows at 3% annually.	
E	Supply Capacity - Moderate	Pessimistic production schedule: mines coming online a year later than latest public estimates. Chinese production stagnant (0% growth annually).	
Supply Capacity - Long Term			
F	Supply Capacity - High	Optimistic production schedule, as above.	Chinese 3% growth. U.S. and ROW grows at 17.2%.
G	Supply Capacity - Moderate	Pessimistic production schedule, as above.	Chinese 0% growth. U.S. and ROW grows at 5.4%.
H	Supply Capacity - Low	Pessimistic production schedule, as above.	Chinese, U.S., and ROW 0% growth.
			Note: % growth in annual terms

Dysprosium Demand Requirement

Applications

Dysprosium is used primarily in the production of NdFeB permanent magnets, an intermediate semi-manufactured good with wide applications in industrial products, ranging from motors in computer hard

[67] Shortfall refers to the difference between projected supply capacity and demand requirement at a moment in time.
[68] Alternatively, $\delta_{y_T} = \delta_{y_1}(1 + CAGR)^{y_T - y_1}$.

drives and refrigerators to electrical vehicles and massive wind turbines, (Goonan 2011). Table 4.2 lists the application of dysprosium-based permanent magnets in 2010. The most common applications were in industrial and automotive motors and electrical bicycles that comprised 50 percent of dysprosium use by weight. Permanent magnets are used in high-performance electric motors and generators used to bilaterally convert mechanical motion to electricity and vice-versa. An estimated 100-200 grams of dysprosium is used in hybrid vehicles and about 25-30 kilograms per megawatt generating capacity of a wind turbine (Hatch 2011). Expected future demands in electric vehicles (hybrid, plug-in, all-electrical) and wind turbines are expected to significantly increase demand for dysprosium applications (Bauer et al. 2011 and Constantinides 2011).

TABLE 4.2 – DYSPROSIUM-BASED PERMANENT MAGNET APPLICATIONS SHARE IN 2010

Dysprosium Permanent Magnet Applications	2010 Application %
Motors, Industrial, General Auto, etc.	37.2%
Electrical Bicycles	13.3%
Misc, Unidentified, Other	13.2%
Generators	6.8%
Torque-Coupled Drivers	5.8%
Magnetic Separation	4.9%
Energy Storage Systems	3.5%
Wind Power Generators	3.1%
Hysteresis Clutch	2.9%
Air Conditioning Compressors and Fans	2.9%
Hybrid & Electric Traction Drive	2.8%
Magnetic Resonance Imaging (MRI)	1.9%
Sensors	1.5%
Total	**100%**
*Misc. includes gauges, brakes, relays & switches, pipe inspection, levitated transportation, reprographics, refrigeration, etc.	

Source: Constantinides (2011)

Dysprosium has a variety of other highly specialized applications, although in much smaller volumes, in digital storage, laser aimers, sonar, and illuminations. More specifically, dysprosium is used in Terfenol-D, a magnetic alloy whose shape and dimensions change with magnetization, properties exploited for acoustic sensors such as naval sonars, vibration cancellation, seismic detection, and machine tooling. Dysprosium-based semiconductor is also used in lasers and other energy-intensive electronics (DoD 2013a). The paired-electrons in dysprosium also makes it an ideal element for radioactivity detection, translating to use in nuclear reactor rods to control fission, radiation monitoring, and medical uses (InvestorIntel 2014).

Global dysprosium consumption was estimated at about 1,600 in 2010 by the USGS and is used as the base figure for demand projections (Goonan 2011). U.S. consumption was estimated at about 181 tonnes in 2012 (Ucore 2013). The military demand of dysprosium is significantly smaller. The estimated yearly DoD demand for REEs used for military applications of permanent magnets is 160 tonnes, 7 tonnes of which are dysprosium (DoD 2012a, Lifton 2013, and Green 2012).

Permanent magnets are produced either through the use of samarium and cobalt or more preferably through neodymium, iron, and boron. The REEs—samarium, neodymium, and praseodymium—are used to effectively "channel" the magnetic currents of iron and cobalt. For NdFeB magnets, dysprosium is used to enhance the already substantial magnetic property of these rare-earth permanent magnets. More specifically, it is used to further strengthen their coercivity, i.e., the ability to resist demagnetization from high temperatures or competing magnetic fields (Hurst 2010b). Because of the superlative feature of NdFeB-dysprosium magnets, it is favored over the SmCo alternative.

Projections A, B, and C

Assumptions

Three dysprosium demand projections are made: evolutionary growth (Projection A), semi-evolutionary growth (B) and aggressive growth (C). The methods are adopted and modified from Alonso et al. (2012) and Bauer et al. (2011). Parameter estimates are referenced from DoD (2013a), Hatch (2011), Goonan (2011), and various industry reports. The assumptions below reflect those shared by the DoE and DoD studies. While Bauer et al. (2011) referenced the International Energy Agency's (IEA) *World Energy Outlook 2010* report, this study incorporates data from the IEA's more recent 2013 report. All three projections preclude stockpiling demand from countries and assume no dysprosium substitutes are available that would diminish demand.

Projection A

Projection A adopts the evolutionary rate based on the growth observed between 2006 and 2010 by the Goonan (2011) which is a 3.7 percent CAGR. This is slightly higher than the 3.2 percent demand growth rate the DoD (2013a) utilizes based on the Council of Economic Advisors' global economic growth forecast rate. In contrast, the IEA's *World Energy Outlook 2013* report assumes the base global growth rate at 3.6 percent (IEA 2013). Because dysprosium applications are in fast-growth industry sectors, a moderately higher Goonan (2011) estimate can be justified.

Projection B

Projection B adopts a semi-evolutionary approach by applying the industry's estimate of the 2010-2015 CAGR for dysprosium demand. Roskill (Kingsnorth and Chegwidden 2012) estimates that dysprosium demand will grow annually at 13 percent during these years. This rate of growth is applied for the years 2016 to 2030. Industry estimates are generally more optimistic than how actual trajectories play out and can be seen as upper bound estimations. Kingsnorth (2011) estimates range between 10 and 13 percent in the 2010- 2020 period. IHS (2013) estimates growth rates between 7 and 8.3 percent between 2010 and 2017 (IHS 2013). Roskill's high-end estimate is applied for this projection in order to establish an upper bound evolutionary estimate.

Projections A and B demand use the following evolutionary growth equation from Alonso et al. (2012) to calculate a given year's projected demand, where Dy is dysprosium demand in year y and $g_{(historical/expert)}$ is the growth rate:

$$D_y = e^{(y-2010)\cdot\ln(1+g)+\ln(D_{2010})}$$

Projection C

Projection C stakes out an aggressive growth scenario using frameworks applied by Bauer et al. (2011) and Alonso et al. (2012). The two most fast-growing dysprosium applications are anticipated to be in the clean energy sectors, specifically in their use in next-generation wind turbines and electrical vehicles. In order to get a sense of the most extreme case of demand projection, these studies incorporate assumptions from IEA's *450 Scenario* which examines how much clean-energy electrification is required to stabilize carbon dioxide levels at 450 parts per million (ppm) which could help limit global temperature rise to 2°C. Using the more recent 2013 IEA report, the 450 Scenario would require total global wind power generation capacity to grow from 238 gigawatts (GW) in 2011 to 663 GW in 2020, doubling to 1,368 GW in 2030 (IEA 2013).

The IEA also projects annual sales target volumes for electrical vehicles (EV), with a target of 7 million global EV sales by 2020 (IEA 2013)[69]. This translates to a CAGR of nearly 25 percent in annual EV sales volume between 2012 and 2020. This rate of growth is assumed for the 2020 to 2030 period. Electrical bicycles (EB), more than 90 percent of which were sold in China in 2013, also use trace amounts of dysprosium in their motors. Sales are expected to increase from 31 million in 2013 to 38 million units worldwide by 2020 (Navigant 2013), equivalent to just less than 3 percent CAGR.

These assumptions are detailed in Table 4.3 and Table 4.4, adopted from Bauer et al. (2011) and updated with more recent data. Dysprosium utilization rate and material intensity figures are upper bound assumptions from the same study. Wind turbine demand projection and electric vehicle projection data are from IEA (2013) while the electrical bicycle projections are from Navigant (2013). Each year's projected technology (wind turbines, EV, and EB) is multiplied by the share of deployed units that is expected to use REEs in that technology. Then each unit of REE-utilizing technology is multiplied by the average kilograms (kg) of REEs. Finally, the expected weight of dysprosium is calculated using the average percentage of dysprosium used in every kilogram of REEs for that technology.

Formally, let T_i be the unit of technology deployed (where i is either wind turbines in gigawatts or electric vehicle sales), let p_{Dy} be the proportion of T that uses dysprosium, let MI_{wt} be the REEs material intensity in kilograms for each unit of $T_i \cdot p_{Dy}$, and let $MI_{\%}$ be the proportion of dysprosium in each kilogram of $T_i \cdot p_{Dy}$. If y is the year, then total demand D for dysprosium for y is simply the sum product:

$$D_y = \sum_i T_{i,y} \cdot p_{Dy} \cdot MI_{wt} \cdot MI_{\%}$$

[69] However, with global sales estimated at only 100,000 in 2012, it is unlikely that this target nor the 5.9 million advertised in a separate IEA publication on electrification are likely to be met (IEA, Global EV Outlook 2013).

TABLE 4.3 – METHOD AND DATA FOR DYSPROSIUM DEMAND REQUIREMENT FROM WIND TURBINES

	Wind Turbines							
	Technology Deployed			% Using Dy		Material Intensity		Dy Demand Estimate
Unit	Gigawatt (GW)			%		kg/GW	%	Tonnes
Description	*Onshore*	*Offshore*	*Total Capacity*	*Onshore*	*Offshore*	*Average weight of REEs per GW*	*Dy weight share*	
2020	530	133	663	75%	75%	600,000	4%	11,934
2030	1,094	274	1,368					24,624
2035	1,347	337	1,684					30,312
CAGR	8.5%							

*Note: CAGR from 2011 to 2035. Total Capacity in 2011 was 238 GW.
Source: Bauer et al. (2011)

TABLE 4.4 – METHOD AND DATA FOR DYSPROSIUM DEMAND REQUIREMENT FROM ELECTRIC VEHICLES[70]

	Electric Vehicles								
	Technology Deployed		% Using Dy		Material Intensity				Dy Demand Estimate
Unit	Million Vehicles		%		kg/EV	kg/EB	%		Tonnes
Description	*Electric Vehicles*	*Electric Bicycles*	*Electric Vehicles*	*Electric Bicycles*	*Average weight of REEs per EV*	*Average weight of REEs per EB*	*Dy weight share, EV*	*Dy weight share, EB*	
2012	1.2		100%	90%	2	0.2	6%	4%	
2013		31							
2020	7	38							1,114
2025	8.7	39.1							1,329
2030	10.9	40.3							1,595
2035	13.6	41.5							1,926
CAGR	24.7%	2.95%							

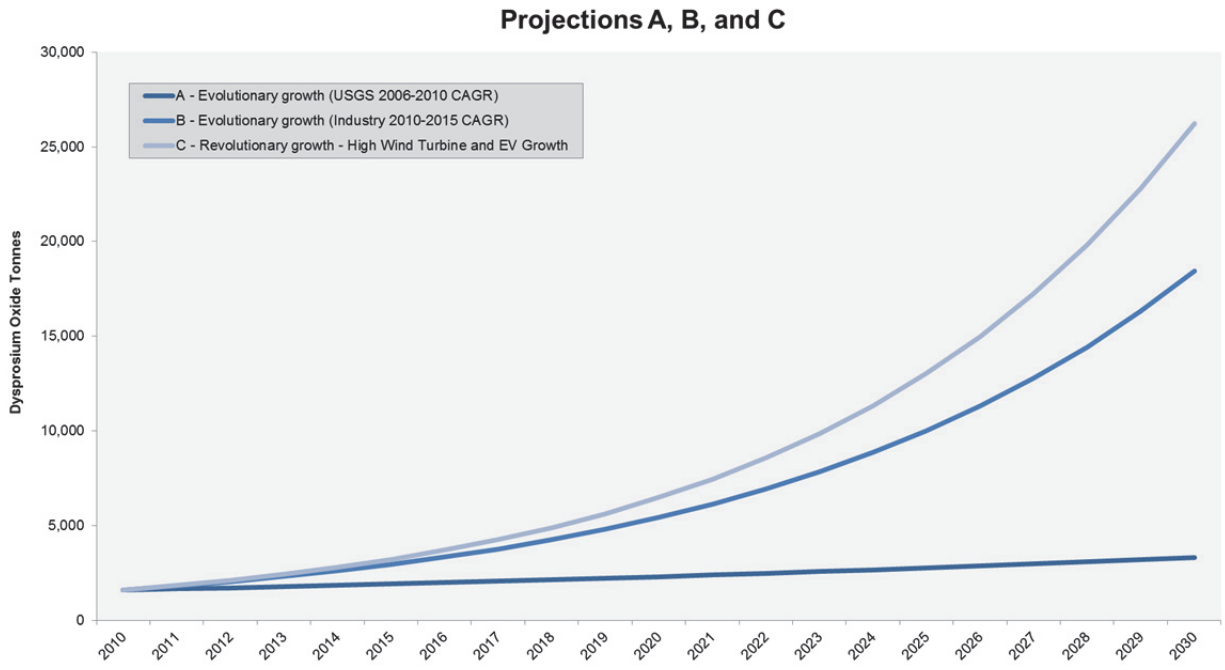
Note: EV values for 2025-2035 based on CAGR estimates for 2012-2020. EB values for 2020-2035 based on CAGR for 2013-2020. Source: Bauer et al. (2011), Navigant (2013)

Findings

As expected, the range of projected demands will vary significantly depending on growth assumptions (Figure 4.3). Projection A, which assumes a slow historical rate of growth, results in 2030 demand just over double the amount from 2010 at approximately 3,300 tonnes. In contrast, Projection B's industry assumptions lead to a much higher demand level of 18,400 tonnes. Finally, the ambitious clean energy goals embedded in Projection C yields a much larger demand at about 26,200 tonnes by 2030 with a CAGR of 15 percent. The projections in A, B, and C are largely consistent with projection ranges found in relevant literature on dysprosium demand projections (Hatch 2011, Kingsnorth and Chegwidden 2010, Goonan 2011, Kingsnorth 2011, Alonso et al. 2012, and Bauer et al. 2011).

[70] 2012 was the latest estimate for the number of electrical vehicles deployed while the latest estimate for electrical bicycles was from 2013.

FIGURE 4.3 – DYSPROSIUM OXIDE DEMAND PROJECTIONS UNDER DIFFERING ASSUMPTIONS



Dysprosium Supply Capacity

Non-Chinese Supply Capacity

In recent decades, dysprosium has been produced only in China. But dysprosium-rich deposits are found elsewhere, most significantly in Greenland and Canada which have about 600,000 to 650,000 tonnes[71] of dysprosium oxide, respectively, claimed by various mining companies. Kenya, Australia, South Africa, and the U.S. have dysprosium projects as well as several African countries including Kenya, Tanzania, and Malawi. Compared to Greenland and Canada, Chinese dysprosium oxide reserves of about123,000 tonnes may seem fairly modest (Shen 2012b). As previously noted, however, it is not merely the tonnage of REOs but also their grades (as percentage of total REOs in the deposits) that determine the value of a deposit. Higher grade levels mean more of the desired REO(s) are recovered from each mined tonne of raw ore, translating to higher profit margins. When dysprosium deposit tonnages are compared against their ore grade ranges, China strikes the best balance (Figure 4.4). For example, although South Africa's Steenkampskraal project has a very rich dysprosium grade (14 percent), its dysprosium oxide tonnage is estimated at a little more than a tenth of China's reserves (TMR 2014).

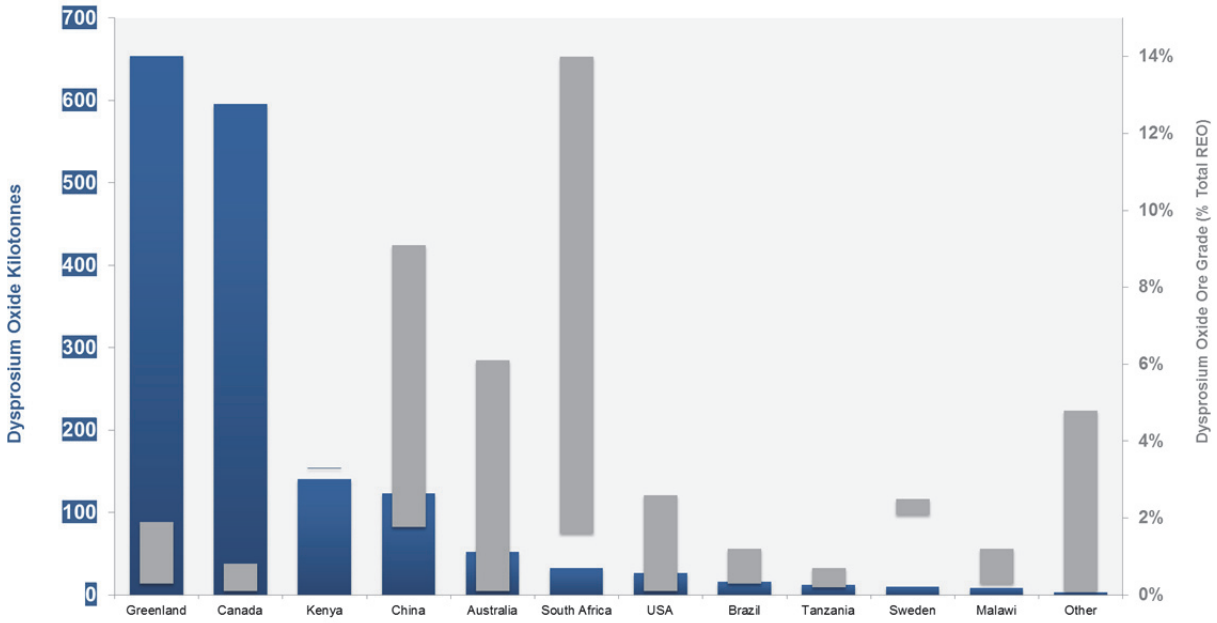
In addition to ore grades, a second significant advantage to Chinese dysprosium productions in Jiangxi, Guangdong, and Fujian[72] is that the production is much easier, and thus cheaper, because much of the material is extracted via a straightforward in-situ leaching process from ion adsorption clays. In contrast,

[71] Global dysprosium oxide demand in 2010 was about 1,600 tonnes (Goonan 2011).
[72] Smaller operations in Hunan and Guangxi.

ores found elsewhere are hard rock formation which requires significantly more energy for drilling and crushing that cuts into profitability (Hedrick 2010). Thus, because dysprosium and other HREEs production are more expensive in non-Chinese deposits, producers have had no incentive to produce these minerals in the past. However, the surge in rare earth prices in 2010 and 2011 provided a strong impetus for non-Chinese producers to dust off old projects and to initiate new ones. Even in the wake of the 2012 price collapse, dysprosium oxide and other HREO prices have remained above pre-2010 levels (Figure 4.5). The five-year average price of dysprosium oxide (2005-2009) was $83.68 per kilogram[73]. After declining from a high of more than $2,300 per kilogram in mid-late 2011, the first quarter 2014 price was still more than five times the pre-2010 price average at a hefty $465 per kilogram, reflecting strong contemporary and anticipated demands in the green technology sector.

Non-Chinese dysprosium projects that are expected to come online in coming years are defined by two attributes. First, they are generally junior mines[74] focused on heavy rare earths. Because of excess surplus in light rare earths whose market value is much lower, producers are focusing on projects with higher concentration distributions of heavy rare earths that have strong market value. Secondly, producers are focused on xenotime deposits which allows for cheaper processing and separation. This is in order to remain competitive against illegal Chinese exports that make their way through to the international market at below official export prices (below FOB China prices), undercutting non-Chinese producers' competitiveness (Northern Minerals 2014).

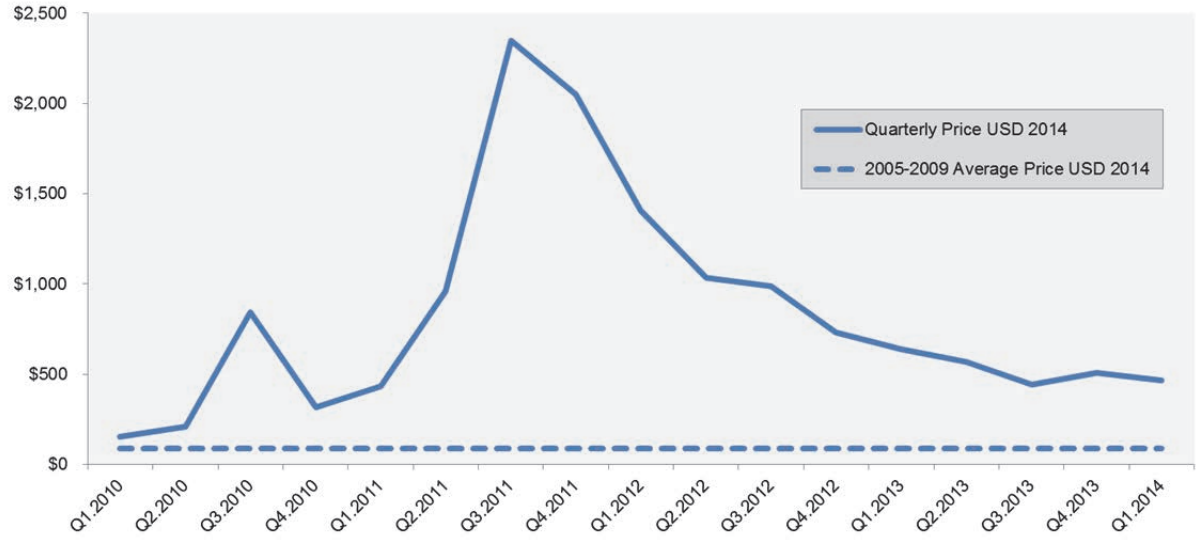
FIGURE 4.4 – GLOBAL DYSPROSIUM OXIDE DEPOSITS AND THEIR ORE GRADE RANGES



Data: Inferred from TMR (2014); Shen (2012a), Shen (2012b); and various industry sources.

[73] Free on board (FOB) export price from China, 2014 U.S. dollars.
[74] Junior mines are venture capital firms that raise capital from investors to finance the prospecting and auditing of reserves in a deposit. Junior miners do not build, own, or operate mines. Once a deposit has been valued and certified, they either proceed to production (at which point the ventures become known as mid-tier miners) or are more typically sold to major miners that have the financial and knowledge wherewithal to construct and operate a mining concern.

FIGURE 4.5 – DYSPROSIUM OXIDE FOB[75] CHINA PRICE ($/KG >99% PURITY) (CONSTANT 2014 USD)



Data: Metal-Pages.com

Projecting a reasonable estimate of dysprosium mining capacity for the short term (2015-2020) is possible. Potential mining operations regularly publish data on their projects' REO estimates, scheduled production start dates, and some indication of projected production levels. Technology Metals Research (TMR) maintains an active database, the TMR Advanced Rare-Earth Projects Index (AREPI), of non-Chinese rare earth operations globally that are in the advanced stages. AREPI includes 51 rare earth projects worldwide outside of China across 16 different countries (Table 4.5). As of February 7, 2014, these projects have formally been declared a REEs reserve under recognized standards such as NI 43-101, the JORC Code or the SAMREC Code (TMR 2014). Advanced status projects include those currently in production as well as though that are certified but undeveloped (meaning production may be many years, even decades away).

A selection of projects with known dysprosium reserves were identified from AREPI. Initial data were populated using data from Hatch (2011). The projects' statuses were updated where possible with open literature on the most recent production levels and expected years of operation through industry literature search. Two projects, Browns Range and Hastings, both in Australia, were added to the roster of projects based on information from literature that suggested that production was probable in the short term. AREPI sources its data from non-government owned operations so a separate research was conducted for REEs projects that are owned or co-owned by state enterprises, namely Dong Pao (Vietnam) and Orissa-Kerela (India) to verify whether significant dysprosium production is taking place or otherwise planned.

[75] FOB (Free On Board) prices are unit prices before transportation fees, customs, and other ancillary costs.

Projections D and E

Assumptions

Supply projections are categorized by geographic sources: Chinese, American, and rest of the world (ROW). For all supply capacity projections (D through H), total supply capacity is the sum of the estimates of Chinese production *quota* and U.S. and ROW *capacity*. For ROW producers, the focus is on total capacity rather than actual production amount because capacity sets the upper bound limit on potential supply. It is also a more reliable estimate since production amounts can vary significantly depending on market conditions.

For the same reason, Chinese production quota, rather than capacity, is counted. This is a more reasonable (conservative) upper bound limit on Chinese levels because Chinese production levels are set lower than their full facility capacities by Beijing's heavy handed tactics to conserve resources and throttle down production (as described in Chapter 2). Thus, in order to arrive at a conservative estimate of China's supply capacity, sanctioned production quotas, rather than full capacity levels, are used.[76]

All projections assume Beijing is successful in clamping down on illegal production. Thus estimates of illicit trade export volumes are excluded, again to arrive at a conservation supply estimate. USGS (2013) and Hatch (2011) were used for estimates on Chinese REEs production and quotas levels. Prospective Chinese dysprosium production levels were inferred from the known ratio of dysprosium oxide to total Chinese REO production in 2010, which was 0.79 percent. Future dysprosium production level assumes this ratio will remain static.

A short-term supply projection to the year 2020 is made using the modified AREPI database. The approach here is to start simple with Projections D and E and start layering it with modest complexity to arrive at shortfall projections at the end.

Projection D

For Projection D, optimistic assumptions are made. First, it assumes that all mining production begins at published expected dates of production. Where no announcement on the production start date is made, a very generous assumption is made that production will begin at the earliest reasonable date which is in 2021. It assumes that Chinese dysprosium supply will increase at a modest 3 percent annual growth rate (Hatch 2011).

Projection E

For Projection E, pessimistic assumptions are made. We assume that non-Chinese production is delayed by one year from published dates of expected operations while Chinese dysprosium production remains flat. Where no announcement on the production date is made, the conservative assumption is made that the project will remain dormant for the rest of the time period.

For both projections, the assumption is that, delays notwithstanding, dysprosium production will proceed sooner or later for non-Chinese suppliers. Furthermore, it assumes these projects will remain productive if they begin operation and will not revert to closures in the projected time period. This is a strong assumption but is reasonable given that the objective of this exercise is to understand upper bound limits on supply capacity rather than to forecast point-estimates on production levels.

[76] Production quota is necessarily equal to or less than capacity.

TABLE 4.5 – PROJECTED NON-CHINESE DYSPROSIUM OXIDE SUPPLY CAPACITIES

Projection D - Optimistic

Project	Country	Owner(s)	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Bear Lodge	USA	Rare Element Resources Ltd.	0	0	0	0	0	0	0	0	23	42	60	120	120	120	120	120	120	120	120	120	120
Bokan	USA	Ucore Rare Metals Inc.	0	0	0	0	0	0	0	95	95	95	95	95	95	95	95	95	95	95	0	0	0
Browns Range	AUS	Northern Minerals	0	0	0	0	0	0	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270
Buena Norte	BRA	Nuclear Industries of Brazil (SOE)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Cummins Range	AUS	Navigator Resources Limited	0	0	0	0	0	0	0	0	0	0	0	283	283	283	283	283	283	283	283	283	283
Dubbo Zirconia Project	AUS	Alkane Resources Ltd.	0	0	0	0	0	0	23	93	93	93	93	93	93	93	93	93	93	93	93	93	93
Eco Ridge	CAN	Pele Mountain Resources Inc.	0	0	0	0	0	0	0	41	41	41	41	41	41	41	41	41	41	41	41	41	41
Eldor	CAN	Commerce Resources	0	0	0	0	0	0	0	0	0	0	0	106	106	106	106	106	106	106	106	106	106
Hastings	AUS	Hastings Rare Metals Ltd.	0	0	0	0	0	0	1,044	1,044	1,044	1,044	1,044	1,044	1,044	1,044	1,044	1,044	1,044	1,044	1,044	1,044	1,044
Hoidas Lake (JV)	CAN	Great Western Minerals Group Ltd.	0	0	0	0	0	0	9	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Kangankunde	MWI	Lynas Corporation Ltd.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Karnasurt	RUS	Uralkali	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Kutessay II	KGZ	Stans Energy Corp.	0	0	0	0	0	0	0	0	0	0	0	92	92	92	92	92	92	92	92	92	92
Kvanefjeld	GRL	Greenland Minerals and Energy Ltd.	0	0	0	0	0	0	0	0	481	481	481	481	481	481	481	481	481	481	481	481	481
Mount Weld*	AUS	Lynas Corporation Ltd.	0	0	95	191	191	191	191	191	191	191	191	191	191	191	191	191	191	191	191	191	191
Mountain Pass	USA	Molycorp Inc.	1	1	1	10	10	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Nechalacho*	CAN	Avalon Rare Metals Inc.	0	0	0	0	0	0	0	51	204	204	204	204	204	204	204	204	204	204	204	204	204
Nolans	AUS	Arafura Resources Ltd.	0	0	0	0	0	0	0	16	64	64	64	64	64	64	64	64	64	64	64	64	64
Norra Kärr	SWE	Tasman Metals Ltd.	0	0	0	0	0	0	0	135	215	295	295	295	295	295	295	295	295	295	295	295	295
Orissa-Kerala	IND	Indian Rare Earths Ltd (SOE)	0	0	0	2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Sarfartoq	GRL	Hudson Resources Inc.	0	0	0	0	0	0	0	0	0	0	0	933	933	933	933	933	933	933	933	933	933
Steenkampskraal	ZAF	Great Western Minerals Group Ltd.	0	0	0	0	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Strange Lake*	CAN	Quest Rare Minerals Ltd.	0	0	0	0	0	0	0	0	111	445	445	445	445	445	445	445	445	445	445	445	445
Zandkopsdrift (JV)	ZAF	Frontier Rare Earths Ltd.	0	0	0	0	0	0	78	156	156	156	156	156	156	156	156	156	156	156	156	156	156
Zeus	CAN	Metamec Explorations Inc.	0	0	0	0	0	0	0	106	144	144	144	144	144	144	144	144	144	144	144	144	144
Total			**5**	**5**	**101**	**207**	**258**	**269**	**1,693**	**2,293**	**3,228**	**3,661**	**3,679**	**5,153**	**5,153**	**5,153**	**5,153**	**5,153**	**5,153**	**5,153**	**5,058**	**5,058**	**5,058**

Projection E - Pessimistic

Project	Country	Owner(s)	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Bear Lodge	USA	Rare Element Resources Ltd.	0	0	0	0	0	0	0	0	0	0	23	42	60	120	120	120	120	120	120	120	120
Bokan	USA	Ucore Rare Metals Inc.	0	0	0	0	0	0	0	0	95	95	95	95	95	95	95	95	95	95	95	0	0
Browns Range	AUS	Northern Minerals	0	0	0	0	0	0	0	270	270	270	270	270	270	270	270	270	270	270	270	270	270
Buena Norte	BRA	Nuclear Industries of Brazil (SOE)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Cummins Range	AUS	Navigator Resources Limited	0	0	0	0	0	0	0	0	0	0	0	Unknown. Esimated earliest possible start date.									
Dubbo Zirconia Project	AUS	Alkane Resources Ltd.	0	0	0	0	0	0	0	23	93	93	93	93	93	93	93	93	93	93	93	93	93
Eco Ridge	CAN	Pele Mountain Resources Inc.	0	0	0	0	0	0	0	0	0	0	0	Unknown. Esimated earliest possible start date.									
Eldor	CAN	Commerce Resources	0	0	0	0	0	0	0	0	0	0	0	Unknown. Esimated earliest possible start date.									
Hastings	AUS	Hastings Rare Metals Ltd.	0	0	0	0	0	0	0	1,044	1,044	1,044	1,044	1,044	1,044	1,044	1,044	1,044	1,044	1,044	1,044	1,044	1,044
Hoidas Lake (JV)	CAN	Great Western Minerals Group Ltd.	0	0	0	0	0	9	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Kangankunde	MWI	Lynas Corporation Ltd.	0	0	0	0	0	0	0	0	0	0	0	Unknown. Esimated earliest possible start date.									
Karnasurt	RUS	Uralkali	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Kutessay II	KGZ	Stans Energy Corp.	0	0	0	0	0	0	0	0	0	0	0	Unknown. Esimated earliest possible start date.									
Kvanefjeld	GRL	Greenland Minerals and Energy Ltd.	0	0	0	0	0	0	0	0	0	120	481	481	481	481	481	481	481	481	481	481	481
Mount Weld	AUS	Lynas Corporation Ltd.	0	0	95	143	191	191	191	191	191	191	191	191	191	191	191	191	191	191	191	191	191
Mountain Pass	USA	Molycorp Inc.	1	1	1	5	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Nechalacho	CAN	Avalon Rare Metals Inc.	0	0	0	0	0	0	0	0	0	51	204	204	204	204	204	204	204	204	204	204	204
Nolans	AUS	Arafura Resources Ltd.	0	0	0	0	0	0	0	0	0	2	64	64	64	64	64	64	64	64	64	64	64
Norra Kärr	SWE	Tasman Metals Ltd.	0	0	0	0	0	0	0	0	135	215	295	295	295	295	295	295	295	295	295	295	295
Orissa-Kerala	IND	Indian Rare Earths Ltd (SOE)	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Sarfartoq	GRL	Hudson Resources Inc.	0	0	0	0	0	0	0	0	0	0	0	Unknown. Esimated earliest possible start date.									
Steenkampskraal	ZAF	Great Western Minerals Group Ltd.	0	0	0	0	0	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Strange Lake	CAN	Quest Rare Minerals Ltd.	0	0	0	0	0	0	0	0	0	111	445	445	445	445	445	445	445	445	445	445	445
Zandkopsdrift (JV)	ZAF	Frontier Rare Earths Ltd.	0	0	0	0	0	0	0	78	156	156	156	156	156	156	156	156	156	156	156	156	156
Zeus	CAN	Metamec Explorations Inc.	0	0	0	0	0	0	0	0	106	144	144	144	144	144	144	144	144	144	144	144	144
Total			**5**	**5**	**101**	**153**	**207**	**265**	**274**	**1,689**	**2,173**	**2,575**	**3,588**	**3,607**	**3,625**	**3,684**	**3,684**	**3,684**	**3,684**	**3,684**	**3,684**	**3,589**	**3,589**

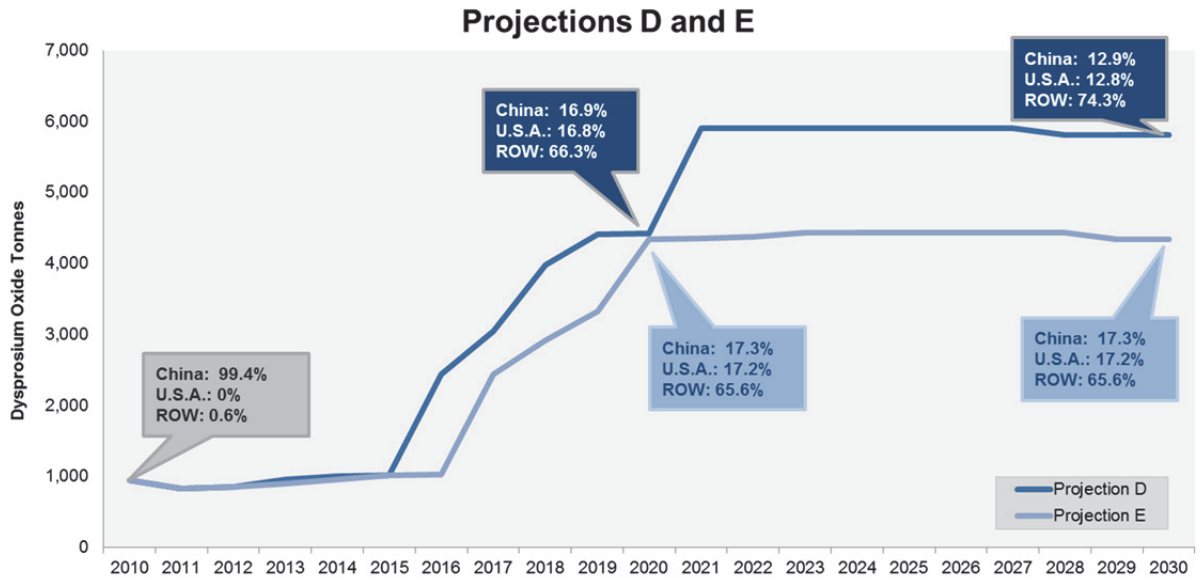
Source: Hatch (2011); (TMR 2014); and various industry reports.

Findings

The 2016-2017 time period is crucial because of the expected introduction of non-Chinese dysprosium supply as projects that have been under development in the past 5-7 years finally come into operation (Figure 4.6). According to Projection D, global ROW capacity could multiply to more than 4.6 times the 2010 levels. ROW capacity share could grow from less than 1 percent in 2010 to roughly 78 to 80 percent. U.S. production levels could also increase from half a percent to the approximately the 3 to 4.5 percent range by 2020.

In all likelihood, however, Projections D and E are significantly underestimating supply capacity for the decade after 2020. This is because these projections do not accommodate for the possibility that marginal projects currently excluded from AREPI may be upgraded to advanced operating status in the future. Their exclusion (and the aforementioned strong assumption that projects remain operational upon opening and do not close down) is why the supply capacities generally flatten out after 2021.

FIGURE 4.6 – GLOBAL DYSPROSIUM SUPPLY CAPACITY PROJECTIONS



Again, it is very difficult to say what the supply capacity of non-Chinese dysprosium producers will be beyond those projects that, as of today, are in very advanced stages of development (i.e., those projects that are currently operating or likely to operate within five years' time). Mining operations take a significant amount of time between initial exploration and production, typically as long as fifteen years or more, as was explained in Chapter 3. Many so-called greenfield projects are on-going to identify potential new deposits, but the time between discovery and production may take a generation's length of time. For example, it takes about ten to fifteen years or more to move from initial discovery to mandated feasibility studies. Afterwards, it could take another five to ten years to obtain licenses, financing, and build the mine and infrastructure before initial production starts. In all, a newly discovered deposit can take decades before it becomes operational. The next three supply capacity projections attempt to incorporate growth projections past 2021 using a top-down approach rather than the bottom-up method used in the 2010-2020 time frame.

Projections F, G, and H

Assumptions

A long term projection is made for the years 2021 to 2030 using three different rates of annual growth rates—low, middling, and aggressive—given the high level of uncertainty discussed above. Supply projection for the long term (ten-year period between 2021 and 2030) is more challenging because of the uncertainty of young or dormant AREPI projects and other projects that may be certified and brought online at some point in the next 15 years. Thus instead of projecting supply for 2021-2030 using a bottom-up approach, the long term supply trajectory is estimated using a top-down method using two

historical growth rates (also referred to as evolutionary growth rates) and a third, non-growth projection as the lowest of upper bound capacity.[77]

Projection F

Projection F shares the same optimistic assumptions of Projection D and incorporates its historical short term estimates (2010 to 2020). 17.2 percent is the CAGR of Projection D's capacity growth between 2010 and 2020. For Projection F, this rate is applied as the annual growth rate for non-Chinese (aggregate U.S. and ROW) capacity during the 2021 to 2030 time period. China's CAGR is a conservative 3 percent.

Projection G

Projection G shares the same assumptions and short term estimates at Projection E. However, the historical annual REO supply growth of 5.4 percent (Alonso et al. 2012)[78] is used to project non-Chinese capacity growth from 2021 to 2030. China's growth is set at 0 percent. This is the middling projection.

Projection H

Projection H assumes stagnant, that is, 0 percent annual growth for both Chinese and non-Chinese production after 2014[79]. Projection H is the "worst case" projection where dysprosium prices fall below marginal costs of production that deter new market entrants while China maintains its strict reign over production and export quotas.

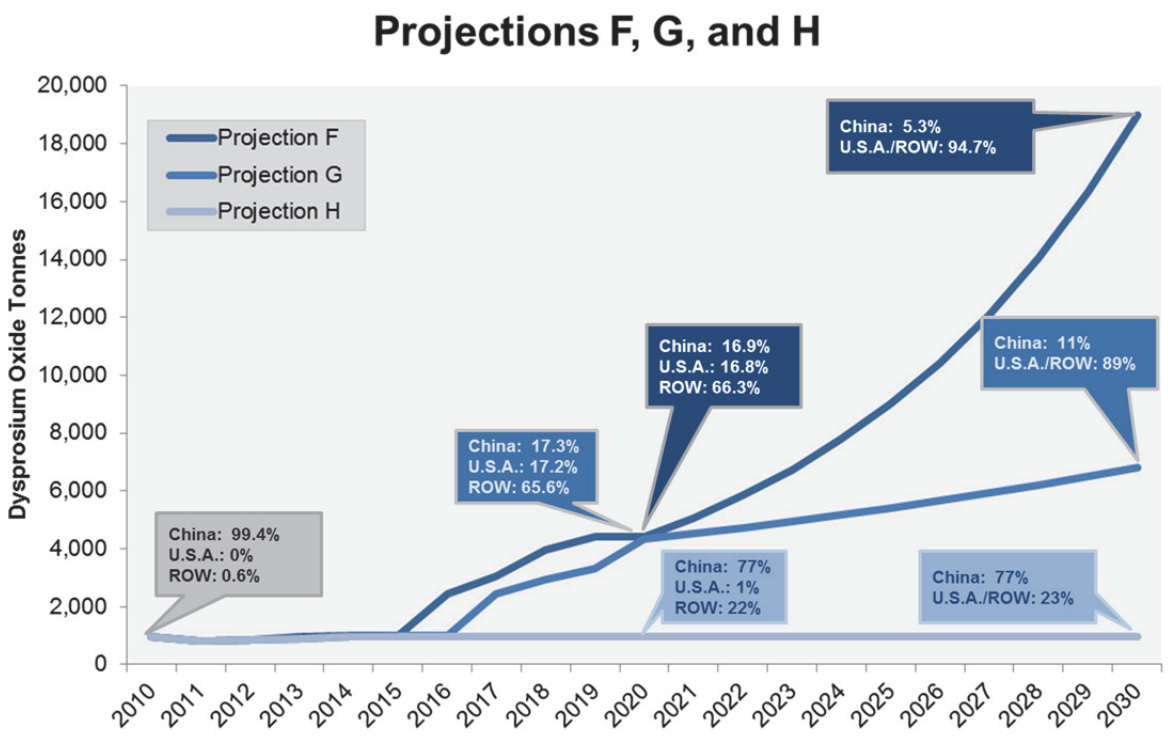
Findings

While it should be clear that Projections F through H are, at best, informed guesses, it suggests the possibility that the Chinese monopoly on dysprosium production could be transitory. If Chinese dysprosium production remains modest in line with its policy focus on industry consolidation and resource conservation measures, the expected trends in non-Chinese production would rapidly overtake Chinese production levels in the future. It is worth nothing that the bulk of ROW production is likely to originate from Australia, Canada, and Greenland in coming years, and possibly South Africa, given friendly regulatory environments and their second-tier but still highly coveted deposit grades.

As displayed in Figure 4.7, in the most optimistic case, China's dysprosium output could shrink to just over 5 percent of total capacity if all projects were sufficiently profitably and pass regulatory hurdles. On the contrary, the most pessimistic projection would be if Chinese production remained stagnant and non-Chinese production remained at 2014-2015 levels. In this case, Chinese dominance would perpetuate, maintaining more than 75 percent of global production with the balance coming largely from Australia and Canada.

[77] The advantage of using past growth rate estimates is that it is anchored on precedence. The downside, however, is that projections are naïve at the country level. Beyond comparison of China versus non-China, the proportional share of countries cannot be deduced since the evolutionary growth rates are applied blindly to the aggregate non-Chinese capacities.
[78] 1970-2010, annual REE growth averaged 6.5% ranging between -21% and 34% per annum. Overall long-term fit curve annual growth rate is 5.4% (Alonso et al. 2012).
[79] 0 percent growth rate adopted from Hatch (2011).

FIGURE 4.7 – GLOBAL DYSPROSIUM OXIDE SUPPLY CAPACITY



Dysprosium Shortfall

Shortfall Projections

Assumptions

Shortfalls are defined as the difference between projected supply capacity and demand requirement at disequilibrium prices. Per the cobweb and stochastic pricing assumptions from theoretical literature, dysprosium oxide prices are disequilibrium prices that result in mismatches in demand and supply quantities that cause shortfalls. Furthermore, exogenous shocks on supply and demand curves, such as regulatory changes, geopolitics, and technological developments could alter the supply and demand dynamics of dysprosium in unexpected ways, rendering forecasts on shortfalls difficult if not moot.

Nonetheless, using supply and demand projections to construct a plausible *range* of magnitudes in capacity shortfall can assist with policy planning. To re-emphasize, these capacity shortfall projections are not akin to predictive models, theoretical, empirical, simulation, or otherwise. They do not have any explanatory or predictive power and no presumption is made to that effect. Additionally, only mining is considered a source of supply: excluded are other potential sources of supplies or demand mitigation alternatives, such as substitutes or substitute technologies (work-arounds), or recycling.

Five cases are generated (Table 4.6). The Best Case (upper bound) is a combination of Projections A and F where supply capacity is high and demand is low. An Average Case is the combination of middling

Projections B and G. A Worst Case (lower bound) is a combination of Projections C and H where there is low capacity supply but high demand.[80] In addition, there are the Low Demand and Low Supply Capacity Case (LL) and the High Demand and High Supply Capacity (HH).

TABLE 4.6 – SHORTFALL PROJECTION GUIDE

Shortfall Projections Legend		
Shortfall	**Supply Capacity**	**Demand**
Best Case	F	A
Average Case	G	B
Worst Case	H	C
LL	H	A
HH	F	C

The demand satisfaction ratio, i.e., the supply to demand ratio, for a given year y is denoted as DS_y. It is the percentage of annual global projected demand D_y that could theoretically be satisfied by a projected annual global supply capacity SC_y in a given year. It is simply SC_y in proportion to D_y:

$$DS_y = \frac{SC_y}{D_y}, where\ 0 \leq\ DS_y \leq 1$$

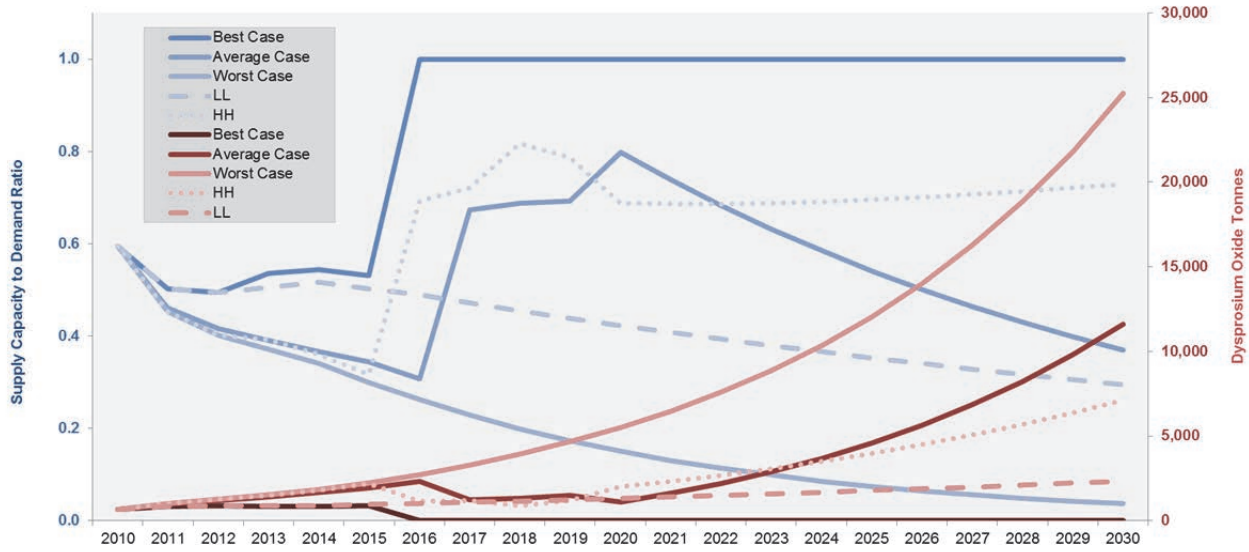
Findings

Figure 4.8 graphs the five cases of the dysprosium demand satisfaction rate. Again, the assumption here is that there are no Chinese export restrictions. In the Best Case, the combination of stagnant demand and aggressively high levels of mine openings worldwide could theoretically meet all demand levels beginning as soon as in 2016. In the Worst Case, demand satisfaction gradually erodes to as low as 4 percent of demand requirement starting in 2029. Figure 4.8 also exhibits the range of shortfall in tonnage. The Best and Worst Case shortfalls range between zero tonnes (in fact, a surplus capacity) to as high as approximately 25,000 tonnes, respectively. For the projection in between the upper and lower bounds from 2015 to 2020, the shortfall ranges consistently between 800 and 1,500 tonnes. In the decade following, however, the scale diverges greatly, with shortfalls ranging from 2,300 tonnes to greater than 11,600 tonnes by 2030.

As expected, the 2016 to 2020 period is the likely transition period when new dysprosium supply capacities come online, increasing the demand satisfaction percentage. If demand continues to be strong past 2020, however, and unless new dysprosium mining capacities open just as aggressively as it did between 2010 and 2018, demand satisfaction may stagnate or regress. This suggests that even with the introduction of new capacities, it is entirely possible that not only could shortfalls persist, but the sheer scale of the shortfall could be in multiples of today's levels. Instead of shortfalls measured in hundreds of tonnes, there is the possibility of shortfall measured in tens of thousands of tonnes. While additional mining is a necessary component to meeting demand, it may not necessarily be a sufficient response, *ceteris paribus*.

[80] This would be a "worst" case since we are assuming dysprosium demand inelasticity due to the lack of substitutes. If substitutes were available, however, demand would elastic and the supply capacity constraints would translates to lower levels of demand.

FIGURE 4.8 – DYSPROSIUM DEMAND SATISFACTION RATES AND SHORTFALL ESTIMATES



Chapter Summary

Dysprosium is a critical rare earth element with important applications in green technology and defense (Chapters 2 and 3). As a relatively young metal with applications in vanguard technologies, industry experts see a high rate of potential demand growth in the coming decades. New sources of dysprosium are due to become operational within the next five years that will help meet some of the demand.

While we cannot know what the actual consumption and mining capacities will be, the range of possibilities based on projections suggest that demand satisfaction rates could remain low indefinitely *if* demand for dysprosium remains strong. This may be the case even if there is an upswing in supply capacities (e.g., Worst Case, LL, and Average Case projections). Alternatively, low shortfalls (and high demand satisfaction) is a competing plausible outcome contingent upon rapid supply capacity growth in China and particularly abroad and slow or stagnant demand growth (Best Case projection).

Because these projections were based on strong assumptions, care was taken to draw inferences without deviating into speculations. To be sure, the core assumptions regarding the lack of deployable substitutes, work-arounds, and recycling technologies are consistent with contemporary reality (although that may change in the future). Similarly, the use of historical, expert, and method-based growth estimates are reasonable and considered standard practices for policy planning.

With these caveats in mind, the projections point to two important points. First, the projections elucidate the fact that mining alone may not be sufficient to meet strong dysprosium demand, no matter how fast supply capacity grows in the next fifteen years. The Best Case projection—where there is no shortfall—is feasible only when demand growth is slow. High supply capacity growth in ROW countries increases the diversity of suppliers which helps mitigate supply risk by undermining Chinese monopoly. However,

even such growth rates are insufficient to meet even modest rates of dysprosium demand growth. This calls attention to the U.S. policy community that while additional mining is necessary, more must be done. Chapter 6 explores what these other policy options are.

The second point is that the wide range of plausible outcomes points to the inherent uncertainty the policy maker faces when deciding how to invest in dysprosium criticality reduction policies. Policies must be pursued so that they are robust against a range of external circumstances, not just one aspired outcome. To this end, Chapter 5 introduces three scenarios (concocted based on optimistic, sober, and worst case assumptions) against which policy options will be evaluated in their effectiveness in reducing dysprosium criticality. More broadly, the chapter introduces the combination of qualitative and quantitative methods for systematically assessing the costs and effectiveness of the policy options and the mixed-integer linear programming technique for assembling optimal policy packages in Chapter 7.

Chapter 5 – Methods for Policy Assessment and Portfolio Optimization

"Despite the enormous publicity that has recently surrounded the mining and processing REE, very little quantitative information is available."
- Xiaoyue Du and T.E. Graedel

Introduction

The preceding trilogy of Chapters 2, 3, and 4 took a historical, contemporary, and prospective look at dysprosium and other rare earths—its politics, economics, and geology and how these factors contribute to dysprosium as a critical element. Through these analyses, we established the unique dysprosium policy challenge confronting the U.S. decision maker today. Starting with this chapter (Chapter 5) and in the two that follow (Chapters 6 and 7), we begin assessing potential policy solutions to that challenge.

The technical contents of this chapter establish the necessary methodological foundations which are applied in Chapters 6 and 7. This chapter is divided into two parts. The first part explains the methodology that is used to systematically assess the policy impact scores of policy options that can reduce dysprosium criticality. It also reviews how the policy options' implementation costs are calculated for the fifteen fiscal years covered in this study (FY 2015 to FY 2029). The contents covered in this first half of the chapter are applied in Chapter 6 where the policy options' costs and effectiveness are evaluated.

The second part of this chapter introduces the quantitative method (mixed-integer linear programming model) that will be used to assemble optimal combinations of policy portfolios (packages) for a range of policy budgets. The model will ensure that the assembled portfolios can reduce dysprosium criticality across three different future scenarios. The scenarios depict optimistic, sober, and worst future cases. This analysis will yield information on how much dysprosium criticality reduction (effectiveness) can be achieved by optimal portfolios for each budget level. The method described in this bottom half of the chapter is applied directly in Chapter 7.

Policy Objectives, Costing, and Effectiveness Scoring

This section introduces what the governing premise—the policy objective—of the policy options is. It then reviews how their implementation costs are assessed and how their effectiveness in meeting the policy objective is assessed. The methods covered here applied in Chapter 6.

Policy Objective: Fulfilling Statutory Requirements by Criticality Reduction

This research evaluates how the U.S. government can best meet the intent, if not the letters, of American statutory objectives by investing in policies to decrease the criticality of dysprosium and rare earths writ large. There are two statutory requirements that bear on dysprosium (and rare earths) strategic planning.

The first statutory requirement is codified in Section 1211 of FY 2006 National Defense Authorization Act (NDAA) (with amendments in Section 1243 in FY 2012) which prohibits the DoD from requisitioning supplies or services from Chinese entities. In addition, 10 U.S. Code § 2533a and b (specialty metal clauses) require that the DoD's acquisition of metal products like permanent rare earth magnets to be wholly sourced from and produced within the U.S. (with certain waiver exceptions).

The second objective, as empowered by Articles I and II of the U.S. Constitution and implemented by the Executive branch[81], is to "ensure fair trade through rigorous enforcement of [U.S.] trade laws and agreements" (International Trade Administration 2014). More specifically, the policy planner would seek to rectify unfair practices such as injurious economic outcomes from Beijing's rare earths policy. This study takes a broad view of rectification to include any action that limits the damage from unfair practices or incentivizes the offending country to lower, if not eliminate, the degree of such practices.

While the planner may expand the scope of objectives, these are considered foundational responsibilities. In practice, this translates to three parallel policy objectives:

- Addressing China's export restrictions of rare earths which has distorted global market prices of the metals,
- Revitalizing U.S. rare earth supply chain or otherwise introducing policies such that DoD contractors properly source rare earth goods from U.S. and other qualified foreign suppliers across the value chain,
- Establishing contingency plans that ensure adequate rare earths supplies to meet essential civilian and defense requirements during a major national emergency.

But how does criticality reduction fulfill these statutory objectives? Let us first begin with a review of the concept of material criticality. Criticality is the assessment of the vulnerability of a certain material to a shortfall, defined as the gap between demand requirement and supply capacity. It is a risk assessment metric designed to gauge whether a material has a high likelihood of supply disruption and shortfall stemming from economic, geopolitical, and technological trends. Statutory requirements, on the other hand, require that defense arms procure rare earths from U.S. sources, plan for emergencies, and advocate on behalf of American stakeholders within free trade regimes.

The two concepts are obviously closely related: lower criticality helps satisfy U.S. legal mandates. The converse, however, is not always true. For example, a contingency plan (such as a stockpile), satisfies requisite planning requirements and would help overcome a period of shortfall, but it does not fundamentally address structural changes—economic, political, and technology—that have caused the shortfall in the first place. Similarly, seeking monetary compensation or trade concessions from China through the WTO is one method for securing reparations for economic injuries from China's rare earth policies. But doing so would not reduce the criticality of dysprosium or rare earths. In contrast, the successful development of substitute technologies could theoretically substantially lower criticality, although the near-term likelihood is low.

The benefit of focusing on reducing criticality reductions rather than simply adhering to specific statutory requirements is that it allows the policy maker to address the root causes dysprosium supply risk. The statutes provide an indication of how to mitigate the consequences of the risk, but do not provide guidance on how to address the cause of the risk. Thus, adopting the criticality reduction framework

[81] As explained by the Legal Information Institute (LII), "The Commerce Clause of the U.S. Constitution empowers Congress to 'regulate commerce with foreign nations,' U.S. Const. Art. I, § 8, cl. 3, while other Article I provisions empower Congress to 'lay and collect taxes, duties, imposts, and excises,' id. at Art. I, § 8, cl. 1, and prohibit states from doing the same without congressional approval, id. at Art. I, § 10, cl. 2. Pursuant to this authority, Congress has enacted numerous federal statutes, including the Tariff Act of 1930, the Trade Act of 1974, and the Trade Agreements Act of 1979.
Article II of the U.S. Constitution empowers the President, 'by and with the advice and consent of the Senate, to make treaties, provided two thirds of Senators present concur.' U.S. Const. Art. II, § 2, cl. 2. Pursuant to this authority, presidents have negotiated numerous international treaties and trade agreements" (LII n.d.).

empowers the policy maker to be systematic and robust in working towards enduring solutions to the dysprosium supply risks.

Policy Implementation Cost

Per the cost-effective framework of this study, the policy cost estimates are calculated in terms of U.S. government fiscal implementation cost for the duration of the study period FY 2015 to FY 2029. The sole exception applies to stockpiling costs which are estimated for the period FY 2014 to FY 2029 since the NDAA of 2014 has already appropriated the funds for FY 2014. For policy options derived from literature, their implementation costs are calculated using updated data and adjustments to the authors' methodologies. Alternatively, for policies modeled from proposals introduced in Congress, cost estimates were elicited from Congressional Budget Office (CBO) literature. The costs for new policies formulated in this research were estimated using government and industry sources with similar program properties.

The total implementation cost is discounted using the real discount rate δ of 4 percent. The 4 percent is an approximate average between the Office of Management and Budget's (OMB) required 7 percent (OMB 2003) and the midway point between the 10- and 20-year real U.S. Treasury note interest rate for FY 2014, which is 1 percent and 1.6 percent, respectively (OMB 2014).[82]

Policy Effectiveness

Criticality Matrix

Policy effectiveness is assessed on the basis of their contribution to mitigating *material importance* and *supply risk* as established in the criticality matrix developed by NRC (2008) and further modified by Bauer et al. (2011). *Material importance* is a function of current and anticipated technological applications, their projected increase (or decrease), and technological progress that could increase efficiency of use, substitution, or work-arounds that affect demand levels. *Supply risk* is a function of geological availability, the technical feasibility of extracting them from known reserves, and political-economic factors such as mining, environmental, labor, and trade regulations that govern the industry.

Both dimensions are scored on an integer scale of 1 (low) to 4 (high)[83]. Those that score highest on both axes are deemed most critical. Thus, *the purpose of any policy option is to lower the criticality score* (i.e., make dysprosium less critical). The consequence of lower criticality is that it reduces American stakeholders' vulnerability to supply disruptions. Therefore, from a policy planning perspective, criticality reduction is equivalent to vulnerability reduction.

The NRC (2008) study defines criticality of nonfuel minerals such as rare earths in the following manner:

> A mineral can be regarded as critical only if it performs an essential function for which few or no satisfactory substitutes exist. This dimension of criticality is therefore related to the demand for a mineral that meets very precise specifications required in certain key applications, but it is not simply releated to overall demand for all applications. Instead, it reflects economic, social, and other consequences if essential functions cannot be delivered. In addition, a mineral can be

[82] The discount rate could be adjusted to higher or lower than 4 percent. However, while the absolute value of the costs would differ, the relative cost-effectiveness of the policy options would not be significantly impacted since the cost comparison would be relative to uniformly discounted values.

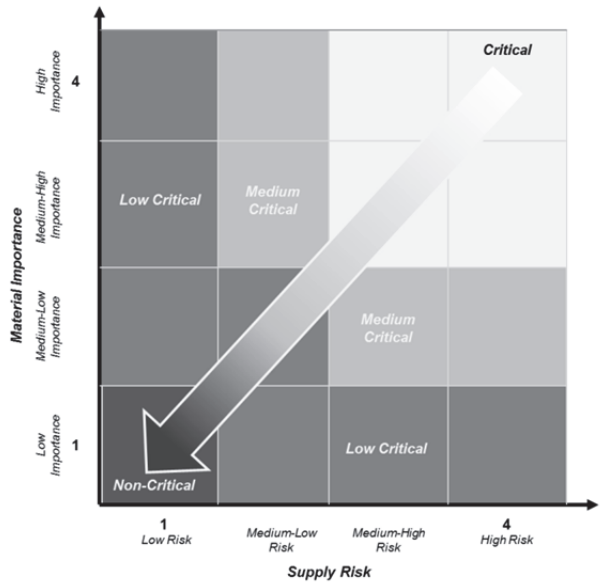
[83] Strictly speaking, no material can become "non-critical" in the absolute sense. There is always a probability of residual supply risk—however low the risk may be—and there is always some minimal level of importance. Thus no material falls below the value of 1 in either axis of the criticality matrix.

> regarded as critical only if an assessment also indicates a high probability that its supply may become restricted, leading either to physical unavailability or to significantly higher prices for that mineral in key applications. In turn, the probability of a restriction in the supply of a critical mineral is more likely to be assessed as high if the aggregate demand for key applications represents a relatively large proportion of the overall supply of the mineral that meets the required specifications…Determining a mineral's criticality, then, is a means by which decision makers can help alleviate potential impacts of a restriction on the supply of a mineral, or avoid supply restriction entirely through informed decisions.

As applied to dysprosium criticality, the practical implications for green technology would include less efficient wind power generation and the inability to meet important commercial or social plans for increasing the share of electric vehicles and bicycles in major consumer markets in Asia and the West. Militarily for the U.S., this means trading off supply security for critical military system components for available permanent magnet supplies from China, potentially at the risk of violating U.S. laws that prohibit such outcomes. Alternatively, it would mean allocating additional costs to systems procurement to afford scarce dysprosium supply or to accept trade-offs in performance by relying on inferior magnets.

Revising the NRC (2008), Bauer et al. (2011) describes the *material importance* dimension as the weighted average of two sub-dimensions: importance of the material to consumers (with a 75 percent weight) and substitutability limitation (25 percent). The *supply risk* dimension is the weighted average of five sub-dimensions: a material's availability (40 percent), competing demand (10 percent), political/regulatory/social factors (20 percent), co-dependence on other markets for material co-production or by-production (10 percent), and diversity of suppliers (20 percent). The two dimensions determine the overall criticality of the mineral. Figure 5.1 illustrates the criticality concept in a matrix framework. The most critical state is in the upper right four quadrants of the matrix. The criticality decreases as it moves further to the bottom left. Table 5.1 explains Bauer et al.'s (2011) criticality rating terminology using dysprosium as an example.

FIGURE 5.1 – RAW MATERIAL CRITICALITY MATRIX



Source: Adopted from NRC (2008) and Bauer et al. (2011)

TABLE 5.1 – BAUER ET AL. (2011) CRITICALITY RATING FOR DYSPROSIUM

Dimension	Sub-Dimension	Weight	Description	Short Term Score	Short Term Weighted Score	Medium Term Score	Medium Term Weighted Score
Dysprosium Importance to Clean Energy	Clean Energy Importance	75%	Captures the importance of the material in magnets, batteries, photovoltaic (PV) films and phosphors used in clean energy technologies.	4	3	4	3
	Substitutability Limitations	25%	Addresses constraints on practically substituting for the material and technology within clean energy technologies. Substitution could occur at any level of the supply chain. This may include using different raw materials, components or even end-use technologies. This includes substitution by element, such as mischmetal for lanthanum in batteries, and also component technology-based substitutions, such as induction motors for permanent magnet motors.	3	0.75	3	0.75
				Criticality Score	**3.75**	**Critcality Score**	**3.75**
Dysprosium Supply Risk	Basic Availability	40%	The extent to which global supply will be able to meet demand. Short term basic availability examines mine and other production relative to demand. Medium-term basic availability examines the potential for other mines to begin producing the material relative to anticipated increases in demand. The qualitative score is informed by the projections in Chapter 4, but may also take into account other factors such as global reserves, mines projected to start up after 2015 and additional supplies from recycling.	4	1.6	4	1.6
	Competing Technology Demand	10%	Whether non-energy-sector demand is expected to grow rapidly, thus constraining the supply of the material available for the energy sector.	2	0.2	2	0.2
	Political, Regulatory, and Social Factors	20%	Risk associated with political, social and regulatory factors within major producer countries. This includes the risk that political instability in a country will threaten mining and processing projects; that countries will impose export quotas or other restrictions; or that social pressures, permitting or regulatory processes will delay the start up of new mines.	4	0.8	4	0.8
	Codependence on Other Markets	10%	Instances where a mineral is a coproduct or byproduct of other minerals found in the same ore deposit. Codependence can be an advantage or a disadvantage, depending on which mineral is driving production levels. In general, coproducts with lower revenue streams (i.e., production rate multiplied by price) will have higher scores because they are less likely to drive production than coproducts with higher revenue.	3	0.3	3	0.3
	Producer Diversity	20%	Market risks due to the lack of diversity in producing countries or companies (e.g., monopoly or oligopoly).	4	0.8	4	0.8
				Criticality Score	**3.7**	**Critcality Score**	**3.7**

Source: Bauer et al. (2011)

Modified Criticality Scoring Using New Weights

The sub-dimension weights in Bauer et al. (2011) assume that the demand comes from the energy sector. In the modified criticality matrix used in this study, the *material importance* and *supply risk* dimensions are expanded to include demand importance of both the defense and clean energy industries. Another important modification is the assessment of the policy impact across a material's supply chain. As reviewed in Chapters 2 and 3, the dysprosium value chain consists of upstream (mining), midstream (separation and processing), and downstream (manufacturing). To capture the essence of policy impact on different parts of the value chain, the "Material Availability" and "Producer Diversity" sub-dimensions are proportionally divided into upstream, midstream, and downstream components.

Each policy option is qualitatively evaluated on its ability to reduce criticality of one or more sub-dimensions of the criticality matrix by the end of the FY 2029 and interpreted into a four-point integer scoring scale that approximates the quartile dysprosium shortfall percentage ranges (based on shortfall projections from Chapter 4). Policies are expected take time to develop, implement, commercialize, and/or mature. Therefore, the scores reflect dysprosium criticality minimization scores at the end of the fifteen year planning period (end of third quarter 2030).

Default Criticality Scoring Method

As the default mode of analysis, each policy option is evaluated as to what criticality rating (1 to 4) it will achieve for a given sub-dimension (as indicated in Table 5.3). For example, if a sub-dimension has a default criticality score of 4, a policy that is rated 3 means that it will change the incumbent rating of that sub-dimension from 4 to the value of 3 (recall that policies should decrease scores to decrease criticality and that the lower is the criticality, the less is the supply shortfall vulnerability).

The qualitative translation of the 1 to 4 criticality rating scheme is as follows. For the *supply risk* sub-dimensions, "low supply risk" is score 1, "medium-low supply risk" is score 2, "medium-high supply risk" is score 3, and "high supply risk" is score 4. For the *material importance* sub-dimensions, "low importance" is score 1, "medium-low importance" is score 2, "medium-high importance" is score 3, and "high importance" is score 4. Dysprosium criticality is determined by plotting the two dimensions' respective scores on the criticality matrix. Based on their coordinates, dysprosium would be "non-critical," "low critical," "medium critical," or "critical" (Figure 5.1). Despite the qualitative veneer, the metric is fundamentally based on quantitative (percentage) range estimates on dysprosium shortfalls, as explained in the final section of this chapter in discussing the ordinal and cardinal properties of the metric.[84]

Lastly, *all policies are evaluated specifically on its final and cumulative impact by the end of FY 2029*. The scores do not describe a policy's impact during the intervening years (FY 2015 to FY 2028), only the criticality status at the end of the 15 year planning period. For example, a score of 2 for a sub-dimension means that by the end of September 2029 (the end of the fiscal year), the criticality of dysprosium (or another metal) for that sub-dimension is expected to be 2 by virtue of the policy's implementation.

R&D Policy Scoring

Exceptions to this scoring system are research and development (R&D) policies. There are three R&D projects for the policy planner to consider: substitution technology, recycling technology[85], and separation/processing technology (discussed in detail in Chapter 6). For recycling and substitution research options, sub-dimensions are first scored on the *percentage* reduction in the default criticality score. This value is further modified by a probability of research success in due consideration of the uncertainty of whether the research will be successful or not. This way, we calculate the *expected* criticality scores of R&D programs. To use a hypothetical example, if the default criticality score is 4, the R&D project's criticality reduction is 50 percent, and the probability of research success is 50 percent, the expected criticality score is 3.[86]

Further explanation of the research probability rate is warranted. Each of the R&D projects are estimated a base probability of success by the private sector without government research funding. This probability is based on the concept of $R\&D^3$ (Research and Development Degree of Difficulty) introduced by Mankins (1998) at the National Aeronautics and Space Administration (NASA). $R\&D^3$ establishes five incrementally higher levels of technical difficulty with correspondingly decreasing probabilities of success summarized in Table 5.2. A full description of the levels is provided in Appendix F. The assignment of $R\&D^3$ levels and the corresponding probability is based on literature review.

When government funding is made available for dysprosium R&D research, it is assumed that the base probability of failure is halved.[87] For example, if a technology is at $R\&D^3$ Level V, it means the base success rate for the foreign/private sector is 20 percent and that the base failure rate is 80 percent. With government R&D funding, however, the failure rate decreases to 40 percent (and success rate rises to 60

[84] While the metric is qualitative and ordinal (numbers representing ordered rank) in appearance, they are fundamentally based on cardinal (numbers representing unique countable values) approximations. This chapter's section on "Note on Criticality Metric's Ordinal and Cardinal Properties" explains this important distinction in detail.
[85] Recycling technology research is subsumed under the Comprehensive Recycling Initiative (CRI) policy option and is not a stand-alone policy option.
[86] $4 \cdot (1 - 0.5^2) = 3$
[87] Failure reduction by 50 percent is the default estimate. However, this parameter should be updated if better data estimates become available. In the interim, sensitivity analysis can be applied for robustness checks.

percent). Thus, if p is the foreign/private sector probability of research failure, XA_k is the pre-policy implementation *ex-ante* criticality score for a given scenario k (the default scenario score), and $CS_{R\&D}$ is the R&D project criticality score (the sub-dimension criticality score a successful research project would achieve), the expected criticality score for the sub-dimension is:[88]

$$R\&D\ Expected\ CS_k = \left(1 - \frac{p}{2}\right) \cdot CS_{R\&D} + \frac{p}{2} \cdot XA_k$$

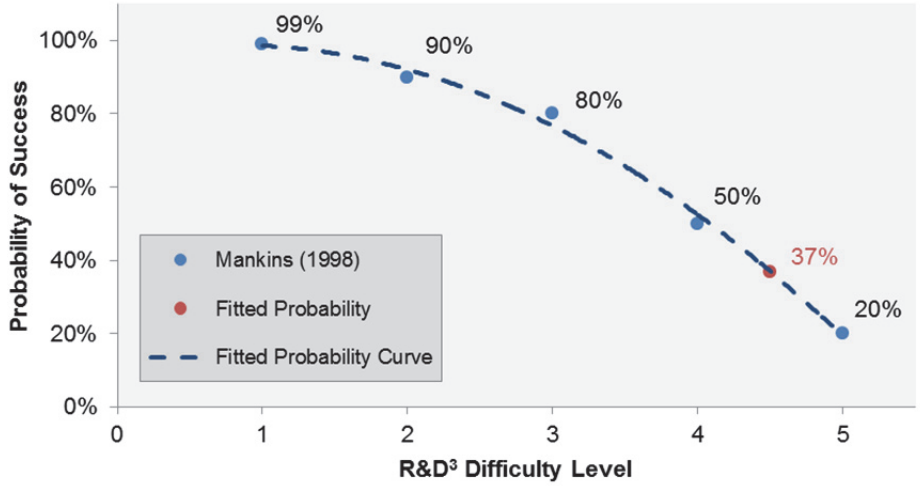
Some of the research falls in between pre-defined R&D^3 category levels, particularly between Level IV and V. A fitted probability curve is used to calculate the mid-point probability (between IV and V) which is approximately 37 percent (Figure 5.2).

TABLE 5.2 – R&D^3 LEVEL DESCRIPTIONS AND PROBABILITIES OF SUCCESS

R&D^3 Level	Description	Estimated Probability of Success
I	A very low degree of difficulty is anticipated in achieving research and development objectives for this technology.	99%
II	A moderate degree of difficulty should be anticipated in achieving R&D objectives for this technology.	90%
III	A high degree of difficulty anticipated in achieving R&D objectives for this technology.	80%
IV	A very high degree of difficulty anticipated in achieving R&D objectives for this technology.	50%
V	The degree of difficulty anticipated in achieving R&D objectives for this technology is so high that a fundamental breakthrough is required.	20%

Source: Mankins (1998)

FIGURE 5.2 – R&D^3 RESEARCH PROBABILITY OF SUCCESS



Data: Mankins (1998)

[88] Alternatively, if q is the probability of success, $R\&D\ Expected\ CS = \frac{1+q}{2} \cdot CS_{R\&D} + \frac{1-q}{2} \cdot XA_k$.

Government research funding will have to meet technical and commercial feasibility milestones. Past DoE rare earth projects were designed to demonstrate or prototype technologies at the DoE's Technology Readiness Level 3 (TRL 3) (described as "in-lab exploration"), all the way up to TRL 7 ("prototyping"), depending on the project. Therefore, in the next round of proposed DoE research funding, the TRL objective is upgraded to Level 9 such that technologies should ultimately operate "in its final form, under the full range of operating conditions" (Bauer et al. 2011). Appendix D describes the DoE's definition of TRLs.

The second basis is whether the end result meets Level 8 of the DoE's Commercial Readiness Level (CRL). CRL 8 is achieved when, "Customer qualifications are complete, and initial products are manufactured and sold. Commercialization readiness continues to mature to support larger scale production and sales. Assumptions are continually and iteratively validated to accommodate market dynamics" (DoE 2012)[89]. Currently, DoE's REACT funding does not require meeting any of CRLs other than a statement by project applicants on the expectation of meeting self-selected CRLs (DoE 2012). Appendix E describes all the CRLs.

Example of a Policy Portfolio Reducing Dysprosium Criticality and Its Cost

Table 5.3 below depicts how three notional policy choices A, B, and C contribute to different sub-dimensions under *material importance* and *supply risk*. Assume Policy A with an implementation cost of $30 million can create a substitute for a critical material, achieving a Substitutability Limitations score of 2 (down from a default score of 3). Policy B can decrement the upstream portions of Material Availability and Producer Diversity criticalities to 2 (down from 4) for $20 million. Policy C can decrement Political, Regulatory, and Social Factors from 4 to 1 for $5 million. When implemented together, the three new policies can decrease the *material importance* criticality from 3.75 to 3.5 and the *supply risk* criticality from 3.7 to 2.7 for a total cost $55 million (Figure 5.3).

The overall criticality ("sum criticality") is simply the sum of scores of the two dimensions of criticality: *material importance* and *supply risk*. The more successful a package is, the greater the reduction in criticality. In our hypothetical assessment, the *ex-ante criticality* score was 7.45, which is the sum of *material importance* criticality score of 3.75 and the *supply risk* criticality score of 3.7.[90] However, with the implementation of policies A, B, and C, the *ex-post* criticality score is 6.2, which represents a sum criticality reduction (effectiveness) of 1.58 points from the default status (Table 5.3) after the policies are introduced.[91]

[89] CRL 9 is the highest level where a technology's "widespread deployment is achieved" (DoE 2012).
[90] *Ex-ante* criticality scores in Table 5.3 taken from Bauer et al. (2011).
[91] The example exhibits a case where Policies A, B, and C have criticality scores lower than the default scores in their respective sub-dimensions (e.g., Policy A's score of 2 is lower than the default score of 3 for substitutability limitations). However, in actuality there may be cases where a policy score is higher than the default score. In these cases, the criticality reduction results in a negative value, meaning the policy option may increase criticality relative to the default score.

FIGURE 5.3 – HYPOTHETICAL EXPECTED CRITICALITY CHANGE FROM NOTIONAL POLICY PACKAGE

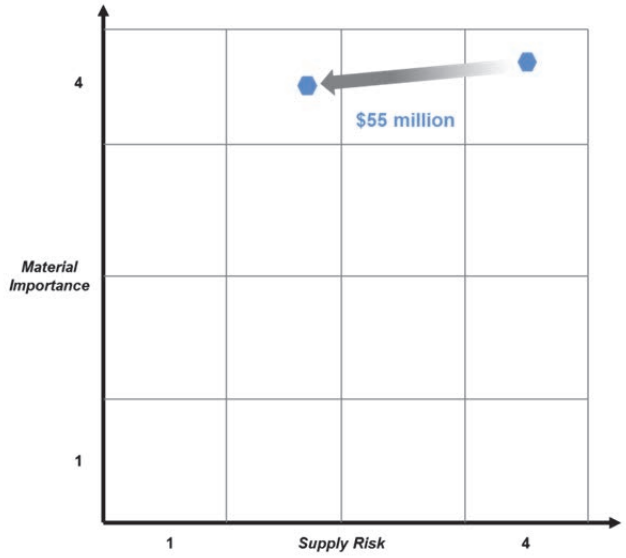


TABLE 5.3 – NOTIONAL POLICY CONTRIBUTIONS TO SUB-DIMENSIONS OF CRITICALITY MATRIX

Dimension	Sub-Dimension	Weight	Policy A	Policy B	Policy C
Material Importance	Defense and Clean Energy Importance	75%	-	-	-
	Substitutability Limitations	25%	2	-	
Supply Risk	Supply Capacity				
	Upstream	13.3%	-	2	-
	Midstream	13.3%	-	-	-
	Downstream	13.3%	-	-	-
	Competing Demand	10%	-	-	-
	Political, Regulatory, and Social Factors	20%	-	-	1
	Codependence on Other Markets	10%	-	-	-
	Producer Diversity				
	Upstream	6.7%	-	2	-
	Midstream	6.7%	-	-	-
	Downstream	6.7%	-	-	-
		Cost	$30M	$20M	$5M

Dimension	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)
Material Importance	4	4	0
	3	2	1
Criticality Score	3.75	3.5	0.25
Supply Risk			
	4	2	2
	4	4	0
	4	4	0
	2	2	0
	4	1	3
	3	3	0
	4	2	1
	4	4	4
	4	4	2
Criticality Score	3.70	2.70	1.33
Sum Criticality	7.45	6.20	1.58

In this fashion, Chapter 6 will review what the policy options are and evaluate their criticality scores and implementation costs. Chapter 7 will develop an overall U.S. dysprosium policy by assessing how different polices can be combined to reduce criticality of dysprosium and at what implementation cost to the U.S. government. The general approach used in Chapter 7 is described in the following section.

Application of Criticality Reduction Planning

For the final analysis in Chapter 7, the various policy options are optimized into packages to maximize criticality reduction based on budget caps. In particular, the optimization is designed to maximize effect

across three distinct scenarios which are introduced below. Optimization is accomplished using a mixed-integer linear programming model.

Three Scenarios

This study devises three scenarios against which the policies are evaluated against. S.I is optimistic in its assumption whereas S.II is pessimistic. S.III assumes the "worst" possible situation. All three scenarios cover the full fifteen fiscal years (FY2015 to FY 2029). A description of each scenario is as follows. Table 5.4 summarizes the criticality scores for the scenarios. Table 5.4 summarizes the baseline criticality scores for the scenarios which are the *ex-ante* scores prior to any policy implementation. These default scores assume base foreign/private sector R&D success probabilities. Thus if a default risk is medium-low (2), this is the *expected* criticality score after accounting for the probability of research failure. The assumption is that incumbent U.S. government R&D funding which are scheduled to expire at the end of FY 2014 will not automatically be continued in FY 2015 unless they are selected as part of the optimization analysis.

The following scenarios' dysprosium criticality scores are heavily predicated on the original dysprosium scoring by Bauer et al. (2011) which was summarized in Table 5.1. The scoring in that study—which found dysprosium to be the most critical element—serves as the status quo expert reference values against which the scenarios' default values are scored. For example, the "optimistic" scenario S.I sub-dimension scores are optimistic relative to Bauer et al.'s (2011) scores. Likewise, the "pessimistic" S.II sub-dimension values are pessimistic relative to how the future might change from Bauer et al.'s (2011) assessment. S.III's "worst case" values are all scored 4, reflecting the only worse (and worst) possible outcome than deemed by Bauer et al. (2011).

S.I (Optimistic) assumes breakthroughs in substitute, recycling, separation and processing technologies for dysprosium are discovered independent of U.S. government funding. It also assumes that China's system of export quotas and tariffs are discontinued. S.I is a future where the private sector (domestic and foreign) researchers have successfully commercialized functional dysprosium- and rare earths-free permanent magnet substitutes, cheaper methods for separating and processing rare earths, and cost-effective recycling technologies.

For the *supply risk* dimension, the upstream and midstream capacity risks are low and medium-low (1.5 and 1) respectively due to recycling expansion, and cost-effective midstream processing. Political risk from China is lowered to medium-low (2) due to Beijing's open dysprosium trade (although the threat lingers). Producer diversity upstream and downstream are rated a medium-high risks (3) due to China's continued dominance in the market. Midstream diversity risk is medium-low (2), however, because new midstream technology can make separation and processing cost-effective enough for non-Chinese firms to compete against Chinese midstream suppliers. The effect on the *material importance* dimension is that dysprosium's importance is medium-low (2) and that substitutability limitations are low (1) thanks to the introduction of substitute technologies.[92]

S.II (Pessimistic) assumes that private and foreign funded research efforts only lead to evolutionary improvement, not breakthroughs, in substitute, recycling, separation and processing technologies. U.S.

[92] Scores for the sub-dimensions *competing demand* and *codependence on other markets* is fixed at Bauer et al.'s (2011) original ratings of medium-low (2) and medium-high (3) risks, respectively, since they are not affected by the scenario assumptions. This is also true for S.II.

government support would likely be required for breakthroughs. It is assumed that China continues to restrict the quantity of dysprosium oxide available to foreign consumers either through continuation of quotas and tariffs or through mass stockpiling. In the case of S.II, the pessimistic assumptions mean that the *material importance* sub-dimensions are unchanged from the original Bauer et al. (2011) scoring. However, China's restricted exports continue to prop up dysprosium prices outside of China, which incentivize U.S. and other non-Chinese producers, processors, and manufacturers to rebuild some capacities. This marginally reduces *supply capacity* and *producer diversity* risks to the medium-high risk range (3 to 3.5).

S.III (Worst Case) is a scenario where *material importance* and *supply risk* are both rated highest in criticality (i.e., they are both high in importance and high in vulnerability to supply disruption). The criticality sub-dimension scores are all high importance (4 for *material importance*) or high supply risk (4 for *supply risk*), meaning the sum scenario criticality score is 8. This scenario serves as a very stringent robustness test of policy effectiveness.

TABLE 5.4 – EX-ANTE CRITICALITY SCORES FOR S.I, S.II, AND S.III

Dimension	Sub-Dimension	Weight	S.I (Optimistic)	S.II (Pessimistic)	S.III (Worst Case)
Material Importance	Defense and Clean Energy Importance	75%	2	4	4
	Substitutability Limitations	25%	1	3	4
		Criticality Score	**1.75**	**3.75**	**4**
Supply Risk	Supply Capacity				
	Upstream	13.3%	1.5	3	4
	Midstream	13.3%	1	3.5	4
	Downstream	13.3%	2	3.5	4
	Competing Demand	10%	2	2	4
	Political, Regulatory, and Social Factors	20%	2	4	4
	Codependence on Other Markets	10%	3	3	4
	Producer Diversity				
	Upstream	6.7%	3	3	4
	Midstream	6.7%	2	3	4
	Downstream	6.7%	3	3	4
		Criticality Score	**2.03**	**3.23**	**4.00**
		Sum Criticality Score	**3.78**	**6.98**	**8.00**

Optimization Model

Chapter 6 reviews the policy options available and qualitatively and quantitatively assess their expected criticality reduction (effectiveness) and their implementation costs covering FY 2015 to FY 2029. The chapter will culminate in a summary of all the policy options' costs and effectiveness (as was described in Table 5.3) when applied in the contexts of scenarios S.I, S.II, and S.III (Table 5.4). The template for the final summary using the hypothetical policies A, B, and C is depicted in Table 5.5.

TABLE 5.5 – POLICY OPTIONS COST AND EFFECTIVENESS SUMMARY TEMPLATE

		S.I	S.II	S.III
		Optimistic	*Pessimistic*	*Worst Case*
Policy Option	**Implementation Cost ($M) FY2015-FY 2029**	**Criticality Reduction (Effectiveness)**	**Criticality Reduction (Effectiveness)**	**Criticality Reduction (Effectiveness)**
Policy A	**$30**	-1	1	2
Policy B	**$20**	0.5	2	4
Policy C	**$5**	1	3	3
etc.				

In Chapter 7, the mixed-integer linear programming model selects policies under a given budget constraint such that it maximizes the sum of criticality reduction (i.e., the sum effectiveness). Formally, let x_i be a binary value 0 or 1, depending on whether a policy is selected or not, respectively, while i refers to a unique policy. Let $E_{i,k}$ be the effectiveness of policy i for a given scenario k where $k = \{S.I, S.II, S.III\}$. Let C_i be the implementation cost of policy i and B_j be the budget level j. Finally, XA_k is the sum *ex-ante criticality* score for scenario *k* before any policies are implemented (Table 5.4). T_k is the threshold sum *ex-post* criticality score for scenario k which serves to set a minimum level of required effectiveness that any selected policy package must meet.

The optimization model is then expressed as:

$$\max \sum_i x_i \cdot E_{i,S.I} + \sum_i x_i \cdot E_{i,S.II} + \sum_i x_i \cdot E_{i,S.III}$$

$$s.t.$$

$$\sum_i x_i \cdot C_i \leq B_j$$

$$XA_{S.I} - \sum_i x_i \cdot E_{i,S.I} \leq T_{S.I}$$

$$XA_{S.II} - \sum_i x_i \cdot E_{i,S.II} \leq T_{S.II}$$

$$XA_{S.III} - \sum_i x_i \cdot E_{i,S.III} \leq T_{S.III}$$

The first expression is the objective function which ensures selection of policies with maximum sum effectiveness. The first constraint ensures that the total implementation cost of any combination of policy selected is equal to or less than the assigned budget level. The next three inequalities ensure that any selected policy package achieves a threshold value of sum *ex-post* criticality score for each scenario. Note that an additional constraint is added if policies are mutually exclusive. For example, if policies i and m are unique and cannot be implemented together, a constraint is added such that $x_i + x_m \leq 1$.

As an example, say policies A, B, and C from Table 5.3 are the three policy options available with their notional effectiveness and cost values shown in the table. The budget is $50 million ($B_{\$50M}$) and T_k, the minimum threshold sum *ex-post* criticality score, is set at or below 3, 4, and 5, for S.I, S.II, and S.III,

respectively. We know that XA_k, the *ex-ante criticality* score, is 3.78, 6.98, and 8, for $XA_{S.I}$, $XA_{S.II}$, and $XA_{S.III}$, respectively, from Table 5.4.

Using these notional values, the optimization model would be:

$$\max\left(-x_A \cdot + \frac{1}{2}x_B + x_C\right) + (x_A + 2x_B + 3x_C) + (2x_A + 4x_B + 3x_C)$$

$$s.t.$$

$$\$30Mx_A + \$20Mx_B + \$5Mx_C \leq \$50M$$

$$3.78 - \left(-x_A \cdot + \frac{1}{2}x_B + x_C\right) \leq 3$$

$$6.98 - (x_A + 2x_B + 3x_C) \leq 4$$

$$8 - (2x_A + 4x_B + 3x_C) \leq 5$$

The solution in this case would be to choose policies B and C whose combined $25M cost meet the budget requirement while also ensuring the *ex-post* criticality score for all three scenarios fall under their threshold minimum values of $T_{S.I} = 3$, $T_{S.II} = 4$, and $T_{S.III} = 5$.

The optimization model gives the best policy package or portfolio to provide the highest sum effectiveness for a given budget. It also provides information that helps the policy planner understand the trade-off between funding and the sum effectiveness that can be achieved at that funding level. In particular, the analysis will assist in identifying policy packages that offer the most cost-effective solutions for decreasing dysprosium criticality along different funding levels. Some budget ranges will experience sharp increases in effectiveness while other ranges will yield little or no changes at all (as will be discussed in Chapter 7). This analysis can help understand just how much less critical dysprosium can become and at what cost to the American government.

Note on Criticality Metric's Ordinal and Cardinal Properties

Ordinal numbers indicate a rank such as first, second, and third in preference. Cardinal numbers indicate quantity or counts, such as one, two, or three widgets (Jacob and Nieder 2007). The difference between cardinality and ordinality can be further elucidated by what analysis can be done with one but not the other. For example, consider the ordinal concept of *utility*—the consumer's rank order of preferences for goods—from microeconomic theory and why utility is not cardinal.

> It makes no sense to ask 'how much more is *A* preferred than *B*?' since that question has no unique answer. Surveys that ask people to rank their 'happiness' on a scale of 1 to 10 could just as well use a scale of 7 to 1,000,000. About all that can be hoped for is that a person who reports he or she is a '6' on the scale one day and a '7' on the next day is indeed happier on the second day. Utility rankings are therefore like the ordinal rankings of restaurants or movies using one, two, three, or four stars. They simply record the relative desirability of commodity bundles (Nicholson 2005).

While it is true that the 1 to 4 criticality metric adopted in this research framework is ordinal, it does not preclude the fact that the metrics can and are based on cardinal values of dysprosium shortfall percentages. In other words, the criticality metric is ordinal because lower scores are preferred over higher scores.

However, the metric retains cardinal properties, because the values represent cardinal ranges of dysprosium shortfall percentages (rather than vague notions of preferences).

Consider this. The reason that Nicholson's (2005) restaurant and film review stars cannot be cardinal is because they are meant to reflect inherently *subjective preferences* of wants that differ from individual to individual. However, if each star represented a different range of revenue projections for the restaurant or movie, then the quantity of stars exhibit cardinal properties. More specifically, say that the stars represent quartiles of restaurant or movie revenue projections from a business owner or investor's perspective, i.e., one star equals revenue for $1 to $25 million, two stars for $26 million to $50 million, three stars for $51 million to $75 million, and four stars for $76 million to $100 million. Then no longer are the stars merely ordinal: they also attain cardinal properties. With cardinality, it is now valid to say that a one star restaurant/film's revenue potential is half the revenue potential of a two star restaurant/film—an analytic claim that could not be said if the stars merely represented orders of preferences.

Formally speaking, the four star scale is *approximately linear* from 1 to 4, not, for example, logarithmic. Say that we take the median value of each of the revenue ranges, which would be $13 million (one star), $38 million (two stars), $63 million (three stars), and $88 million (four stars). The difference between each of these medians is constant and equal to each other (i.e., linear) at $25 million.[93]

Analogously, the four point integer criticality reduction matrix assumes the linear representation of inherently cardinal values. More specifically, the 1 to 4 point integer scale act as proxies for the linear quartile ranges of probabilities and proportions. To take one concrete example, consider the "material availability" sub-dimension under *supply risk.* For this sub-dimension, criticality assessments such as "high" (4), "medium-high" (3), "medium-low" (2), and "low" (1) are mandated upon the associated risk of dysprosium falling into 100-76 percent dysprosium shortfall (4), 51-75 percent shortfall (3), 26-50 percent shortfall (2), and 0-25 percent shortfall (1), respectively. As in the revamped cardinal infusion of the restaurant/film star metric, the objective dysprosium shortfall ranges—while imprecise and subject to uncertainty—nonetheless establishes cardinal traction to the 4 point criticality metric. Table 5.6 explains this study's cardinal interpretation of the 1-to-4 criticality metric scores into quartile percentage ranges for the other sub-dimensions from the Bauer et al. (2011) framework. The policy effectiveness assessments in Chapter 6 are premised on these cardinal quartile equivalencies.

[93] The same would be the case if comparing the difference between each range's minimum or maximum values.

TABLE 5.6 – QUARTILE PERCENTAGE RANGE EQUIVALENCE OF CRITICALITY METRIC SCORES

Dimension	Sub-Dimension	Weight	Description	Cardinal Description
Dysprosium Importance	Defense and Clean Energy Importance	75%	Importance of the material in clean energy and defense technologies	Proportion of applications that can be substituted without trade-offs in performance (green technology and military). 1=(76%~100%), 4=(<1%~25%).
	Substitutability Limitations	25%	Addresses constraints on practically substituting for the material and technology within defense or clean energy technologies.	Probability of successfully implementing substitution both technologically and commercially. 1=(76%~100%), 4=(<1%~25%).
Dysprosium Supply Risk	Material Availability	40%	The extent to which global supply will be able to meet demand.	Shortfall, the ratio of supply capacity and demand requirement. 1=(76%~100%), 4=(<1%~25%).
	Competing Technology Demand	10%	Whether non-energy or non-defense sector demand is expected to grow rapidly, thus constraining the supply of the material available for the energy sector.	The probability new competing technologies demanding dysprosium will emerge. 1=(<1%~25%), 4=(76%~100%).
	Political, Regulatory, and Social Factors	20%	Risk associated with political, social and regulatory factors within major producer countries. This includes the risk that political instability in a country will threaten mining and processing projects; that countries will impose export quotas or other restrictions; or that social pressures, permitting or regulatory processes will delay the start up of new mines.	The probability that political, social, or regulatory factors that lead to supply restrictions will occur. 1=(<1%~25%), 4=(76%~100%).
	Codependence on Other Markets	10%	Instances where a mineral is a coproduct or byproduct of other minerals found in the same ore deposit. Codependence can be an advantage or a disadvantage, depending on which mineral is driving production levels. In general, coproducts with lower revenue streams (i.e., production rate multiplied by price) will have higher scores because they are less likely to drive production than coproducts with higher revenue.	The proportion of heavy rare earth mines that are co-dependent on minerals that are even more valuable. 1=(<1%~25%), 4=(76%~100%).
	Producer Diversity	20%	Market risks due to the lack of diversity in producing countries or companies (e.g., monopoly or oligopoly).	China's global share of heavy rare earths production. 1=(<1%~25%), 4=(76%~100%).

Chapter Summary

This methods chapter introduced the combined qualitative and quantitative methodology that is applied in Chapters 6 and 7. The technical methods and terminology introduced in this chapter lay the groundwork for a systematic analysis of U.S policy options' costs and criticality reduction effectiveness in Chapter 6 and for assembling optimal policy portfolios under budget constraints in Chapter 7. The criticality framework relies heavily on work by Bauer et al. (2011) and NRC (2008).

This chapter established that the policy maker's primary objective should be to seek reduction in dysprosium's criticality level. It explained that active pursuit of criticality reduction necessarily fulfills U.S. statutory requirements (primarily relating to DoD acquisition and stockpiling and the pursuit of fair treatment and redress for American firms in commercial relations with trading partners). This criticality reduction framework forms the common basis for scoring policies' effectiveness in Chapter 6.

Specifically, each policy option is evaluated on their ability to reduce criticality of one or more sub-dimensions of the criticality matrix by the end of the FY 2029 and interpreted as a 1 to 4 integer scale representing potential quartile percentage ranges of dysprosium shortfall based. Policies are by default scored on what level of criticality is achieved through policy implementation. R&D policies, however, impact criticality reduction differently. These policies increase the private sector's research success

probability by halving the default probability of failure. The implementation costs are estimated for the fifteen fiscal year planning period (FY 2015 to FY 2029).

The second portion of the chapter introduced the three scenarios: S.I (optimistic), S.II (sober), and S.III (worst case). The uncertainty of future dysprosium shortfalls highlighted in Chapter 4 necessitates that any dysprosium criticality reduction planning must account for the fact that policies be reasonably robust against various future states. The policy portfolio optimization is designed such that the portfolios meet minimally acceptable criticality levels after their implementation, regardless of the allocated budget size. The portfolio optimization method is a mixed integer linear programming model which maximizes the sum dysprosium criticality reduction values for a given level of allocated budget. The portfolio optimization and analysis of its result are completed in Chapter 7.

This chapter has reviewed the methodology for analyzing an optimal portfolio solution to the dysprosium challenge. Chapter 6 begins assessing the costs and effectiveness of the roster of policy options.

Chapter 6 – U.S. Policy Options

"Relying on the WTO alone to fight back against Chinese protectionism is a losing strategy. The United States should employ an array of tools."
–Mark Wu

Introduction

This chapter conducts an overview of U.S. policy activities implemented and deliberated by the White House and Congress with regards to dysprosium and rare earth magnet supply chain vulnerabilities in recent years. It then presents ten policy options organized along four "policy areas" which the U.S. may wish to pursue. The options include actual policies that have been passed into law (e.g., appropriation for DoD stockpiling), modifications of past proposals (e.g., reforms to U.S. mining regulations), continuation of current policy programs with modifications (e.g., DoE research and development programs), or altogether new policy options (e.g., U.S. trade restrictions). The four policy areas are:

- Supply Chain Development
- Substitute Technology
- Trade Restrictions
- Contingency Planning

The Supply Chain Development area includes four policy options. The first reforms U.S. domestic mining regulations to speed up mining licensing. The second option provides continued scientific research funds to improve rare earth separation and processing technology. The third option is meant to assure midstream and downstream NdFeB magnet supply capacities that meet DoD acquisition requirements.[94] The last policy option calls for research into cost-effective recycling technology and the start of a national recycling infrastructure.

The Substitute Technology policy area comprises a single option, which is research and development of substitute technologies for NdFeB magnets. The Trade Restriction policy area includes the U.S. option of imposing export restrictions on China's own critical materials to cajole and deter Beijing from instituting dysprosium and other rare earths export barriers. Alternatively, the U.S. could impose import restrictions of Chinese dysprosium to support American mining, separation/processing, and manufacturing capacity growth. Contingency Planning includes the DoD policies designed to meet dysprosium demand during emergencies through stockpiles and buffer inventory.

The policy options would be implemented in the FY 2015 to FY 2029 time frame, which is the chosen planning horizon for this study. Each policy is assessed on its effectiveness in reducing the criticality sub-dimensions[95] adopted from the DoE criticality matrix (Bauer et al. 2011). Implementation costs are then estimated for the policies' funding timeframe. In departure from the NRC (2008) and Bauer et al. (2011) methods which only considered criticality of raw materials, this study takes into account the supply security *across* the entire value chain of dysprosium: the supply capacities of mining (upstream), separation/processing (midstream), and manufacturing capacities (downstream).

The inclusion of mid- and downstream capacity assessment is crucial for government and commercial U.S. national security stakeholders that are bound by U.S. regulations that require domestic or "qualified country" sourcing of metals while prohibiting integration of Chinese-sourced materials. Unlike its

[94] As discussed in Chapters 3 and 4, NdFeB magnets are superior permanent magnets that achieve superlative performance through the use of dysprosium. NdFeB magnets are used in an array of clean energy and military technology systems.
[95] Sub-dimensions are those weighted criteria that fall under the two primary dimensions of criticality, *supply risk* and *material importance*.

commercial counterparts whose clientele are non-defense related, defense firms must walk a tightrope balancing cost-effectiveness *and* reliability of supply source.

U.S. Government Actions

The Cost of Inaction

Before proceeding further, it is worthwhile to consider what the alternative to inaction is.[96] From a national security standpoint, two problems abound due to wholesome reliance on China's integrated rare earth supply chain.

First, current U.S. military acquisition rules prohibit procurement from Chinese components and require permanent magnets to be sourced from U.S. or "qualified countries" (DoD 2012b and 10 U.S. Code § 2533). However, U.S. defense integrators may have violated these regulations given Chinese monopoly of dysprosium and permanent magnet production (an issue elucidated later in this chapter). Without a change in the dysprosium criticality status quo, abiding by these regulations will likely be difficult if not futile going forward. Again, assuming that the U.S. does not adopt any of the policies contained in this chapter, the only alternatives are either to formally continue incorporating Chinese components into our defense systems or to halt or slow systems procurements to abide by the letter of the law (Chapter 3 reviewed the variety of weapons systems that use rare earths).

Secondly, should the status quo not change, in a major future contingency with China (e.g., Taiwan Straits, South China Sea, or the Korean peninsula), the impact of dysprosium shortfall will likely be felt indirectly and in lagged time (DoD 2013a). This is because deployed weapons systems and munitions at the beginning of the conflict will not need the materials immediately since the magnets and other dysprosium-laced components will already have been integrated into them. However, the need for dysprosium/critical rare earths will become acute beginning in the latter stages of the conflict as destroyed or damaged platforms need to be repaired and depleted smart munition stocks need to be replenished. Without a domestic supply stream or a contingency supply, the shortage of spare parts/replacement components or potential substitution with inferior components could degrade military capabilities. Even post-conflict, the U.S. would face challenges securing adequate supplies of said materials to rebuild its military forces (DoD 2013a).

The immediate short term consequences of policy action or inaction will be undiscernible because most of the U.S. policy options discussed here will likely not be impactful until close to the end of the fifteen fiscal year planning period. Not much can be done immediately in the aftermath of China's systematic consolidation of the industry. However, the ground work for more comprehensive U.S. rare earth industry revitalization and vulnerability reduction has been laid down by initiatives by both Congress and the White House in recent years which are reviewed next.

[96] Inaction referring to no federal government investments in any policies, including stockpiling, that can help reduce dysprosium criticality, whether by increasing supply capacity or decreasing demand importance.

Congressional Activity

Both the Executive and Legislative branches of the U.S. government have actively promoted policy actions in regards to critical materials supply. In Congress, several House of Representatives and Senate hearings have taken place and a number of bills concerning critical raw materials and rare earths have been introduced over the years. Grasso (2013) compiled a summary of Congressional bills since FY2011 to FY2013 that have been introduced in that time period and is replicated in Appendix G.

H.R. 3304 - NDAA for FY2014 contains meaningful but modest provisions that give the President more flexibility regarding the National Defense Stockpile (NDS). Subtitle A, Section 1411 adds to the President's responsibility in the "recovery of any strategic and critical materials under section 3(a) [of the Strategic and Critical Materials Stock Piling Act] that may be available from excess materials made available for recovery purposes by other Federal agencies" (Public Law 113-66).

Subtitle B, Section 1411 adds clarifying language to enable the executive branch to "maintain and manage a national defense stockpile and allow the Defense Logistics Agency to more proactively engage in the market. These changes would grant the President the authority to conserve strategic and critical materials" (Public Law 113-66).[97] Section 1412 appropriated $41 million to the NDS to acquire "materials determined to be strategic and critical" between FY2014 and FY2019. Dysprosium is one of the six authorized critical materials (H.R. 3304 2013) (see Appendix H for an excerpt of H.R. 3304).[98]

The original House version of the bill, H.R. 1960, included two reporting requirements to Congress which were excluded in H.R. 3304. First, it would have required the DoD to detail how the DoD planned to pursue its three-pronged on supply diversification, substitution, and waste reclamation (recycling). The second reporting requirement asked the DoD to detail and assess the cost and merits of substituting REEs used for the F-35 aircrafts (National Defense Authorization Act for FY 2014).[99] Table 6.1 outlines other Congressional activities relevant to REEs that have either been considered or are still under review.

[97] How such "conservation" will be implemented is ambiguous in the bill.
[98] The other materials are erroniobium, yttrium oxide, cadmium zinc tellurium substrate materials, lithium ion precursors, and triamino-trinitrobenzene and insensitive high explosive molding powders.
[99] U.S. reliance on Chinese-made permanent magnets required the DoD to temporarily waive restrictions against the use Chinese components in the F-35 for 24 months (2012-2013) in order to keep the F-35 on schedule (Ucore 2014).

TABLE 6.1 – RECENTLY PROPOSED U.S. HOUSE AND SENATE BILLS PERTAINING TO RARE EARTHS

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

Data: Grasso (2013)

Executive Branch Activities

In 2010, the White House initiated collaboration between the White House Office of Science and Technology Policy (OSTP), DoE, and DoD, the U.S. Department of Interior and the USGS, the National Economic Council, the Office of the U.S. Trade Representative (USTR), and the National Security Council to address the issue of critical materials (Green 2011). The agencies outlined six objectives for achieving critical materials supply. The objectives described by the DoE's Bauer et al. (2011) study are:

1. Promote supply diversification
2. Mitigate the long-term risks associated with a dependence on critical materials with careful consideration of the full domestic manufacturing supply chain
3. Establish federal R&D priorities
4. Inform government and industry decision making
5. Promote environmentally sustainable practices in mineral extraction and use
6. Prepare a next-generation workforce

The DoE has funded R&D on rare earths and critical materials for several years, particularly in rare earths recycling, processing, and substitution technologies. The scope and funding of the programs increased over the years, growing from a handful of programs to two large consolidated multi-year initiatives, the $120 million Critical Materials Institute (CMI) and the $37.5 million Rare Earth Alternatives in Critical

Technologies for Energy (REACT). Research into substitution comprises the bulk of the research budget (Bauer et al. 2011). Table 6.2 lists major R&D projects funded by the DoE since FY 2010 culminating with CMI and REACT in the most recent years.[100]

REACT funding is disbursed among a variety of researchers in the national labs, universities, and commercial entities over one to three year periods. Awards range from about $400,000 to as high as $5.4 million, with the majority of projects in the $1.5 to $3 million range. Because of the importance and supply vulnerabilities of rare earths permanent magnets, the vast majority of the fourteen REACT projects relate to substitute permanent magnet technologies that would either not use or decrease the amount of required dysprosium and other rare earths. A breakdown of the REACT research programs is provided in Table 6.3.

The DoE manages most of the R&D initiatives through three program offices which oversee research programs in national laboratories and other critical materials innovation programs. The three offices are (Bauer et al. 2011):

- The Office of Basic Energy Sciences which conducts materials and chemical separation research through the Material Sciences and Engineering Division and Chemical Sciences, Geosciences, and Biosciences Division, respectively
- The Advanced Research Projects Agency-Energy (ARPA-E) which assumes high-risk, high-return investments the private sector is unwilling or unable to engage in independently
- The Office of Energy Efficiency and Renewable Energy (EERE), which oversees clean energy investments that reduce oil dependence and promote environmental protection. Specific rare earths-related research is undertaken by the Vehicle Technologies Program, the Wind Program, the Solar Program, and Advanced Manufacturing Office.

Six national DoE laboratories conduct research on critical materials: Ames Laboratory, Argonne National Laboratory, Brookhaven National Laboratory, Pacific Northwest Laboratory, Sandia National Laboratories, and Lawrence Berkeley National Laboratory. Ames has historically been the leader in rare earth and critical materials research but peers labs also conduct independent research into technologies that may lead to work-arounds that can reduce dependence on these materials (Bauer et al. 2011).

The idea for CMI was conceived by the DoE in December 2011for the purpose of consolidating disparate research on clean energy critical materials to an inter-disciplinary effort. Research focus includes material substitutes, recycling, and demand efficiency. Formally established in January 2013 at the DoE's Ames Laboratory, it is the most recent iteration of the DoE's "innovations hubs" which are modeled after the Manhattan Project and Bell Labs to increase collaboration across institutions and

[100] The Innovative Manufacturing Initiative's (IMI) 3-year $120 million research agenda is broadly focused on new manufacturing processes that would be faster, cheaper, and energy-efficient. Two research foci are of particular relevance to critical materials supply: (1) reactions and separations and (2) high-temperature processing and sustainable manufacturing. Both are research agendas that necessarily require materials research for innovations in manufacturing processes (Bauer et al. 2011). For a roster of funded research, go to: http://www5.eere.energy.gov/projects/foa/project/innovative-manufacturing-initiative. The DoE's SBIR funds initiatives for more competitive domestic REEs production capacity by investing in researches that help decrease the cost of REE ore processing and separation. Specifically, these include research that would enable "increasing separation factors in solvent extraction techniques while utilizing green chemistry techniques, reducing physical separation steps required in mineral processing, and new processes to avoid intermediates in the production of high-purity metals." Secondly, the program aims for technologies that enable easier separation of specific or multiple REEs from raw ores (and thus more efficient production). Finally, the program is looking into developing extraction chromatography, an alternate extraction method to the more common solvent extraction method that could potentially be greener (Bauer et al. 2011). A review of DoE-funded programs on www.sbir.govbetween 1994 and 2013 could not confirm these projects, except for extraction chromatography.

stakeholders in critical energy-related challenge areas (Cho 2013).[101] Unlike REACT, which acts as a project sponsor, CMI conducts its research within its network of interdisciplinary researchers from various institutions coordinated by Ames. These include several national laboratories including Idaho National Laboratory, Lawrence Livermore National Laboratory and Oak Ridge National Laboratory; and universities including Brown University, Colorado School of Mines, Florida Industrial and Phosphate Research Institute, Iowa State University, Purdue University, Rutgers, and the University of California at Davis. Private sector participants include Advanced Recovery, Cytec Industries, GE, Molycorp, OLI Systems, and Simbol Materials (CMI 2014a).

CMI has short-term, medium-term, and long-term objectives which are disbursed across four research "focus areas." The short-term goal is to improve on ore separation agents that can increase production cost-effectiveness. The medium-term goal is to increase efficiency in recycling. The long-term goal is to find new elemental and technological substitutes to critical materials (CMI 2014a). The concomitant focus areas are Focus 1 – Supply Diversity; Focus 2 – Developing Substitutes; Focus 3 – Improving Reuse and Recycling; and Focus 4 – Crosscutting Research. Appendix J has additional details on each of the sub-areas while Appendix K lists published and publicized research from CMI.

While the CMI has won plaudits from Congress and industry, political risk is still a concern particularly during times of budget constraints. Cho (2013) posit that, "The hubs will have to prove their worth at a time when budgets are likely to be tight." Similarly, he astutely notes that "none of the [projects are] ready for the real world," which is the same challenge with REACT. In particular, there is circumspection among members of the House who worry about duplicative DoE research programs (Cho 2013). As the initial round of rare earths research funding comes to a close at the end of FY2015, the new fiscal year provides the U.S. policy planner with a natural opportunity to assess the material criticality landscape, review past investments, and plan forward under new constraints. The next section will review prospective policy options in this next phase of policy planning. As previously discussed, many of the policy options have direct and indirect implications for rare earths other than dysprosium. In due acknowledgement of this fact, while the intent and focus of this dissertation are on dysprosium, it nonetheless alludes to rare earths in general—which necessarily includes dysprosium—where relevant and applicable.

[101] Other energy innovations hubs established and forthcoming include the Consortium for Advanced Simulation of Light Water Reactors (CASL) at Oak Ridge National Laboratory, Joint Center for Artificial Photosynthesis (JCAP), Energy Efficient Buildings (EEB), and the Joint Center for Energy Storage Research (JCESR). Each of these hubs have been awarded about $120 million for 5 years with the possibility of a 5-year renewal (Cho 2013).

TABLE 6.2 – SELECTION OF DEPARTMENT OF ENERGY RESEARCH PROGRAMS RELATED TO RARE EARTHS

Program	Description	FY	Funding ($M)
Materials Science and Engineering Program	R&D on critical materials at Ames National Laboratory	2010	$5
Applied Magnet Research Program	R&D on permanent magnet at Ames National Laboratory	2010	$2
Alternate Motor Design Program	R&D on alternative design of motors that do not use REEs at Oak Ridge National Laboratory	2010	$1.4
Basic Earth Science	The Nation's future electric systems will need cost-effective, reliable, high-capability power electronic components and devicesto control and link complex high voltage networks, measure and control flow, and reduce energy losses in long-distance transmission. Power electronics are particularly important in interfacing new, renewable electrical power sources to the existing grid distribution systems. In particular, wide bandgap materials that permit single devices to control current flows at higher voltages with high efficiency could make power electronics affordable and enable efficient tools to control and manage electricity. Focus areas in basic materials research will be initiatedin low defect density, wide bandgap semiconductors; magnetic materials for high frequency inductors, including nonrare earth based materials; and next generation dielectrics.	2012	$3.5
Energy Innovation Hub Program	R&D on critical materials	2012	$19.4
Advanced Electric Motors (formerly Propulsion Materials Technology)	A magnetic materials effort will be initiated to develop non-rare earth magnets for high efficiency electric motors. This work represents a critical issue for competitive production of domestic hybrid electric vehicles and will be conducted in concert with other programs, agencies, and industry partners to accelerate the market penetration of devices using these materials.	2015	$13.6
Critical Materials Hub	In FY 2015, the Critical Material Hub, a 5 year award competitively awarded in FY 2013 to a team led by the Ames National Laboratory, will focus on technologies that will enable American manufacturers to make better use of the critical materials we have access to as well as reduce or eliminate the need for materials that are subject to supply disruptions. These critical materials, including many rare earth elements, are essential for American competitiveness in the clean energy industry and other strategic industries like defense. This fourth year of funding for the Hub will enable it to continue to integrate scientific research, engineering innovation, and manufacturing and process improvements to provide holistic solutions to critical materials challenges facing the Nation.	2012-2015	$120 (total)
Rare Earth Alternatives in Critical Technologies for Energy (REACT)	Mutli-year R&D funding to 14 rare earth substitution and recycling research with partner institutions. Disbursed in FY2011. See Appendix for full description of the REACT programs.	2012-2015	$37.5 (total)

Data: DoE (2014a)

TABLE 6.3 – DESCRIPTION OF PROJECTS FUNDED BY REACT

Lead Research Organization	Partner Organizations	Funding	Lead Location	Start	End	Project Description
Ames Laboratory	General Motors, Molycorp, NovaTorque	$3,065,922	Ames, IA	1/1/2012	3/31/2015	Ames Laboratory is developing a new class of permanent magnets based on the more commonly available element cerium for use in both EVs and renewable power generators. Cerium is 4 times more abundant and significantly less expensive than the rare earth element neodymium, which is frequently used in today's most powerful magnets. Ames Laboratory will combine other metal elements with cerium to create a new magnet that can remain stable at the high temperatures typically found in electric motors. This new magnetic material will ultimately be demonstrated in a prototype electric motor, representing a cost-effective and efficient alternative to neodymium-based motors.
Argonne National Laboratory	Electron Energy Corporation	$2,998,093	Argonne, IL	1/1/2012	3/31/2015	ANL is developing a cost-effective exchange-spring magnet to use in the electric motors of wind generators and EVs that uses no rare earth materials. This ANL exchange-spring magnet combines a hard magnetic outer shell with a soft magnetic inner core--coupling these together increases the performance (energy density and operating temperature). The hard and soft magnet composite particles would be created at the molecular level, followed by consolidation in a magnetic field. This process allows the particles to be oriented to maximize the magnetic properties of low-cost and abundant metals, eliminating the need for expensive imported rare earths. The ultimate goal of this project is to demonstrate this new type of magnet in a prototype electric motor.
Baldor Electric Company	Arnold Magnetic Technologies Corp, ABB	$3,045,385	Richmond Heights, OH	1/31/2012	12/31/2014	Baldor is developing a new type of traction motor with the potential to efficiently power future generations of EVs. Unlike today's large, bulky EV motors which use expensive, imported rare-earth-based magnets, Baldor's motor could be light, compact, contain no rare earth materials, and have the potential to deliver more torque at a substantially lower cost. Key innovations in this project include the use of a unique motor design, incorporation of an improved cooling system, and the development of advanced materials manufacturing techniques. These innovations could significantly reduce the cost of an electric motor.
Brookhaven National Laboratory	American Superconductor Corporation	$1,506,594	Upton, NY	1/1/2012	6/30/2014	Brookhaven National Laboratory is developing a low-cost superconducting wire that could be used in high-power wind generators. Superconducting wire currently transports 600 times more electric current than a similarly sized copper wire, but is significantly more expensive. Brookhaven National Laboratory will develop a high-performance superconducting wire that can handle significantly more electrical current, and will demonstrate an advanced manufacturing process that has the potential to yield a several-fold reduction in wire costs while using a negligible amount of rare earth material. This design has the potential to make a wind turbine generator lighter, more powerful, and more efficient, particularly for offshore applications.

Lead Research Organization	Partner Organizations	Funding	Lead Location	Start	End	Project Description
Case Western Reserve University		$1,850,000	Cleveland, OH	1/1/2012	3/31/2015	Case Western is developing a highly magnetic iron-nitride alloy to use in the magnets that power electric motors found in EVs and renewable power generators. This would reduce the overall price of the motor by eliminating the expensive imported rare earth minerals typically found in today's best commercial magnets. The iron-nitride powder is sourced from abundant and inexpensive materials found in the U.S. The ultimate goal of this project is to demonstrate this new magnet system, which contains no rare earths, in a prototype electric motor. This could significantly reduce the amount of greenhouse gases emitted in the U.S. each year by encouraging the use of clean alternatives to oil and coal.
Dartmouth College		$397,433	Hanover, NH	1/1/2012	3/30/2013	Dartmouth is developing specialized alloys with magnetic properties superior to the rare earths used in today's best magnets. EVs and renewable power generators typically use rare earths to turn the axles in their electric motors due to the magnetic strength of these minerals. However, rare earths are difficult and expensive to refine. Dartmouth will swap rare earths for a manganese-aluminum alloy that could demonstrate better performance and cost significantly less. The ultimate goal of this project is to develop an easily scalable process that enables the widespread use of low-cost and abundant materials for the magnets used in EVs and renewable power generators.
Northeastern University	Arnold Magnetic Technologies Corporation, Columbia University, General Motors R&D, University of Massachusetts-Amherst, University of Nebraska-Lincoln	$2,303,343	Boston, MA	2/24/2012	12/31/2013	Northeastern University is developing bulk quantities of rare-earth-free permanent magnets with an iron-nickel crystal structure for use in the electric motors of renewable power generators and EVs. These materials could offer magnetic properties that are equivalent to today's best commercial magnets, but with a significant cost reduction and diminished environmental impact. This iron-nickel crystal structure, which is only found naturally in meteorites and developed over billions of years in space, will be artificially synthesized by the Northeastern University team. Its material structure will be replicated with the assistance of alloying elements introduced to help it achieve superior magnetic properties. The ultimate goal of this project is to demonstrate bulk magnetic properties that can be fabricated at the industrial scale.
Pacific Northwest National Laboratory	Ames Laboratory, Electron Energy Corp, United Technologies Research Center, University of Maryland, University of Texas at Arlington	$5,388,091	Richland, WA	1/1/2012	4/23/2015	PNNL is working to reduce the cost of wind turbines and EVs by developing a manganese-based nano-composite magnet that could serve as an inexpensive alternative to rare-earth-based magnets. The manganese composite, made from low-cost and abundant materials, could exceed the performance of today's most powerful commercial magnets at temperature higher than 200°C. Members of PNNL's research team will leverage comprehensive computer high-performance supercomputer modeling and materials testing to meet this objective. Manganese-based magnets could withstand higher temperatures than their rare earth predecessors and potentially reduce the need for any expensive, bulky engine cooling systems for the motor and generator. This would further contribute to cost savings for both EVs and wind turbines.

Lead Research Organization	Partner Organizations	Funding	Lead Location	Start	End	Project Description
QM Power	Oak Ridge National Laboratory, Smith Electric Vehicles, University of Delaware	$2,917,392	Lee's Summit, MO	1/1/2012	12/31/2014	QM Power is developing a new type of electric motor with the potential to efficiently power future generations of EVs without the use of rare-earth-based magnets. Many of today's EV motors use rare earth magnets to efficiently provide torque to the wheels. QM Power's motors would contain magnets that use no rare earth minerals, are light and compact, and can deliver more power with greater efficiency and at reduced cost. Key innovations in this project include a new motor design with iron-based magnetic materials, a new motor control technique, and advanced manufacturing techniques that substantially reduce the cost of the motor. The ultimate goal of this project is to create a cost-effective EV motor that offers the rough peak equivalent of 270 horsepower.
University of Alabama	University of California at San Diego, Mississippi State University	$822,993	Tuscaloosa, AL	2/8/2012	9/30/2013	The University of Alabama is developing new iron- and manganese-based composite materials for use in the electric motors of EVs and renewable power generators that will demonstrate magnetic properties superior to today's best rare-earth-based magnets. Rare earths are difficult and expensive to refine. EVs and renewable power generators typically use rare earths to make their electric motors smaller and more powerful. The University of Alabama has the potential to improve upon the performance of current state-of-the-art rare-earth-based magnets using low-cost and more abundant materials such as manganese and iron. The ultimate goal of this project is to demonstrate improved performance in a full-size prototype magnet at reduced cost.
University of Houston	National Renewable Energy Laboratory, SuperPower, Tai-Yang Research, TECO-Westinghouse Motor Company	$3,986,375	Houston, TX	2/22/2012	12/31/2014	The University of Houston is developing a low-cost, high-current superconducting wire that could be used in high-power wind generators. Superconducting wire currently transports 600 times more electric current than a similarly sized copper wire, but is significantly more expensive. The University of Houston's innovation is based on engineering nanoscale defects in the superconducting film. This could quadruple the current relative to today's superconducting wires, supporting the same amount of current using 25% of the material. This would make wind generators lighter, more powerful and more efficient. The design could result in a several-fold reduction in wire costs and enable their commercial viability of high-power wind generators for use in offshore applications.
University of Minnesota	Oak Ridge National Laboratory	$4,200,931	Minneapolis, MN	1/1/2012	3/31/2015	The University of Minnesota is developing an early stage prototype of an iron-nitride permanent magnet material for EVs and renewable power generators. This new material, comprised entirely of low-cost and abundant resources, has the potential to demonstrate the highest energy potential of any magnet to date. This project will provide the basis for an entirely new class of rare-earth-free magnets capable of generating power without costly and scarce rare earth materials. The ultimate goal of this project is to demonstrate a prototype with magnetic properties exceeding state-of-the-art commercial magnets.

Lead Research Organization	Partner Organizations	Funding	Lead Location	Start	End	Project Description
University of Texas at Dallas		$2,805,640	Richardson, TX	6/7/2012	12/31/2014	UT Dallas is developing a unique electric motor with the potential to efficiently power future classes of EVs and renewable power generators. Unlike many of today's best electric motors--which contain permanent magnets that use expensive, imported rare earths--UT Dallas' motor completely eliminates the use of rare earth materials. Additionally, the motor contains two stators. The stator is the stationary part of the motor that uses electromagnetism to help its rotor spin and generate power. The double-stator design has the potential to generate very high power densities at substantially lower cost than existing motors. In addition, this design can operate under higher temperatures and in more rugged environments. This project will focus on manufacturing and testing of a 100 kW motor with emphasis on low cost manufacturing for future use in EVs and renewable power generators.
Virginia Commonwealth University	Arnold Magnetic Technologies, Northeastern University, Brookhaven National Laboratory, University of California-San Diego, Moog Inc., Bayer Technology Services	$2,188,225	Richmond, VA	1/1/2012	12/31/2013	VCU is developing a new magnet for use in renewable power generators and EV motors that requires no rare earth minerals. Rare earths are difficult and expensive to process, but they make electric motors and generators smaller, lighter, and more efficient. VCU would replace the rare earth minerals in EV motor magnets with a low-cost and abundant carbon-based compound that resembles a fine black powder. This new magnet could demonstrate the same level of performance as the best commercial magnets available today at a significantly lower cost. The ultimate goal of this project is to demonstrate this new magnet in a prototype electric motor.

Source: DoE (2014b)

Policy Effectiveness Scoring Review

Chapter 5 provided an in-depth illustration of the policy effectiveness scoring and cost estimation method. This section will *briefly* review the method before proceeding to discuss the policy areas, the policy options, and the estimation of their costs and effectiveness. The reader is nonetheless encouraged to reference Chapter 5 for more details and explication of assumptions, especially in regards to the descriptions of S.I, S.II, and S.III.

The fundamental framework for this analysis is the modified criticality matrix adopted from NRC (2008) and Bauer et al. (2011) which plots a mineral's criticality based on two dimensions*: supply risk* and *material importance*. Each of these dimensions is comprised of weighted sub-dimensions. Both primary dimensions and sub-dimensions are scored in a 1 to 4 integer scale. Generally speaking, the policy planner prefers *lower* scores (lower criticality of dysprosium). A lower score in *supply risk* means a lower risk of supply disruption. A lower score in *material importance* means that the material (in this case, dysprosium) is made less irreplaceable, essential, or important by developing substitution. It is the objective of this research to understand how to reduce these numbers as much as possible within budgetary limits.

The following is a review of the qualitative equivalence of the 1 to 4 integer criticality score from Chapter 5. For the *supply risk* sub-dimensions, "low supply risk" is score 1, "medium-low supply risk" is score 2, "medium-high supply risk" is score 3, and "high supply risk" is score 4. For the *material importance* sub-dimensions, "low importance" is score 1, "medium-low importance" is score 2, "medium-high importance" is score 3, and "high importance" is score 4. Dysprosium criticality is determined by plotting the two dimensions' respective scores on the criticality matrix. Based on their coordinates, dysprosium would be "non-critical," "low critical," "medium critical," or "critical" (Figure 6.1).

Policies are scored on their ability to reduce one or more of dysprosium criticality sub-dimensions. In the criticality scoring chart for each policy, the criticality sub-dimensions affected by a specific policy under discussion will be highlighted in blue. The reduction is achieved in one of two ways: either by percentage reduction of the *ex-ante* score (the score before the policy is applied) or by achieving a new, hopefully lower, fixed score.

R&D policies chiefly reduce *ex-ante* criticality scores by percentage reduction (e.g., a sub-dimension *ex-ante* score of 4 is halved by 50 percent to 2, the *ex-post* score or post-policy implementation score). Other policies transform the *ex-ante* values to fixed *ex-post* criticality scores.[102] For example, recall from Chapter 5 that a hypothetical Policy A's impact on a given sub-dimension—substitutability limitations—is 2. If the *ex-ante* score for substitutability limitation was 3, then the *ex-post* sub-dimension score now

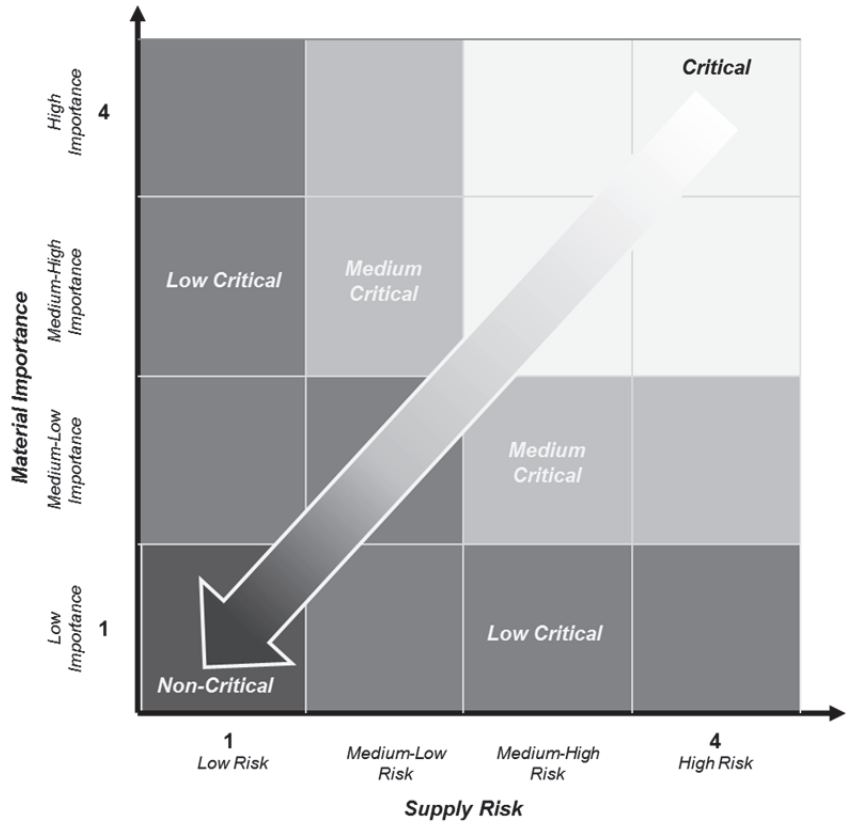
[102] As explained in Chapter 5, by default most policies change the criticality of sub-dimensions by lowering it to a new criticality level. For R&D funding initiative, however, government funding works by decreasing the base failure of on-going private sector/foreign research on the topic.

becomes 2 after Policy A's implementation.[103] This is true regardless of the impacted sub-dimension's *ex-ante* values. Say that the *ex-ante* score was 4, the *ex-post* score for that sub-dimension would still be 2.

Importantly, the policy's criticality reduction (effectiveness) is the point difference between the sub-dimension's *ex-ante* score and its *ex-post* score. For example if the *ex-ante* score was 4 and its *ex-post* score was 3, the criticality reduction (effectiveness) is simply the difference between the two, which is 1. This number is then multiplied by the weight of the sub-dimension.

As explained in Chapter 5, three different future scenarios are derived, each with assumptions that inform the default *ex-ante* (pre-policy implementation) criticality scores. The three scenarios are S.I (optimistic assumptions), S.II (sober assumptions), and S.III (worst case). A policy impacts the relevant sub-dimension(s) of each scenario by the same percentage or fixed *ex-post* score. For example, regardless of the scenario, a policy will always reduce a sub-dimension's *ex-ante* score by 50 percent or will always achieve fixed *ex-post* scores of 2. However, because the *ex-ante* scores differ across the scenarios, the criticality reduction (effectiveness) score will subsequently differ.

FIGURE 6.1 – RAW MATERIAL CRITICALITY MATRIX



Source: Adapted from NRC (2008) and Bauer et al. (2011)

[103] To reiterate, the policy's Criticality score is not subtracted from the *ex-ante* score. Rather, it *replaces* the *ex-ante* score as the new *ex-post* score.

Policy Area 1 – Supply Chain Development

Background to Policy Area 1

Mere access to non-Chinese dysprosium-bearing ores does not enhance supply security if separation, processing, and manufacturing capacities reside in China. Without American mid- and downstream capacities, U.S.-sourced dysprosium-bearing ores will have to be shipped back to China, negating any pretense of supply security. From a "naïve" global supply and demand framework, this should not necessarily matter so long as free trade enables equal access to all parties. However, from a supply security planning perspective, an independent supply chain with access to domestic and non-Chinese foreign mines, processors, and manufactures is preferable. There is inherent tension between the "naïve" worldview and a security worldview, a tension that has not been helped by the seemingly paradoxical U.S. policies that for decades have encouraged the reliance on permanent magnet manufacturing capacities to China, while at the same time requiring defense contractors to source those goods from a hollowed out domestic manufacturing base.

Increasingly wary of China's clout in the rare earth market, especially in regards to increasing U.S. reliance on Chinese metals manufacturing for defense industrial needs, Congress initiated changes to U.S. defense acquisition policy. Section 1211 of FY 2006 NDAA (with amendments in Section 1243 in FY 2012) prohibited the DoD from "acquir[ing] supplies or services covered by the United States Munitions List (USML) (22 CFR Part 121), through a contract or subcontract at any tier, from any Communist Chinese military company" (DoD 2012b). In addition, the FY 2007 NDAA separated the specialty metal clauses from the Berry Amendment—which requires preferential U.S. acquisition of American sourced materials for DoD procurement—and incorporated it into the United States Code (10 U.S. Code § 2533) with certain exemptions and waivers from the clause .

Congressional attempts to understand the global supply chain of the U.S. defense industrial base have proven difficult due to the complexity of the global supply chain and the fact that primary systems integrators themselves, such as Sikorsky, Lockheed Martin, General Dynamics, and Northrop Grumman, are rarely cognizant of the byzantine network of sub-tier suppliers, according to a study commissioned by the U.S.-China Economic and Security Review Commission (Synthesis Partners 2007). According to one former Pentagon official, neither the Pentagon nor its contractors fully understand where many subcomponents come from and the topic has historically remained an issue that "nobody at the Pentagon really wants to face" (Buchanan 2008). Still, according to the *Wall Street Journal*, an undisclosed DoD report to Congress is quoted to have asserted that, "The growing U.S. supply of [rare earths] is increasingly capable of meeting the consumption of the defense industrial base" (Areddy and Hodge 2012).

Prospectively, that assertion may have turned out to be true in due time, but the report turned out to be ill-timed. Rare earths became a political firestorm in early 2014, when it was publicly revealed that the Pentagon waived the ban on foreign sources on behalf of Northrop Grumman and Honeywell International for Lockheed Martin's F-35 components in 2012 and 2013. In the case of Northrop Grumman, Japanese-sourced permanent magnets for integration into its Active Electronically Scanned

Array (AESA) radar were found to have originated from China.[104] Non-compliance of target assemblies used for positioning doors and landing gears produced by Honeywell International were also found to have been waived by the Pentagon (Shiffman and Shalal-Esa 2014 and Shalal-Esa 2014a). Subsequent investigations found that other defense components incorporated non-U.S. specialty metals into the F-35s, B-1Bs, F-16s, and SM-3 IIA missiles (currently under development) (Shalal-Esa 2014b).

These incidents confirmed before policy makers that the U.S. permanent magnet supply chain had indeed been displaced abroad to China while also highlighting the importance of having robust midstream and downstream capacities in addition to upstream capacities. The following policies in Policy Area 1 are candidates that can help revitalize the domestic supply chain.

Domestic Upstream Development

Policy Option Background

There is potential for even greater domestic dysprosium mining in the U.S. However, current U.S. regulations are believed to deter investments by mining interests, according to the most recent report by the Fraser Institute (Wilson and Cervantes 2013). Development of American dysprosium mining can be supported by reforms to the U.S. mining regulatory framework which are characterized by overlapping jurisdictions that cause long delays in permitting and costly lawsuits by advocacy groups. The success of the Mountain Pass (CA) operation and the progress so far in Bokan Mountain (AK) and Bear Lodge (WY) are more exceptions than the norm.

U.S. Dysprosium and Other Heavy Rare Earths Mining Potential

The U.S. has several potential rare earths deposits. Table 6.4 outlines a selection of rare earth deposits with unknown quantity and quality of dysprosium. In addition, vast swaths of the southeastern U.S. coastland are believed to have potential rare earths placer deposits (Long et al. 2010). But despite these potential reserves, the large majority of these deposits has been idle for decades or has not been surveyed since the mid-20th century. The only active deposit is in Mountain Pass with Bokan Mountain and Bear Lodge up and coming in the near future.

Technically speaking, Mountain Pass alone has deposits that are worth more than 100 years of U.S. rare earths consumption.[105] As we discussed in Chapter 3, however, the mere geological presence of rare earths (and especially heavy rare earths like dysprosium) does not translate to secure supply. Recall that Mountain Pass is primarily a light rare earths deposit with insignificant dysprosium and other critical rare earths production. The other regional deposits—except for Bear Lodge and Bokan Mountain which are discussed below—are of unknown heavy rare earths grades and may not be cost-effective enough to justify mining operations. Even so, it will be at least a decade or more before they can be properly surveyed, certified, financed, licensed/permitted, and operational.

[104] According to Shiffman and Shalal-Esa (2014), the Chinese permanent magnet manufacturer was identified as Chengdu Magnetic Material Science and Technology Co. based in Chengdu, Sichuan province. Open sources do not indicate what kind of permanent magnets are used specifically for the AESA radar. However, Chengdu Magnetic Material Science and Technology supplies SmCo magnets, magnets which can be readily sourced from American suppliers.

[105] Recent U.S. TREO consumption estimates are withheld or not available by the USGS due to industry proprietary issues. The latest data available is from 2008 when U.S. consumption was estimated at 7,410 tonnes. The five year average between 2004 and 2008 was 7,704 tonnes (USGS 2014b).

TABLE 6.4 – U.S. RARE EARTH DEPOSITS AND THEIR STATUSES

Deposit	State	Tonnage (tonne)	Grade (% TREO)	Contained TREO (tonne)	Dysprosium	Status
Iron Hill	Colorado	2,424,000,000	0.4	9,696,000		Inactive
Elk Creek	Nebraska	39,400,000				Primarily niobium production
Bokan Mountain	Alaska	34,100,000	0.48	164,000	Yes	Development
Bald Mountain	Wyoming	18,000,000	0.08	14,400		
Hick's Dome	Illinois	14,700,000	0.42	62,000	Yes	No activity
Wet Mountains	Colorado	13,957,000	0.42	59,000	Yes	Last explored in 1950s
Mountain Pass	California	13,588,000	8.24	1,120,000	Yes	Producing
Bear Lodge	Wyoming	10,678,000	3.6	384,000	Yes	Development
Scrub Oaks	New Jersey	10,000,000	0.38	38,000		
Mineville	New York	9,000,000	0.9	80,000		Last iron ore production in 1971
Diamond Creek	Idaho	5,800,000	1.22	70,800	Yes	Last explored in 1950s
Pajarito	New Mexico	2,400,000	0.18	4,000		
Pea Ridge	Missouri	600,000	12	72,000	Yes	Last iron ore production in 2001
Lemhi Pass	Idaho	500,000	0.33	1,650	Yes	Explored in 2000s
Hall Mountain	Idaho	100,000	0.05	50		Last explored in 1970s
Music Valley	California	50,000	8.6	4,300	Yes	Last explored in 1957
Gallinas Mtns.	New Mexico	46,000	2.95	1,400		Last production in 1950s

Data: Long et al. (2010)

U.S. Mining Regulation Is Less Friendly Than Peer Countries

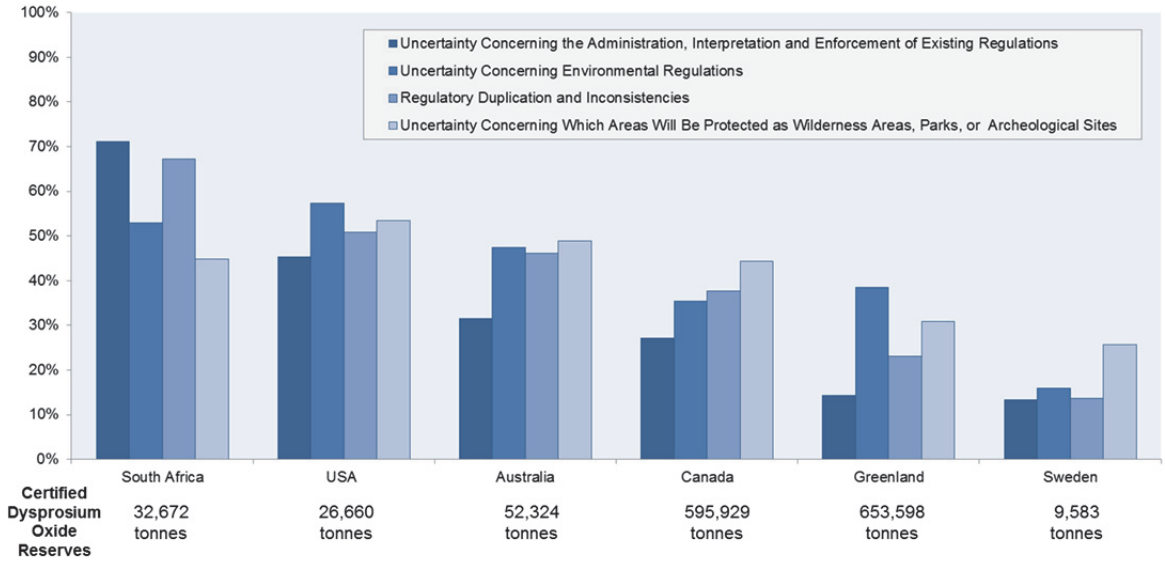
Contrary to the common perception, the chief deterrent to U.S. mining operations is not necessarily the strength of the environmental and labor protection laws. Most countries, including the U.S. and other developed economies, meet the environmental regulatory standards established by the World Bank. Rather, it is the endemic delays in mine permitting that is the "most significant risk to mining projects in the United States," according to Behre Dolbear Group whose report ranked U.S. permitting delays second to last (right above Papau New Guinea) in a survey of 25 countries (Wyatt and McCurdy 2013).[106] The average time it takes to obtain mining permits in the U.S. is about seven to ten years. In contrast, Canada and Australia, both of which have similarly stringent environmental protection laws as the U.S., generally license mining operators within one or two years (Wyatt and McCurdy 2013 and Tanton 2013).[107]

Industry research faults overlapping regulatory bodies (local, state, and federal) that require sequential rather than concurrent process for obtaining licenses as one culprit in permitting delays (Tanton 2013). The competing and compounding jurisdictions create uncertainties regarding duplication and inconsistencies in regulatory enforcement, applications of environmental statutes, and zoning protection. These are cited as top reasons that "mildly" or "strongly" deter U.S. mining investments when compared against its peer economies (South Africa, Australia, Canada, Greenland, and Sweden) that also have dysprosium (and other heavy rare earth) mining potentials (Figure 6.2) (Wilson and Cervantes 2013).

Furthermore, prolific litigation against proposed mining developments also plays a large role in delaying mine developments (Tanton 2013). According to the USGS, of seventeen proposed mines between 2000 and 2009, about half were subject to lawsuits, six of which never reached commercialization (Figure 6.3) (Long et al. 2010).

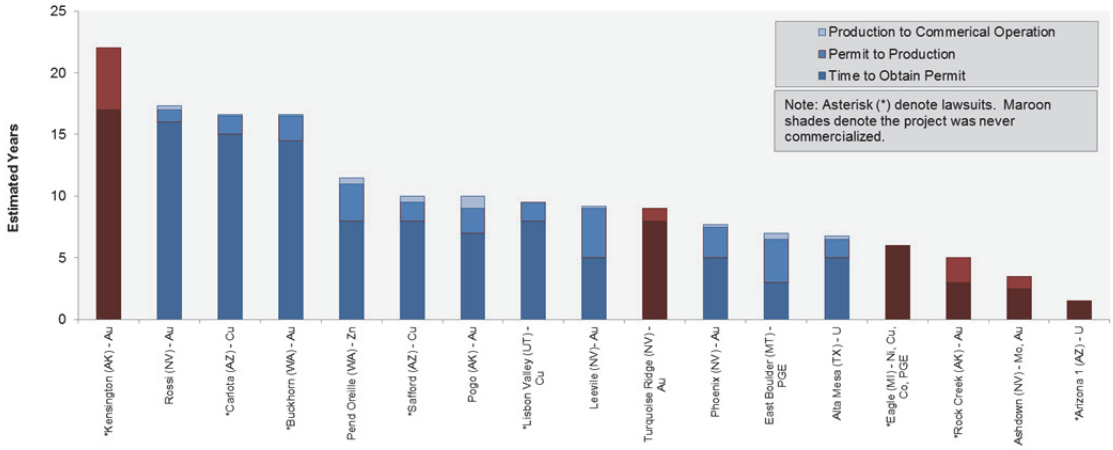
[106] The U.S. ranked sixth overall, preceded by Australia, Canada, Chile, Brazil, and Mexico (Wyatt and McCurdy 2013).
[107] Greenland has a good potential of becoming a major REEs supplier. According to Hudson Resources, which is developing the Sarfartoq project in Greenland, the country has an even more attractive mining environment than Canada. These include a fast six-month period for obtaining permits which is issued by a single government agency, subsidized energy by the EU, no royalties, and no aboriginal land claims that require negotiation (Hudson Resources 2013).

FIGURE 6.2 – DETERRENTS TO MINING INVESTMENTS IN POTENTIAL NON-CHINESE DYSPROSIUM SUPPLIER COUNTRIES (SURVEY OF MINING BUSINESS LEADERS)



Data: Wilson and Cervantes (2013); (TMR 2014); Shen (2012a); Shen (2012b); and various industry sources

FIGURE 6.3 – HISTORICAL EXAMPLES OF TIME REQUIRED TO OBTAIN PERMITS, CONSTRUCT, AND COMMISSION MINES IN THE U.S.



Data: Long et al. (2010)

Regulatory Regime Variations across States

Differences in state-level mining regulations are significant. Wyoming, Nevada, Utah, Kentucky, West Virginia, Idaho, and Arizona are traditionally known for mining-friendly regulatory regimes (Tanton, 2013). In contrast, the regulatory burden on states with rare earth reserves tends to be fairly high according to Tanton (2012), whose study rated state level permitting difficulties. The Fraser Institute (Wilson and Cervantes 2013) survey of mining business leaders' opinions on the regulatory deterrents to investing in U.S. states echoes this sentiment. Although data is limited, as illustrated in Table 6.5,

California, Colorado, New Mexico, and Alaska—which are all believed to have various levels of rare earth deposits—have unfavorable investment ratings.

TABLE 6.5 – MINING INVESTMENT CLIMATE OF U.S. STATES WITH RARE EARTH RESERVES

States with Rare Earth Reserves	State Permit Hurdle Level (1=Low, 4=High)	Deterrents to Mining Investments in the U.S. (Survey of Mining Company CEOs)				Estimated TREO (tonnes)
		Uncertainty Concerning the Administration, Interpretation and Enforcement of Existing Regulations	Uncertainty Concerning Environmental Regulations	Regulatory Duplication and Inconsistencies	Uncertainty Concerning Which Areas Will Be Protected as Wilderness Areas, Parks, or Archeological Sites	
California*	3	88%	93%	81%	69%	1,124,300
Colorado	3	59%	72%	62%	63%	9,755,000
New Mexico	2	57%	56%	60%	58%	5,400
Alaska*	3	44%	61%	48%	53%	164,000
Idaho	2	35%	50%	44%	61%	72,500
Illinois	3	NA	NA	NA	NA	62,000
Nebraska	2	NA	NA	NA	NA	
New York	3	NA	NA	NA	NA	80,000
Wyoming*	NA	15%	24%	39%	33%	398,400
	Asterisk (*) denotes states with current or propsective rare earth mining projects. The state permitting metrics mean the following: 4 = Effective or real moratorium/prohibition; 3 = Possible but extremely difficult and time consuming; 2 = Straightforward: comparative to any other industrial permit; and 1 = Expedited and encouraged: "fast track."					

Data: Tanton (2012) and Wilson and Cervantes (2013)

American rare earth projects in Mountain Pass (CA), Bokan Mountain (AK), and Bear Lodge (WY) are the only ones that are currently in operation or with potential for near-term operations (the latter two have high dysprosium production prospects). Mountain Pass is currently active and producing light rare earths. Bokan Mountain and Bear Lodge are estimated to begin initial production in the 2016 to 2017 period (Ucore 2013 and Rare Element Resource 2014a). Figure 6.4 outlines the project schedules for the two deposits.

Bear Lodge is fortunately located in a highly favorable mining jurisdiction, Wyoming, which has helped expedite the project progress. The other two projects, however, are situated in less mining-friendly states and their progress to date belies unique characteristics that may not be easily reprised by other rare earth ventures.

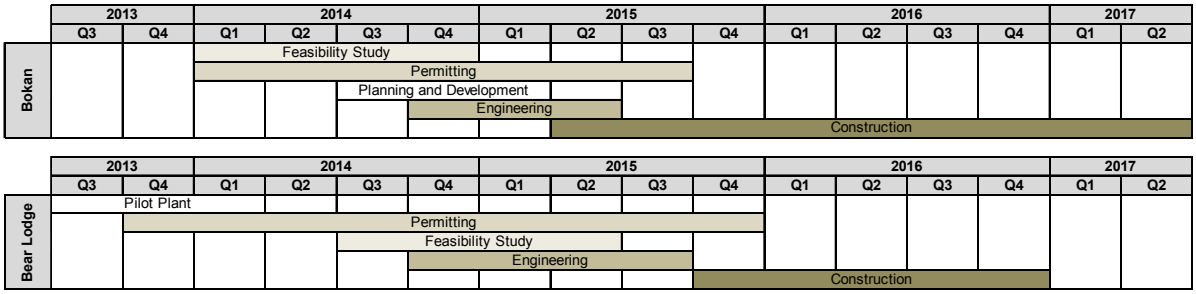
Situated in the most unfavorable mining state, California, Mountain Pass was originally shut down in 2002 because of environmental concerns. It took nearly a decade, including an offer by Chevron (which inherited the mine in its acquisition of Union Oil Company of California or Unocal) to assume financial responsibilities for a massive cleanup of toxic waste from past operations and years of additional regulatory reviews before Molycorp could resume operations.[108] A similar arrangement where costly environmental regulatory risks are assumed by an external third party is rare.

In the case of Bokan Mountain, it took extraordinary political capital at the state, local, and federal levels to fast track its development. The effort involved the DoD, DoE, the Senate Subcommittees on REE Procurement for Military and National Security Purposes and on Energy and Natural Resources, coordination with the USGS, U.S. Department of Agriculture (USDA), and U.S. Forestry Service (USFS) for priority permitting intervention, and lobbying from groups such as USMMA (Ucore 2013). Mobilizing resources at the level of the federal government is a significant and costly burden for a small-

[108] A private group, Molycorp Minerals, LLC, purchased the Mountain Pass project from Chevron Corporation in 2008. Molycorp became publicly traded in 2010, a year after production restarted in Mountain Pass. Chevron inherited the liabilities for the environmental damage caused during the rare earth production years from its preceding own, Unocal. Chevron ultimately decided to sell the project in order to focus on its energy business, but retained the liabilities nonetheless (Humphries 2013).

to-medium size business to undertake. It is fair to say that Mountain Pass and Bokan Mountain have been relatively successful (so far) *despite* the regulatory burdens.

FIGURE 6.4 – BOKAN MOUNTAIN AND BEAR LODGE PROJECT DEVELOPMENT SCHEDULES



Data: Ucore (2013) and Rare Element Resources (2014b)

Policy Effectiveness and Cost

The policy objective is to hasten federal and state mining permits to the level of the Australians and Canadians whose environmental protection laws are on par with the U.S. Domestic mining policy should therefore be focused on shortening the mine permit processing time and discouraging frivolous lawsuits—all objectives encased in H.R. 761 (see Appendix I for an excerpt of the bill). Among other items, H.R. 761 proposes streamlining overlapping jurisdictions, limiting litigious action against the federal agency overseeing the streamlined process, and introducing exemptions to land classification on federal lands to facilitate infrastructure development in support of domestic critical material production (National Strategic and Critical Minerals Production Act of 2013).

This bill would establish a single authority to process mine permits as in Australia and Canada. By introducing statutory limitations, it would also shield the permits from becoming mired in long and costly litigations. In addition, the measure proposes to discourage frivolous lawsuits by transferring the financial burden of lawsuits from the judiciary to the plaintiffs (National Strategic and Critical Minerals Production Act 2013). The intent here is not to endorse H.R. 761, but rather to elucidate one standing policy proposal that, if enacted, could stand to make American rare earth mining more competitive.

In the timeframe of the study, the chief effect of this policy would be to provide regulatory clarity and reduce political risk of the operation and development of Mountain Pass, Bokan Mountain, and Bear Lodge. In the long run, closer to and beyond FY 2029, this policy option would provide modest incentives for further surveys and development of rare earth resources within the U.S. The policy's effects of increasing the likelihood of the successes of the Bokan Mountain and Bear Lodge operations and the prospective initiation of new dysprosium (and other heavy rare earth) mining projects in the U.S. are expected to reduce the *ex-post supply risk* of *upstream supply capacity* to the medium-low/low category (score of 1.5). In addition, the proliferation of non-Chinese dysprosium production outside of China increases supplier diversity, thereby lowering the *upstream supplier diversity* risk to medium-low/medium-high (score of 2.5).[109] Finally, by reducing the regulatory risks associated with U.S. mining, this policy would decrease the *ex-post* risk of *political, regulatory, and social factors* sub-dimension to

[109] Only further global diversification would reduce the capacity and diversity risks. The proposed policy option only increases the capacity and diversity of U.S. dysprosium suppliers.

medium-low/medium-high level (score of 2.5).[110] Table 6.6 summarizes these scores (note that the three sub-dimensions impacted by this policy are highlighted in blue).

It is worthwhile walking through how the criticality scoring scheme works by using the examples of scenarios S.I and S.II and the impact of this policy option on one sub-dimension, *upstream supply capacity*, in particular. Let us first review the data (refer to Table 6.6). The policy criticality score for *upstream supply capacity* is 1.5. This means that once the policy is implemented, the introduction of U.S. mining permitting reforms would substantially decrease regulatory risk in the U.S. and speed up the developing (and financing) of mining projects. Therefore, the risk level for that specific sub-dimension becomes low/medium low risk (1.5) from whatever the *ex-ante* scores were.

The S.I and S.II *ex-ante* scores for *upstream supply capacity* are 1.5 and 3, respectively. The score is 1.5 for S.I because in that scenario, successful functional substitutes for permanent magnets substantially decrease the demand for dysprosium while cost-effective recycling technology increases supply capacities. China has also dismantled export barriers. For these reasons, from the perspective the U.S. policy planner, the risk of dysprosium supply disruption is low. For S.II, however, the sober scenario assumptions state that no significant breakthroughs in substitution or recycling are available and China has continued to restrict exports. The overall *ex-ante supply risk* picture from the U.S. policy planner's perspective is thus higher than in S.I.[111]

Now, if the policy planner were to implement the domestic upstream development policy option, it would altogether change the risk level for the *upstream supply capacity* sub-dimension for S.I and S.II. This new risk level is simply the aforementioned policy critical score of 1.5. In the case of S.I, the sub-dimension risk level remains the same (from 1.5 to 1.5). The introduction of new policy reforms is not expected to substantially impact the overall dysprosium risk picture (even if mining for dysprosium is easier) because the dysprosium risk profile was already low. In contrast, in the case of S.II, the risk level transitions from 3 to 1.5.[112] Because the overall dysprosium risk profile is so much higher (no substitutes with no supply from recycling or from China), the introduction of fast-tracked U.S. dysprosium production substantially reduces the supply capacity risk.

In the contexts of scenarios S.I, S.II, and S.III, the sum criticality reduction (effectiveness) translates to 0, 0.53, and 0.73, respectively.[113] With the implementation of this policy, the *ex-post* criticality scores for each of the scenarios would be 3.85 (S.I), 6.45 (S.II), and 7.27 (S.III) as summarized in Table 6.6.[114]

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[110] Further decrease would require the mitigation of regulatory risk from China, which is not addressed by this policy option.

[111] All analysis is done from a U.S. policy planner's dysprosium criticality reduction perspective. Of course, as alluded to in previous chapters, from the mining investor's perspective, S.II dynamics would prop up dysprosium prices and provide greater incentive for non-Chinese dysprosium mining.

[112] Note that this is *not* a subtraction from the *ex-ante* value to the new value. Rather it is the *replacement* of the *ex-ante* value by the policy criticality score, which becomes the *ex-post* value.

[113] Recall that the criticality reduction (effectiveness) for a given scenario is the difference between the *ex-ante* score and the *ex-post* score. Let us take the *upstream supply capacity* sub-dimension as an example. The S.I *ex-ante* score is 1.5 and the *ex-post* score is 1.5 so the effectiveness is 0 (after multiplying by the weight, 13.3 percent). For S.II, however, the effectiveness is $(3 - 1.5) \cdot 13.3\% = 0.2$ and for S.III, it is $(4 - 1.5) \cdot 13.3\% = 0.33$. The same calculations are done for the two other sub-dimensions impacted by this policy option (highlighted in blue) and they are summed for each scenario. These sums directly translate to the aforementioned sum criticality reduction (Effectiveness) numbers. For example for S.I it is 0, whereas for S.II it is $0.2 + 0.3 + 0.03 = 0.53$ and for S.III it is $0.33 + 0.3 + 0.1 = 0.73$.

[114] The *ex-post criticality* score for a scenario is simply the sum of the *ex-post* sub-dimension scores from *material importance* and *supply risk* dimensions. Thus for S.I it is $1.75 + 2.1 = 3.85$, for S.II it is $3.75 + 2.7 = 6.45$, and for S.III it is $4 + 3.27 = 7.27$.

The cost of adopting H.R. 761 is estimated at less than $300,000 a year according to the Congressional Budget Office (CBO), mostly for hiring additional employees (CBO 2013). The CBO notes that the cost of streamlining the permitting process across different agencies is marginal because the "agencies are performing most of those activities under current law" with past appropriations. Additional, the CBO estimates that H.R. 761 would yield a modest saving of $50,000 a year in attorney fees based on historical data from 2003 to 2012. The present value (PV) cost of the policy between FY2015 and FY 2029 is approximately $2,900,000 using a discount rate of 4 percent.[115]

TABLE 6.6 – DOMESTIC UPSTREAM PRODUCTION EFFECTIVENESS

Domestic Upstream Production													
FY2015-FY2029 Cost ($M)		$2.9		S.I (Optimistic)			S.II (Pessimistic)			S.III (Worst Case)		
Dimension	Sub-Dimension	Weight	Policy Criticality Score	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)
Material Importance	Defense and Clean Energy Importance	75%		2	2	0.00	4	4	0.00	4	4	0.00
	Substitutability Limitations	25%		1	1	0.00	3	3	0.00	4	4	0.00
			Criticality	1.75	1.75	0.00	3.75	3.75	0.00	4	4	0.00
Supply Risk	Supply Capacity - Upstream	13.3%	1.5	1.5	1.5	0.00	3	1.5	0.20	4	1.5	0.33
	Supply Capacity - Midstream	13.3%		1	1	0.00	3.5	3.5	0.00	4	4	0.00
	Supply Capacity - Downstream	13.3%		2	2	0.00	3.5	3.5	0.00	4	4	0.00
	Competing Demand	10%		2	2	0.00	2	2	0.00	4	4	0.00
	Political, Regulatory, and Social Factors	20%	2.5	2	2.5	0.00	4	2.5	0.30	4	2.5	0.30
	Codependence on Other Markets	10%		3	3	0.00	3	3	0.00	4	4	0.00
	Producer Diversity - Upstream	6.7%	2.5	3	2.5	0.03	3	2.5	0.03	4	2.5	0.10
	Producer Diversity - Midstream	6.7%		2	2	0.00	3	3	0.00	4	4	0.00
	Producer Diversity - Downstream	6.7%		3	3	0.00	3	3	0.00	4	4	0.00
			Criticality	2.03	2.10	0.00	3.23	2.70	0.53	4.00	3.27	0.73
			Sum Criticality	**3.78**	**3.85**	**0.00**	**6.98**	**6.45**	**0.53**	**8.00**	**7.27**	**0.73**

Midstream Separation and Processing R&D

Policy Option Background

The midstream process of separating different rare earths and processing them into higher purity oxides is the single most expensive process in the rare earth supply chain, costing approximately $800 million in capital investments alone (which averages out to about $40,000 per tonne per year, excluding labor and chemical material costs) (Hayes-Labruto et al. 2013). What is more, according to the DoE, "traditional separation technologies are generally considered inefficient, environmentally unfriendly and unsustainable" because the solvent extraction technique requires the use of hazardous chemicals, require large capital investments, and long processing times (Bauer et al. 2011).

Depending on the type of REE-bearing ore that is extracted, the presence of radioactive thorium can substantially—many times prohibitively—increase the cost and time of ore processing. Improving solvent extraction or developing a different technique altogether could lead to substantial cost-savings,

[115] See Chapter 5 for discussion on the selection of the 4 percent discount rate.

ultimately translating to greater supply that is produced more cheaply through environmentally-sustainable means.

Until recently, the DoE has not focused research on rare earths separation and processing technology. The most similar past research have been on nuclear fuel separation and extraction of actinide series of elements (atomic numbers 90 to 103 which includes uranium and plutonium) which required separating the actinides from the lanthanides (rare earths). In fact, because actinides share commonalities with lanthanides, knowledge gained from nuclear fuel processing is believed to be applicable to improving rare earths processing.[116] Examples of new methods currently being pursued by U.S. and foreign researchers are outlined in Table 6.7. CMI's Focus Area 1 on supply diversification also has research projects that aim to increase the efficiency and effectiveness of critical materials mining, including projects specific to REEs beneficiation, recovery, separation, and new applications of coupled production elements, namely LREEs (CMI 2012).

TABLE 6.7 – POTENTIAL NEW METHODS OF SEPARATING AND EXTRACTING REES

New Method	DoE Description
Supercritical fluid extraction	"Supercritical fluid is a substance at a temperature and pressure above its critical point. In this methodology, the rare earth material (such as an ore) is dissolved in an acid. The dissolved rare earth is contacted with SC CO_2 that contains an extractant. This creates two phases: the acid phase and the SC CO_2 phase. The rare earth metal binds with the extractant and remains in the SC CO_2. The two phases can be separated and the rare earth metal can be isolated by removing the CO_2 (by reducing the pressure or temperature)."*
Biological extraction	"Studies have demonstrated the use of bacteria to concentrate rare earth metals from dilute solutions. One study examined the adsorption of REEs onto bacterial cell walls (Takahashi 2005). In acidic solutions, from an initial concentration of 100 micrograms of an REE mixture per liter, the bacteria preferentially adsorbed REEs onto its cell surface, with europium and samarium seeing the highest enrichment."*
Electrochemistry	"Materials and Electrochemical Research Corporation (MER) received a Small Business Innovation Research (SBIR) 2010 Phase I award to develop an electrochemical route to convert rare earth ore into high-purity metals. Specifically, the work focused on producing refined neodymium oxide. The processing innovation developed in the work yields a magnetic material with a higher energy density. For the work, MER recently won an R&D 100 award. MER has also recently been awarded an SBIR Phase II award to further the R&D effort for the innovative technology."*
Desferal	"Geochemists in Germany developed a method to efficiently extract rare earth metals from ferromanganese nodules using the solvent desferrioxamine-B, also known by its commercial name, Desferal, a treatment for the iron-intoxication disease hematochromatosis. Desferal binds more strongly to some metals than others and when applied to ferromanganese nodules, effectively and efficiently extracts rare earth metals, leaving other metals behind in the nodules. By refining their ore-leaching method, the team was able to extract up to 80 percent of four rare earth metals from some ferromanganese nodules."±

Data: *Bauer et al. (2011) and ±Gabrielsen (2014)

Policy Effectiveness and Cost

Cost-effective separation and processing technology could help the U.S. establish midstream capacity that can compete with China's traditionally lower operating costs. For this reason, the *ex-post* policy criticality risk for *midstream supply capacity* is rated low supply risk (score of 1). However, because

[116] Past research into actinide processing was conducted by the Oak Ridge National Laboratory, the Lawrence Berkeley National Laboratory, and Argonne National Laboratory under the direction of the DoE's Office of Basic Energy Science; the Savannah River National Laboratory supported by the Office of Environmental Management; and the Office of Nuclear Energy which directed research across the national laboratories and universities (Bauer et al. 2011).

Chinese midstream suppliers are still likely to comprise a substantial portion of global capacity, the *supply risk* with *midstream producer diversity* is assessed to be medium-low (score of 2).

Midstream research is considered technically very challenging and the research difficulty is assessed to lie between Levels IV and V according to the definitions established by R&D[3] (Mankins 1998). This translates to a research probability success rate of approximately 37 percent and a failure probability of 63 percent.[117] With U.S. government research funding, the failure rate is halved to 31.5 percent, yielding a research success probability of 68.5 percent (per the method described in Chapter 5).

Taking into account the modified research probability, the *ex-post* criticality score for *midstream supply capacity* is 1 (S.I), 1.79 (S.II), and 1.95 (S.III).[118] Similarly, the *ex-post* criticality score for *midstream supply diversity* is 2 (S.I), 2.32 (S.II), and 2.63 (S.III).[119] Taken together, the sum criticality reduction (effectiveness) are 0 (S.I), 0.27 (S.II), and 0.37 (S.III).[120] Table 6.8 summarizes these findings.

Research would be funded via incumbent DoE research programs such as the CMI and REACT. The effectiveness is measured on whether the project successfully reached both TRL 9 and CRL 9 by the end of the funding period.[121] If Level 9 is reached for both metrics, then the project is a success and considered to have an immediate impact on transforming the productivity of U.S. rare earths mining.

$8.2 million is the approximate pro-rated cost of research funds based on past DoE appropriate funds for REACT and CMI. The estimated total budget for all rare earth research in the FY 2012 to FY 2015 budget was about $100 million ($37.5 million from REACT plus about half of CMI's $120 million budget after subtracting estimated non-REE research programs and program overhead costs). When split evenly among the three major rare earth R&D research areas—separation and processing, recycling, and substitution—the funding for each area is about $32.5 million or about $8.125 million per fiscal year. Pro-rated across fifteen fiscal years, the present value of the research budget with a real discount δ rate of 4 percent equals to about $95 million.

[117] See Chapter 5 for discussion on the derivation of 37 percent project probability of success based on a fitted probability curve extrapolated from Mankins (1998).

[118] Recall from Chapter 5 R&D expected criticality score is calculated as $R\&D\ Expected\ CS_k = \left(1 - \frac{p}{2}\right) \cdot CS_{R\&D} + \frac{p}{2} \cdot XA_k$. p represents the default probability of success, $CS_{R\&D}$ represents the *ex-post* (after) sub-dimension criticality score if the research is successful, and XA_k represents the *ex-ante* (before) sub-dimension criticality score before research funding. Thus, the *midstream supply capacity* expected score S.I is calculated as $0.685 \cdot 1 + 0.315 \cdot 1 = 1$; the expected score for S.II is calculated as $0.685 \cdot 1 + 0.315 \cdot 3.5 = 1.79$; and the expected score for S.III is $0.685 \cdot 1 + 0.315 \cdot 4 = 1.95$. The expected scores for *midstream supply diversity* is calculated in similar fashion.

[119] The *ex-post* scores for the *midstream supply diversity* sub-dimensions is calculated using the same expected score method illustrated for the *midstream supply capacity* sub-dimensions above.

[120] This is the sum of each scenario's sub-dimension criticality reduction (effectiveness) values. For S.I it is 0, while for S.II it is $0.228 + 0.046 = 0.27$ (rounded) and for S.III it is $0.27 + 0.09 = 0.37$.

[121] TRL refers to Technology Readiness Level and CRL refers to Commercial Readiness Level (see Chapter 5).

TABLE 6.8 – MIDSTREAM SEPARATION AND PROCESSING R&D EFFECTIVENESS

Midstream R&D Separation and Processing													
FY2015-FY2029 Cost ($M)	$95			S.I (Optimistic)			S.II (Pessimistic)			S.III (Worst Case)		
Dimension	Sub-Dimension	Weight	Policy Criticality Score	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)
Material Importance	Defense and Clean Energy Importance	75%		2	2	0.00	4	4	0.00	4	4	0.00
	Substitutability Limitations	25%		1	1	0.00	3	3	0.00	4	4	0.00
			Criticality	1.75	1.75	0.00	3.75	3.75	0.00	4	4	0.00
Supply Risk	Supply Capacity - Upstream	13.3%		1.5	1.5	0.00	3	3	0.00	4	4	0.00
	Supply Capacity - Midstream	13.3%	1	1	1	0.00	3.5	1.79	0.23	4	1.95	0.27
	Supply Capacity - Downstream	13.3%		2	2	0.00	3.5	3.5	0.00	4	4	0.00
	Competing Demand	10%		2	2	0.00	2	2	0.00	4	4	0.00
	Political, Regulatory, and Social Factors	20%		2	2	0.00	4	4	0.00	4	4	0.00
	Codependence on Other Markets	10%		3	3	0.00	3	3	0.00	4	4	0.00
	Producer Diversity - Upstream	6.7%		3	3	0.00	3	3	0.00	4	4	0.00
	Producer Diversity - Midstream	6.7%	2	2	2	0.00	3	2.32	0.05	4	2.63	0.09
	Producer Diversity - Downstream	6.7%		3	3	0.00	3	3	0.00	4	4	0.00
			Criticality	2.03	2.03	0.00	3.23	2.96	0.27	4.00	3.63	0.37
			Sum Criticality	**3.78**	**3.78**	**0.00**	**6.98**	**6.71**	**0.27**	**8.00**	**7.63**	**0.37**

DoD Midstream and Downstream Development

Policy Option Background

At the end of 2013, only two non-Chinese rare earths companies—the American company Molycorp and Australia's Lynas—were making progress towards vertical integration of the supply chain. Lynas's Mount Weld project is projected to be the single largest non-Chinese dysprosium and heavy rare earths producer. However, as a foreign producer, Lynas cannot supply to the DoD under current regulations (separation and processing takes place at a new facility built in Malaysia). On the other hand, while Molycorp is an American company, it is primarily a light rare earths producer with insignificant amounts of dysprosium and heavy rare earths production.

In fact, much of the Molycorp's downstream capacities reside abroad. Moving down the supply chain, separation and processing facilities are located in China and Estonia, an alloying facility is in Arizona, and permanent magnet production facilities are in China, Thailand, and Japan (Molycorp 2013d and Humphries 2013).[122] More specifically, Molycorp Jiangyin (JAMR) in Jiangyin, Jiangsu Province in China refines heavy rare earths from the region's rich ion-adsorption deposits. Molycrop also acquired a processing plant in Estonia (AS Silmet, since renamed Molycorp Silmet) that refines rare earth oxides and metals for export. Molycorp Magnequench produces magnetic powders in its Tianjin, China and Korat, Thailand facilities. NdFeB magnets are manufactured by Intermetallics Japan, a joint venture between Molycorp, Daido Steel, and Mitsubishi Corporation, each of whom has roughly a third equity stake in the

[122] Other processing and manufacturing facilities for zirconium, gallium, indium, and rhenium are located in China, Canada, Japan, and South Korea (Molycorp 2013b).

venture (Molycorp 2013b). Thus Molycorp represents a classic example of a contemporary global supply chain that sufficiently satisfies commercial end-users but falls short of DoD statutory requirements.

The other two U.S. heavy rare earth projects—Bokan Mountain, owned by the Canadian company Ucore Rare Metals Inc. and Bear Lodge owned by the Colorado-based Rare Element Resources Ltd.—have promising dysprosium reserves. Critically, both projects are building ore separation and processing facilities. Ucore has stated that it will use an experimental rare earth extraction method that uses nanotechnology to separate individual REEs far more efficiently than traditional solvent-based processing. The so-called Solid Phase Extraction (SPE) technology is being co-developed by Ucore and IntelliMet LLC, a Montana firm (Lasley 2013). In October 2012, the Pentagon contracted with Ucore (via its subsidiary Landmark Alaska L.P.) on a joint six-month project on the SPE which provided the DoD with access to data on the SPE technology (Ucore 2012). Rare Element Resources will also build separation and processing facilities in Wyoming which would be able to refine rare earths up to approximately 95 to 97 percent purity using traditional solvent leaching process (Rare Element Resources 2014a).

Policy Effectiveness and Cost

As reviewed in Chapter 5, a couple of NdFeB manufacturers, Hitachi Metals Ltd. in South Carolina and Indiana-based Thomas & Skinner, Inc.[123], have reconstituted and retained their facilities in the U.S., respectively. A few more are able to produce the magnets under license (USMMA 2013). Thus, a domestic supply chain is nearly complete. The only gap is the high purity oxide and metal forming capacities which still reside abroad, primarily in Japan and China.

To ensure the supply of domestically sourced rare earths magnets to the defense industrial base in compliance with relevant regulations, this policy option expands the DoD's Trusted Foundry Program to include rare earths permanent magnets. The Trust Foundry Program is managed by the DoD's Defense Microelectronics Activity (DMEA) which assures U.S. national security stakeholders access to secured yet cost-effective integrated circuits and other sensitive microelectronic technologies. DMEA achieves this by certifying commercial suppliers and by its in-house design, manufacturing, testing, and evaluation capabilities at a Sacramento, CA facility (DMEA 2014a). The DoD describes the mission of the DMEA as follows:

> The Department has found it critical to National Security to maintain an ability to produce legacy microelectronics long after they are available from commercial foundries which move to more advanced technology levels based upon the global market. The Defense Microelectronics Activity (DMEA) uniquely accomplishes this mission for the Department by providing both a trusted and assured supply of microelectronics parts that are no longer available from, or bid by, commercial sources but are essential to combat operations. This is a critical capability in an atmosphere of increasing worldwide supply chain risks with threats to defense microelectronics. The threats include risks, such as, counterfeiting, Trojan horses, unreliability and rapid obsolescence coming from an unpredictable and unsecure supply chain. As fiscal pressures force the Department to maintain its weapon systems longer than originally planned and their extended combat use increases attrition, the need for DMEA's unique capabilities increases (DoD 2013b).

[123] In October 2012, the DoD contracted with Thomas & Skinner in a "defense supply-chain assessment…regarding the requirement for competitive domestic [NdFeB] magnets or their substitutes to support defense supply-chain manufacturing capacity" (Thomas & Skinner 2012).

The challenge the DoD faces regarding semiconductors are remarkably similar to the rare earth permanent magnet situation:

> Microelectronics is a crucial technology and central for all operations within the Department. Yet, as vital as this technology is to Department operations, the defense market represents less than 0.1% share of the total global semiconductor market. The Department frequently requires legacy microelectronics long after commercial foundries have moved on to advanced technology levels. As such, the semiconductor industry does not respond to the Department's unique needs of ultra-low volumes, long availability time frames, or its high-level security concerns. In these cases, DMEA procures a license to produce technologies in-house that are no longer commercially manufactured or are unavailable due to no-bids owing to low volume requirements. These licenses enable DMEA to be the Department's microelectronics supplier of last resort, providing the Department with a long-term, trusted, and assured source (DoD 2013b).

Under this policy proposal, there are *two* distinct policy options to be discussed in the next two sections.

Expansion of DoD Trusted Foundry Certification Process

First, the Trusted Foundry Program will be expanded to include the specialty metals covered under 10 U.S. Code § 2533. The program would be responsible for certifying that rare earth magnets are manufactured by U.S. firms and that the rare earth materials were extracted, separated, and processed from mines and facilities in the U.S. and said "qualifying countries." Congress could also expand the "qualified countries" to include Australia and Japan whose ores and processing capacities, respectively, can bridge gaps in the U.S. supply chain in the short term. The certification process will help the DoD to comply with statutory requirements regarding hitherto opaque sub-tier supply chains while providing top- and sub-tier contractors with a roadmap towards compliance. Appendix L describes the current DMEA process flow for commercial accreditation as a trusted foundry which would serve as a template for accrediting specialty metal producers.

A certification process would have the effect of carving a new market for American NdFeB permanent magnet manufacturing capacity. This can incentivize expansion of downstream American (or other qualified nation) production capacity by clarifying a roadmap for conducting business with DoD contractors.[124] For these reasons, the policy would decrease the *downstream supply capacity* risk to medium-low (2) and *downstream producer diversity* risk to medium-high (3).[125] The sum criticality reduction (effectiveness) of this policy are 0 (S.I), 0.2 (S.II), and 0.33 (S.III) which translates to *ex-post* criticality scores of 3.78, 6.78, and 7.67 for the respective scenarios (Table 6.9).

According to the DoD 2013b, the annual operating budget for the Foundry accreditation program was $35 million in FY 2014. Using this as a basis for rare earth permanent magnet accreditation initiative, the present cost translates to approximately $405 million between FY 2015 to FY 2029.

[124] The demand for DoD-consistent sources of supply may also have an indirect effect on incentivizing non-Chinese upstream and midstream producers.

[125] The scores are equivalent to the S.I *ex-ante criticality* scores (Table 6.9). This is because of the assumption that the DoD Accreditation policy is not expected to reduce criticality any more than what the scores would be in the optimistic S.I case.

TABLE 6.9 – DOD DOWNSTREAM ACCREDITATION EFFECTIVENESS

DoD Downstream Accreditation												
FY2015-FY2029 Cost ($M)	$405			S.I (Optimistic)			S.II (Pessimistic)			S.III (Worst Case)		
Dimension	Sub-Dimension	Weight	Policy Criticality Score	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)
Material Importance	Defense and Clean Energy Importance	75%		2	2	0.00	4	4	0.00	4	4	0.00
	Substitutability Limitations	25%		1	1	0.00	3	3	0.00	4	4	0.00
			Criticality	1.75	1.75	0.00	3.75	3.75	0.00	4	4	0.00
Supply Risk	Supply Capacity - Upstream	13.3%		1.5	1.5	0.00	3	3	0.00	4	4	0.00
	Supply Capacity - Midstream	13.3%		1	1	0.00	3.5	3.5	0.00	4	4	0.00
	Supply Capacity - Downstream	13.3%	2	2	2	0.00	3.5	2	0.20	4	2	0.27
	Competing Demand	10%		2	2	0.00	2	2	0.00	4	4	0.00
	Political, Regulatory, and Social Factors	20%		2	2	0.00	4	4	0.00	4	4	0.00
	Codependence on Other Markets	10%		3	3	0.00	3	3	0.00	4	4	0.00
	Producer Diversity - Upstream	6.7%		3	3	0.00	3	3	0.00	4	4	0.00
	Producer Diversity - Midstream	6.7%		2	2	0.00	3	3	0.00	4	4	0.00
	Producer Diversity - Downstream	6.7%	3	3	3	0.00	3	3	0.00	4	3	0.07
			Criticality	2.03	2.03	0.00	3.23	3.03	0.20	4.00	3.67	0.33
			Sum Criticality	**3.78**	**3.78**	**0.00**	**6.98**	**6.78**	**0.20**	**8.00**	**7.67**	**0.33**

DoD Trusted Foundry Downstream Capacity for Permanent Magnets

Second, an "in-house" DoD rare earths metal processing and magnet manufacturing capacity of "last resort" could be established in partnership with DoE component programs such as the DoE's CMI. The facility could be located at the Air Force Research Laboratory's Materials and Manufacturing Directorate at Wright-Patterson Air Force Base, OH or at the Ames Laboratory.

This policy would decrease the *ex-post* risks to medium-low (2) for both *midstream/downstream supply capacities* and for *midstream/downstream supplier diversity*. As a result, it is expected to lower the criticality scores for scenarios S.II and S.III. However, it could slightly *increase* the criticality in S.I. (i.e., the criticality reduction (effectiveness) score for S.I is a negative value). This is because we can expect some degree of a crowding out effect by the government's entry into the midstream market. More specifically, would-be private businesses could be displaced by the government's production presence. While this ensures supply and quality control for the DoD, it discourages private investment in midstream and downstream capacities under scenario assumptions in S.I which potentially reduces supplier diversity and economic efficiency.

The sum criticality reduction (effectiveness) of the DoD Trust Foundry expansion would be -0.07 (S.I), 0.53 (S.II), and 0.8 (S.III), translating to *ex-post* criticality scores of 3.85 (S.I), 6.45 (S.II), and 7.2 (S.III) (see Table 6.10).

This policy option is very capital-intensive as it requires building processing and magnet-making plants. The separation plant cost estimate ranges between $200 million to $300 million with an annual operating cost of up to $60 million based on estimates from the Bear Lodge project economic pre-feasibility study (Rare Element Resources 2012). The magnet plant would cost about $60 million based on Hitachi's latest NdFeB magnet manufacturing facility in China Grove, North Carolina (Salisbury Post 2012). The operating cost of the program is assumed to be similar to the DMEA's own operational cost for running

its semiconductor production facility, which was $48 million in FY 2014 (DoD 2013b). In sum, the present cost of this policy option is approximately $1.8 billion for FY 2015 to FY 2029.[126]

TABLE 6.10 – DOD TRUSTED FOUNDRY EFFECTIVENESS

DoD Trusted Foundry													
FY2015-FY2029 Cost ($M)		$1,800		S.I (Optimistic)			S.II (Pessimistic)			S.III (Worst Case)		
Dimension	Sub-Dimension	Weight	Policy Criticality Score	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)
Material Importance	Defense and Clean Energy Importance	75%		2	2	0.00	4	4	0.00	4	4	0.00
	Substitutability Limitations	25%		1	1	0.00	3	3	0.00	4	4	0.00
			Criticality	1.75	1.75	0.00	3.75	3.75	0.00	4	4	0.00
Supply Risk	Supply Capacity - Upstream	13.3%		1.5	1.5	0.00	3	3	0.00	4	4	0.00
	Supply Capacity - Midstream	13.3%	2	1	2	-0.13	3.5	2	0.20	4	2	0.27
	Supply Capacity - Downstream	13.3%	2	2	2	0.00	3.5	2	0.20	4	2	0.27
	Competing Demand	10%		2	2	0.00	2	2	0.00	4	4	0.00
	Political, Regulatory, and Social Factors	20%		2	2	0.00	4	4	0.00	4	4	0.00
	Codependence on Other Markets	10%		3	3	0.00	3	3	0.00	4	4	0.00
	Producer Diversity - Upstream	6.7%		3	3	0.00	3	3	0.00	4	4	0.00
	Producer Diversity - Midstream	6.7%	2	2	2	0.00	3	2	0.07	4	2	0.13
	Producer Diversity - Downstream	6.7%	2	3	2	0.07	3	2	0.07	4	2	0.13
			Criticality	2.03	2.10	-0.07	3.23	2.70	0.53	4.00	3.20	0.80
			Sum Criticality	**3.78**	**3.85**	**-0.07**	**6.98**	**6.45**	**0.53**	**8.00**	**7.20**	**0.80**

Comprehensive Recycling Initiative

Policy Option Background

Comprehensive Recycling Initiative Objective

There is today virtually no post-consumer recycling of dysprosium or any other heavy rare earths for that matter. As we will see, the challenge for the policy planner is not merely whether recycling technology exists or not, but also whether it is sufficiently economical for the recycling to take off as a viable supply mode absent high price dysprosium price points. Research into recycling methods and e-waste collection frameworks has the potential to make a substantial contribution to reducing dysprosium criticality. Overcoming this hurdle, however, is technically demanding and reason enough to disarm the mistaken notion that rare earth recycling is a "low hanging fruit."

Reck and Graedel (2012) note that, "modern technology has produced a conundrum: the more intricate the product and the more diverse the materials set it uses, the better it is likely to perform, but the more difficult it is to recycle so as to preserve the resources that were essential to making it work in the first place." Any prospective dysprosium recycling effort must meet this challenge head-on. The proposed Comprehensive Recycling Initiative (CRI) policy option is designed expressively for this purpose.

CRI is comprised of two distinct components: (1) R&D funds for recycling technology innovation that increases the efficiency *e* of dysprosium (and other CREEs) that are recycled from discarded consumer

[126] Lower ranger estimate is $1.5 billion for the same time frame.

goods; and (2) the introduction of an updated recycling regulatory framework that increases the collection rate c of discarded consumer goods that contain CREEs.

The objective of CRI is to increase the End-of-Life recycling rate (EOL_{RR}) from less than 1 percent today to 25 percent or greater.[127] According to Binnemans et al. (2013), this is simply the product of the scrap collection rate c (proportion of EOL products with dysprosium that is collected) and recycling process efficiency e (proportion of dysprosium recovered and purified for reuse):[128]

$$EOL_{RR} = c \cdot e$$

To achieve this goal, both c and e would have to be greater than or equal to 50 percent at the minimum. Additionally, the recycling technology must meet two important capability and quality thresholds. First, the proposed technology must be able to separate the desired metal scraps from small integrated units (such as personal electronics) as well as from bulk discrete units such as from permanent magnets from auto vehicles and wind turbines. Second, the research would develop or improve upon separation and processing techniques that can extract high grade dysprosium and other HREEs at greater than 98 percent pure oxides.

Theoretical Benefits of Metal Recycling

We first discuss the prospective benefits of recycling dysprosium. In theory, metals can be recycled infinitely due to their atomic composition (unlike plastic, whose molecular structure is prone to degradation from heat, ultraviolet light, and other environmental factors) (Verhoef et al. 2004 and Reck and Graedel 2012). Ideally, as metal is repeatedly recycled, the need for virgin mining and the associated costs in terms of carbon footprint, water usage, and other environmental impact would also be minimal (Graedel et al. 2011). Generally speaking, scrap metal recycling consumes less energy than primary production by a factor of 10 to 20 (Reck and Graedel 2012). Wellmer and Becker-Platen (2007) estimate that recycled aluminum requires only 5 percent of the energy required for primary ore extraction and processing, 20 percent for copper, and 50 percent for lead.

According to Wellmer and Dalheimer (2012), raw material consumption follows a learning curve characterized by slow, rapid, and stagnant stages of growth. They posit that if a majority of economies were to industrialize, "It is conceivable that…the world economy may reach a stage at which total demand and secondary material supply from historical consumption are in balance as a result of leveling

[127] EOL (which is distinct from EOL_{RR}) measures the percent of discarded metals that is recycled. It is the ratio of the mass of EOL metal that is recycled to the mass of that metal in products. In materials cycle terminology, the ultimate objective of rare earths recycling is to create a "closed life cycle." Graedel et al. (2011) defines that the "Life cycle of a metal is closed if EOL products are entering appropriate recycling chains, which leads to scrap metal in the form of recyclates displacing primary metals." On the other hand, "The life cycle is open if EOL products neither are collected for recycling nor enter those recycling streams that are capable of recycling the particular metal efficiently." Typical consequences of open cycles include products ending up in landfills, informal recycling where metals are inefficiently recovered, or any other end state where the metal's chemical and physical properties are lost in the ecosphere.

[128] There are three sources of recyclable metals or "recyclates": *home scrap*, *new scrap*, and *old scrap*. Home scrap is generated during the manufacturing phase of alloyed metals and is readily and inexpensively re-incorporated into the facility's manufacturing process. Home scrap volume is typically not included in recycling statistics. New scrap, otherwise known as pre-consumer scrap, is also generated during the manufacturing phase, but is sold to the market. Their known quality and purity make them valuable in the metals market. Finally, old scrap, otherwise known as post-consumer scrap, are metals integrated into consumer products which require substantial more effort to disassemble and extract (Graedel et al. 2011). Recycling old scrap presents the biggest challenge for all metals, but particularly so for dysprosium and other REEs which are typically used in trace amounts. Because home scrap and new scrap are already recycled, prospective discussions on dysprosium EOL_{RR} refers to old scrap (post-consumer scrap).

off of growth rate in consumption."[129] Figure 6.5 illustrates the case of imbalance between fast rising demand and the lag in recyclates available (Case A). In contrast, Case B exhibits an ideal equilibrium where constant demand and short product lifetime[130] results in a high proportion of demand met by recyclates.

Of course, there are caveats to how much can be generalized between different metals. Graedel et al. (2011) makes the case that comparing recycling rates between different metals is problematic because of differing lifetimes, dissipation rates, and recovery and separation processes. More specifically, "recycling efficiency is highly product-specific. The form in which a metal is used (pure, alloyed, etc.), the quantity of a metal in a specific product, the design of a product (easy or hard to disassemble), and the monetary value of the metal all play a role."[131] Historic trends on nickel recycling and Markov chain modeling by Reck and Graedel (2012) find that at best, recycling efficiency e of common metals such as nickel is only about 52 percent.

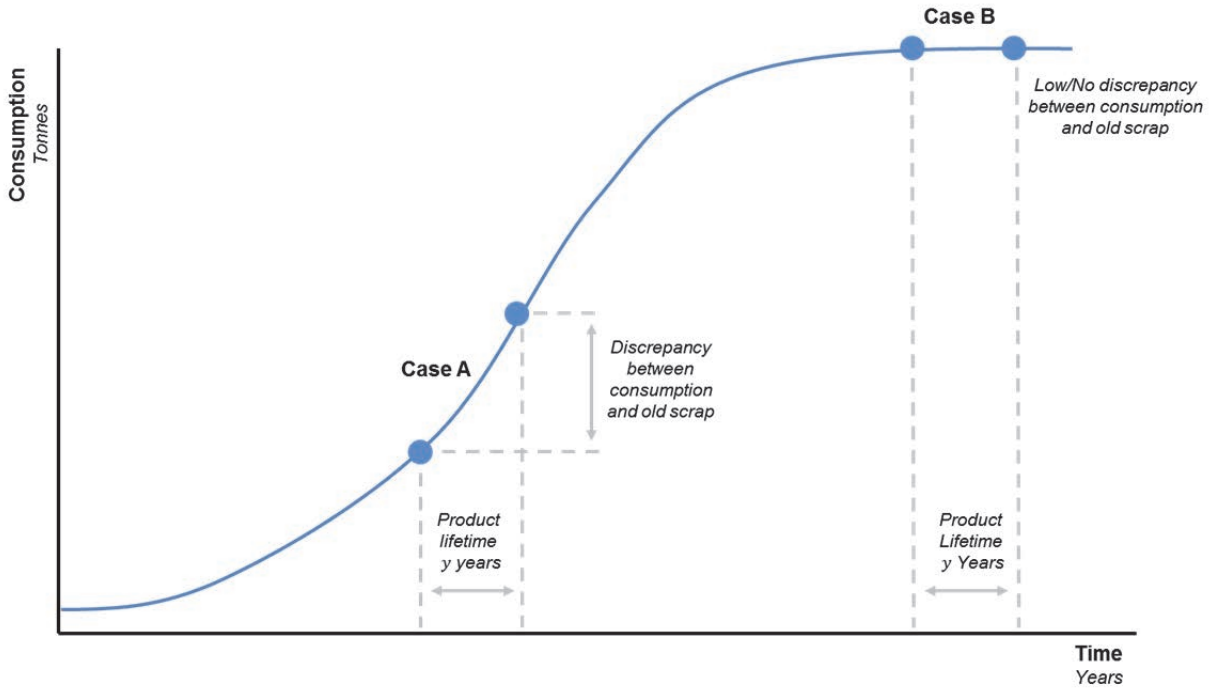
For one, the length of a metal product's lifetime has an important impact on scrap supply. Consider for example copper products, whose lifetime is between 30 to 50 years (Wellmer and Dalheimer 2012). Such long lead time translates to longer intermediate periods where recyclates are unavailable. During these intervening years, primary production is necessarily the sole source of metal supply until the products reach their EOL. Fluctuations in demand and supply during those years also mean that the recyclate volumes will also fluctuate many decades after, with consequential imbalances in recyclate shortage or surplus. Graedel et al. (2011) explains how the imbalance may result:

> High growth rates in metal demand in the past, together with long product lifetimes (often several decades), result in available old-scrap quantities that are typically much smaller than the metal demand in production, which leads to [recycled contents] much smaller than 100%. Even a very efficient EOL recycling system would not provide enough old scrap.

The case of lead recycling represents a textbook case for a closed life cycle (i.e., Case B). It is characterized by a relatively short life cycle of about 5 to 7 years and constant demand volume that enables recycling to supply virtually all of the demand needs, consistently greater than 90 percent in industrialized economies in the last decade and half. In contrast, because dysprosium application is fairly recent compared to major metals such as copper or lead that have been in use for centuries, dysprosium will likely remain along the high growth curvature of the learning curve for the foreseeable future (i.e., Case A). Total recycled dysprosium supply will remain small as a proportion of demand in the foreseeable future.

[129] The authors' "balance" refers to a situation where metal demand is equal to total supply (the sum of production from mines and from recycled materials).
[130] Product lifetime is the time from a product's manufacturing to its end of use by the consumer (which may be signaled by discard into the waste system, a recycling system, or indefinite "storage" on the shelf).
[131] Graedel et al. (2011) note that academic literature demonstrating the dynamics of these factors in recycling efficiency is rare, perhaps with exceptions to works by Van Schaik (2004) and Chancerel and Rotter (2009) (see Graedel et al. 2011).

FIGURE 6.5 – RECYCLATE AVAILABILITY IN AN IDEALIZED GROWTH CURVE OF COMMODITY



Source: Adapted from Wellmer and Dalheimer (2012)

Obstacles to Dysprosium Recycling

Dysprosium and other rare earth recycling is expensive due to the complexity in the logistics, the technical difficulty in sorting, separating, and processing the materials, and the high energy consumption required (Schüler et al. 2011). In a far-ranging review of current literature on rare earth recycling, Binnemans et al. (2013) do not mince words on the challenges facing rare earths recycling from permanent magnets, writing that the "direct re-use of magnets or alloys is impossible and technological challenges for REE-recovery are substantial." There are at least three obstacles to dysprosium and other rare earth recycling.

First, recovering dysprosium from e-waste deposits (urban mining) is a tougher challenge than the already intricate and costly recovery from geological mining, separation, and processing. Binnemans et al. (2013) posit that extracting rare earth magnets embedded in "complex, multi-material electronic and electrical equipment are much more difficult to recycle." Wellmer and Dalheimer (2012) nicely sum up the unique phenomenon created by electronic wastes, writing that, "Humans are creating 'ore deposits' in the technosphere that are far more complex than nature-created deposits in the geosphere as they combine elements which do not normally occur together in nature." The challenge in "mining" for elements from the technosphere is "technologically far more challenging than mining the geosphere."

The compact integration of traces of elements on one hand and the large dispersal of these electronics that must be individually broken down on the other translate to low metal unit values that make it difficult to justify their extraction (Reck and Graedel 2012 and Graedel et al. 2011). This feature substantially increases the energy consumption necessary for dismantling them. According to Wellmer and Dalheimer

(2012), "Energy requirements…rise exponentially to prohibitive levels for highly dispersed metals in chemicals or for the recycling of complex equipment such as electronic components which require excessive energy for disaggregating."

Second, recovered rare earths are qualitatively inferior compared to raw materials from the geosphere (Bauer et al. 2011). Each iteration of recycling and recovery process negatively affects the magnetic properties of dysprosium over time. REO extraction from scrap is no less challenging and costly than extraction from mined ore and yet they tend to yield poorer grades of metal (Clancy 2014). For example, neodymium scraps recovered from NdFeB magnets have inferior properties compared to raw neodymium due to impurities introduced in the magnet manufacturing process. Research to date has not been known to demonstrate commercial feasibility in using scrap to create new NdFeB magnets of comparable quality as those manufactured from scratch (Takeda et al. 2006 and Saito et al. 2006).

Third and lastly, shorter life cycles of modern consumer electronics make e-waste recycling particularly challenging. Wellmer and Dalheimer (2012) note that with the rapid pace of change in e-wastes, "technological development for optimal recycling with maximum recovery of minor elements can hardly keep pace." Thus for every new generational leap in consumer electronics and its concurrent increase in design complexity, customized recycling techniques become iteratively less efficient and effective, rendering recycling relatively more expensive compared to primary production.

The silver lining is that with short lifetimes, consumer electronics more or less yields a constant stream of recyclable materials. Of course, not all specialty metals, dysprosium included, are used in small amounts in complex integrated units. The use of neodymium and dysprosium in large wind turbines, for example, constitute what are called discrete units that enjoy some economies of scale. On the one hand, their size makes dysprosium and rare earths recovery far more cost-effective. On the other hand, their longer lifetimes (15 to 30 years) mean much longer lead times before they can be recycled (Schüler et al. 2011).

Current State of Recycling

Given these significant hurdles, it should not be surprising that the recycling rate for dysprosium and other rare earths is among the lowest of elements on the periodic table. The reality is that rare earth recycling is, "inefficient or essentially nonexistent because of limits imposed by social behavior, product design, recycling technologies, and the thermodynamics of separation" (Reck and Graedel 2012). Whereas major metals such as copper, zinc, gold, and iron are recycled at greater than 50 percent[132], recycling of rare earths is consistently on the lower end of the spectrum. Dysprosium, like most other rare earths, has a negligible EOL_{RR} of less than 1 percent (Table 6.11) (Graedel et al. 2011).[133] According to the EC (2013), only about 10 tonnes of recycled dysprosium would be available worldwide. However, as

[132] According to Graedel et al. (2011), "Only 18 of the 62 metals do we estimate the EOL-RR to be above 50%, and it was usually barely above that level. Another three metals are in the 26% to 50% group, and three more were in the 11% to 25% group. For a very large number, little or no EOL recycling is occurring."

[133] An alternative metric, the Recycled Content (RC) rate, is the percentage of new and old scrap metal that goes into the production and fabrication of a metal alloy. Dysprosium's RC rate is between 1 and 10 percent (Graedel et al. 2011). This is because a larger proportion of new scrap (pre-consumer scrap) from the metal fabrication process is being "recycled" into dysprosium alloy production. Recall, however, that new scrap (and home scrap) is not recycled from post-consumer waste. So as long as post-consumer dysprosium is not being recycled, the EOL_{RR} will remain low.

greater numbers of products that use dysprosium reach EOL, particularly bulk goods such as wind turbines and electrical-hybrid vehicles, recycled supply may reach as high as 460 tonnes by 2030.[134]

TABLE 6.11 – RARE EARTH RECYCLING RATES

	LREE						HREE										
REE	Sc	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y
End-of-Life Recycling Rate	<1%	<1%	<1%	<1%	<1%	NA	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%

Data: Graedel et al. (2011)

In addition to collection of post-consumer scrap, effective recycling also requires cost-effective technology to breakdown goods and to extract the metal contents from within. There must also be sufficient price incentive to justify this expensive process. In the case of dysprosium in particular, both the technology and favorable economic conditions have historically been unavailable which explains the low recycling rate (Goonan 2011). It was not until the very recent and *very* substantial price spikes in 2010 and 2011 that there has been a renewed interest in recycling as a viable supply option (Schüler et al. 2011 and Mogi and Kirschbaum 2010).

According to the Japan Metal Economics Research Institute, the cost-effective recycling price point for rare earths was about 10 times the price level in 2010 (Mogi and Kirschbaum, 2010). For dysprosium oxide, this translates to about $2,500 per kilogram in today's terms, which was approximately its value at the height of the price peak in mid-2011. As of March, 2014, the price was $525 per kilogram, which may not be enough to justify dysprosium recycling given current technology (Metal-Pages 2014).

Even if the price were right, customized recycling technology must also be in place to recover specialty metals such as dysprosium. For example, many EOL electronics and permanent magnets with neodymium and dysprosium can or are being collected as e-wastes. But with no element-specific (i.e., dysprosium) recycling technology existing at present, its overall recycling efficiency is near zero and it will either be discarded or become a trace element in recycled metal.

As it currently stands, "state-of-the-art pre-processing facilities are often still optimized for mass recovery, at the expense of recovery of precious and specialty metals" (Reck and Graedel 2012). In the European Union where waste of electrical and electronic equipment (WEEE) is collected via legislative fiat, the historic collection rate is estimated between 25 to 40 percent. Most of the recovery effort is focused on primary metals (such as steel) which can be recovered inexpensively in large bulks rather than harder-to-recover precious and specialty metals such as REEs.

The Japanese private sector has been leading much of the ground-breaking research in R&D recycling. Hitachi has developed custom-built machinery for separating rare earth magnets from electronic waste (hard drives, motors, air conditioners, etc.) and an experimental "dry" process for extracting rare earths (Hitachi 2010 and Clenfield 2010[135]). Mitsui Metal Mining Co. has plans to recycle rare earths from

[134] Industry expert Jack Lifton quotes a rough estimate of about 200 tonnes of recycled Chinese dysprosium from permanent magnets but acknowledges that there is a high level of data uncertainty (Lifton 2013).
[135] See Goonan (2011).

NiMH batteries (Walters, Lusty, and Hill 2011). Kosaka Smelting and Refining (a subsidiary of Dowa Holdings) is also developing REEs reclamation technology from post-consumer electronics (Tabuchi 2010 and Goonan 2011). In 2012, Belgium chemical company Solvay developed and built a pair of recycling and processing facilities in France designed to recover rare earths from low-energy light bulbs at a cost of $19.5 million (Recycling Today 2012).

However, these technologies are proprietary and their development accelerated at the height of the rare earths price hike. In the U.S., General Electric is believed to be assessing recyclability of phosphors and permanent magnets (Walters, Lusty, and Hill 2011). With prices now only at a fraction of the estimated price-effectiveness value, it is currently unclear what the actual recycling rates are for these private initiatives.

Examples of known dysprosium and other rare earths recovery methods each have distinct advantages and disadvantages. The classic method of simply remelting scrap is easy but produces very low rare earth yields. An alternative method would be to use iterative process of selective extractive chemical agents, an approach that has been proven in the laboratory but is not cost-effective (Messenger 2012).[136] Researchers at the Ames Laboratory have developed a method using molten magnesium that can extract dysprosium, neodymium, and praseodymium without negatively affecting its magnetic properties, although this method, like others, is not yet believed to commercially feasible (Mick 2012). Binnemans et al. (2013) outlines the respective advantages and disadvantages of other recycling methods for rare earth magnets (Table 6.12).

TABLE 6.12 – RARE EARTH MAGNET RECYCLING METHODS

Method	*Direct re-use in current form/shape*	*Reprocessing of alloys to magnets after hydrogen decrepitation*	*Hydrometallurgical methods*	*Pyrometallurgical methods*	*Gas-phase extraction*
Advantage	- Most economical way of recycling (low energy input,no consumption of chemicals) - No waste generated	- Less energy input required than for hydrometallurgical and pyrometallurgical routes - No waste generated - Especially suited for hard disk drives (little compositional change over the years)	- Generally applicable to all types of magnet compositions - Applicable to non-oxidized and oxidized alloys - Same processing steps as those for extraction of rare earths from primary ores	- Generally applicable to all types of magnet compositions - No generation of waste water - Fewer processing steps than hydrometallurgical methods - Direct melting allows obtaining master alloys - Liquid metal extraction allows obtaining REEs in metallic state	- Generally applicable to all types of magnet compositions - Applicable to non-oxidized and oxidized alloys - No generation of waste water
Disadvantage	- Only for large easily accessible magnets (wind turbines, large electric motors and generators in hybrid and electric vehicles) - Not available in large quantities in scrap today	- Not applicable to mixed scrap feed, which contains magnets with large compositional variations - Not applicable to oxidized magnets	- Many process steps required before obtaining new magnets - Consumption of large amounts of chemicals - Generation of large amounts of waste water	- Larger energy input required - Direct smelting and liquid metal extraction cannot be applied to oxidized magnets - Electroslag refining and the glass slag method generate large amounts of solid waste	- Consumption of large amountsof chlorine gas - Aluminum chloride is very corrosive

Source: Modified from Binnemans et al. (2013)

Recycling Collection Framework

Effective e-waste collection is a necessary precondition for raising EOL_{RR} levels. Binnemans et al. (2013) write, "Efficient recycling of rare earths requires the development of environmentally-friendly, fully integrated and logistically sound recycling flow sheets." In order to enable higher rates of recycling, the collection rate c of disposed consumer goods must rise. CRI aims to introduce a new national U.S. policy

[136] Extraction of up to 99 percent of dysprosium oxide and 82 percent of neodymium oxide has been demonstrated through experimental extractive techniques using reagents (Messenger 2012).

framework that leverages existing policy and logistical infrastructures to increase collection of e-wastes with dysprosium and other critical rare earths.

In the U.S., the Resource Conservation and Recovery Act (RCRA) undergirds waste disposal regulations, including prohibition against incineration of certain types of electronic scrap or their disposal into landfills (USGS 2001c). Legislated nearly four decades ago to help recover hazardous material from consumer waste, however, the RCRA framework is inadequate for meeting the needs of collecting and recovering specialty metals from discarded technology.

E-waste policies differ across state lines, however. According to latest data from the Electronics TakeBack Coalition (ETBC) which works to promote e-waste recycling, 25 states covering nearly two-thirds of the American population have some form of e-waste recycling legislation (ETBC 2013). The vast majority of the states with e-waste programs do so via "producer responsibility laws" where the waste collection responsibility falls upon manufacturers of obsolete equipment (ETBC 2011a). California's Electronic Waste Recycling Act of 2003 is unique among state e-waste legislations in that it has implemented an Electronic Waste Recycling Fee. The fee is collected by electronics vendors who retain 3 percent of the proceeds. The balance is used by the state to fund the reimbursement of private collectors and recyclers of covered e-waste (CalRecycle 2012).[137]

According to the latest ETBC data from 2011, the states with the highest per capita collection rate were Oregon, Washington, and Minnesota, ranging between 5.9 to 6.4 pounds per person. The lowest three states were Oklahoma, West Virginia, and Virginia, ranging between 0.2 to 0.6 pounds per person. The ETBC summarizes some best practices based on its review of enacted e-waste legislations and their performance over a one year period in 2009 to 2010. Some key distinguishers between high and low collection states were that high collection programs:

- had either a convenience collection requirement (e.g., a requirement for the presence of a collector for each county or city), a collection quota, or both,
- relied on diversity of collectors from public, private, and non-profit sectors,
- set high performance (quota or otherwise) requirements for manufacturers complemented by minimum thresholds,
- enforced ban on e-waste disposition into landfills and incinerators,
- incorporated flexibility to expand the scope of accepted e-waste and,
- incorporated data transparency to ensure public accounting of manufacture's compliance (ETBC 2011a).[138]

[137] Between 2007 and 2010, the range of total annual reimbursement claims was between $75 million and $96 million (CalRecycle 2012). California's 3-year average operating budget for the program was $4.4 million per year (State of California Department of Finance available from http://www.ebudget.ca.gov/.

[138] Any conclusions on causality between these policy facets and outcomes should be tempered for several reasons. First, the "covered" e-wastes vary between states. California collects laptops, monitors, TVs, and portable DVDs players but no computers or its peripherals, other TV peripherals, or personal electronic devices. Illinois and New York's covered lists, however, are extensive, covering virtually all aforementioned categories (ETBC 2011b). The variance is in part explained by the political feasibility and technology prodigiousness at the time of legislative pass. California's law was a vanguard, coming online in 2005 before smart phones or e-readers were introduced, whereas Illinois's law was implemented in 2010 and New York's in 2011. Second, the producer responsibility laws would disproportionally favor states with greater presence by technology companies. If producers are responsible for collection but their in-state operating footprint is light, there will be a correspondingly light collection system in place, unless a program like California's reimbursement program exists to induce a collection and recycling

In order to prevent fraud and abuse based on past cases, ETBC recommends that recyclers receive e-Stewards (or R2) certification. e-Stewards standard ensures that the recycling chain conforms to the Basel Convention and that no child labor, prison labor, incinerators, or landfills are involved in the process. It also ensures that hazardous e-waste is not shipped to developing countries where regulation is far less robust (e-Stewards n.d.).

Even for states without extensive e-waste recycling, a fairly basic collection infrastructure is already in place throughout the U.S. which can be used as an on-ramp for expanding e-waste recycling (Goonan 2011). Discarded fluorescent light bulb are currently collected for mercury removal which can serve as a pathway for other EOL component collection, particularly as LEDs begin to replace fluorescents as the default efficient lighting technology. In the case of fluorescent bulbs, the collection rate is not more than 30 percent. As previously noted, however, even in the most optimistic case, the collection rate would be unlikely to exceed 50 percent. A more likely rate, based on the collection rate of platinum group metals in electronics, would between 5 to 10 percent (Reck and Graedel 2012).[139]

Complex electronic product design makes rare earths separation "difficult or impossible" (Hagelüken, 2007 as cited in Graedel et al. 2011). Recycling costs can be tempered through product designs that make it easier to disassemble, but doing so will require prevailing against the headwind of increasing product complexity. According to Reck and Graedel (2012), the degree of material mixing today is greater than ever before. The failed Electronic Device Recycling Research and Development Act of 2009 (S. 1397) would have appropriated R&D funding for collection and recycling technology of e-wastes. In particular, it included provisions that made recycling-friendly product designs as criteria for funding as well as studies to examine such a feasibility. More influential has been the Electronic Product Environmental Assessment Tool (EPEAT), an international U.S.-based consortium of private, industry, and government stakeholders, which rates electronics on their ease of disassembly (EPEAT 2014). Adopted by the U.S. federal government as an acquisition criteria for its electronic hardware requirement, EPEAT has also been adopted by Massachusetts, California, universities, and Fortune 500 countries. Incorporating specialty metal recovery as a criterion for EPEAT rating would have a meaningful impact towards incentivizing product designs that would decrease the front end costs of EOL component separation.

E-waste legislations have historically stemmed from a focus on environmental protection and hazardous material removal rather than recovery of specialty metals. As a result, the EOL electronics recycling program currently does not include electronic components from which rare earth magnet recovery is most promising. Table 6.13 lists the covered e-wastes in each of the 25 states as of October 2011.

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market that works independent of producers' geo-presence. Finally, the ETBC draws on a snapshot of statistics from 2009 to 2010 which does not control for important variables such as possible changes in legislative scope of covered electronics, programs' ramp-up and maturation periods, and regional economics especially in the wake of the Great Recession. These major caveats notwithstanding, however, the ETBC's best practices do stand alone as sensible guiding principles on their own merit.

[139] Incentivizing consumers and producers to participate in collection may require measures such fees, legal mandates, or cost subsidies to increase collection rates from so-called hibernating goods within households (Graedel et al. 2011).

TABLE 6.13 – E-WASTES COLLECTED IN THE 25 STATES WITH E-RECYCLING PROGRAMS

State	Computer	Laptop	Monitor	TV	Computer Peripherals				TV Peripherals				Cellphone	Game Console	MP3 Player	e-Reader	Small Servers	Digital Picture Frame
					Printer	Fax	Scanner	Keyboard and Mouse	DVD Player	VCR	Converter Box	Cables or Satellite Receiver						
California		✓	✓	✓					✓									
Connecticut	✓	✓	✓	✓	✓													
Hawaii	✓	✓	✓	✓	✓													
Illinois	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Indiana	✓	✓	✓	✓		✓		✓	✓	✓								
Maine		✓	✓	✓	✓									✓				✓
Maryland	✓	✓	✓	✓														
Michigan	✓	✓	✓	✓	✓													
Minnesota	✓	✓	✓	✓	✓	✓		✓	✓									
Missouri	✓	✓	✓															
New Jersey	✓	✓	✓	✓														
New York	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
North Carolina	✓	✓	✓	✓	✓	✓	✓	✓										
Oklahoma	✓	✓	✓															
Oregon	✓	✓	✓	✓	2015													
Pennsylvania	✓	✓	✓	✓	✓			✓										
Rhode Island	✓	✓	✓	✓														
South Carolina	✓	✓	✓	✓	✓													
Texas	✓	✓	✓	✓														
Vermont	✓	✓	✓	✓	✓			✓										
Virginia	✓	✓	✓															
Washington	✓	✓	✓	✓														
West Virginia	✓	✓	✓	✓														
Wisconsin	✓	✓	✓	✓	✓	✓		✓	✓	✓								

Source: ETBC (2011b)

Most states currently do not collect beyond a narrow scope of e-wastes except for Illinois and New York. More critically, dysprosium is not contained in most of these products and even if so, they are in minute amounts. Thus for a complete collection of dysprosium, the scope of the collection must expand beyond e-waste to include a new category of critical materials that includes dysprosium and other CREEs. For dysprosium, an expanded collection would include those products with dysprosium-based permanent magnets as listed in Table 6.14. Prospective federal dysprosium legislation should cover this gap between collection infrastructure and covered electronics.

TABLE 6.14 – DYSPROSIUM PERMANENT MAGNET APPLICATIONS

Dysprosium Permanent Magnet Applications
Motors, industrial, general auto, etc.
Electrical Bicycles
Magnetic Separation
Magnetic Resonance Imaging (MRI)
Torque-coupled drivers
Sensors
Hysteresis Clutch
Generators
Energy Storage Systems
Wind Power Generators
Air conditioning compressors and fans
Hybrid & Electric Traction Drive

Source: Constantinides (2011)

In conclusion, this policy option proposes a new federal legislation incorporating aforementioned best practices from existing state e-waste programs. Its objective is to leverage existing programs by expanding the criteria of collection from fluorescent lights and e-waste (if applicable) to include discarded goods with permanent magnets. A federal program office within the Environmental Protection Agency (EPA) would work in close coordination with said state recycling infrastructures as they exist either through producer responsibility laws or consumer fee laws. Through incentive programs, mandates, or both, states would collect EOL products with permanent magnets in automobiles, generators, and other industrial or medical devices that will be enable separation, extraction, and processing of dysprosium and other critical materials.

Policy Cost and Effectiveness

The policy effectiveness for CRI is scored on what percentage of criticality reduction the policy achieves (rather than the default assessment method which is to score on what criticality level the policy achieves). Figure 6.6 illustrates the hypothetical shortfall tonnage reductions by CRI in the various projections described in Chapter 4 (Figure 6.7 shows the percent difference in shortfall with and without the CRI in those same projections).[140] These reductions assume that the lifetime of a product containing dysprosium is about seven years after which it enters the e-waste cycle. The projection also assumes an EOL_{RR} of 25 percent per the aforementioned objective of reaching a 50 percent collection rate c and 50 percent recycling efficiency e. Assuming a successful CRI implementation, the policy could decrease shortfall anywhere between 300 tonnes (Worst Case and LL Projections in Figure 6.5) and 1,800 tonnes (Projection HH). The percent difference in shortfalls between projections with CRI and without ranges between about 3 percent (Worst Case Projection, Figure 6.6) and 24 percent (LL Projection).

[140] The Best Case projections are not illustrated in these figures because their projected shortfalls with and without CRI are zero.

FIGURE 6.6 – TONNAGE DIFFERENCE IN SHORTFALL REDUCTIONS FROM ASPIRED CRI IMPLEMENTATION

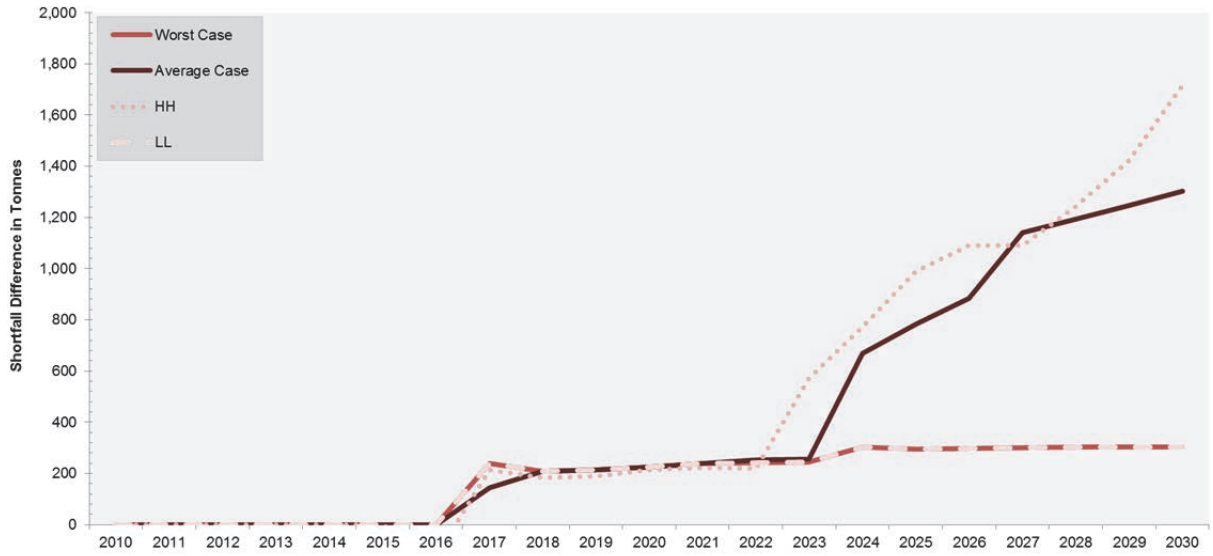
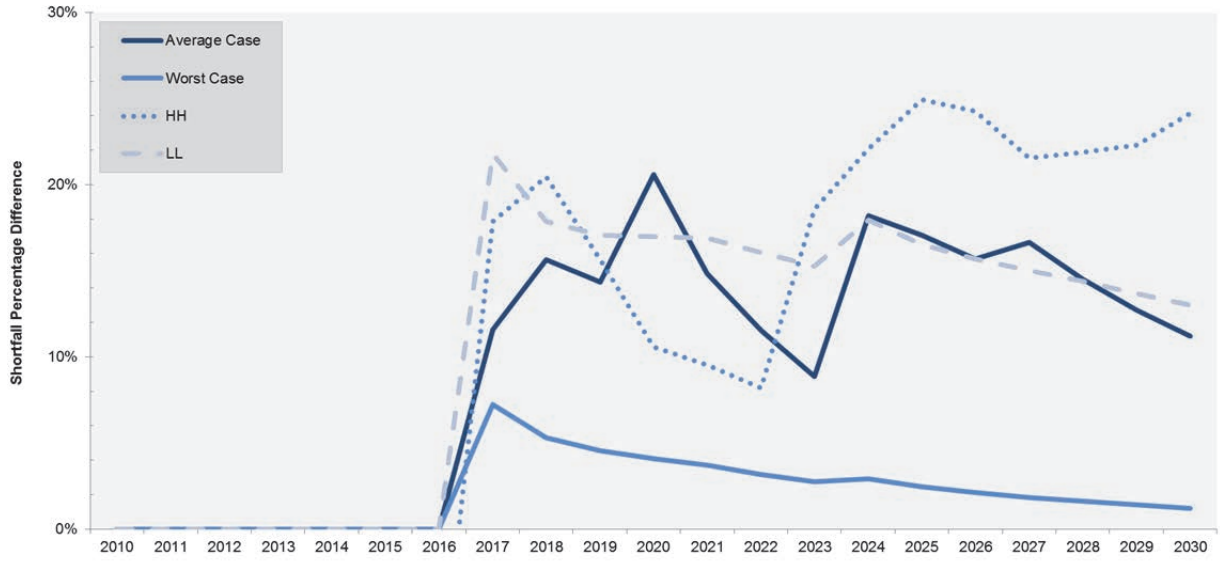


FIGURE 6.7 – PERCENTAGE DIFFERENCE IN SHORTFALL REDUCTIONS FROM ASPIRED CRI IMPLEMENTATION



In reality, however, the recycling technology research success probability is less than certain. Assuming an R&D[3] Level IV difficultly, the probability of research success is about 50 percent at base private/foreign sector research. With government funding, the failure rate is halved and the success rate increases to 75 percent. The expected recycling efficiency rate is:

$$e_{expected} = p_{success} \cdot e_{success} + (1 - p_{success}) \cdot e_{fail}$$

If $p_{success}$ is 75 percent, $e_{success} \equiv e$ (50%), and $e_{fail}$is 1 % per Table 6.11, then:[141]

$$e_{expected} = 75\% \cdot 50\% + 25\% \cdot 1\% = 37.75\%$$

In turn, with $e_{expected}$ of 37.75 percent and c of 50 percent, the expected EOL_{RR}:[142]

$$Expected\ EOL_{RR} = 37.75\% \cdot 50\% = 18.88\%$$

The expected EOL_{RR} approximates an 18.88 percent increase in the downstream supply capacity and downstream supplier diversity sub-dimensions over the long term,[143] with the ultimate effect of reducing the sub-dimensions' *ex-ante criticality* scores by the same percentage amount. The CRI's criticality reduction (effectiveness) is 0.08 (S.I), 0.11 (S.II), and 0.15 (S.III). The sum *ex-post* criticality score are 3.71 (S.I), and 6.87 (S.II), and 7.85 (S.III) as summarized in Table 6.15.

The implementation cost consists of an EPA program office dedicated to coordinating the rare earths recycling program and is assumed to be on the same scale as the incumbent RCRA Waste Management and Recycling program which was approximately $12 million per year between FY 2010 and FY 2012 (EPA 2014). Assuming δ of 4 percent, the expected PV of the implementation cost between FY 2015 and FY 2029 is $234 million ($139 million for the collection program and $95 million for recycling R&D).

[141] Numbers rounded to the nearest hundredth value where appropriate.

[142] An alternative method would have been to set the policy objective percentages for e and c higher so that expected EOL_{RR} equals 25 percent. That, however, requires setting both metrics to greater than 50 percent, which is unrealistic. 50 percent for both metrics is already a high bar. As discussed above, the e for nickel—which is far more common and easier to recover than dysprosium—is only 52 percent. The collection rate c of platinum group metals is 5 to 10 percent while an easier item such as fluorescent lamps is only 30 percent.

[143] Recycling increases the supply capacity by the percentage of expected EOL_{RR}. Assume that the average life cycle of dysprosium-containing consumer products is seven years. If a cohort of products containing 500 tonnes of dysprosium were produced and purchased in Year 1, then the products are discarded and entered into the recycling stream at Year 8 (after seven years of consumption). With an expected EOL_{RR} of 18.88 percent, the total recovered dysprosium of that cohort is just short of 94 tonnes. This value is added to the tonnage of dysprosium extracted from mines in Year 8, say about 1,000 tonnes. The total supply for Year 8 therefore is 1,094 tonnes. In year 15, the total supply will be 1,000 tonnes from mines (assuming mining volume remains constant) plus about 205 tonnes (1,094 multiplied by 18.88 percent), which equals to a total of 1,205 tonnes.

TABLE 6.15 – COMPREHENSIVE RECYCLING INITIATIVE EFFECTIVENESS[144]

Comprehensive Recycling Initiative (CRI)												
FY2015-FY2029 Cost ($M)	$234			S.I (Optimistic)			S.II (Pessimistic)			S.III (Worst Case)		
Dimension	Sub-Dimension	Weight	Expected Criticality Reduction %	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)
Material Importance	Defense and Clean Energy Importance	75%		2	2	0.00	4	4	0.00	4	4	0.00
	Substitutability Limitations	25%		1	1	0.00	3	3	0.00	4	4	0.00
			Criticality	1.75	1.75	0.00	3.75	3.75	0.00	4	4	0.00
Supply Risk	Supply Capacity - Upstream	13.3%	18.9%	1.5	1.22	0.03	3	2.43	0.03	4	3.25	0.03
	Supply Capacity - Midstream	13.3%		1	1	0.00	3.5	3.5	0.00	4	4	0.00
	Supply Capacity - Downstream	13.3%		2	2	0.00	3.5	3.5	0.00	4	4	0.00
	Competing Demand	10%		2	2	0.00	2	2	0.00	4	4	0.00
	Political, Regulatory, and Social Factors	20%		2	2	0.00	4	4	0.00	4	4	0.00
	Codependence on Other Markets	10%		3	3	0.00	3	3	0.00	4	4	0.00
	Producer Diversity - Upstream	6.7%	18.9%	3	2.43	0.01	3	2.43	0.01	4	3.25	0.01
	Producer Diversity - Midstream	6.7%		2	2	0.00	3	3	0.00	4	4	0.00
	Producer Diversity - Downstream	6.7%		3	3	0.00	3	3	0.00	4	4	0.00
			Criticality	2.03	1.96	0.08	3.23	3.12	0.11	4.00	3.85	0.15
			Sum Criticality	**3.78**	**3.71**	**0.08**	**6.98**	**6.87**	**0.11**	**8.00**	**7.85**	**0.15**

[144] Weighted criticality reduction values assume recycling technology R&D difficulty of $R\&D^3$ Level IV with 50 percent probability of success. With government assistance, the probability of success increases to 75 percent, yielding an expected criticality reduction percentage of 18.75 percent.

Policy Area 2 – Functional Substitute R&D

Background to Policy Area 2

This policy area is comprised of a single policy option which is to fund research for substitutes that provides a work-around to incumbent technology reliant on dysprosium, namely the NdFeB magnet. Wellmer and Dalheimer (2012) posit two types of substitutions: material (elemental) substitution and functional (technological) substitution. This section briefly reviews both substitution possibilities. However, because material substitution is considered highly unlikely, the policy option is formulated exclusively as a research effort on functional substitutes.

Material Substitution

In material substitution, the primary material is swapped with another from the periodic table. A classic example is swapping copper in telephone wires with other metals with similar conductivity. Another historical example of material substitution is the case of cobalt. Prices skyrocketed when the world's largest producer, Zaire (present-day Democratic Republic of Congo), was embroiled in the 1977-78 Shaba crises. Despite belief that no material substitution for cobalt existed, a viable substitute was found in ferrites (iron) not long after the crisis erupted (Wellmer and Becker-Platen 2007).[145]

Literature establishes that elemental substitution of rare earths is unavailable and likely to remain so in the foreseeable future (Spindell 2013). Despite two decades of research, scientists have found no substitutes for NdFeB magnets (Smith 2009b and Walters, Lusty, and Hill 2011). The only material substitute for dysprosium is its heavy rare earth peer, terbium, which has no performance penalty but is even more rare and expensive than dysprosium itself (Haxel et al. 2002; Hatch 2011; and Bauer et al. 2011). Elemental substitution has been and is likely to be an unlikely reality for dysprosium.

Functional Substitution

Functional substitution occurs when alternative technologies achieve similar or better performance as the original technology either by obviating the need for the primary material in question or by minimizing the required amount of the material. An example of a substitute technology would be the advent of glass fiber cables that use silica, which is virtually inexhaustible. Similarly, the obsolescence of lead in modern printing with the advent of computer printing is another example.

Currently, no such perfect functional substitute is available for NdFeB magnets. The ratio of magnetic strength to weight found in NdFeB magnets has no parallel (Lynas 2012). Available functional substitutes are legacy technologies that force trade-offs in performance (Halme et al. 2012 and Haxel et al. 2002). Steve Duclos, the Chief Scientist at General Electric Global Research, points out that,

> There's no question that rare earths do have some properties that are fairly unique, but for many applications these properties are not so unique that you cannot find similar properties in other materials. [REEs] are just better, from either a weight, strength, or optical property and that's why people have moved to them…It always comes down to a tradeoff. You can build a

[145] Incidentally, a 1976 report by the German government found that a cobalt shortage would result in the loss of 6 million jobs, which proved misplaced in light of the relatively quick ferrite substitution that took place (Wellmer and Becker-Platen 2007).

motor that does not have rare earth permanent magnets in it. It will be bigger and heaver for a given amount of power or torque that you want (Hurst 2010a).

While (sintered) NdFeB designs are not necessarily the best across all performance categories, the sum of its qualities make it the choice for technology integrators. The next best alternative, the sintered SmCo magnet, is only 40 to 67 percent the strength of NdFeB magnets (BGS 2011 and Stanford Magnets 2014). And while it has a higher operating temperature, its integration into machinery is substantially more difficult than the NdFeB designs. Generally, the marginal benefits of NdFeB alternatives are low to negligible. The tradeoffs of the various permanent magnet designs in terms of their cost, magnetic power, coercivity, maximum working temperature, and machinability are seen in Table 6.16.

In addition to performance, another critical factor to consider is that the vast majority of SmCo, aluminum nickel cobalt (AlNiCo) and ferrite magnet production are based in China. Those that are based outside of China, including the U.S., have historically been reliant on Chinese REOs (Adams et al. 2013). For DoD planners, these tradeoffs are unacceptable and as such, the DoD excludes functional substitutes as part of its planning (DoD 2013a and Hurst 2010a).

TABLE 6.16 – COMPARISON OF PERMANENT MAGNETS[146]

Material	Cost Index	Maximum Energy Products (BH)max(MGOe)	Coercivity Hci(KOe)	Maximum Working Temperature (°C)	Machinability	Notes	Supply Security
NdFeB (sintered)	0.65	Up to 45	Up to 30	180	Fair	Superior strength and allows for miniaturization. Strong resistance to heat but less than sintered SmCo.	75 percent of production base in China and about 20-22 percent in Japan. Largely dependent on Chinese REEs.
NdFeB (bonded)	0.5	Up to 10	Up to 11	150	Good		
SmCo (sintered)	1	Up to 30	Up to 25	350	Difficult	Stable at high temperatures but more brittle. Cobalt prices volatile and samarium mostly imported from China.	60 percent of production base in China. One U.S. manufacturer (Electron Energy Corporation) but is dependent on Chinese REEs.
SmCo (bonded)	0.85	Up to 12	Up to 10	150	Fair		
Alnico	0.3	Up to 10	Up to 2	550	Difficult	Strong temperature stability but easily de-magnetized and weak magnetic strength.	50 percent of production base in China.
Hard Ferrite	0.05	Up to 4	Up to 3	300	Fair	Most common but susceptible to temperature changes.	85 percent of production base in China.

Data: Stanford Magnets (2014); Adams et al. (2013); and Richardson et al. (2012)

Current State of Substitution Research

In the absence of viable material substitution, most material science research focus on engineering work-around solutions (Spindell 2013). A list of on-going research on functional substitutes for REE-dependent applications by the DoE is listed in Table 6.17. It is believed that the DoE's ARPA-E research goal is to find alternative permanent magnets that exceed performances of NdFeB magnets by the end of

[146] (BH)max is the Maximum Energy Product (the product of magnetizing force H and induction B) and is the standard measure of a magnet's strength. It is where the strength is greatest for a given weight of magnetic material. GOe (Gauss Oersted) is the unit of measure for magnetic strength. MGOe refers to mega (million) GOe units. Hci is the Intrinsic Coercive Force, which is the ability of the material to resist demagnetization and are also measured in Oe (Oersted). KOe refers to kilo (thousand) Oe units (Alliance LLC n.d.; K&J Magnetics, Inc. n.d.; and Arnold Magnetic Technologies 2014).

the decade (Vernon 2012). As was the case with other DoE research projects, substitution research milestones range between TRL 3 (in-lab exploration) and TRL 7 (prototyping) and are therefore not yet ready for commercialization.

The private sector has also taken initiative to find workable solutions around expensive permanent rare earth magnets. In recent years, there have been reports that U.S., Japanese, and European industries have successfully found technical substitutes. American automobile manufacturer General Motors is believed to be researching substitute technologies to NdFeB magnets. Japanese and French automakers Toyota Motor Corporation and Renault SA, respectively, have already developed electric vehicles that do not use rare earths (Reddall and Gordon 2012). In 2012, Toshiba Corporation developed a dysprosium-free permanent magnet using high concentrations of iron, samarium (a non-critical heavy rare earth) and cobalt. Through assistance from Japan's New Energy and Industrial Technology Development Organization's (NEDO) Rare Metal Substitute Materials Development Project, Toshiba reported developing a high iron concentration SmCo magnet that performs comparably with neodymium permanent magnets which usually use dysprosium to attain heat-resistance magnetism. Mass production was to have begun in 2012-2013 (Toshiba 2012). Chinese wind turbine makers are also believed to be researching rare earths-free generator designs (Hayes-Labruto et al. 2013).

It is not clear, however, what the extent of performance trade-off is in these developments since they are proprietary information. Based on literature review to date, there is not yet a widely commercialized alternative to the NdFeB magnet. What is clear is that the area of technical substitution is very dynamic as private and public research endeavors in the U.S., Japan, and Europe continue. Based on this information, this study assumes that the DoD (2013a) estimate that approximately 19.1 percent of civilian dysprosium requirements are substitutable with legacy technology is a reasonable one.[147]

TABLE 6.17 – DOE FUNCTIONAL SUBSTITUTE TECHNOLOGY RESEARCH

Potential Substitute	DoE Description	Application
Enhanced Magnetic Coercivity for Non-RE Magnets	"Precise control of the structure of a crystalline magnetic material can significantly enhance magnetic properties (Herzer 1997). For example, an ARPA-E REACT project led by Northeastern University seeks to create an ordered magnetic crystal structure of iron and nickel. This structure is found naturally in meteorites and forms under cooling conditions experienced in space—as slow as 0.2 Kelvin per millennium. The team will develop methodologies to synthesize the magnetic material, achieving the properties that developed over millions of years as these materials were formed in space. If successful, the novel magnets (with no rare earth content) could have properties equivalent to those of rare earth magnets."*	Permanent magnets
Non-composite magnets	"The University of Delaware is striving to create a new magnetic material that is based on an idea of 'nano-composite' magnets. It is a complex process that could slash the use of neodymium and samarium in magnets by 30 or 40 percent."^	Permanent magnets
Induction motors	Induction motors are bulkier than those that rely on rare earths. However, "some manufacturers have reconsidered induction motors, which are larger (for a given power rating) than PM [permanent magnet] motors but are easier to cool and potentially more efficient. Several niche EVs [Electrical Vehicles], including the Tesla Roadster	Motors

[147] The scenario criticality scores already assume this level of substitution. Thus, a substitutability limitation sub-dimension score of 3, for example, means that the criticality level is 3 despite the fact that 19.1 percent of dysprosium needs could be substituted.

	and Mini-E, already use induction motors. Toyota announced in early 2011 that it was also developing an induction motor design that could be used in a range of vehicles with electric drives."*	
Switched reluctance motors	"Switched reluctance motors (SRMs), which operate by electronically switching an electromagnetic stator field to drive an iron stator, have emerged as another potential substitute for PM motors. SRMs have traditionally suffered from noise and vibration problems, but advances in electronic control and precision machining of motor parts have made them more viable. The Advanced Research Projects Agency-Energy recently awarded General Atomics and the University of Texas at Dallas a $2.8 million grant under its Rare Earth Alternatives in Critical Technologies (REACT) program to develop a "double stator" SRM for electric drive vehicle use."*	Motors
Hybrid drive permanent magnet wind turbines	"As manufacturers seek to reduce rare earth content in wind turbines, they have turned to a range of design options. "Hybrid drive" PM turbines, which use a PM generator in conjunction with a geared drive, have received increasing interest. These turbines operate at higher speeds than direct-drive turbines and require a more complicated gearing system, but require PMs one-third the weight of direct-drive turbines, with correspondingly less rare earth content (Constantinides 2011). Hybrid drive turbines currently represent a small fraction of the wind turbine market, but could represent more than half of wind power generation over the next decade (Constantinides 2011)."*	Wind turbines
Superconducting turbines	"Superconducting generator turbines…do not use permanent magnets and show promise for turbines in the 10 MW+ range. American Superconductor has been developing a 10 MW Sea Titan turbine prototype that uses a direct-drive high-temperature superconducting generator (AMSC 2011)."[±]	Wind turbines

Source: *Bauer et al. (2011); ^Hurst (2010a); and [±]AMSC (2011)

Functional Substitute R&D

Policy Effectiveness and Cost

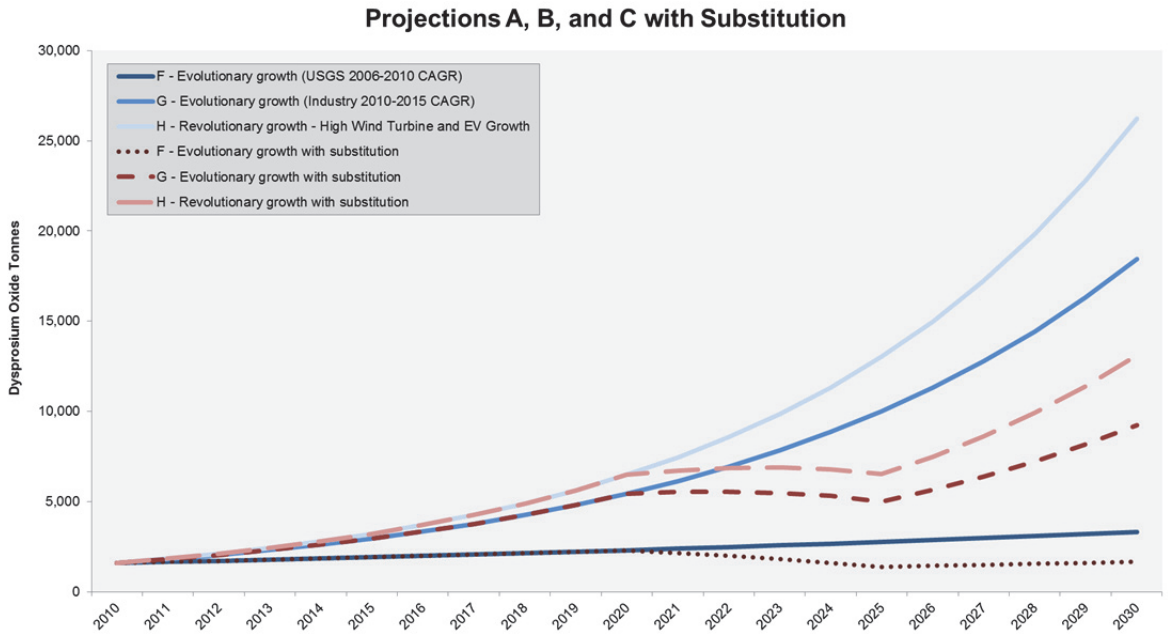
This study proposes that the R&D into substitution technology that meets high threshold requirements in performance quality, competitive costs, and requires resources that are less prone to supply disruptions than dysprosium. In other words, the proposition is that a permanent magnet substitute should result in only superior tradeoffs. This is a tall order, but it could nonetheless have revolutionary impact on how dysprosium is assessed as a critical element.

As a policy option, the DoE would continue to support R&D into functional substitution of dysprosium NdFeB permanent magnets and its applications in high performance motors with the objective of attaining both TRL 9 and CRL 8. Functional substitutes must meet performance requirements equal to or exceeding properties of NdFeB magnets. In effect, the research would support the innovation of a "perfect substitute" for NdFeB magnet (i.e., a substitute that performs exactly (or better) as the incumbent at the same (or better) price point).

If researchers discover a functional substitute that is equal to or better than the NdFeB magnets and similar in price, it is assumed that consumers will be indifferent between the new substitute and NdFeB magnets. This means that a consumer is just as likely to choose one or the other with equal probability, 50 percent. Figure 6.8 depicts a case where a substitute is developed in 2020 and 10 percent of projected

demand switches over to the new magnet each year until the substitution rate reaches 50 percent in 2025.[148]

FIGURE 6.8 – HYPOTHETICAL PROJECTION WITH NDFEB MAGNET SUBSTITUTION



This policy impacts the two sub-dimensions of the *material importance* dimension: *defense and clean energy importance* and *substitutability limitations*. The *ex-post* criticality score for the *importance* sub-dimension is decremented (i.e., better) by the expected substitution rate $s_{expected}$:

$$s_{expected} = p_{success} \cdot s_{success} + (1 - p_{success}) \cdot s_{fail}$$

Because functional substitution research is difficult, the R&D[3] technology development difficulty is set at Level IV which translates to a foreign/private sector success probability of 37 percent. However, government funding halves the failure rate, increasing the probability of success $p_{success}$ to 68.5 percent. $s_{success}$ is the substitution rate if research is successful, which is 50 percent. s_{fail} is the substitution rate if research is unsuccessful and is assumed to be 10 percent since residual knowledge from the research effort could be expected to be of some practical substitution utility. Taken together, $s_{expected}$ equals 37.4 percent meaning that the demand-side importance of dysprosium is expected to be reduced by that percentage.[149] The *ex-post* criticality scores for the *importance* sub-dimension are then calculated by reducing the respective *ex-ante criticality* scores by 37.4 percent. This yields *ex-post* scores of 1.25 (S.I) and 2.5 (S.II and S.III).[150]

[148] While the timing of the discovery and consumer adaptation rates are notional, such a gradual transition is normal as consumers reconfigure machinery to be compatible with the new technology. Furthermore, demand for NdFeB magnets will unlikely go away completely, given the continued utility and legacy of predecessor permanent magnet designs that are still in use.
[149] $s_{expected} = 68.5\% \cdot 50\% + 31.5\% \cdot 10\% = 37.4\%$
[150] *Ex-post* criticality score of the *importance* sub-dimension of a given scenario multiplied by $1 - S_{expected}$.

The *substitutability limitation* sub-dimension is scored using the default method (the criticality level achieved). The technological development and commercialization of a perfect substitute for NdFeB magnets would reduce substitutability limitations to the lowest importance/risk (1). Nonetheless, the scoring is still subject to the probability of research success/failure, $p_{success}$. Using the same approach applied in the Midstream Separation and Processing R&D scoring, the *ex-post* criticality scores for *substitutability limitations* are 1 (S.I), 1.63 (S.II), and 1.95 (S.III).

In summary, the sum criticality reduction (effectiveness) of functional substitutes is 0.56, 1.46, and 1.64 for scenarios S.I, S.II, and S.III, respectively (Table 6.18).

TABLE 6.18 – FUNCTIONAL SUBSTITUTE R&D EFFECTIVENESS

Functional Substitute R&D													
FY2015-FY2029 Cost ($M)	$95			S.I (Optimistic)			S.II (Pessimistic)			S.III (Worst Case)		
Dimension	Sub-Dimension	Weight	Criticality Score / Reduction %	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)
Material Importance	Defense and Clean Energy Importance	75%	50%	2	1.25	0.56	4	2.50	1.12	4	2.50	1.12
	Substitutability Limitations	25%	1	1	1	0.00	3	1.63	0.34	4	1.95	0.51
			Criticality	1.75	1.19	0.56	3.75	2.29	1.46	4	2.36	1.64
Supply Risk	Supply Capacity - Upstream	13.3%		1.5	1.5	0.00	3	3	0.00	4	4	0.00
	Supply Capacity - Midstream	13.3%		1	1	0.00	3.5	3.5	0.00	4	4	0.00
	Supply Capacity - Downstream	13.3%		2	2	0.00	3.5	3.5	0.00	4	4	0.00
	Competing Demand	10%		2	2	0.00	2	2	0.00	4	4	0.00
	Political, Regulatory, and Social Factors	20%		2	2	0.00	4	4	0.00	4	4	0.00
	Codependence on Other Markets	10%		3	3	0.00	3	3	0.00	4	4	0.00
	Producer Diversity - Upstream	6.7%		3	3	0.00	3	3	0.00	4	4	0.00
	Producer Diversity - Midstream	6.7%		2	2	0.00	3	3	0.00	4	4	0.00
	Producer Diversity - Downstream	6.7%		3	3	0.00	3	3	0.00	4	4	0.00
			Criticality	2.03	2.03	0.00	3.23	3.23	0.00	4.00	4.00	0.00
			Sum Criticality	**3.78**	**3.22**	**0.56**	**6.98**	**5.52**	**1.46**	**8.00**	**6.36**	**1.64**

Policy Area 3 – Trade Restrictions

Background to Policy Area 3

Two retaliatory trade actions are possible for the United States. The first alternative is to institute export restrictions (within the bounds of the 1994 GATT framework) on U.S. raw materials for which the Chinese are import-dependent. The goal is to impose costs on China if it fails to abide by an appellate decision that stays the original findings. The second alternative is to apply import restrictions (via quota or tariffs) on Chinese dysprosium and NdFeB magnets. The goal here is to preserve higher dysprosium prices to incentivize re-development of U.S. dysprosium production, processing, and manufacturing capabilities. The objective of these restrictions is not to seek economic redress nor is it necessarily to seek compliance with WTO findings, although both would be beneficial. Rather, trade retaliations should help achieve the overarching policy pursuit of dysprosium criticality reduction.

Note that the two policies work against each other. Export restrictions are designed to open up Chinese supplies for U.S. consumers while the import restrictions are designed to wall off Chinese supply. In short, a well calibrated export restriction regime may impel China to keep its rare earth supply open to world markets and do so without resorting to market manipulation using aggressive stockpiling acquisition and disbursements. This will restore equitable rare earth market prices but it would also likely maintain U.S. reliance on Chinese rare earths.

If the U.S. desires to wean away from Chinese supplies and restore indigenous production and manufacturing capacities, it could simply let Chinese non-compliance slip. If China does comply, then import barriers would be necessary to preserve competitive pricing for U.S. suppliers and manufacturers. In short, retaliatory export restrictions act as a cost imposition method that exchanges supply security for supply access. Import restrictions, on the other hand, exchanges Chinese supply for greater supply security.

Either of these two retaliatory actions carries significant political risks, however. If the U.S. has legal standing for measured retaliatory action—such as if China were to continue restrictions even after the WTO confirms that Beijing's policies are illegal—then some of the risk is mitigated. Nonetheless, any form of retaliatory action can easily escalate to unknown effect, particularly if Beijing reacts strongly. Furthermore, the collateral effect of either restriction policy for other stakeholders domestically and abroad can outweigh positive gains in supply security. Thus while trade restriction alternatives are highly cost-effective, they must be considered "volatile" options which may just as well backfire politically and economically and calls for judicious deliberation before they are employed.

Given these concerns, as a default measure, trade restrictions are assumed to be "funded but not executed." This is a conservative measure to allocate standby funding so that if the situation calls for implementing either the import or export restrictions, the funds have been appropriately budgeted. Secondly, we assume that by default these two alternatives are *not* executed under the optimistic S.I scenario (which assumes that China is committed to open-trade and voluntarily dismantles its rare earths export barriers). However, the funds are allocated in case these positive assumptions unravel and the scenario alters to a negative or worst case outlook. An overview of the WTO lawsuit is provided followed by a closer assessment of the two retaliatory alternatives.

The WTO Dispute Settlement Body Rules Against Beijing

The Raw Materials Case (2009 to 2013)

Export restrictions are a familiar facet of the global trade history with much of the precedent set on the basis of national security claims by the U.S. during the Cold War.[151] Lim and Senduk (2013) note that while *quantitative* restrictions (quotas)—import and export—are expressively prohibited under GATT Article XI and, when read together with Article II, permits import tariffs and duties with the understanding that parties will, over time, work to phase them out, "regulation of export *duties* is somewhere between uncertain and plain non-existent under GATT-WTO rules (emphasis added)." Articles XI, XX, and XXI offer exemptions for reasons of "temporary" relief of shortages, resource conservation and environmental protection, and national security, respectively. Beijing justified its export restrictions on the basis of Articles XI and XX (but did not include Article XXI, the de facto Cold War-era justification). Other examples of export restrictions include countries that were or are in process of ascension into WTO, such as China, Russia, and Ukraine, which have been permitted to exercise restrictions with the understanding that they will be throttled down upon full membership (unless otherwise explicitly exempted) (Lim and Senduk 2013).[152]

What distinguishes the more recent developments in export restrictions from the past, however, are two-fold. First, from a legal perspective, export restrictions on raw materials by developing economies have been increasingly citing resource conservation and environmental reasons as justifications rather than the traditional security argument. This is an area in trade jurisprudence that has not yet been fully developed and poses both legal and policy challenges for exporters and importers (Lim and Senduk 2013). Secondly, the export restrictions have been "further compounded by a high level of concentration of the production [raw materials] in a few countries" (EC 2010). Chief among the countries that are primary suppliers with restrictive export controls is China. A RAND report found that China is in a unique position as the single largest producer for 11 materials (Silberglitt et al. 2013).[153]

Whereas in the past, the legal tussle over export restrictions revolved around the exemption clause in Article XI (temporary relief for shortages) and Article XX (national security exemption), the *raw*

[151] Traditionally, past defense of export restrictions have been based on reasons for national security. In 1949 and 1951, U.S. export restrictions against Czechoslovakia were contested under GATT auspices. In the first case, the U.S. successfully argued that restrictions could be applied to non-military goods as well as military goods on national security grounds according to GATT Article XXI. The U.S. lost the suit in the second case, but the two countries agreed to suspend mutual GATT obligations henceforth. These set the precedent for the U.S. to maintain the position that GATT-WTO signatories held discretion when invoking the national security clause, as was seen in the U.S. embargo against Cuba, cases against Poland and the USSR in 1982, and in 1985 against Nicaragua. Whether such discretion is in fact granted under the GATT-WTO framework, however, is a topic of significant controversy. An EU complaint against Washington's Cuban embargo was settled bilaterally outside of GATT whereby "The United States neither prevailed on nor surrendered its interpretation of Article XXI." In the case of Nicaragua, the U.S. obviated an authoritative interpretation on Article XXI by a GATT panel by consenting to a judicial panel only under the condition that the panel would not examine Article XXI's justification. This tactic, whereby member states can premeditate the terms of a WTO panel jurisdiction, is no longer a legal feasibility in the new WTO framework. All members are now bound to a WTO dispute settlement panel and cannot, for example, preclude an authoritative interpretation of Article XXI. It is therefore possible that a future case involving Article XXI may or may not uphold the subjective reading (Lim and Senduk 2013).

[152] Others, such as the so-called Cairns Group comprised of WTO members, have made a case for export restrictions based on their desire to develop value-added export industries (Kim 2010). Cairns Group members include Argentina, Australia, Bolivia, Brazil, Canada, Chile, Colombia, Costa Rica, Guatemala, Indonesia, Malaysia, New Zealand, Paraguay, Philippines, South Africa, Thailand, and Uruguay (Kim 2010).

[153] With Chinese production accounting for greater than 80 percent for minerals such as rare earths, antimony, tungsten, and magnesium, export restrictions have resulted in significant global price hikes in these materials as was discussed in Chapter 2 (Silberglitt et al. 2013).

materials case was the first time a WTO case centered over the interpretation and application of Article XX (resource conservation and environmental protection). The WTO panel and appellate panel both rejected China's justification for Article XI given the long duration of quotas that were demonstrably not "temporary" in duration. Justification for Article XX was rejected not only because China failed to demonstrate any curb on materials consumption required for meaningful resource conservation, but more controversially, because exemption clauses were judged to be superseded by China's commitments to its Accession Protocol Paragraph 11.3 (Lim and Senduk 2013) which binds Beijing to elimination of all export taxes and tariffs not otherwise listed among 84 exempted products (Baroncini 2012).

The ruling had two important consequences. First, the WTO panel ruling still did not clarify whether the WTO permitted or prohibited export tariffs and duties. Secondly, Lim and Senduk (2013) point to the fact that the case did not settle the question on whether countries can subjectively determine and invoke national security concerns as afforded by Article XXI, as was vigorously argued by the U.S. and which was implicitly understood as being so by GATT-WTO signatories.[154] Even though the WTO suit concluded favorably for the plaintiffs, from a legal perspective, the China raw materials case seems only to have established the specific issue over which of the two obligations—the WTO Accession Protocols or GATT-WTO itself—superseded the other in cases of apparent conflict. As a result, member states are still in the dark about the legality of export duties and tariffs, and the proper applications of exemptions clauses in Article XI and Article XX. As the WTO jurisprudence governing export restrictions stands, "without additional rules, the WTO is [still] less effective at regulating export restrictions" (Lim and Senduk 2013).

The Rare Earths Case (2012 to Present)

On March 26, 2014, the WTO's Dispute Settlement Body (the Panel) ruled that Chinese export restrictions on rare earths, tungsten, and molybdenum were in violation of GATT rules as well. The Panel rejected China's argument that the restrictions were driven by concern for natural resource conservation and mitigation of environmental hazards of mining. Rather, it found that the restrictions were "designed to provide Chinese industries that produce downstream goods with protected access to the subject materials" (WTO 2014a). Beijing had invoked "General Exceptions" under Article XX(b) as justification for its export duties, specifically citing the necessity to "protect human, animal, or plant life or health." As for the export quotas, Beijing again invoked Article XX(g) as it did in the precedent raw material case, citing the need for conservation of exhaustible natural resources.

The Panel refuted both claims. Regarding the export duties, following the logic from the 2012 raw materials case, the Panel found that China had no privilege to the GATT "General Exceptions" clause, reinforcing the precedent regarding China's *prima facie* obligations to the Accession Protocols. More importantly, the Panel took the additional step to clarify that even if China were privileged to the "General Exceptions," the tariffs would still be found unjustified in the protection of human, animal, and plant life or health (this being the case even after the Panel affirmed China's assertion that, "mining and production of rare earths, tungsten, and molybdenum have caused grave harm" to its environment) (WTO 2014a).

[154] Lim and Senduk (2013) raise two interesting questions. How would the WTO panel have ruled if China had succeeded in convincing it of a true critical shortage of materials or if it had decided to invoke Article XXI? If the latter, would the US, having a clear stake in preserving the subjective determination of Article XXI and maintaining that it remains uncontested, still have filed a suit with the WTO?

Secondly, the Panel judged that China's claims to Article XX(g) failed the "even-handedness" criteria, whereby justifications for invoking Article XX(g) requires both the right intent as well as its effects. Regarding the intent, the Panel concluded that Beijing's export quotas were primarily designed to "control the international market for a natural resource" rather than to conserve resources. Regarding the effect, the Panel judged that, "the overall effect of the foreign and domestic restrictions is to encourage domestic extraction and secure preferential use of those materials by Chinese manufacturers" (WTO 2014a).[155]

On April 25, 2014, China notified the WTO of its intent to file an appeal and followed up with an official appeal in early June (McLeod 2014b). The WTO appellate body has up to 90 days to respond with a final decision (WTO 2014b).[156] Appendix M outlines the entire WTO dispute and appeal process. Should the appellate outcome uphold the findings against China, Beijing would be obligated to begin implementing changes either immediately or within an agreed "reasonable period of time." If Beijing fails to comply within the agreed timeframe, the parties can negotiate compensations to the plaintiffs. If no compensation is agreed upon within 20 days, the plaintiffs are entitled to seek permission from the Panel to impose retaliatory sanctions against China. According to the WTO,

> In principle, the sanctions should be imposed in the same sector as the dispute. If this is not practical or if it would not be effective, the sanctions can be imposed in a different sector of the same agreement. In turn, if this is not effective or practicable and if the circumstances are serious enough, the action can be taken under another agreement. The objective is to minimize the chances of actions spilling over into unrelated sector while at the same time allowing the actions to be effective (WTO 2014a).

In practice, what this means is that even if the appeal eventually affirmed the initial ruling against China, delay tactics can allow Beijing to keep the quotas and tariffs in place at least for another 12 months from March 26, 2014.

Beijing Comes Out on Top

The great irony, however, is that the WTO dispute settlement, including the prospective appeals decision, may be all moot. As one industry expert put it, "It is an interesting move by the WTO, but academic. The material impact on the market in terms of supply and demand will be negligible" (as cited in King 2014). This is because data suggests that there has been no rare earth "shortfall" effect on non-Chinese consumers as a consequence of the Chinese quotas. China's export levels in recent years have been *below* the official quota figures (Figure 6.9), largely because the migration of rare earth processing and manufacturing capacities to China has already been accomplished.

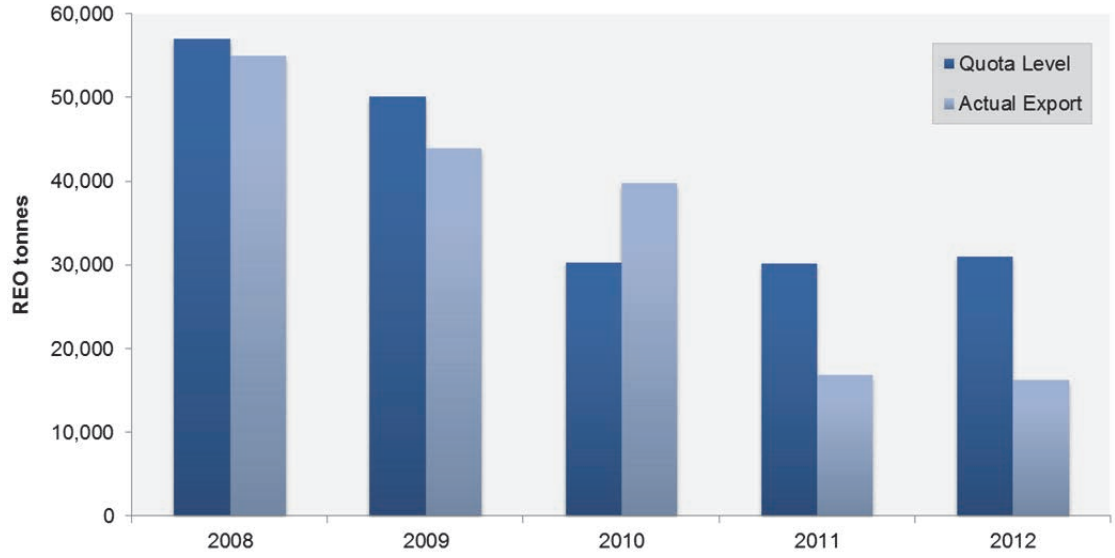
More specifically, while non-Chinese processors and manufacturers may have experienced a temporary supply shock with the drastic quota cuts in 2010, their prompt migration to China in the months and years afterwards allowed them to meet their demands there. The introduction of new non-Chinese sources has also met some of the demand. As a result, China no longer needs to export as much rare earth ores (including dysprosium) abroad for processing and manufacturing. As discussed in Chapter 2, China is

[155] The Panel also found Beijing to be in violation of WTO obligations regarding restrictions on export trading rights to producers for the same reasons the quotas were in violation.

[156] According to the WTO, "Parties to a dispute can appeal a panel's ruling. Appeals have to be based on points of law, such as legal interpretation — they cannot re-open factual findings made by the panel. Each appeal is heard by three members of a permanent seven-member Appellate Body comprising persons of recognized authority and unaffiliated with any government" (WTO 2014b).

both the world's largest rare earth producer and consumer, and as its self-reliance grows throughout the value chain, fewer rare earths need to be exported abroad for these intermediate steps and then re-imported. China's exports restrictions have accomplished their goals of enticing foreign rare earth processing and manufacturing capacities and integrating them within its own borders.

FIGURE 6.9 – CHINESE RARE EARTHS EXPORTS HAVE FALLEN BELOW QUOTA LEVELS



Data: USGS (2008a, 2009a, 2010a, 2011a, and 2012a) and Hatch (2013d)

According to Wu (2014), Beijing has successfully used similar strategies before by exploiting the substantial time lag in WTO procedures to consolidate market gains. As the adage goes, China's *modus operandi* has been to act now, apologize later. He writes,

> The WTO, in effect, provides countries with a free pass to breach its rules temporarily. So long as a violating country ends its illegal policy in a reasonable period of time following a final judgment, it need not worry about being punished. WTO rulings do little to dissuade China from continuing to take advantage of the free pass to advance other unfair and illegal policies when the gains are large enough. China has done this in industry after industry, from semiconductors to electronic payment services. This approach typically involves contravening trade rules just long enough to allow domestic players to build up their market position without incurring WTO sanctions. China then undoes the policy and claims that it is respectful of WTO judgments. But undoing China's gains afterward often proves difficult.

Seeking economic redress is difficult under the WTO framework. In fact, it is not necessarily in the U.S. interest either, according to Wu (2014). This is because the dispute settlement process seeks to "force compliance with the law rather than provide economic justice for past harm." Furthermore, the U.S. has been on the losing end of many trade disputes and any forceful enforcement of economic redress would leave the U.S. with significant financial liabilities from past trade cases in which it found itself at the losing end of settlement disputes.

Secondly, the Chinese would still be able to manipulate rare earth market prices through its massive resource stockpiling program. As noted in Chapter 2, China has a history of purchasing and selling fuel

and non-fuel minerals in bulk to control commodities prices as they see fit. Such similar tactics can be used to restrict foreign access to Chinese rare earths, especially the heavy rare earths, while preferentially releasing discount volumes to domestic processors and manufacturers.

In sum, the U.S. and its partners may have won the battle, but China has clearly won the war by having successfully induced the bulk of the global rare earth production, processing, and manufacturing (and technologies) to relocate to China.

Export Restrictions on China's Import-Dependent Materials

Policy Effectiveness and Cost

Assuming the appeals panel upholds the original case findings, one U.S. policy option is to enforce Chinese compliance through measured retaliation against China's own import-dependent materials.[157] Applying pressure on vulnerable Chinese resource dependency can be an effective method to deter China from constricting supply to its trading partners. Crucially, even if China complies and dismantles export restrictions, a credible threat can discourage Beijing from using its stockpile program to manipulate the market.

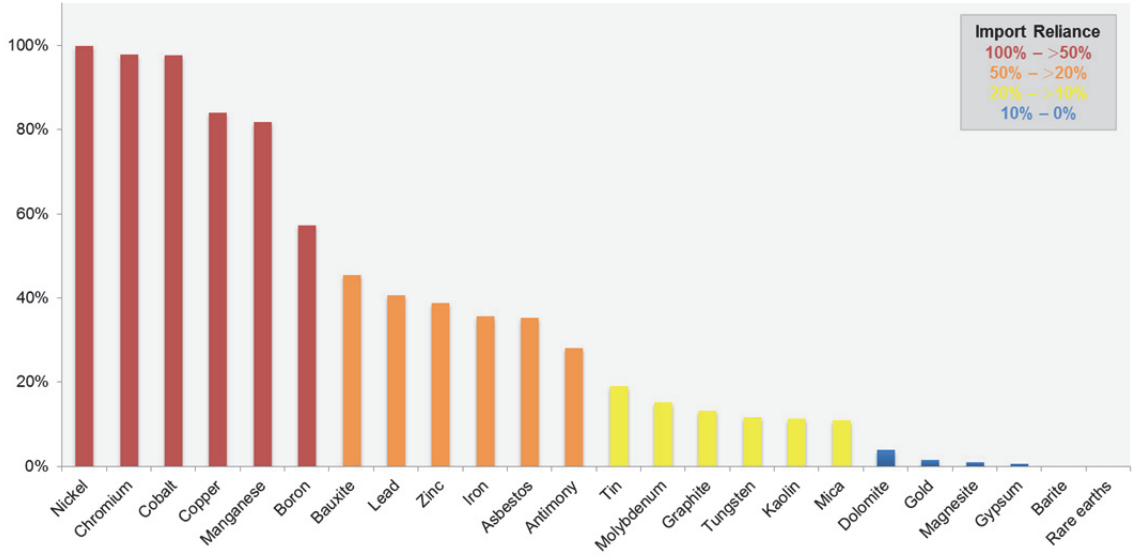
Figure 6.10 lists a sample of raw materials which the Chinese were import reliant on between 2010 and 2012. Based on available data from the USGS, UN Comtrade, and Chinese customs, China was more than 50 percent reliant on nickel, chromium, cobalt, copper, manganese, and boron. China was also at least 20 to 50 percent reliant on foreign supply for bauxite, lead, zinc, iron, asbestos, and antimony, even though it was a major producer for all of these materials.

There are two downsides to this approach, however. First, except for boron for which the estimated U.S. production is about 18 percent of world supply[158], the U.S., Japan, and EU either do not produce any of the Chinese import-reliant materials or are minor producers (Figure 6.10). For example, the U.S. is a minor producer of copper (market share of 8 percent versus China's 10 percent) and iron (2 percent versus China's 45 percent). Other lower import-reliant materials are precisely so because China is a major or principal producer of those materials. Therefore, any sanctions against China will require cooperation from a variety of countries that are not party to the WTO dispute, a fact that might be problematic within the WTO framework. Even if it were legal, convincing these governments to join in such an endeavor would be politically very difficult given China's importance status as *the* major global consumer and importer of raw materials.

[157] Import reliance is the percentage of net import (import less export) divided by the apparent consumption. Apparent consumption is the sum of domestic production and net import. Due to data limitations, certain assumptions are made. First, stockpiling is held constant at net zero. Second, import reliance figures were calculated only for primary production from mines and exclude wastes and scraps. Thus the import reliance figure may be under/over-stating the actual figure. Finally, only materials with consistent data regarding production, export, and import were used to calculate import reliance proportions. Thus, there may be other materials for which China is import reliant on but is not reflected in this analysis. The 24 materials reviewed here, however, cover a broad cross-section of the candidate materials, from major metals to specialty ones.

[158] Data on U.S. boron production has been withheld by the USGS for proprietary reasons. The last publicly released data on U.S. boron production was in 2007 which reported an estimated 1,150,000 tonnes of production in 2006. This figure has been applied for the 2013 world production share estimate, yielding the 18 percent estimate (USGS 2007b and 2014b).

FIGURE 6.10 – SELECT EXAMPLES OF CHINESE IMPORT-RELIANT RAW MATERIALS



Data: USGS (2009a, 2010a, 2011a, and 2012a); China Customs Statistics via HKTDC Research (2014); and UN Comtrade

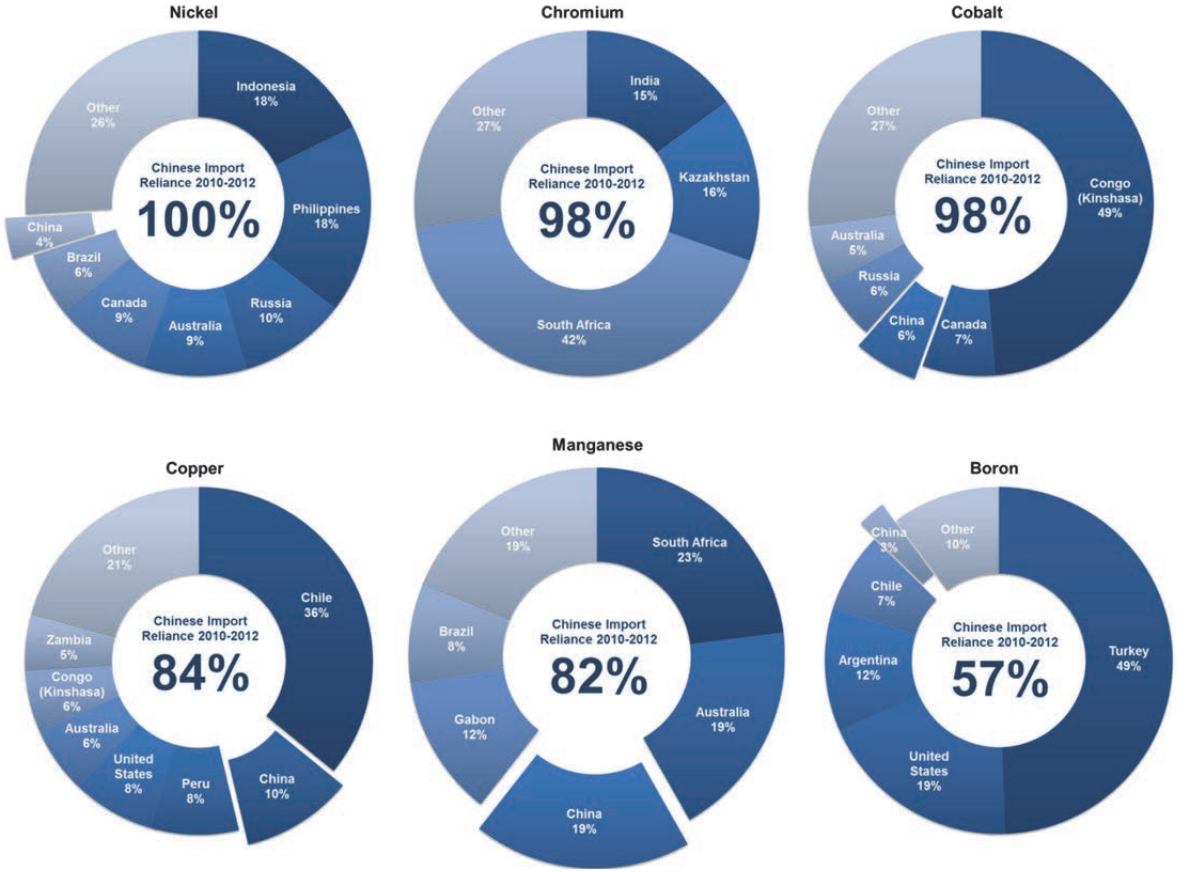
The second drawback is that forcing Chinese compliance would only reinforce the high criticality of rare earths by re-instating Chinese market power. If China complies or is forced to comply via retaliatory actions, the discriminatory barriers would be leveled. However, in a free market without these trade barriers, the massive re-introduction of Chinese rare earths would collapse global rare earths prices, putting into doubt the viability of many of the new non-Chinese production capacities. Lifton asserts that if the price of rare earths between Chinese domestic and foreign markets converged again, "the floodgates could open and wash away the Lynas plan in Malaysia and Molycorp's Mountain Pass mine in California" (as cited in King (2014)). Recent news report confirm that the continuing fall in rare earth prices and the WTO's ruling have negatively affected stock prices of publicly traded companies such as Lynas whose stock price fell nearly 50 percent since the beginning of 2014 (Stringer 2014).

By turning back the clock a decade, the economic dynamics are restored where competitive Chinese marginal productivity will once again run foreign producers to the margins. In fact, compared to a decade ago, the U.S. rare earth industry would emerge *weaker* because not only would the world remain reliant on Chinese rare earths, but its reliance on Chinese processing and manufacturing would be far greater than ever before.

Despite these drawbacks, based on currently available information, the best material for U.S. export prohibition against China would be boron. Boron is used mostly in glass and ceramics industry with applications in abrasives, cleaning products, insecticides, and semiconductor production. Boron is a strong candidate for export prohibition because while China does have a large reserve (32 million tonnes compared to the U.S.'s 40 million tonnes), most of it is low grade, making China increasingly import-dependent as its demand grows (USGS 2014a). Washington may either try to institute an ambitious boron export quota and/or tariff on China (in response to China's global restrictions on rare earths

exports), or it could take a modest approach and seek to restrict only U.S. exportation of boron and third-party resale of U.S.-origin boron.

FIGURE 6.11 – MAJOR PRODUCERS OF TOP CHINESE IMPORT-RELIANT MATERIALS[159]



Data: USGS (2009a, 2010a, 2011a, and 2012a); China Customs Statistics via HKTDC Research (2014); and UN Comtrade

Coordinating the export ban would fall under the responsibility of the United State Trade Representative (USTR). Implementation of this ban would be the responsibility of the Department of Commerce's Bureau of Industry and Security's (BIS) Export Administration (EA) and Export Enforcement (EE) programs. The FY 2014 budgets for the two programs were $56.8 million and $48 million, respectively (DoC 2014). Historically, the bulk of BIS's responsibility concerned non-proliferation and export controls of sensitive military and dual-use technologies in coordination with the Department of State. However, the BIS is also responsible for implementing the export ban of U.S. crude oil via an export

[159] The import reliance percentage is the figure inside the "hub" and is the average from 2009 to 2012. The national percentages along the circumference are the respective global mining production share of each material in 2013. Thus, it is possible that, while the average from 2009-2012 shows 100% reliance and yet in 2013 China was producing 4% nickel, making China not 100% reliance in 2013..

licensing system in accordance with the Energy Policy and Conservation Act of 1975 (EPCA) (Clinton et al. 2014).[160]

American export restrictions can compel China to dismantle its own system of export restrictions. But in exchange for restoration of Chinese supply of dysprosium, it is possible that the return to a single-price global market for dysprosium (where the price would be lower than the current market for non-Chinese consumers) could discourage development of non-Chinese mining projects. Thus, supply access increases, but potentially at the cost of supplier diversity. For this reason, the *supply capacity* sub-dimensions for downstream, midstream, and upstream, are all rated medium-low supply risks (2) while the *supply diversity* sub-dimensions are rated high supply risks (4). Because a successful export restriction works as a deterrent to future Chinese decisions that might curtail or otherwise dissuade free export of dysprosium, the *political, regulatory, and social factors* sub-dimension is rated a low supply risk (1). Under these assumptions, the expected sum criticality reduction of U.S. export restriction is -0.27, 0.93, and 1.4 for scenarios S.I, S.II, and S.III, respectively (Table 6.19).

No additional funding for the USTR is considered since current staffing levels were sufficient to manage and coordinate the critical materials and rare earths cases with the WTO. Similarly, the increased labor burden on the BIS is unlikely to be substantial given that there are only two U.S. producers of boron, 80 percent of whose production goes to domestic consumers. Nonetheless, as a conservative measure, it is assumed that two permanent full time staff are hired, one at the senior General Schedule 15 level (GS-15) and another at the GS-13 level at the BIS.[161] The hiring cost assumptions are outlined in Table 6.20, based on data from the DoC (DoC 2014). The present value of the total implementation cost of the policy is estimated at nearly $3.9 million between FY 2015 and FY 2029, using a discount rate δ of 4 percent.

[160] The export licensing scheme was authorized by the Export Administration Act of 1979 (EAA) and implemented through the BIS's Export Administration Regulations (EAR) "Short Supply Controls" component. Since the expiration of the EAA in 1984, however, the export prohibition has been implemented by the executive branch under authorization of the International Emergency Economic Powers Act (50 USC § 1701). Notably, the ban allows for some leeway. For example, the BIS reviews requests for export "on a case-by-case basis and…generally will approve such applications if BIS determines the proposed export is consistent with the national interest and purposes of the [EPCA]." In particular, EAR allows automatic approvals of crude oil exports to Canada "for consumption or use therein" (Clinton et al. 2014).

[161] Additional staff may be assigned to (1) the EA's Office of Exporter Services's (OExS) Export Management and Compliance Division (EMCD) which ensures EAR compliance and processes licensing requests; (2) the EE's Office Export Enforcement (OEE) which is responsible for detecting, preventing, and investigating violations of EAR and other export control laws; and/or (3) the Office of Enforcement Analysis (OEA) which monitors and evaluates public and classified information to assist in compliance enforcement (DoC 2014).

TABLE 6.19 – EXPORT RESTRICTION EFFECTIVENESS

Export Restriction													
FY2015-FY2029 Cost ($M)	$3.9			S.I (Optimistic)			S.II (Pessimistic)			S.III (Worst Case)		
Dimension	Sub-Dimension	Weight	Policy Criticality Score	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)
Material Importance	Defense and Clean Energy Importance	75%		2	2	0.00	4	4	0.00	4	4	0.00
	Substitutability Limitations	25%		1	1	0.00	3	3	0.00	4	4	0.00
			Criticality	1.75	1.75	0.00	3.75	3.75	0.00	4	4	0.00
Supply Risk	Supply Capacity - Upstream	13.3%	2	1.5	2	-0.07	3	2	0.13	4	2	0.27
	Supply Capacity - Midstream	13.3%	2	1	2	-0.13	3.5	2	0.20	4	2	0.27
	Supply Capacity - Downstream	13.3%	2	2	2	0.00	3.5	2	0.20	4	2	0.27
	Competing Demand	10%		2	2	0.00	2	2	0.00	4	4	0.00
	Political, Regulatory, and Social Factors	20%	1	2	1	0.20	4	1	0.60	4	1	0.60
	Codependence on Other Markets	10%		3	3	0.00	3	3	0.00	4	4	0.00
	Producer Diversity - Upstream	6.7%	4	3	4	-0.07	3	4	-0.07	4	4	0.00
	Producer Diversity - Midstream	6.7%	4	2	4	-0.13	3	4	-0.07	4	4	0.00
	Producer Diversity - Downstream	6.7%	4	3	4	-0.07	3	4	-0.07	4	4	0.00
			Criticality	2.03	2.30	-0.27	3.23	2.30	0.93	4.00	2.60	1.40
			Sum Criticality	**3.78**	**4.05**	**-0.27**	**6.98**	**6.05**	**0.93**	**8.00**	**6.60**	**1.40**

TABLE 6.20 – ANNUAL COST ASSUMPTIONS, ESTIMATES, AND PRESENT VALUE OF TOTAL IMPLEMENTATION COST

Expenses	Annual Cost GS-13	Annual Cost GS-15	Total
Salary	$93,395	$129,822	$223,217
Benefits	$35,000	$35,000	$70,000
Equipment	$10,000	$10,000	$20,000
Travel/Transportation	$5,500	$5,500	$11,000
Other	$5,000	$5,000	$10,000
Total	$148,895	$185,322	$334,217
FY 2015-FY2029 PV	**$3,864,592**		

Data: DoC (2014)

Import Restrictions on Chinese Rare Earths

Policy Effectiveness and Cost

Another alternative is for the U.S. to apply import restrictions (via quotas, tariffs, or both) against Chinese dysprosium across the value chain, from ores all the way to semi-manufactured goods. One advantage of these restrictions compared to export restrictions is that import barriers would address both rare earth criticality as well as shortfalls. Insulating the American rare earth market across the full value chain from Chinese sources would maintain (or rather, re-introduce) a two-tiered price system where prices are higher in the U.S. domestic market than it is in China and/or the world market. Higher prices would maintain incentives to explore and mine rare earth reserves within the U.S. Most crucially, restrictions against Chinese-manufactured rare earth metals and semi-manufactured goods would help revitalize new markets for domestic processing and manufacturing capabilities.

The legal justification for import restrictions is debatable and the strength of the argument lies partially on whether Beijing contravenes the WTO ruling. In the case that the WTO appeal panel upholds the original March 2014 finding against China and the latter does not cease export restrictions, the U.S. has a stronger case to retaliate. If on the other hand Beijing complies and undoes the export restrictions, the U.S. justification for import restriction may not hold up to WTO scrutiny if challenged. One possible legal justification for erecting U.S. import barriers would be to cite Articles XX(b) and XX(g) (environmental and human health protection, respectively). The argument would be that consumption of high-polluting and ineffectively regulated Chinese dysprosium is complicit in harming the environment and human health and that the U.S. would restrict imports until sufficient environmental controls were in place.

In theory, this would serve as an incentive for China to better implement environmental safeguards in order to maximize exports abroad. In practice, this arrangement would serve China's preference to reserve its dysprosium for its own consumption while simultaneously introducing price incentives for American rare earth mining, processing, and manufacturing. We can expect this *quid quo pro* to be satisfactory to both parties.

Again, however, if the U.S. imports were challenged before the WTO, the citation of Articles XX(b) and XX(g) will likely fail based on WTO statutory precedent, namely "Classic" cases from the 1990s such as *Tuna/Dolphin, Shrimp/Turtle*, and *US-Gasoline* (Wu and Salzman 2013). In these cases, the U.S. introduced pro-environment legislations requiring shrimp and tuna to be sourced from fishing trawlers that use special gears that do not harm dolphins and turtles. Congress also introduced legislation requiring baseline gasoline toxic emission levels from domestic and foreign suppliers. In all three cases, the WTO ruled against the U.S., citing the discriminating effects on foreign exporters, mainly from developing countries. According to Wu and Salzman (2013), while the WTO tries to maintain a balance between trade and environmental protection, "trade law is still suspected as favoring trade liberalization over environmental protection, limiting the ability of countries to regulate the environmental practices of their trading partners." Thus, if challenged by Beijing or a third party before the WTO, this strategy may not be successful in the long run. Nonetheless, given the long legal process, this policy option strategy may buy enough time for the U.S. to revitalize its domestic capacity.

To review, if Beijing does comply with an appellate outcome consistent with the Panel's initial findings, justifying U.S. retaliatory action would be difficult. It may be possible to pursue import barriers based on Articles XX(b) and XX(g) and Beijing may very well not challenge Washington as that would suit Beijing's preference to maintain a self-contained Chinese rare earth market. Admittedly ironic as it may be, such a *quid quo pro* may work to the benefit of both parties. To reiterate, however, should Beijing (or other parties) challenge the legality of such barriers before the WTO, Washington would likely lose the case based on precedence.

U.S. import restrictions of Chinese dysprosium would positively impact U.S. downstream, midstream, and upstream dysprosium suppliers. Therefore, *supplier capacities* across the value chain are scored medium-low supply risks (2). The introduction of American capacities also increases the diversity of suppliers, thus the *supplier diversity* sub-dimensions across the value chain are scored medium-low risks (2). Criticality reductions (effectiveness) for S.I, S.II, and S.III are -0.07, 0.73, and 1.2, respectively (Table 6.21).

The estimated present value of the policy implementation cost between FY 2015 and FY 2029 is $10.3 million. The estimate is based on CBO cost estimates of H.R. 975[162] which, like the proposed import restraints on dysprosium, sought to curb steel imports into the U.S. from foreign suppliers (CBO 1999 and H.R. 975 1999). The bulk of the cost is in the administration and monitoring of the policy through the DoC which would license exports of dysprosium and dysprosium-derived exports. The CBO estimate does not include fees and tariff revenues to the government, thus the cost figure is closer to the ceiling of actual costs.

TABLE 6.21 – IMPORT RESTRICTION EFFECTIVENESS

Import Restriction													
FY2015-FY2029 Cost ($M)	$10.3			S.I (Optimistic)			S.II (Pessimistic)			S.III (Worst Case)		
Dimension	Sub-Dimension	Weight	Policy Criticality Score	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)
Material Importance	Defense and Clean Energy Importance	75%		2	2	0.00	4	4	0.00	4	4	0.00
	Substitutability Limitations	25%		1	1	0.00	3	3	0.00	4	4	0.00
			Criticality	1.75	1.75	0.00	3.75	3.75	0.00	4	4	0.00
Supply Risk	Supply Capacity - Upstream	13.3%	2	1.5	2	-0.07	3	2	0.13	4	2	0.27
	Supply Capacity - Midstream	13.3%	2	1	2	-0.13	3.5	2	0.20	4	2	0.27
	Supply Capacity - Downstream	13.3%	2	2	2	0.00	3.5	2	0.20	4	2	0.27
	Competing Demand	10%		2	2	0.00	2	2	0.00	4	4	0.00
	Political, Regulatory, and Social Factors	20%		2	2	0.00	4	4	0.00	4	4	0.00
	Codependence on Other Markets	10%		3	3	0.00	3	3	0.00	4	4	0.00
	Producer Diversity - Upstream	6.7%	2	3	2	0.07	3	2	0.07	4	2	0.13
	Producer Diversity - Midstream	6.7%	2	2	2	0.00	3	2	0.07	4	2	0.13
	Producer Diversity - Downstream	6.7%	2	3	2	0.07	3	2	0.07	4	2	0.13
			Criticality	2.03	2.10	-0.07	3.23	2.50	0.73	4.00	2.80	1.20
			Sum Criticality	**3.78**	**3.85**	**-0.07**	**6.98**	**6.25**	**0.73**	**8.00**	**6.80**	**1.20**

[162] House bill H.R.975 sought, "to provide for a reduction in the volume of steel imports, and to establish a steel import notification and monitoring program."

Policy Area 4 – Contingency Planning

Background to Policy Area 4

The U.S. Department of Defense's Defense Logistics Agency (DLA) administers a National Defense Stockpile (NDS) on behalf of the Under Secretary of Defense for Acquisition, Technology, and Logistics (AT&L) as authorized by The Strategic and Critical Materials Stockpiling Act (50 U.S.C. 98 et seq.) A national stockpile was first instituted following World War I and re-organized into the NDS program in 1939 to reduce U.S. reliance on foreign imports during emergencies. Inventories were maintained throughout the Cold War but were steadily offloaded to the market in the 1990s and 2000s (DLA 2012).

The NDS was re-evaluated in 2006 by an inter-agency work group led by the Deputy Undersecretary of Defense for Industrial Policy which recommended reforms to the NDS program. In successive studies reported to and approved by Congress, the decision was made to reformulate the NDS into the Strategic Materials Security Program (SMSP). The SMSP would have more flexibility to dispose of and acquire critical materials, specialize in commodity expertise, evaluate DoD material requirements, and conduct risk assessments, market data collection and analysis, geopolitical analysis, and strategic planning (DLA 2012). In particular, both the NDAAs of FY 2011 and FY 2012[163] put special focus on rare earths, requiring the DoD to examine the rare earth supply vulnerabilities and recommend policy actions (Public Law 111-383 and Public Law 112-81).

The stockpile is funded through the NDS Transaction Fund and stored in government facilities located across the United States where their conditions and qualities are checked at least biannually for use in national emergencies (DoD 2013a). Release of materials from NDS is authorized either by Congress or by executive authority as codified in Section 5(b) and Section 7, respectively. Stockpiles are not maintained for all materials—actual levels depend on requirements and authorized funding available for the NDS Transaction Fund. FY 2014 NDAA programmed $41 million for the Transaction Fund for disbursement between FY 2014 and FY 2019.

By statute, the Secretary of Defense is required to report biannually to Congress on the recommendations for stockpile requirements of critical raw materials assessed on the basis of a military conflict scenario. More specifically,

> NDS requirements are based on a congressionally-mandated Base Case scenario, a 4-year scenario that assumes 1 year of conflict (based on the classified, priority Defense Planning Scenarios promulgated by the Secretary of Defense for DoD programming and budgeting purposes) and 3 years of recovery/regeneration. By law, the Base Case must include estimates of all relevant defense sector demands (including attrition and consumption replacement from the conflict year) as well as essential civilian sector demands. For the purpose of this analysis, the 2013 NDS Base Case is postulated to begin in 2015 and last until the end of 2018 (DoD 2013a).

The Base Case scenario is anchored on the DoD-approved defense planning scenarios sourced from the 2012 *National Defense Strategy*. In particular, the base case imagines a four-year scenario with a major conflict in the first year followed by three years of force replenishment and national recovery. The

[163] Section 843 of Public Law 111-383 FY 2011 NDAA and Section 853 of Public Law 112-81 FY 2012 NDAA.

conflict scenario includes a "catastrophic" attack on the U.S. homeland, deterrence and defeat of two regional aggressors, deterrence and defeat of a "highly-capable" aggressor, and response to multiple counter-insurgencies.[164]

According to the Base Case scenario assumptions, 23 materials would experience shortfalls, six of which were rare earths. These are the heavy rare earths dysprosium, erbium, terbium, thulium, yttrium, and the light rare earth scandium. In particular, dysprosium was expected to be in shortfall of 47 tonnes[165] (DoD 2013a). Table 6.22 lists the expected material shortfalls of REEs according to assumptions in the base case scenario and the study's recommended levels of stockpiles for each.[166]

TABLE 6.22 – BASE CASE SCENARIO PROJECTED RARE EARTH SHORTFALLS

	NDS Inventory 2012	Base Case Shortfall (Tonne)
Dysprosium	0	47
Erbium	0	124
Scandium	0	0.57
Terbium	0	7
Thulium	0	20
Yttrium	0	1,899

Data: DoD (2013a)

Effectiveness Evaluation

Policy Area 4 – Contingency Planning options are designed by DoD (2013a) to bridge estimated dysprosium shortfalls during high intensity conflict and/or a major homeland attack. The two candidate contingency policy options are Traditional Stockpiling and Buffer Stock Inventory.[167]

The contingency plan is best considered an "insurance" policy that ensures limited quantities of dysprosium to qualified military and civilian requirements during a national emergency. A contingency plan is useful during the 15 year planning period (FY 2015 to FY 2029) because many policy options, particularly R&D options that have high impacts on criticality reduction, take those many years to be developed, commercialized, or implemented. If an emergency were to occur before FY 2029 while policies are still in maturation (during which timeframe dysprosium would likely remain a highly critical mineral) a contingency plan can provide some dysprosium backstop capability to buy time for the policy maker to accelerate or otherwise reorient dysprosium criticality reduction plans.

The policies' full impacts are not realized until the end of FY 2029, regardless of which package of policies the policy maker selects. Therefore, a contingency insurance policy is a necessity in all cases.

[164] Further details are classified. Model assumptions are found DoD (2011) Appendix 3 – Base Case Assumptions and Requirements (Unclassified).
[165] An alternate peace time disruption scenario where China completely restricted exports is estimated to result in a shortfall of 87 tonnes. The peacetime shortfall is higher than the conflict shortfall because the DoD assumes decrements to civilian demand in the latter but not in the former.
[166] The recommended inventory figures differ from the shortfall levels because the study takes into account the contribution of complementary policy alternatives, such as substitutes or emergency buys, which can help meet the shortfall.
[167] Two additional contingency options are proposed in the DoD (2013a) study (the "Extra Buy" and "Reduced Exports" strategies) but they are not incorporated into this planning framework because neither are expected to be meaningful for meeting dysprosium shortfall requirements in an emergency (see Appendix N). Nonetheless, these options may still be viable for other critical materials.

Contingency plans should be considered complementary to portfolio analysis but analytically independent. Thus their cost estimation is conducted outside the portfolio planning framework that governs Policy Areas 1, 2, and 3. In Chapter 6, we will see that contingency costs are added to the cost of the optimal policy portfolio to calculate the final cost of policy implementation.[168]

Traditional Stockpiling

Policy Effectiveness and Cost

Traditional stockpiling follows the default method of building and maintaining an inventory of critical materials to be released in times of exigencies. A DoD-sponsored experts group rated the probability of a stockpile successfully releasing its inventory during a time of emergency at 74 percent, taking into account such considerations as warehouse/infrastructure destruction or damage, poorly maintained inventory, theft, and other factors that could reduce the availability of stockpiles (DoD 2013a).

While the President and Congress may release the stocks as they see fit, the intent of the stockpile, like the Strategic Petroleum Reserve, is for use in terms of national emergencies. As such, the NDS inventory is treated as a contingency tool for use during and after a major military conflict or a homeland incident or both. In keeping with the statutory description of the NDS, the stockpile is meant to provision sufficient materials for the previously described four-year scenario. Thus the stockpiles are designed to meet 100 percent of the contingency requirements (as defined by the DoD), *after* incorporating probability of stockpiling failure.

The formula for the expected net present value (NPV) for Traditional Stockpiling based on the DoD (2013a) study:

$$Expected\ NPV_i = \sum_{t=0}^{15} \frac{C_t}{(1+\delta)^t}$$

t is the fiscal year $t = \{0,15\}$ for a given year between FY 2014 and FY 2029, inclusive. C_0 is the dysprosium acquisition price plus the storage cost for the first year, which is the product of the market price MP and the tonnes of dysprosium oxide x plus S the storage cost. In subsequent years, C_t is the expected cost between a conflict outcome and a non-conflict outcome. For each year $t = 1$ to $t = 14$ is:

$$C_t = S \cdot (1-p) + r \cdot MP \cdot x \cdot p$$

$S \cdot (1-p)$ is the weighted cost of storage each year where S is the annual storage cost and p is the probability of a major conflict. In the event of a conflict, the net cost is the product of the recoupment fraction r (fraction of acquisition price of the metal), the original acquisition market price MP, the tonnes of stockpiled dysprosium x, and the probability of conflict p. In the final year $t = 15$, C_{15} is the storage cost minus the expected sales price of the stockpile:

$$C_t = S - r \cdot FP \cdot x \cdot (1-p)$$

[168] By way of analogy, contingency plans and optimal policy portfolios are equivalent to what auto insurance is to automobiles. The insurance policy is a necessary complement to a new (or used) car but the purchase of one is mostly analytically independent of the other. However, for budgeting purposes, auto expenses include both the monthly car loan and the auto insurance premium. The same logic applies to portfolio expense and contingency plan expenses.

FP is the estimated future price of dysprosium oxide based on the ten year historical average. As explained in DoD (2013a), this is standard financial planning practice for long term commodity pricing. The C_t formulas are summarized in Table 6.23 and the variables are explained in Table 6.24. With a discount rate δ of 4 percent, the calculated expected NPV is just under $62 million.

TABLE 6.23 – EXPECTED NET PRESENT VALUE OF TRADITIONAL STOCKPILING COST FY 2014 – FY 2029

Traditional Stockpiling Expected Net Present Value		
FY	**Cost Formula**	**Cost**
2014	MPx + S	$36,889,613
2015	S(1-p) + rMPx(p)	$3,251,798
2016	S(1-p) + rMPx(p)	$3,126,729
2017	S(1-p) + rMPx(p)	$3,006,470
2018	S(1-p) + rMPx(p)	$2,890,837
2019	S(1-p) + rMPx(p)	$2,779,651
2020	S(1-p) + rMPx(p)	$2,672,741
2021	S(1-p) + rMPx(p)	$2,569,944
2022	S(1-p) + rMPx(p)	$2,471,100
2023	S(1-p) + rMPx(p)	$2,376,057
2024	S(1-p) + rMPx(p)	$2,284,670
2025	S(1-p) + rMPx(p)	$2,196,799
2026	S(1-p) + rMPx(p)	$2,112,306
2027	S(1-p) + rMPx(p)	$2,031,064
2028	S(1-p) + rMPx(p)	$1,952,946
2029	S - rFPx(1-p)	($10,715,053)
	Expected NPV	**$61,897,673**

Data: DoD (2013a)

TABLE 6.24 – ASSUMPTIONS AND VARIABLE DESCRIPTIONS FOR TRADITIONAL STOCKPILING COST CALCULATIONS[169]

Variable	Value	Unit	Description
x	64	Dysprosium oxide (tonnes)	Level B - No-Risk Stockpile.
MP	$525,000	Market price ($ per tonne)	Prevailing market price at time of purchase (2014).
S	$3,289,613	Storage cost/year	Derived from operation costs at three government depot sites (Scotia, NY; Warren, OH; and Hammond, IN). Includes leases, security, communications, utilities, vehicles, facility maintenance, equipment maintenance, and recapitalization. Operations costs were aggregated and divided by totol indoor square footage (SF) to yield a $/SF/year value for each site. Overall, the storage costs are a small percentage of the acquisition cost of a material. At each of the three facilities, there is sufficient space for new material storage.
r	84%	Expected recoupment percentage	84 percent based on historical NDS recoupment fraction.
FP	$421,702	Projected future price ($ per tonne)	Long term (10 year) average real price. In the presence of uncertainty, it is common practice to assume that material prices over a period of time will regress towards the mean long run price. Therefore, a model for the prevailing market price can be expected to resemble the average price over recent history.
p	0.37%	Probability of a major conflict each year	Base case scenario probability.

Data: DoD (2013a) and Arafura (2014b)

Buffer Stock Inventory

Policy Effectiveness and Cost

An alternative to the Traditional Stockpiling is a Buffer Stock Inventory (DoD 2013a). For a buffer stock, material suppliers maintain an inventory of critical materials by contract with the federal government. An annual fee is paid to the suppliers to maintain the stockpile. The U.S. government has the option to purchase the inventory at an agreed price should the need arise. The probability of a successful implementation of a buffer stock inventory is lower than traditional stockpiling with experts giving it a 49 percent probability of success. Thus a larger amount of dysprosium oxide must be contracted (95 tonnes) (DoD 2013a).

Based on previous Defense Logistics Agency (DLA) experience contracting with third parties, DoD (2013a) estimates a 15 percent annual fee of the acquisition cost of dysprosium oxide. The study is careful to note, however, that actual contract terms may vary and that this figure is an estimate. This study makes an additional assumption that the acquisition contract price is set at the current market price MP. The expected annual cost therefore is the weighted cost of annual maintenance fee (no conflict scenario) plus the weighted cost of purchasing the pre-arranged dysprosium oxide volume at the pre-arranged price (in the case of a conflict):

$$C_t = (1 - p) \cdot MP \cdot x + p \cdot MP \cdot x$$

[169] The x value is the desired stockpile tonnage divided by the probability of success: 47 tonnes divided by 74 percent probability of success, which equals to 64 tonnes. Recoupment is the sales return of the stockpile at the end of the fifteen fiscal year planning period.

As before, the expected NPV is the discounted sum (δ of 4 percent) of $C_{i,t}$ for FY 2014 to FY 2029 which comes to $93.5 million (Table 6.25). The variables and assumptions are explained in Table 6.26.

TABLE 6.25 – EXPECTED NET PRESENT VALUE OF BUFFER STOCK INVENTORY

Buffer Stockpile Inventory Expected Net Present Value		
FY	**Cost Formula**	**Cost**
2014	(1-p)fMPx+pMPx	$7,718,508
2015	(1-p)fMPx+pMPx	$7,421,642
2016	(1-p)fMPx+pMPx	$7,136,195
2017	(1-p)fMPx+pMPx	$6,861,726
2018	(1-p)fMPx+pMPx	$6,597,813
2019	(1-p)fMPx+pMPx	$6,344,051
2020	(1-p)fMPx+pMPx	$6,100,049
2021	(1-p)fMPx+pMPx	$5,865,432
2022	(1-p)fMPx+pMPx	$5,639,838
2023	(1-p)fMPx+pMPx	$5,422,921
2024	(1-p)fMPx+pMPx	$5,214,347
2025	(1-p)fMPx+pMPx	$5,013,796
2026	(1-p)fMPx+pMPx	$4,820,957
2027	(1-p)fMPx+pMPx	$4,635,536
2028	(1-p)fMPx+pMPx	$4,457,246
2029	(1-p)fMPx+pMPx	$4,285,814
	Expected NPV	**$93,535,870**

Data: DoD (2013a)

TABLE 6.26 – ASSUMPTIONS AND VARIABLE DESCRIPTIONS FOR BUFFER STOCK INVENTORY COST CALCULATIONS[170]

Variable	Value	Unit	Description
x	96	Dysprosium oxide (tonnes)	Level B - No-Risk Stockpile.
MP	$525,000	Market price ($/t)	Prevailing market price at time of purchase (2014).
p	0.37%	Probability of a major conflict each year	Base case scenario probability.
f	15%	Annual fee as % of acquisition cost.	Actual fee may vary based on contract terms, but past DLA experience suggests 15% is a reasonable estimate.

Data: DoD (2013a) and Arafura (2014b)

[170] The x value is the desired stockpile tonnage divided by the probability of success: 47 tonnes divided by 49 percent probability of success, which equals to about 96 tonnes.

Chapter Summary

This chapter has reviewed past, current, and prospective U.S. critical materials policies that impact the dysprosium market. Several bills have been proposed in Congress (both House and Senate) in recent years although none have been ratified into law. Nonetheless, Congress has shown keen interest in critical material supply issues (including dysprosium and other rare earths) by prodding reforms to the NDS process and appropriating funds to replenish the NDS with key materials, including dysprosium. Congress has also closely tracked this topic in light of possible contraventions of defense acquisition policies following reports of integration of Chinese permanent magnets into U.S weapons systems. The DoE has a prominent role in rare earths scientific research on important topics such as substitution, recycling, and separation/processing through grants as well as original research through the CMI.[171]

These and other prospective policy options were organized into four Policy Areas: Supply Chain Development (Policy Area 1), Functional Substitute R&D (Policy Area 2), Trade Restrictions (Policy Area 3), and Contingency Planning (Policy Area 4). Each of these Policy Areas comprises one or more policy options whose effectiveness in reducing criticality sub-dimension(s) were evaluated and scored and whose implementation costs until FY 2029 were estimated. The policies' effectiveness scores reduced the *ex-ante* S.I, S.II, and S.III criticality sub-dimensions (from Chapter 5) to *ex-post* policies effectiveness scores.

Unlike other Policy Areas, Contingency Planning will be implemented separate from and in addition to the optimized policy portfolios in Chapter 6. The contingency policy option acts as insurance in the event that a major conflict or national emergency occurs before the policy planner has had time to sufficiently reduce dysprosium criticality. For example if a major Pacific conflict were to occur in the near future, none of the proposed policies would have been sufficiently implemented to either increase dysprosium supply or reduce its importance. The only possibility of minimally bridging the supply shortfall—however limited in scope and duration—would be via the DoD's (2013) contingency plans. Table 6.27 summarizes the individual policy options for each of the four Policy Areas, their respective implementation cost over the fifteen fiscal years, and their contribution to criticality reduction across the three scenarios S.I, S.II, and S.III.

Using the data synthesized in this chapter, the following chapter will optimize the selection of these policy options into policy portfolios for different levels of budget allowance. This will then allow a trade-off analysis between the policy planner's allowable budget and the expected criticality reduction.

[171] In addition, as reviewed in this chapter and in Chapter 2, Japanese, European, and Chinese researchers are also investing substantial effort into rare earth R&D.

TABLE 6.27 – SUMMARY OF POLICY OPTIONS COSTS AND EFFECTIVENESS

Policy Area	Policy Option	FY2015-FY2029 Cost ($M)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)
1	Domestic Upstream Production	$2.9	3.78	3.85	0.00	6.98	6.45	0.53	8.00	7.27	0.73
	Midstream R&D Separation and Processing	$95	3.78	3.78	0.00	6.98	6.71	0.27	8.00	7.63	0.37
	DoD Downstream Accreditation	$405	3.78	3.78	0.00	6.98	6.78	0.20	8.00	7.67	0.33
	DoD Trusted Foundry	$1,800	3.78	3.85	-0.07	6.98	6.45	0.53	8.00	7.20	0.80
	Comprehensive Recycling Initiative (CRI)	$234	3.78	3.71	0.08	6.98	6.87	0.11	8.00	7.85	0.15
2	Functional Substitute R&D	$95	3.78	3.22	0.56	6.98	5.52	1.46	8.00	6.36	1.64
3	Export Restriction	$3.9	3.78	4.05	-0.27	6.98	6.05	0.93	8.00	6.60	1.40
	Import Restriction	$10.3	3.78	3.85	-0.07	6.98	6.25	0.73	8.00	6.80	1.20
4	Traditional Stockpiling	$61.9	Meet Emergency Consumption Requirements for 4Years			Meet Emergency Consumption Requirements for 4 Years			Meet Emergency Consumption Requirements for 4 Years		
	Buffer Stockpile	$93.5									

Chapter 7 – U.S. Policy Strategy

"The United States Government and industry need a comprehensive strategic materials strategy for the entire value chain."
- J.A. Green & Company

Introduction

This chapter utilizes the qualitative metrics synthesized in Chapter 6 to formulate optimal policy portfolios (policy packages) for various budget levels. As detailed in Chapter 6, the optimization method maximizes the sum criticality reduction (effectiveness) across three potential scenarios for a given budget. The utility of this optimization analysis is two-fold.

First, the policy planner can be assured that they are stewarding public resources for maximum effectiveness. Squeezing out efficiencies is an ever greater imperative during budget austerity. The challenge is compounded by the fact that strategic planning, especially in the case of dysprosium (and other rare earths) which experience high price volatility, is fraught with economic, scientific, and geopolitical uncertainty. This criticality reduction optimization framework is one tool that can support this strategic planning process under such conditions.

Secondly, this approach supports sound policy planning by informing the decision maker with crucial trade-off analysis. Assessing the adequacy of budgets in light of multiple dimensions of uncertainties is challenging. The optimization analysis provides the policy planner with an indication of the cost-effectiveness of a planned budget. It empowers the planner to understand whether a particular budget is sufficient to meet a criticality reduction objective, whether there are cost-saving potentials, or whether a marginal increase in the planned budget has the potential for outsized return on criticality reduction.

The criticality reduction framework is premised on a mix of qualitative and quantitative assessments that can be influenced by exogenous economic, technological, and geopolitical factors we do not know. It is likely that the breadth and quality of data will improve over time but for now, a caveat noted by Bauer et al. (2011) in their influential DoE critical materials study is worth re-iterating:

> It is important to keep in mind that these are qualitative assessments, informed by some quantitative analyses. There is much uncertainty in the attributes examined, particularly in the medium term. While the collection of assessments is valuable to inform policy priorities and R&D investment, it will be important to revisit the analyses moving forward as more data become available and as material supply and demand change.

With this caveat, this research has attempted to incorporate the most current understanding available regarding the dysprosium supply chain—the scope and quality of which is reasonably approximate to the level of information that policy makers will need to base their decisions on today. Therefore, the crucial question is, what is the best use of national resources to reduce dysprosium criticality given what we know? This research provides one possible method for answering that question.[172]

This chapter begins with portfolio optimizations using a mixed-integer linear programming model from Chapter 6 whereby dysprosium criticality reduction is maximized subject to budget constraints using the roster of policy options from Chapter 6. The limits of criticality reduction according to the model are

[172] Another important limitation of the study is that the policy effectiveness values may differ based on the complex inter-state dynamics between the U.S., China, WTO, and other governments which are difficult to model. Potential alternative tools for assessing such complexity and uncertainty could be advanced game theoretic modeling, RAND's PortMan (Portfolio Analysis and Management) tool, or another RAND method, the Robust Decision Making tool (RDM).

discussed, followed by analysis of the cost-effectiveness trade-offs of the different optimal portfolios. Portfolios with the best value for money—defined as those optimized combinations of policies that decrease proportionally higher levels of dysprosium criticality for every dollar invested (otherwise known as high marginal effectiveness)—are then identified. These select portfolios are referred to as Sweet Spot Portfolios because not only are they optimized to achieve maximum criticality reduction for a given budget but they are also able to capture superior value for money relative to other portfolios within a budgetary range.

The chapter then proceeds with a robustness assessment that accounts for lower probabilities of policy implementation success and a higher-than-expected implementation cost. These "sober" sets of assumptions yield a new set of optimized portfolios with different limits on the maximum criticality reduction that can be achieved. The cost of stockpiling for contingencies is then incorporated to estimate a final "total cost" that includes the portfolio implementation plan plus the selected contingency plan.

Optimal Policy Portfolios

Policy Portfolio Infeasibility Regions

Chapter 6 provided an extensive review of the U.S. government's roster of policy options. As we consider how these policies can be assembled into cost-effective policy portfolios, it is helpful first to understand the limits of how much vulnerability can actually be reduced. For example, is it reasonable to believe that the policies can be expected to reduce criticality (vulnerability) to the absolute minimum in the criticality matrix? What is the maximum U.S. dysprosium supply vulnerability that the policy planner can expect to achieve?

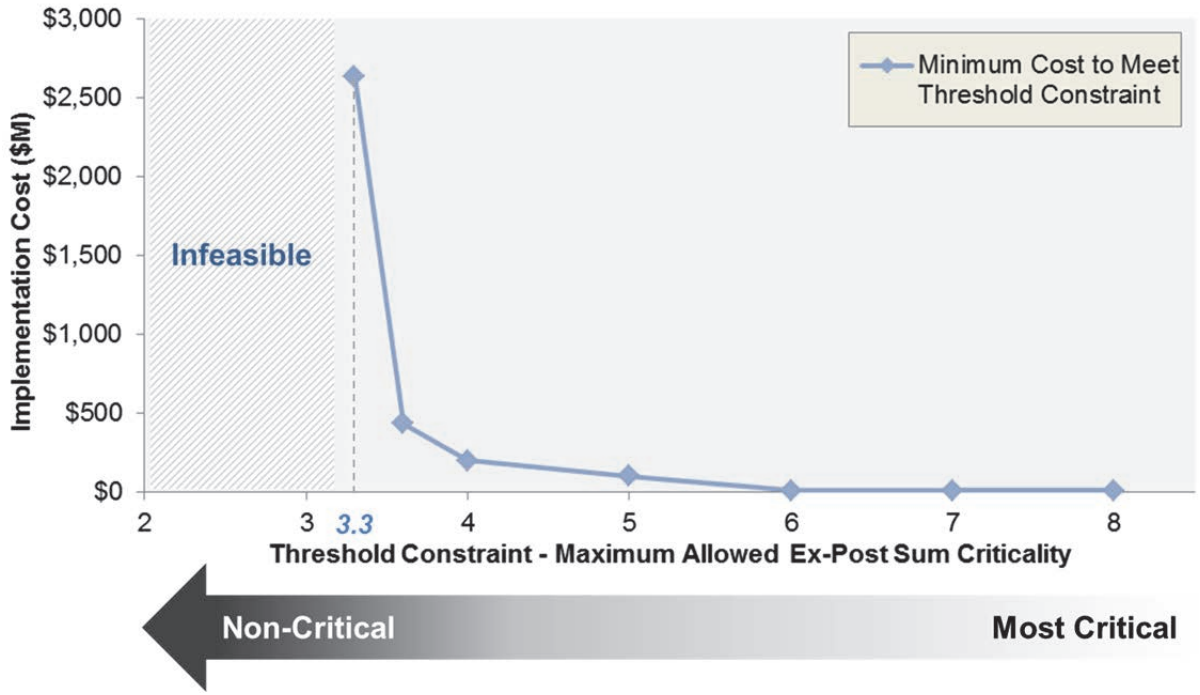
We start by referring to the optimization model from Chapter 6 and use it to test whether the model can assemble policy portfolios that meet very stringent requirements. When portfolios that meet the requirements are successfully assembled, the requirement is "feasible." However, when no combination of policies can meet a requirement, it is "infeasible." The requirement that we test is what was referred to Chapter 6 as T_k, the threshold sum *ex-post* criticality score for a scenario k (simply also referred to as the threshold constraint, henceforth).

Threshold constraint T_k is the *highest* sum criticality score that a policy portfolio must not exceed at a given budget level for scenario k.[173] In other words, T_k is the maximum total vulnerability (criticality) that the U.S. policy planner is willing to tolerate. Technically, this means that the *ex-post* sum of the scores for *material importance* and *supply risk* dimensions must be equal to or less than T_k after an optimized policy portfolio is implemented.[174] We can expect that the more stringent (lower) the threshold constraint, the higher the budget requirement will be to sufficiently lower the *ex-post* sum at or belowT_k. Alternatively stated, the lower the T_k, the higher the minimum required budget to assemble a policy package that can meet the more stringent constraint.

[173] Recall that lower scores are better than higher scores in the criticality matrix framework, so lower sum Criticality scores means lower dysprosium criticality, which translates to lower U.S. vulnerability to supply disruptions.
[174] Another way of putting it is to say that the sum of the weighted sum of the *material importance* sub-dimensions and the weighted sum of *supply risk* sub-dimensions must be equal to or less than T_k.

Assume that the threshold constraint is uniformly set across all three scenarios such that, $T_{S.I} = T_{S.II} = T_{S.III}$. Figure 7.1 exhibits the optimization result which shows the policy portfolio implementation cost for each level of T_k from 2 to 8.[175] It demonstrates the feasibility limits we can expect from the roster of policy options reviewed in Chapter 6. According to this analysis, sum criticality scores are infeasible below T_k of 3.3. As the constraint is relaxed ($T_k > 3.3$), however, policy packages can meet the necessary minimum sum criticality scores at rapidly decreasing cost. In other words, the less stringent the requirement is to decrease dysprosium criticality, the less money is required to meet the receding thresholds. Based on our analysis, if the U.S. government were to seek maximum dysprosium criticality reduction and set the threshold to $T_k = 3.3$, the total implementation cost would be approximately $2.64 billion. However, by changing the threshold slightly to $T_k = 3.78$, it could afford a policy portfolio for $431 million, a much lower cost than $2.64 billion..

FIGURE 7.1 – COSTS FOR MAXIMIZING CRITICALITY REDUCTION UNDER THRESHOLD CONSTRAINTS



Cost-Effectiveness Trade-Off Curve

Now that we know the feasibility limit, the next question is what the minimum budget would be to reduce U.S. vulnerability to dysprosium supply disruptions. In particular, we are interested in the budget necessary to reduce vulnerability to the criticality level equivalent to the optimistic scenario, S.I. Recall that Chapter 6 introduced three scenarios: S.I (optimistic), S.II (sober), and S.III (worst case). So the question is, if the policy planner sought to assemble a portfolio such that the dysprosium vulnerabilities in S.II and S.III are equivalent to S.I (that is, even if the sober or worst case assumptions were to come true, U.S. dysprosium supply vulnerabilities would be no worse off than it would have been in the optimistic

[175] Recall that the lowest value of T_k is 2 (which is the sum of the lowest criticality score—1—for the two dimensions) while highest possible value is 8 (which is the sum of the highest criticality score—4—for the two dimensions).

case), what would such a portfolio look like, and importantly, what is the minimum budget amount to assemble such a policy package?

S.II and S.III vulnerability levels are set equal to the S.I vulnerability level simply by setting all the scenarios' T_k value equal to (or less than) S.I's sum criticality score, which is 3.78 (see Chapter 6)[176]. This new constraint (requirement for the optimization) ensures that the optimal policy portfolio would result in vulnerability levels that are at least as good as it would be under S.I.

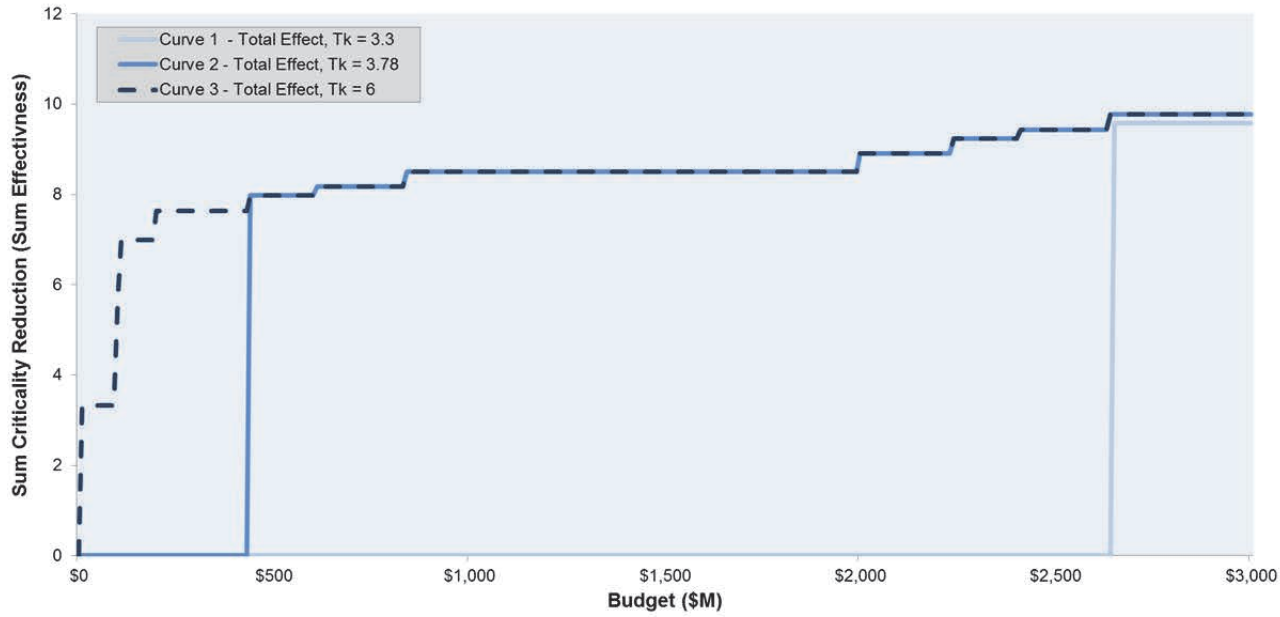
In addition to the constraint $T_k = 3.78$, we also analyze what the optimal portfolios would be if the constraints were at the maximum threshold, $T_k = 3.3$ as per our preceding analysis, and if the constraint were much more relaxed, $T_k = 6$. These variations provide insight into what the required budget is and how policy portfolios differ—or are similar— based on the threshold constraints. Three different cost-effectiveness trade-off curves are derived for each of the three different threshold constraints. Curve 1 sets T_k to 3.3, which as reviewed above, is the highest feasible threshold value. Curve 2 sets T_k to 3.78, which is the *ex-ante* sum criticality score for S.I. The purpose is to find an optimal portfolio that does not exceed 3.78 even under the more pessimistic S.II and S.III. Curve 3 sets T_k to 6 which is a fairly relaxed constraint that provides room for analysis on the relative cost-effectiveness of portfolios at the lower end of the budget spectrum. This constraint would not reduce as much criticality but its portfolios may nonetheless be less costly and of interest to policy planners in the current budget- austere climate.

The curves represent optimized policy portfolio's effectiveness under threshold constraints at each budget level. The implementation budget ranges from $0 to $3 billion (which is enough to afford all policy options) at $10 million intervals (costs are total present values between FY 2015 and FY 2029 discounted at 4 percent to FY 2015).

Figure 7.2 exhibits the optimized effectiveness of reducing dysprosium criticality across *all three scenarios* (i.e., the sum effectiveness) at different implementation budgets. With a relaxed threshold constraint $T_k = 6$, a policy portfolio can be assembled at a relatively low cost ($10 million, Curve 1). However, under the more stringent constraint $T_k = 3.78$, the minimum investment amount is $440 million (Curve 2). The minimum cost then rises significantly to nearly $2.64 billion to meet $T_k = 3.3$ (Curve 3).

[176] The sum criticality score is the sum of *material importance* score and the *supply risk* score. For S.I, the scores were 1.75 and 2.03, respectively, summing to 3.78.

FIGURE 7.2 – BEST POSSIBLE CRITICALITY REDUCTION (EFFECTIVENESS) FOR GIVEN BUDGET



Note that the maximum sum criticality reduction differs slightly between the curves even at the same budget levels (i.e., Curves 1 and 3 after $2.64 billion mark). The difference is attributed to the stringency of the threshold constraints and the differences in the policy effectiveness scores. Table 7.1 illustrates how with a budget of $2.65 billion, the optimal portfolios for $T_{S.I} = 3.78$ and $T_{S.I} = 6$ have sum criticality scores of 3.48. However, this value is above the threshold constraint $T_{S.I} = 3.3$ by 0.18 which means that these portfolios are unsuitable with tighter constraints. These differences, however subtle, necessitate different portfolio selections which in turn lead to small differences in maximum sum criticality reductions.[177]

TABLE 7.1 – DIFFERING THRESHOLD CONSTRAINT EXPLAIN DISCREPANCIES IN OPTIMAL PORTFOLIOS

Threshold Constraint	Budget ($M)	Cost ($M)	Sum Criticality Score			Sum Criticality Reduction (Effectiveness)
			S.I	S.II	S.III	
Sum Criticality Reduction, $T_k = 3.3$	$2,650	$2,636	3.28	3.13	2.78	9.57
Sum Criticality Reduction, $T_k = 3.78$ & 6	$2,650	$2,642	3.48	2.93	2.58	9.77

Policy Utility of the Cost-Effectiveness Trade-Off Curve

There are three implications of the cost-effectiveness trade-off curve analysis for the U.S. policy planner. First, the policy maker has an indication of how much a given budget could reduce U.S. vulnerability to dysprosium supply disruptions. If appropriated $10 million, $500 million, or $2 billion, the policy

[177] We will see below that the difference in policy selection is between the two mutually exclusive trade restriction alternatives (Chapter 6 details the rationale for exclusivity). For practical purposes, the import and export restrictions are considered interchangeable given similarities in low scale costs and effectiveness.

planner now has an idea of how much dysprosium supply vulnerability could be reduced at each of those figures. For those budgets, the sum criticality reduction (effectiveness) would be 3.33, 7.97, and 8.9, respectively, when $T_k = 6$ (Curve 1).

Secondly, the policy maker has an indication of how much criticality reduction will be affected if appropriated funds undergo unexpected budgets cuts (like the recent sequestration experienced throughout the U.S. federal government under the Budget Control Act of 2011). A uniform 10 percent across the board budget cut would result in budgets of $9 million, $450 million, and $1.8 billion. How would this affect dysprosium criticality reduction planning? The cost-effectiveness trade-off curve informs us that the optimal portfolios under the $10 million budget and the $9 million are identical and that there would be no difference in the sum criticality reduction (effectiveness) value. The same goes for the $450 million—its optimal portfolio is identical to the $500 million policy portfolio with no degradation in criticality reduction. So in both cases, we can expect the budget cuts to have little effect on dysprosium criticality planning. The same is not true for the $1.8 billion budget, however. The analysis suggests that the optimal portfolio under sequestration differs from the $2 billion portfolio and that the sum criticality reduction (effectiveness) value is 8.51, rather than the $2 billion's 8.9. Such advanced knowledge will be invaluable for the policy makers as they consider the impact of proposed budget modifications and negotiate acceptable budget modifications.

This leads to the third impact of the cost-effectiveness analytical framework: marginal effectiveness, which is the evaluation of how much the sum criticality reduction (effectiveness) changes with each additional dollar investment. *Crucially, not every additional increase in budget allocation produces the same increase in sum criticality reduction (effectiveness)*. For certain budget intervals, each additional $10 million increase yields greater than 1 sum criticality score reduction. For other intervals, there are no increases in yields or are much smaller than 1. For example, for Curve 3 in Figure 7.2, the initial $10 million investment yields an increase in 3.33 sum criticality reduction. However, the next $10 million investment (for a total budget of $20 million) yields a zero increase—the sum criticality reduction is still 3.33. Hypothetically, if the policy planner had a budget of $20 million, the best plan in that case would be to appropriate $10 million to the optimal policy portfolio and allocating the balance to other priority projects.

In contrast, say that a planner's allocated budget is $100 million (still on Curve 1 with $T_k = 6$). With that budget, the optimal policy portfolio yields a criticality reduction of 4.9 points. However, with an additional $10 million (total budget of $110 million), a different portfolio can be purchased and the criticality reduction jumps to 6.17. The extra $10 million afforded an additional 1.27 criticality reduction. Given the steep increase in effectiveness (i.e., steep slope), the $110 million budget offers the policy planner a superior value. Marginal analysis is important because it helps the policy planner utilize the budget much more efficiently. This is discussed in greater detail in the following section.[178]

[178] The implicit argument here is that budgets are not necessarily "fixed" but rather revised through the fiscal planning process. This is because in practice, government program budgets are reviewed, negotiated, and compromised within the Executive Branch and with Congress before final appropriations are made for the fiscal year.

Sweet Spot Portfolios

The unique optimal portfolios are plotted in the cost-effectiveness setup in Figure 7.3 (using the same color-coded scheme) where the *curves represent slopes between unique optimal portfolios* (this is distinct from Figure 7.2 whereby the lines represent the maximum effectiveness values). As just described, the steepness of the slope informs the marginal effectiveness of the optimal portfolio. The steeper the slope is between two portfolios, the larger the increase in cost-effectiveness. Conversely, the flatter the slope, the lower the marginal gain is in cost-effectiveness. Thus, the greater the slope, the greater the sum criticality reduction (effectiveness) the policy planner gains for each dollar spent. This means that even if a portfolio's absolute cost is higher than other portfolios in the environs, it is a better "deal" for the policy planner because effectiveness increases substantially for each additional ("marginal") dollar investment.

What this enables the policy planner to do is to select policy portfolios that are not only (1) optimal (recall that *all* the portfolios are optimal for their budget) but also (2) captures greater value for money. Henceforth these portfolios are called *Sweet Spot Portfolios*, four of which are identified in Figure 7.4.

Two explanations are worthwhile. First, it is possible to have multiple Sweet Spot Portfolios (known as "local optima") for a given curve. We witness this with Curve 2 and Curve 3. For Curve 2, Portfolios 5 and 11 are marginally superior to its peer portfolios because they sit on top of a steep curve. The same is true for Curve 3 whose Sweet Spot Portfolios are Portfolios 3 and 11 (the latter is shared with Curve 2). The arrows in Figure 7.4 indicate the location of the Sweet Spot Portfolios for each curve. Strictly speaking, Curve 1 only has one feasible portfolio that meets the stringent $T_k = 6$ requirement (Portfolio 12). In practice, however, because Portfolios 11 and 12 are sufficiently similar to each other in cost and effectiveness, Portfolio 11 is also considered adequate for $T_k = 6$.

Secondly, there are two clusters of optimal portfolios, identified as Region I and Region II in Figure 7.4. The clustering is due to the large cost associated with the DoD Trusted Foundry Program policy option whose $1.8 billion price tag creates a yawning gap between the two Regions. In Region I, Curve 2's Sweet Spot Portfolio is Portfolio 5 while Curve 3's is Portfolio 3 which sits at the inflexion point. Region I is infeasible under the 3.3 threshold constraint. In Region II, Curves 2 and 3, share Portfolio 11 as the local optima. Portfolio 12, the sole candidate for Curve 1, also resides in Region II.[179]

[179] Strictly speaking, there are other portfolios that are also local optima for Regions I and II, chiefly Portfolios 1, 7, and 9. However, because the marginal gain from Portfolio 1 to Portfolio 3 is so large, the latter serves very practically as the local optima. For Portfolios 7 and 9, the marginal increases are so subtle that they are bypassed, again as a matter of practicality.

FIGURE 7.3 – OPTIMIZED UNIQUE POLICY PORTFOLIOS FOR EACH THRESHOLD CONSTRAINT

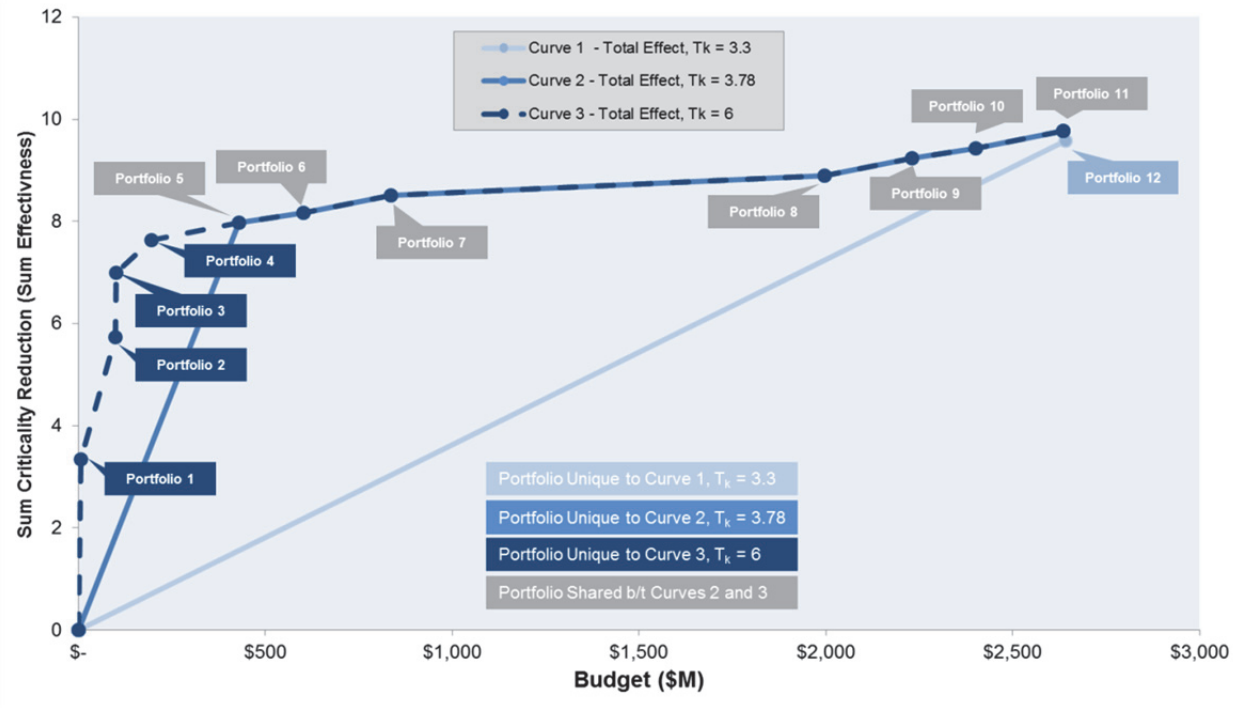
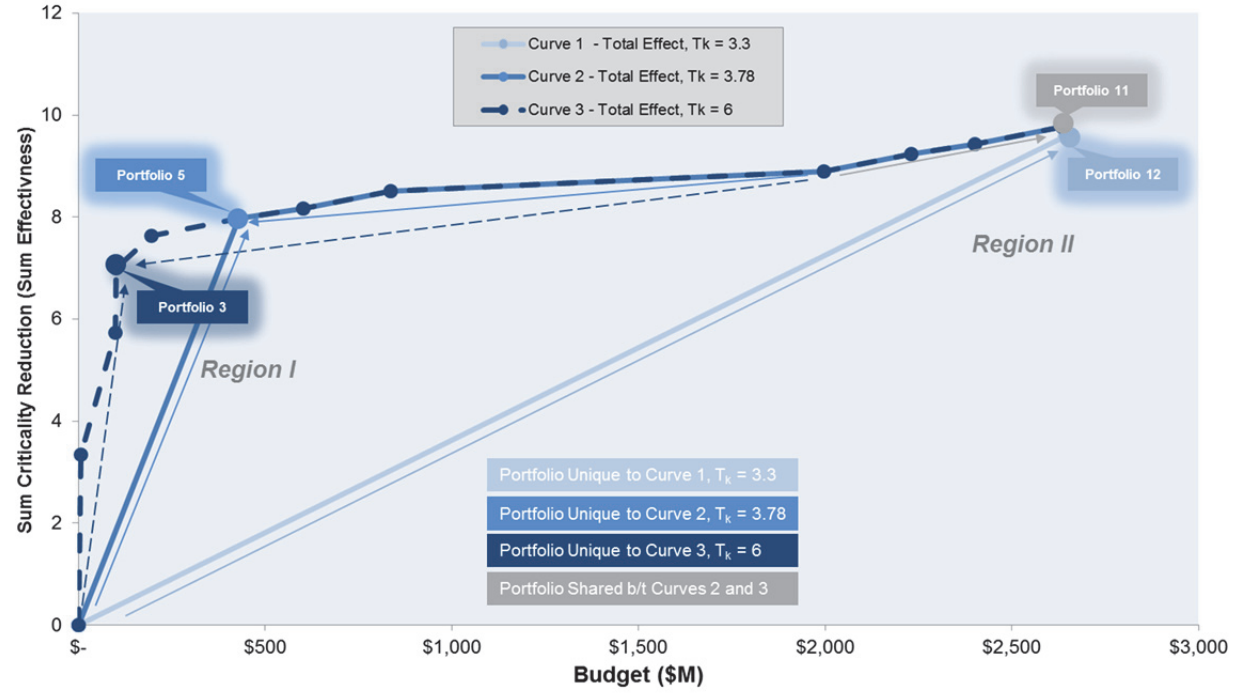


FIGURE 7.4 – OPTIMAL PORTFOLIOS WITH HIGH MARGINAL COST-EFFECTIVENESS



What does portfolio selection look like in practice? Recall that we are assuming a modifiable budget. Say that the initial proposed budget is $100 million and the $T_k = 6$ (Curve 3). The policy planner can easily afford Portfolio 2 for $99 million and end up with a surplus. However, for an additional $2 million

to the budget ($102 million total), the planner can afford Portfolio 3. This would be an efficient allocation of public resources because the additional funds would yield increasing marginal dysprosium criticality reduction even if the absolute cost is more.

Alternatively, say the initial proposed budget is $500 million. The planner can either assemble Portfolio 5 ($431 million) or consider allocating an additional $102 million for Portfolio 6. However, because the slope is decreasing, the marginal return is low and does not offer good return on value. Therefore, the planner is better off forsaking both options, choosing Portfolio 3, and using the surplus for other priority initiatives.

Table 7.2 summarizes the *ex-post* criticality scores and costs for the Sweet Spot Portfolio while Figure 7.5 visually depicts the Sweet Spot Portfolio effectiveness on the criticality matrix. It should be apparent that even under the relatively relaxed threshold constraint of $T_k = 6$, a modest investment in Portfolio 3 for $102 million can have a respectable decline in criticality across all three scenarios. The downside to Portfolio 3, as was discussed in the preceding chapter, is that the legality of export restrictions *absent Chinese intransigence* under the WTO framework is cloudy at best (on the other hand, the U.S. would have a stronger standing if the WTO appeals panel confirms the original findings against China's export restrictions on rare earths but Chinese fails to oblige).

Portfolio 5 represents the best portfolio for meeting $T_k = 3.78$ in which all scenarios must be at least equal to or better than this S.I sum criticality score.[180] According to this analysis, the sum criticality under Portfolio 6 comes to 3.4 (S.I) and 3.7 (S.II and S.III) with dimension scores not more than 2.4 at most for the scenarios. This places dysprosium clearly out of the critical material zone and into the buffers of medium-high critical materials.

There is a large budget jump between Portfolio 5 and Portfolios 11 and 12 (all three portfolios satisfy thresholds 3.78 and 6). Note that Portfolios 11 and 12 are distinct but essentially identical versions of each other (the former includes Export Restrictions while the latter selects Import Restrictions). These policies are most appropriate if the objective is to attempt to push dysprosium further towards the "non-critical" zone in the criticality matrix and if such funds are available (just over $2.23 billion).

The sum criticality scores for Portfolio 11 are 3.5 (S.I), 2.9 (S.II), and 2.6 (S.III) while the scores for Portfolio 12 are 3.3 (S.I), 3.1 (S.II), and 2.8 (S.III). The marginal return is clearly lower than Portfolios 3 and 5, but these are the best portfolios available if maximum reduction in dysprosium criticality is a stringent objective and/or if the allocated budget cannot be revised downward (very unlikely).

Otherwise, assuming the policy planner has free range in setting both the threshold and budget, t*he most sensible option is to opt for Portfolio 5 given the $2.2 billion differential* between it and Portfolios 11 and 12. Portfolio 5 is optimally designed for the budget and offers a high value-for-money proposition compared to other portfolios. Most importantly, it strikes balances between fiscal responsibility and sufficient dysprosium criticality reduction.

[180] As previously noted, Portfolio 6 is also the local optimum for $T_k = 6$.

TABLE 7.2 – SUMMARY OF SWEET SPOT PORTFOLIO EFFECTIVENESS

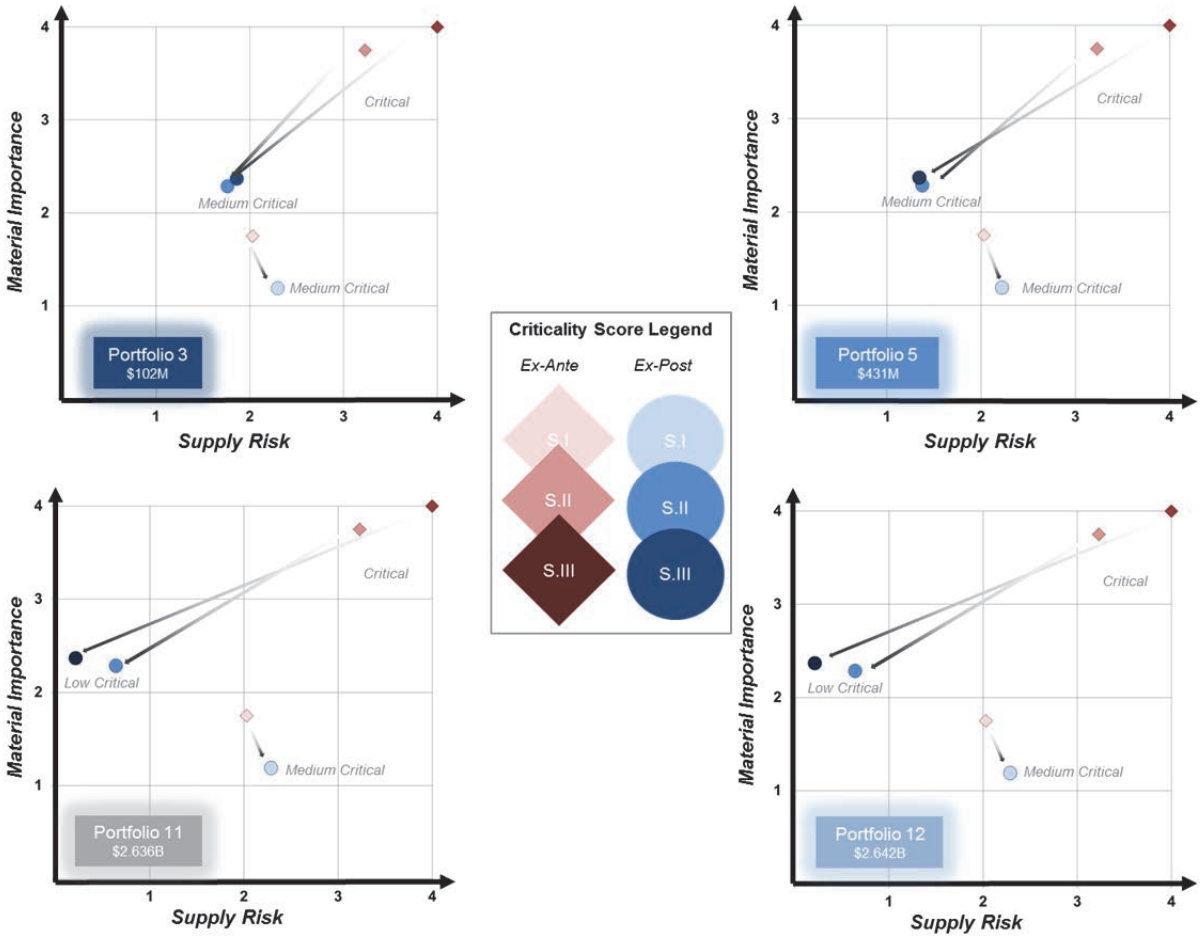
	Portfolio 3	Portfolio 5
T_k	6	3.78
Cost ($M)	$102	$431

	Material Importance	Supply Risk	Sum Criticality	Material Importance	Supply Risk	Sum Criticality
S.I	1.2	2.3	3.5	1.2	2.2	3.4
S.II	2.3	1.8	4.0	2.3	1.4	3.7
S.III	2.4	1.9	4.2	2.4	1.4	3.7

	Portfolio 11	Portfolio 12
T_k	6 and 3.78	3.5
Cost ($M)	$2,636	$2,642

	Material Importance	Supply Risk	Sum Criticality	Material Importance	Supply Risk	Sum Criticality
S.I	1.2	2.3	3.5	1.2	2.1	3.3
S.II	2.3	0.6	2.9	2.3	0.8	3.1
S.III	2.4	0.2	2.6	2.4	0.4	2.8

FIGURE 7.5 – DYSPROSIUM CRITICALITY MATRIX OF SWEET SPOT PORTFOLIO EFFECTIVENESS



Portfolio Policy Composition

The discussions so far have focused on the tradeoff of budget versus effectiveness while alluding to optimal policy portfolios only in the abstract. Here we take a closer look at the portfolios' policy compositions. Table 7.3 summarizes the optimized policy portfolios' policy selections and their implementation costs. Each optimal portfolio is numbered 1 through 12. The color-coded cells allude to whether the portfolio applies singularly to $T_k = 6$ (dark navy), applies only to $T_k = 3.78$ (blue), applies only to $T_k = 3.3$ (light blue), or applies to both $T_k = 3.78$ and $T_k = 6$ (gray).

The order in which the policies are chosen suggests that some are more valuable than the others. Why did the model choose the three policies (domestic down production, functional substitution R&D, and export/import) before the others? Why were midstream R&D and CRI chosen next before the DoD accreditation and Trusted Foundry programs?

The reason of course, is because some policies' effectiveness-cost ratios are superior to others (summarized in Table 7.4).[181] The policies with the highest, most outsized effective-cost ratios form the "core" of nearly all optimal portfolios—export restrictions[182], domestic upstream production, and functional substitution R&D (in approximate order)—as depicted in Figure 7.6. Note that the three policies combined are equivalent to Portfolio 3. Indeed, the trio comprises the pillars of the majority of optimal portfolios for budgets greater than or equal to $102 million (Portfolios 3 to 12). Even when the budget is less than that, Portfolios 1 and 2 are essentially combinations of the three policies. Given their consistent selection, therefore, the three policies are considered immune to changes in budget levels.

With additional funding, Portfolio 5 captures these core policies plus the next couple policies with the largest effectiveness-cost ratios it can fit in the budget—midstream R&D and CRI. Finally, with the maximum budget level, Portfolios 11/12[183] include the last two policies with the smallest ratios—DoD downstream accreditation and the Trusted Foundry—reflecting the diminishing marginal return of each additional dollar investment.

[181] The effectiveness-cost ratio for a policy is the total effectiveness (which is the sum of the criticality reduction for each scenario) divided by the implementation cost

[182] Import restrictions were selected once as an alternative to export restrictions (recall that the two trade policy choices are mutually exclusive). Generally, export restrictions are a superior (dominant) choice over import restrictions in terms of cost and effectiveness values ($3. 9 million for a total effectiveness of 2.07 for the former, versus $10.3 million for a total effectiveness of 1.87 for the latter). However, export restrictions would increase S.I scores by a higher margin than import restrictions would (increase of S.I criticality by 0.27 versus 0.0, respectively). Thus, import restriction is selected for Portfolio 12 because selecting export restriction would increase S.I criticality above Curve 1's $T_{S.I} = 3.3$ requirement, as was discussed in Table 7.1. *For the sake of simplicity, however, these two mutually exclusive trade restriction policies are references as a single policy option manifesting in two alternative forms.*

[183] Portfolios 11 and 12 are referenced as a single alternate for the same reasons that the aforementioned trade restrictions policies are considered alternatives to a single policy option.

TABLE 7.3 – OPTIMIZED POLICY PORTFOLIOS

Policy Portfolio	Implementation Cost ($M)	Policy Area 1					Policy Area 2	Policy Area 3		Threshold Constraint (T_k=3.3)	Threshold Constraint (Tk=3.78)	Threshold Constraint (Tk=6)
		Domestic Upstream Production	Midstream R&D Separation and Processing	DoD Downstream Accreditation	DoD Trusted Foundry	Comprehensive Recycling Initiative (CRI)	Functional Substitute R&D	Export Restriction	Import Restriction			
1	$7	✓						✓				✓
2	$99						✓	✓				✓
3	$102	✓					✓	✓				✓
4	$197	✓	✓				✓	✓				✓
5	$431	✓	✓			✓	✓	✓			✓	✓
6	$602	✓	✓	✓			✓	✓			✓	✓
7	$836	✓	✓	✓		✓	✓	✓			✓	✓
8	$1,997	✓	✓		✓		✓	✓			✓	✓
9	$2,231	✓	✓		✓	✓	✓	✓			✓	✓
10	$2,402	✓	✓	✓	✓		✓	✓			✓	✓
11	$2,636	✓	✓	✓	✓	✓	✓	✓			✓	✓
12	$2,642	✓	✓	✓	✓	✓	✓		✓	✓		

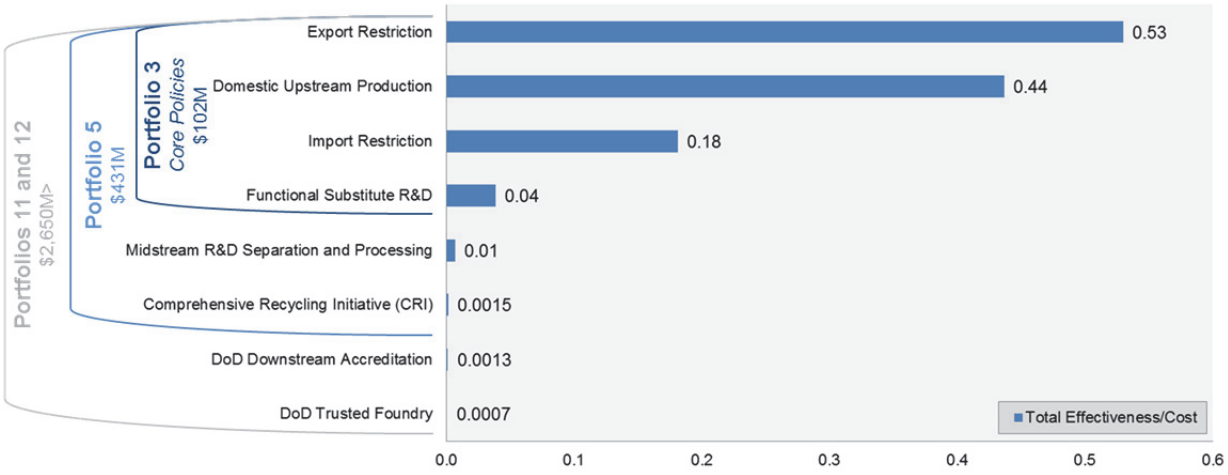
Note: Maroon font color denotes marginal optimal portfolios.

TABLE 7.4 – CALCULATION OF POLICY EFFECTIVENESS-COST RATIO[184]

Policy Area	Policy Option	Cost ($M)	Criticality Reduction (Effectiveness)			Total Effectiveness	Total Effectiveness /Cost
			S.I	S.II	S.III		
1	Domestic Upstream Production	$2.9	0.00	0.53	0.73	1.27	$0.44
	Midstream R&D Separation and Processing	$95	0.00	0.27	0.37	0.64	$0.01
	DoD Downstream Accreditation	$405	0.00	0.20	0.33	0.53	$0.0013
	DoD Trusted Foundry	$1,800	-0.07	0.53	0.80	1.27	$0.0007
	Comprehensive Recycling Initiative (CRI)	$234	0.08	0.11	0.15	0.34	$0.0015
2	Functional Substitute R&D	$95	0.56	1.46	1.64	3.66	$0.04
3	Export Restriction	$3.9	-0.27	0.93	1.40	2.07	$0.53
	Import Restriction	$10.3	-0.07	0.73	1.20	1.87	$0.18

[184] The equation for a given policy's effectiveness-cost ratio is $\frac{\sum_k Criticality\ Reduction_k}{Cost}$ where k is the set of S.I, S.II, and S.III.

FIGURE 7.6 – EFFECTIVENESS-COST RATIOS OF POLICY OPTIONS



Portfolio Robustness Testing

In the following section, we test the robustness of the Sweet Spot Portfolio policy selections. This is done two ways. In the first case, a breakeven analysis is conducted to gauge how much certain policies' effectiveness or implementation costs must improve (or degrade) for a Sweet Spot Portfolio's policy composition to change. For example, if during optimization Policy A was chosen but not Policy B, how much of Policy B's effectiveness would need to improve for it to replace Policy A? If the magnitude of the required change is small, it establishes a valid reason to believe that the policies are similar enough to challenge the others' selection. If on the other hand, the magnitude of the required change is large, it signifies that the policy selections are reasonably stable since the likelihood of such large discrepancies is limited.

In the second instance, we decrease the probability of policy implementation success for all policy options, decrease the effectiveness of government R&D funding, and increase the policy costs. A new optimization is done and the new criticality reduction values are compared against the default criticality reduction values at the same budget levels. We also ask if the optimal policy selections under these new "sober" input assumptions are consistent with the original policy selections. If not, the reasons are investigated and alternative costs for assembling Portfolios 3, 5, and 11/12 are estimated. The re-analysis using these sober assumptions helps dispel naïve expectations on portfolio cost and effectiveness.

Breakeven Analysis

Chapter 6 conducted a comprehensive review of policy options that were translated into qualitative metrics of the criticality matrix. Due to the inherently subjective nature of qualitative metrics, however, it is beneficial to examine how robust the analytical outcomes are using breakeven analysis. We start with the case of Portfolio 3 which is the optimal case with a budget of $110 million (actual cost of $101.8

million).[185] The portfolio's composition includes the domestic upstream production, functional substitution R&D, and export restriction policies that together yield a sum total effectiveness (criticality reduction) of 6.99 points[186] (Table 7.5). This constitutes the Base portfolio for Portfolio 3.

But why not select import restriction rather than export restriction as the option? To test this, in what is referred to as the test case Alternative 1, we swap the two policies and see that for a total cost of $108.2 million, the total effectiveness value is 6.79 points—0.2 points less than the Base portfolio. Given this differential, import restriction's effectiveness must increase by at least 11 percent to justify its replacement of export restriction in Portfolio 3.[187] Furthermore, the cost to implement import restriction is $10.3 million, compared to a cost of $3.9 million for export restriction. While the cost difference in percentage is large, they are both small in absolute terms. Thus, this is a relatively marginal difference in both effectiveness and implementation, which suggests that import restrictions may viably replace export restrictions. Crucially, this is consistent with the preceding analysis in this chapter which has argued that the Policy Area 3 (Trade Restriction) policies should be considered roughly equivalent alter egos.

In the next case (Alternative 2), instead of the import restriction option, we swap out the Base portfolio's functional substitution R&D policy with the midstream R&D separation and processing policy, both of which cost the same $95 million. Using the same calculation method as Alternative 1, midstream R&D's total effectiveness value (0.64 by default) must meet or exceed that of functional substitution R&D (3.66), which represents a 473 percent increase in effectiveness.[188] Such a large increase is unlikely and unreasonable so we can be confident that Alternative 2 does not represent a viable challenger to Portfolio 3.[189]

The same analysis is conducted for Portfolio 5 whose allocated budget is $440 million. Portfolio 5's original Base composition includes Portfolio 3's selection plus the midstream R&D and the CRI, for a total cost of $430.8 million. The composition of its challenger portfolio, Alternative 3, swaps out midstream R&D, functional substitution R&D, and the CRI (which together costs $424 million) with a single option, the DoD downstream accreditation for $405 million. The total effectiveness differential between the Base and Alternative 3 is 4.64, a gap which can be plugged or exceeded if the accreditation's total effectiveness value increased 770 percent—an improbable feat given that no well-planned and executed dysprosium production verification and licensing program can so drastically reduce the *material importance* or *supply risk* of dysprosium.[190] No breakeven analysis for Portfolios 11 and 12 are necessary since they invest and account for all possible policy options.

[185] The sum cost of the three policies in Portfolio 3 is $\$2.9M + \$95M + \$3.9M = \$101.8M$.
[186] The sum of the total effectiveness of the three policies in Portfolio 3 is $1.27 + 3.66 + 2.07 = 6.99$.
[187] Import restriction's total effectiveness score (1.87 by default) must meet or exceed export restriction's total effectiveness score of 2.07 so $\frac{2.07-1.87}{1.87} = 11\%$.
[188] Recall from Chapter 6 that the functional substitute R&D's effectiveness is significantly high because a perfect substitute to dysprosium (and other rare earths-based permanent magnet) drastically reduces the demand for—and therefore the criticality and vulnerability of—dysprosium.
[189] The other policies, such as CRI, DoD downstream accreditation, and Trusted Foundry are not considered because their stand-alone costs are each beyond the allotted $110 million budget.
[190] As before, the sole remaining policy option—the DoD Trusted Foundry—is not analyzed here because its $1.8 billion price tag would not be affordable under the $440 million budget.

TABLE 7.5 – BREAKEVEN ANALYSIS OF SWEET SPOT PORTFOLIO COMPOSITION

Policy Option	Cost ($M)	Total Effectiveness	Total Effectiveness /Cost Ratio	Portfolio 3 ($110M Budget)			Portfolio 5 ($440M Budget)		Portfolios 11 and 12 ($2,650M Budget)
				Base	Alternative 1	Alternative 2	Base	Alternative 3	Base
Domestic Upstream Production	$2.9	1.27	0.44	✓	✓	✓	✓	✓	✓
Midstream R&D Separation and Processing	$95	0.64	0.01			✓	✓		✓
DoD Downstream Accreditation	$405	0.53	0.0013					✓	✓
DoD Trusted Foundry	$1,800	1.27	0.0007						✓
Comprehensive Recycling Initiative (CRI)	$234	0.34	0.0015				✓		✓
Functional Substitute R&D	$95	3.66	0.04	✓	✓		✓		✓
Export Restriction	$3.9	2.07	0.53	✓		✓	✓	✓	(✓)
Import Restriction	$10.3	1.87	0.18		✓				(✓)
Total Cost ($M)				$101.8	$108.2	$101.8	$430.8	$411.8	$2,635.8
Sum Total Effectiveness				6.99	6.79	3.97	7.97	3.87	9.77
Alternate Policy's Effectiveness Required to Match Base				NA	2.07	3.66	NA	4.64	NA
Required Effectiveness Change (%) to Match Base				NA	11%	473%	NA	770%	NA

Cost Premiums and Lowered Policy Success Probabilities

In the next set of robust analysis, three modifications are made. First, the original set of *non-R&D* policy option criticality reduction (effectiveness) values is translated to expected values with a 50 percent probability of success (compared to the default assumption of 100 percent). Second, the R&D policy options (functional substitutes and midstream separation and processing) and the recycling technology R&D success rates are modified such that U.S. government funding reduces the base private sector/foreign research failure by 25 percent instead of the original 50 percent.[191] Lastly, policy option costs will be increased uniformly by 15 percent.[192] Table 7.6 summarizes the modified policy effectiveness and costs.

[191] See Chapter 2 and Chapter 5 for details and examples.

[192] The Policy Area 4 option costs are also increased but with a different approach. In the case of traditional stockpiling, the 15 percent cost premium was applied to the market price MP and storage cost S in the NDS present value calculation that was explained in Chapter 5. What this means is that the government's dysprosium oxide acquisition price is 15 percent above the default market price and that storage costs are also higher, which together raise the total net present value of the policy option by $11 million. Similarly for the buffer stock inventory cost, the MP is raised by 15 percent. The original 15 percent annual fee paid to suppliers is also raised by the same margin to 17.3 percent. The overall price increase is nearly $30 million above the original estimate of $93.5 million.

TABLE 7.6 – POLICY OPTIONS COSTS AND EFFECTIVENESS WITH SOBER ASSUMPTIONS

Policy Area	Policy Option	FY2015-FY2029 Cost ($M)	S.I (Optimistic)			S.II (Pessimistic)			S.III (Worst Case)		
			Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)	Ex-Ante Criticality Score	Ex-Post Criticality Score	Criticality Reduction (Effectiveness)
1	Domestic Upstream Production	$3.3	3.78	3.82	0.00	6.98	6.72	0.27	8.00	7.63	0.37
	Midstream R&D Separation and Processing	$109	3.78	3.78	0.00	6.98	6.77	0.21	8.00	7.72	0.28
	DoD Downstream Accreditation	$466	3.78	3.78	0.00	6.98	6.88	0.10	8.00	7.83	0.17
	DoD Trusted Foundry	$2,070	3.78	3.82	-0.03	6.98	6.72	0.27	8.00	7.60	0.40
	Comprehensive Recycling Initiative (CRI)	$269	3.78	3.75	0.03	6.98	6.94	0.05	8.00	7.94	0.06
2	Functional Substitute R&D	$109	3.78	3.32	0.47	6.98	5.79	1.20	8.00	6.67	1.33
3	Export Restriction	$4.5	3.78	3.92	-0.13	6.98	6.52	0.47	8.00	7.30	0.70
	Import Restriction	$11.8	3.78	3.82	-0.03	6.98	6.62	0.37	8.00	7.40	0.60
4	Traditional Stockpiling	$73	Meet Emergency Consumption Requirements for 4Years			Meet Emergency Consumption Requirements for 4Years			Meet Emergency Consumption Requirements for 4Years		
	Buffer Stockpile	$123.3									

Since the policies are overall less effective, we can expect "less bang for the buck." For each dollar spent, the overall sum criticality reduction (effectiveness) of a given portfolio is much smaller than under default assumptions. In addition, the allowable threshold constraint is much more limited than before. While the maximum feasibility threshold T_k was 3.3 as discussed above, under sober assumptions, the maximum T_k value is 4.8.[193]

This is reflected in the new curve, Curve SA.1 in Figure 7.7, which plots below Curve 3 (from Figure 7.4). At each given budget, the optimal portfolio returns lower sum criticality reduction (effectiveness). This is true for the Sweet Spot Portfolios, Portfolios 3, 5, and 11/12. More specifically, at the same $110 million budget allocated to Portfolio 3, Curve SA.1 has no feasible portfolio. Thus the sum criticality reduction (effectiveness) is zero and the difference in effectiveness between Portfolio 3 and Curve SA.1 at the budget level is 6.99, which is of course the effectiveness value of Portfolio 3. With a budget of $440 million, Portfolio 5's effectiveness is 7.97 while Curve SA.1's effectiveness is 5.15 (difference of 2.82 points). Lastly, with a budget of approximately $2.65 billion, Portfolio 11/12 returns an effectiveness of 9.77 versus Curve SA.1's return of 5.93 (difference of 3.85 points). The portfolios' effectiveness are uniformly low under sober assumptions.

Taking a closer look at Curve SA.1, the practical reason why the policy planner gets less value from each budget level is because the budget simply cannot accommodate the same number of policies (because they are more expensive) of the same quality (because they are less effective). Table 7.7 exhibits the differences in optimal policy selections in Portfolios 3, 5, and 11/12 on one hand, and the optimal portfolios under Curve SA.1 on the other, at the same three budget levels ($110 million, $440 million, and $2.65 billion). At $440 million[194], Curve SA.1's policy roster is identical to Portfolio 3 except for the absence of CRI which it cannot afford. Otherwise, all the other Portfolio 3 policies are included. Similarly, at $2.65 billion, the two portfolios are identical except that Curve SA.1's selection excludes the DoD downstream accreditation policy which does not fit in the budget.

While the same budget numbers may not yield the same portfolios under the two assumptions, it is worth investigating the cost to replicate Portfolios 3, 5, and 11/12 under sober assumptions. For example, the

[193] Recall that the smaller the T_k, the less vulnerable the U.S. is to dysprosium supply disruptions.
[194] Skipping $110 million because we have seen that that is not a feasible budget under sober assumption in Curve SA.1

cost to replicate Portfolio 3 under sober assumptions is $117 million (versus $102 million under default assumptions). Portfolio 5 replication cost is about $495 million (versus $431 million under default assumptions). Finally, Portfolio 11/12's replication cost is about $3.043 billion (versus $2.565 billion under default assumptions). Table 7.7 lists the costs as well as the associated sum criticality reduction (effectiveness) for the replicated portfolios.

FIGURE 7.7 – DIFFERENCE IN SUM CRITICALITY REDUCTION (EFFECTIVENESS) WITH SOBER ASSUMPTIONS

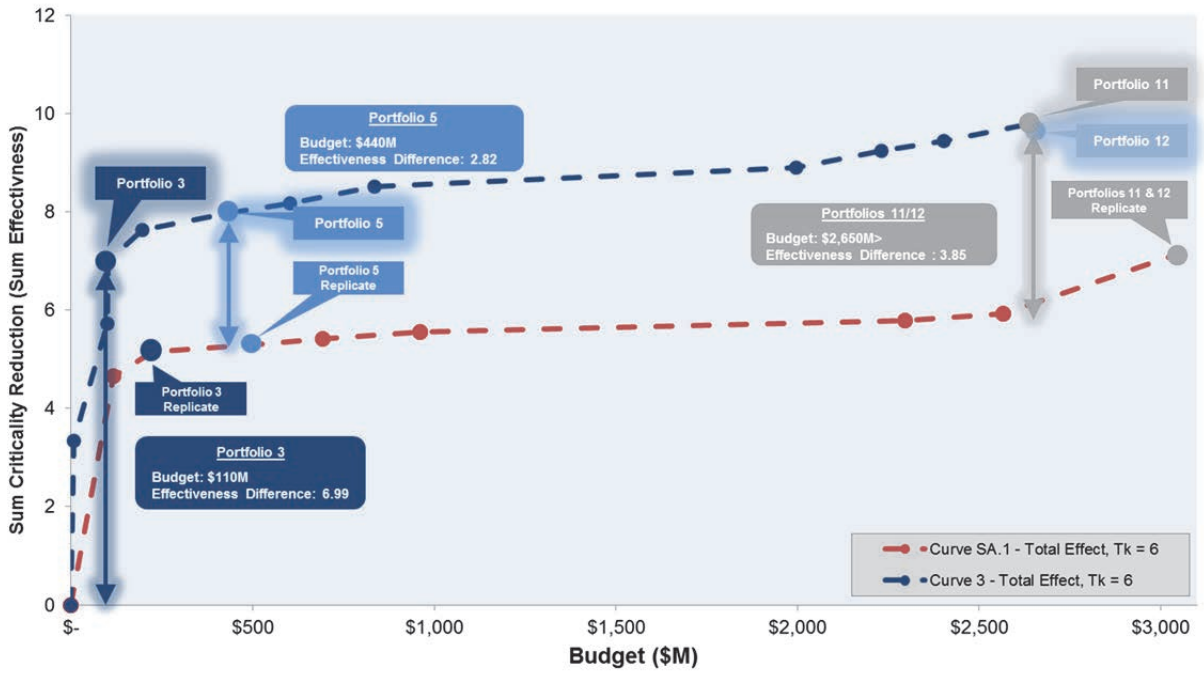


TABLE 7.7 – DIFFERENCES IN POLICY SELECTION BETWEEN SWEET SPOT PORTFOLIOS AND SOBER ASSUMPTION PORTFOLIOS

Budget ($M)	Marginal Optimal Portfolio	Implementation Cost ($M)	Policy Area 1					Policy Area 2	Policy Area 3		Sum Criticality Reduction (Effectiveness)
			Domestic Upstream Production	Midstream R&D Separation and Processing	DoD Downstream Accreditation	DoD Trusted Foundry	Comprehensive Recycling Initiative (CRI)	Functional Substitute R&D	Export Restriction	Import Restriction	
$110	3	$102	✓					✓	✓		6.99
	-	$0									0
Cost to Replicate Portfolio 3 with Sober Assumptions		$117	✓					✓	✓		4.66
$440	5	$431	✓	✓			✓	✓	✓		7.97
	Curve SA.1	$226	✓	✓				✓	✓		5.15
Cost to Replicate Portfolio 5 with Sober Assumptions		$495	✓	✓			✓	✓	✓		5.29
$2,650>	11	$2,636	✓	✓	✓	✓	✓	✓	✓		9.77
	12	$2,642	✓	✓	✓	✓	✓	✓		✓	9.57
	Curve SA.1	$2,565	✓	✓		✓	✓	✓	✓		5.93
Cost to Replicate Portfolios 11/12 with Sober Assumptions		$3,031	✓	✓	✓	✓	✓	✓	✓		6.19

The sober assumption analysis has important and useful implication for the policy planner. First, the policy planner is no longer naïve about the range of reasonable outcomes from the Sweet Spot Portfolios. For example, if appropriated a fixed $440 million budget, the planner can reasonably expect a criticality

reduction of 7.97 from Portfolio 5 while cognizant of the risk that should the worst set of coincidences occur, the criticality reduction could be as low as 5.15.

Second, the policy planner may need to secure budgets greater than the default portfolio cost estimate. For example, we have seen that the range of effectiveness that can be expected from Portfolio 3 spans from 0 to 6.99. In order to minimize regret and reduce the likelihood of the worst happening (i.e., sum criticality reduction turns out to be 0), the policy maker may need to negotiate $117 million to fund Portfolio 3 rather than the default estimated cost of $102 million. This way, there will be sufficient resources to fund Portfolio 3 even if costs are higher and policy probabilities of success are lower than expected as portrayed under the sober assumptions. Most importantly, it greatly minimizes the odds of zero criticality reduction since Portfolio 3's effectiveness is a respectable 4.66 points even under sober assumptions, so long as sufficient funds are available.[195]

In summary, the breakeven analysis has yielded greater confidence in the robustness of the Sweet Spot Portfolios' policy selections by demonstrating that the qualitative effectiveness estimates—though inherently subjective—are reasonably outside the margins of interpretive error. Secondly, comparative analysis using sober assumptions has provided the policy planner with a range of portfolio criticality reduction capabilities as well as costs. While ranged estimates are less precise than point-estimates, they enable more robust planning by informing the policy maker of the risks associated with cost estimation increases (and how much in additional funds would be required) as well as shortfalls in portfolio performance which may not necessarily return the full expected sum criticality reduction (effectiveness) projected under default assumptions.

Incorporating Policy Area 4 – Contingency Plans

So far, our analysis has focused on the optimization of policy options from Policy Areas 1, 2, and 3. Policy Area 4 includes two alternatives proposed by the DoD (2013a) study that serve as a backstop to dysprosium shortfalls in case of a national emergency.[196] As was explained in Chapter 6, the contingency plans are devised to provide sufficient materials reserves to bridge military and "essential" civilian needs during said contingency.

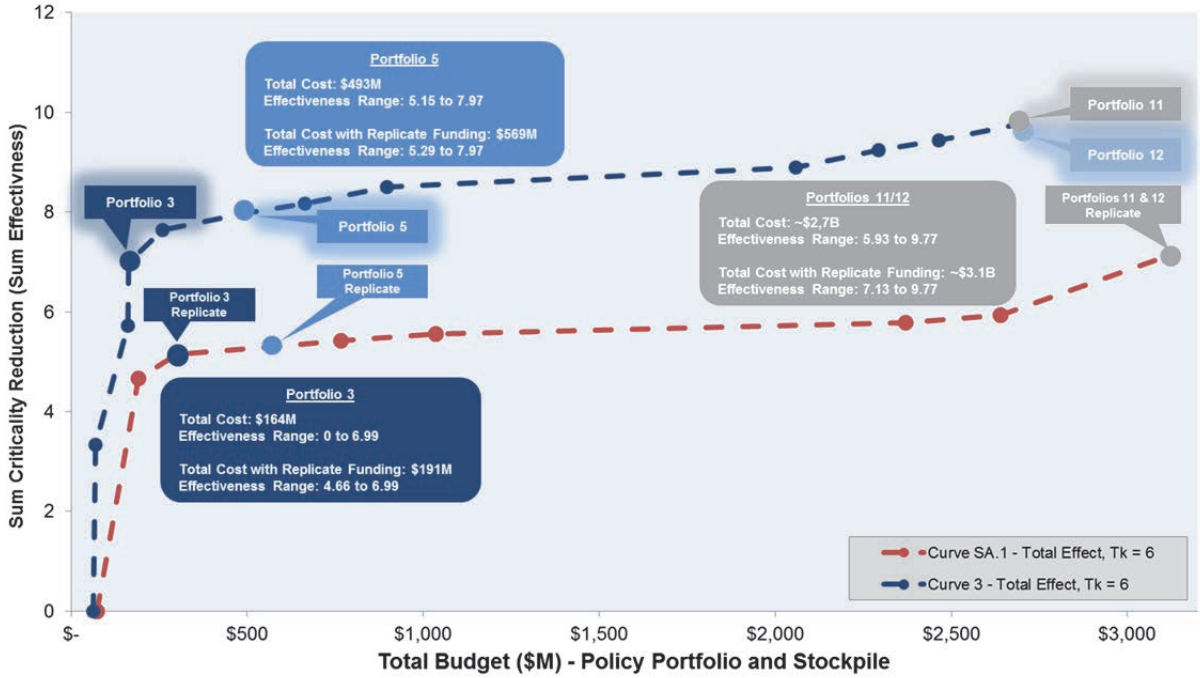
The two contingency alternatives are the National Defense Stockpile (NDS) and the Buffer Stock Inventory. The former is the default method and is run by the DoD whereas the latter relies on private suppliers to maintain stockpiles for a fee that will be sold to the government at an agreed price should the need arise. Based on a net present value analysis in Chapter 6, the NDS would cost the U.S. government just short of $62 million whereas the Buffer Stock Inventory would cost about $93.5 million at the same level of stop-gap effectiveness for the prescribed Base Case Scenario (after accounting for risks and hazards that can contribute to either alternative's failure). Given the superior value for money, the NDS is the preferred contingency alternative.

[195] Similar logic applies to Portfolios 3 and 11/12. The additional cost needed to ensure sufficient funding to replicate Portfolio 5 under sober conditions is $64 million while the cost for Portfolios 11/12 is $478 million.
[196] The two Policy Area 4 alternatives are considered mutually exclusive: either a traditional government-held stockpile by the NDS or a private buffer stock as proposed by the DoD (2013a) study.

In relation to the Sweet Spot Portfolios discussed above, the contingency policy alternatives ensure that the U.S. has access to dysprosium in case an emergency occurs before the fifteen fiscal year planning period. Recall that the planning assumption is that the portfolios require those fifteen years for the policies to yield its expected effectiveness. For example, fifteen years is what would be expected for new R&D discoveries to become commercialized, for legislative reforms to pass and impact mining developments, and for recycling infrastructures to be set up and running. As these plans unfold, however, dysprosium criticality will likely remain high. If an emergency occurs at this vulnerable stage, the negative impact on U.S. stakeholders will be high. To counteract this potential loss, the contingency plan serves as a minimally guaranteed dysprosium supply to meet essential civilian and military dysprosium demand requirement should the worst happen. By the end of the fifteen years, the assumption is that criticality will have been sufficiently reduced and that the stockpile will no longer be necessary and sold back to the market.[197]

The final, "total cost" of dysprosium criticality reduction planning is the sum of the selected Sweet Spot Portfolios' costs plus the cost for NDS.[198] Figure 7.8 plots the *total cost that includes portfolio costs and the stockpile*. Because of the addition of a constant cost value (the NDS cost), the curves have shifted to the right relative to Figure 7.7. The text boxes inside the figure explain the final total cost for each Sweet Spot Portfolio and their respective effectiveness ranges (which were reviewed above). The boxes also contain a secondary cost estimate which accounts for how much additional funding would be required to replicate the original Sweet Spot Portfolios under sober conditions (also reviewed above) and the criticality reduction effectiveness range that can be expected.

FIGURE 7.8 – SWEET SPOT PORTFOLIOS AND STOCKPILING: TOTAL COSTS AND EFFECTIVENESS RANGES



[197] Net present cost calculations for Contingency Plan alternatives in Chapter 6 incorporate the dysprosium resale value.
[198] The total costs are simply the sum of the portfolios' implementation costs plus the cost to stockpile dysprosium for the NDS.

Chapter Summary

This chapter utilized the qualitative metrics synthesized in Chapter 6 and incorporated the data into the optimization model from Chapter 6. The result is an analysis of several different unique policy portfolios tailored to reduce dysprosium criticality and American vulnerability to dysprosium supply disruption. While all the dozen portfolios are optimal (they maximize dysprosium criticality reduction (effectiveness) at a given budget level), three top portfolios—the so-called Sweet Spot Portfolios, Portfolios 3, 5, and 11/12—emerged as not only optimal but also marginally cost-effectiveness (they capture superior value for money).

The next step of the analysis was to check the robustness of the Sweet Spot Portfolios to examine whether the policy compositions were stable or not. The assessment confirmed that Portfolios 11 and 12 are interchangeable (as was earlier asserted). Furthermore, we found that Portfolios 3 and 5 would require extremely large discrepancies in qualitative interpretation of the effectiveness metrics in order for selected policy compositions to be replaced by non-selected policies. In the next stage of the robustness check, we re-optimized the portfolios using decremented policy effectiveness values and higher costs. The analysis yielded a sober set of data that established a lower bound estimate for the portfolios' effectiveness as well as an upper bound cost estimate.

Selecting the appropriate portfolio amongst Portfolios 3, 5, and 11/12 depends on a couple factors. First is the budget. As reviewed in Figure 7.8, Portfolio 3's total cost (portfolio implementation cost plus the NDS contingency plan) may range between $164 million to $191 million. In the best case, the portfolio would decrease dysprosium to medium criticality, while in the worst case, dysprosium would remain a critical material. Numerically, the effectiveness (criticality reduction) range would vary between 0 and 7 or between 5 and 7, depending on the funding level, respectively.

The total cost for Portfolio 5 (portfolio cost plus the NDS contingency plan) is estimated between $493 million to $569 million and has a higher likelihood of reducing dysprosium criticality to medium criticality than under Portfolio 3. However, in the worst case, there is residual risk that dysprosium may still remain a critical material, although less likely than under Portfolio 3. The portfolio's effectiveness ranges between 5 and 8.

Finally, the total cost for Portfolios 11/12 would range between $2.7 billion and $3.1 billion (again total cost includes both the portfolio cost plus the NDS contingency plan). The criticality reduction in this case would effectively push dysprosium to low criticality under favorable conditions. Under less favorable conditions, however, dysprosium has a strong likelihood of becoming a medium critical material. Numerically, Portfolios 11/12's criticality reduction would range either between 6 and 10 or between 7 and 10, depending on the allocated budget, respectively.

The second factor that informs the Sweet Spot Portfolio selection is how much criticality reduction the planner would like to achieve. The greater the desired reduction, the more expensive it is. Portfolio 3 is the product of a fairly relaxed condition which (technically) allows dysprosium criticality to remain up to

as near as the edge of the critical zone.[199] In contrast, the analytical requirement governing Portfolio 5 was that portfolios must decrease dysprosium criticality levels under all scenarios to at least S.I's default criticality levels.[200] Finally, Portfolios 11 and 12 meet a very stringent requirement in which dysprosium criticality falls within or very close to the low criticality zone (under default assumptions).[201]

Crucially, this analysis enables the policy maker to utilize allocated public resources efficiently for maximum effect in reducing dysprosium criticality. The chapter has reviewed practical implications of this analysis by walking through scenarios that assist strategic planning. For example, the portfolio cost-effectiveness trade-off curve enables the planner to understand what the best policy combinations are under different budget scenarios. It provides the planner with an indication of how much effectiveness will be lost (or gained) in prospective budget decrements. Equally important, the policy maker now has a tool to make informed decisions (and negotiations) on how much budget *should* be allocated.

[199] Numerically, this means that the sum of the *supply risk* and *material importance* dimensions is no more than 6 (i.e., the threshold constraint T_k is 6) for any of the three scenarios S.I (optimistic), S.II (sober), and S.III (worst case).
[200] Portfolio 5's threshold constraint is 3.78, which is meant to ensure that the *ex-post* criticality of S.II and S.III are at least as good as under the *ex-ante* S.I scenario.
[201] The feasible threshold constraint o $T_k = 3.3$ demands that Portfolios 11/12 exceed even beyond the optimistic scenario in S.I and effectively ensure that dysprosium becomes a very low critical material.

Chapter 8 – Conclusion

"Had my hand on the dollar bill
And the dollar bill blew away
But the sun is shining down on me
And it's here to stay."
- Music lyrics by Rare Earth from their song,
"I Just Want to Celebrate"

Introduction

This concluding chapter summarizes research findings derived from a new planning framework for analyzing American strategies to reduce vulnerability to dysprosium supply disruption by the year 2030. Specifically, this study aims to contribute to the policy research arena in three substantial ways. First, it introduces a new strategic planning framework for the U.S. policymaking community in regards to critical materials. Second, it provides a comprehensive narrative of the political economy of dysprosium and rare earths and its technical and geological underpinnings of the industry. Lastly, it recommends an integrated, optimized, and fiscally responsible policy portfolio for reducing dysprosium criticality and improving America's resiliency to supply disruptions for each of three budget ranges.

A New Planning Framework and Tool

This dissertation serves as a "one-stop shopping" destination for the U.S. policy planner seeking to understand the complex political, economic, and technical dynamics governing dysprosium and to find a comprehensive solution to decreasing U.S. vulnerability dysprosium supply disruptions. Leveraging the recent surge of interest and research in rare earths, it combines both qualitative and quantitative data and methods to provide a systematic explication, diagnosis, and treatment of the dysprosium supply challenge. This dissertation presents a framework for maximizing dysprosium criticality reduction under budget constraints using a combination of qualitative metrics and quantitative optimization mixed-integer model.

The first step is to understand the unique political, economic, and technical dynamics that define the criticality of a material such as dysprosium. This establishes the empirical and qualitative foundations for understanding why a given material is "critical" and equally importantly, what role policies can have in reducing the criticality.

In the second step, a roster of policy options is considered (derived from literature and additionally synthesized by the author) that can address the sub-causes of material criticality in the *material importance* and *supply risk* dimensions. Their effectiveness were interpreted as a1 to 4 scoring metric of increasing risk (1 = low risk, 2 = medium-low risk, 3 = medium-high risk, and 4 = high risk). The policy's implementation costs were estimated for the 15 year planning period.

In the subsequent quantitative analysis, the synthesized data were used as input coefficients and costs to determine how to combine the policies to maximize the combination's (i.e., portfolio's) sum criticality reduction (effectiveness) value for each increasing budget level (in $10 million increments). The result is a cost-effectiveness trade-off curve and the identification of unique optimal portfolios of policies that reduce dysprosium criticality.

Three candidate Sweet Spot Portfolios were identified for three different ranges of portfolio implementation budgets (low, moderate, and high). Not only do these Sweet Spot Portfolios yield the highest effectiveness for their given budgets, they also provide the policy planner with superior value for

money, meaning that although their absolute costs may be marginally higher than other portfolios in the respective budget ranges, their effectiveness increases substantially for each additional dollar investment.

There are three practical planning benefits of this approach for the policy planner. First, the planner is able to select and assemble policy options that can best reduce dysprosium criticality or vulnerability to supply disruption, given an allocated budget. Secondly, if budgetary pressures call for additional cost saving measures, the planner has an indication of how much savings are possible, and if budgets are cut involuntarily, how much those cuts will affect dysprosium criticality reduction effectiveness. Lastly, if the optimized portfolio at a given budget level does not sufficiently decrease dysprosium criticality, the planner has an analytical framework for justifying additional funding to meet required dysprosium criticality reduction levels. At the very least, senior decision makers can be forewarned of the potential consequences of budget reductions on dysprosium criticality or vulnerability to supply disruption.

Dysprosium Supply Risk

The Politics and Economics of Dysprosium and Rare Earths

China rose to become the leading rare earths producer today through strategic investment in the industry spanning the decades. Eager to capitalize on its abundant geological reserves and to exploit its unique properties, Beijing has sought to develop mining capacities, invest in scientific research, and in the last decade, consolidate lucrative global midstream and downstream rare earth production facilities within its borders. This consolidation is now largely complete, with greater than 90 percent of upstream and midstream capacities and at least 75 percent of downstream NdFeB magnet capacity currently residing within China. In particular, China has a monopoly of valuable heavy rare earths, including dysprosium, at least for the near term.

Beijing's strategy for capturing the global rare earth value chain was two-fold. First, China's rise as an upstream monopolist was abetted by its geological endowment of large and easy to excavate (read less costly) deposits, particularly of heavy rare earths which include dysprosium. In addition, China's historically lax environmental controls and regulatory oversight translated to operational cost savings against which U.S. operations (chiefly the Mountain Pass, CA) and other foreign miners could not compete against, leading to their closures.

Secondly, to capture the midstream and downstream capacities, Beijing instituted export restriction measures that created a two-price system—a domestic price that effectively subsidized Chinese suppliers and an international market price that was much higher (on average approximately 280 percent higher at its peak in 2011) and thus penalized foreign rare earth importers, such as midstream and downstream suppliers who were dependent on Chinese rare earths. Beijing's restrictions were more stringent on unprocessed rare earths but less stringent for processed or manufactured rare earth goods. This created financial pressures that forced foreign rare earth processors and manufacturers to either close down or relocate their business to China to take advantage of lower rare earth ore prices. And so they did. By the second half of the 2000s, the majority of U.S., Japanese, and European midstream and downstream businesses had relocated to China.

This gradual migration and degradation of the U.S. rare earth supply chain was long observed by a small number of industry observers. It was not until 2009, however, with Beijing's drastic cuts in export quotas and the concomitant rise in prices afterwards that rare earths gained the attention of policy makers worldwide. In the years since, the U.S. along with the Japanese and European governments among others,

have prevailed against Beijing's export barriers on critical materials and rare earths in two successive suits before the WTO. Governments worldwide, particularly Japan whose high technology manufacturing base relies heavily on China rare earths, have invested extensively in securing alternative supplies of rare earths outside of China. They were joined by the U.S., European, and Korean governments in research into substitutions and better cost-effective recycling technologies. The initial price surge in 2009 to 2011 (since deflated) also gave impetus for miners to restart, accelerate, or consider rare earth mining operations in countries with rare earth reserves, chiefly Australia but also the U.S., Canada, Greenland, South Africa, India, and Vietnam among others.

Geology of Rare Earths

Undergirding the political and economic fracas of rare earths is a non-human factor: the abundant presence of rare earths within China's political borders. The abundance is not merely in terms of quantity (just less than half of the world's reserve) but also in valuable heavy rare earths in the form of ion-adsorption which are significantly easier to extract than heavy rare earths found in other deposits around the world. The triumvirate of rare earths quantity, elemental distribution, and quality gives China a natural (pun not intended) advantage in the political economy of rare earths.

Dysprosium Material Importance: The NdFeB Permanent Magnet

By far, the most significant use of dysprosium is in small quantities in the manufacture of NdFeB permanent magnets. These magnets have superior overall qualities in terms of power (magnetism), coercivity (resistance to heat and de-magnetization), and efficiency (smaller amounts that still yield superlative performances which allow for miniaturization) than all its predecessors, such as the SmCo and ferrite magnets. While little known or understood outside the high technology manufacturing industries, permanent magnets permeate in sizes small and large in all facets of modern life, from automobiles to green energy and defense systems. For the average consumer, permanent magnets are used in hard drives, autos, smart phones, and medical devices. Removed from the households but impacting our societal livelihood are their uses in next generation wind turbines and advanced military weapons systems. With greater demand for technology goods that shrink in size without sacrificing performance, dysprosium-laced permanent magnets play an increasingly important role in the modern economy. Furthermore, as a relatively "young" technology metal whose commercial applications have only recently been exploited in the last several decades, dysprosium's full potential still lies in waiting.

Dysprosium, the Most Critical Rare Earth

This dissertation relies on precedent-setting research by NRC (2008) and Bauer et al. (2011) who introduced the criticality matrix for defining the term criticality and a systematic framework for diagnosing which raw materials meet that criteria. The more important a material is to society (the *material importance* dimension of the criticality matrix) and the more risk there is of a supply disruption for that material (the *supply risk* dimension), the more critical or vulnerable the material. Dysprosium ranks high in both dimensions as confirmed by Bauer et al. (2011), DoD (2013a), and industry sources.

This hypothesis was simulated using projections on dysprosium supply and demand dynamics into the year 2030. The supply projections assumed varying degrees of mining supply capacities (in China and outside) using historical and prospective compounded annual growth rates (CAGR) which account for volatility. Both "ground up" and "top down" approaches were used. The former approach individually calculated the dysprosium mining supply capacities of the world's heavy rare earth mines using industry literature. The latter approach super-imposed historical (low CAGR) and hypothetical (high CAGR) to

project potential supply capacities and distinguished growth rates between Chinese production and non-Chinese (rest of the world or ROW) productions.

The demand projections were similarly premised on conservative and aggressive ground up and top down assumptions. The ground up approach individually calculated the amount of dysprosium that would be required for the world economy to meet aspired green technology usage rates using data methods from Bauer et al. (2011), the IEA, and industry literature. The top down approach super imposed historical and prospective CAGR estimates to simulate a range of demand trajectories.

Combining the two set of projections together, a range of potential shortfalls (difference between supply capacity and demand) in dysprosium were derived. In the best case, the shortfalls will be limited if demand requirements are stable and supply capacities grow steadily outside of China. In the hypothetical worst case, however, the shortfall can be very acute. It is important to reiterate, however, that these theoretical projections were motivated not so much to predict, as much as it is to illustrate the planning conundrum the policy maker faces and explicate why dysprosium is consistently deemed the most critical material by industry and policy stakeholders.[202]

This exercise, although abstract, illuminated two important insights the U.S. policy planner should take into account for future planning. The first is that mining alone—whether in China or abroad—will not necessarily be able to meet increasing demand levels. While new mining capacities are necessary, other measures to decrease demand (e.g., via substitution) and increase supply (e.g., via recycling) would be necessary to meet shortfalls. Secondly, the projections elucidate the inherent uncertainty the policy maker faces when deciding how to invest in dysprosium criticality reduction policies. Policies must be planned such that they are robust against a range of future scenarios rather than a single expected scenario. The U.S. policy maker is advised to consider multiple policy options for a comprehensive approach to dysprosium criticality reduction as summarized next.

The Policy Options for Reducing Dysprosium Criticality

While China is the dominant rare earths producer, it is increasingly also a net importer as well, especially of the heavy/critical rare earths (including dysprosium) as its technology manufacturing base matures. Meeting shortfall demand by opening up Chinese rare earths trade thus may not improve American supply of dysprosium given China's own voracious demand for the material.

What options does the American policy maker have? Ten policy choices recommended by U.S. government agency reports, legislators, or otherwise synthesized by the author were classified along four Policy Areas (Supply Chain Development, Functional Substitute R&D, Trade Restrictions, and Contingency Plans). Each policy option was qualitatively evaluated on its ability to reduce criticality of one or more sub-dimensions of the criticality matrix by the end of the FY 2029 and interpreted into the aforementioned 4 point integer scale. The policy implementation costs for the fifteen fiscal year planning period (FY 2015 to FY 2029) were also estimated.

A distinction is made between policy options under Policy Areas 1, 2, and 3 versus Policy Area 4's Contingency Plans. The lattermost contingency plans—stockpiling and buffer stocks—were not evaluated with the qualitative metric scheme for the reason that their intention and design by the DoD

[202] Recall that both supply and demand projection assumed that critical technologies—such as cost-effective recycling and comparably functional substitutes—do not significantly improve beyond contemporary capabilities.

were narrowly to provision emergency supplies in case of extreme national emergencies rather than to reduce material criticality as aspired by this research. Nonetheless, we discussed the importance of the contingency plan as a necessary "insurance" policy that could mitigate dysprosium shortfalls in an emergency. The policies in Policy Areas 1, 2, and 3 take time to develop, implement, commercialize, and/or mature before dysprosium criticality is minimized at the end of the 15 year planning period (late 2030). Should the worst happen during this vulnerable stage, the contingency plan provides a limited backstop capability for the U.S. to meet exigency needs and yields the policy maker breathing room to readjust the strategic plan. In the end, the NDS option was selected over the buffer stock since it provided the same contingency service for less cost ($62 million for the NDS versus an estimated $93.5 million for the buffer stock).

Three Sweet Spot Optimal Portfolios for Three Budget Ranges

Having grappled with the origins of dysprosium criticality and potential solutions, the study leveraged a linear programming model, which is a mathematical optimization method, to help the planner calculate how much dysprosium criticality reduction can be achieved under various budget levels ranging from zero to $3 billion to implement policy options. Using the policies' qualitative effectiveness metrics and cost estimates from Chapter 6, the optimization model formulated a dozen optimal combinations of policy options, referred to as policy portfolios, for different budget levels.[203] This yielded a trade-off curve between increasing budgets and diminishing gains in the portfolios' criticality reductions.

Among these portfolios, three in particular, Portfolios 3, 5, and 11/12, occupied the aforementioned sweet spots of their respective budget ranges. Thus, depending on which of the three budget ranges—rounded up to the nearest $10 million increment—a proposed budget falls into (less than or equal to $430 million, $440 million to $2 billion inclusive, and $2.01 billion and above), *the final budget should be the cost to assemble the respective Sweet Spot Portfolio for that budget range*. Table 8.1 summarizes the budget ranges that these three portfolios govern and their costs (portfolio cost, the NDS contingency plan cost, and the sum of these two which equal the total cost). The Sweet Spot Portfolios are so called because each reflects the lowest budget to accomplish specific policy objectives.

Portfolio 3 is the Sweet Spot Portfolio for a small portfolio budget (excluding the NDS contingency plan) that is equal to or less than $430 million over the next 15 years. Portfolio 3 offers the highest per dollar vulnerability reduction value but it may not be resilient enough to shield the U.S. from critical shortfalls in the worst of cases. This portfolio consists of investments in three policy options. First is U.S. domestic mining permitting reforms. Second is R&D on functional substitutes. Third is export restrictions on raw materials that China is import-dependent on in order to compel Beijing to dismantle its rare earth export restrictions or deter it from manipulating global supplies henceforth. Portfolio 3's actual implementation cost is $102 million. With the NDS contingency insurance of $62 million, the total cost is about $170 million.[204]

Portfolio 5 is the Sweet Spot Portfolio for a moderate budget between $431 million to just under $2 billion (inclusive).[205] Portfolio 5 is designed to sufficiently decrease U.S. dysprosium vulnerability so

[203] Optimal meaning they maximized sum criticality reduction (effectiveness) while staying true to budget limitations.
[204] Portfolio 3 selects export restrictions as the default policy. However, if the policy maker would like to reserve adequate funds for implement import restrictions instead, then the total cost would rise by $6.4 million or $170.4 million. The total effectiveness would decrease by 0.2, but this is negligible given the uncertainty of the effectiveness values, particularly as they pertain to trade restriction policies.
[205] $1.997 billion.

that the U.S. would not experience acute shortages even in the pessimistic (S.II) and worst case (S.III) scenarios. It includes Portfolio 3's three policy options plus two more policy options. First is the Comprehensive Recycling Initiative (CRI) that invests in both cost-effective dysprosium recycling technology R&D and legislation to increase collection rates of e-wastes that contain dysprosium. Second is R&D investment in better rare earths midstream (separation and processing) technologies that can improve the competitiveness of U.S. rare earth suppliers. The actual portfolio cost is $431 million, with the total cost rising to about $500 million after adding the NDS contingency plan of $62 million.[206]

Portfolios 11 and 12 are the Sweet Spot Portfolios for budgets greater than approximately $2 billion[207] and they comprise all seven policy options, including funding for a DoD accreditation regime to clarify for and incentivize U.S. and qualified countries' rare earth suppliers as certified trusted sources of dysprosium and derivative products for the U.S. military. It also includes expanding the DoD's pre-existing Trusted Foundry program to include government-owned dysprosium (and other critical rare earths) midstream and downstream capacities to meet DoD requirements. Portfolios 11 and 12 would achieve the maximum reduction in American dysprosium vulnerability with the given set of policy options at the lowest possible budget. But the price tag is still hefty. Portfolios 11 and 12 cost $2.64 billion and $2.65 billion, respectively, with total costs rising by $62 million each to approximately $2.7 billion after funding the NDS.

The policy compositions of the three portfolios were checked for robustness by assessing how much a competing (non-selected) policy's effectiveness would have to increase in order to viably replace one or more of the Sweet Spot Portfolios' selected policies. The analysis confirmed that Portfolios 3 and 5 were stable while also affirming an earlier qualitative assertion that Portfolios 11 and 12 were largely interchangeable (and practically identical)—the difference stemming solely in the selection of either one of the two mutually exclusive Trade Restriction options.[208] Effectiveness values were not rounded to significant figures during the analysis but are rounded here in the final analysis.

TABLE 8.1 – SUMMARY CHART OF SWEET SPOT PORTFOLIOS[209]

Sweet Spot Portfolio	Budget Range Governed by Sweet Spot Portfolio ($M)±	Sum Criticality Reduction (Effectiveness)	Sweet Spot Portfolio Cost ($M)	NDS Contingency Plan ($M)	Total Cost ($M)±
3	≤ $430	7	$102	$62	$170
5	$440 - $2,000	8	$431		$500
11 (12)	$2,010 ≤	10	$2,636 ($2,642)		$2,700 ($2,710)

Note: Cost estimates cover the period between FY 2015 and FY 2029. ± denotes costs are rounded up to nearest $10M.

Advocating for the Sweet Spot Portfolios

The Sweet Spot Portfolios' estimated impact on dysprosium criticality levels by late 2030 are visually illustrated on the criticality matrix in Figure 8.1. Portfolios 11/12 offer the best absolute criticality

[206] Like Portfolio 3, Portfolio 5 selects export restrictions as the default policy. However, if the policy maker would like to reserve adequate funds for implement import restrictions instead, then the total cost would rise by $6.4 million or $494.4 million. The total effectiveness would decrease by 0.2, but this is negligible given the uncertainty of the effectiveness values, particularly as they pertain to trade restriction policies.

[207] Greater than or equal to $1.998 billion.

[208] Regardless of which policy portfolio is ultimately chosen, the policy maker is assumed to continue countering China's unfair trade practices via the WTO and to fund the NDS as required by law.

[209] Figures in parenthesis refer to Portfolio 12 figures.

reduction proposition, with a strong possibility of reducing dysprosium to a low critical material. This is achieved through the portfolios' sum criticality reduction (effectiveness) of about 10 points (Table 8.1). Even under worst conditions, Portfolios 11/12 could still reduce dysprosium to medium criticality by 2030. These premium benefits, however, come with a hefty $2.7 billion price tag (including the contingency plan cost). Because these portfolios constitute big ticket items, appropriations may be difficult in a constrained budget environment.

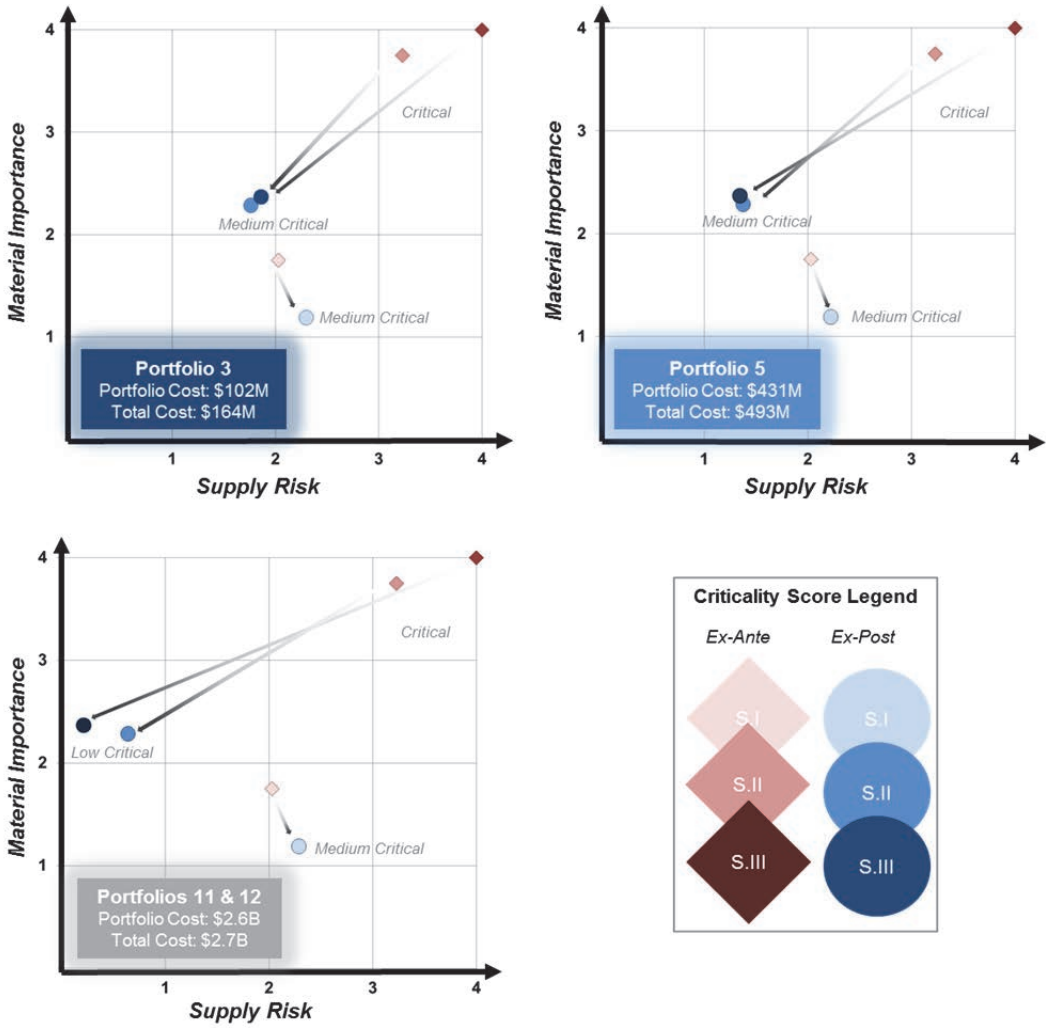
On the other extreme, Portfolio 3's relatively minimum composition nonetheless captures the minimal "core" policies (domestic mining permits reform, functional substitute R&D, and export restriction cost imposition/deterrence on China). As a "budget" option, Portfolio 3 provides the policy planner with an alternative to inaction. For $164 million (including the contingency plan cost), Portfolio 3 can be expected to help achieve some modest reductions in dysprosium criticality under fair conditions (medium critical abutting critical status), although the prognosis that dysprosium remains a critical material is high. The expected sum criticality reduction (effectiveness) is approximately 7.

Portfolio 5 offers a compromise between the two other portfolios. It is superior to Portfolios 11/12 in terms of cost proposition (it is political easier to justify $493 million than $2.7 billion) while increasing the expected range of reduced criticality deeper into the medium critical region than offered by Portfolio 3 (the expected sum criticality reduction (effectiveness) from Portfolio 5 is 8). While Portfolio 5 does not ensure dysprosium falling below medium criticality into the coveted low criticality zone and although the likelihood of dysprosium remaining critical persists, Portfolio 5 is a politically palatable alternative should the advocacy for Portfolios 11/12 be compromised.[210]

All three portfolios are optimal for their budgets and deliver strong value propositions to the American public. However, given the reality of the constrained federal budget environment in the foreseeable future, Portfolios 11/12 will likely face strong headwinds even though they offer the highest reduction in dysprosium criticality and vulnerability. Thus, under the indefinite future of budgetary austerity, Portfolios 3 and 5 represent the more serious contenders for adaptation. In choosing between these two portfolios, the decision maker must weigh the prospect of comparatively higher reductions in dysprosium criticality (effectiveness 7 versus 8, respectively) and its associated vulnerabilities for U.S. stakeholders against higher budgetary requirements ($164 million versus $493 million).

[210] The policy maker should also be aware that because export and import restriction policies may potentially run afoul of WTO rules and because of the unknown effects—politically and economically—of these policies, this study's recommendation is that these policies are funded on a standby basis only. They would be implemented only after serious deliberation on their actual effectiveness value given the legal and political contexts of the decision-making period. The study assumes that these policies are not implemented in a situation where China has complied by WTO regulations, such as those assumed in S.I (optimistic scenario).

FIGURE 8.1 – SWEET SPOT PORTFOLIOS' EFFECT ON DYSPROSIUM CRITICALITY REDUCTION BY 2030



Conclusion

This dissertation provided a consolidated narrative of the complex interplay of politics, science, and economics of dysprosium. While dysprosium is an obscure material, its unique property (so critical to cutting edge technologies today and likely into the future), the larger geopolitical context, and constraining geological characteristics have made the element the most critical material today. Many U.S. policy options have been recommended to the American policy maker, including newly synthesized ones in this research. This study systematically evaluated these policies' effectiveness and costs and incorporated these qualitative data into a new optimized strategic planning framework that maximizes dysprosium criticality reduction or minimizes its vulnerability to supply disruptions, while cognizant of budgetary constraints.

Appendices

Appendix A – Military Applications of Permanent Magnets

Weapon Systems	Army	Marine Corps	Navy	Air Force
AGM-114 Hellfire Air-to-Surface missile	✓			✓
Joint Direct Attack Munition (JDAM) Precision Guidance Kit	✓	✓	✓	
PAC-3 Anti-Ballistic Missile	✓			
AIM-9 Sidewinder Air-to-Air Missile		✓	✓	✓
AIM-120 Advanced Medium-Range Air-to-Air missile		✓	✓	✓
Harpoon Anti-Ship Missile		✓	✓	✓
Trident 5D Submarine-Launched Ballistic Missile			✓	
Minuteman-III Intercontinental Ballistic Missile				✓
Weapon Platforms	**Army**	**Marine Corps**	**Navy**	**Air Force**
M109 Paladin Howitzer	✓			
AH-64 Apahce Helicopter	✓			
M2 Bradely Fighing Vehicle	✓			
M1 Abrams Main Battle Tank	✓	✓		
Stryker Fighter Vehicle	✓			
Arleigh Burke-Class Destroyer			✓	
Nimitz-Class Aircraft Carrier			✓	
Littoral Combat Ship			✓	
Unmanned Underwater Vehicle			✓	
SSN-774 Virginia-Class Attack Submarine			✓	
B-52 Bomber				✓
F-15 Eagle Fighter				✓
F-16 Falcon Fighter				✓
F-18 Hornet Fighter		✓	✓	
F-22 Raptor Fighter				✓
F-35 Joint Strike Fighter		✓	✓	✓
MQ-1B Predator Drone				✓
Other Systems	**Army**	**Marine Corps**	**Navy**	**Air Force**
Laser Rangefinder	✓			
Laser Target Designators	✓			
Satellite Communication	✓			
Towed Decoys		✓	✓	✓
Aegis Radar			✓	
Firefinder Anti-Rocket/Anti-Artillery Radar			✓	
Underwater Mine Detection			✓	

Source: Adams et al. (2013)

Appendix B – Advanced Non-Chinese Rare Earth Projects

Project	Country	Owner(s)
Aksu Diamas (Canakli)	Turkey	AMR Mineral Metal Inc.
Buena Norte	Brazil	Indústrias Nucleares do Brasil S/A (INB)
Dong Pao	Vietnam	Vitacomin, Toyota Corp./Sojitz (JV)
Dubbo Zirconia Project	Australia	Alkane Resources Ltd.
Kamasurt	Russia	Lovozersky Mining Company
Mount Weld	Australia	Lynas Corporation Ltd.
Mountain Pass	USA	Molycorp Inc.
Nolans	Australia	Arafura Resources Ltd.
Orissa,Tamil Nadu and Kerala	India	Indian Rare Earths
Steenkampskraal	South Africa	Great Western Minerals Group Ltd.
Uranium tailings	Kazakhstan	Kazatomprom/Sumitomo (JV)
Zandkopsdrift (JV)	South Africa	Frontier Rare Earths Ltd.
Araxá	Brazil	MBAC Fertilizer Corp.
Ashram	Canada	Commerce Resources Corp.
Bear Lodge	USA	Rare Element Resources Ltd.
Bokan	USA	Ucore Rare Metals Inc.
Browns Range	Australia	Northern Minerals Limited
Buckton	Canada	DNI Metals Inc.
Charley Creek (JV)	Australia	Crossland Strartegic Metals Ltd.
Clay-Howells	Canada	Canada Rare Earth Corp.
Cummins Range	Australia	Navigator Resources Limited
Eco Ridge	Canada	Pele Mountain Resources Inc.
Elliott Lake Teasdale	Canada	Appia Energy Corp.
Foxtrot	Canada	Search Minerals Inc.
Glenover (JV)	South Africa	Galileo Resources PLC
Grande-Vallée	Canada	Orbite Aluminae Inc.
Hastings	Australia	Hastings Rare Metals Limited
Hoidas Lake (JV)	Canada	Great Western Minerals Group Ltd.
Kangankunde	Malawai	Lynas Corporation Ltd.
Kipawa (JV)	Canada	Matamec Explorations Inc.
Kutessay II	Kyrgyzstan	Stans Energy Corp.
Kvanefjeld	Greenland	Greenland Minerals and Energy Ltd.
La Paz	USA	AusAmerican Mining Corp. Ltd.
Lavergne-Springer	Canada	Canada Rare Earth Corp.
Lofdal	Namibia	Namibia Rare Earths Inc.
Milo	Australia	GBM Resources Ltd.
Montviel	Canada	Geomega Resources Inc.
Mrima Hill	Kenya	Pacific Wildcat Resources Corp.
Nechalacho	Canada	Avalon Rare Metals Inc.
Ngualla	Tanzania	Peak Resources Ltd.
Niobec	Canada	IAMGOLD Corporation
Norra Kärr	Sweden	Tasman Metals Ltd.
Olserum	Sweden	Tasman Metals Ltd.
Round Top	USA	Texas Rare Earth Resources Corp.
Sarfartoq	Greenland	Hudson Resources Inc.
Serra Verde	Brazil	Mining Ventures Brasil Ltda.
Solikamsk Processing Plant	Russia	Solikamsk Magnesium Works
Songwe	Malawai	Mkango Resources Ltd.
Sørensen	Greenland	Greenland Minerals and Energy Ltd.
Storkwitz	GER	Seltenerden Storkwitz AG
Strange Lake	Canada	Quest Rare Minerals Ltd.
TANBREEZ	Greenland	Rimbal Pty Ltd
Tantalus	Madagascar	Tantalus Rare Earths AG
Two Tom	Canada	Canada Rare Earth Corp.
Wigu Hill Twiga	Tanzania	Montero Mining and Exploration Ltd.
Xiluvo (JV)	Mozambique	Galileo Resources PLC
Zone 3	Greenland	Greenland Minerals and Energy Ltd.
Shaded projects denote those currently actively producing REEs.		

Data: TMR (2014) and Walters, Lusty, and Hill (2011)

Appendix C – China, Just Another Brick in the Wall?

In 2010, the European Commission (EC) reported that, "many emerging economies are pursuing industrial development strategies by means of trade, taxation, and investment instruments aimed at preserving their resource base for their exclusive use" (EC 2010). In particular, the preferred policy tools to restrict material outflow have been through taxes, quotas, and subsidies for domestic buyers. Dramatic historical precedents such as the 1970s OPEC oil embargo aside, countries have implemented restrictions on goods for various reasons, sanctioned and unsanctioned by the 1947 General Agreement on Tariffs and Trade (GATT) and its successor, the WTO (EC 2010).[211]

Research at the OECD focused on contemporary trends in export restriction by emerging economies and provided detailed accounts of the vehicles of these restrictions, such as the use of export taxes, licensing requirement, bans, quotas, and others (Kim 2010; Peeling et al. 2010), and their impact on global trade and supply (Korinek and Kim 2010). Their findings suggest that export restriction of commodity-producing countries is not unprecedented in emerging economies.

Previous studies, such as the ones by RAND (2013) and EC (2010), have weighted the governance indicator levels as important measures that factor into a material criticality rating. While this is intuitive, research linking a country's economic growth level and its raw materials export restriction policy has been sparse save for works by the OECD and by Lim and Senduk (2013). The OECD studies provide an important foray into this topic, reinforcing the hypothesis that emerging economies are likely to adopt restrictive export policies of raw materials. Thus, while China may be the most obvious source of supply disruption today, other countries at similar stages of growth may very well restrict exports of other raw materials. According to Lim and Senduk (2013), "The issue is not simply one concerning China. There are other potential areas of litigation… The Indian Government has proposed a ban on iron ore exports to conserve ore for India's own industrial needs. Russian timber and Indian chromite tell a similar story" (Lim and Senduk 2013). Most recently, the Indonesian government banned the export of nickel ores starting in January 2014, prompting Japan to consider raising the issue with the WTO. Jakarta cited the desire to increase indigenous refining and smelting capacities to increase export value (Mao 2014 and Asmarini and Taylor 2014).

The OECD research cites several reasons why developing economies might resort to export restriction. These include the desire to spur development of its manufacturing sector through subsidies, the development of its raw materials and ore refining and processing capacities, the preservation of its natural resources for future domestic consumption, and a desire for better environmental conservation. Table Appendix C.1.1 lists some other cited reasons for export restrictions according to a review of Trade Policy Review (TPR) country reports by the OECD.

[211] According to an OECD analysis, "There is no single GATT/WTO article dealing exclusively with export restrictions." While quantitative restricting (imports and exports) is generally prohibited under Article XI of GATT 1994 while there is no binding agreement on export duties. Precedent rulings do acknowledge that high exports duties are tantamount to quantitative restrictions, in principle, export duties are generally allowed. Exceptions are made to quantitative restrictions under Articles XI:2, XX, XXI, that is, for reasons under critical food shortages, general exceptions, and security exception. Given the ambiguity surrounding the issue, there is much room for interpretation and abuse of export restriction clauses (Kim 2010).

Lim and Senduk (2013) offer an extensive review of GATT-WTO jurisprudence governing export restrictions leading to the 2011-2012 Chinese raw material case WTO ruling. Their analysis contextualizes Chinese export restrictions within the larger shift in global trade dynamics, from one that has traditionally focused on dismantling import restrictions (and one where export restrictions were readily justified on grounds of national security during the Cold War), to a brave new landscape defined by frictions over the merits of whether and how to regulate export restrictions. They write:

> As a result of China's and Asia's rising demand for energy and raw materials, industrial rivalry, and growing demand for adequate food supplies, the WTO is heading into uncharted waters. As free trade became more widely accepted, the problem has become less about how even more trade can be achieved, and more about how the demand for commodities which it has helped facilitate can be met. The old national security-based understanding of export controls and restrictions, and its accompanying discourse, must cede to the present-day realities of unprecedented economic globalization (Lim and Senduk 2013).

In addition, the high profile of GATT Article XX in the China raw materials case (resource conservation and environmental protection) may be indicative of a larger friction between developed economies and developing peers—one where the former views the latter as a source of cheap raw materials whereas the latter considers itself a manufacture exporter rapidly climbing up the value-added ladder (Lim and Senduk 2013). How the WTO comes to resolve the ambiguity on export restrictions remain to be seen, particularly as the dispute parties await the panel's judgment on the rare earths suit. Lim and Senduk (2013) offer potential approaches to handling the export restriction question first by referencing regional free trade regimes such as NAFTA and EU. NAFTA generally prohibits export restrictions that lead to price discrimination (although it grants exceptions to Mexico) whereas the EU's prohibitions are much more stringent and uniform. The on-going discussions over the Trans-Pacific Partnership (TPP) Agreement might be another case where implementation of the non-price discrimination clause to export restrictions could potentially be introduced. In fact, all American post-NAFTA trade agreements have included price non-discrimination clauses. Other possible measures that are mentioned include tighter language on conservation and shortage exemption clauses and the application of anti-subsidy clauses in Article I among others (Lim and Senduk 2013).

TABLE APPENDIX C.1.1 – ILLUSTRATIVE LIST OF RATIONALES FOR EXPORT RESTRICTIONS IN TPRS

1. Export restrictions for non-economic reason: security

- The United Nations Security Council Resolutions (e.g., sanctions against particular countries)
- The Convention on Chemical Weapons
- The Treaty on Nuclear Non-Proliferation
- Multilateral export control arrangements (to prevent the spread of chemical and biological weapons); the Missile Technology Control Regime; the Nuclear Suppliers Group; the Zangger Committee (control of nuclear materials and related high technology); the Wassenaar Arrangement (control of exports of conventional weapons and dual use products)

2. Export restrictions for non-economic reason: life, public health, safety, and environmental reason

- The Basel Convention on the Transboundary Movement of Hazardous Waste and their Disposal
- The Convention on International Trade in Endangered Species of Fauna and Flora (CITES)
- The Montreal Protocol on Substances that Deplete the Ozone Layer

3. Export restrictions for economic reasons but in accordance with international or bilateral agreements or

arrangements

- International commodities agreements on sugar, coffee, and petroleum

4. Export restrictions for maintenance of adequate supply of essential products; or for promotion of downstream industries

- Forestry products (such as log and timber)
- Fishery products (including seasonable restraint for a biological rest period of fish)
- Mineral products, metals, precious stones
- Hides and skins and leather
- Agricultural products (seasonal measures are introduced in some cases)

Source: Kim (2010)

Appendix D – DoE Technology Readiness Level (TRL) Scale

Relative Level of Technology Development	TRL	TRL Definition	Description
Basic Technology Research	1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.
Research to Prove Feasibility	2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
	3	Analytical and experimental critical function and/or characteristic proof of concept	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
Technology Development	4	Component and/or system validation in laboratory environment	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
	5	Laboratory scale, similar system validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.
Technology Demonstration	6	Engineering/pilot-scale, simlar (prototypical) system validation in a relevant environment	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.
System Commissioning	7	Full-scale, similar (prototypical) system demonstrated in a relevant environment	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an air-craft, in a vehicle, or in space).
	8	Actual system completed and qualified through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.
System Operations	9	Actual system operated over the full range of expected conditions	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.

Source: DoE (2011)

Appendix E – DoE Commercial Readiness Level (CRL) Scale

CRL	Description
1	Knowledge of applications, use-cases, & market constraints is limited and incidental, or has yet to be obtained at all.
2	A cursory familiarity with potential applications, markets, and existing competitive technologies/products exists. Market research is derived primarily from secondary sources. Product ideas based on the new technology may exist, but are speculative and unvalidated.
3	A more developed understanding of potential applications, technology use-cases, market requirements/constraints, and a familiarity with competitive technologies and products allows for initial consideration of the technology as product. One or more "strawman" product hypotheses are created, and may be iteratively refined based on data from further technology and market analysis. Commercialization analysis incorporates a stronger dependence on primary research and considers not only current market realities but also expected future requirements.
4	A primary product hypothesis is identified and refined through additional technology-product-market analysis and discussions with potential customers and/or users. Mapping technology/product attributes against market needs highlights a clear value proposition. A basic cost-performance model is created to support the value proposition and provide initial insight into design trade-offs. Basic competitive analysis is carried out to illustrate unique features and advantages of technology. Potential suppliers, partners, and customers are identified and mapped in an initial value-chain analysis. Any certification or regulatory requirements for product or process are identified.
5	A deep understanding of the target application and market is achieved, and the product is defined. A comprehensive cost-performance model is created to further validate the value proposition and provide a detailed understanding of product design trade-offs. Relationships are established with potential suppliers, partners, and customers, all of whom are now engaged in providing input on market requirements and product definition. A comprehensive competitive analysis is carried out. A basic financial model is built with initial projections for near- and long-term sales, costs, revenue, margins, etc.
6	Market/customer needs and how those translate to product needs are defined and documented (e.g. in market and product requirements documents). Product design optimization is carried out considering detailed market and product requirements, cost/performance trade-offs, manufacturing trade-offs, etc. Partnerships are formed with key stakeholders across the value chain (e.g. suppliers, partners, customers). All certification and regulatory requirements for the product are well understood and appropriate steps for compliance are underway. Financial models continue to be refined.
7	Product design is complete. Supply and customer agreements are in place, and all stakeholders are engaged in product/process qualifications. All necessary certifications and/or regulatory compliance for product and production operations are accommodated. Comprehensive financial models and projections have been built and validated for early stage and late stage production.
8	Customer qualifications are complete, and initial products are manufactured and sold. Commercialization readiness continues to mature to support larger scale production and sales. Assumptions are continually and iteratively validated to accommodate market dynamics.
9	Widespread deployment is achieved.

Source: DoE (2012)

Appendix F – Complete R&D^3 Level Descriptions and Probabilities of Success

Level I

Probability of Success in "Normal" R&D Effort 99%

A very low degree of difficulty is anticipated in achieving research and development objectives for this technology (including both the system concept, as well as performance, reliability and cost goals). Only a single, short-duration technological approach needed to be assured of a high probability of success in achieving technical objectives in later systems applications.

For example, a simple interpolation of an existing capability (e.g., an RF device at a new frequency, but one that is bracketed by the frequencies of past devices) or a modest extrapolation (e.g., a new engine at a thrust of N lbs, where an existing engine exists at a thrust of N/2 lbs for the same propellant and with similar other performance/cost goals).

Level II

Probability of Success in "Normal" R&D Effort 90%

A moderate degree of difficulty should be anticipated in achieving R&D objectives for this technology. A single technological approach will probably be sufficient; however, this R&D should be conducted early to allow an alternate approach to be pursued if needed in order to be assured of a high probability of success in achieving technical objectives in later systems applications.

For example, a significant, but not extreme extrapolation from some existing capability (e.g., an RF device at a new frequency that is significantly different from current frequencies in use, but which should be achievable with devices similar to those already in use) or a modestly new capability (e.g., a new engine that is somewhat reusable — say a few firings— with some degree of integrated health management, where an existing engine exists that is expendable for the same propellant and with similar other performance goals).

Level III

Probability of Success in "Normal" R&D Effort 80%

A high degree of difficulty could be anticipated in achieving R&D objectives for this technology. At least two technological approaches will probably be needed and these efforts should be conducted early enough to allow an alternate subsystem approach to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications.

For example, a very significant extrapolation from some existing capability (e.g., an RF device at a new frequency that is quite different — e.g., a factor of 5 — from current frequencies in use, and requires new RF devices, possibly operating on different physical principals from those already in use) or a significantly new capability (e.g., a new engine that is very reusable — say a 10s of firings — with a high

degree of integrated health management, where the existing engine is expendable, possibly with a different propellant, but still with similar other performance goals).

Level IV

Probability of Success in "Normal" R&D Effort 50%

A very high degree of difficulty should be anticipated in achieving R&D objectives for this technology. Multiple technological approaches need to be pursued. These activities should be conducted early enough to allow an alternate system concept to be pursued in order to allow managers to be assured of a high probability of success in achieving technical objectives in later systems applications.

For example, a dramatic extrapolation from some existing capability (e.g., an RF device at a very different frequency — e.g., factors of 10 — than those in use, and requiring completely new RF devices, operating on different physical principals from those already in use, as well as various other new subsystems/component technologies, such as heat rejection) or a significantly new capability (e.g., a new engine that is air breathing as well as very highly reusable — say a 100s of firings — with a very high degree of integrated health management, where the existing engines are expendable rockets, possibly with different propellants, and with other different performance goals).

Level V

Probability of Success in "Normal" R&D Effort 10%-20%

The degree of difficulty should be anticipated in achieving R&D objectives for this technology is so high that a fundamental breakthrough in physics/chemistry/etc. is needed. Basic research in key areas needed before feasible system concepts can be refined.

Source: Mankins (1998)

Appendix G – Selected Legislative Activity

Note: The following is a faithful reproduction of an extensive compilation of legislative activities in the Appendix of Grasso (2013).

Members of Congress have introduced rare-earth related bills during the 112th and 111th Congresses. Selected measures related to national defense issues are described below.

Legislation Introduced in the 112th Congress

P.L. 112-239 (H.R. 3310, 112th Congress), the National Defense Authorization Act for FY2013

H.R. 4310 was introduced on March 29, 2012, passed the House on May 18, 2012, and referred to the Senate Armed Services Committee on June 19, 2012. The bill has several rare earth-related provisions, as described below.

Section 901. Additional Duties of Deputy Assistant Secretary of Defense for Manufacturing and Industrial Base Policy and Amendments to the Strategic Materials Protection.

- Appoints Assistant Deputy Secretary of Defense for Manufacturing and Industrial Base Policy as Chair of the Strategic Materials Protection Board Chair;
- Requires that Board's findings be reviewed by the Secretary of Defense, congressional defense committees of Congress, and published in the Federal Register within 90 days of the Board meeting;
- Broadens the scope of duties assigned to the Office of the Assistant Deputy Secretary of Defense for Manufacturing and Industrial Base Policy to better provide oversight of the defense supply chain, including contractors and strategic materials, to ensure that there are no supply chain vulnerabilities regarding the nation's defense requirements;
- Specifically, "ensuring reliable sources of materials critical to national security, such as specialty metals, armor plate, and rare earth elements."[212]

Section 1603. National Security Strategy for National Technology and the Industrial Base.

- Requires the Secretary of Defense to develop a national security strategy for the national technology and industrial base, based on a prioritized assessment of risks and challenges to the defense supply chain, and ensuring that the national technology and industrial base is capable of achieving certain national security objectives;
- Ensuring reliable sources of materials critical to national security, such as specialty metals, armor plates and rare earth elements;

[212] H.R. 4310, Section 901, (c), (16)

- Reducing both the presence and risk of counterfeit parts in the supply chain.[213]

S. 3254, the proposed National Defense Authorization Act for FY2013, was introduced on June 4, 2012, and referred to the Senate Armed Services Committee. While the enacted bill[214] did not include a provision on rare earths, Senate Rept. 112-173 contained a statement that reflected the Committee's view on the role of rare earth materials for defense purposes, as repeated here.[215]

Essential role of rare earth materials

> Rare earth materials play an essential role in several critical weapons components and systems such as precision-guided munitions, electric ship drives, command and control centers, and aircraft, tanks, and missile systems. The committee notes the predominance of unreliable foreign sources for rare earth materials, including China, which provides roughly 94 percent of the world's rare earth oxides and nearly all rare earth metal within the defense- related supply chain and which has repeatedly decreased export quotas and imposed embargoes of these critical materials. Even with the development of the domestic-supply chain there may be continued reliance on production of certain heavy rare earth elements from China. The importance of rare earth materials for national defense applications necessitates a thorough understanding of vulnerabilities in the rare earth supply chain and the development of pragmatic, actionable risk mitigation plans to reduce the likelihood of supply interruptions. The committee encourages the Department of Defense to carefully consider the role of U.S. producers and potential means to develop reliable domestic sources to meet Department rare earth materials requirements.[216]

P.L. 111-393, the Ike Skelton National Defense Authorization Act for FY2011

Section 843 of the Ike Skelton National Defense Authorization Act for FY2011 (P.L. 111-383) and S.Rept. 111-201 (accompanying S. 3454, the proposed Senate National Defense Authorization Act for FY2011) required the Secretary of Defense to conduct an assessment of rare earth supply chain issues and develop a plan to address any vulnerabilities.

Section 843

Section 843 required the Secretary of Defense, within 180 days of enactment of the act,[217] to report to Congress with an assessment of the supply and demand for rare earth materials in defense applications. The assessment would identify whether any rare earth materials would be:

> (1) Critical to the production, sustainment, or operation of significant United States military equipment; or
>
> (2) Subject to interruption of supply, based on actions or events outside the control of the Government of the United States.[218]

[213] H.R. 4310, Section 1604, (9), (10)
[214] P.L. 112-239 was enacted into law, January 2, 2013.
[215] Items of Special Interest, S.Rept.112-173.
[216] Ibid.
[217] P.L. 111-83 was signed into law on January 7, 2011. Thus, the DoD report would have come due on or around July 7, 2011.
[218] Section 343, P.L. 111-83.

For every rare earth material identified that would meet these criteria, the Secretary of Defense would develop a plan for the long-term availability of such materials with the goal of establishing "an assured source of supply of such material in critical defense applications by December 31, 2015." The plan would consider the following:

> (1) An assessment of whether the material should be included in the National Defense Stockpile;
>
> (2) in consultation with the United States Trade Representative, the identification of any trade practices known to the Secretary that limit the Secretary's ability to ensure the long- term availability of such material or the ability to meet the goal of establishing an assured source of supply of such material by December 31, 2015;
>
> (3) An assessment of the availability of financing to industry, academic institutions, or not- for-profit entities to provide the capacity required to ensure the availability of the material, as well as potential mechanisms to increase the availability of such financing;
>
> (4) An assessment of the benefits, if any, of Defense Production Act funding to support the establishment of an assured source of supply for military components;
>
> (5) An assessment of funding for research and development
>
> (6) Any other risk mitigation method determined appropriate by the Secretary that is consistent with the goal of establishing an assured source of supply by December 31, 2015; and,
>
> (7) For steps of the rare earth material supply chain for which no other risk mitigation method, as described in paragraphs (1) through (6), will ensure an assured source of supply by December 31, 2015, a specific plan to eliminate supply chain vulnerability by the earliest date practicable.

H.R. 4402, the National Strategic and Critical Minerals Production Act

H.R. 4402, the National Strategic and Critical Minerals Production Act of 2012, was introduced on Apri19, 2012, passed the House on July 12, 2012, and was referred to the Senate on July 16, 2012. The bill would have required both the Secretary of the Interior and the Secretary of Agriculture to more efficiently develop domestic sources of the minerals and materials of strategic and critical importance to U.S. economic and national security, and manufacturing competitiveness.[219]

H.R. 3449, Defense Supply Chain and Industrial Base Security Act

H.R. 3449 was introduced by Representative Paul Ryan on November 16, 2011, and referred to the House Armed Services Committee. The bill would have required the Secretary of Defense to develop a defense supply chain and industrial base strategy, and subsequent plan, designed to secure the supply chain and industrial base sectors that the Secretary judges critical to U.S. national security.

[219] H.R. 4402

H.R. 2184, Rare Earth Policy Task Force and Materials Act

H.R. 2184 was introduced by Representative Mike Coffman on June 15, 2011. The bill would establish a Rare Earth Policy Task Force for a period of 10 years within the Department of the Interior for the purpose of developing a plan to ensure the long-term supply of rare earth materials.[220] The Task Force would be directed to assist federal agencies in reviewing laws, regulations, and policies that discourage investment in, exploration for, and development of, domestic rare earths. The Task Force would also be required to submit an annual report that would provide a plan for research, development, demonstration, and commercial application to ensure the long-term, secure, and sustainable supply of rare earth materials sufficient to satisfy the national security, economic well-being, and industrial production needs of the United States (based on specific criteria). The bill was referred to the Committee on Natural Resources and to the Committee on Science, Space, and Technology.

H.R. 2090, Energy Critical Elements Advancement Act of 2011

H.R. 2090 was introduced by Representative Randy Hultgren on June 2, 2011, and was referred to the Subcommittee on Energy and the Environment. The bill would require the Secretaries of Energy and Interior to establish a research program to advance basic materials science, chemistry, physics, and engineering associated with energy critical elements.

H.R. 2011, National Strategic and Critical Minerals Policy Act of 2011

H.R. 2011 was introduced on May 26, 2011, by Representative Doug Lamborn and referred to the House Committee on Natural Resources, Subcommittee on Energy and Mineral Resources. On July 20, 2011, the committee ordered the bill to be reported, as amended. On October 14, 2011, the bill was amended by the Committee on Natural Resources and placed on the Union Calendar.

The bill would require the Secretary of the Interior to (1) conduct an assessment of the United States' capability to meet current and future demands for the minerals critical to domestic manufacturing competitiveness, economic, and national security in a time of expanding resource nationalism; (2) conduct an assessment of the current mineral potential of federal lands, and an evaluation of mineral requirements to meet current and emerging needs for economic and national security, and U.S. industrial manufacturing needs (such an assessment would address the implications of any potential mineral shortages or supply disruptions, as well as the potential impact of U.S. dependence on foreign sources for any minerals); and (3) conduct an inventory of rare earth elements and other minerals deemed critical based on the potential for supply disruptions, including an analysis of the supply chain for each mineral.

Finally, the bill would set policy goals for federal agencies to coordinate responsibilities for:

- facilitating the availability, development, and production of domestic mineral resources to meet national needs;

[220] The Task Force would be chaired by the Secretary of the Interior and would include the Secretaries (or a designee of each Secretary) of Energy, Agriculture, Defense, Commerce and State. Other members would include the Director of the Office of Management and Budget, the Chairman of the Council on Environmental Quality.

• promoting the development of economically sound and stable policies for domestic industries that promote mining, materials, and metals processing;

• creating a mechanism for assessing the U.S. mineral demand, supply, and needs; and

• minimizing duplication and delays in administering federal and state laws, regulations, and permit issuance and authorizations necessary to explore, develop, and produce minerals, and build and operate mineral-related facilities.[221]

H.R. 2284, Responsible Electronic Recycling Act

H.R. 2284 was introduced by Representative Gene Green on June 22, 2011, and on June 29 was referred to the Subcommittee on Energy and the Environment. This bill would include the establishment of a Rare Earth Materials Recycling Initiative, designed to assist in and coordinate the development of research in the recycling of rare earth materials found in electronic devices.

H.R. 1875, Building Our Clean Energy Future Now Act of 2011

H.R. 1875 was introduced by Representative David Cicilline on May 12, 2011, and referred to the House Committees on Ways and Means, Transportation and Infrastructure, Energy and Commerce, and Science, Space, and Technology. On May 26, 2011, the bill was referred to the Subcommittee on Energy and Environment. The bill seeks to lower gas prices by making investments in cleaner energy technologies and infrastructure.

H.R. 1388, the Rare Earths Supply Chain Technology and Resources Transformation Act of 2011.

H.R. 1388 was introduced by Representative Mike Coffman on May 6, 2011, and referred to the House Committee on Science, Space, and Technology, Subcommittee on Energy and the Environment, and the Committees on Natural Resources and Armed Services. The bill is also referred to as the Restart Act of 2011. The bill seeks to reestablish a competitive domestic rare earths supply chain within DoD's Defense Logistics Agency (DLA).

H.R. 1540, the National Defense Authorization Act for FY2012

H.R. 1540 was introduced by Representative Howard McKeon on April 14, 2011. Section 835 would require the DLA Administrator for Strategic Materials to develop an inventory of rare earth materials to support defense requirements, as identified by the report required by Section 843 of the Ike Skelton National Defense Authorization Act for FY2011 (P.L. 111-383). Also, Amendment #87 to H.R. 1540

[221] H.R. 2011, Section 3. Congressional Declaration of Policy

would require the Secretary of Defense to report back to Congress on the feasibility and desirability of recycling, recovering, and reprocessing rare earth elements, including fluorescent lighting used in DoD facilities. H.R. 1540 (H.Rept. 112-78) passed the House, May 26, 2011. On June 6, 2011, it was received in the Senate and referred to the Senate Committee on Armed Services.

S. 734, the Advanced Vehicle Technology Act of 2011

S. 734 was introduced by Senator Debbie Stabenow on April 5, 2011, and referred to the Committee on Natural Resources. The proposed bill would create a basic and applied research program, within the Department of Energy (DoE), focused on the development and engineering of new vehicle technologies. DoE is to promote, among many other goals, the exploration of substitutes and recycling of potential critical materials, including rare earth elements and precious metals. The Senate Committee on Energy and Natural Resources held a hearing on May 19, 2011.

H.R. 1367, the Advanced Vehicle Technology Act of 2011

H.R. 1367 was introduced by Representative Gary Peters on April 5, 2011, and referred to the Committee on Science, Space and Technology. On April 7, 2011, the bill was referred to the Subcommittee on Energy and Environment. S. 734 and H.R. 1367 are similar.

H.R. 1314, the Resource Assessment of Rare Earths (RARE) Act of 2011

H.R. 1314 was introduced by Representative Henry Johnson on April 1, 2011, and on April 6 was referred to the House Natural Resources Committee, Subcommittee on Energy and Mineral Resources. The bill would direct the Secretary of the Interior, through the Director of the U.S. Geological Survey, to examine the need for future geological research on rare earth elements and other minerals and determine the criticality and impact of a potential supply restriction or vulnerability.

H.R. 952, the Energy Critical Elements Renewal Act of 2011

On March 8, 2011, Representative Brad Miller introduced the Energy Critical Elements Renewal Act of 2011. The bill was referred to the Committee on Science, Space, and Technology. The bill would develop an energy critical elements program, amend the National Materials and Minerals Policy Research and Development Act of 1980, establish a temporary program for rare earth material revitalization, and serve other purposes.

S. 383, the Critical Minerals and Materials Promotion Act of 2011

On February 17, 2011, Senator Mark Udall introduced the Critical Minerals and Materials Promotion Act of 2011. One June 9, 2011, the bill was referred to the Committee on Energy and Natural Resources, Subcommittee on Energy. The bill was referred to the Committee on Energy and Natural Resources. The

bill would require the Secretary of the Interior to establish a scientific research and analysis program to assess current and future critical mineral and materials supply chains, strengthen the domestic critical minerals and materials supply chain for clean energy technologies, strengthen education and training in mineral and material science and engineering for critical minerals and materials production, and establish a domestic policy to promote an adequate and stable supply of critical minerals and materials necessary to maintain national security, economic well-being, and industrial production with appropriate attention to a long-term balance between resource production, energy use, a healthy environment, natural resources conservation, and social needs.[222]

H.R. 618, the Rare Earths and Critical Materials Revitalization Act of 2011

On February 10, 2011, Representative Leonard Boswell introduced the Rare Earths and Critical Materials Revitalization Act of 2011. The bill was referred to the Committee on Science, Space, and Technology.

The bill seeks to develop a rare earth materials program and amend the National Materials and Minerals Policy, Research and Development Act of 1980. If enacted, it would provide for loan guarantees to revitalize domestic production of rare earths in the United States.

S. 1113, the Critical Minerals Policy Act of 2011

On May 26, 2011, Senator Lisa Murkowski introduced the Critical Minerals Policy Act of 2011, which was referred to the Committee on Energy and Natural Resources. On June 9, 2011, the Subcommittee on Energy held a hearing. The bill generally defines what critical minerals are but would request that the Secretary of the Interior establish a methodology (in consultation with others) that would identify which minerals qualify as critical. The Secretary of the Interior would direct a comprehensive resource assessment of critical mineral potential in the United States, including details on the critical mineral potential on federal lands. S. 1113 would establish a Critical Minerals Working Group to examine the permitting process for mineral development in the United States and facilitate a more efficient process, specifically, a draft performance metric for permitting mineral development and report on the timeline of each phase of the process. The DOI would produce an Annual Critical Minerals Outlook report that would provide forecasts of domestic supply, demand, and price for up to 10 years. DoE would lead research and development on critical minerals and workforce development that would support a fully integrated supply chain in the United States. Title II of the bill recommends mineral-specific action (led by DoE) for cobalt, helium, lead, lithium, low-btu gas, phosphate, potash rare earth elements, and thorium. Title III would, among other things, authorize for appropriation $106 million.

Legislation Introduced in the 111th Congress

In the 111th Congress, two bills were enacted that contain provisions affecting rare earth policy. The first was P.L. 111-84 (H.R. 2647), the National Defense Authorization Act for FY2010. Section 843 of P.L.

[222] S. 383, Section 6, Supply of Critical Minerals and Materials.

111-84 required GAO to examine rare earths in the defense supply chain, and it also required the Secretary of Defense to assess the defense supply chain and develop a plan to address any shortfalls or other supply chain vulnerabilities.[223] The second bill was P.L. 111-383, the Ike Skelton National Defense Authorization Act for FY2011, which contains a provision (Section 843) that requires the Secretary of Defense to undertake an assessment of the supply chain for rare earth materials and determine which, if any, rare earths are strategic or critical to national security and to develop a plan to address any supply chain vulnerabilities.[224] Other legislative provisions are listed below.

H.R. 4866, the Rare Earths Supply-Chain Technology and Resources Transformation Act of 2010

On March 17, 2010, Representative Mike Coffman introduced the Rare Earths Supply-Chain Technology and Resources Transformation Act of 2010 (RESTART). The bill was referred to three committees: the House Armed Services Committee, the House Ways and Means Subcommittee on Trade, and the House Financial Services Committee.

The bill sought to create a new interagency initiative on rare earth supply chain issues. H.R. 4866 would have established a federal government-wide interagency working group, at the Assistant Secretary level, from the Departments of Commerce, Defense, Energy, the Interior, and State, with participants from the U.S. Trade Representative (USTR) and White House Office of Science and Technology Policy. The working group would have assessed the rare earth supply chain to determine which rare earths were critical to national and economic security. Based on a critical designation, rare earth elements would have been stockpiled by the Defense Logistics Agency (DLA) as part of the National Defense Stockpile. The DLA would have made, if necessary, a commitment to purchase rare earth raw materials for processing and refining, including purchases from China. Stockpiling would have been terminated when the working group agencies determined that rare earths were no longer critical to U.S. national security or economic well- being.[225]

[223] P.L. 111-84 was signed into law on October 28, 2009

[224] It should be pointed out that much of the language of the RESTART Act, proposed by Representative Mike Coffman, was included as an amendment to the FY2011 Ike Skelton National Defense Authorization Act, which was passed in the House on May 28, 2010, during the 111th Congress.

[225] The bill directs the Secretaries of Commerce, of Defense, of Energy, of the Interior, and of State to (1) appoint an Executive Agent, at the Assistant Secretary level, to serve as a representative on an interagency working group to reestablish a competitive domestic rare earth supply chain, and (2) assess and report to Congress on the chain, determining which rare earth elements are critical to national and economic security. It directs the United States Trade Representative (USTR) and the Office of Science and Technology Policy also to appoint representation to such working group. It requires the Secretary of Defense to commence procurement of critical rare earth materials and place them in a national stockpile, and the Defense Logistics Agency, Defense National Stockpile Center, to serve as administrator of the stockpile. It authorizes the administrator, if necessary to meet U.S. national security and economic needs, to purchase rare earth materials from the People's Republic of China. It instructs the USTR to (1) initiate and report to Congress on a comprehensive review of international trade practices in the rare earth materials market; or (2) initiate an action before the World Trade Organization (WTO) as a result of the review. It directs the Secretaries of Commerce, of the Interior, and of State to report to the domestic rare earth industry about mechanisms for obtaining government loan guarantees to reestablish a domestic rare earth supply chain. It directs the Secretaries of Defense and of Energy to issue guidance for the industry related to obtaining such loan guarantees. It expresses the sense of the Congress regarding a prioritization of Defense Production Act projects with respect to the domestic rare earth supply chain.

H.R. 6160, the Rare Earths and Critical Materials Revitalization Act of 2010

On September 22, 2010, Representative Kathleen Dahlkemper introduced the Rare Earths and Critical Materials Revitalization Act of 2010. The bill sought to develop a rare earth materials program and amend the National Materials and Minerals Policy, Research and Development Act of 1980. If enacted, the bill would have provided for loan guarantees to revitalize domestic production of rare earths in the United States. The bill was passed by the House on September 29, 2010, and forwarded to the Senate Committee on Energy and Natural Resources.

S. 3521, the Rare Earth Supply Technology and Resources Transformation Act of 2010

S. 3521 was introduced by Senator Lisa Murkowski on June 22, 2010. Congress held a hearing on the bill before the Senate Committee on Energy and Natural Resources, Subcommittee on Energy, on September 30, 2010. The text of the bill offered a "Sense of the Congress" statement that

> (1) the United States faces a shortage of key rare earth materials that form the backbone of both the defense and energy supply chains; (2) the urgent need to reestablish a domestic rare earth supply chain warrants a statutory prioritization of projects to support such reestablishment; (3) there is a pressing need to support innovation, training, and workforce development in the domestic rare earth supply chain; and (4) the Departments of Energy, of the Interior, of Commerce, and of Defense should each provide funds to academic institutions, federal laboratories, and private entities for innovation, training, and workforce development in the domestic rare earth supply chain.

S. 4031, the Rare Earths Supply-Chain Technology and Resources Transformation Act of 2010

S. 4031 was introduced by then-Senator Evan Bayh on December 15, 2010, and referred to the Senate Committee on Energy and Natural Resources. The bill would have promoted exploration and development of a domestic supply of rare earths, and reestablished a U.S. competitive rare earth supply chain for rare earths in the United States and in the countries of foreign allies.

Source: Grasso (2013)

Appendix H – H.R. 3304 FY2014 NDAA Excerpts

Subtitle B--National Defense Stockpile

SEC. 1411. USE OF NATIONAL DEFENSE STOCKPILE FOR THE CONSERVATION OF A STRATEGIC AND CRITICAL MATERIALS SUPPLY.

(a) Presidential Responsibility for Conservation of Stockpile Materials.--Section 6(a) of the Strategic and Critical Materials Stock Piling Act (50 U.S.C. 98e(a)) is amended--

(1) by redesignating paragraphs (5) and (6) as paragraphs (6) and (7), respectively; and

(2) by inserting after paragraph (4) the following new paragraph (5): "(5) provide for the appropriate recovery of any strategic and critical materials under section 3(a) that may be available from excess materials made available for recovery purposes by other Federal agencies;".

(b) Uses of National Defense Stockpile Transaction Fund.--Section 9(b)(2) of such Act (50 U.S.C. 98h(b)(2)) is amended--

(1) by redesignating subparagraphs (D) through (L) as subparagraphs (E) through (M), respectively; and

(2) by inserting after subparagraph (C) the following new subparagraph (D): "(D) Encouraging the appropriate conservation of strategic and critical materials.".

(c) Development of Domestic Sources.--Section 15(a) of such Act (50 U.S.C. 98h-6(a)) is amended, in the matter preceding paragraph (1), by inserting ``and appropriate conservation'' after ``development''.

SEC. 1412. AUTHORITY TO ACQUIRE ADDITIONAL MATERIALS FOR THE NATIONAL DEFENSE STOCKPILE.

(a) Acquisition Authority.--Using funds available in the National Defense Stockpile Transaction Fund, the National Defense Stockpile Manager may acquire the following materials determined to be strategic and critical materials required to meet the defense, industrial, and essential civilian needs of the United States:

(1) Ferroniobium.

(2) Dysprosium Metal.

(3) Yttrium Oxide.

(4) Cadmium Zinc Tellurium Substrate Materials.

(5) Lithium Ion Precursors.

(6) Triamino-Trinitrobenzene and Insensitive High Explosive Molding Powders.

(b) Amount of Authority.--The National Defense Stockpile Manager may use up to $41,000,000 of the National Stockpile Transaction Fund for acquisition of the materials specified in subsection (a).

(c) Fiscal Year Limitation.--The authority under this section is available for purchases during fiscal year 2014 through fiscal year 2019.

Source: Public Law 113-66

Appendix I – H.R. 761 National Strategic and Critical Minerals Production Act of 2013

TITLE I—DEVELOPMENT OF DOMESTIC SOURCES OF STRATEGIC AND CRITICAL MINERALS

SEC. 101. IMPROVING DEVELOPMENT OF STRATEGIC AND CRITICAL MINERALS.

Domestic mines that will provide strategic and critical minerals shall be considered an "infrastructure project" as described in Presidential Order "Improving Performance of Federal Permitting and Review of Infrastructure Projects" dated March 22, 2012.

SEC. 102. RESPONSIBILITIES OF THE LEAD AGENCY.

(a) In General.—The lead agency with responsibility for issuing a mineral exploration or mine permit shall appoint a project lead who shall coordinate and consult with cooperating agencies and any other agency involved in the permitting process, project proponents and contractors to ensure that agencies minimize delays, set and adhere to timelines and schedules for completion of the permitting process, set clear permitting goals and track progress against those goals.

(b) Determination Under NEPA.—To the extent that the National Environmental Policy Act of 1969 applies to any mineral exploration or mine permit, the lead agency with responsibility for issuing a mineral exploration or mine permit shall determine that the action to approve the exploration or mine permit does not constitute a major Federal action significantly affecting the quality of the human environment within the meaning of the National Environmental Policy Act of 1969 if the procedural and substantive safeguards of the permitting process alone, any applicable State permitting process alone, or a combination of the two processes together provide an adequate mechanism to ensure that environmental factors are taken into account.

(c) Coordination On Permitting Process.—The lead agency with responsibility for issuing a mineral exploration or mine permit shall enhance government coordination for the permitting process by avoiding duplicative reviews, minimizing paperwork and engaging other agencies and stakeholders early in the process. The lead agency shall consider the following best practices:

(1) Deferring to and relying upon baseline data, analyses and reviews performed by State agencies with jurisdiction over the proposed project.

(2) Conducting any consultations or reviews concurrently rather than sequentially to the extent practicable and when such concurrent review will expedite rather than delay a decision.

(d) Schedule For Permitting Process.—At the request of a project proponent, the lead agency, cooperating agencies and any other agencies involved with the mineral exploration or mine permitting process shall enter into an agreement with the project proponent that sets time limits for each part of the permitting process including the following:

(1) The decision on whether to prepare a document required under the National Environmental Policy Act of 1969.

(2) A determination of the scope of any document required under the National Environmental Policy Act of 1969.

(3) The scope of and schedule for the baseline studies required to prepare a document required under the National Environmental Policy Act of 1969.

(4) Preparation of any draft document required under the National Environmental Policy Act of 1969.

(5) Preparation of a final document required under the National Environmental Policy Act of 1969.

(6) Consultations required under applicable laws.

(7) Submission and review of any comments required under applicable law.

(8) Publication of any public notices required under applicable law.

(9) A final or any interim decisions.

(e) Time Limit For Permitting Process.—In no case should the total review process described in subsection (d) exceed 30 months unless agreed to by the signatories of the agreement.

(f) Limitation On Addressing Public Comments.—The lead agency is not required to address agency or public comments that were not submitted during any public comment periods or consultation periods provided during the permitting process or as otherwise required by law.

(g) Financial Assurance.—The lead agency will determine the amount of financial assurance for reclamation of a mineral exploration or mining site, which must cover the estimated cost if the lead agency were to contract with a third party to reclaim the operations according to the reclamation plan, including construction and maintenance costs for any treatment facilities necessary to meet Federal, State or tribal environmental standards.

(h) Application To Existing Permit Applications.—This section shall apply with respect to a mineral exploration or mine permit for which an application was submitted before the date of the enactment of this Act if the applicant for the permit submits a written request to the lead agency for the permit. The lead agency shall begin implementing this section with respect to such application within 30 days after receiving such written request.

(i) Strategic And Critical Minerals Within National Forests.—With respect to strategic and critical minerals within a federally administered unit of the National Forest System, the lead agency shall—

(1) exempt all areas of identified mineral resources in Land Use Designations, other than Non-Development Land Use Designations, in existence as of the date of the enactment of this Act

from the procedures detailed at and all rules promulgated under part 294 of title 36, Code for Federal Regulations;

(2) apply such exemption to all additional routes and areas that the lead agency finds necessary to facilitate the construction, operation, maintenance, and restoration of the areas of identified mineral resources described in paragraph (1); and

(3) continue to apply such exemptions after approval of the Minerals Plan of Operations for the unit of the National Forest System.

SEC. 103. CONSERVATION OF THE RESOURCE.

In evaluating and issuing any mineral exploration or mine permit, the priority of the lead agency shall be to maximize the development of the mineral resource, while mitigating environmental impacts, so that more of the mineral resource can be brought to the market place.

SEC. 104. FEDERAL REGISTER PROCESS FOR MINERAL EXPLORATION AND MINING PROJECTS.

(a) Preparation Of Federal Notices For Mineral Exploration And Mine Development Projects.—The preparation of Federal Register notices required by law associated with the issuance of a mineral exploration or mine permit shall be delegated to the organization level within the agency responsible for issuing the mineral exploration or mine permit. All Federal Register notices regarding official document availability, announcements of meetings, or notices of intent to undertake an action shall be originated and transmitted to the Federal Register from the office where documents are held, meetings are held, or the activity is initiated.

(b) Departmental Review Of Federal Register Notices For Mineral Exploration And Mining Projects.—Absent any extraordinary circumstance or except as otherwise required by any Act of Congress, each Federal Register notice described in subsection (a) shall undergo any required reviews within the Department of the Interior or the Department of Agriculture and be published in its final form in the Federal Register no later than 30 days after its initial preparation.

TITLE II—JUDICIAL REVIEW OF AGENCY ACTIONS RELATING TO EXPLORATION AND MINE PERMITS

SEC. 201. DEFINITIONS FOR TITLE.

In this title the term “covered civil action” means a civil action against the Federal Government containing a claim under section 702 of title 5, United States Code, regarding agency action affecting a mineral exploration or mine permit.

SEC. 202. TIMELY FILINGS.

A covered civil action is barred unless filed no later than the end of the 60-day period beginning on the date of the final Federal agency action to which it relates.

SEC. 203. RIGHT TO INTERVENE.

The holder of any mineral exploration or mine permit may intervene as of right in any covered civil action by a person affecting rights or obligations of the permit holder under the permit.

SEC. 204. EXPEDITION IN HEARING AND DETERMINING THE ACTION.

The court shall endeavor to hear and determine any covered civil action as expeditiously as possible.

SEC. 205. LIMITATION ON PROSPECTIVE RELIEF.

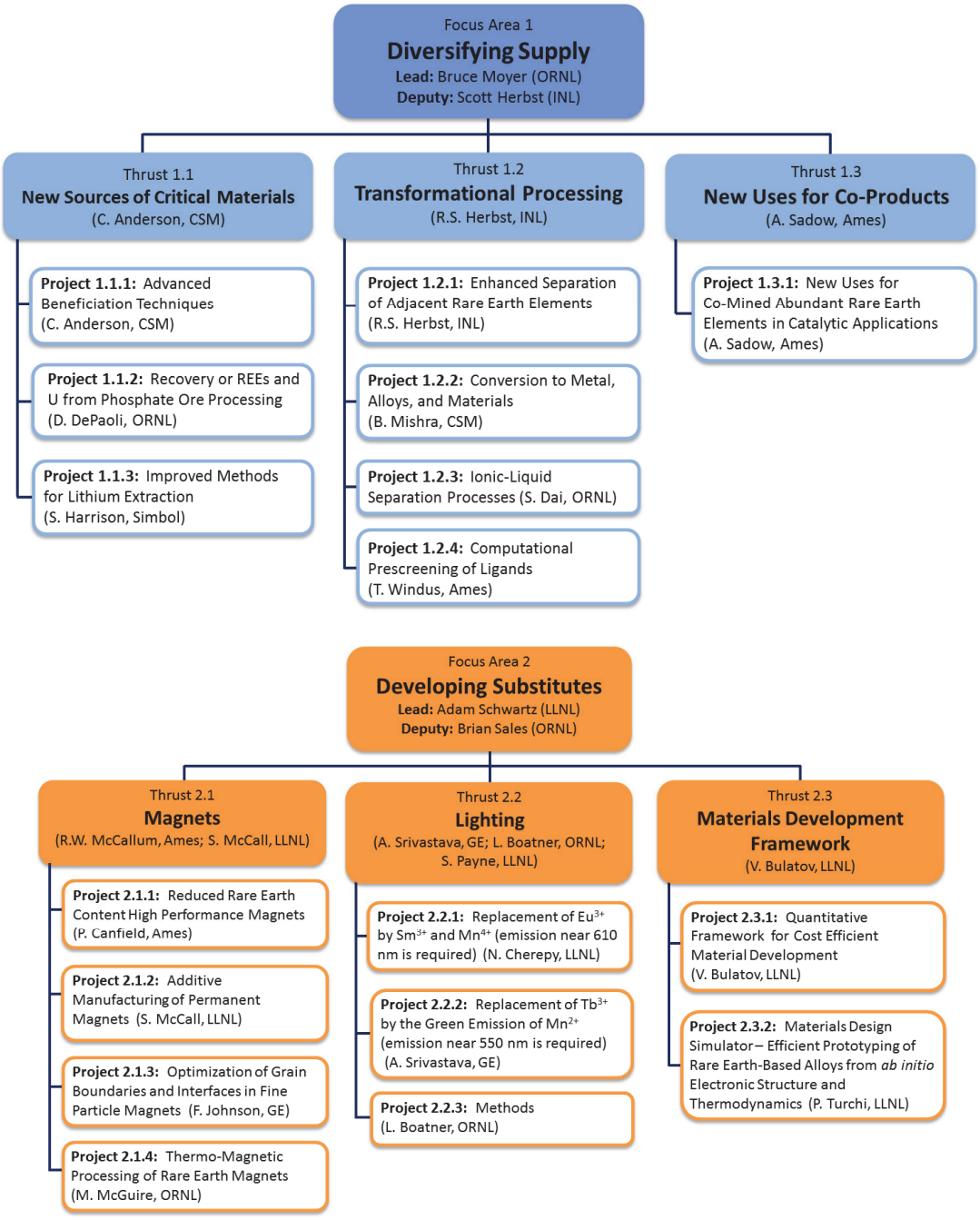
In a covered civil action, the court shall not grant or approve any prospective relief unless the court finds that such relief is narrowly drawn, extends no further than necessary to correct the violation of a legal requirement, and is the least intrusive means necessary to correct that violation.

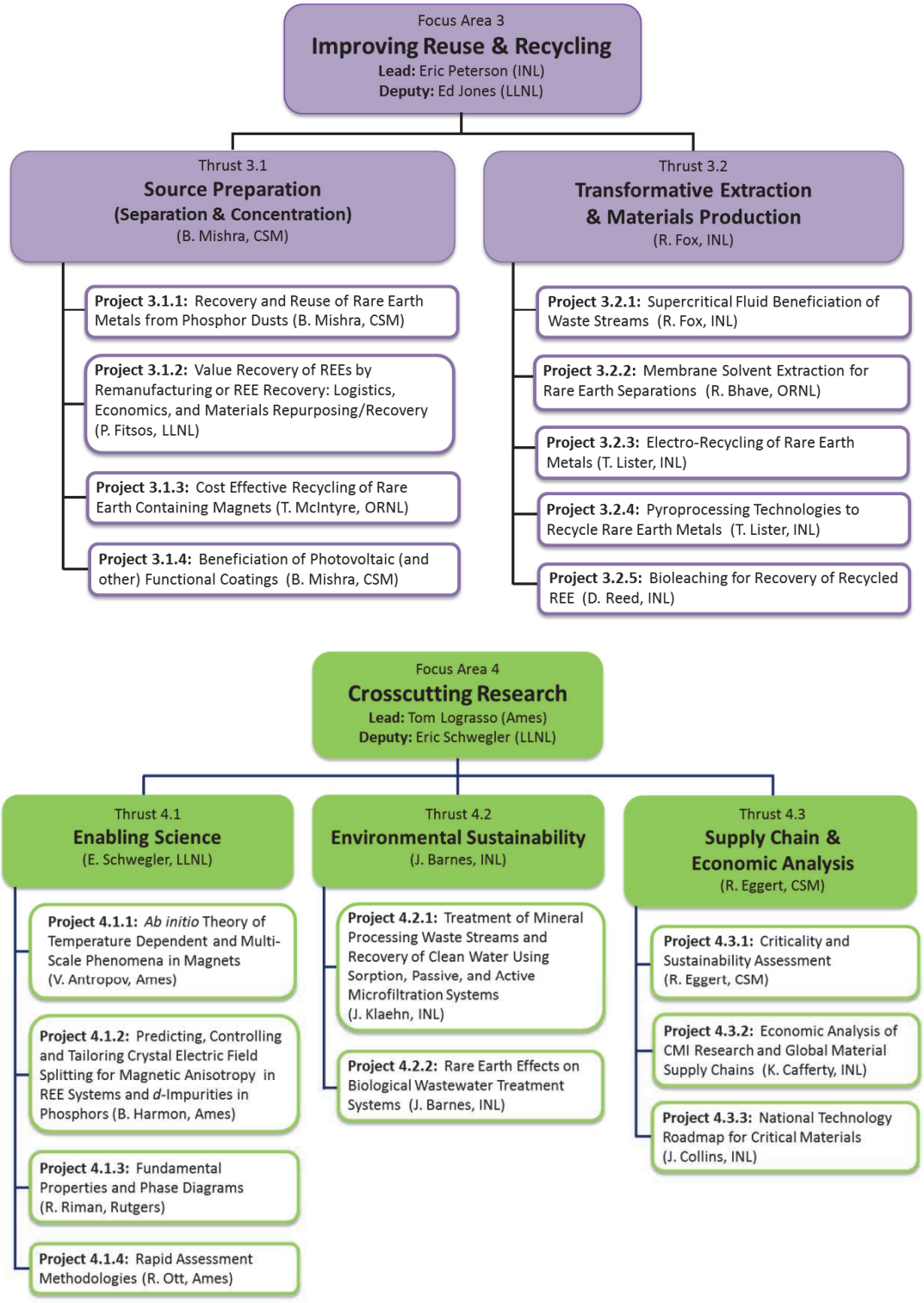
SEC. 206. LIMITATION ON ATTORNEYS' FEES.

Sections 504 of title 5, United States Code, and 2412 of title 28, United States Code (together commonly called the Equal Access to Justice Act) do not apply to a covered civil action, nor shall any party in such a covered civil action receive payment from the Federal Government for their attorneys' fees, expenses, and other court costs.

Source: National Strategic and Critical Minerals Production Act (2013)

Appendix J – CMI Research Focus Areas





Source: CMI (2014b)

Appendix K – CMI Research Publications

- Brajendra Mishra leads the Source Preparation (Separation and Concentration) thrust area in the Improving Reuse and Recycling focus area for CMI and is the primary investigator for two research projects -- Beneficiation of Photovoltaic (and other) Functional Coatings in this focus area, and the research project "Conversion to Metal, Alloys, and Materials" within the focus area Diversifying Supply thrust on transformational processing. Mishra has coauthored several papers recently, including "**Challenges of Recycling End-of-Life Rare Earth Magnets**" in the November 2013 issue of *JOM, The Journal of Minerals, Metals & Materials Society (TMS)*; ISSN 1047-4838, "**Fatigue crack growth simulations of interfacial cracks in bi-layered FGMs using XFEM**" in the October 2013 issue of *Computational Mechanics*, and "**Fatigue-life estimation of functionally graded materials using XFEM**" in the October 2013 *Engineering with Computers*.

- Michael McGuire and Brian Sales published several technical papers during 2013. Sales is the deputy lead for the focus area Developing Substitutes, and McGuire is the project lead for the project "Thermo-magnetic processing of rare earth magnets" in the thrust strong permanent magnets with reduced rare earth content. They are co-authors on four technical publications in 2013:

    - "**Magnetotransport properties of single-crystalline LaFeAsO**" in *Physical Review B* published Oct. 21, 2013

    - "**Doping dependence of the spin excitations in the Fe-based superconductors Fe1+yTe1-xSex**" in *Physical Review B* published June 12, 2013

    - "**Glass-like phonon scattering from a spontaneous nanostructure in AgSbTe2**" in *Nature Nanotechnology* published in June 2013

    - "**Effect of pressure, temperature, fluorine doping, and rare earth elements on the phonon density of states of LFeAsO studied by nuclear inelastistic scattering**" in *Physical Review B* published Feb. 25, 2013

- Within the diversifying supply focus area, Sheng Dai leads the project Ionic-Liquid Separation Processes in the transformational processing thrust, and David DePaoli leads the project Recovery of REEs and Uranium from Phosphate Ore Processing in new sources of critical materials thrust. They are co-authors of "**Influence of temperature on the electrosorption of ions from aqueous solutions using mesoporous carbon materials**" in *Separation and Purification Technology*, published Sept. 15, 2013, and "**Neutron imaging of ion transport in mesoporous carbon materials"** in *Physical Chemistry Chemical Physics*, volume 15, issue 28 published in 2013.

- Ryan Ott leads the project Rapid Assessment Methodologies in the Enabling Science thrust of the Crosscutting Research focus area. He is coauthor on "**Defecting twin boundaries in nanotwinned metals**" published in *Nature Materials* in August 2013.

- Bill McCallum leads the strong permanent magnets with reduced rare earth content thrust in the Developing Substitutes focus area, and Iver Anderson is involved in technology deployment for CMI. They were co-authors of "**Phase and Elemental Distributions in Alnico Magnetic Materials**" in *IEEE Transactions on Magnetics*published July 2013.

- Vladimir Antropov, leader for the project Ab initio Theory of Temperature Dependent and Multi-Scale Phenomena in Magnets within the focus area Croscutting Research and thrust of enabling science, is co-author of "**Atomic Structure and Magnetic Properties of HfCo7 Alloy**" in *IEEE Transactions on Magnetics* published July 2013.

- Bruce Harmon, leader for the project Predicting, Controlling and Tailoring Crystal Electric Field Splitting for Magnetic Anisotropy in REE Systems and D-Impurities in Phosphors within the focus area Croscutting Research and thrust of enabling science, is co-author of several recent technical publications:

    - "**Crystallographic, electronic, thermal, and magnetic properties of single-crystal SrCo2As2**" in *Physical Review B* published July 25, 2013.

    - "**Angle-resolved photoemission spectroscopy study of BaCo2As2**" in *Physical Review B* published June 21, 2013.

    - "**Magnetism-dependent phonon anomaly in LaFeAsO observed via inelastic x-ray scattering**" in *Physical Review B* published March 27, 2013.

- Richard Riman leads the Fundamental Properties and Phase Diagrams project in the Enabling Science thrust of the Crosscutting Research focus area. He is coathor of "**Rare-earth-doped biological composites as in vivo shortwave infrared reporters**," published in *Nature Communications* in July 2013 and "*Optoelectronic properties of graphene thin films deposited by a Lanmuir-Blodgett assembly*" in*Nanoscale* in 2013.

- Scott McCall leads the Additive Manufacturing of Permanent Magnets research project in the thrust strong permanent magnets with reduced rare earth content, in the focus area Developing Substitutes. He's a co-author of "**Shape-influenced magnetit properties of CoO nanoparticles**" in the *Journal of Nanoparticle Research*, May 2013, and "**Self-irradiation damage to the local structure of plutonium and plutonium intermetallics**" in the *Journal of Applied Physics* published March 7, 2013.

- Paul Canfield leads the Reduced Rare Earth Content High Performance Magnet project in the thrust strong permanent magnets with reduced rare earth content in the focus area Developing Substitutes. Canfield and CMI scientist Sergey Bud'ko are co-authors of "**A family of binary magnetic icosahedral quasicrystals based on rare earths and cadmium**" in *Nature Materials*, published August 2013, and "**Anisotropic impurity states, quasiparticle scattering and nematic transport in underdoped Ca(Fe1-xCox)(2)As-2**" in *Nature Physics* published in April 2013.

- Corby Anderson leads the New Sources of Critical Materials thrust in the Diversifying Supply focus area for CMI and is the primary investigator for the research project "Advanced Beneficiation Techniques," which includes researcher Patrick Taylor. They are co-authors for "**A**

Primer on Hydrometallurgical Rare Earth Separations" in the August 2013 issue of *JOM, The Journal of Minerals, Metals & Materials Society (TMS)*; ISSN 1047-4838

Source: CMI (2014c)

Appendix L – DMEA Trusted Foundry Program

DMEA is the program manager for the DoD Trusted Foundry program. The program provides a cost-effective means to assure the integrity and confidentiality of integrated circuits during design and manufacturing while providing the US Government with access to leading edge microelectronics technologies for both Trusted and non-sensitive applications.

Trusted – Is the confidence in one's ability to secure national security systems by assessing the integrity of the people and processes used to design, generate, manufacture and distribute national security critical components (i.e., microelectronics).

Within this context, "trusted sources" will:

- Provide an assured "Chain of Custody" for both classified and unclassified ICs.
- Ensure that there will not be any reasonable threats related to disruption in supply
- Prevent intentional or unintentional modification or tampering of the ICs and
- Protect the ICs from unauthorized attempts at reverse engineering, exposure of functionality or evaluation of their possible vulnerabilities.

DoD Instruction 5200.44, Protection of Mission Critical Functions to Achieve Trusted Systems and Networks (TSN) requires that;

"In applicable systems, integrated circuit-related products and services shall be procured from a trusted supplier accredited by the Defense Microelectronics Activity (DMEA) when they are custom-designed, custom-manufactured, or tailored for a specific DoD military end use (generally referred to as application-specific integrated circuits (ASICs))."

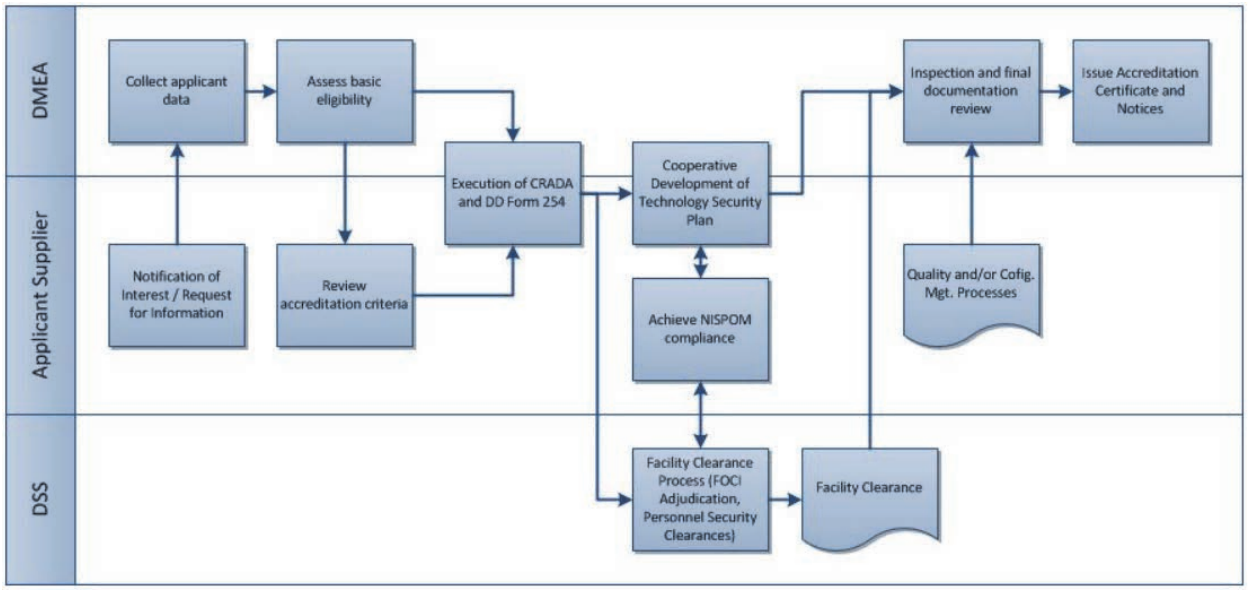
DMEA accredits suppliers in the areas of integrated circuit design, aggregation, broker, mask manufacturing, foundry, post processing, packaging/assembly and test services. These services cover a broad range of technologies and is intended to support both new and legacy applications, both classified and unclassified. Additionally, the use of the Trusted Suppliers' Trusted Flow is adequate to protect Critical Program Information as required by DODI 5200.39, Critical Program Information (CPI) Protection within the Department of Defense.

A key part of the DoD Trusted Foundry program is that it uniquely provides the US Government with guaranteed access to leading edge trusted microelectronics services for the typically low volume needs of the US Government. DMEA and NSA co-fund the Trusted Foundry program to facilitate this. The Trusted Access Program Office (TAPO) facilitates and administers the contracts and agreements with industry to provide US Government users with:

- Leading edge foundry services including multi-project wafer runs, dedicated prototypes, and production in both high- and low-volume models
- A library of standard IP blocks
- Limited packaging and test services

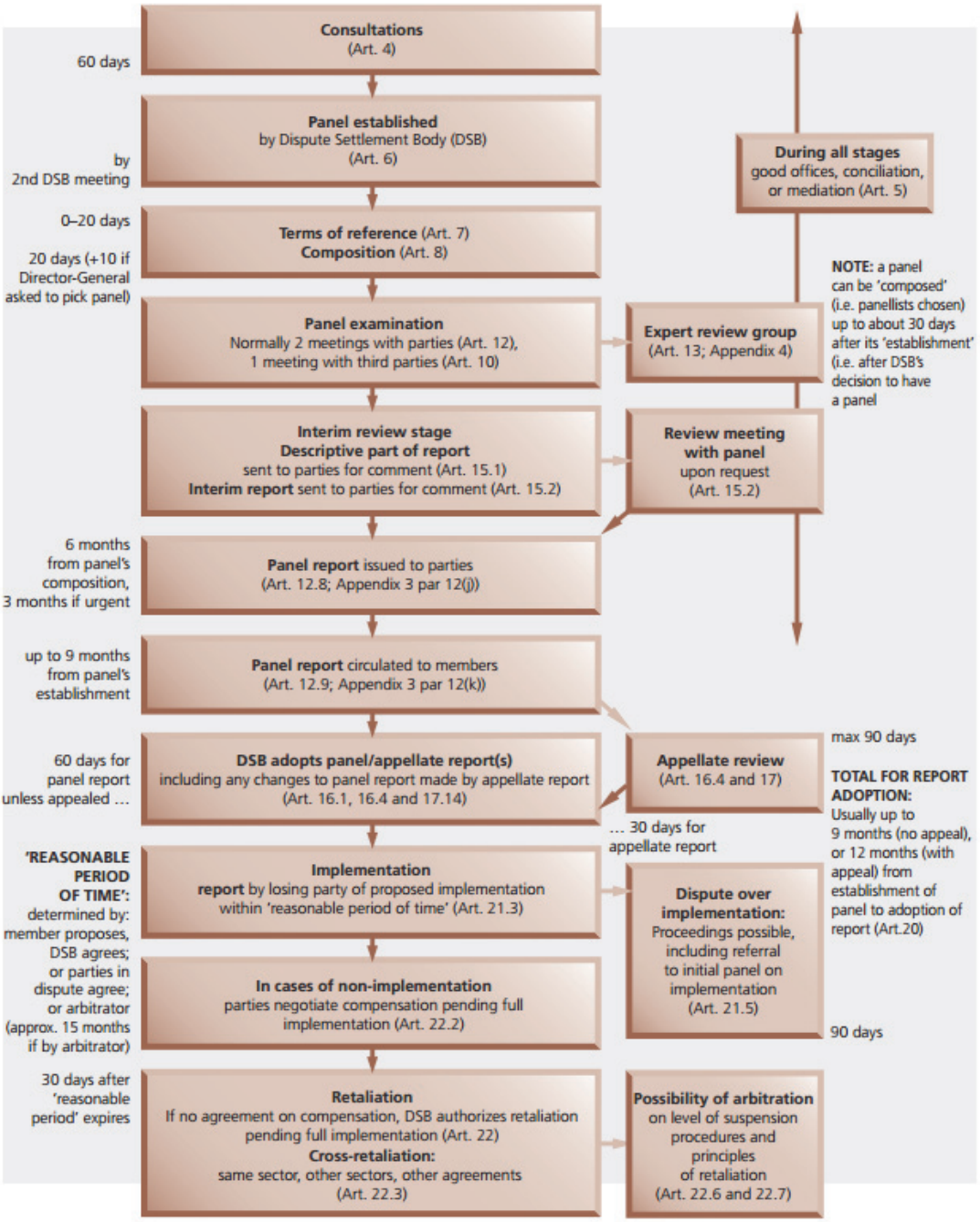
Source: DMEA (2014a)

FIGURE APPENDIX L.1.1 – TRUSTED SUPPLIER ACCREDITATION PROCESS



Source: DMEA (2014b)

Appendix M – The WTO Panel Process



Source: WTO (2011)

Appendix N – Other Potential Contingency Plan Options

In addition to the stockpiling and buffer stock contingency options, DoD (2013a) proposes complementary actions that can help alleviate shortages during a national emergency. These are so-called "Extra Buy" and "Reduced Exports" options. The Extra Buy option calls for the U.S. to make pre-arrangements with foreign suppliers to purchase additional critical materials during wartime at premium prices by taking advantage of surplus production capacities that are underutilized during peacetime. The "Reduced Exports" option calls for the U.S. to guarantee no more than 50 percent of critical raw materials to foreign consumers in the first year of a crisis and then no more than 85 percent in following two years (DoD 2013a). In the case of dysprosium, the extra buys would be severely limited since much of existing production capacity is in China. Export reductions have the potential to contribute to shortfall mitigation, although the DoD (2013a) report is vague on the implementation mechanism.

Extra Buys

According to the DoD (2013a), the extra buy through increased imports works through a pre-arrangement between the U.S. and foreign governments and suppliers that would allow the U.S. government the option of purchasing up to half of surplus production capacity output (at a premium price) after a ramp-up time of six months from the time of request during a time of emergency. For example, say a foreign supplier has x tonnes of total capacity to produce a mineral. If during peacetime, only y tonnes are produced, where $x > y$, the excess capacity is $z = x - y$. During wartime, the U.S. would have access to $\frac{z}{2}$ surplus capacity for its contingency needs.

Unfortunately, the DoD estimates no extra capacity for dysprosium (as well as erbium, terbium, thulium, and scandium) and rates a zero contribution to supply mitigation in its study. The study does not explicitly state why this is. However, this is a reasonable conclusion for two reasons. First, China is the primary dysprosium supplier and is expected to maintain leadership for the short-term. A conflict with China would mean the U.S. would not be able to exploit surplus capacity even if Chinese miners did have leeway. Secondly, the extra buy option is possible only if suppliers—foreign or domestic—have unused mining production capacities. However, given the possible shortfalls in dysprosium today and in the 15 year planning period, it is highly unlikely that surplus foreign production would be available, even if non-Chinese production comes online between 2016 and 2018 (Chapter 4).

Reduced Exports

According to the DoD (2013a), the reduced export option is designed such that,

> During a national emergency, the United States will guarantee the availability of materials to produce only 85 percent of those finished goods it exports in peacetime…The reduced U.S. export option tightens this guarantee to only 50 percent in the first year of the scenario except for material used to defense-related exports.

The study is equivocal about how the policy would be implemented—perhaps due to political sensitivities—noting only that the U.S. government "would not necessarily take active steps to reduce exports. Rather, it will not guarantee the availability of materials to produce a certain portion of goods for export." The best explanation is most likely a formal export restriction under GATT Article XXI

exemption for national security reasons. If applied, based on the DoD's export reduction method, export quotas equivalent to 50 percent peacetime export levels in the first year and 85 percent in three following years would be placed on dysprosium oxide and derivate products, principally NdFeB permanent magnets.

Citations and References

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