DETERMINING CRITICALITY OF RARE EARTH ELEMENTS IN THE PETROLEUM REFINING INDUSTRY

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A thesis submitted in partial fulfillment of the requirements for a baccalaureate degree in Energy, Business and Finance with honors in Energy, Business and Finance

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ABSTRACT

The Rare Earth Elements (REEs) are a group of 17 elements consisting of the 15 lanthanides, yttrium, and scandium. REEs play an important role in technologies across a number of industries including electronics, defense, energy, and petroleum refining, which is the focus of this report. China has historically dominated all aspects of REE mining and production. Over the past decade, China has increasingly reduced REE export quotas, and these reductions caused REE prices to reach unimaginably high levels in 2010 and 2011. These events revealed the vulnerability of REE supply and the volatility of the REE market, and prompted global efforts to diversify supply.

The petroleum refining industry felt the effects of these price spikes, as the use of REE in fluid catalytic cracking catalysts is the largest domestic use of REE. Lanthanum and cerium are used to stabilize the catalysts used in the fluid catalytic cracking (FCC) portion of the petroleum refining process, which is the process that breaks crude oil into separate petroleum products. Alternative catalysts were developed that employed less REE in response to the high price environment; however, a higher REE concentration in FCC catalysts has proven to produce the highest levels of activity and highest gasoline yields (McClean et al, 2012).

This report proposes a mechanism for identifying and quantifying the risks facing the supply of REEs in the petroleum refining industry. 5 Key Supply Risk Factors (KSRFs) have been determined, and the risks facing the supply of lanthanum and cerium were evaluated through the scope of these KSRFs in 3 hypothetical supply-demand case scenarios. As the demand for REEs continues to grow, it is important for oil producers to recognize and understand the risks that threaten supply, and to use this information to develop effective strategies to mitigate risk.
# TABLE OF CONTENTS

List of Figures .......................................................................................................................... iii

List of Tables ........................................................................................................................... v

Acknowledgements .................................................................................................................. vi

Chapter 1 Introduction ............................................................................................................. 1

  Hypothesis and Objectives ................................................................................................. 2

Chapter 2 Background: Rare Earth Elements (REEs) ............................................................. 4

  Basic Geology and Mineralogy of REEs ........................................................................... 5
  Brief History of REE Production ..................................................................................... 7
  Current Worldwide Reserves and Production ............................................................... 11
  Applications of REE ........................................................................................................ 14

Chapter 3 REEs in Petroleum Refining ................................................................................... 17

  The Petroleum Refining Process: An Overview ............................................................ 18
  Fluid Catalytic Cracking (FCC) Process ........................................................................ 22
  Zeolite Catalysts ............................................................................................................. 23
  Importance of REEs to Petroleum Refining ................................................................... 24

Chapter 4 Methodology of Determining Element Criticality .................................................. 32

  Key Supply Risk Factors (KSRFs) ............................................................................... 33
  Case Scenarios .............................................................................................................. 39
  Criticality Index ............................................................................................................. 43

Chapter 5 Results and Conclusions .......................................................................................... 63

  Summary ...................................................................................................................... 69

Appendix A  Trade Scores by Country ................................................................................... 70

Appendix B  EPI Scores by Country ...................................................................................... 73

REFERENCES ........................................................................................................................ 75
LIST OF FIGURES

Figure 2-1: Separation Process at Mountain Pass Mine ..........................................................7
Figure 2-2: Export Quotas for Domestic Chinese REE Producers and Traders .................9
Figure 2-3: Select Rare Earths Price Index 2002-July 2010 ....................................................9
Figure 2-4: Percentages of World Reserves and Production by Country .............................12
Figure 2-5: The REE Supply Chain ......................................................................................13
Figure 2-6: Distribution Percentages of REEs by End Use ...................................................15
Figure 3-1: Crude Oil Refining ..........................................................................................19
Figure 3-2: Fractional Distillation .......................................................................................20
Figure 3-3: Fluid Catalytic Cracking Unit ...........................................................................23
Figure 3-4: Effect of Rare Earth on Catalyst Activity ..........................................................25
Figure 3-5: Effect of REEs on Gasoline Yield and Octane ..................................................26
Figure 3-6: BASF's Phosphorous Modified Phinesse Catalyst Compared to Catalysts with
Varying REE Percentages by Weight ..............................................................................30
Figure 4-1: Percentage CE and La Used and REE Demand Growth Rates by End Use .......35
Figure 4-2: Mountain Pass REE Production ........................................................................41
Figure 4-3: REE Deposits Containing Cerium ....................................................................45
Figure 4-4: Deposits Containing Cerium and Requiring 10 Years or Less to Develop .........46
Figure 4-5: REE Deposits Containing Lanthanum ..............................................................48
Figure 4-6: Deposits Containing Lanthanum and Requiring 10 Years or Less to Develop.....50
Figure 4-7: Deposits Containing Cerium Outside of the US and Top Performing EPI
Countries ..........................................................................................................................51
Figure 4-8: Cerium Deposits Outside the US and Top Performing EPI Countries
Requiring 10 Years or Less to Develop ...........................................................................53
Figure 4-9: Deposits Containing Lanthanum Outside the US and Top Performing EPI
Countries ..........................................................................................................................55
Figure 4-10: Lanthanum Deposits Outside the US and Top Performing EPI Countries
Requiring 10 Years of Less to Develop ................................................................. 56

Figure 4-11: Cerium Deposits Requiring 3 Years or Less to Develop ......................... 59

Figure 4-12: Lanthanum Deposits Requiring 3 Years or Less to Develop .................... 61

Figure 5-1: Criticality Index Graph for Cerium in the Domestic Supply Case Scenario .... 63

Figure 5-2: Criticality Index Graph for Lanthanum in the Domestic Supply Case Scenario .. 64

Figure 5-3: Criticality Index for Cerium in the Overproduction Case Scenario ............... 65

Figure 5-4: Criticality Index for Lanthanum in the Overproduction Case Scenario ........... 66

Figure 5-5: Criticality Index for Cerium in the Electric Vehicles Case Scenario ............... 67

Figure 5-6: Criticality Index for Lanthanum in the Electric Vehicles Case Scenario .......... 68
LIST OF TABLES

Table 2-1: Light vs. Heavy REEs .................................................................4
Table 2-2: REE Crustal Abundance (ppm) ....................................................5
Table 2-3: Reserves and Production Figures by Country (metric tons) ..............12
Table 2-4: REE End Uses by Element .........................................................15
Table 2-5: REE Applications by Industry .....................................................16
Table 3-1: Petroleum Products and Descriptions .........................................17
Table 3-2: Effects of Reducing REE Content and Increasing TSA .................27
Table 3-3: Daily Refinery Sales Volume and Revenues Using Full- and Low-REE Catalysts ........................................................................28
Table 3-4: US Daily Refiner Sales Volumes and Prices by Petroleum Product (as of Jan ’13) ..............................................................................28
Table 3-5: Impact of REE Cost on Refinery Revenues ..................................29
Table 4-1: KSRF Scores for Cerium in the Domestic Supply Case Scenario ....44
Table 4-2: KSRF Scores for Lanthanum in the Domestic Supply Case Scenario ....47
Table 4-3: KSRF Scores for Cerium in the Overproduction Case Scenario ........51
Table 4-4: KSRF Scores for Lanthanum in the Overproduction Case Scenario ....54
Table 4-5: KSRF Scores for Cerium in the Electric Vehicles Case Scenario ..........57
Table 4-6: KSRF Scores for Lanthanum in the Electric Vehicles Case Scenario ....60
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Chapter 1

Introduction

The group of elements known as the Rare Earth Elements (REEs) is comprised of the 15 lanthanides, atomic numbers 57 to 71, as well as yttrium and scandium, atomic numbers 39 and 21, respectively (Humphries, 2012). REEs are used in a number of technologies including catalysts for automobiles and petroleum refining, magnets for wind turbines and defense technologies, and phosphors in lighting and computer and TV screens, among others (Humphries, 2012). The elements are deemed “rare” because they are found in low concentrations and are difficult to extract economically (Emsley, 2001). China holds almost 50% of the global REE reserves (Gambogi, 2013), and until 2012, production of REEs was almost exclusive to China (Humphries, 2012). Over the past decade, China has been steadily decreasing its REE export quotas, reducing the supply of REEs available to the rest of the world. This became especially problematic in 2010 and 2011, when Chinese quota reductions caused REE prices to skyrocket, in some cases, to more than 5 times their 2009 prices (Gambogi and Cordier, 2012). Although prices have since fallen, these events alerted the world of the vulnerability of REE supply and the volatility of REE prices. Many countries have taken action to secure a domestic supply of REEs, and in just one year, China’s share of global REE production fell from 97% to 86% due to new and increased production from countries like the United States and Australia (Gambogi, 2013).

One industry in which a steady supply of Rare Earth Elements is especially important is the petroleum refining industry. In fact, the use of REEs in fluid catalytic cracking (FCC) units for petroleum refining is the largest domestic use of REEs (DOE, 2011). Fluid catalytic cracking is a process that uses REE-containing catalysts to crack heavy oils at extremely high temperatures
into gasoline and diesel fuel, heavy oil, coke and light hydrocarbon gases (Cleveland, 2011).
Lanthanum and cerium are the two main REEs used in the petroleum refining industry, and they serve the purpose of stabilizing the negative charge of the zeolite catalysts employed in the FCC process (Sadeghbeigi, 2012). Although they only account for up to 5% of the FCC catalysts by weight, REEs play an extremely important role in the FCC process, increasing catalyst activity and hydrothermal stability. Essentially, REEs allow for increased gasoline yield per unit of FCC catalyst, and they allow catalysts to remain effective for longer periods of time (Sadeghbeigi, 2012). Although low and zero REE catalyst alternatives were created in response to the high REE price environment of the past few years, it has been proven that catalysts that contain at least 3% REE by weight are more active and produce higher gasoline yields (McLean et al, 2012).

REEs are considered critical materials according to the National Science and Technology Council, which defines critical elements as those serving an essential function in the manufacture of a product, the absence of which would cause significant social consequence, and whose supply is vulnerable to disruption (Telleen, 2012). Thus, it is extremely important for consumers of REEs to be aware of and understand the risks facing the supply of each REE, as awareness is the first and most important step in developing strategies to mitigate risk. This report presents a mechanism for identifying the risks present in a supply-demand scenario and determining the criticality of an individual rare earth element under specific circumstances.

**Hypothesis and Objectives**

There are 5 main sources of risk facing supply of REEs in every supply-demand scenario. These Key Supply Risk Factors (KSRFs) are producer diversity, availability of resources, demand from alternative applications, international trade environment, and environmental regulations. This report provides a mechanism for exploring the risks associated with each KSRF in depth, as
well as a methodology for quantifying each KSRF based on the overall risk to the supply of a specific REE that is associated with it. The numbers assigned to each KSRF are then graphed individually and averaged to represent the overall Criticality Index for each element in each scenario. The graphical representation of the data allows REE consumers to clearly recognize and understand the impact of each KSRF on an element’s criticality.

The purpose of the Criticality Index and its graphical representation is to assist consumers of REEs in identifying risk, predicting the potential effects of this risk, and ultimately preparing for such risk by developing a mitigation strategy. This report focuses specifically on the application of the REEs lanthanum and cerium in the petroleum refining industry and the risks that threaten their supply.
Chapter 2

Background: Rare Earth Elements (REEs)

There are 17 elements that comprise the Rare Earth Element group. 15 of these elements are lanthanides with atomic numbers ranging from 57 to 71 on the periodic table: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium (Castor and Hedrick, 2006). Additionally, yttrium and scandium (Humphries, 2012), atomic numbers 39 and 21, respectively, are considered Rare Earth Elements as they share similar chemical and physical properties with the lanthanides. The rare earth elements are considered to be either light or heavy depending on their atomic weight and chemical and physical properties (Castor and Hedrick, 2006).

Table 2-1: Light vs. Heavy REEs

<table>
<thead>
<tr>
<th>Light REEs</th>
<th>Atomic Weight</th>
<th>Heavy REEs</th>
<th>Atomic Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lanthanum (La)</td>
<td>138.91</td>
<td>Gadolinium (Gd)</td>
<td>157.25</td>
</tr>
<tr>
<td>Cerium (Ce)</td>
<td>140.12</td>
<td>Terbium (Tb)</td>
<td>158.93</td>
</tr>
<tr>
<td>Praseodymium (Pr)</td>
<td>140.91</td>
<td>Dysprosium (Dy)</td>
<td>162.50</td>
</tr>
<tr>
<td>Neodymium (Nd)</td>
<td>144.24</td>
<td>Holmium (Ho)</td>
<td>164.93</td>
</tr>
<tr>
<td>Promethium (Pm)</td>
<td>144.91</td>
<td>Erbium (Er)</td>
<td>167.26</td>
</tr>
<tr>
<td>Samarium (Sm)</td>
<td>150.36</td>
<td>Thulium (Tm)</td>
<td>168.93</td>
</tr>
<tr>
<td>Europium (Eu)</td>
<td>151.96</td>
<td>Ytterbium (Yb)</td>
<td>173.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lutetium (Lu)</td>
<td>174.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scandium (Sc)</td>
<td>44.956</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yttrium (Y)</td>
<td>88.906</td>
</tr>
</tbody>
</table>

Source: Castor and Hedrick, 2006; Grasso, 2012

The Rare Earth Elements are actually quite abundant in the earth’s crust, despite the misleading title. In fact, cerium, the most abundant rare earth element, is more abundant than copper and lead (Long et al, 2010). As shown in Table 2-2, the elements range in crustal
abundance from cerium at 64 parts per million, to thulium and lutetium at less than 0.5 parts per million, with light REEs typically occurring in higher abundance than heavy (Castor and Hedrick, 2006). They were deemed “rare” because of the fact that they are found in low concentrations and are difficult to extract economically (Emsley, 2001).

**Table 2-2: REE Crustal Abundance (ppm)**

<table>
<thead>
<tr>
<th>Element</th>
<th>Crustal Abundance</th>
<th>Element</th>
<th>Crustal Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>La</td>
<td>30</td>
<td>Dy</td>
<td>3.5</td>
</tr>
<tr>
<td>Ce</td>
<td>64</td>
<td>Ho</td>
<td>0.80</td>
</tr>
<tr>
<td>Pr</td>
<td>7.1</td>
<td>Er</td>
<td>2.3</td>
</tr>
<tr>
<td>Nd</td>
<td>26</td>
<td>Tm</td>
<td>0.33</td>
</tr>
<tr>
<td>Pm</td>
<td>NA</td>
<td>Yb</td>
<td>2.2</td>
</tr>
<tr>
<td>Sm</td>
<td>4.5</td>
<td>Lu</td>
<td>0.32</td>
</tr>
<tr>
<td>Eu</td>
<td>0.88</td>
<td>Sc</td>
<td>22</td>
</tr>
<tr>
<td>Gd</td>
<td>3.8</td>
<td>Y</td>
<td>22</td>
</tr>
<tr>
<td>Tb</td>
<td>0.64</td>
<td>TOTAL</td>
<td>190.37</td>
</tr>
</tbody>
</table>

*Sources: Castor and Hedrick, 2006; Long et al, 2010*

**Basic Geology and Mineralogy of REEs**

REEs occur together naturally in certain types of rare earth minerals (Castor and Hedrick, 2006). However, high concentration of REEs in a mineable ore deposit is rare and found most often in uncommon varieties of igneous rock. Some ore deposits with the highest potentially useful concentrations of REE-bearing minerals include alkaline rocks and placer deposits (Long et al, 2010).

The formation of alkaline igneous rocks is a complex process that results from the cooling of magmas in the Earth’s mantle. The process “extracts and concentrates those elements that do not fit into the structure of the common rock-forming minerals” (Long et al, 2010). The rocks undergo further change when they ascend into the Earth’s crust, and as a result, the mineral deposits that can be found in these formations are unique, diverse and difficult to classify. Placer deposits are formed by the process of erosion, which concentrates dense minerals and sediments
into formations that contain rare earth minerals along with other heavy minerals (Long et al, 2010). The two major commercial sources of REEs are bastnasite and monazite mineral deposits. Bastnasite is rich in light REEs and is primarily found in alkaline rocks and carbonatites, which are igneous rocks composed of carbonate minerals (Kitto et al, 1992; Long et al, 2010). Both the Mountain Pass mine in California and the Bayan Obo mine in Inner Mongolia in China are classified as carbonatites with bastnasite mineral deposits. Monazite ores generally have a lower abundance of REEs than bastnasite and can be found in placer deposits (Long et al, 2010).

Rare earth minerals, once extracted, can contain multiple individual REEs. Each element must be separated and refined through a series of complex chemical processes to remove impurities, namely the radioactive element, thorium. Due to the radioactive nature of the waste product, the process of separation and refining is heavily regulated, requiring special disposal methods. It imposes high handling and disposal costs on producers, especially in the United States. The complex separation and refining process, coupled with the fact that the unique nature of each rare earth mineral demands unique mining processes that must be tested before production can begin, make rare earth production challenging and expensive (Long et al, 2010). Figure 2-1 below shows the separation of REEs as it occurs at the Mountain Pass Mine in California.
Brief History of REE Production

Although today China is the world’s leading producer of REEs, this was not always the case. The United States was once in China’s position, dominating the REE industry from the 1950s through the 1980s. The REEs mined at the Mountain Pass facility in southeastern California accounted for 100 percent of U.S. domestic supply and one third of global REE exports. In the late 1970s, however, China realized the potential implications of United States’ dominance of the REE industry and recognized that, with such large deposits of rare earths in their own country, they had the potential to compete in the market. From 1978 to 1989, China increased its production of REEs by 40% annually, quickly surpassing the United States to become the largest global producer. Most of the Chinese production is mined from the Bayan Obo mine in Baotou, Inner Mongolia (Levkowitz et al, 2010).
Due to financial support from government-owned Chinese banks, rare earth mining companies in China were able to produce REEs at low costs, and thus, were able to export their products at lower prices than anywhere else. The Chinese increased exports of REEs and ultimately drove the prices so low that, eventually, non-Chinese competitors were unable to stay in business (Levkowitz et al, 2010). In fact, since 1998, China has provided more than 80% of the world’s REE raw materials (Castor and Hedrick, 2006). In 2002, the United States’ Mountain Pass mine in California shut down, causing the U.S. to be completely dependent on foreign, mostly Chinese, imports for domestic REE supply (Levkowitz et al, 2010).

In recent years, China has asserted its dominance in the industry in a number of controversial ways that have greatly concerned importers of REEs and pushed them to seek new, alternative sources of supply. Between 2005 and 2010, China reduced their REE export quotas by 54% (See Figure 2-2 below). The Chinese government announced in August 2009 that it would be banning the export of 5 REEs within 5 years. Additionally, in July 2010, China further reduced the export quota for the second half of the year by 72%, causing major spikes in the prices of some REEs (Levkowitz et al, 2010). Lanthanum and cerium metal prices rose more to than 5 times their 2009 prices, and prices for neodymium and dysprosium rose 285% and 171%, respectively (Gambogi and Cordier, 2012). In the United States, the estimated value of rare earths imported increased dramatically from $161 million in 2010 to $802 million in 2011 (Cordier, 2012; Gambogi, 2013). By reducing export quotas, China also hopes to force foreign companies to develop production facilities in their country (Levkowitz et al, 2010).
In addition to cutting export quotas, the Chinese government has initiated an effort to consolidate the REE industry in the country and gain more control of it. They closed some small, illegal mines, merged others, and implemented stricter standards, hoping to reduce the number of
mines from 123 to 10. They will implement a unified pricing mechanism to decrease illegal mining and stabilize the market, as well as begin to stockpile their REE resources (Levkowitz et al, 2010).

Importers of REEs surely felt the blow of these recent developments in China, and countries like the United States, Australia, and Canada have taken action. In fact, as of August 2012, 441 exploration projects led by 269 different companies were active in 37 countries outside of China (Hatch, 2012). The United States, Canada, Australia are leading the efforts with several projects already in the advanced stages of development (Hatch, 2012). In 2010, U.S.-based rare earth mining company, Molycorp, announced their plans to reopen the Mountain Pass mine and has made steady progress since then. Most recently, in January 2013, the company announced that all key components of the new, state-of-the-art facility were operational and that they had begun ramping up to the full-scale run rate (Molycorp, 2013). By the end of 2013, the facility is expecting to at a capacity of 19,050 tons/yr (Molycorp, 2013). Australia has two major REE projects, the Dubbo Zirconia project and the Nolans Bore project, that are both expected to be producing by 2014. Canada has increased exploration efforts, with ongoing feasibility and resource estimate projects at Thor Lake, Kipawa and Strange Lake (Gambogi and Cordier, 2012).

In the United States, the government has also been active in addressing the growing issue of potential REE supply shortages. The Department of Energy has funded multiple research efforts through partnerships with laboratories across the country, and they released a Critical Materials Strategy in 2011 and 2012. The Department of Defense is reviewing its rare earth supply chain and released a report in 2012 assessing the criticality of rare earths to their operations. Additionally, the White House Office of Science and Technology Policy has formed an Interagency Work Group to establish REE mineral prioritization and early warning mechanisms that includes the Departments of Energy, Defense, Interior, Commerce, State and Justice, as well as the Environmental Protection Agency and the Office of U.S. Trade
Current Worldwide Reserves and Production

Today, China dominates all aspects of the REE industry, from reserves to manufacturing. With 55,000,000 metric tons of rare earth oxide in reserves, China holds just under half of the world’s total reserves, which total up to 113,778,000 metric tons. The Commonwealth of Independent States (CIS), made up of a group of former Soviet republics, follows China with 19,000,000 metric tons in reserves, and the United States has the third most reserves with 13,000,000 metric tons. Additionally, China produces 87% of the global REE supply, followed by the United States, India, Australia, India, Malaysia, and Brazil, which produce negligible amounts in comparison (Gambogi, 2013).

Figure 2-4 and Table 2-3 below provide visual comparisons and data regarding global reserves and production. The graphs clearly display China’s dominance in the industry. It also makes visible that there are many other places in the world with reserves that are not being utilized for production, most notably Russia and other former members of the Soviet Union, as well as the United States.
Figure 2-4: Percentages of World Reserves and Production by Country

Table 2-3: Reserves and Production Figures by Country (metric tons)

<table>
<thead>
<tr>
<th>Country</th>
<th>Reserves</th>
<th>Production</th>
<th>% of Total Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>55,000,000</td>
<td>95,000</td>
<td>86.00%</td>
</tr>
<tr>
<td>Commonwealth of Independent States</td>
<td>19,000,000</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>United States</td>
<td>13,000,000</td>
<td>7,000</td>
<td>6.40%</td>
</tr>
<tr>
<td>India</td>
<td>3,100,000</td>
<td>2,800</td>
<td>2.56%</td>
</tr>
<tr>
<td>Australia</td>
<td>1,600,000</td>
<td>4,000</td>
<td>3.65%</td>
</tr>
<tr>
<td>Brazil</td>
<td>36,000</td>
<td>300</td>
<td>0.27%</td>
</tr>
<tr>
<td>Malaysia</td>
<td>30,000</td>
<td>350</td>
<td>0.32%</td>
</tr>
<tr>
<td>Other Countries</td>
<td>22,000,000</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>113,766,000</td>
<td>109,450</td>
<td></td>
</tr>
</tbody>
</table>

Source: Gambogi, 2013

Not only does China lead the world in reserves and production of REEs, but also every other step in the REE supply chain. The REE powerhouse provides 100% of the world’s refining capacity, produces 89% of the world’s rare earth alloys, and manufactures the majority of the world’s permanent magnets (Levkowitz, 2010).
Figure 2-5: The REE Supply Chain

1. Mine rare earth ore
2. Separate ore into oxides
3. Refine oxides to metal
4. Form metals into alloys
5. Manufacture magnets / other components

<table>
<thead>
<tr>
<th>No U.S. Production</th>
<th>Limited U.S. Production</th>
<th>No U.S. Production</th>
<th>Limited U.S. Production</th>
<th>Limited U.S. Production of SmCo magnets; No U.S. production of NdFeB magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>China produces about 97 percent of rare earth ore.</td>
<td>According to industry, China produces about 97 percent of rare earth oxide</td>
<td>Refined metal is available exclusively from China.7</td>
<td>According to industry, China produces 80 percent of rare earth alloys.</td>
<td>According to industry, China produces 75 percent of NdFeB magnets and 60 percent of SmCo magnets.</td>
</tr>
</tbody>
</table>

Figure 2-5 above notes China’s dominance compared to the United States in all aspects of the supply chain. Building an REE supply chain is dependent on many complex factors, some of which can hinder other countries from being competitive. The process is both time and capital intensive. The first step, exploration, involves a large capital investment to locate suitable REE deposits. Exploration is a very uncertain process, and the amount of capital and time required to successfully locate a favorable deposit can vary greatly. The process involves extensive trenching, drilling, and sampling along with concurrent environmental studies and metallurgical testing (Long et al, 2010). Once a suitable deposit has been discovered, the appropriate permits must be obtained. Generally, permitting will require an approved plan of operations, a positive environmental impact study, and permission from a government agency (Long et al, 2010). Next, the necessary infrastructure for mining and processing must be built, also requiring a huge amount of capital investment and time. A detailed engineering design must be drafted, construction bids must be made, and contracts must be awarded. Once construction is complete, the equipment must be thoroughly tested and operated on a ramp-up schedule until the full commercial production rate is achieved (Long et al, 2010). Up until this point, a huge amount of capital has been invested without any revenues from mineral sales as compensation. In 2010, the largest of the proposed new mining operations, including Molycorp’s Mountain Pass mine, reported pre-mining capital requirements of half a billion dollars or more (Long et al, 2010). In fact, Molycorp spent just under $1 billion over about 2 years to revive the mine and production.
Investing in this type of project may be risky for countries that do not have a steady supply of rare earth oxides besides China. In addition, many of the more developed countries such as the United States have strict environmental regulations around mining, especially the mining of potentially radioactive substances, which commonly accompany REEs. Building production facilities that meet the strict environmental regulations can add time and money to the development process of mining projects. Experts also believe that the development of new technology, which requires large capital investment, will be necessary to compete with the Chinese in the REE industry (GAO, 2010). With all of these factors standing as barriers to REE supply chain development, the shift from Chinese dominance in the industry will surely take time.

Applications of REE

Rare Earth Elements have a number of applications in a variety of different areas. Their supply is critical to a number of different groups both in the public and private sector. They are used in green technology as critical components of wind turbines, electric vehicles, photovoltaic power systems, and high efficiency lighting systems (United States Department of Energy [DOE], 2011). They are used in defense as components in guidance and control systems, targeting and weapon systems, electric motors, and communication devices, among various other uses (Grasso, 2012). Additionally, they are used as catalysts in the automobile and petroleum refining industry, phosphors in color televisions and flat panel displays, permanent magnets and in numerous medical devices (Humphries, 2012). Figure 2-6 and Tables 2-4 and 2-5 show the various applications and end uses of REEs.
Figure 2-6: Distribution Percentages of REEs by End Use

**Domestic REE Distribution by End Use**

<table>
<thead>
<tr>
<th>Light Rare Earths (more abundant)</th>
<th>Major End Use</th>
<th>Heavy Rare Earth (less abundant)</th>
<th>Major End Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lanthanum</td>
<td>hybrid engines, metal alloys</td>
<td>Terbium</td>
<td>phosphors, permanent magnets</td>
</tr>
<tr>
<td>Cerium</td>
<td>auto catalyst, petroleum refining, metal alloys</td>
<td>Dysprosium</td>
<td>permanent magnets, hybrid engines</td>
</tr>
<tr>
<td>Praseodymium</td>
<td>magnets</td>
<td>Erbium</td>
<td>phosphors</td>
</tr>
<tr>
<td>Neodymium</td>
<td>auto catalyst, petroleum refining, hard drives in</td>
<td>Yttrium</td>
<td>red color, fluorescent lamps, ceramics, metal</td>
</tr>
<tr>
<td></td>
<td>laptops, headphones, hybrid engines</td>
<td></td>
<td>alloy agent</td>
</tr>
<tr>
<td>Samarium</td>
<td>magnets</td>
<td>Holmium</td>
<td>glass coloring, lasers</td>
</tr>
<tr>
<td>Europium</td>
<td>red color for television and computer screens</td>
<td>Thulium</td>
<td>medical x-ray units</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lutetium</td>
<td>catalysts in petroleum refining</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ytterbium</td>
<td>lasers, steel alloys</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gadolinium</td>
<td>magnets</td>
</tr>
</tbody>
</table>

Source: Gambogi, 2013

Table 2-4: REE End Uses by Element

Source: Humphries, 2012
Table 2-5: REE Applications by Industry

<table>
<thead>
<tr>
<th>Industry</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive</td>
<td>Catalysts for pollution control; catalytic converter catalyst substrate; rechargeable batteries; fuel cells; colored plastics</td>
</tr>
<tr>
<td>Ceramics</td>
<td>Oxygen sensors; structural ceramics for bearings; jet engine coatings; investment molds; refractories; pigments</td>
</tr>
<tr>
<td>Chemicals</td>
<td>Oil refinery fluid cracking catalysts; pharmaceuticals; water treatment; catalysts; moisture control, dryers, and detection</td>
</tr>
<tr>
<td>Defense</td>
<td>Lasers; missile guidance and control; visual displays; radar; electronic countermeasures; communication; shielding</td>
</tr>
<tr>
<td>Electronics</td>
<td>Capacitors; cathodes; electrodes; semiconductors; thermistors; traveling wave tubes (TWTs); radio frequency circulators and toroids; yttrium iron garnet (YIG) ferrites</td>
</tr>
<tr>
<td>Glass</td>
<td>Polishing compounds; decolorizing; colorizing; increase refraction; decrease dispersion; radiation stabilization; absorber</td>
</tr>
<tr>
<td>Illumination</td>
<td>Trichromatic fluorescent lamps; mercury lamps; carbon arc lamps; gas mantles; auto headlamps; long-glow phosphors</td>
</tr>
<tr>
<td>Magnets</td>
<td>Speakers and headphones; linear motors; antilock braking systems; tape and disk drives; gauges; electric motors; pumps; ignition</td>
</tr>
<tr>
<td>Medical</td>
<td>Contrast agents; magnetic resonance imaging (MRI); positron emission tomography (PET); radioisotope tracers and emitters</td>
</tr>
<tr>
<td>Metallurgy</td>
<td>Alloying agents in aluminum, magnesium, iron, nickel, and steel alloys; superalloys; pyrophoric alloys; lighter flints; armaments</td>
</tr>
<tr>
<td>Phosphors</td>
<td>Cathode-ray tubes (CRTs); fluorescent lighting; radar and cockpit displays; x-ray intensifying screens; temperature sensors</td>
</tr>
<tr>
<td>Other</td>
<td>Simulated gemstones; textiles; magnetic refrigeration; hydrogen fuel storage; lubrication; photography; nuclear uses</td>
</tr>
</tbody>
</table>

*Source: Castor and Hedrick, 2006*

As these tables and figures demonstrate, REEs have a wide variety of uses in our society, and their importance continues to grow as technology improves. Therefore, it is important for the United States to maintain a steady safe supply of REEs.
Chapter 3

REEs in Petroleum Refining

Petroleum, or crude oil, is the term used to describe oil as it comes out of the ground and before it is processed. It is a fossil fuel created from the decay of plants and animals over millions of years beneath the earth’s surface, and it occurs naturally in varying colors and viscosities. Crude oil is made up of approximately 84% carbon, 14% hydrogen and small amounts of sulfur, nitrogen oxygen, and trace metals and salts. It also contains a number of energy-rich hydrocarbons, which, once refined, can be used to create useful products such as gasoline, kerosene, and diesel (Freudenrich, 2001). Table 3-1 below lists and describes the various petroleum products.

Table 3-1: Petroleum Products and Descriptions

<table>
<thead>
<tr>
<th>Petroleum Product</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aviation Gasoline</td>
<td>Gasoline prepared especially for aviation piston engines</td>
</tr>
<tr>
<td>Bitumen / Asphalt</td>
<td>Solid, semi-solid or viscous hydrocarbon used primarily for road surfacing and roofing material</td>
</tr>
<tr>
<td>Fuel Oil</td>
<td>Comprises all residual fuels and used for industrial fuel</td>
</tr>
<tr>
<td>Gas / Diesel Oil</td>
<td>Heavy oils used for diesel fuel and heating oil</td>
</tr>
<tr>
<td>Kerosene</td>
<td>Medium oil used as fuel for jet engines and tractors</td>
</tr>
<tr>
<td>Liquefied Petroleum Gases</td>
<td>Light hydrocarbon fractions of the paraffin series including propylene and butylene among others</td>
</tr>
<tr>
<td>Lubricants</td>
<td>Hydrocarbons used for motor oil, grease, and other lubricants</td>
</tr>
<tr>
<td>Motor gasoline</td>
<td>Light hydrocarbon used as fuel for motor vehicles excluding aircraft</td>
</tr>
<tr>
<td>Naphtha</td>
<td>Intermediate feedstock for further use in petrochemical industry or gasoline production</td>
</tr>
<tr>
<td>Paraffin Waxes</td>
<td>Residue from dewaxing lubricants</td>
</tr>
<tr>
<td>Petroleum Coke</td>
<td>Solid residue used as a feedstock in coke ovens for the steel industry, for heating purposes, for electrode manufacture and for production of chemicals</td>
</tr>
<tr>
<td>Refinery gas</td>
<td>Gas produced from refinery processes including hydrogen, methane, ethane and olefins</td>
</tr>
<tr>
<td>Other Oil Products</td>
<td>Includes tar, sulfur, and grease</td>
</tr>
</tbody>
</table>

Sources: International Energy Agency [IEA]; Freudenrich, 2001
The refining process is complex and involves a number of different steps and chemical processes to separate and purify the petroleum. One step in the process is cracking, which involves breaking the larger hydrocarbons found in crude oil into more valuable and marketable smaller ones, such as gasoline and kerosene. One type of cracking is fluid catalytic cracking, which uses catalysts to speed the cracking reaction (Freudenrich, 2001). The primary catalysts used in the fluid catalytic cracking (FCC) process are zeolite cracking catalysts, which generally contain between 1 and 5% rare earth oxide by weight. The REEs found in these catalysts are Lanthanum (La) and Cerium (Ce) (Goonan, 2011). Cerium oxide can also be found in some FCC additives used to reduce sulfur oxide (SOx) emission; however, because the majority of FCC units currently do not use such additives, demand is low (DOE, 2011).

**The Petroleum Refining Process: An Overview**

The petroleum refining process and the different physical and chemical processes involved in it will be explained in further detail in this overview. Figure 3-1 below provides a simplified visual of the entire refining process.
The first step of the refining process involves simply dividing the crude oil into separate components, or fractions, through a process known as atmospheric distillation. The crude oil is heated and passed through the distillation columns. The different boiling points of the different components of crude oil allow for the separation of the light and heavy hydrocarbons, and they are collected as vapor and condensed liquids in the various trays of the distillation column (Wansbrough; EIA, 2012). The atmospheric distillation process is illustrated below in Figure 3-2.
During the atmospheric distillation process, the crude oil is boiled at temperatures up to 750°F. Beyond this temperature, the oil will thermally crack (i.e. break apart into smaller hydrocarbons) and slow the distillation process. The heavier oils with boiling points exceeding this temperature, called bottoms, are collected at the bottom of the atmospheric distillation column and are separated further in the vacuum distillation column. The low-pressure environment created by the vacuum reduces the boiling point of the bottoms to a temperature at which they can vaporize without cracking, allowing them to separate and continue on in the refining process (Energy Information Administration [EIA], 2012).

The next step of the petroleum refining process involves the use of chemical processes to convert the heavy hydrocarbons into lighter hydrocarbons for use in creating the final petroleum
products. This is accomplished through cracking, and there are two types of cracking used in petroleum refining: thermal and catalytic. Coking is a thermal cracking technique, involving heating the heaviest oils to temperatures above 900°F to break them into light hydrocarbons and coke, a heavy, almost pure carbon residue that is sold for use in other industries. Fluid catalytic cracking (FCC) uses REE-containing catalysts to crack heavy oils at extremely high temperatures into gasoline and diesel fuel, heavy oil, coke and light hydrocarbon gases. These residual hydrocarbon gases, along with those produced from distillation enter the alkylation unit, where they are combined with isobutene and catalysts to create alkylate, a valuable blending component in gasoline (Cleveland, 2011). Together, the FCC and alkylation units account for approximately 45-50% of refinery gasoline production (DOE, 2011). Hydrocracking is another technique similar to FCC, which uses different catalysts along with hydrogen gas at lower temperatures and higher pressures to crack heavy oils into kerosene and gasoline (Freudenrich, 2001).

The lighter oils and naphtha generated from the atmospheric distillation process, as well as those generated from the cracking processes, are hydrotreated to remove impurities such as sulfur, nitrogen, oxygen and water among other impurities. After being treated for impurities, the naphtha continues to the catalytic reformer, where catalysts are used to combine the lightweight substance with aromatics for later use in chemicals and gasoline blending (Freudenrich, 2001). Some naphtha runs through the isomerization unit, which converts n-butane, n-pentane and n-hexane into isoparaffins, also for use in gasoline blending (SET Laboratories, 2008). The final step in the process is blending, in which the treated fractions are cooled and blended to create the final petroleum products (Freudenrich, 2001).
Fluid Catalytic Cracking (FCC) Process

REEs play an important role in the petroleum refining process, namely in the fluid catalytic cracking portion. The FCC process is considered to be the most important petroleum refinery technologies, and together with the alkylation unit, it produces approximately 45-50% of refinery gasoline (DOE, 2011; Hudec, 2011). During the FCC process, heavy oils generated from distillation enter the FCC unit and are heated to approximately 1,000°F, at which point the oil begins to vaporize. In the presence of high-activity zeolite catalysts, the cracking occurs in the oil’s vapor phase as the mixture of both the catalyst and the vapor are carried up the riser, a vertical pipe-like structure within the FCC unit. The mixture exits the riser and enters the reactor vessel, where the catalyst is quickly separated from the vapor by means of an inertial separation device. The spent catalyst is then stripped of any residual hydrocarbon vapors and sent to the regenerator, while the vapor is sent to the fractionator to be separated. The regenerator restores the catalyst to activity, heats it (simultaneously providing heat for the cracking reaction), and delivers it through the slide valve to circulate through the unit again (Sadeghbeigi, 2012). A basic model of a FCC unit can be seen below in Figure 3-3.
Zeolite Catalysts

Zeolites are solid acids and are the key ingredients in FCC catalysts. About 40 known types of zeolites exist in nature including faujasite, mordenite, offretite, and chabazite among others. Additionally, about 150 synthesized zeolites exist as a result of scientific breakthroughs in the early 1950s. The zeolites that are used in FCC are actually synthetic versions of the naturally occurring zeolites known as faujasites. These synthetic catalysts were introduced to the FCC process in 1962, quickly replacing the formerly used silica-alumina catalysts as they were more active and significantly increased the gasoline yields from FCC units. The specific zeolites applied in the FCC process are Type X and Type Y. Type X zeolite has a lower silica-alumina ratio and a lower thermal and hydrothermal stability than type Y, and thus, is used significantly less than type Y in modern FCC units (Weitkamp, 1999; Sadeghbeigi, 2012, Pavol, 2011).
A zeolite is typically made up of silicon and aluminum atoms that are tetrahedrally joined by oxygen atoms. The primary building blocks of the zeolite structure are SiO$_4$ and AlO$_4$ tetrahedra, which, when linked at their corners by a shared oxygen atom, cause the three-dimensional framework of the structure to be negatively charged. Sometimes referred to as molecular sieves, zeolites have a network of very small pores that cover their framework. Inside the pores of the zeolite structure are water molecules and small cations, generally sodium, that balance the negative framework charge. These characteristics of zeolites make them excellent ion exchangers (Weitkamp, 1999).

In order to enhance activity and thermal stability of zeolites, the sodium content must be reduced. Lanthanum and Cerium were discovered to be useful cations (positively charged ions) for replacing the positively charged sodium in the zeolite structure through ion exchange. REEs are trivalent in nature, meaning that they possess 3 valence electrons. This characteristic allows them to form “bridges” between the acid sites on the zeolite framework. These bridges serve to stabilize the aluminum atoms in the zeolite structure, preventing them from separating from the lattice when the catalyst is exposed to the high temperatures of the FCC unit. As a result, REEs increase FCC catalyst activity, as well as the thermal and hydrothermal stability of the zeolites in the FCC process (Sadeghbeigi, 2012).

**Importance of REEs to Petroleum Refining**

The use of REEs in FCC units for petroleum refining is the largest domestic use of REEs (DOE, 2011), and FCC catalysts are a refinery’s second highest raw material cost behind crude oil (Baillie and Schiller, 2011). Although only accounting for up to 5% by weight of FCC catalysts (Goonan, 2011), REEs are extremely valuable to the FCC process, increasing catalyst
activity and hydrothermal stability, which ultimately increases the gasoline yield per unit of catalyst and allows catalysts to remain effective longer (Sadeghbeigi, 2012).

Catalyst activity refers to the ability of a catalyst to convert a standard feedstock to gasoline, lighter products, and coke (BASF). Essentially, it is the effectiveness of a catalyst in promoting cracking (Indian Oil). It can be measured using a Microactivity (MAT) test, which is essentially a small-scale fixed-bed cracking reactor containing several grams of catalyst, over which a standard gas oil is passed at fixed operating conditions (BASF). The results of a MAT test are influenced by the following factors: catalyst to oil ratio, feedstock quality, reactor temperature, and space velocity (Sadeghbeigi, 2012). Figure 3-4 below depicts the increase in activity that occurs as the weight percentage of REEs in an FCC catalyst increases. A mere 4% increase in the weight percentage of REEs increases catalyst activity by almost a third.

**Figure 3-4:** Effect of Rare Earth on Catalyst Activity

![Figure 3-4: Effect of Rare Earth on Catalyst Activity](source)

Increased weight percentage of REEs in FCC catalysts also increases gasoline yield, but it does so at the expense of gasoline octane (Sadeghbeigi, 2012). That being said, it is important to note that, with the increased use of high-octane ethanol for gasoline blending in recent years, octane loss has become less of a concern in United States (DOE, 2012). Octane is measured using two units: Motor Octane Number (MON) and Research Octane Number (RON) (Sadeghbeigi,
MON is a measurement of the anti-knock capability of a fuel sample compared to a test standard in a single-cylinder, variable-compression test engine running at 900 rpm. RON is a measurement of the anti-knock capability of a fuel compared to a reference fuel in a variable-compression, spark-ignition engine running at a constant speed of 660 rpm. In other words, MON and RON measure how well a fuel will function in an engine run under high load at high speed (BASF). Below is a graph that illustrates the effects of REEs on gasoline yield and octane. The benefits of increased REE weight percentage on the percent of gasoline yielded overshadow the slight loss of octane that occurs.

**Figure 3-5: Effect of REEs on Gasoline Yield and Octane**

![Graph showing effects of REEs on gasoline yield and octane](source: Sadeghbeigi, 2012)

It is clear that the use of REEs in FCC zeolite catalysts has many positive effects for the petroleum refining industry. However, in light of the extremely high REE prices over the last few years, refiners have begun to seek cost-reducing alternatives to REEs. There are several approaches that can be taken to reduce REE levels in FCC catalysts while still maintaining the conversion levels of the average FCC catalyst, which contains 3% rare earth by weight (Ismail,
One approach would be for the refiner to use a greater amount of low rare earth catalyst in
the FCC process, essentially bringing up the overall presence of rare earths in the FCC unit by
using a larger amount of the lower rare earth catalyst. Another approach involves using a catalyst
with a bigger total surface area (TSA) (Ismail, 2011). The bigger the surface area (m$^2$/g) of the
zeolite, the more active the catalyst (Sadeghbeigi, 2012). An additional approach involves
replacing REEs with alternate materials, such as phosphorous, to stabilize the zeolite catalysts
(Grace, 2012). BASF’s CORE (Cost Optimized Rare Earth) and Phinesse (Phosphorous
modification for Stabilization of Zeolite Y) catalysts (McLean et al, 2012), as well as W.R.
Grace’s REpLaCeR family of catalysts (Grace, 2012), are examples of zero and reduced rare
earth catalysts that utilize these approaches.

Various combinations of these approaches have been implemented by chemical
companies in response to the high REE price environment. While the results produced by these
REE-alternative catalysts have been comparable to standard REE catalysts, it remains still that a
higher REE content creates the best conversion results. Table 3-2 below provides data from
BASF regarding the effects of a reduction in REE content paired with an increase in TSA.
Activity is measured using the MAT test explained above. The table below also includes the
percentage of the original petroleum feedstock converted by the catalyst into the respective
petroleum products (gasoline, liquefied petroleum gas, etc.).

Table 3-2: Effects of Reducing REE Content and Increasing TSA

<table>
<thead>
<tr>
<th></th>
<th>2.8% REE</th>
<th>1.8% REE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>360 m$^2$/g TSA</td>
<td>390 m$^2$/g TSA</td>
</tr>
<tr>
<td><strong>Activity</strong></td>
<td>Actual</td>
<td>Actual</td>
</tr>
<tr>
<td>MAT%</td>
<td>76.7</td>
<td>76.6</td>
</tr>
<tr>
<td><strong>Gasoline</strong></td>
<td>wt%</td>
<td>43.33</td>
</tr>
<tr>
<td><strong>Liquefied Petroleum Gas</strong></td>
<td>wt%</td>
<td>20.73</td>
</tr>
<tr>
<td><strong>Light Cycle Oils</strong></td>
<td>wt%</td>
<td>15.11</td>
</tr>
<tr>
<td><strong>Bottoms</strong></td>
<td>wt%</td>
<td>11.89</td>
</tr>
</tbody>
</table>

Source: McLean et al, 2012
Because the REE content reduction was offset with an increase in TSA, there was only a slight loss in catalyst activity. One issue of concern is the increase in the amount of liquefied petroleum gas produced, which some refineries may not have the capacity to handle (Ismail, 2011). However, the main issue has to do with the changes in the amounts of petroleum products produced, which could result in revenue losses for petroleum refiners. The monetary impacts of a reduction of REE content in FCC catalysts can be seen in Table 3-3 below. Currently in the United States, there are approximately 134 operating oil refineries (EIAa, 2012). The table compares the daily sales volumes by petroleum product of an average refinery (gallons per day), as well as the daily revenues earned from these sales, when using 2.8% REE catalysts (the industry norm) as opposed to 1.8%. Ultimately, the changes in production caused by reducing the REE content of the catalyst result in a daily loss of $23,279.72. Table 3-4 provides the raw data used to make these calculations.

Table 3-3: Daily Refinery Sales Volume and Revenues Using Full- and Low-REE Catalysts

<table>
<thead>
<tr>
<th></th>
<th>2.8% REE</th>
<th>1.8% REE</th>
<th>% Change in Production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gallons per refinery per day</td>
<td>Daily Revenues</td>
<td>Gallons per refinery per day</td>
</tr>
<tr>
<td>Gasoline</td>
<td>202,414.93</td>
<td>$576,882.54</td>
<td>-2.88%</td>
</tr>
<tr>
<td>Liquefied Petroleum Gas</td>
<td>34,335.07</td>
<td>$30,592.55</td>
<td>5.89%</td>
</tr>
<tr>
<td>Light Cycle Oils</td>
<td>99,967.91</td>
<td>$326,595.16</td>
<td>-4.57%</td>
</tr>
<tr>
<td>Bottoms</td>
<td>41,632.84</td>
<td>$103,041.27</td>
<td>2.44%</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>$1,037,111.52</td>
<td></td>
</tr>
</tbody>
</table>

Source: EIAb, 2013

Table 3-4: US Daily Refiner Sales Volumes and Prices by Petroleum Product (as of Jan ’13)

<table>
<thead>
<tr>
<th></th>
<th>US Refiner Sales Volume (gal/day)</th>
<th>US Refiner Prices ($/gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>27,123,600</td>
<td>$2.850</td>
</tr>
<tr>
<td>Liquefied Petroleum Gas</td>
<td>4,600,000</td>
<td>$0.891</td>
</tr>
<tr>
<td>Light Cycle Oils</td>
<td>13,395,700</td>
<td>$2.475</td>
</tr>
<tr>
<td>Bottoms</td>
<td>5,578,300</td>
<td>$3.267</td>
</tr>
</tbody>
</table>

Source: EIAb, 2013
Each year, petroleum refiners use approximately 680,000 tons (616,885,800 kg) of FCC catalysts in the refining process (U. Turaga, personal communication, April 8, 2013).

Additionally, each year in the United States, approximately 5,449,085,000 barrels of crude oil are refined (EIAb, 2013). As such, it can be assumed that a barrel of oil requires about 0.000125 tons of REE, or 0.113 kg (EIAb, 2013). On a daily basis, refineries refine approximately 14,929,000 barrels of crude oil daily, meaning that an individual refinery refines about 111,410.45 barrels of crude oil per day. Thus, a petroleum refinery requires approximately 12,612.67 kg of FCC catalyst daily. The current price of lanthanum and cerium oxide is $10.00/kg (Lynas, 2013).

Given all of this information, the impact of catalyst cost on revenues was determined (see Table 3-5). The weight of REEs consumed was determined using total weight of FCC catalyst consumed daily and multiply it by the weight percentages of REEs in the catalyst (i.e. 2.8% and 1.8% by weight of catalyst). Overall, in comparison to the lower-REE content FCC catalyst, the 2.8% REE catalyst would allow a refiner to earn $22,018.45 more each day in revenues. Therefore, it is financially beneficial for refiners to use catalysts with higher REE content.

Table 3-5: Impact of REE Cost on Refinery Revenues

<table>
<thead>
<tr>
<th></th>
<th>2.8% REE Catalyst</th>
<th>1.8% REE Catalyst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Weight of REEs Consumed (kg)</td>
<td>353,1548231</td>
<td>227,0281006</td>
</tr>
<tr>
<td>Daily Revenues from Refinery Sales</td>
<td>$1,037,111.52</td>
<td>$1,013,831.80</td>
</tr>
<tr>
<td>Daily Cost of REEs in Catalysts</td>
<td>$3,531.55</td>
<td>$2,270.28</td>
</tr>
<tr>
<td>Revenues - Catalyst Cost</td>
<td>$1,033,579.97</td>
<td>$1,011,561.52</td>
</tr>
</tbody>
</table>

Source: EIAb, 2013; Turaga (personal communication), 2013; Lynas, 2013

BASF utilizes the alternative material approach in combination with a reduction in REE content in the development of its Phinesse catalyst. The Phinesse catalyst uses phosphorous to replace 50% of the REE content in stabilizing the FCC catalyst’s negative zeolite framework. Again, the results produced by this catalyst were comparable to the average 3% Rare Earth Oxide (REO) by weight catalyst, but the average catalyst exhibited better results. Figure 3-6 below depicts the performance of the Phinesse catalyst in comparison to the average catalyst and
catalysts with simply reduced REE content. In general, the average 3% REE by weight catalyst had the highest level of activity, regardless of the catalyst-to-oil ratio, which is a ratio of the catalyst circulation rate to the rate that fresh petroleum is added to the FCC unit (Indian Oil). The Phinesse catalyst and the catalysts containing 1, 2, and 3% rare earth oxide by weight were all tested under equal conditions. Each of the catalysts was employed at catalyst-to-oil ratios of 3, 4, 5, and 6. The ultimate result was that, at every catalyst-to-oil ratio, the catalyst with the greatest amount of REE (3% by weight) was the most active.

**Figure 3-6:** BASF’s Phosphorous Modified Phinesse Catalyst Compared to Catalysts with Varying REE Percentages by Weight

![Graph showing catalyst activity vs. cat/oil ratio](source: McLean et al, 2012)

In a high REE price environment, refiners may be quick to adopt REE alternatives that will provide immediate cost savings. However, it is important to understand that this may not always be the best decision. Refiners must consider the changes in catalyst performance that REE-alternative catalysts could cause, and they must have a solid understanding of the overall profitability of their FCC unit. This includes not only the costs, but also the yield objectives and
the margin benefits from different yields (Ismail, 2011). A reduction in gasoline yield, or the
yield of any other petroleum product could significantly impact a refinery’s revenues.

Since the price spikes of 2010 and 2011, the price of REEs have begun to fall to their
previous levels. In light of this normalization of prices, many refineries are switching back to
catalysts with full levels of rare earths due to their superior performance. Additionally, the United
States is shifting to heavier petroleum resources from oil sands and shales, and these heavier oils
require more FCC catalyst per barrel for cracking (Baird, 2012). Catalysts containing higher
levels of REE will provide the highest activity levels, and require the least amount of catalyst to
reach these activity levels due to the higher concentration of REE. A catalyst with a lower REE
content may be able to achieve similar activities, but greater amounts of catalyst will be required
to do so. Petroleum refiners are already expected to demand more catalyst per barrel of oil. To
keep this increase in catalyst per barrel of oil at a minimum, it makes sense to use the most active
catalysts. Thus, catalysts with high REE content are a great choice for petroleum refiners, as they
will be able to provide the necessary activity levels while using the least amount of catalyst.
Chapter 4

Methodology of Determining Element Criticality

According to the National Science and Technology Council, critical elements are defined as those that serve an essential function in the manufacture of a product, the absence of which would cause significant economic or social consequence, and whose supply is vulnerable to disruption (Telleen, 2012). There are a variety of factors that play a role in determining criticality, and these factors may have different impacts on supply in different situations.

In this chapter, a mechanism for measuring the risks present and determining the criticality of REEs in various supply-demand situations will be presented. The mechanism will be employed under the circumstances of 3 supply-demand case scenarios, which will be explained in further detail. The first step is to identify factors that could potentially pose a risk to the supply of REEs. The next step is to quantify the level of risk that each factor represents in different situations. Using this information, the final step is to calculate the scenario-specific criticality index of each element, a measure that will enlighten REE consumers of the amount of risk that faces a specific element under the circumstances of each scenario. The data provided through this mechanism will be useful for REE consumers, allowing them to not only gain awareness of the risks facing REEs that are critical to their industry in different scenarios, but also to understand how severe of an impact the risks might have. The mechanism will also be a valuable tool that can help consumers understand and prepare for any future supply scenarios that may occur by altering the data to reflect the changing impacts of supply risk factors.
Key Supply Risk Factors (KSRFs)

Several Key Supply Risk Factors were identified to measure the risks facing the REEs used in Petroleum Refining. These risk factors include producer diversity, resources, demand from alternative applications, international trade, and environmental regulations. The significance of each factor and how it pertains to the elements Cerium and Lanthanum, the two main REEs used in petroleum refining, is explained in this section.

Producer Diversity

Producer Diversity is a measurement of the importance a geographically diverse supply of REEs to meet demand. The level of risk that this KSRF represents is dependent on the amount of the element that can be produced domestically, which is a determining factor of how much supply will need to be obtained from foreign sources. In the event that domestic production does not meet a demand, maintaining a geographically diverse supply is crucial to mitigating risks. If an issue arises with one foreign source that makes trade with that source no longer viable or economical, it is important to have other sources to fall back on to obtain the necessary supply. The detrimental effects of having a non-diversified supply source were seen in 2009 and 2010, when most of the world was almost solely reliable on China for their REE supply, and China sharply reduced REE exports. The prices of REE shy rocketed in response to the reduction in supply, but since China was the main producer, there was nowhere else to turn and no market mechanism to bring the prices back down. The United States and other consumers of REE were forced to pay the unusually high REE prices.

If the element can be produced in large amounts domestically, the risk represented by Producer Diversity is low. In this case, regardless of whether there is or is not a geographically diverse supply of the element, a large portion of the demand can be satisfied domestically, and the United States will require less foreign supply of REEs. However, if the element does not exist in
the United States at all, or it exists in low quantities, it must be obtained from foreign producers. In this situation, Producer Diversity is an extremely important risk factor in obtaining supply. In general, an element’s risk of supply is reduced significantly when it can be obtained from multiple geographic locations. Geographic diversity creates opportunities for trade between different countries with different political regimes and trade policies, providing alternative options for consumers in the event that trade with one supplier is no longer sensible or viable. Additionally, a geographically concentrated supply of REEs presents opportunities for market manipulation by producing countries due to the lack of competition in the market. This creates even more risk for consumers of REEs, who will be forced to trade under unfair circumstances simply because there are few other options.

**Resources**

The availability of financial, human, and physical resources to mine and produce REE is crucial for the development of an REE project, and this KSRF seeks to measure the risk associated with the availability of these resources. The risk level increases when REEs must be obtained from foreign sources, as there is less confidence as to their availability. Some considerations for this KSRF include the location and size of the REE deposit. The availability of financial resources to fund REE mining projects is impacted by whether or not the mining industry is nationalized or privatized. The availability of the human resources (skilled engineers) and physical resources (mining infrastructure and capacity) needed to extract and produce REEs is impacted by how developed the mining industry is in a country. Additionally, the larger the deposit, the larger the mining project would need to be, and the larger the amount of financial, physical, and human resources that would be required to develop it.

**Demand from Alternative Applications**

The Demand from Alternative Applications KSRF measures the impact on the supply of cerium and lanthanum for petroleum refining that the demand from other industries has. The level
of risk that this KSRF presents depends on the growth of other industries, and consequently, their demand for REEs.

Cerium and lanthanum have a variety of end uses, and thus, demand for them comes from a number of different industries. Together, the two elements make up approximately 60% of the total REE demand. Cerium accounts for about 33% of the demand with an expected growth rate of 4-6% through 2020, while lanthanum accounts for about 30% and is expected to grow at a rate of 5-7% through 2020 (Goonan, 2011). Figure 4-1 below is a graphical representation of the percentage of cerium and lanthanum demanded by end use, as well as the estimated growth in REE demand for each end use through 2020.

**Figure 4-1:** Percentage CE and La Used and REE Demand Growth Rates by End Use

*Of all the various REEs used in each industry, the percentage of La and Ce

*Source: Otto, 2011; Goonan, 2011*
Overall, cerium is in higher demand in more industries than lanthanum. However, the impact of Demand from Alternative Applications on the supply of cerium and lanthanum for petroleum refining will be impacted by whichever industry is growing the fastest at the time of analysis.

*International Trade Environment*

International Trade Environment is a measurement of the risks associated with obtaining foreign supply of cerium and lanthanum through trade. The value of this KSRF is determined by taking into consideration the importance of international trade in each case scenario, as well as the country trade scores, which are based on the following items for each country that the United States will trade with: the existence of trade agreements, the value of the imports consumed by the United States from each country as a percentage of that country’s GDP, as well as each country’s Economic Freedom Index score as determined by The Heritage Foundation. The country trade scores were calculated on a 0 to 10 scale using a formula that considers each of the items mentioned previously and their respective weights, as explained below.

In terms of trade agreements, the existence of both Free Trade and Preferential Trade Agreements were considered. The main difference between the two types of agreements is that a Free Trade Agreement (FTAs) is a reciprocal trade agreement between two or more countries and a Preferential Trade Agreement (PTAs) are unilateral and non-reciprocal (WTO, 2013). In general, Free Trade Agreements ease the trade process for all countries involved, allowing parties to the agreement to grant special privileges to each other in terms of tariffs and trade policies (Punyakumpol). Preferential Trade Agreements include preference programs such as the Generalized System of Preferences (GSP), African Growth and Opportunity Act, Caribbean Basin Initiative, and the Andean Trade Preference Act, which are designed to assist developing countries by granting enhanced access to the United States market (US Trade Representative, 2013). The existence of either a Free Trade or Preferential Trade Agreement between the United
States and a trade partner is expected to reduce the risks associated with trade. Since FTAs provide a significantly higher amount of trade flexibility, they were given a heavier weight than PTAs in the formula to determine each country’s trade score. FTAs were weighted 20% and PTAs were weighted only 15%.

The value of the US imports from a country as a percentage of the country’s GDP reflects the strength of trade relations between the US and that country and reveals how reliant on the US that country may be. The higher this percentage, the more it can be assumed that that country values their trade relationship with the United States. While trade agreements make trade simpler, they are not the only indicator of the potential for a successful trade partner. This item was given a weight of 30% because it provides insight into the likelihood of a potential successful trade relationship with any country, whether they have an established trade agreement or not.

Lastly, each country’s Economic Freedom Index was valued at 35% of the country trade score. This index measures ten components of economic freedom: property rights, freedom from corruption, fiscal freedom, government spending, business freedom, labor freedom, monetary freedom, trade freedom, investment freedom, financial freedom (The Heritage Foundation, 2013). Countries with a high level of economic freedom can be expected to be open to trade and to be more stable trade partners.

Each country with REE deposits was assigned a trade score that reflects the risk associated with trading with them using the mechanism below. The scores are on a scale of 0 to 10, 0 being no risk associated with that country and 10 being the highest amount of risk.

- Free Trade Agreement – Weight: 20%
  - No = 10, Negotiating = 5, Yes = 0

- Preferential Trade Agreement – Weight: 15%
  - No = 10, Yes = 5

- U.S. Imports for Consumption as a percentage of country’s GDP – Weight: 30%
Average Percentage = 10, > Average Percentage = 5

- Economic Freedom Index – Weight: 35%
  - Score = 10 – (EFI score/10)

Refer to Appendix A to view the raw data used to determine each country’s final trade score. The KSRF value was ultimately determined by considering the amount of international trade that would take place and looking at the average trade score of all the countries that would be involved in trading. Domestic production would obviously have no international trade risk, as there is no trade involved.

**Environmental Regulations**

Environmental regulations and the general level of environmental conscientiousness of a country have a large impact on the mining and production of REEs and the mining industry in general. This KSRF reflects the level of risk associated with such restrictions. Environmental regulations pose potential risks to the supply of REEs by restricting the number of deposits that can be mined and the methods by which they can be refined, ultimately raising the costs of production. Every country has different level of concern for the environment, some more than others. As such, the value of the Environmental Regulations KSRF will vary depending on the country in which the REEs are produced. This KSRF takes into account existing environmental regulations in the country of production and the country’s Environmental Performance Index (EPI) score. The EPI “ranks countries on performance indicators tracked across policy categories that cover environmental public health and ecosystem vitality” (EPI, 2012). The higher a country’s EPI score, the better their environmental performance. Thus, it is assumed that the environmental regulations are stricter in countries with higher EPI scores, meaning that there is a higher risk to REE supply associated with those countries. Refer to Appendix B for the individual country scores.
Case Scenarios

This report analyzes REE criticality in 3 different supply-demand case scenarios. Each scenario has different implications for each of the KSRFs, and, thus, a different REE criticality index will be determined for each scenario. The case scenarios analyzed in this report are Domestic Supply, Overproduction, and Electric Vehicles. These scenarios were chosen as they represent potential directions towards which the current supply-demand situation could be headed. As such, before detailing these hypothetical case scenarios further, it is important to note the current situation in the United States.

As of 2012, the United States was producing 7,000 metric tons of REEs per year from the Mountain Pass mine in Southern California (Gambogi, 2013). The mine became operational in 2012, 10 years after operations at the site were discontinued. Production is expected to increase through 2013. The US imported $615 million of refined rare earths throughout 2012, 86% of which came from China. Other sources of rare earth imports included France and Japan (Gambogi, 2013). The remainder of this section will detail the 3 hypothetical supply-demand case scenarios.

Domestic Supply

In the Domestic Supply case scenario, the United States is seeking to satisfy as much REE demand with domestic supply as possible. The Mountain Pass mine is operating at the Phase 1 run rate, producing 19,050 metric tons of rare earth oxide per year (Molycorp, 2013). New mining projects are in the exploration and early development phases. In this scenario, the United States is able to supply 100% of the cerium and lanthanum demand for petroleum refining. The overall supply of REEs is increased, quantity demanded increases, and prices begin to fall. However, the private sector faces several roadblocks to mine development throughout the process, namely the strict environmental regulations in the United States. These laws present
several challenges for mining companies that increase development costs as well as the time needed to develop the mines.

The Mountain Pass mine is producing 19,050 metric tons of rare earth oxide per year (Molycorp, 2013). Figure 4-2 below shows the breakdown of REE production at the mine. Cerium and lanthanum account for 49.6% and 33.8% of the production from this mine, respectively (Zhanheng, 2011). As such, in the Domestic Supply scenario, the Mountain Pass mine is producing 9,449 metric tons of cerium and 6,439 metric tons of lanthanum per year. Petroleum refining demands approximately 1,980 metric tons of cerium oxide and 17,800 metric tons of lanthanum oxide globally per year, and these numbers are expected to grow at a rate of 8-10% per year (Goonan, 2011; Otto, 2011). The United States provides 19% of the global refining capacity (BP, 2012), and so, it can be assumed that they make up approximately 19% of the global demand for cerium and lanthanum in petroleum refining. This would mean that the United States would need 376 metric tons of cerium and 3,382 metric tons of lanthanum. Thus, the Mountain Pass mine will be able to cover the total domestic demand for cerium and lanthanum in the US petroleum refining industry.
**Overproduction**

In the Overproduction case scenario, REE production outside of China has increased dramatically. In fact, global production has increased so much that REE prices have fallen to record lows due to excess supply. The United States has ceased exploration and development efforts for new projects, and the Mountain Pass mine has been forced to shut down once again because operation has become uneconomical. A main reason that it has become uneconomical for the United States to continue producing REEs is because of the strict environmental regulations placed upon producers at all stages of project development and operation, which have resulted in high production costs. This is also the case for other countries that maintain high environmental standards such as Canada and Brazil.
The EPI Index (refer to Key Supply Risk Factors section) separates the countries included in the Index into 5 groups based on their scores: Strongest Performers, Strong Performers, Modest Performers, Weak Performers, and Weakest Performers. The United States is a Modest Performer, ranking 49th out of 132 countries in the Index (EPI, 2012). For the purposes of this case scenario, it will be assumed that, in addition to the United States, the countries in the Strongest and Strong Performer groups on the EPI Index will no longer be able to produce REEs economically. This is due to the fact that, like in the United States, the oversupply of REEs has caused REE prices to drop so low that it is now uneconomical for the countries with strict environmental regulations, as these regulations make production more expensive than production in countries with more lenient environmental regulations. The top performing countries that also possess REE deposits are Uruguay, South Korea, the Philippines, Gabon, Canada, Thailand, Brazil, Colombia, Malaysia, Poland, Denmark, Finland, New Zealand, Germany, Sweden, and Norway (EPI, 2012).

The United States is once again reliant on foreign supply of REEs, with a small portion of supply coming from the stockpile that had been generated over the years of operation at Mountain Pass. The supply of REEs has been reduced significantly, and demand is high, as it has grown over the past few years due to low prices. Prices are beginning to rise once again; however, now, unlike during 2008-2010, there is a significant amount of production occurring outside of China. The United States is seeking trade partners and alternatives to REEs in order to satisfy the domestic REE demand.

*Electric Vehicles (EVs)*

In this scenario, the electric vehicle industry is growing rapidly due to advances in technology. Whereas in the past, EVs employed nickel metal hydride (NiMH) batteries, which incorporate a number of rare earths including lanthanum, cerium, neodymium, and praseodymium, the newer models use lithium ion (Li-ion) batteries, which do not require rare
earth (DOE, 2011). The battery alloy end use makes up approximately 10% of total cerium demand and 16% of total lanthanum demand (Goonan, 2011). Thus, demand for cerium and lanthanum is decreasing, supply is increasing, and prices are falling. The Mountain Pass mine is operating at current rates, producing 7,000 metric tons of REEs per year (Gambogi, 2013). Of this, cerium comprises 3,472 pounds and lanthanum comprises 2,366 (Zhanheng, 2011).

Assuming that the United States accounts for 19% of REE demand for cerium and lanthanum in the petroleum refining industry, a number that is consistent with the percentage of refining capacity the US provides (BP, 2012), 376 metric tons of cerium and 3,382 metric tons of lanthanum would be required to meet domestic industry demand. The domestic production along with the reduction in demand for cerium and lanthanum will ultimately reduce the United States’ reliance on foreign supply of cerium and lanthanum, although it will not eliminate it completely. Increased production levels have been achieved by various countries outside of China, including Australia, Canada, Malaysia and Brazil.

Criticality Index

The Criticality Index is a measure of the criticality of a rare earth element based on each of the KSRFs. The risk level associated with each KSRF in each case scenario will be scored on a scale of 0 to 10, 0 being no risk and 10 being the highest amount of risk. The average of these scores is the element’s criticality index. In this section, the criticality index of cerium and lanthanum will be established in each of the 3 case scenarios.
Domestic Supply

Cerium: 3.4

Table 4-1: KSRF Scores for Cerium in the Domestic Supply Case Scenario

<table>
<thead>
<tr>
<th>KSRF</th>
<th>Producer Diversity</th>
<th>Resources</th>
<th>Demand from Alternative Applications</th>
<th>International Trade</th>
<th>Environmental Regulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>2</td>
<td>1</td>
<td>6</td>
<td>2</td>
<td>6</td>
</tr>
</tbody>
</table>

- Producer Diversity: 2

Production at the Mountain Pass mine alone in this case scenario would be more than enough to cover the global demand for cerium oxide in the petroleum refining industry. However, cerium is the most highly demanded REE worldwide, making up approximately 33% of total REE demand (Goonan, 2011). Therefore, it can be expected that some very small portions of supply will have to be obtained from foreign sources due to demand from alternative applications.

Cerium is the REE found in the highest concentrations in the earth’s crust (Castor and Hedrick, 2006). In fact, out of the 799 known REE deposits worldwide, 618 of them contain cerium (Nieto et al, 2012). Figure 4-3 below is a screenshot of a map produced by the Penn State REE Deposit Database that marks the location of all REE deposits containing cerium. The green markers indicate mines that are currently producing cerium, and the blue markers indicate deposits that require 3 years to develop.
Because cerium is located in so many places around the world, the risk associated with producer diversity is very low. There is a high likelihood that the supply necessary to meet increased domestic demand can be easily obtained, and there are many options of potential suppliers in the event that one relationship is no longer beneficial.

- **Resources:** 1

  In this scenario, the United States is able to meet the entire demand for cerium in petroleum refining with domestic supply. As such, the availability of resources is no longer a risk facing supply. There is a slight chance that a very small portion of supply will be obtained from foreign sources due to demand from alternative applications, and, thus, the score for this KSRF is 1.

- **Demand from Alternative Applications:** 6

  As mentioned earlier, cerium is the most highly demanded REE and it is used in a number of different applications. In comparison to these other applications, the amount used in petroleum refining is very small, and thus, it can be expected that there will be a
great amount of competition for the supply of cerium for uses in other applications.

- International Trade: 2

  In the Domestic Supply scenario, the International Trade risk is very low, as there is enough supply to cover demand for cerium in petroleum refining. Due to demand from other applications and the small amounts of cerium used in petroleum refining, there is a slight chance that supply may be obtained from foreign sources. In that event, the countries that would be potential trade partners for the United States in this scenario would be those with deposits that contain cerium and require 10 years or less to develop, as those are the most likely to be producing in the near future when this scenario takes place. Figure 4-4 below shows the locations of the deposits that meet these criteria. Australia, Bangladesh, Brazil, Canada, China, Malaysia, South Africa and Thailand have the most deposits containing cerium and requiring 10 years or less to develop, making them the most viable trade partners.

**Figure 4-4: Deposits Containing Cerium and Requiring 10 Years or Less to Develop**

![Map showing deposits containing cerium and requiring 10 years or less to develop](source: Nieto et al, 2012)

The average trade score of the viable trade countries is 5.57, representing a
medium level of risk. The highest trade score among the viable partners, and thus, the riskiest trade partner, is Brazil with a score of 7.22/10. The least risky trade partner is Canada, which has a score of 2.95/10 (See Appendix A). However, because there is only a low chance that trade will occur to obtain supply due to the large amount of domestic supply, the ultimate score of the KSRF is 2.

- **Environmental Regulations: 6**

  The United States has a number of environmental regulations that dictate how and where mining can occur and that have hindered REE mine development in the past. It is expected that environmental regulations will continue to impact mine development, and thus, represents a high level of risk. Additionally, the creation of new environmental regulations could potentially result in decreased domestic production capacity that would essentially force the United States to meet demand with foreign supply. The United States EPI score is 56.59, and the average of the viable trade partners is 57.5 (EPI, 2012) (See Appendix B). This means that the most viable trade partners in this scenario also have high environmental standards, which represents a higher level of risk.

**Lanthanum: 4.0**

**Table 4-2: KSRF Scores for Lanthanum in the Domestic Supply Case Scenario**

<table>
<thead>
<tr>
<th>KSRF</th>
<th>Producer Diversity</th>
<th>Resources</th>
<th>Demand from Alternative Applications</th>
<th>International Trade</th>
<th>Environmental Regulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>7</td>
</tr>
</tbody>
</table>

- **Producer Diversity: 3**

  Petroleum Refining demands more lanthanum per year than any other application that employs the element. Additionally, the United States has the most refining capacity of any other country in the world, providing approximately 19% of the global refinery capacity (BP, 2012). This implies that the United States has the highest demand for
lanthanum oxide for use in petroleum refining.

In this case scenario, the supply produced at Mountain Pass is enough to cover the domestic demand for lanthanum oxide. However, due to demand from competing applications, there is a slight chance that a portion will have to come from foreign suppliers. Because more lanthanum is required than cerium for petroleum refining, the risk associated with this KSRF is higher for lanthanum than for cerium.

Lanthanum is the second most abundant REE in the earth’s crust behind cerium (Castor and Hedrick, 2006). Of the 799 known REE deposits, 601 of them contain lanthanum (Nieto et al, 2012). Figure 4-5 below is a screenshot from the interactive Penn State REE Deposit Database that marks the location of all REE deposits containing lanthanum. The green markers indicate mines that are currently producing cerium, and the blue markers indicate deposits that require 3 years to develop.

**Figure 4-5: REE Deposits Containing Lanthanum**

![REE Deposits Containing Lanthanum](source: Nieto et al, 2012)

Figure 4-5 clearly demonstrates that lanthanum can be found in many different locations around the world. This means that the risk associated with Producer Diversity is low, as any demand unable to be met with domestic supply can be met relatively easily.
with foreign supply. The availability of mineral resources, high likelihood that demand will be met with domestic supply, and the high importance of lanthanum to petroleum refining were the determining factors behind the KSRF score of 3.

- **Resources: 2**

  Because lanthanum is so important to the petroleum refining industry, the availability of resources to produce and refine it is crucial. Most if not all of the supply in this scenario will be produced domestically, and thus, we can be confident in the availability of physical, human, and financial resources. However, the potential for a small amount of foreign supply creates a small amount of risk associated with lack of proper resources.

- **Demand from Alternative Applications: 5**

  Petroleum refining accounts for approximately 46% of the total global demand for lanthanum oxide; other industries make up a much smaller percentage of the demand in comparison (Goonan, 2011). However, competition from alternative applications of lanthanum threatens the supply available for use in petroleum refining.

- **International Trade: 3**

  In this scenario, foreign producers will supply only a very small portion, if any, of the demand for lanthanum. Thus, the risk associated with International Trade is low. The countries that represent the most viable trade partners in this scenario are those possessing deposits that contain lanthanum and can be developed within 10 years from the current time. Figure 4-6 below is a screenshot from the Penn State REE Deposit Database that depicts the locations of the deposits that fulfill these criteria. Just as was determined for Cerium, Australia, Bangladesh, Brazil, Canada, China, Malaysia, South Africa and Thailand have the most deposits containing lanthanum and requiring 10 years
or less to develop, making them the most viable trade partners.

**Figure 4-6:** Deposits Containing Lanthanum and Requiring 10 Years or Less to Develop

The average trade score for these countries is 5.57, representing a medium level of risk. The most risky trade partner would be Brazil, and the least risky partner would be Canada (See Appendix A). The high importance of lanthanum and the slight chance that foreign supply will be required to meet demand were the determining factors behind the KSRF score of 3.

- **Environmental Regulations: 7**

  The strict environmental regulations of the United States represent a major source of risk to the availability and price of domestic supply of lanthanum. Because lanthanum is such a critical REE to the petroleum refining industry, this KSRF was given a high score. Additionally, like cerium, the average EPI score of the most viable competitors is higher than the United States’ EPI score, meaning that they, too, have strict environmental standards. The highest environmental performer of the viable trade partners is Malaysia with an EPI score of 62.51/100, and the lowest environmental performer is South Africa with an EPI score of 34.55/100 (EPI, 2012) (See Appendix B).
Overproduction

Cerium: 6.8

Table 4-3: KSRF Scores for Cerium in the Overproduction Case Scenario

<table>
<thead>
<tr>
<th>KSRF</th>
<th>Producer Diversity</th>
<th>Resources</th>
<th>Demand from Alternative Applications</th>
<th>International Trade</th>
<th>Environmental Regulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>6</td>
<td>5</td>
<td>7</td>
<td>9</td>
<td>7</td>
</tr>
</tbody>
</table>

- **Producer Diversity: 6**

In this scenario, producer diversity is extremely important and represents a large source of risk simply because the United States is relying on foreign supply. It is important that there are a number of viable countries from which the US can obtain REEs in the event that an issue occurs with a supplier. Figure 4-7 below is a map depicting the REE deposits containing cerium in the countries that could potentially produce REEs in this case scenario. The United States and the EPI top environmental performer countries are not included.

**Figure 4-7: Deposits Containing Cerium Outside of the US and Top Performing EPI Countries**

![Map of cerium deposits outside the US and top performing EPI countries](Source: Nieto et al, 2012)

A large number of cerium deposits exist outside of the US and the top scoring
EPI countries, and it is likely that supply will be able to be obtained from multiple
countries. This and the fact that a relatively small amount of cerium is needed for
petroleum refining purposes were the factors that determined the KSRF score of 6.

- **Resources: 5**

  Resources represent a moderate source of risk in this scenario. Because the US is
  reliant on foreign supply, there is less confidence as to the availability of proper
  resources. However, the reduction in overall supply and the excess human and physical
  resources from countries that are no longer able to produce REEs will likely reduce the
  risk associated with this KSRF.

- **Demand from Alternative Applications: 7**

  The demand from alternative applications represents a significant risk in this
  scenario. With the supply of REEs significantly reduced, it will already be more difficult
  to obtain supply. However, demand for cerium from other industries, will make obtaining
  adequate supply even more difficult. Cerium is used in much greater amounts than
  petroleum refining in glass polishing, glass additives, automobile catalytic converters,
  and metallurgy (excluding batteries) (Goonan, 2011).

- **International Trade: 9**

  As this scenario depends primarily on trade with foreign countries, the
  international trade factor represents a major source of risk. The most viable potential
  trade partners in this scenario would be countries that possess cerium deposits and require
  less than 10 years to develop. Figure 4-8 below depicts the locations of these deposits
  among the producing countries in this scenario. Australia, Bangladesh, China, South
  Africa, and Vietnam are the most viable trade partners, as they contain the most deposits
  that meet these criteria.
The average trade score of the viable trade partners is 5.94, representing a moderately high risk. The riskiest trade partner is South Africa, with a score of 7.06/10, and the least risky trade partner is Australia with a trade score of 4.34/10 (See Appendix A). The importance of international trade in this scenario and the moderately high average trade score of the potential trade partners were the determining factors behind the KSRF score of 9.

- Environmental Regulations: 7

This scenario demonstrates the huge impact that environmental regulations can have on REE supply. In this case, albeit drastic, 17 countries that possess REE deposits are unable to produce them due to strict environmental regulations. The availability of supply from the other countries hinges on whether or not their production will be limited by environmental regulations, as well. The average EPI score for the 5 viable trade partners is 45.32, which is below the average of all the countries included in the Index. South Africa had the lowest EPI score with 34.55/100 and Australia had the highest with
a 56.61/100 (EPI, 2012) (See Appendix B). This represents a relatively low risk to supply of cerium. Due to these factors, the KSRF was given a score of 7.

**Lanthanum: 7**

**Table 4-4: KSRF Scores for Lanthanum in the Overproduction Case Scenario**

<table>
<thead>
<tr>
<th>KSRF</th>
<th>Producer Diversity</th>
<th>Resources</th>
<th>Demand from Alternative Applications</th>
<th>International Trade</th>
<th>Environmental Regulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>7</td>
<td>5</td>
<td>6</td>
<td>10</td>
<td>7</td>
</tr>
</tbody>
</table>

- **Producer Diversity: 7**

  Because the United States has no domestic production in the scenario, the risk associated with producer diversity is high. It is crucial for the supply of lanthanum to be diverse so as to reduce the risk of supply disruption if one supplier is unable to come through. Additionally, because lanthanum is so critical to the petroleum refining industry and such a large amount is needed, this risk of supply disruption could have a heavy impact.

  Lanthanum is found in many locations around the world. Figure 4-9 below is a depiction of the lanthanum deposits found in the countries that can produce in this scenario.
The fact that the supply of lanthanum is diverse, but that a large amount will have to be obtained from foreign sources, determined the KSRF score of 7.

- **Resources:** 5

  Like for cerium, this KSRF has a moderate level of risk associated with it in this case scenario. Because the United States is completely reliant on foreign supply, there is some question as to whether or not resources are adequate to meet demand. However, there will be an excess of human resources and production capacity in the countries that can no longer produce. It is expected that the excess human resources will be allocated to the foreign countries that will become the sole producers, and that countries no longer mining REEs will be able to produce imported rare earth oxides domestically.

- **Demand from Alternative Applications:** 6

  In this scenario, the supply of REEs has been greatly reduced. As such, different industries will be competing for a reduced supply. However, petroleum refining demands significantly more lanthanum than any other industry, meaning that the petroleum refining industry faces little risk to supply of lanthanum due to competition from other...
industries.

- **International Trade: 10**

  This factor is given a score of 10 to represent the high level of risk associated with international trade in this scenario due to the fact that the United States is 100% reliant on foreign supply. Because petroleum refining requires so much lanthanum, the risk associated with this KSRF is especially high. The most viable potential trade partners would be countries with lanthanum deposits requiring 10 years or less to develop. Just as for cerium, the countries with the most deposits meeting these criteria are Australia, Bangladesh, China, South Africa and Vietnam. Figure 4-10 below depicts the locations of these deposits.

  **Figure 4-10:** Lanthanum Deposits Outside the US and Top Performing EPI Countries Requiring 10 Years of Less to Develop

  [Map showing lanthanum deposits outside the US and top performing EPI countries requiring 10 years of less to develop]

  *Source: Nieto et al, 2012*

  The average trade score of the viable trade partners is 5.94, with South Africa being the most risky and Australia the least (See Appendix A). This moderately high level of risk along with the amount of lanthanum demanded and the fact that the US is 100% reliant on foreign supply were the determining factors of the score for this KSRF.
• Environmental Regulations: 7

Environmental regulations represent a large source of risk in this scenario, especially as 17 countries are unable to produce REEs because of them. The supply of REEs from other countries is also largely impacted by environmental regulations and how strict they are. The average EPI score of the trade partners is a 45.32, which is below the average score of all the countries included in the Index. South Africa has the least risk associated with environmental regulations and Australia the most (EPI, 2012) (See Appendix B). This means that while there is currently a relatively low amount of risk associated with these countries, there is a high risk that supply would be severely disrupted if a country changes their regulations.

Electric Vehicles (EVs)

Cerium: 3.8

Table 4-5: KSRF Scores for Cerium in the Electric Vehicles Case Scenario

<table>
<thead>
<tr>
<th>KSRF</th>
<th>Producer Diversity</th>
<th>Resources</th>
<th>Demand from Alternative Applications</th>
<th>International Trade</th>
<th>Environmental Regulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>7</td>
</tr>
</tbody>
</table>

• Producer Diversity: 2

The reduced demand for cerium for use in NiMH batteries will make more domestic supply of cerium available to other industries, including the petroleum refining industry. Additionally, the amount that will be produced domestically at the Mountain Pass mine will be more than enough to cover the small amount of demand required for petroleum refining. As such, there is a low likelihood that supply will need to be obtained from foreign sources, so the risk associated with Producer Diversity is low.

• Resources: 2

Similarly, because supply can be covered domestically at current production
levels and there is a low chance that foreign supply will be necessary to meet demand, the risk associated with availability of resources is low.

- **Demand from Alternative Applications: 5**

  The battery alloy end use employs the 5th highest amount of cerium by metric tonnage, with glass polishing, glass additives, automobile catalytic converts, and metallurgy (excluding batteries) all employing greater amounts of the element. In fact, battery alloys accounts for 10% of total global cerium demand (Goonan, 2011). Therefore a reduction in demand for cerium for this specific end use is likely to create only a small reduction in the competition for cerium supply for use in alternative applications. Therefore, this KSRF was given a score of 5 to reflect the moderate level of risk to cerium supply associated with the demand for the element from other industries.

- **International Trade: 3**

  There is only a slight chance that foreign supply of cerium will have to be obtained to meet supply in this case scenario due to the adequate levels of domestic production. Additionally, in the event that international trade is required to meet demand, only small amounts of the element will be needed. As this scenario is hypothetically taking today and at the current domestic production levels, the most viable trade partners would be those countries that are currently producing cerium or have mines that require 3 years or less to develop. Figure 4-11 below depicts the geographic locations of these mines.
Using the information provided from the Penn State REE Deposit Database (Nieto et al, 2012) and the most recent REE production data provided by the USGS (Gambogi, 2013), the most viable trade partners in this scenario are China, India, Australia, Malaysia, and Brazil. The average trade score of these countries is 6.16, representing a moderately high level of risk. The riskiest trade partner in this scenario would be India with a trade score of 7.34, and the least risky would be Australia with a score of 4.34 (See Appendix A). The moderately high level of risk associated with the potential trade partners coupled with the low likelihood of obtaining REE supply through international trade determined the KSRF score of 3.

- Environmental Regulations: 7

In this scenario, Environmental Regulations represent the highest risk to supply as the implementation of more stringent environmental regulations in the United States would be the most likely cause for decreased domestic production. As the Mountain Pass mine is the only domestic source of production, anything that could potentially disrupt supply from the mine represents a major source of risk. In the event that this does occur,
the average EPI score of the potential trade partners (China, India, Australia, Malaysia, and Brazil) is 51.7, which is below the US score of 56.59 and just below the average of all the countries included in the Index, which is 51.88 (EPI, 2012) (See Appendix B). This means that the risk associated with environmental regulations in the event that international trade is required would be moderate.

**Lanthanum: 6.4**

**Table 4-6: KSRF Scores for Lanthanum in the Electric Vehicles Case Scenario**

<table>
<thead>
<tr>
<th>KSRF</th>
<th>Producer Diversity</th>
<th>Resources</th>
<th>Demand from Alternative Applications</th>
<th>International Trade</th>
<th>Environmental Regulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>9</td>
<td>8</td>
</tr>
</tbody>
</table>

- **Producer Diversity: 6**

  In this scenario, only about 70% of the demand for lanthanum in the petroleum refining industry can be met with domestic supply. Taking into consideration the fact that some of the lanthanum that is produced domestically will be used for purposes other than petroleum refining, this amount is even less. As such, a significant portion of the demand must be satisfied with foreign supply, meaning that Producer Diversity represents a significant amount of risk. It is important for the United States to have a geographically diverse supply to mitigate potential issues that may occur with a single supplier.

Lanthanum is quite abundant in the Earth’s crust, and therefore, it will be relatively easy to establish a diversified supply.

- **Resources: 6**

  As a significant portion of supply will be coming from foreign producers, there is less confidence in the availability of sufficient resources to meet REE demand. Thus, the risk associated with this KSRF is considered to be moderately high.

- **Demand from Alternative Technologies: 3**
Behind petroleum refining, the battery alloy end use demands the greatest amount of lanthanum per year, making up approximately 16% of the global lanthanum demand (Goonan, 2011). Therefore, a reduction in the use of lanthanum in NiMH batteries would reduce the amount of competition for lanthanum and the risk of supply associated with this competition significantly.

- **International Trade:** 9

As a significant amount of lanthanum will need to be obtained from foreign sources, international trade represents a major source of risk. As was the case for cerium, the most viable trade partners in this scenario would be those countries possessing deposits containing lanthanum and requiring 3 years or less to develop. Figure 4-12 below shows the locations of the deposits that fit these criteria.

**Figure 4-12:** Lanthanum Deposits Requiring 3 Years or Less to Develop

Again, like cerium, the most viable trade partners using the data provided by the Penn State REE Deposit Database (Nieto et al, 2012) and the most recent USGS REE production data (Gambogi, 2013) are China, India, Australia, Malaysia, and Brazil. The average trade score of 6.16 for these countries represents a moderately high level of risk.
(See Appendix A). This fact, the importance of trade in this scenario, and the importance of lanthanum to petroleum refining accounts for the KSRF score of 9.

- Environmental Regulations: 8

  Environmental Regulations represent a major risk to supply of lanthanum, especially in the United States. The United States’ high EPI score of 56.59 and the average of the trade partners of 51.7 were the determining factors behind the KSRF score of 8 (EPI, 2012) (See Appendix B).
Chapter 5
Results and Conclusions

The criticality index of each of the KSRFs and the average for each element were compiled to create Criticality Index graphs for each element in each case scenario. These graphs provide a visual representation of the data, illustrating the risk associated with each KSRF and the overall element criticality. By graphing the data in this way, the impact of each KSRF on the element’s ultimate Criticality Index can be clearly recognized and understood. Additionally, the variations in the impacts of the KSRFs on criticality among the different case scenarios can be recognized. These graphs are intended to assist REE consumers in predicting and preparing for the effects of potential REE supply scenarios. The information they provide will be useful in the initial planning stages of the preparation process. This section contains the Criticality Index graphs for Cerium and Lanthanum in each of the 3 hypothetical case scenarios.

Domestic Supply

Figure 5-1: Criticality Index Graph for Cerium in the Domestic Supply Case Scenario

"Domestic Supply" Criticality Index
Cerium: 3.4
Figure 5-1 above depicts the criticality of cerium in the Domestic Supply case scenario. The graph illustrates that demand from alternative applications and environmental regulations represent the major sources of risk in this scenario. The overall criticality index of 3.4 for cerium implies that the risk of supply for cerium is low. When developing a plan for obtaining supply of cerium under circumstances like those of the Domestic Supply scenario, REE consumers in the petroleum refining industry must prepare for challenges in the areas of demand from other industries and environmental regulations. Further research should be conducted to determine which specific industries are growing the most at the time and what the impact of that growth will be on the demand for cerium or lanthanum. Additionally, research should be conducted regarding the environmental regulations that are creating the most complications in the mining industry, how they can be avoided, and if foreign supply is needed, which countries have a regulatory environment that is conducive to REE mining.

Figure 5-2: Criticality Index Graph for Lanthanum in the Domestic Supply Case Scenario

Figure 5-2 above depicts the criticality of lanthanum in the Domestic Supply case scenario. The overall Criticality Index of 4.0 for the element indicates a moderately low level of
risk facing supply. For this element, the biggest sources of risk come from environmental regulations and demand from alternative applications. When developing a plan for obtaining lanthanum under the circumstances of this scenario, one must prepare accordingly for difficulties in these areas. Consumers in the petroleum refining industry must be aware of the alternative uses of lanthanum and be mindful of new developments in those industries. In terms of environmental regulations, like for cerium, it is important for consumers to gain an understanding of the domestic regulations that complicate mining, as well as the regulatory environment of their potential trade partners.

Overproduction

Figure 5-3: Criticality Index for Cerium in the Overproduction Case Scenario

Figure 5-3 above is a visual representation of the Criticality Index for cerium in the “Overproduction” case scenario. The main source of risk is International Trade, as in this scenario, the United States is completely reliant on foreign supply. With this knowledge, consumers of REEs must adequately prepare for any issues surrounding international trade that could disrupt the supply of cerium. It is important to establish trade relations with multiple
producers of REEs to prepare for any potential trade complications that may arise with a single supplier. Research must be conducted as to which countries may be the best options depending on the current political and economic situation. Also representing high levels of risk are Demand from Alternative Applications and Environmental Regulations. If obtaining an adequate supply of cerium for use in petroleum refining becomes unfeasible due to any of these factors, substitution or recycling should be considered.

**Figure 5-4:** Criticality Index for Lanthanum in the Overproduction Case Scenario

Similarly to cerium, the International Trade KSRF represents the greatest source of risk for lanthanum. Producer Diversity and Environmental Regulations are also major sources of risk, mostly due to lanthanum’s importance to petroleum refining. Because so much lanthanum is required to satisfy demand, these KSRFs represent greater risks to supply. Petroleum refining is the primary application of lanthanum, and as such Demand from Alternative Applications represents a lower level of risk. Additionally, the excess of human and financial resources available from the countries that are no longer producing in this scenario reduces the risk
associated with Resources. REE consumers in this scenario should focus on mitigating risks surrounding international trade and diversifying supply.

*Electric Vehicles (EVs)*

**Figure 5-5:** Criticality Index for Cerium in the Electric Vehicles Case Scenario

The greatest sources of risk in this scenario come from Environmental Regulations and Demand from Alternative Applications. Overall, cerium has a relatively low criticality index in this scenario, largely due to the large supply of domestic REEs being produced. Environmental regulations are the biggest threat to this supply, and thus, the Environmental Regulations KSRF was given the highest score. Consumers of REEs need to be aware of the existing and potential future regulations that could affect mining for REEs and prepare accordingly for any potential supply disruptions. Additionally, as cerium is used for a variety of applications besides petroleum refining, it is important for consumers to be aware of any changes in competing markets that could decrease or, as in this case scenario, increase the supply of cerium available to them.
Lanthanum has a relatively high Criticality Index in this scenario with the most risk stemming from International Trade and Environmental Regulations. Unlike for cerium, the domestic supply of lanthanum in this case scenario does not cover the demand for the element in the petroleum refining industry. This means that a portion of the supply will be obtained from foreign sources, increasing the risks associated with international trade. REE consumers in the petroleum refining industry must account for the risks that accompany international trade and prepare by obtaining supply from geographically diverse locations. It is important to be aware of the trade environments of the potential trade partners and to be prepared in the event that a supplier is no longer a viable trade partner. While international trade represents the risks associated with foreign supply, environmental regulations have a large impact on the availability of domestic supply, and thus, are given a high score in this scenario. Awareness of current and potential future environmental regulations facing the mining industry is crucial to predicting the availability of lanthanum.
Summary

Recent history has revealed the true price volatility of Rare Earth Elements and the detrimental effects that this volatility could have on a number of industries. As REE demand continues to grow, it is imperative that consumers have a stable and reliable supply of REEs to meet demand. Consumers must be able to identify potential risks to supply, understand the severity of these risks, and use this knowledge to implement strategies to mitigate these risks. The methodology for developing a Criticality Index for REEs outlined in this report is a tool designed to help consumers to be able to do just this.

Five main areas of risk have been identified that could potentially cause supply disruptions: producer diversity, availability of resources, demand from alternative applications, international trade environment, and environmental regulations. These risk factors vary in importance under different circumstances, as can be seen by the varying results for each element in each case scenario in this report. The landscape of the REE market is constantly changing, and it is important to evaluate the implications of changing circumstances through the scope of these main risk factors. Awareness is the most crucial step in mitigating risk, and this tool will be extremely valuable in providing REE consumers with an overview of the risk environment surrounding REE supply.
## Appendix A

### Trade Scores by Country

<table>
<thead>
<tr>
<th>Countries with REE Deposits</th>
<th>Free Trade Agreement¹</th>
<th>FTA Score</th>
<th>Preferential Trade Agreement²</th>
<th>PTA Score</th>
<th>US Imports for Consumption ($millions)³</th>
<th>GDP ($billions)⁴</th>
<th>Imports/GDP</th>
<th>Imports Score</th>
<th>Economic Freedom Index⁵</th>
<th>EFI Score</th>
<th>TOTAL TRADE SCORE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Afghanistan</td>
<td>No</td>
<td>10   yes</td>
<td>5</td>
<td>20.1</td>
<td>18.315</td>
<td>0.11%</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>9.25</td>
<td>6.1155</td>
</tr>
<tr>
<td>Angola</td>
<td>No</td>
<td>10   yes</td>
<td>5</td>
<td>13,756.40</td>
<td>104.288</td>
<td>13.19%</td>
<td>5</td>
<td>46.7</td>
<td>5.33</td>
<td>7.57</td>
<td>6.842</td>
</tr>
<tr>
<td>Argentina</td>
<td>No</td>
<td>10   yes</td>
<td>5</td>
<td>4,525.10</td>
<td>444.612</td>
<td>1.02%</td>
<td>10</td>
<td>48</td>
<td>5.2</td>
<td>7.43</td>
<td>4.3415</td>
</tr>
<tr>
<td>Armenia</td>
<td>No</td>
<td>10   yes</td>
<td>5</td>
<td>91.8</td>
<td>10.251</td>
<td>0.90%</td>
<td>10</td>
<td>68.8</td>
<td>3.12</td>
<td>5.888</td>
<td>5.888</td>
</tr>
<tr>
<td>Australia</td>
<td>Yes</td>
<td>0    yes</td>
<td>5</td>
<td>10,172.80</td>
<td>1486.91</td>
<td>0.68%</td>
<td>10</td>
<td>83.1</td>
<td>1.69</td>
<td>7.493</td>
<td>7.493</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>No</td>
<td>10   yes</td>
<td>5</td>
<td>4,869.50</td>
<td>113.855</td>
<td>4.28%</td>
<td>5</td>
<td>53.2</td>
<td>4.68</td>
<td>7.43</td>
<td>7.43</td>
</tr>
<tr>
<td>Benin</td>
<td>No</td>
<td>10   yes</td>
<td>5</td>
<td>2</td>
<td>7.3</td>
<td>0.03%</td>
<td>10</td>
<td>55.7</td>
<td>4.43</td>
<td>7.3005</td>
<td>7.3005</td>
</tr>
<tr>
<td>Bolivia</td>
<td>No</td>
<td>10   yes</td>
<td>5</td>
<td>873.5</td>
<td>24.06</td>
<td>3.63%</td>
<td>10</td>
<td>50.2</td>
<td>4.98</td>
<td>7.493</td>
<td>7.493</td>
</tr>
<tr>
<td>Brazil</td>
<td>No</td>
<td>10   yes</td>
<td>5</td>
<td>30,367.90</td>
<td>2492.91</td>
<td>1.22%</td>
<td>10</td>
<td>57.9</td>
<td>4.21</td>
<td>7.2235</td>
<td>7.2235</td>
</tr>
<tr>
<td>Burundi</td>
<td>No</td>
<td>10   yes</td>
<td>5</td>
<td>9.6</td>
<td>2.356</td>
<td>0.41%</td>
<td>10</td>
<td>48.1</td>
<td>5.19</td>
<td>7.5665</td>
<td>7.5665</td>
</tr>
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<td>Cameroon</td>
<td>No</td>
<td>10   yes</td>
<td>5</td>
<td>322.2</td>
<td>25.649</td>
<td>1.26%</td>
<td>10</td>
<td>51.8</td>
<td>4.82</td>
<td>7.437</td>
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</tr>
<tr>
<td>Canada</td>
<td>Yes</td>
<td>0    yes</td>
<td>5</td>
<td>316,396.50</td>
<td>1738.95</td>
<td>18.19%</td>
<td>5</td>
<td>79.9</td>
<td>2.01</td>
<td>2.9535</td>
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</tr>
<tr>
<td>China</td>
<td>No</td>
<td>10   no</td>
<td>10</td>
<td>398,466.80</td>
<td>7298.15</td>
<td>5.46%</td>
<td>5</td>
<td>51.2</td>
<td>4.88</td>
<td>6.708</td>
<td>6.708</td>
</tr>
<tr>
<td>Colombia</td>
<td>Yes</td>
<td>0    yes</td>
<td>5</td>
<td>22,390.90</td>
<td>327.626</td>
<td>6.83%</td>
<td>5</td>
<td>68</td>
<td>3.2</td>
<td>3.37</td>
<td>3.37</td>
</tr>
<tr>
<td>Congo</td>
<td>No</td>
<td>10   yes</td>
<td>5</td>
<td>475.1</td>
<td>14.75</td>
<td>3.22%</td>
<td>10</td>
<td>41.1</td>
<td>5.89</td>
<td>7.8115</td>
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</tr>
<tr>
<td>Denmark</td>
<td>No</td>
<td>10   no</td>
<td>10</td>
<td>6,749.30</td>
<td>332.019</td>
<td>2.03%</td>
<td>10</td>
<td>76.2</td>
<td>2.38</td>
<td>7.333</td>
<td>7.333</td>
</tr>
<tr>
<td>Egypt</td>
<td>No</td>
<td>10   yes</td>
<td>5</td>
<td>1,925.90</td>
<td>235.719</td>
<td>0.82%</td>
<td>10</td>
<td>57.9</td>
<td>4.21</td>
<td>7.2235</td>
<td>7.2235</td>
</tr>
<tr>
<td>Finland</td>
<td>No</td>
<td>10   no</td>
<td>10</td>
<td>4,420.10</td>
<td>263.488</td>
<td>1.68%</td>
<td>10</td>
<td>72.3</td>
<td>2.77</td>
<td>7.4695</td>
<td>7.4695</td>
</tr>
<tr>
<td>Gabon</td>
<td>No</td>
<td>10   yes</td>
<td>5</td>
<td>4,432.10</td>
<td>15.97</td>
<td>27.75%</td>
<td>5</td>
<td>56.4</td>
<td>4.36</td>
<td>5.776</td>
<td>5.776</td>
</tr>
<tr>
<td>Germany</td>
<td>No</td>
<td>10   no</td>
<td>10</td>
<td>96,539.20</td>
<td>3607.36</td>
<td>2.68%</td>
<td>10</td>
<td>71</td>
<td>2.9</td>
<td>7.515</td>
<td>7.515</td>
</tr>
<tr>
<td>Ghana</td>
<td>No</td>
<td>10   yes</td>
<td>5</td>
<td>779</td>
<td>38.394</td>
<td>2.03%</td>
<td>10</td>
<td>60.7</td>
<td>3.93</td>
<td>7.1255</td>
<td>7.1255</td>
</tr>
<tr>
<td>Greenland</td>
<td>No</td>
<td>10   no</td>
<td>10</td>
<td>7.5</td>
<td>1.27</td>
<td>0.59%</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Guinea</td>
<td>No</td>
<td>10   yes</td>
<td>5</td>
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Average 3.71%

Appendix B

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1 Source: The Heritage Foundation, 2013
REFERENCES


Zhanheng, Chen (2011, January). “Global Rare Earth Resources and Scenarios of
Future Rare Earth Industry.” *Journal of Rare Earths*, **29**(1), 1-6.
ACADEMIC VITA

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khg5021@psu.edu

EDUCATION

The Pennsylvania State University
B.S. Energy, Business, and Finance
• Minors: German and International Studies
  University Park, PA
Aug. 2009-May 2013

IES Abroad Vienna: European Society and Culture
German and International Business
Vienna, Austria
Aug.-Dec. 2011

Arcadia University: Renewable Energy Policy and Development
Focus on Market Solutions for Renewable Energy in Developing Countries
Bonn, Germany
June-July 2010

HONORS AND AWARDS

Scholarships, College of Earth and Mineral Sciences, Penn State University
• Hess Scholarship in EME 2012-2013
• John and Elizabeth Holmes Teas Scholarship 2011-2012
• John C. and Marilyn B. Redmond Scholarship 2010-2011

Awards
• EMSAGE (College of Earth and Mineral Sciences Academy of Global Experience) Laureate 2013
• President’s Freshman Award 2009

EXPERIENCE

Research Assistant
  University Park, PA
Aug. 2012-May 2013

Alberta Energy Challenge
Penn State Competition Team
Edmonton, Alberta
Fall 2012
• Business case competition focused on the Canadian Oil Sands Industry

Southwestern Energy
Supply Chain Intern
Houston, TX
May-Aug. 2012
• Investigated seven departments of Supply Services group to define metrics and develop a standardized and streamlined quarterly reporting mechanism

GBR Financial Services, GmbH
Intern
Vienna, Austria
Aug.-Dec. 2011
• Researched the global and European cellulosic fiber market and conducted a company analysis
### Activities

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<th>Activity</th>
<th>Year</th>
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<td>Presidential Leadership Academy</td>
<td>2010-2013</td>
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<td>• Selected through intensive interview process to participate in a 3-year program that cultivates leadership and critical thinking skills</td>
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<td>Penn State Club Swim Team</td>
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<td>• Coach (2012-2013)</td>
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<td>Study Abroad Peer Adviser</td>
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<td>Women’s Varsity Swim Team</td>
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