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PREDICTING THE U.S. SUPPLY OF RARE EARTH ELEMENTS CONSIDERING CURRENT WORLD RESERVES USING GOOGLE MAPS AND FUSION TABLES

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ABSTRACT

Rare earth elements (REEs) are crucial to green technology such as hybrid-electric vehicles, wind turbines, and fluorescent light bulbs. As of 2011, China dominates the world's production of REEs and is reducing export quotas. An economic analysis of REEs' supply and demand trends was performed; the conventional supply-demand-price relationship can be applied to REEs if global economic growth is considered.

To predict the locations of future rare earths' mines and create future supply scenarios, a geographic visualization tool was built with Google Fusion Tables. Five case scenarios with varying levels of demand were created by filtering several variables including: (1) international political atmosphere; (2) greenhouse gas regulations; (3) environmental mining regulations; and (4) applicability ratio of REEs.

The future supply scenarios, deposits with heavy REEs and deposits with "critical" REEs (high supply risk and high importance to green technology) led to conclusions and suggestions to secure the REEs' supply. The most realistic scenario with Japan's current demand levels shows how the United States possesses REEs' resources and the development of these resources needs to be expedited. The United States does not have significant resources with heavy REEs. While dysprosium is the most critical element, there are fewer potential locations to mine for europium in the United States. Further exploration is required to gain additional information about the inferred rare earths' resources. Also, further research is required to find alternative materials to replace REEs and decrease the REEs' applicability ratio, since the rare earths ore will be eventually depleted. While domestic mines are developing, alternative materials are being researched, and recycling programs are advancing, the United States should strengthen trade relationships with Australia and Canada as these countries have developing REEs' mines.

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Chapter 1

Introduction

Rare earth elements (REEs) comprise the group of elements called lanthanides with atomic numbers between 57 and 71 and yttrium (Castor and Hedrick, 2006). REEs are crucial for producing green technology (rechargeable batteries, compact fluorescent light bulbs, and high power density motors) designed to reduce pollution and greenhouse gas emissions (Molycorp, 2011). REEs are also applied in the defense industry as components of lasers and night vision goggles (Hedrick, 2004). Deposits with high concentrations of REEs are rare. The ores at these deposits consist of rare earth oxides (REOs) with varying grades of rare earth minerals (REMs) containing REEs.

China has the largest amount of REOs, 48% of the of the world's reserves (Cordier, 2011a). In 1992, Deng Xiaoping compared China's monopoly on rare earths to the Middle East's monopoly on oil; however, that comparison is no longer valid (Stone, 2009). In 2009, the United States imported 51% of the total amount of petroleum products consumed, with the highest percentage, 23.3%, coming from Canada (EIA, 2010). In contrast, the United States imported 100% of its rare earths' needs with 92% originating from China (Cordier, 2011a). There is a global rare earths monopoly currently, and it is probably more concerning than Middle East's monopoly on oil. While the United States possesses 12% of the world's reserves of REOs and could develop some deposits into active mines, the United States did not produce any REOs in 2010 (Cordier, 2011a).

This monopoly has prompted action from the United States' government. The Department of Energy (DOE), the United States Geological Survey (USGS), and the Department of Defense (DOD) are advising Congress of the rare earths situation. One bill in the House of Representatives will stimulate domestic REOs production (Govtrack.us, 2011). The USGS compiled a database detailing the global "REE Mines, Deposits, and Occurrences" and a report describing the rare earths' deposits in the United States (Orris and Grauch, 2002; Long et al, 2010). With these two references, a geographic visualization tool was created to help analysts predict the future supply of REEs based on the location, status or number of years required to develop the deposit, type of REE, and applications of the REEs. This tool is available as a public table entitled "REEs' Deposits Database" at http://www.google.com/fusiontables/.

Hypotheses and Objectives

REEs' importance to green technologies and defense applications increases the need for the United States to have a diversified stock of REEs sources. Relying on China for 92% of the country's demand dramatically increases the risk of a REEs' supply interruption in the future. To prevent a REEs' shortage, the United States should develop domestic sources of REEs and secure additional international sources. More geological exploration is necessary to determine the status, quantity, and quality of the rare earths' deposits in the United States.

Using data from the United States Geological Survey (USGS), a geographic visualization tool was created to predict the locations of future rare earths' mines. Users can filter several categories including country, state, REMs, REEs, applications, tonnage and grade, deposit type, status, years needed to develop, etc. Analysts at the DOE, DOD, and USGS can use this tool during the decision making process of choosing where future mines will be located. Five scenarios forecasting the future REEs supply were created through this tool. The scenarios predicted the supply of REEs based on four variables with different severities including (1) international political atmosphere; (2) greenhouse gases regulations; (3) environmental mining regulations; and (4) applicability ratio. Also, this tool identified locations with REEs identified as "critical" due their supply risk and importance to green technology by the Department of Energy (DOE). These locations should have priority in development plans.

After examining the background information on REEs and the future supply scenarios, it is clear that the United States needs to focus on several tasks in the near future. The following tasks should be accomplished within the next five years: expedite the development and permitting process of domestic rare earths' mines, strengthen trade relationships with Australia and Canada, and increase research seeking alternatives materials to replace REEs.

Chapter 2

REEs' Background: Importance, Distribution, and Geology

Before the supply of REEs can be predicted, a thorough description of these elements and their applications must be obtained. The societal importance of REEs is examined through the definition of REEs, the difficulties with refining REOs, and the industrial applications of REEs. The geographic distribution of the REEs' reserves, production, and consumption depict an imbalanced international trade relationship with China controlling the production and many countries without developed reserves. Important deposits such as Mount Weld in Australia and Thor Lake in Canada are being developed. The geology of these deposits is defined by the types of REEs' deposits and the REMs present at the deposits.

The Importance of REEs

REEs are essential to the American society because of their chemical properties required for many types of applications from green technology to defense equipment. The United States' government is considering legislation to secure the future supply of REEs. REOs are difficult to process because the REEs have similar chemical properties. The important applications of REEs include permanent magnets in wind turbines and batteries in electric vehicles as well as lasers in defense equipment.

Definition of REEs and Potential Legislation

REEs, defined as the lanthanides and yttrium, have only recently been widely applied to a variety of industries including renewable energy, defense, and petroleum refining. The process of extracting the elements from the oxides was discovered in 1950 (Haxel et al, 2002). REEs research began during World War II due to the interest in nuclear weapons and continued into the 1970s. The amount of research on REEs' technology dissipated in the 1990s and now, there are just a few rare earths' research projects (Stone, 2009).

REEs can be further defined by their molecular weight and divided into light rare earth elements (LREEs) and heavy rare earth elements (HREEs). LREEs have atomic numbers between 57 and 64 and include: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, and europium. HREEs have atomic numbers between 65 and 71 and include: gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium and yttrium (Castor and Hedrick, 2006). Yttrium is classified as a HREE despite its weight because its chemical properties are most closely related to HREEs. In general, HREEs are scacer than the LREEs and experience higher demand levels because of their applications to advanced technology (Long et al, 2010).

In the 112th Congress, two pieces of legislation affecting all REEs were introduced in the House of Representatives and referred to committees (Govtrack.us, 2011). The goal of the Rare Earths and Critical Materials Revitalization Act of 2011 is to develop a rare earth materials program supporting exploration, extraction, recycling, and information sharing (Civic Impulse H.R. 618, 2011). The Energy Critical Elements Renewal Act of 2011 would establish a similar program. However, it encompasses rare earths and all materials critical to the energy sector (Civic Impulse H.R. 952, 2011). At the time of publication of this thesis, both bills remain in committee.

Processing Difficulties

HREEs and LREEs are typically found together because of their trivalent nature (Castor and Hedrick, 2006). It is difficult and expensive to separate the individual elements due to the REEs' chemical similarities. Because each REO has a different composition of REMs, every processing plant must be developed uniquely. The process depends on the type of mineral and the intended end product. Accounting for this variability increases the amount of pre-production time when a rare earths' mine is being established.

At the Mountain Pass mine in California, the processing production follows a different procedure than the mine at Bayan Obo in Inner Mongolia. At Mountain Pass, the ore undergoes hot flotation followed by hydrochloric acid leaching to remove calcite. Roasting eliminates the carbon dioxide and converts cerium from the +3 state to +4 (Bautista and Mishra, 2000). Strong acid leaching forces all of the rare earths except cerium into the solution and then the elements are recovered by purification and extraction techniques. In contrast, the bastnasite ore from Inner Mongolia, China is recovered as a byproduct of iron ore production. The REO is converted into solution by sulfuric acid and then roasted. Following the roasting process, an aqueous leach produces a solution of all the REEs, and then the REEs can be precipitated out either as a mixed sulfate or hydroxide (Bautista and Mishra, 2000). In addition to these two examples, there are many other different processes to refine REOs into concentrated and separated REEs.

Applications

REEs are crucial for producing components of green technology such as hybrid and electric vehicles, wind turbines, and fluorescent light bulbs. The defense industry requires equipment dependent on REEs. Many other industries rely on REEs including ceramics, electronics, petroleum refining, and metal alloys (Castor and Hedrick, 2006). A complete table of REEs' uses and applications by industry is shown in Table 2-1.

In addition to knowing the general applications of REEs, it is also important to know which REEs are applied to which applications. The Lynas Corporation compiled a chart of rare earths' usage by application shown in Table 2-2. Using this data, it was possible to correlate the individual elements to the associated REMs and the typical applications (Table 2-3).

Table 2-1. REEs' uses and applications by industry. **Source: Castor and Hedrick, 2006.**

Industry	Uses
Automotive	Catalytic converter catalyst substrate; Rechargeable batteries; Fuel cells; Colored plastics
Ceramics	Oxygen sensors; Structural ceramics for bearings; jet engine coatings; Investment molds; Refractories; Pigments
Chemicals	Oil refinery fluid cracking catalysts; Pharmaceuticals; Water treatment; Catalysts; Moisture control, dryers, and detection
Defense	Lasers; Missile guidance and control; Visual displays; Radar; Electronic countermeasures; Communication; Shielding
Electronics	Capacitors; Cathodes; Electrodes; Semiconductors; Thermistors; Traveling wave tubes (TWTs); Radio frequency circulators and toroids; Yttrium iron garnet (YIG) ferrites
Glass	Polishing compounds; Decolorizing; Colorizing; Increase refraction; Decrease dispersion; Radiation stabilization; Absorber
Illumination	Trichromatic fluorescent lamps; Mercury lamps; Carbon arc lamps; Gas mantles; Auto headlamps; Long-glow phosphors
Magnets	Speakers and headphones; Linear motors; Antilock braking systems; Tape and disk drives; Gauges; Electric motors; Pump; Ignition
Magnetostrictive	Sonar systems; Precise Actuators; Precisions positioning; Vibratory screens; Speakers; Ultrasonics to kill bacteria
Medical	Contrast agents; Magnetic resonance imaging (MRI); Positron emission tomography (PET); Radioisotope tracers and emitters
Metallurgy	Alloying agents in aluminum, magnesium, iron, nickel, and steel alloys; Superalloys; Pyrophoric alloys; Lighter flints; Armaments
Phosphors	Cathode-ray tubes (CRTs); Fluorescent lighting; Radar and cockpit displays; X-ray intensifying screens; Temperature sensors
Other	Simulated gemstones; Textiles; Magnetic refrigeration; Hydrogen fuel storage; Lubrication; Photography; Nuclear uses

Table 2-2. Rare earths' usage by application (%). **Source: Long et al, 2010.**

Application	*La*	*Ce*	*Pr*	*Nd*	*Sm*	*Eu*	*Gd*	*Tb*	*Dy*	*Y*
Magnets	--	--	23.4	69.4	--	--	2	0.2	5	--
Battery alloys	50	33.4	3.3	10	3.3	--	--	--	--	--
Metal alloys	26	52	5.5	16.5	--	--	--	--	--	--
Auto catalysts	5	90	2	3	--	--	--	--	--	--
Petroleum refining	90	10	--	--	--	--	--	--	--	--
Polishing compounds	31.5	65	3.5	--	--	--	--	--	--	--
Glass additives	24	66	1	3	--	--	--	--	--	2
Phosphors	8.5	11	--	--	--	4.9	1.8	4.6	--	69.2
Ceramics	17	12	6	12	--	--	--	--	--	53
Other	19	39	4	15	2	--	1	--	--	19

Table 2-3. REEs' information by element. Red shading indicates "critical" classification by the DOE.

Atomic Number	*Name*	*Abbreviation*	*Light or Heavy*	*Mineral*	*Application*
39	Yttrium	Y	Heavy	Bastnasite, Fergusonite, Monazite, Samarskite, Xentime, Gadolinite, Polycrase	Phosphors, Ceramics
57	Lanthanum	La	Light	Monazite, Bastnasite, Allanite, Cerite	Petroleum refining, Batteries, Phosphors
58	Cerium	Ce	Light	Monazite, Bastnasite, Allanite, Cerite, Samarskite, Perovskite	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining
59	Praseodymium	Pr	Light	Monazite, Bastnasite	Magnets, Batteries
60	Neodymium	Nd	Light	Monazite, Bastnasite	Magnets, Batteries
61	Promethium	Pm	Light	Does not occur naturally	
62	Samarium	Sm	Light	Monazite	Batteries
63	Europium	Eu	Light	Bastnasite, Monazite	Phosphors
64	Gadolinium	Gd	Heavy	Bastnasite, Monazite, Gadolinite	Magnets
65	Terbium	Tb	Heavy	Monazite, Cerrite, Xenotime, Gadolinite	Phosphors, Magnets
66	Dysprosium	Dy	Heavy	Bastnasite, Monazite,(Euxenite, Fergusonite, Gadolinite, Polycrase)	Magnets, Lasers
67	Holmium	Ho	Heavy	Gadolinite, Bastnasite, Monazite	Phosphors
68	Erbium	Er	Heavy	Bastnasite, Monazite	Lasers
69	Thulium	Tm	Heavy	Bastnasite, Monazite	Rarest rare earth - No known commercial applications
70	Ytterbium	Yb	Heavy	Euxenite, Xenotime	Lasers, Silicon photovoltaic cells
71	Lutetium	Lu	Heavy	Bastnasite, Monazite	Metal alloys, Nuclear industry

According to the DOE, metal alloys use the most REEs by volume, followed by electronics, such as iPods and monitors. Figure 2-1 displays the distribution of rare earths' applications in the United States. The fluorescent light bulb industry comprises a large percent of REEs applications because of the phosphor coating; 12% of REO are applied to phosphors (DOE, 2010). While catalytic converters require only a small amount of cerium, it has a large impact because catalytic converters are produced in massive quantities (DOE, 2010).

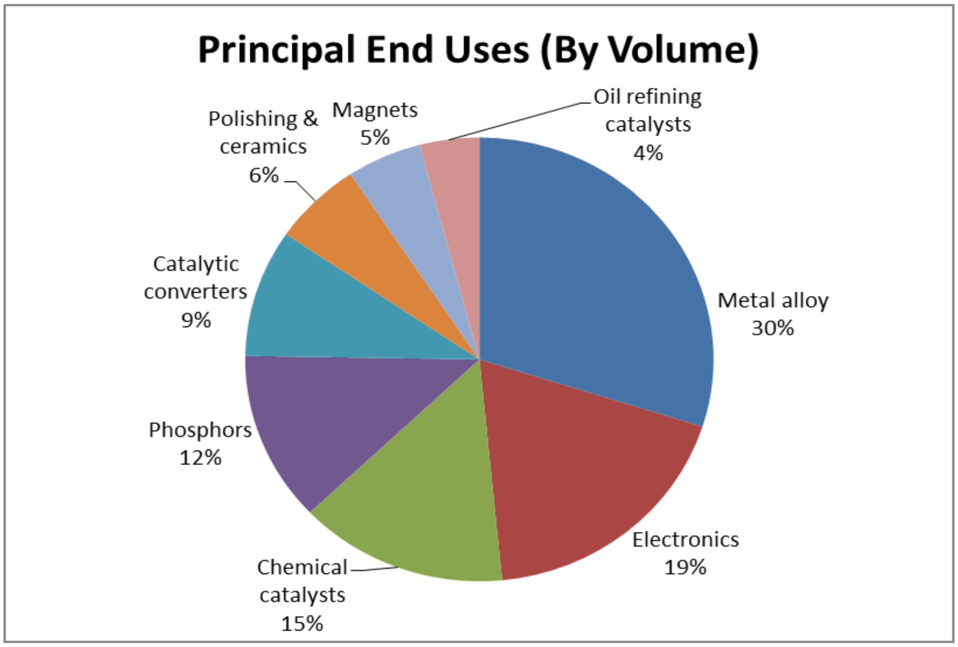

Figure 2-1. A pie chart displaying the distribution of domestic REEs' applications by volume. **Source: DOE, 2010.**

Green Technology

Hybrid and electric vehicles consume large amounts of REEs. The nickel-metal hydride (NiMH) batteries used in hybrid and electric vehicles contain about 1 kilogram of neodymium and about 10 kilograms of lanthanum (Bryce, 2009). The NiMH battery requires a cathode with the formula AB_5 where A is a mixture of rare earths including lanthanum, cerium, neodymium and praseodymium called mischmetal, and B is a combination of nickel, cobalt, manganese and/or aluminum (DOE, 2010). Cerium, the most abundant REE, is an important component of catalytic converters in all cars (DOE, 2010).

Renewable energy sources typically require some components dependent on REEs. Large wind turbines need powerful motors, and these motors are most effective with rare earth permanent magnets (Molycorp, 2011). Ytterbium and sometimes terbium can be used in silicon photovoltaic cells to convert solar radiation into electricity (Richards, 2006).

Phosphors are used in fluorescent light bulbs, a more energy efficient light source than incandescent lighting but not as efficient as light emitting diodes (LEDs). In a fluorescent light bulb, electricity excites the mercury vapor inside the light bulb and the vapor emits ultraviolet light to excite a phosphor coating on the inside of the bulb. The phosphor coating contains lanthanum, cerium, europium, terbium, and yttrium (DOE, 2010). LEDs require cerium and europium to create white light (DOE, 2010). Organic LEDs could eventually eliminate the need for REEs but are just in the early stages of development (DOE, 2010). The phosphor market is probably the most important in terms of dollar value, because phosphors are used in color cathode-ray tubes and liquid crystal displays in computer monitors and televisions (Castor and Hedrick, 2006).

Defense Applications

According to the Pentagon, the United States uses 5% of the world's supply of REOs for defense (Coppel, 2011). REEs can be used to produce lasers designed for high precision missiles or detecting underwater mines (Molycorp, 2011). Also, night vision goggles rely on the phosphors produced from REEs. REEs are also crucial to communications due to the application of speakers and sound system components (Hedrick, 2004). Yttrium and gadolinium are used in tracking targets with guidance and radar (Hedrick, 2004). There is no tracking system in place to determine where the how much REO is used for each system (Coppel, 2011). Since REEs are important for defense applications, there is an increased need to create a cohesive plan to secure the future REEs supply.

Miscellaneous Applications

REEs are applied extensively in several other areas including ceramics, petroleum refining, glass additives, polishing compounds, and metal alloys. REOs can produce coloring for glass and ceramic glazes. Praseodymium oxide produces a yellow or green color while neodymium oxide produces blue to lavender colors and erbium oxide produces a pink color

(Campbell and Keane). In petroleum refining, lanthanum is used as the catalyst during fluid catalytic cracking, a process intended to convert high molecular weight hydrocarbons such as crude oil into useful products such as gasoline. Fluid catalytic cracking increases the oil refinery yield by 7% (Lynas, 2010). Cathode ray tube (CRT) monitors require cerium as a glass additive to stabilize the glass from the electron beam (Lynas, 2010). Most television and computer screens, including LCD, Plasma, and CRT, must be polished with REEs' polishing compounds before being sold. Metal alloys, such as cast iron and steel, utilize cerium and other REEs to create stronger alloys (Molycorp, 2011).

The Geographic Distribution of REEs

Despite the name, "rare earth," REMs actually are quite prevalent. However, it is rare to find a deposit of these minerals with a high enough concentration to be profitably mined. They are not often highly concentrated, because they can be substituted in many various crystal lattices and thus are typically widely dispersed in the earth's crust (Castor and Hedrick, 2006).

It is crucial to know what countries control the supply of REMs. Almost half of the rare earths' reserves are currently located in China (Cordier, 2011a). That statistic could change as the United States continues to explore its resources and technology advances to upgrade deposits designated as resources to reserves. Russia and associated nations control about 17% of the global REOs' reserves. The United States controls about 12% of the global REOs' reserves with India and Australia following (Cordier, 2011a). Brazil and Malaysia have about 0.04% and 0.03% respectively, which was not enough to appear on the pie chart in Figure 2-2.

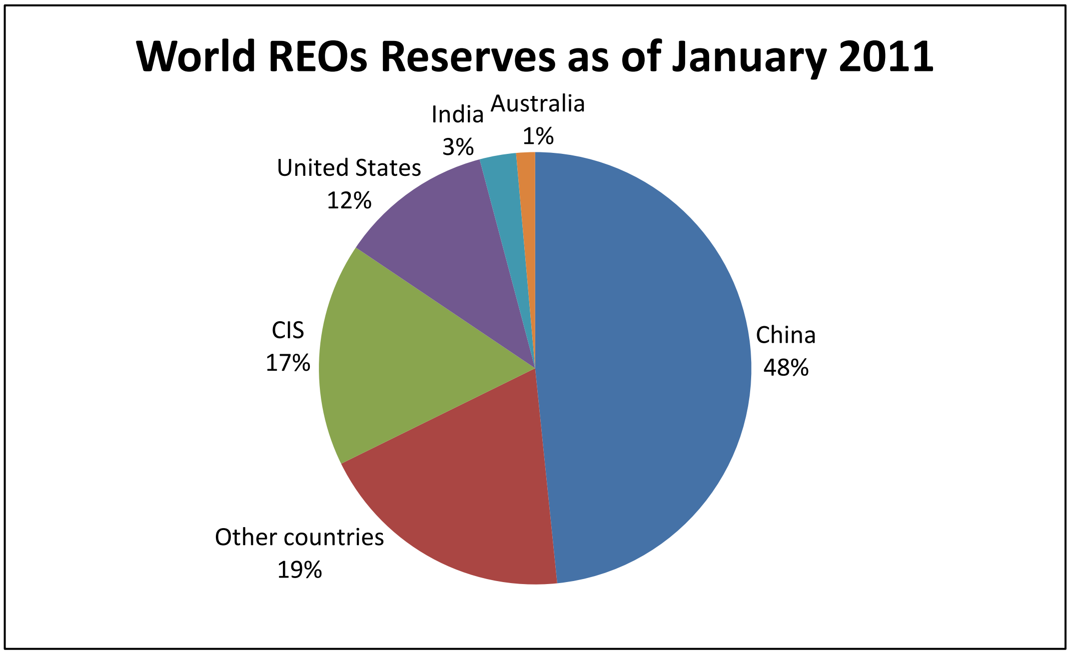

Figure 2-2. A pie chart showing the amount of REOs' reserves located in each country as a percentage of the global reserves. **Source: Cordier, 2011a**

The countries with REOs' reserves are not necessarily producing REEs. This can be seen in the differences between Figure 2-2 and Figure 2-3. A variety of countries own REOs, however just a few are producing REOs. For example, the Commonwealth of Independent States, Russia and other allied countries, owns 17% of the world's reserves of REOs but does not have an active mine. Similarly, Canada has 14 deposits with development times of ten years or less. Canada did not produce any REOs during 2010 because China is able to produce REOs much more cheaply. China dominates the production and extraction of REOs. Between 2006 and 2009, the United States relied on China for 92% of rare-earth metals, compounds, etc. (Cordier, 2011a). In Figure 2-3, China's dominance of the current production of REEs is clearly displayed.

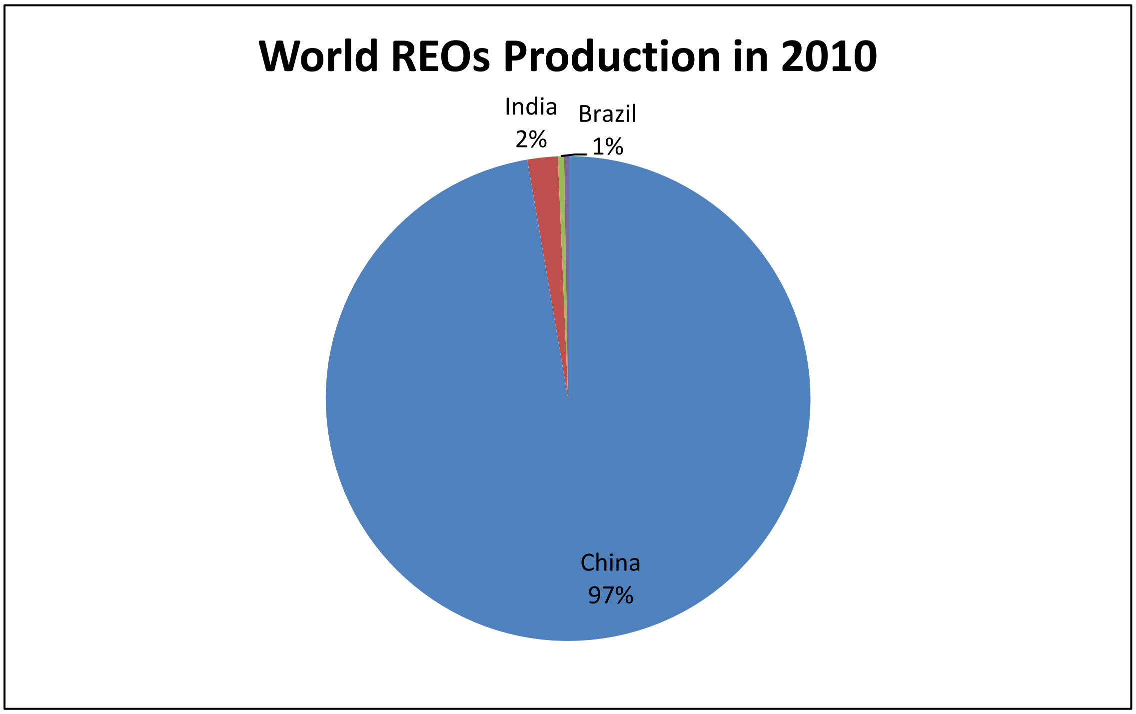

Figure 2-3. A pie chart presenting the production of REOs by country in 2010 as a percentage of the global production. Note how China controls almost 100% of the production. **Source: Cordier, 2011a**

Dependence on China for REEs could lead to supply interruptions. Between September and November 2010, the Chinese government placed an export ban on REOs going to Japan due to a dispute over territory (Bradsher, 2010). If the United States were to ever find itself in a similar situation, the demand for REEs would not be met because the United States does not have a national stockpile, and at the time of publication of this thesis, there are no active mines (Cordier, 2011a). Recently, the Chinese government has been reducing the export quotas on REEs by 35% due to the need to improve environmental regulations (Bradsher, 2010). In addition to a reduction in the amount of REOs exported, Chinese export taxes on REEs has increased by 10% (Bradsher, 2010). A national rare earths' stockpile is being created in China and it may contain up to 100,000 metric tons of REOs "to protect national resources, reduce pollution, and save energy" (Areddy, 2011a). The stockpile would provide more than a year's supply of China's demand for rare earths; in 2010, China consumed 72,000 tons of rare earths (Lynas, 2010).

Fortunately, dependence on foreign REEs can be significantly reduced. Since the consumption distribution (Figure 2-4) is similar to the reserves distribution (Figure 2-2), it will be possible for the United States to provide enough REEs to support its demand. In 2010, consumers in the United States utilized 11,000 metric tons of REOs (Cordier, 2011a). Within the United States, there is a REOs' reserve base of 13,000,000 metric tons. Assuming demand remains constant, the domestic reserves would provide over 1,000 years of rare earths. Japan is interested in developing ways to recycle REEs, because Japan consumes a significant amount of REEs but does not have any reserves or resources.

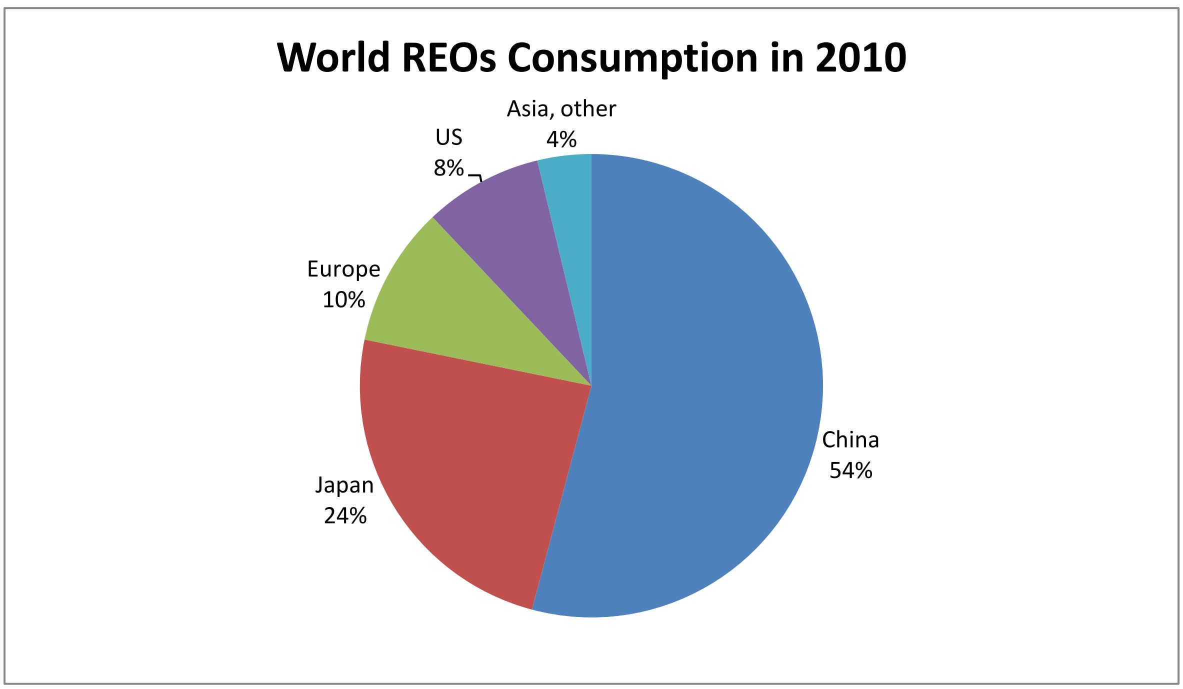

Figure 2-4. A pie chart illustrating the consumption of REOs by country as a percentage of the global consumption. **Source: Lynas, 2010**

Important Deposits

Bayan Obo, located in Inner Mongolia, China, is currently the most prolific rare earths' mine in the world with the largest extent of REOs reserves. 48 billion metric tons of REOs' resources (approximately 70% of the world's resources) are located here (Nebler, 2007). Also, Bayan Obo has significant amounts of iron ore (Nebler, 2007). It has a variety of REMs including bastnasite and monazite, and it can produce both HREEs and LREEs (Orris and Grauch, 2002). As a carbonatite deposit, it has typical mineralogical and chemical features of igneous carbonatites surrounded by other igneous rocks such as gabbro and quartz syenite (Jones et al, 1996). The structure of this deposit is complex because of significant plate movement throughout history (Drew et al, 1991). During Permian times, tectonic movement may have generated hydrothermal fluids and separated plutons (Drew et al, 1991).

The most important rare earths' deposit in the United States is Mountain Pass in southern California. It was discovered in 1949 and has changed owners several times throughout the years (Long et al, 2010). Between 1965 and 1995, the majority of the world's REOs came from this location (Castor, 2008). This location stopped mining REO in 2002 due to several violations of environmental regulations but has been processing ore from its stockpiles. Mountain Pass is the only domestic deposit with sufficient exploration data to be categorized as economically viable (Long et al, 2010). Bastnasite is the primary REM and makes up about 15% by volume of the ore body (Jones et al, 1996). The ore is located in Proterozoic, igneous rocks such as biotite, hornblende, and granite (Long et al, 2010). In contrast to the Bayan Obo ore, the Mountain Pass ore has a higher barium oxide content and lower fluorine content (Long et al, 2010). Molycorp has secured the permits and will begin mining operations by 2012 (Molycorp, 2011).

Mount Weld is located in Western Australia and is owned by the Lynas Corporation. It mostly contains LREEs; the LREEs were probably deposited via long-term leaching and redeposition by ground water (Castor and Hedrick, 2006). There are significant amounts of REE phosphates and yttrium enriched minerals (Castor and Hedrick, 2006). A pilot plant was established in 1993 (Orris and Grauch, 2002). It is characterized by the lateritic weathered carbonatite surrounding the deposit (Jones et al, 1996). From the apatite rich layers to the Al-phosphate-rich layers, the amount of calcium oxide decreases while the amount of iron and aluminum oxides increases (Jones et al, 1996).

In Canada, the Thor Lake deposit is being extensively explored in preparation of development because it is the largest HREEs resource in North America (Long et al, 2010). The concentration of HREEs increases with depth (Avalon). The ore also contains some zirconium, niobium, and tantalum (Long et al, 2010). It is located in the Peralkaline Blachford Lake intrusion with syenites, granites, and gabbros (Avalon). If the Chinese government limits exports from the Bayan Obo deposit, Mountain Pass along with Thor Lake and Mount Weld should produce the majority of the future supply of rare earths for the United States.

The Geology of REEs

While rare earths' deposits vary widely throughout the world, they can be classified into several deposit types: alkaline igneous, carbonatite, hydrothermal, ion adsorption, and placer. These deposit types can help geologists predict what REMs may be found at a deposit because the types identify origins of the rare earth deposits. Alkaline igneous deposits originate from the cooling of magma in the Earth's magma (Long et al, 2010). This magma cooling process involves extracting and concentrating rare earth and other economically valuable minerals. Carbonatite deposits are typically rare (Long et al, 2010). In order to be classified as a carbonatite deposit, the igneous rocks must contain at least 50% carbonates (Mitchell, 2004). Other igneous deposits, such as pegmatites, are typically small and only of interest to mineral collectors (Long et al, 2010). Hydrothermal fluids can create rare earths' deposits with high concentrations (Samson and Wood, 2004). Bastnasite, an important REM, can precipitate when a fluoride and sulfate magmatic fluid mix with calcium rich water (Samson and Wood, 2004). Ion adsorption deposits are formed when rare earths leach out of igneous rocks and attach onto clays (Long et al, 2010). Placers, the most prevalent rare earths' deposit type, are formed from weathered sediments concentrate into a denser mineral (Long et al, 2010). These deposits occur in alluvial beds and near shorelines (Orris and Grauch, 2002).

The three most significant REMs are monazite, bastnasite, and xenotime. Monazite is found throughout the United States and contains a variety of REEs including La, Ce, Pr, Nd, Sm, and Tb (Chevron Mining, 2008). Unfortunately, monazite typically contains thorium, a weakly radioactive element (Haxel et al, 2002). This radioactivity complicates environmental mining permits as companies will need a plan to manage the excess radiation. Bastnasite typically contains HREEs such as Y, Eu, Gd, Dy, Er, Tm, Lu (Chevron Mining, 2008). It is typically easy to crush and is more desirable than monazite (Castor and Hedrick, 2006). Xenotime is not as common as the other two minerals and is typically associated with metamorphic rocks (Jones et al, 1996). Xenotime contains Y, Tb, and Yb (Chevron Mining, 2008).

Chapter 3

The Economics of REEs

With any material, the dynamic relationship between supply and demand forces the price towards an equilibrium point in a free market. The historical trends of the supply and demand of REEs from 1964 to 2008 were examined by equating the production of REOs to supply and apparent consumption of REOs to demand. The analysis shows REEs follow the conventional supply-demand-price relationship if global economic growth is considered through the intrinsic REOs' price growth rate. After the quantitative analysis was performed, the qualitative effects of external factors on supply and demand are considered.

Historical Analysis

The historical production, consumption, and price statistics of REOs provided by the USGS exhibit the supply-demand-price relationship (USGS, 2010). The United States' mines dominated the production of REOs between 1965 and 1984 (Haxel et al, 2002). After a transitional period, Chinese mines began to monopolize REOs' production in 1991 (Haxel et al, 2002). As shown in Figure 3-1, the world's production of REOs has significantly increased over the past 40 years (USGS, 2010). At some point in the future, this trend will level off as the supply constraint is reached. When Chinese mines began to dominate the rare earths industry (around 1990), the rate of production increased significantly. From 1960 to 1990, the annual increase in REOs production rate was approximately 2,000 metric tons per year. Once Chinese mines started producing REOs, the increase in production doubled to 4,000 metric tons per year.

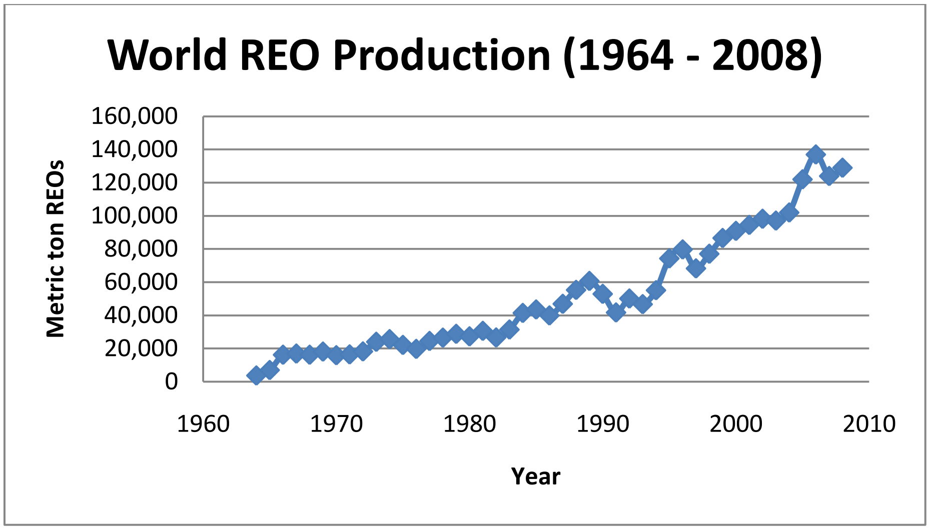

Figure 3-1. A graph of the global production of REOs versus time (1964-2008). **Source: USGS, 2010**

In contrast to global production, production of REOs within the United States peaked in 1984 and then sharply declined (USGS, 2010). There was a short period of increased domestic REOs production in the early 1990s followed by a steady decline. The United States' production of REOs declines occurred at approximately the same time as China's initial REEs' production.

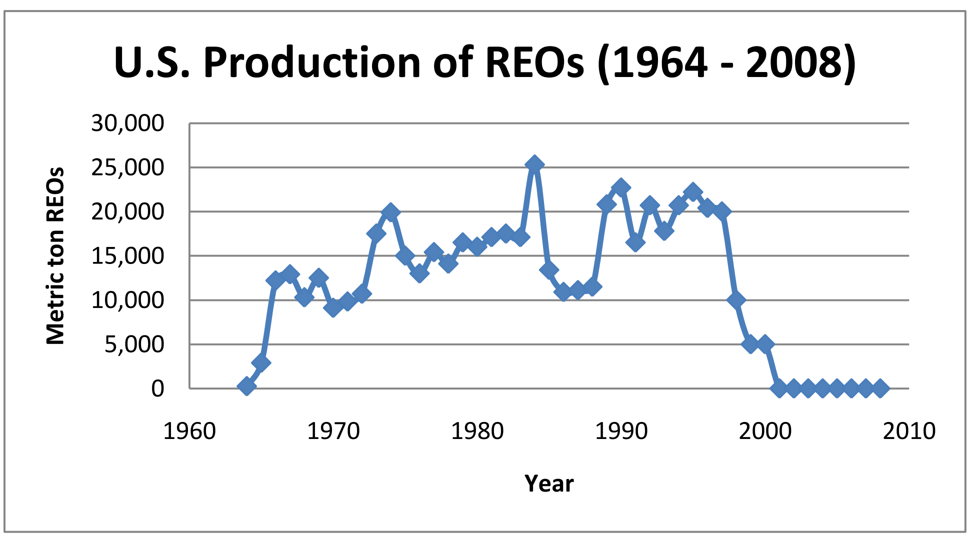

Figure 3-2. A graph of the production of REOs in the United States versus time (1964 – 2008)**. Source: USGS, 2010**

The United States' apparent consumption (production + imports - exports) steadily increased when the American mines were producing REOs and decreased sharply when Chinese mines began to produce REOs (Figure 3-3). In the past 10 years, the domestic consumption appears to be leveling out as it varies between 5,000 and 10,000 metric tons REOs.

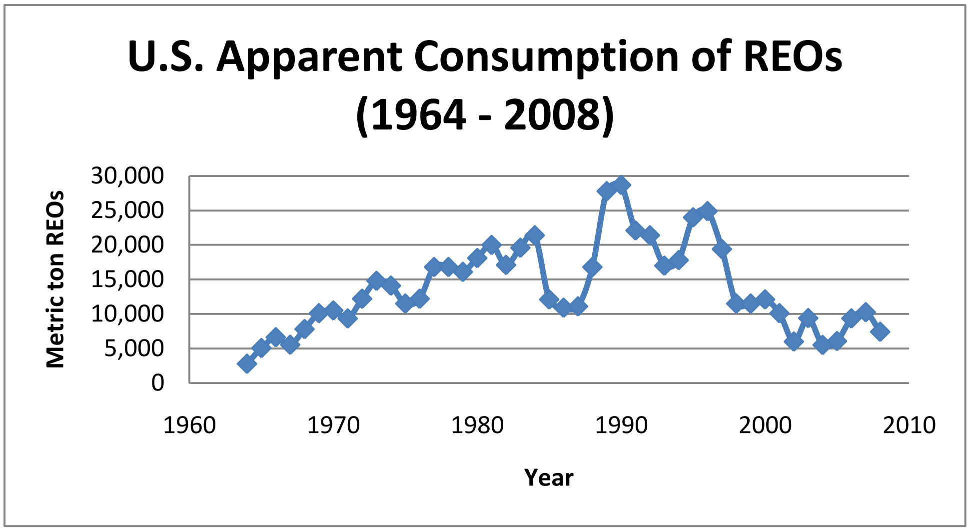

Figure 3-3. A graph of the apparent consumption of REOs in the United States versus time (1964 – 2008). Apparent consumption was calculated by subtracting the exports from the production and imports. **Source: USGS, 2010**

There is a correlation between domestic REOs production and domestic apparent consumption (Figure 3-4). Both quantities increase and decrease at approximately the same time and follow the same overall trends. However, the demand trend leads the supply trend. As the consumption or demand increases, production or supply should increase to meet the demand. Also, if demand decreases, then supply will eventually decrease; the surplus will cause the price of REOs to fall. The supply lags demand because the factors controlling supply are relatively more time constrained. Supply factors, such as labor and equipment, require time to increase or decrease. In contrast, demand factors can fluctuate on a shorter timescale because increasing an order for more REOs does not require time. When apparent consumption is plotted as a function of production, it has an R^2 value of 0.665. This is a reasonable correlation value because production is a parameter used to calculate apparent consumption.

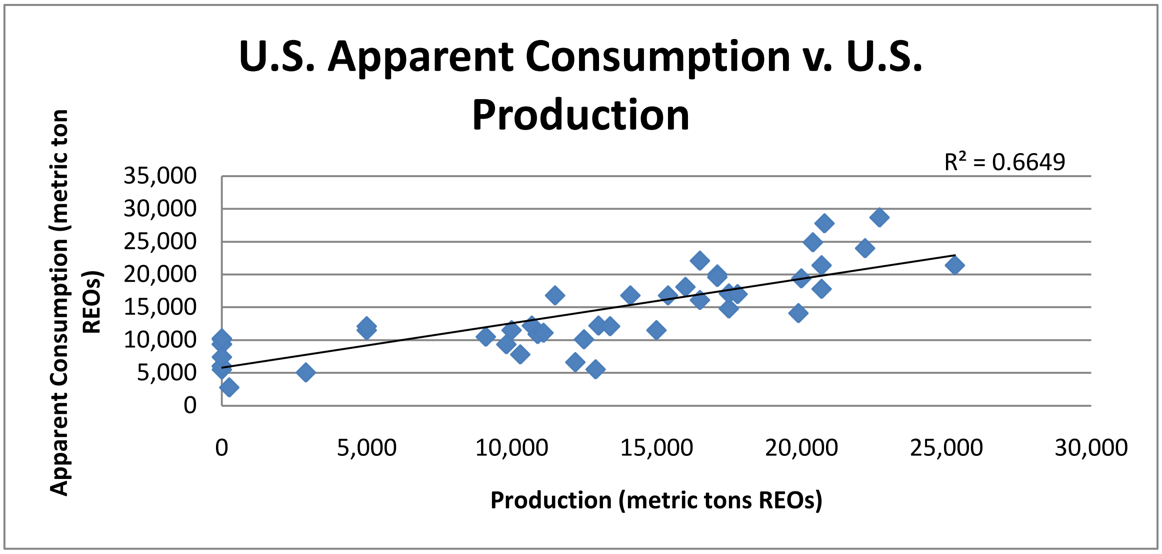

Figure 3-4. A graph depicting REOs' apparent consumption in the United States versus REOs' domestic production using historical data from 1964-2008. **Source: USGS, 2010**

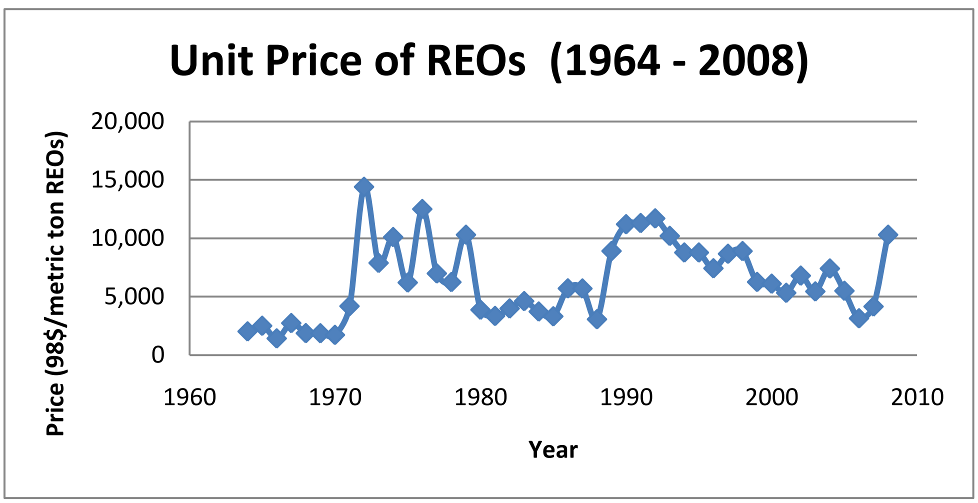

Figure 3-5. A graph of the historical trend of the REOs' unit price in 1998 dollars per metric ton of REOs from 1964-2008. **Source: USGS, 2010**

The price of REOs has varied greatly in the past 40 years as shown in Figure 3-5 (USGS, 2010). The unit price of REOs was calculated using a weighted average of the rare earth imports' and exports' values normalized to the apparent consumption (Cordier, 2011b). Since REOs are typically bought through a negotiated purchase and not traded on metal exchanges, it is difficult to predict the future price (DOE, 2010). Illegal purchasing of REEs occurs in China; as much as one-third of all rare earths leaving China are smuggled out (Coppel, 2011). These prices are not recorded, so the price data may contain some error (DOE, 2010).

Two major events affected most metals' prices in the past 20 years: the dissolution of the USSR in 1991 and the growth of China's economy starting in 1998 (Papp et al, 2008). The USSR was a significant global consumer of metals to support their industrial growth, and when it disbanded, the demand decreased, leading to an excess supply and depressed metal prices. While most metal prices increased when China's economy started to grow because of increased demand, the price of REEs decreased, because China produced REEs cheaply with few environmental controls implemented at the Chinese rare earths' mines (Papp et al, 2008). China's fast-paced economic growth led to a notable increase in demand starting in the 1990s. In 2007, the Chinese government tightened export controls, causing the price to increase (Papp et al, 2008).

To determine if apparent consumption or production has a greater impact on unit price, price was graphed as a function of both, and an R^2 value was calculated (Figures 3-6 and 3-7). The higher R^2 value for the consumption-price relationship may indicate a slightly stronger correlation. However, it is probably not statistically significant. Both R^2 values are low because of the negotiated price contracts and the large number of factors determining the prices of REOs.

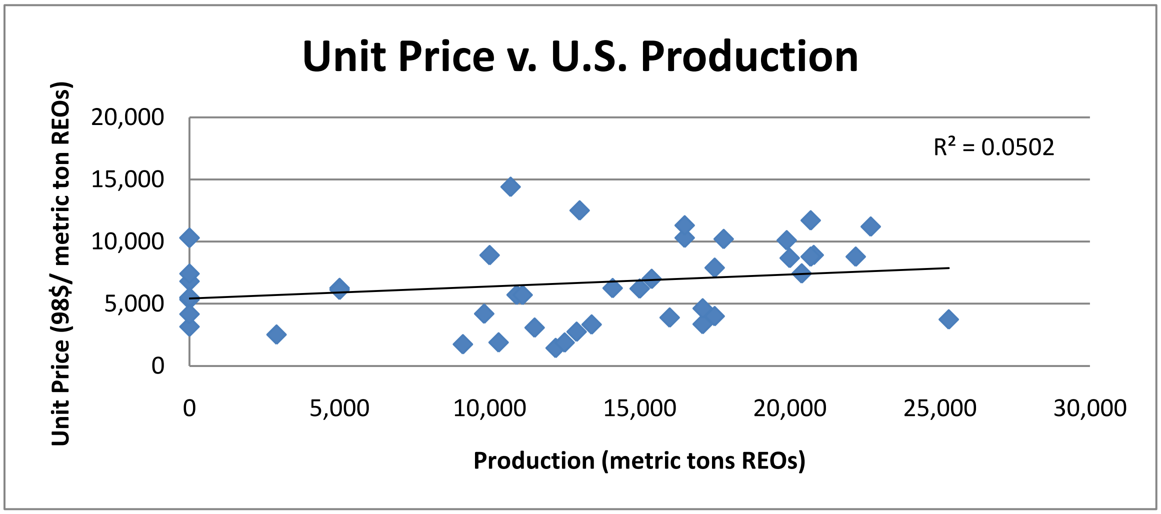

Figure 3-6. A graph correlating the U.S. production versus the REOs' unit price using historical data from 1964-2008. **Source: USGS, 2010**

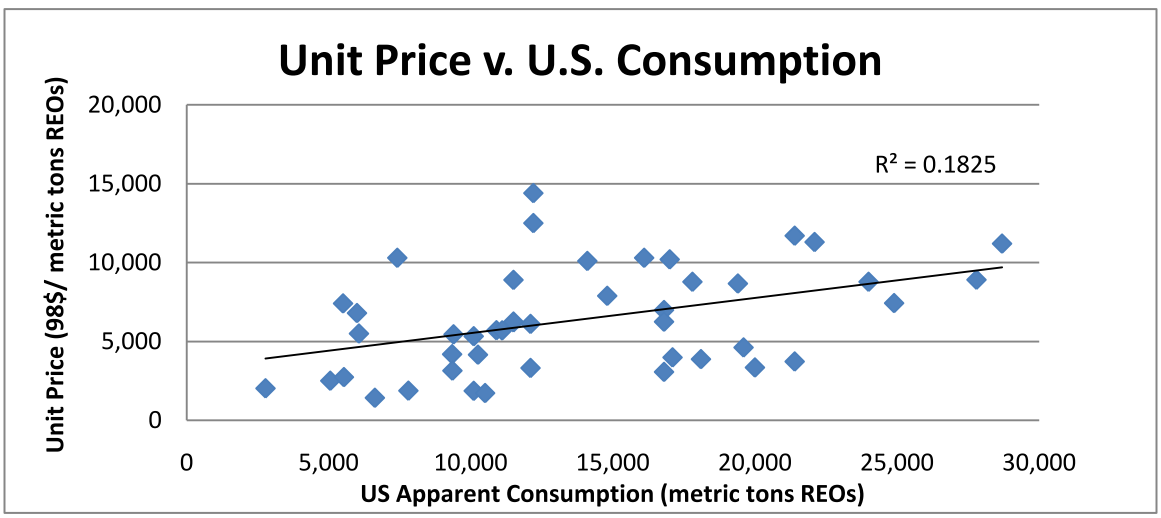

Figure 3-7. A graph correlating the U.S. consumption versus the REOs' unit price using historical data from 1964-2008. **Source: USGS, 2010**

As basic economic principles dictate, the supply and demand govern the price of REOs. The price of any material depends on the supply of that material. When the supply is high and demand is low, the price decreases. In contrast, when the supply is low and the demand is high, the price increases. With the case of non-renewable resources such as REOs, the price will rise over time as the resource becomes scarcer and the demand remains constant. These interactions manipulate the REOs' price towards the equilibrium point, where there is neither a shortage nor a surplus of REOs, and the marginal cost equals the marginal benefits. The typical dynamic relationship between supply and demand is illustrated in Figure 3-8. Typical supply and demand trends are inversely related with respect to price.

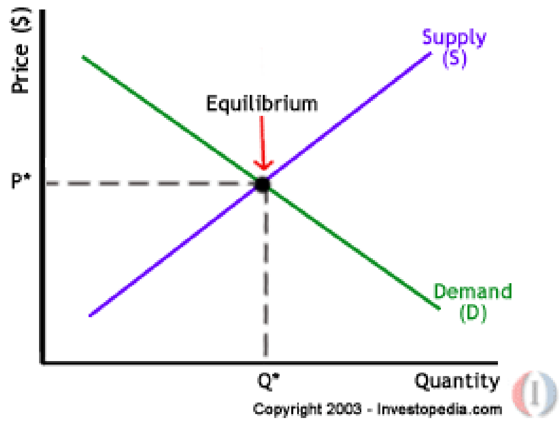

Figure 3-8. A graph depicting the typical supply-demand-price relationship. **Source: Investopedia.com**

To determine if REOs follow the typical supply-demand-price relationship, the trendlines from Figures 3-6 and 3-7 were plotted on the same graph in Figure 3-9 and compared to the typical trends from Figure 3-8. For the REOs industry, production can be equated to supply and apparent consumption equated to demand. Supply follows the typical trend by increasing with price. On the other hand, demand does not follow the typical trend of decreasing with price; instead demand for REOs increases with price. This anomaly is caused by global economic growth, leading to an increase in demand for REOs over time, is not accounted for in the unit price versus demand analysis.

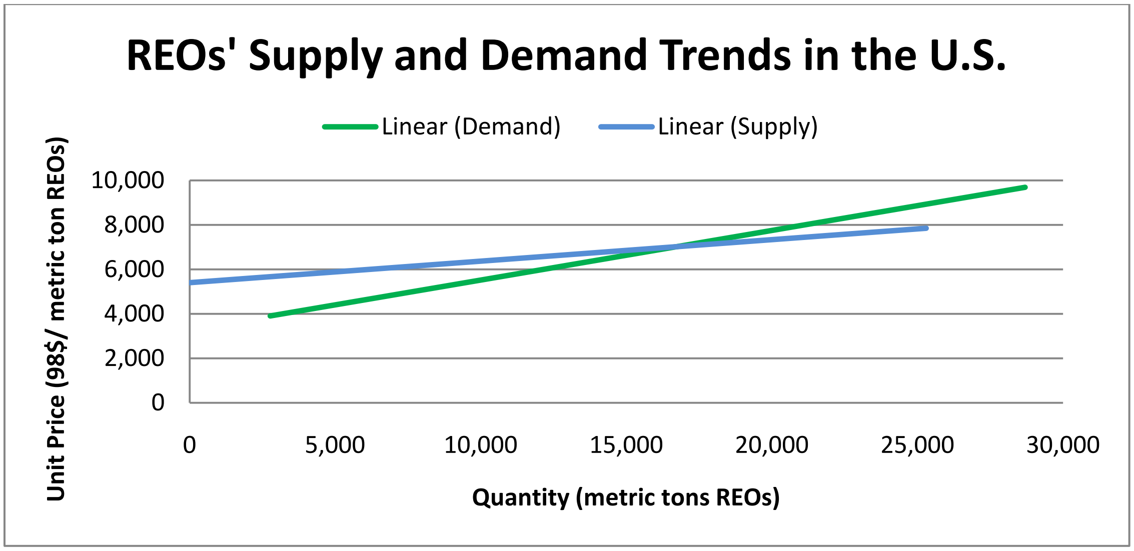

Figure 3-9. A graph of the REOs' supply and demand trendlines from Figures 3-6 and 3-7 in the U.S. with respect to price using historical data from 1964-2008. **Source: USGS, 2010**

To account for overall economic growth, the intrinsic REOs' price growth rate was calculated by subtracting the world gross domestic product (WGDP) growth rate from the REOs' price growth rate. The intrinsic REOs' price growth rate could then be graphed as a function of supply and demand. The growth rates are defined by the equations below. The WGDP data was converted into 1998 dollars to be consistent with the REOs' price data (World Bank Group, 2011; Sahr, 2009).

$$REOs'\ Price\ Growth\ Rate = \frac{Price_{Year\ 2} - Price_{Year\ 1}}{Price_{Year\ 1}}$$

$$WGDP\ Growth\ Rate = \frac{WGDP_{Year\ 2} - WGDP_{Year\ 1}}{WGDP_{Year\ 1}}$$

$$Intrisic\ REOs'\ Price\ Growth\ Rate = REOs'\ Price\ Growth\ Rate - WGDP\ Growth\ Rate$$

When the WGDP growth rate is high, the overall economy is doing well, which will lead to higher demand levels for REOs, as well as most products. A poorly performing economy represented by a low WGDP growth rate will dampen the demand for REOs and other products. When the intrinsic REOs' price growth rate is greater than zero, the price of REOs is growing faster than the WGDP. Under this condition, the decrease in demand stemming from the relatively high price of REOs will more than offset the increase in demand due to global economic growth. An intrinsic REOs' price growth rate less than zero is caused by the global economy is growing faster than the price of REOs. So, the negative price effect on demand is more than offset by the positive global economic growth effect. Therefore, demand should have a decreasing trend, while supply should have an increasing trend with respect to the intrinsic REOs' price growth rate. The supply-demand-intrinsic REOs' price growth rate relationships are displayed in Figures 3-10 and Figure 3-11. Both relationships have low R^2 values because production and consumption are two of many factors impacting the intrinsic REOs' price growth rate.

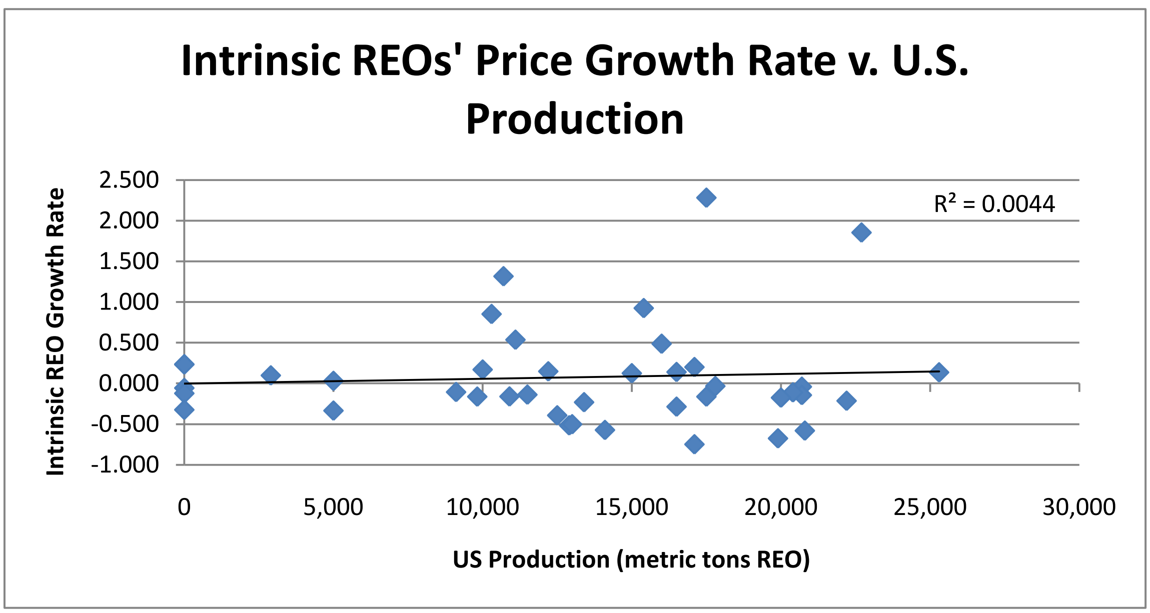

Figure 3-10. A graph depicting the intrinsic REOs' price growth rate versus the U.S. production. Notice the slight increasing trend. The historical data used ranged from 1964-2008. **Source: USGS, 2010; World Bank Group, 2011; Sahr, 2009**

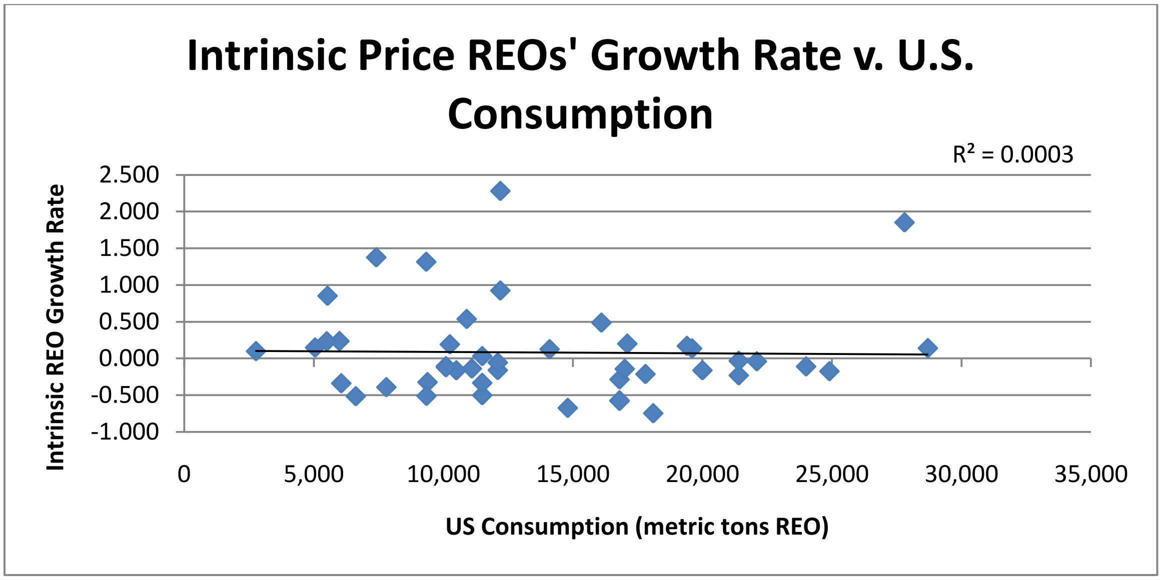

Figure 3-11. A graph illustrating the intrinsic REOs' price growth rate versus the U.S. consumption. Notice the slight decreasing trend. The historical data used ranged from 1964-2008. **Source: USGS, 2010; World Bank Group, 2011; Sahr, 2009**

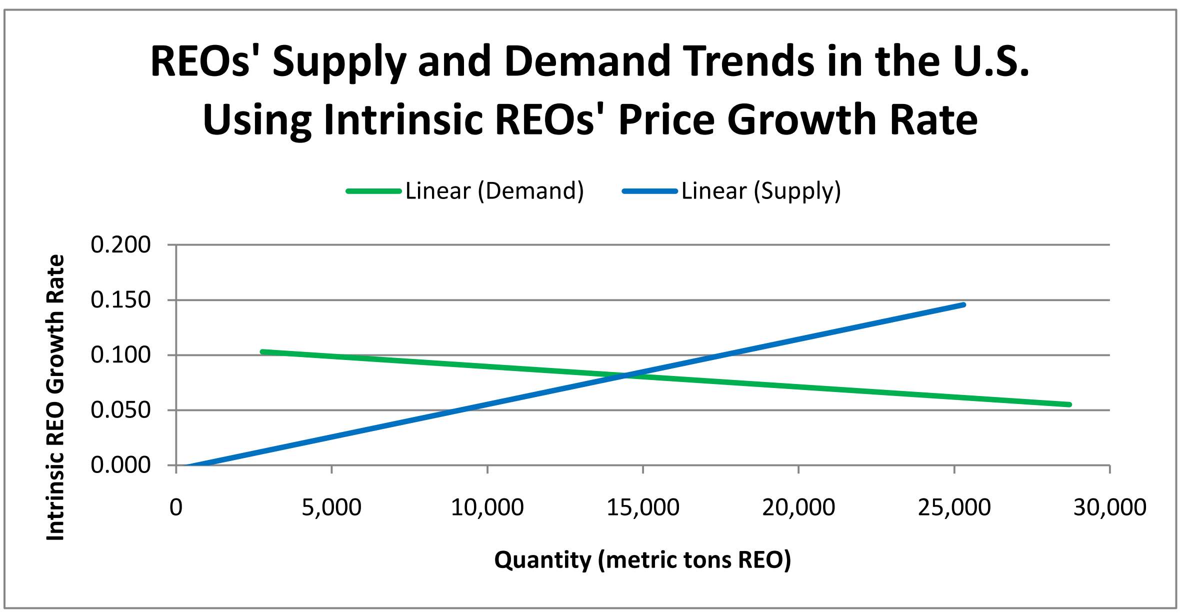

Figure 3-12. A graph of the REOs' supply and demand trendlines in the U.S. from Figures 3-10 and 3-11 with respect to the intrinsic REOs' price growth rate to account for global economic growth. The historical data used ranged from 1964-2008. **Source USGS, 2010; World Bank Group, 2011; Sahr, 2009**

Figure 3-12 shows how rare earths follow the typical supply-demand-price trends (shown in Figure 3-8) if global economic growth is accounted for in the intrinsic REOs' price growth rate. This analysis of the historic supply, demand, and price trends is useful in predicting how the future supply scenarios may be affected by demand and price. Also, examining the factors controlling the supply and demand can help build future supply scenarios.

Factors that Affect the Economics of REEs

Since supply and demand are intrinsically related, it is difficult to isolate factors affecting just one or the other. Usually external factors affect both supply and demand including the following:

- Cost of Production/Price of REEs
  - Environmental Mining Regulations
  - Extraction Research
  - Primary Product Price
- Alternatives & Applicability ratio
- Recycling

The cost of production and the price of REEs control the profitability of a rare earths' deposit and if consumers can buy large quantities of REEs. If REEs are costly to produce and thus expensive to buy, then the demand of REEs will decrease and the supply will increase. Several secondary factors determine the cost of production and consequently the price of REEs including: mining environmental regulations, extraction research, and the primary product price if the rare earths are being mined as a byproduct or coproduct.

Environmental mining regulations can affect the cost of REEs production by stipulating the installation of costly environmental controls. If a mine is required to implement extensive environmental controls, production could be cost prohibitive. Often monazite, a REM with LREEs, is found containing thorium, a weakly radioactive element (Castor and Hedrick, 2006). Therefore, in the United States, there are restrictive environmental regulations on handling monazite. Mountain Pass, a mine producing REOs, was closed after a spill incident led to some thorium contaminated ground water (Castor and Hedrick, 2006). In contrast, currently there are very few environmental regulations in China enabling short development times and low REOs' production costs. Without environmental controls, the development time required for a new mine is reduced, as no permits need to be issued. The United States has the longest development time in the world of seven to ten years due to permitting delays (Behre Dolbear, 2011). The cost of environmental regulations can increase the cost of production, and thus decrease the demand and increase the supply.

Another important factor controlling the cost of production and thus the supply and demand of REEs is research to improve extraction techniques. As mentioned earlier, it is difficult to design a REEs processing plant due to the difficulties in separating each individual element within the REM. If new technology is developed to standardize and simplify the extraction and processing of REEs, then the supply of REEs could increase. This type of research requires an industry-academic partnership. Since 2005, China's two state-run research labs have made significant breakthroughs. The Rare Earth Materials Chemistry and Applications lab is associated with Peking University to research separation techniques (Humphries, 2010). Also, the Baotou Research Institute, the largest rare earths' research lab in the world, is located in China (Humphries, 2010). When the Mountain Pass mine reopens in 2012, it will be implementing several improvements to improve extraction and reduce production cost. Molycorp will use advanced extraction techniques to increase the rare earth recovery from 60% to 95% (Smith, 2010). Also, a 30% decrease in the reagents used will decrease the cost of separation and processing (Smith, 2010). When a product costs less to make and thus buy, consumers are capable of buying more, increasing demand.

If a REO is produced as a byproduct or coproduct, then price of the primary product affects the price of REEs. A byproduct is a material produced during the processing of another commodity such as iron and typically is of lesser value (Humphries, 2010). A coproduct is a material produced with another mineral of the same value. While both products influence each other, the price of the primary product controls the supply of the secondary product. If the price of the primary product increases, the supply of REEs will increase as the supply of the primary product increases. Then, the price of REEs will decrease, increasing demand.

If alternative materials with similar chemical properties as rare earths' were available, the demand for REEs would decrease and eventually supply would also decrease. If REEs were no longer critical to certain applications or if different technology were developed to perform the same tasks, there would not be any need to mine for REEs. The demand of REEs will decrease as the demand for the alternative materials increases. Research must be done to find alternative materials with the ability to mimic rare earths. Unfortunately, the Rare-earth Information Center associated with Iowa State University closed in 2002 because of lack of funding (Ames Laboratory, 2002). The United States no longer leads the world in the number of rare earth patents, and it is unlikely that the United States will be a knowledge source for rare-earth innovation in the near future (Fifarek et al, 2010). So, demand for REEs is expected to remain at high levels because of the lack of alternatives research.

Furthermore, if the amount of REEs needed for a particular application, REEs' applicability ratio, is reduced, then the supply and demand will decrease. For example, if the amount of lanthanum needed for one hybrid vehicle were reduced from 10 kg to 1 kg, then lanthanum demand would decrease and eventually supply would decrease. A reduction of the REEs' applicability ratio would decrease demand, because a smaller amount of REEs would be needed for the application. This reduction in demand would increase the life expectancy of rare earths' mines, because the mines would be depleted at a slower rate.

Another important factor in determining the supply of REEs is the amount of REEs being recycled. A closed material loop encourages sustainability. Currently, REEs are not typically recycled due to lack of infrastructure, low yields, and high cost (Kara et al, 2010). Companies in

Japan are extensively researching the ability to recycle REEs, but there has been little progress in the past 15 years (Kara et al, 2010). Japanese companies are motivated to recycle REEs, because Japan does not have any known REEs reserves or resources and it is one of the world's leading REEs consumers (Lynas, 2010). Companies in the United States should also be increasing the number of REEs recycling plants and researching how to increase the efficiency of REEs recycling process. The overall demand for REEs may increase, because a closed material loop may encourage consumers to buy more. If consumers knew their commonly used technology, such as iPods and computer monitors, would be recycled at the end of its useful life, then they might be willing to upgrade more frequently. Also, if recycling REEs costs less in terms of production, then the demand will increase, as the price decreases.

Factors that Affect Supply

There are two major factors that mainly affect supply: abundance of rare earths' mines and the international policies. The abundance of REEs has a direct relationship with the supply of REEs on the market. The typical trend is as time progresses, more mines start producing ore. The increase in the number of mines and thus the abundance of REEs increases the supply of REEs. Another way to increase the supply of REEs is further exploration of existing mines. If REEs' resources become reserves and economical to mine, then the supply of REEs will increase as the mines increase production. The international political atmosphere has a significant impact on the supply of REEs. If the countries controlling the production of REEs are willing to trade with the countries consuming REEs, then the supply is increased. However, this is not the case; China controls 97% of the world's production of REEs and has export controls on REEs (Cordier, 2011a). These restrictions create an unstable international political atmosphere causing uncertainty concerning the future REEs supply. The Chinese government considers REMs to be strategic materials, so foreign investors cannot mine rare earths and can participate only in smelting and separation projects as a joint venture (Tse, 2011). The Chinese development plan for rare earths includes stockpiling REMs and consolidating rare-earth producers to eliminate competition and financial loss (Tse, 2011). While this plan may improve China's economy, it threatens the REEs' supply for countries around the world. Individual countries such as the United States will need to start to stimulate domestic production to prevent a severe shortage.

Factors that Affect Demand

Four factors affect only the demand of REEs including:

- Number of Buyers
- Greenhouse Gas Emission Regulations
- Prices of Applications – e.g. Wind Turbines
- Consumer Expectation of Supply

Just as the abundance of rare earths' mines is directly related to the supply of REEs reserves, resources, and active mines, the number of buyers is directly related to demand. As the number of companies manufacturing products dependent on REEs increases (such as Toyota), demand will increase because the companies will want to buy REEs to use in their applications. Similarly, if the number of companies manufacturing products dependent on REEs decreases, demand will decrease.

The factor of greenhouse gas (GHG) emission regulations impacts the demand of REEs in terms of quantity and quality. If a global or national law were passed regulating the amount of GHGs that can be produced, the demand will increase significantly for REEs. The application of REEs such as wind turbines, silicon photovoltaic cells and batteries for hybrid vehicles would be in demand (DOE, 2010). The Clean Energy Technology Manufacturing and Export Assistance Act of 2011 has been introduced to the House of Representatives to assist businesses producing technology to reduce GHGs emissions (Civic Impulse HR 502, 2011). If this bill passes, REEs needed for these applications will also be in demand unless alternative materials are found. However, if regulations concerning GHGs are not passed, then the demand will continue with its current trend. Regulating GHGs is a controversial topic and it may have significant economic impacts. American legislators are considering the best way to handle this issue. There have been four bills proposed to the 112^{th} session of Congress limiting the ability of the Environmental Protection Agency (EPA) to regulate GHGs (Govtrack.us, 2011). If the EPA does not regulate the GHGs, the politicians will control any future guidelines regarding GHG emissions. Regardless what agency drafts the regulations, there will be a significant time investment and debate before GHGs regulations will be agreed upon and set.

The prices of REEs' applications influence the demand level of REEs. If applications such as electric vehicles and wind turbines cost less, then the demand for REEs will increase. Manufacturers' demand will be stimulated by the consumers' desire for their products. The prices of REEs' applications may decrease if there is a government subsidy or incentive program to use green technology and reduce pollution. Also, if research about these applications found a less expensive way to produce the applications, the price of the applications would decrease. Similarly, if prices for these applications increase due to the cost of some other component, then the demand for REEs would decrease.

Consumers control the overall level of demand, and consumer expectation of supply significantly impacts the demand. China's Ministry of Industry and Information Technology intends to follow the "2009-2015 Rare Earth Development Plan" to strengthen China's control of rare earths (Lifton, 2010). Also, the Chinese government plans to increase its demand for rare earths as it builds enough winds turbines to produces 133 gigawatts of electricity over the next ten years. Despite the increase in demand, there will not be any new rare earth mining permits issued during this time (Lifton, 2010). At the time of publication of this thesis, demand is expected to increase as consumers are expecting the supply of REEs to decrease. The increased demand is stimulated from a desire to prevent a shortage if supply were to decrease or be interrupted. However, if supply were expected to be steady, then demand typically will not decrease.

Consumers are not compelled to buy less of a product if the supply is secure, only forestall potential supply interruptions.

When consumers expect supply to decrease, stockpiles may be created; the creation REEs' stockpiles is a topic being extensively discussed extensively in Japan, China, and the United States. China and Japan have begun to stockpile REEs (Humphries, 2010). The Japanese government decided to stockpile REEs to prevent another shortage of REEs similar to the shortage between September and November of 2010 when China banned selling Japan REEs. In contrast, the goal of the Chinese stockpile is to accumulate a supply, while it tries to improve environmental controls on the REEs mines (Humphries, 2010). China's leaders are concerned that the environmental damage done to their country during economic growth could damage public health, social stability, and China's international image (DOD, 2010). The United States Congress is considering a bill to create a REEs stockpile. The DOD report explains how a stockpile would provide security for materials needed for defense, defined as critical (DOD, 2010). The United States has a precedent for creating stockpiles of critical materials under the National Defense Stockpile which includes 25 commodities at 17 locations (DOE, 2010). The REEs stockpile would consist of raw materials to be refined at a later date (DOE, 2010). However, the American Physical Society and Materials Research Society put forth how a stockpile would not provide a long-term solution and how the United States needs to stimulate the domestic REEs industry (Jaffe et al, 2011). The stockpile would assist in the short term while domestic mines are developed (Coppel, 2011). Once the domestic rare earths' mines are established, then the stockpile would no longer be necessary.

Supply and Demand Conclusions

Some general conclusions can be drawn about the economics of REEs after analyzing the historical statistics. The world production of REOs has increased significantly over the last 40 years. The United States was the main producer of REOs from mid 1960s to the mid 1980s; however, China now is the main producer of REOs. The United States is a net importer and relies almost exclusively on China for its supply. Throughout the last 40 years, the price has varied greatly but has followed a general increasing trend.

The typical supply and demand model of increasing supply and decreasing demand with price can be applied to REEs if global economic growth is considered in the intrinsic REOs' price growth rate. The R^2 values of the comparison of supply and demand to price are less than 0.6 (a typical significance cutoff value) because many factors determine the price of REOs. In contrast to the weak price relationships, the supply and demand are directly correlated to each other at a moderate level. The demand trend leads the supply trend; when demand increases, the mines increase production to meet the need after a time, and if demand decreases, production will eventually also decease.

Since supply and demand control the price of REOs, it is important to know the external factors affecting these trends. The most important factors affecting supply and demand include: environmental mining regulations, research of extraction techniques and alternative materials, international political atmosphere, price of REEs' applications, and consumer expectation of supply. If extensive environmental controls are required, the cost of production will increase, decreasing supply and increasing demand. However, research about extraction techniques, alternative materials, applicability ratio, and recycling can help reduce the cost of production. When the cost of production decreases, the demand and supply will also increase. Greenhouse gas emissions regulations and incentives for electric cars and renewable energy can increase the demand of REEs' applications. Expectation of the future supply situations also affects the demand. If supply is expected to decrease, then demand will increase to prevent a shortage.

Rare earths follow the expected supply-demand-price relationship. The general future economic outlook of REOs is probably increasing prices as China reduces supply. Many supply scenarios can be predicted based on the factors determining supply and demand. The geographic visualization tool was created to examine five possible scenarios in Google Fusion Tables.

Chapter 4

Querying and Visualizing the REEs' Data

According to the homepage of Google Fusion Tables, "Google Fusion Tables is a modern data management and publishing web application that makes it easy to host, manage, collaborate on, visualize, and publish data tables online" (Google, 2011). Google Fusion Tables allows for large datasets, such as the REEs' Deposits Database, to be mapped and dynamically filtered. It also provides other features such as graphs, timelines, and motion plots; these other features were not used in this application. Google Fusion Tables (http://www.google.com/fusiontables) was chosen to be the interface for this REEs' Deposits Database over Google Earth because of its filtering and sharing capabilities. However, Google Fusion Tables does lack certain features, such as "OR" filtering and a dynamic legend, and could be improved. Overall, Google Fusion Tables provides a variety functions to easily analyze the REEs' deposits data.

Pros and Cons of Google Fusion Tables

There are many advantages to Google Fusion Tables. This application is relatively easy to use and learn; it does not require extensive training before useful analysis can be completed. Unlike other geographic tools such as ArcMap, the general public can quickly understand how to use this tool. Since web mapping sites such as Google Maps and MapQuest are well-known, the learning curve will be shortened for this application. While it is not completely intuitive, the overall design is simplistic and functional.

Google Fusion Tables allows the user to filter for deposits with specific attributes. Under the "View" menu, the "Filter" option permits the user to apply criteria to the dataset and limit the data displayed. This filtering tool enables the user to explore where rare earths' deposits are located based on the attributes of the deposits including:

- Country
- State or Province
- Estimated Location
- Reserves/Resources Designation or Number
- Years Needed to be Developed
- REE Mineralogy
- REEs
- Heavy or Light elements
- Applications
- Byproduct production
- Tonnage and Grade
- Other Ore or Significant Minerals
- Gangue and Rockforming Minerals
- Age
- Deposit Type
- Host Rock
- Company

The user can filter based on an exact match or all values less than or greater than a particular value. The user may also filter for deposits containing a particular attribute, such as neodymium being one of the elements present. Once the filter has been applied, the top of the map or table shows what criteria have been applied to the data. In contrast, Google Earth does not provide the user with any filtering abilities. Google Earth only allows users to search for the specific name of a deposit rather than the attributes attached to each location.

Also, Google Fusion Tables directly imports and exports Excel files (.xls, .xlsx, and .csv extensions) and Google Earth files in Keyhole Markup Language (KML) format. After a file with a series of latitude-longitude points has been imported into Google Fusion Tables, the points can be plotted on a world map. In contrast, in order to import an Excel file into Google Earth an Excel to KML converter macro is required or the points must be entered manually as placemarks, which is a significant time commitment. Once a dataset has been imported to Google Fusion Tables and filtered based on certain conditions, the new dataset can be exported to Excel or

Google Earth. The formatting and information in the "info window," the window shown when the user clicks on a particular site, is retained with the dataset is exported from Google Fusion Tables to Google Earth (See Figure 4-1 for an example of an info window). The placemarks' colors will not be retained when the dataset is exported from Google Fusion Tables to Google Earth. Google Earth is capable of creating a file readable by Excel but it is cumbersome process. First, the data must be saved as a compressed KML file, KMZ format, and the KMZ file can be opened in Excel as an XML file. Google Fusion Tables is a user friendly application and compatible with Excel and Google Earth.

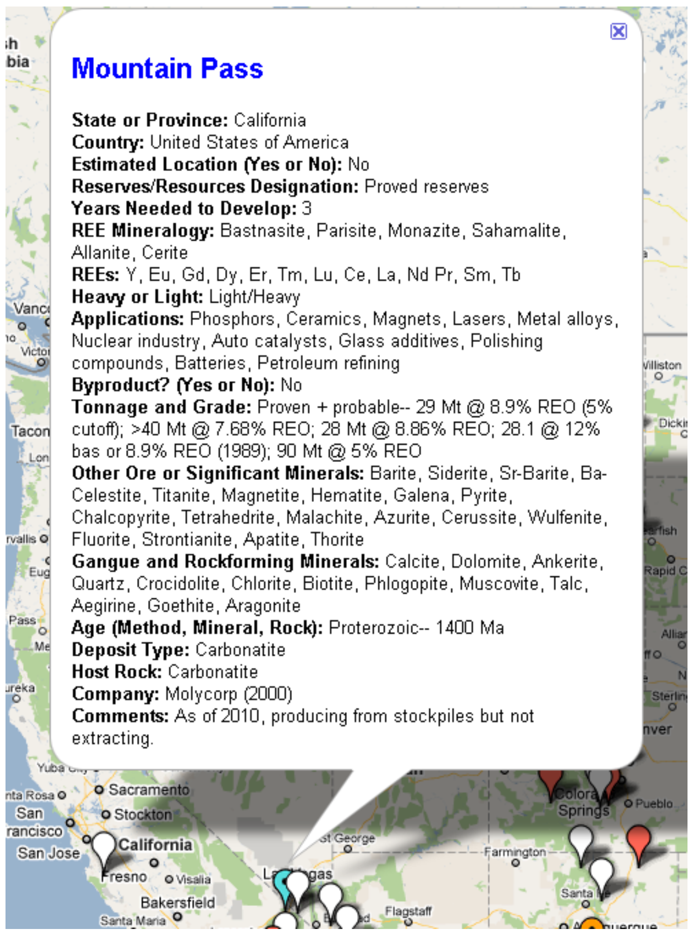

Figure 4-1. A screen capture of the "Info Window" that appears when a deposit is selected in Google Fusion Tables.

Another benefit of Google Fusion Tables is the ability to easily share the data and maps with any internet user. Google Fusion Tables has several levels of sharing. The first level is "private" where only the owner of the data can see and edit it. The next level is "unlisted" and anyone with the link to the data can view it. The most visible sharing level is "Public" and this enables everyone to access the data. Since the REEs' Deposits Database was based on the public data from the USGS, it is appropriate to make this altered database and geographic visualization tool available to the public, in addition to the analysts at the DOE or USGS. This dataset can also be embedded into other websites related to the REEs industry.

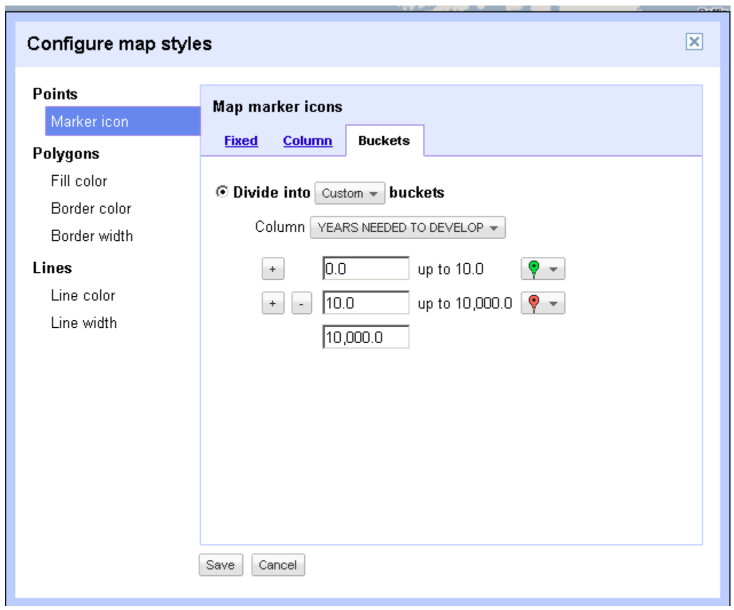

Figure 4-2. A screen capture of the "Configure styles" dialogue box. This configuration would show the deposits with development times 10 years or less in green and the rest in red.

Google Fusion Tables contains the ability to create categories to determine the placemark design of each location. Clicking on the "Configure styles" link will open a dialogue box allowing the user to change styles under the heading of "Buckets." (Figure 4-2). The user determines the number of categories or buckets and the column where the data is located. For example, if the user wanted to view the deposits with a development times of less than 10 years to be green and the rest to be red, the user would divide the data into custom buckets, select the "Years Needed to Develop" column. Then, the user would set the divisions at 0, 10, and 10,000 and select the desired marker colors. The "Buckets" option can be used only on numeric data, so the fields that can be sorted into Buckets are Reserves/Resources Number, Years Needed to Develop, or Timeline (1=Short, 2=Long).

One of the major drawbacks of the Google Fusion Tables application is its lack of an "OR" filtering option. When filtering data, the user can apply additive criteria and the locations displayed must satisfy all of the criteria. This feature is equivalent to the application of the "AND" Boolean logic operator, but the "OR" operator is not an option in Google Fusion Tables. However, Microsoft Access can be used to run this query. At which point, an Excel file can be exported and then imported into Google Fusion Tables.

Another drawback of Google Fusion Tables is the inability to create a custom legend, which could lead to confusion when sharing a dataset. An option for creating a legend is available through the Google Maps Application Programming Interface (API), a set of code libraries provided by the developers of Google Maps in JavaScript and ActionScript (Roth and Ross, 2009). Since the Google Maps API was out the scope of this project, a legend was created in Excel to assist in interpreting the database (Refer to Table 5-2).

While Google Fusion Tables is able to create many types of graphs, it lacks the ability to create histograms. A histogram would be useful to show the cumulative number of mines through time or the number of mines within each state. This feature would help to visualize what states should receive additional funding if the government were to invest in the REEs industry.

While there are three drawbacks to the Google Fusion Tables interface, it is the best interface for the REEs' Deposits Database because of the filtering options and options of exporting and sharing the data with the public. Learning to use these options does not require much effort on the part of the user.

How to Use Google Fusion Tables

This section instructs users on how to use REEs' Deposits Database within Google Fusion Tables. First, the REEs' Deposits Database must be located and the basic functions of scrolling and switching visualization modes must be understood. Then, more advanced skills such as filtering, importing, and exporting the data will be explained.

Locating the REEs' Deposits Database and Scrolling through the Database

In order to use the geographic visualization tool, the user must first locate the REEs' Deposits Database within the public tables available on Google Fusion Tables. The database can be accessed by anyone as long as the user has a Google account. If a user does not have an account and wants to access the database, a Google account can be quickly created. The database can be found through the search box and public tables listing of the Google Fusion Tables. First, click on "Public tables" in the left hand column of the Google Fusion Tables homepage (http://www.google.com/fusiontables/Home). Then, type "REEs' Deposits Database" in the search box at the top of the page and click the "Search tables" button. The "REEs' Deposits Database" should appear in the list in the center of the screen. Click on "REEs' Deposits Database" to open the database.

The table visualization is automatically opened and the first 100 deposits are visible and as many fields that can fit horizontally are visible; approximately ten fields are typically shown. To scroll through all of the fields or columns, use the arrows in the upper right hand corner of the table. The "Deposit Name" will remain in the leftmost column when scrolling right and left for convenience. To view more locations, click on the next button above of the table in the upper right-hand corner displayed in Figure 4-3.

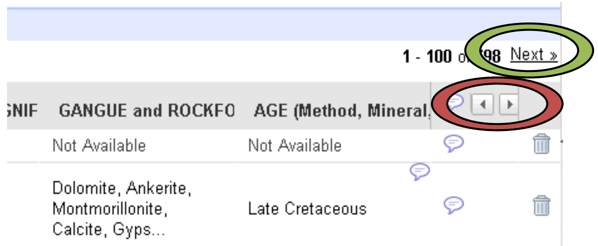

Figure 4-3. A screen capture of the scrolling options in Google Fusion Tables. To scroll through the columns, use the right and left arrows, circled in red in the top right corner. To scroll through the rows of deposits use the "Next" button, circled in green.

Switching between Table and Map Visualization Modes

Once in the database, the table visualization mode is displayed. To switch to the map visualization mode, click on the "Visualize" menu and select "Map" as shown in Figure 4-4. Similarly, if the map visualization is displayed and the user needs to switch to the table view, click on the "Visualize" menu and select "Table." Once in the map visualization, clicking on the placemark balloon produces an info window displaying information about the chosen deposit as shown in Figure 4-1.

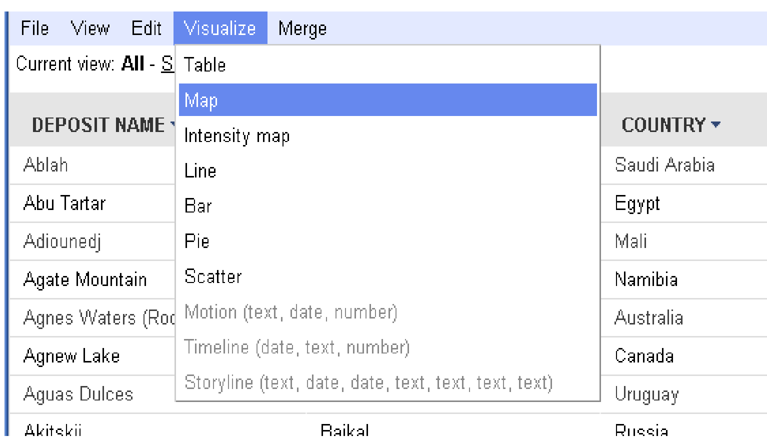

Figure 4-4. A screen capture of the "Visualize" menu where the user can switch from the table visualization and the map visualization.

While there are additional options available under the "Visualize" menu, they are not compatible with the REEs' Deposits Database. Specific numeric data is required to operate the Line, Bar, Pie, and Scatter views. The Intensity map is equivalent to a choropleth or thematic map and would be useful if it could aggregate the number of deposits in each state or country and produce a map. However, at this point, Google Fusion Tables does not offer this option, so the intensity map is not a useful tool with this data.

Filtering the Data

In order to filter the data and only view data meeting the specified criteria, the filtering window must be open. There are two ways to open the filtering window and both can be done either in the table or map visualization. The filtering window is where the user inputs criteria to view only deposits meeting the criteria. The first way is to open the "View" menu and select the "Filter" option as shown if Figure 4-5. The second way to open the filtering window is to select "Show options" in the top left-hand corner underneath the "Visualize" menu as shown in Figure 4-6.

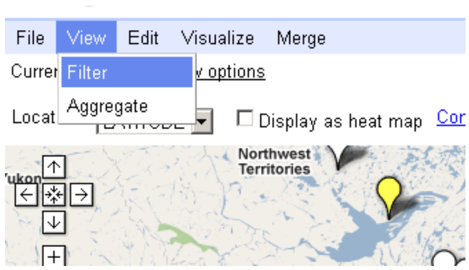

Figure 4-5. A screen capture of the "View" menu where the user can open the filtering window.

Figure 4-6. A screen capture of the options in the top left corner. "Show options" will open the filtering window.

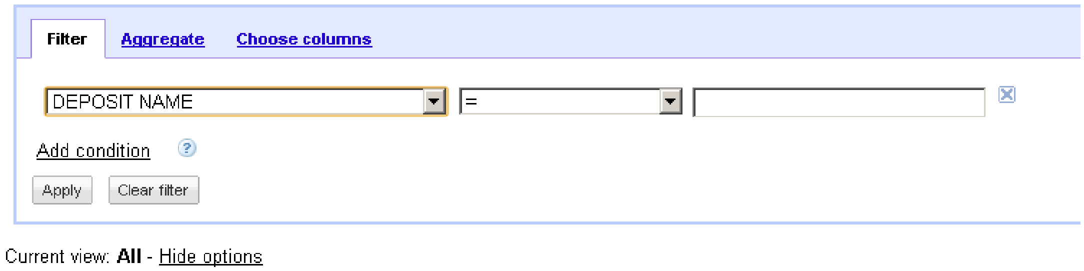

Figure 4-7. A screen capture of the filtering window in Google Fusion Tables.

Once the filtering window is open, the desired criteria are entered into the three dropdown boxes shown in Figure 4-7. In the first dropdown box, the column to be filtered should be selected. The middle dropdown box specifies the filter operator, how to filter data. Figure 4-8 shows the options for the filtering actions. The third search box is where the desired criteria are entered.

Figure 4-8. A screen capture of the operator options in the middle dropdown box of the filtering window.

The filtering operators in the middle dropdown box provide a variety of functions. The “=” operator yields results matching the criteria exactly. “Not equal to” excludes the records found with the “=” operator. The next four filtering operators can be used only with numeric data, such as Years Needed to Develop. The “<” operator yields results less than the criteria while the “<=” operator yields results less than or equal to the criteria. The “>” operator shows records more than the criteria while the “>=” operator shows records more than or equal to the criteria. To use a wild card at the end of the criteria and find records starting with the criteria entered, the “Starts with” operator should be used. This operator could be useful because the elements, minerals, and applications are listed in order of decreasing dominance. Similarly, “ends with” is equivalent to placing a wild card at the beginning of the criteria but is probably not useful for this application. The “Contains” operator will search within the category being filter and return records including the criteria listed. For the REEs’ Deposits Database, the “Contains” operator should be used to filter REEs Mineralogy, REEs, or Applications fields. One example of using “contains” is filtering for deposits applicable to magnets by filtering for “APPLICATIONS contains Magnets.” “Contains ignoring case” performs the same action as “Contains” but is not case sensitive. “Does not contain” excludes deposits found with the “Contains” operator. “Matches” is equivalent to Microsoft Access’ LIKE criteria, and symbols, such as an underscore or percentage sign, can be used as wildcards.

There are several commonly filtered fields in the REEs’ Deposits Database. For example, if the user wanted to only view deposits in the United States, the required filter would be “COUNTRY = United States of America.” If the user wanted to filter for deposits with fewer than ten years needed to develop, the need filter is “YEARS NEEDED TO DEVELOP <= 10.” Another filtering example would be if the user wanted to find deposits with neodymium (Nd), then the filter window would read “REEs contains Nd.” Furthermore, these conditions can be combined by selecting the “Add condition” button at the bottom of the filtering window to yield deposits meeting all of the criteria (Figure 4-9). In this example, the results would be United States’ deposits with Nd with fewer than ten years needed to develop.

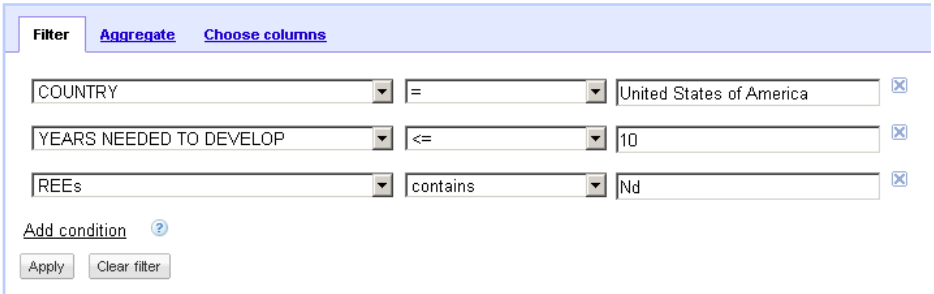

Figure 4-9. A screen capture of additives filters. This example would only yield deposits in the U.S. with a development time of less than or equal to 10 years and contain neodymium.

Importing and Exporting the Data

Google Fusion Tables can import a variety of files including: comma-separated files (.csv), Microsoft Excel files (.xls, .xlsx), OpenDocument Spreadsheets (.ods), and Google Earth files (.kml) or a document from Google Spreadsheets. After the data has been manipulated in Google Fusion Tables, the dataset can be exported to .csv or .kml files.

The import process follows a straightforward wizard located under “Import Table” from the “New Table” menu. First, the file to be imported is selected and uploaded. Then, the columns to be imported are specified and a description can be added to help other users know about the dataset. Once the dataset is uploaded, it can be filtered and manipulated in Google Fusion Tables.

After the data points are filtered, the dataset can be exported back into an Excel file for further processing in Microsoft Access or to a KML file which Google Earth can utilize. To export the data in table form to Excel in a csv file, click the “File” menu and the “Export” option. Exporting to Excel can be done in the table or map visualization mode. If there is a filter applied to the dataset, then only deposits meeting the criteria will be exported.

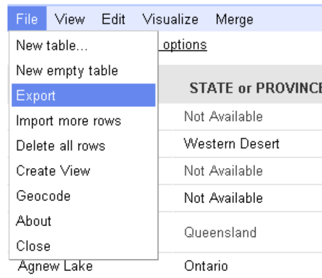

Figure 4-10. The "File" menu contains the "Export" option that sends the data to Excel in csv format.

To export the data to Google Earth as a KML file, Google Fusion Tables must be in the map visualization. Then, select the "Export to KML" link from the list of links at the top of the map as shown in Figure 4-11. It is possible to import an Excel file and then convert it into a KML file or vice versa. The workflow processes to import and export different file types are displayed in Figures 4-12 and 4-13.

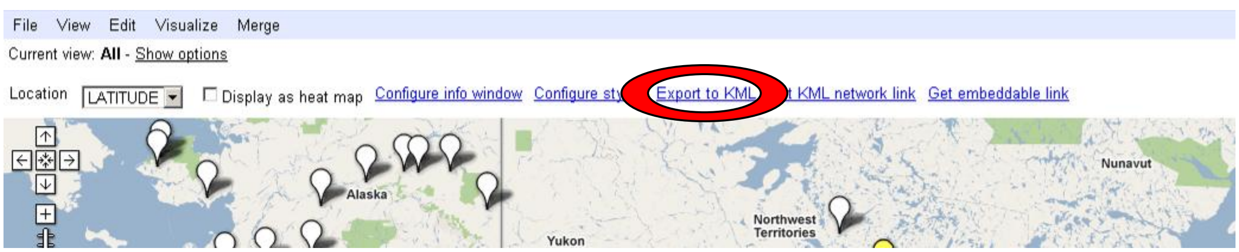

Figure 4-11. A screen capture of the links at the top of the map. "Export to KML" allows users to export the dataset into Google Earth.

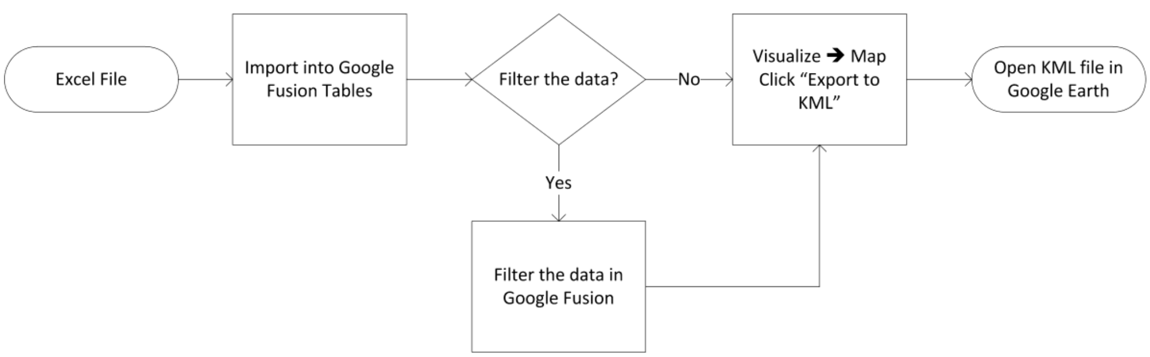

Figure 4-12. The workflow process to import an Excel file into Google Fusion Tables, filter it, and export a KML file.

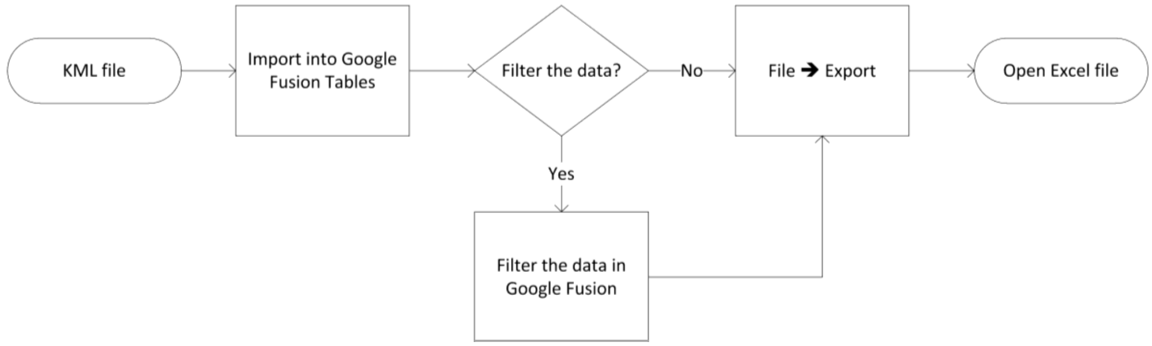

Figure 4-13. The workflow process to import a KML file into Google Fusion Tables, filter the data, and export an Excel file.

Google Fusion Tables enables the user to filter, export, and share the data easily. Despite its' lack of legend and histogram, this is the best application for the REEs' Deposits Database.

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Chapter 5

Overview of the REEs' Deposits Database

The REEs' Deposits Database is based on the "Rare Earth Element Mines, Deposits and Occurrences" report by the USGS (Orris and Grauch, 2002). In order to improve the utility and usability of this database, several important modifications were made to the existing data including: location changes, organizational changes, and column additions. The main contents of the REEs' Deposits Database includes: location data, status data, geology data, and miscellaneous data as shown in the list below.

Location Data
- Deposit Name
- Latitude/Longitude
- Country
- State or Province
- Estimated Location

Status Data
- Reserves/Resources Designation or Number
- Years Needed to be Developed

Geology Data
- REE Mineralogy
- REEs
- Heavy or Light Elements
- Applications
- Byproduct production
- Tonnage and Grade
- Other Ore or Significant Minerals
- Gangue and Rockforming Minerals
- Age
- Deposit Type
- Host Rock

Miscellaneous Data
- Company
- Comments
- References

Location Data

The "Deposit Name" field provides the title of the deposit used by the local population. Some deposits have multiple names or nicknames; these other names are listed in parentheses. The location data associated with the deposit is provided in political terms in the "State or Province" and "Country" fields. Also, the specific latitude-longitude point is provided.

The latitude and longitude information is contained in their respective fields. The USGS database had the latitude and longitude data in the format of degrees, minutes, and seconds (DMS). In contrast, the REEs' Deposits Database in Google Fusion Tables uses the decimal degrees format, because Google Fusion Tables can only map latitude and longitude points if they are in the decimal degrees format. Google Earth will accept latitude and longitude in both formats.

Location data had to be added to the deposits lacking latitude and longitude data. Of the original 798 sites, 269 lacked latitude and longitude data. For these locations, an Internet search was performed to approximate a latitude-longitude point for the deposit. The website was then added in the "References" field. The original "Location source" field from the USGS report was combined with the "References" field to improve usability.

The location data contains a degree of error of ± 1 minute in latitude or longitude. These points are not designed to assist companies in deciding exactly where to establish a mine but to provide the general area where the deposit is most likely located. The deposits with estimated locations from the Internet search have a "Yes" in the "Estimated Location" field. In 2010, the USGS published a new report providing details about the rare earths' deposits in the United States (Long et al, 2010). These deposits with precise location data have a "No" in the "Estimated Location" field.

Status Data

The USGS REEs database utilized a "Status" field containing comments if the location is currently producing or just a potential resource and if REEs were being produced as a byproduct or as a primary product (Orris and Grauch, 2002). Some locations did not have any data in this field because of conflicting reports or lack of information (Orris and Grauch, 2002). The "Status" field was standardized into the Google Fusion Tables database through the "Reserves/Resources Designation" field, which contains one of five statuses: proved reserves, probable reserves, measured resources, indicated resources, and inferred resources. Other extraneous comments originally located in the "Status" field, such as "Nb resource," were moved to the "Comments" field.

These standardized statuses are defined by the amount of exploration information known about the deposit and the economic feasibility as shown in Figure 5-1. Resources are defined as deposits with concentrations of naturally occurring materials where economic extraction is feasible either currently or in the future (USGS, 2011). In contrast, reserves are resources that are economically feasible to extract immediately (USGS, 2011). Proved reserves have a high level of certainty associated with the knowledge of profitability of the deposit. Probable reserves have the same level of certainty for economical feasibility as proved reserves but less is known about the deposit. Measured resources are related to proved reserves but are less economically feasible to recover with current technology. Indicated resources are similar to probable reserves but are less economically feasible to recover currently. Inferred resources have the least amount of information known about them and cannot be assessed for economic feasibility.

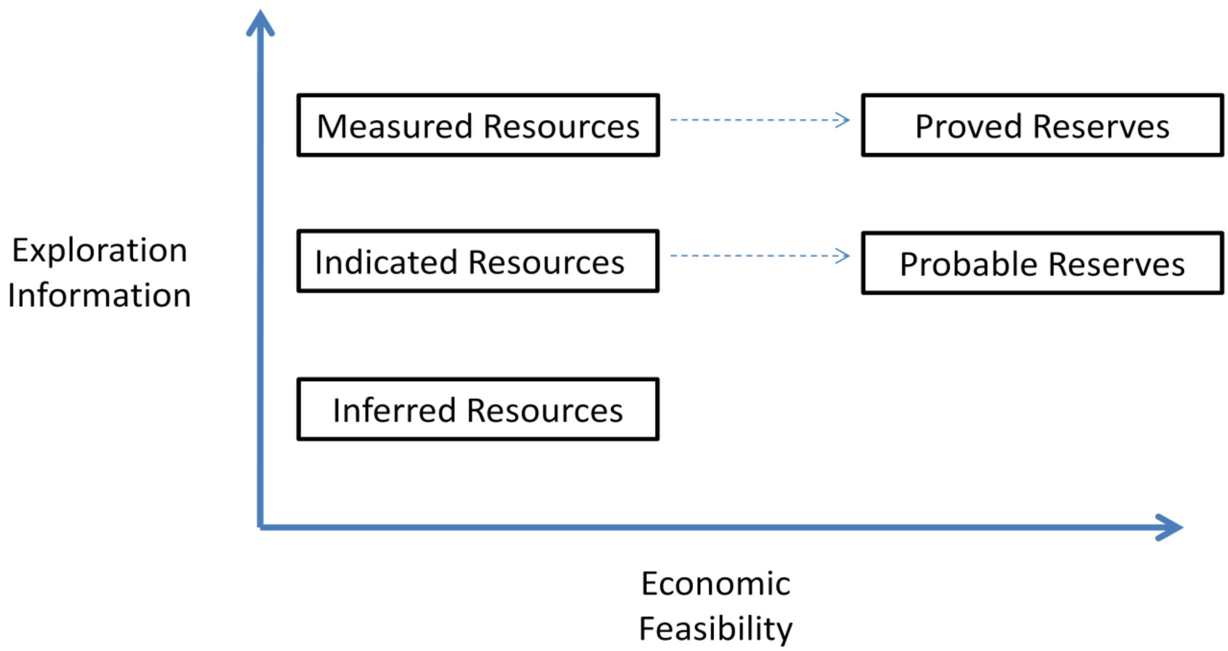


Figure 5-1. A visual showing reserves and resources designation's dependency on exploration information and economic feasibility. **Based on Wood, 2010**

The "Reserves/Resources Number" field directly corresponds with the status in the "Reserves/Resources Designation" field as shown in Table 5-1. To make filtering the data in Google Fusion Tables easier, the "Reserves/Resources Number" field was coded. Frequently, the user will want to view deposits with a "Reserves/Resources Designation" of measured resources, probable reserves, or proved reserves. Since Google Fusion Tables does not have an "OR" filtering operator, a workaround was accomplished by filtering for a Reserves/Resources Number less than three.

Table 5-1. The direct relationship between the "Reserves/Resources Designation" field and the "Reserves/Resources Number" field in the REEs' Deposits Database.

Reserves/Resources Designation	Reserves/Resources Number
Proved reserves	1
Probable reserves	2
Measured resources	3
Indicated resources	4
Inferred resources	5

The time needed for each deposit to develop is associated with the "Reserves/Resources Designation." The "Years Needed to Develop" field was created to give users a sense of development time needed for each location. Establishing a rare earths' mine requires a significant amount of time. After a deposit has been discovered and explored, investors need to be found and permits must be obtained (Long et al, 2010). In the next step, a processing plant must be designed and built, and then the mine will begin to operate (Long et al, 2010). The reserves/resources designation provides an indication of where each deposit is in the development process. The colors of the deposits' placemarks are determined by the "Years Needed to Develop" field. If a placemark has a black circle on it, that deposit is classified as a reserve. (See Table 5-2.)

Table 5-2. The legend of the REEs' Deposits Database. The two timelines are based on Reserves/Resources Designation and the countries' permitting delay times. The placemark coding is located in the "Icon" field of the database.

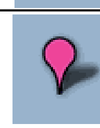
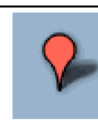
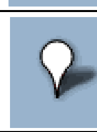
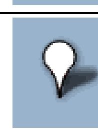
	Short Timeline (Years & Symbol)		Long Timeline (Years & Symbol)	
Proved reserves	0		0	
Probable reserves	3		7	
Measured resources	5		10	
Indicated resources	7		15	
Inferred resources	9999		9999	

Table 5-3. A list of the countries within with short and long timeline groups. The short timeline implies fewer permitting delays as compared to those countries with the long timeline.

Short Timeline Countries		Long Timeline Countries
• Afghanistan	• Mongolia	• Bolivia
• Angola	• Morocco	• Congo (Zaire)
• Argentina	• Mozambique	• Denmark
• Armenia	• Myanmar	• Egypt
• Australia	• Namibia	• Finland
• Bangladesh	• Nigeria	• Germany
• Benin	• North Korea	• Greenland
• Brazil	• Paraguay	• India
• Burundi	• Philippines	• Indonesia
• Cameroon	• Rwanda	• Kazakhstan
• Canada	• Sierra Leon	• New Zealand
• China	• Somalia	• Norway
• Colombia	• South Africa	• Poland
• Gabon	• Sri Lanka	• Romania
• Ghana	• Suriname	• Russia
• Guinea	• Taiwan	• Saudi Arabia
• Guyana	• Tajikistan	• South Korea
• Kenya	• Tanzania	• Sweden
• Kyrgyzstan	• Thailand	• United Arab Emirates
• Liberia	• Turkey	• United States of America
• Libya	• Uganda	
• Madagascar	• Ukraine	
• Malawi	• Uruguay	
• Malaysia	• Uzbekistan	
• Mali	• Venezuela	
• Mauritania	• Vietnam	
• Mexico	• Zimbabwe	

The values in "Years Needed to Develop" field were based on the "Reserves/Resources Designation" and the country where the deposit was located. Throughout the world, the development time varies for deposits with the same tonnage and grade due to permitting delays and political corruption (Behre Dolbear, 2011). Therefore, the countries were divided into two groups with two different timelines: short and long. The countries in each group are shown in Table 5-3. The "Timeline (1 = Short, 2 = Long)" field indicates if the deposit is located in a country categorized by the short timeline (value = 1) or the long timeline (value = 2). The short timeline is defined by 3, 5, 7, and unknown number of years (represented by 9999). The long timeline is defined by 7, 10, 15, and unknown number years (represented by 9999) as shown in Table 5-2. The 9999 value was implemented to enable filtering by "Years Needed to Develop" in Google Fusion Tables. The "Icon" field is the last column of the database and contains the information for the Google Fusion Tables to use the correct placemark for the deposit.

The two country groups were based on the Behre Dolbear's "Ranking of Countries where it would be Best to Develop Mines" (Behre Dolbear, 2011). In this report, analysts ranked the countries for time lost due to permitting delays. As expected, many of the countries without permitting delays (short timeline) are developing nations and located in Africa. Without restrictive environmental regulations, development time for rare earths' mines is shortened. The developed countries, such as the United States, take longer to establish a rare earths' mine due to permitting delays. However, some developed countries, such as Australia, have found ways to expedite this process. Australia had the fastest permitting time of the twenty-five countries included in the Behre Dolbear report. In contrast, the United States ranked last. Because only twenty-five countries were ranked in the Behre Dolbear report, the remaining countries were grouped based on an extrapolation of the data.

Geology Data

The USGS database provided the "REE Mineralogy" field listing the REMs found at each deposit using abbreviations for the minerals. The abbreviations were removed and replaced with the full mineral name. Similarly, the abbreviations were removed and replaced with the full mineral name for the "Other Ore or Significant Minerals" and "Gangue and Rock-forming Minerals" fields.

Using the data from the "REE Mineralogy," the "REEs" field was created and it lists the elements typically found in the REMs. This information came from sources shown in Appendix A. Anatase and gittinsite are considered by the USGS to be REMs. However, anatase typically contains only TiO_2 and gittinsite contains only $CaZrSi_2O_7$, not any REEs. Therefore, neither were included in the "REE Mineralogy" field but in the "Other Ore or Significant Minerals" field.

The "Applications" field was created, using the "REEs" field. The information correlating REMs, REEs, and applications is shown in Appendix A and was based the rare earths' usage by application as shown in Table 2-2 in the Importance section (Lynas, 2010).

The "Byproduct? (Yes or No)" field indicates if REEs are produced or may in the future be produced as a byproduct or coproduct at each location. Often REEs are produced as byproducts because it is more economical to produce a primary mineral such as iron ore.

Further geological information is provided in the "Other Ore or Significant Minerals," "Gangue and Rock-forming Mineral," "Age (Method, Mineral, Rock)," "Deposit Type," "Age" and "Host Rock" fields. The "Tonnage and Grade" field provides the data, if available, about the amount and concentration of REMs. The tonnage is provided in metric tons and the concentration or grade can be provided as a percentage or in parts per million (ppm). This information is helpful to geologists or companies planning to develop a rare earths' mine. These fields were mostly unchanged from the USGS database.

Miscellaneous Data

The remaining fields (Company, Comments, and References) provide deposit-specific information and may not be useful in predicting which rare earths' deposits will develop into mines but do provide further information about a specific location. "Company" data is provided for the mine if it is known which business owns the mineral rights at the location. While this information is useful, it may not be current and should be viewed with caution. The "Comments" field provides additional information not be covered by any of the other fields. It can contain information about the status of the location or more information about accuracy of the information. The “References” field cites where the USGS found the data and additional websites used during the update of the information. This field will be useful once a deposit has been identified to be developed and further information is required.

Chapter 6

Future Supply Scenarios and Critical Deposits

The REEs' Deposits Database was filtered to show potential mine locations in five possible future supply scenarios varying demand level. Then, the HREEs' deposits in the United States were examined to determine if the United States could support domestic demand of HREEs. Finally, the domestic deposits containing any one of the DOE critical elements (Dy, Nd, Eu, Y, Tb) were analyzed.

Future Supply Scenarios

Five future supply scenarios with varying levels of demand forecasted the location of REEs' deposits using the REEs' Deposits Database on Google Fusion Tables. These scenarios include:

- Scenario 1: Low Demand Levels
- Scenario 2: United States' Current Demand Levels
- Scenario 3: Moderate Demand Levels
- Scenario 4: High Demand Levels
- Scenario 5: Japan's Current Demand Levels

Four variables were used to develop the scenarios (1) international political atmosphere; (2) greenhouse gas regulations; (3) environmental mining regulations; and (4) REEs' applicability ratio. These variables were chosen because of their significant impact on the available REEs' deposits and their possibility to change in severity in the future. Using the REEs' Deposits Database, these variables were translated into properties of the deposits including location, reserves/resources designation, applications, and years needed to develop. The flowchart shown in Figure 6-1 displays the development of the five scenarios in Google Fusion Tables.

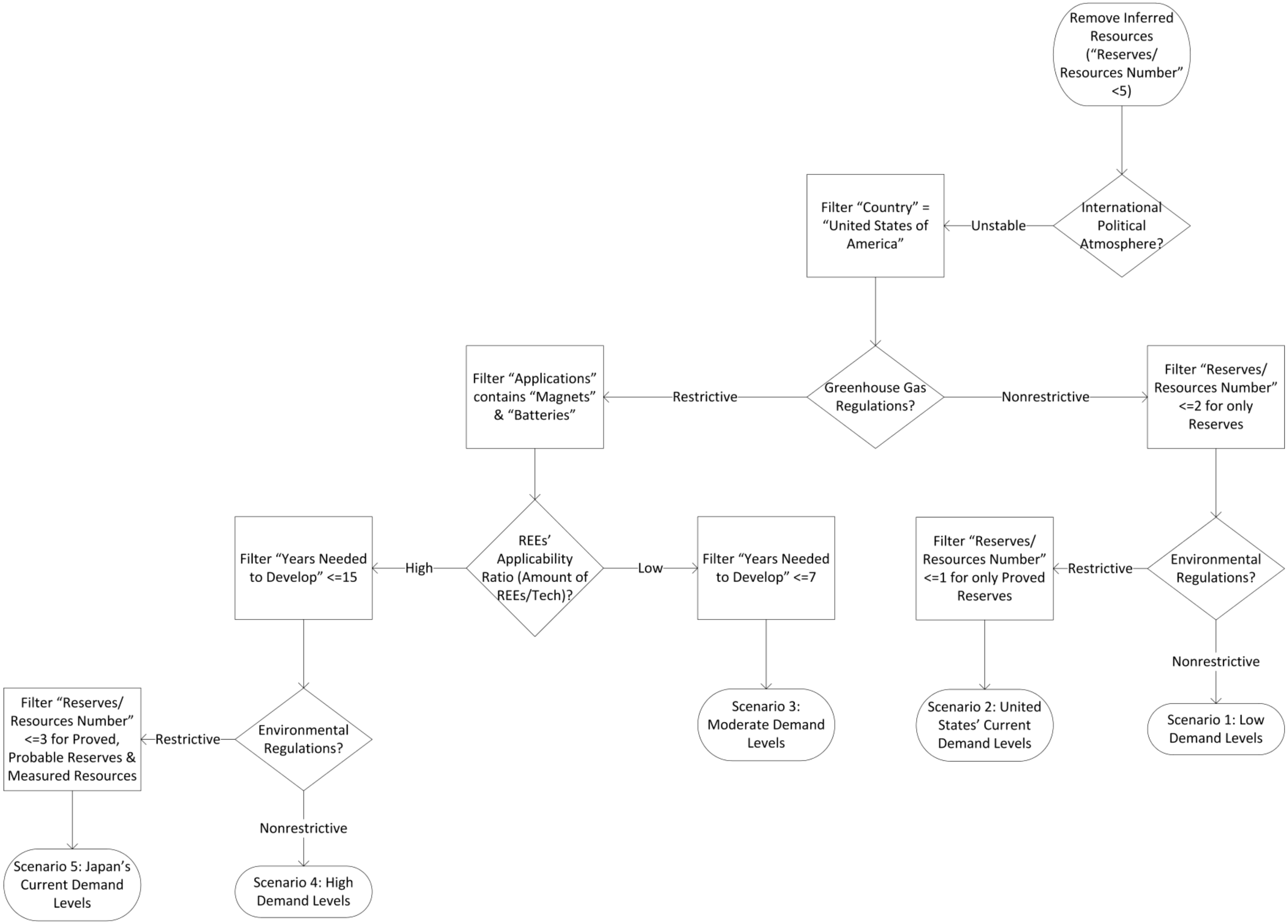


Figure 6-1. The flowchart illustrating the development of the five future supply scenarios. The variables included in analysis are international political atmosphere, greenhouse gas regulations, environmental regulations, and REEs' applicability ratio, which were translated into deposits' properties including location, reserves/resources designation, applications, and years needed to develop.

Before considering any of the variables, the inferred resources were filtered out of scenarios because of the lack of information describing these deposits. The database was filtered for deposits coded with Reserves/Resources Numbers less than five (as explained in Table 5-1). In the future as more exploration information becomes available and the database is updated, the inferred resources may be upgraded to the indicated resources reserves/resources designation and be included in the analysis. Figure 6-2 shows the original 798 REEs' deposits in the database and Figure 6-3 shows the 333 deposits included in this scenario-based analysis.

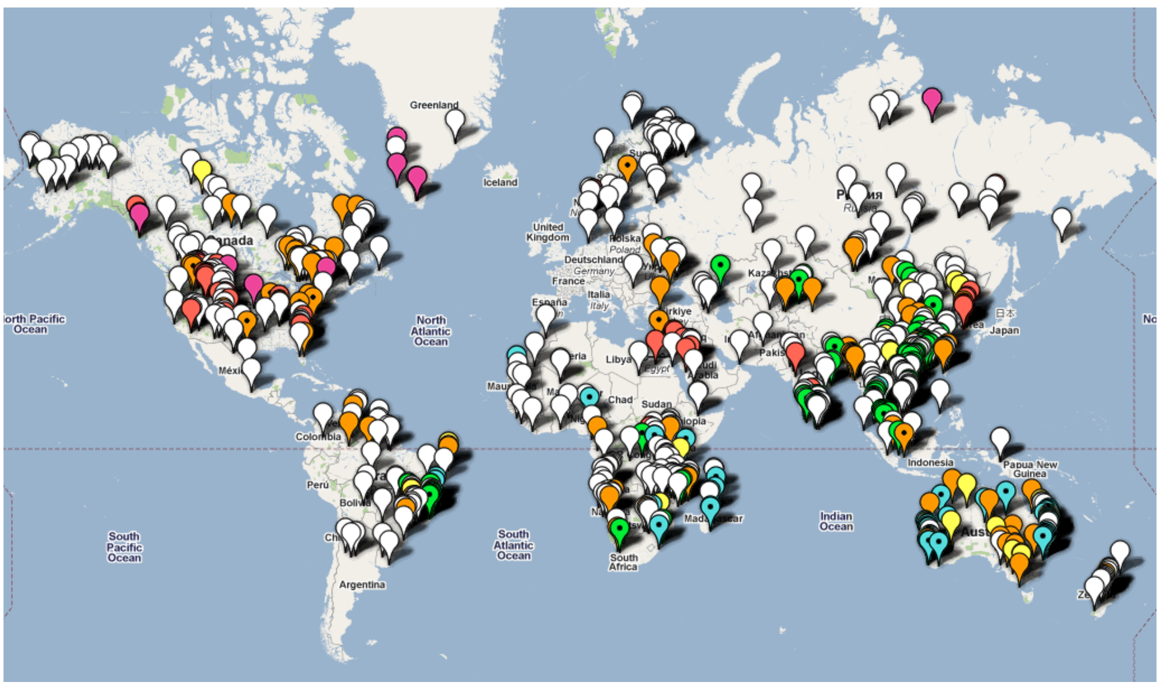


Figure 6-2. A screen capture of the global view of all rare earths' deposits. Refer to Table 5-2 for a legend.

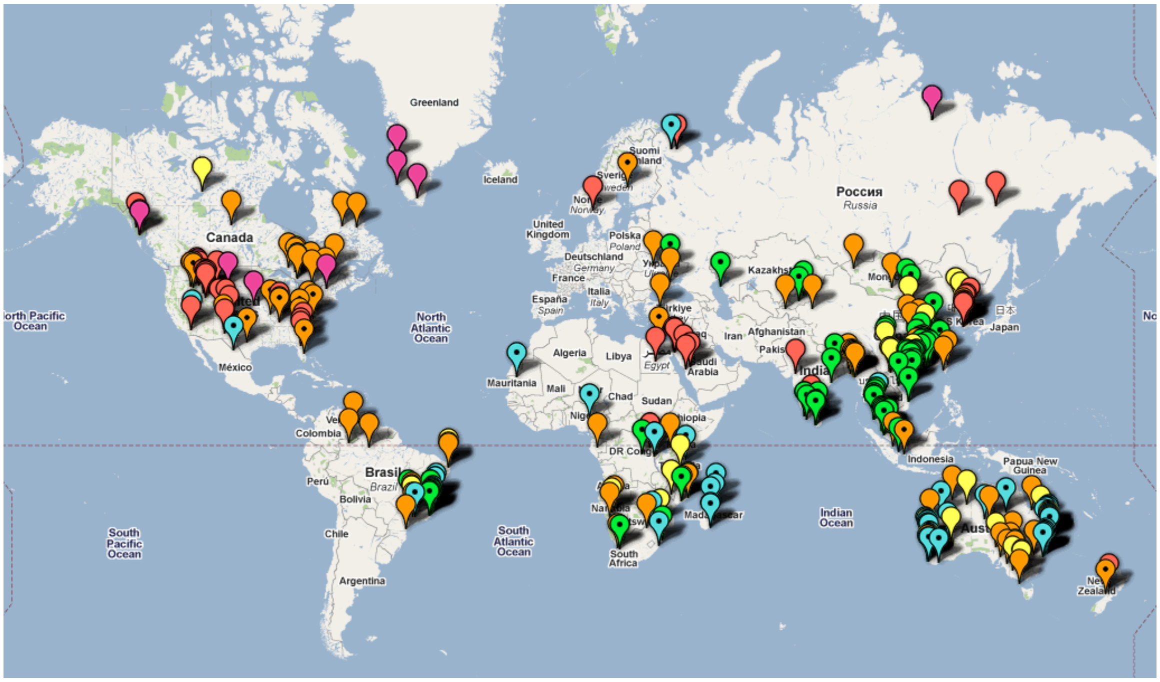


Figure 6-3. A screen capture of the global view of rare earths' deposits with inferred resources removed. Refer to Table 5-2 for a legend.

The first variable considered in the development of the future supply scenarios is the stability of the international political atmosphere. As discussed in Chapter 3, if countries with significant rare earths' deposits are willing to trade with countries without developed mines, then there is a stable international political atmosphere and all of the deposits across the world can be considered. An unstable international atmosphere is classified by countries with significant rare earths' deposits imposing export quotas preventing other countries from meeting their rare earths' demand or a country striving to reduce dependence on foreign REEs. With an unstable international political atmosphere, it will be necessary to spatially filter the REEs' database for the deposits located within the countries of interest. Since the domestic deposits within the United States should be developed to reduce dependence on foreign REEs, the five future supply scenarios assume there is an unstable international atmosphere and only consider deposits in the

United States (Figure 6-4). This variable is accounted for by applying the filter “COUNTRY = United States of America” and reduces the number of deposits to 44 from 333.

Figure 6-4. A screen capture of the United States rare earths’ deposits excluding inferred resources. Refer to Table 5-2 for a legend.

The second variable is how restrictive the greenhouse gas (GHG) regulations are. Currently, the United States does not have any regulations on the production and emission of carbon dioxide and other greenhouse gases and thus the regulations are nonrestrictive. If the greenhouse gas regulations continue to be non-restrictive, it will be economical to develop only proved and probable reserves because there will be a lower level of demand. The filter applied to account for non-restrictive GHG regulations was “Reserves/Resources Number <= 2.” Figure 6-5 shows the available deposits after this filter is applied.

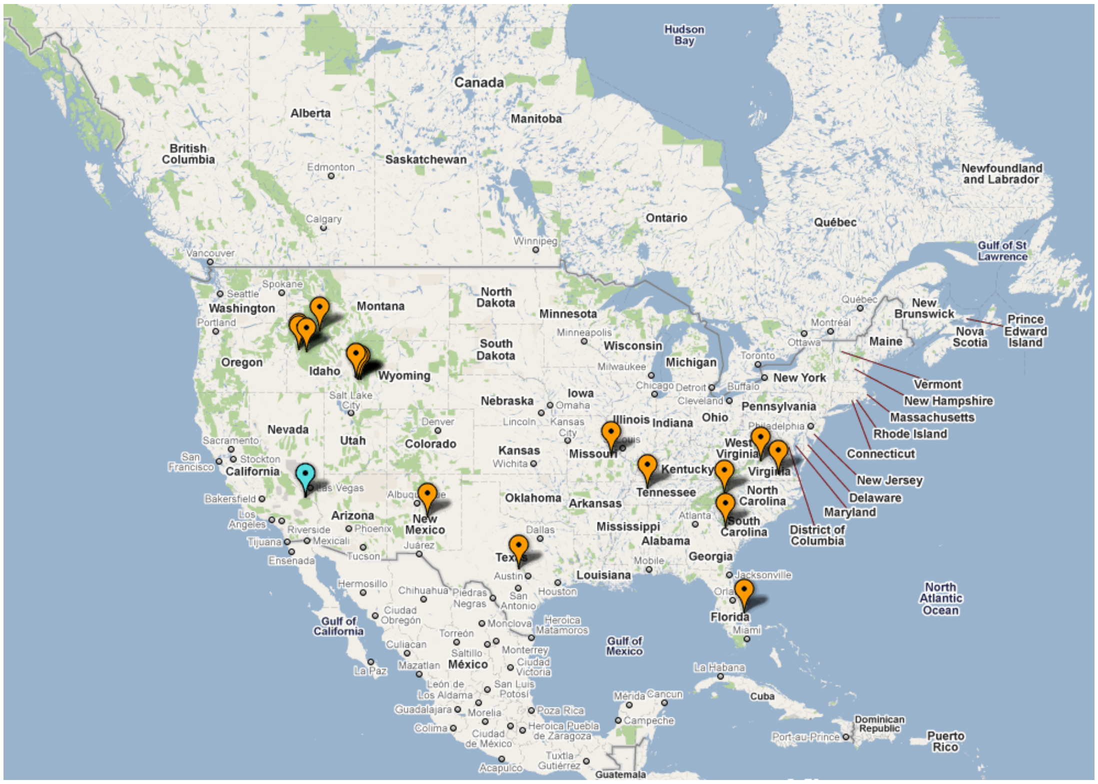


Figure 6-5. A screen capture of the REEs' Deposits Database filtered for United States' proved and probable reserves representing an unstable international atmosphere, nonrestrictive greenhouse gas emissions, and nonrestrictive environmental regulations or Scenario 1: Low Demand Levels. Refer to Table 5-2 for a legend.

If international greenhouse gas emissions regulations were enacted or the United States' government decided to internally impose regulations, then the demand will increase for rare earth permanent magnets used in wind turbines and the NiMH batteries used in electric cars. Therefore, the deposits able to produce REEs for both magnets and batteries will be the most critical deposits to develop (Figure 6-6). The filter applied to account for restrictive GHG regulations was "APPLICATIONS contains Magnets" AND "APPLICATIONS contains Batteries."

Figure 6-6. A screen capture of the REEs' Deposits Database filtered for an unstable international political atmosphere and restrictive greenhouse gases. Refer to Table 5-2 for a legend.

The third variable considered when determining the profitability and practicality of developing a deposit into a mine was the environmental regulations about mining. These regulations will vary by country and perhaps by state or province. If the environmental regulations for rare earths' mines are restrictive and environmental controls will cost the companies significant sums of money, then it will be economical to develop only the deposits with high concentrations and amounts of REEs (those deposits with a lower Reserves/Resources Number). On the other hand, if the environmental regulations are nonrestrictive, it might be economical to create mines from deposits with lower tonnages and grade requiring more processing with a higher impact to the environment. In terms of filtering, nonrestrictive mining regulations do not require additional filtering since all deposits are viable to develop. To incorporate restrictive mining regulations into the future supply scenarios, the reserves/resources designation must be restricted.

The final variable to consider in the development of future supply scenarios is the applicability ratio, defined as the amount of REEs within the technologies of interest. The REEs' applicability is expected to decrease as time progresses, because research and development teams will be developing products of equal quality with less REEs or alternative materials to replace the need for REEs in each technology. An economical alternative material would eliminate demand for REEs, and the REEs' applicability ratio would be equal to zero. As the REEs' applicability ratio decreases, the demand will decrease and only deposits with a short development time will be developed. Therefore, to account for a low REEs' applicability ratio, only deposits with a development time less than or equal to seven years will be considered. In contrast, if the applicability ratio is high, demand will be high. In the high applicability ratio scenario, deposits with longer development times will still be viable options.

These four variables regarding the international political atmosphere, GHG regulations, environmental regulations and the REEs' applicability ratio create five future supply scenarios with varying levels of demand: low, United States' current, moderate, high, and Japan's current levels.

Scenario 1: Low Demand Levels

The low demand level future supply scenario forecasts (1) an unstable international atmosphere; (2) nonrestrictive greenhouse gas regulations; and (3) nonrestrictive environmental mining regulations. The unstable international political atmosphere specifies how the United States is focusing on developing domestic deposits. Nonrestrictive greenhouse gas regulations cause the REEs' demand to increase at its current rate; the economical deposits to develop are proved and probable reserves. Nonrestrictive environmental regulations do not impose environmental control costs on rare earth mining companies. So, mining companies can develop rare earths' deposits with lower grades possibly requiring additional processing and might negatively impact the environment. Therefore, there is no need to further filter the potential mines. The applicability ratio is not considered in this scenario because all of the potential mines already satisfy strictest requirements.

This low demand scenario portrays 18 possible locations where rare earths' mines could be established (See Figure 6-4). Mountain Pass, California is included in these possible locations. Quartz and clay are the dominant gangue materials at possible deposits in this scenario. The potential mine locations encompass a variety of deposit types including igneous-affiliated, phosphorite, alluvial, and shoreline placers. Of the 18 possible mine locations in this scenario, seven of them are located in Idaho in two clusters. The southern Idaho cluster contains mostly byproduct rare earths' deposits. Most of these Idaho deposits are past REEs producers; therefore, the USGS has a significant amount of tonnage and grade data about these deposits. The Gallinas Mountains in New Mexico is the only deposit with a significant quantity of HREEs.

Scenario 2: United States' Current Demand Levels

The second scenario examines the United States' current demand levels with (1) an unstable international political atmosphere; (2) nonrestrictive greenhouse gas regulations; and (3) restrictive environmental mining regulations. The difference in this scenario from the low demand scenario is the prediction of restrictive environmental regulations (Figure 6-7). The restrictive environmental regulations force the mining companies to spend money on environmental studies and remediation work once the mine closes. Therefore, it probably would be economical to develop only proved reserves. Again, the REEs' applicability ratio was not considered because it would not impact the already limited choices. This scenario reflects the current situation in the United States with no greenhouse gas regulations and restrictive environmental regulations about mining since mines must implement environmental controls and prepare a plan for mine closure.

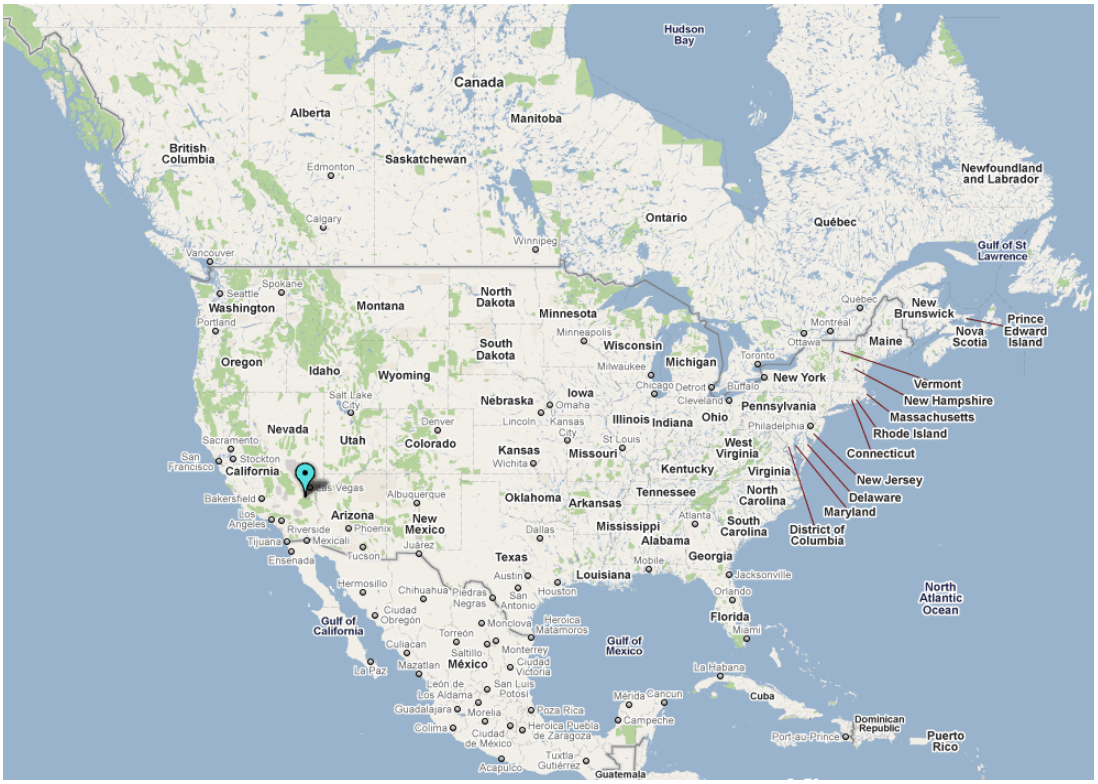


Figure 6-7. A screen capture of Scenario 2: United States' Current Demand Levels - Unstable international political atmosphere, nonrestrictive greenhouse gas regulations, and restrictive environmental regulations. The only deposit is Mountain Pass, CA. Refer to Table 5-2 for a legend.

The current levels of demand in the United States predict only one possible deposit to develop economically: Mountain Pass, California. This scenario underlines the importance of the Mountain Pass mine. Molycorp, Inc. is in the process of restarting the mine and processing plant and should be ready in 2012; currently, ore is being processed from the stockpiles from when the mine closed in 2002. The mine closed due to environmental violations associated with thorium, a radioactive element, entering the ground water (Castor and Hedrick, 2006). While Mountain Pass has a large reserve base, the majority of the ore contains LREEs. Therefore, if this scenario occurs, the demand for HREEs will outstrip the supply. Applications utilizing HREEs, such as lasers, silicon photovoltaic cells, and the nuclear industry, will face severe shortages if current levels of supply and demand continue.

Scenario 3: Moderate Demand Levels

The next future supply scenario with moderate levels of demand portrays (1) an unstable international political atmosphere; (2) restrictive greenhouse gas regulations; and (3) a low REEs' applicability ratio. The restrictive greenhouse gas regulations will increase the demand for green technology utilizing REEs, such as permanent magnets and batteries in wind turbines and electric vehicles. The low REEs' applicability ratio may have stemmed from a future discovery of alternative materials to replace REEs or an improvement in rare earth applications decreasing the amount of REEs needed for each technology. The environmental regulations were not considered, because the scenario already meets strict criteria.

The moderate demand scenario portrays 17 possible locations where mines could be developed (Figure 6-8). It provides a similar view to the low demand scenario but has one fewer deposit. The Sheep Creek deposit was not included in the moderate demand scenario because of the unknown nature of the minerals. The United States can support a higher level of demand for green technology because most of the deposits from the low demand scenario also appear in the moderate demand scenario. Developing these deposits would help secure the REEs supply for applications within the United States.

Figure 6-8. A screen capture of Scenario 3: Moderate Demand Levels - Unstable international political atmosphere, restrictive greenhouse gases, low applicability ratio. Refer to Table 5-2 for a legend.

Scenario 4: High Demand Levels

The next scenario considers (1) an unstable international political atmosphere; (2) restrictive greenhouse gas regulations; (3) a high REEs' applicability ratio; and (4) nonrestrictive environmental mining regulations (Figure 6-9). The high REEs' applicability ratio implies alternative materials to replace REEs were not found. Therefore, it would be practical and probably economical to invest in developing mines with longer development times. There is a high level of demand stemming from the restrictive greenhouse gas regulations and high REEs' applicability ratio allowing for a large number of possible locations to be developed into rare earths' mines. Nonrestrictive environmental mining regulations do not require additional filtering because environmental controls will not be implemented, so the available deposits will not be limited by the cost of production.

Figure 6-9. A screen capture of Scenario 4: High Demand Levels - Unstable international political atmosphere, restrictive greenhouse gas regulations, high applicability ratio, nonrestrictive mining regulations. Refer to Table 5-2 for a legend.

In the high demand levels scenario, 39 potential mine locations are feasible to develop and these locations are scattered throughout the United States (Figure 6-9). Several western states have high concentrations of these deposits including Idaho, Colorado, and New Mexico. There is a series of rare earths' deposits in North Carolina, South Carolina, and Georgia. Two of these deposits, Hilton Head Island and Cumberland Island, are located near protected areas and are unlikely to be developed. Several potential mines contain HREEs including: Hicks Dome, Gallinas Mountains, Elk Creek, Music Valley, and Mineville Iron District. As expected, most of the potential mine locations have monazite as the dominant mineral and monazite contains mostly

LREEs. Tonnage and grade information is provided for 34 out of the 39 locations. This information will enable the mining companies to quickly evaluate for the most profitable deposits. Mudstone and sandstone are the primary host rocks for the majority of these deposits. The ownership information is incomplete; it is provided for approximately one-third of the locations. If the remaining two-thirds of the locations are not owned, those properties could be bought by new companies looking to enter the rare earths industry. Overall, this high demand scenario leads to many feasible potential mining locations.

Scenario 5: Japan's Current Demand Levels

The final scenario forecasts (1) an unstable international political atmosphere; (2) restrictive greenhouse gas regulations; (3) a high REEs' applicability ratio; and (4) restrictive environmental mining regulations. This scenario represents the current demand level of Japan without considering the 2011 earthquake. The 2011 earthquake will probably decrease the demand level in the short term as rebuilding infrastructure is a higher priority than company growth (Areddy, 2011b). However, the demand is expected to return to the high levels exhibited before the earthquake. The demand may increase as the Japanese population may want to invest in wind energy (Areddy, 2011b). As a developed country, the Japanese government sets restrictive environmental standards. Environmental standards reduce the practicality of developing deposits requiring additional processing. Japan is one of the largest consumers of REEs due to Toyota's use of REEs in the production of electric and hybrid-electric cars. Since there are no rare earths' deposits in Japan, Japanese companies must rely on imported REEs completely. With the Chinese government reducing the REEs export quotas, Japanese companies are forced to look elsewhere for sources of REEs. While Japanese scientists are researching how to reduce the applicability, no feasible alternative materials for REEs have been found yet and the REEs' applicability ratio remains high.

Figure 6-10 displays the scenario for Japan's current level of demand with 21 potential rare earths' deposits, approximately half as many in the high demand scenario. All of these deposits can be developed in ten years or less, and only four of the deposits in this scenario have estimated locations. Since the majority of the deposits have known locations, it will be relatively easy to update the exploration data. Similar to previous scenarios, the majority of these deposits contain mostly LREEs. Therefore, some alternative materials must be developed to fill the deficit between supply and demand of HREEs. Carbonatite, phosphorite, and placers dominate the deposits in this scenario.

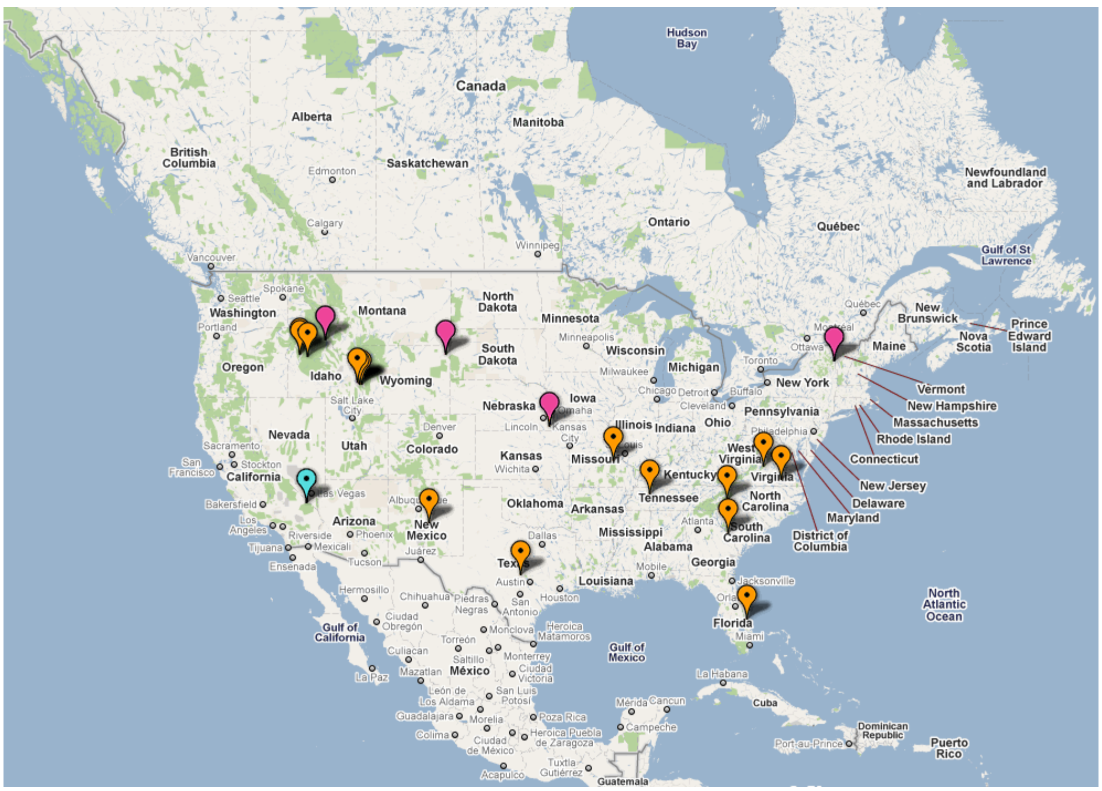


Figure 6-10. A screen capture of scenario 5: Japan's Current Demand Levels - Unstable international political atmosphere, restrictive greenhouse gas regulations, high applicability ratio, and restrictive environmental mining regulations. Refer to Table 5-2 for a legend.

More scenarios can be developed by applying different filters in other parts of the world. These five scenarios predict the possible locations of REEs' supply based on the GHG regulations, environmental regulations, and REEs' applicability ratio within the United States in the future. While the United States' current demand level scenario predicts Mountain Pass as the only deposit feasible to develop, the future outlook probably looks more similar to Japan's current demand level scenario. There will be an increased demand for green technology and reducing GHGs, and it is unlikely any economical alternatives will be discovered within the next ten years. The mining regulations in the United States are restrictive, as evidenced by the EPA requiring extensive permits and shutting down Mountain Pass in 2002 due to environmental violations. In the Japan's current demand scenario, there are 21 deposits to develop into active mines; however, these deposits contain mostly LREEs, not HREEs.

Heavy Rare Earth Elements Deposits

While HREEs and LREEs are often found at the same locations due to their trivalent nature, they are not found in the same amounts. Typically, HREEs are much scarcer than LREEs (Long et al, 2010). Due to the limited supply, HREEs experience a higher level of demand for applications such as lasers, metal alloys used in the nuclear industry, and silicon photovoltaic cells (Lynas, 2010). The deposits containing HREEs are more profitable to develop because the price of HREEs is higher than LREEs' price.

The REEs' Deposits Database establishes four categories of deposits based on atomic weight. If a deposit has a value of "Light" in the "Light or Heavy" field, then the deposit only contains LREEs. Similarly, "Heavy" indicates only HREEs present at the location. Since LREEs and HREEs are typically found together, most deposits will either be "Light/Heavy" or "Heavy/Light." "Light/Heavy" indicates more LREEs present than HREEs and "Heavy/Light" indicates more HREEs in the ore than LREEs.

Using the REEs' Deposits Database, the geographic distribution and prevalence of HREEs' and LREEs' deposits was analyzed (Figures 6-11 and 6-12). The HREEs' and LREEs' deposits have similar geographic distribution. There are slightly more HREEs' deposits in the southwest corner. The sheer number of deposits does not reflect how HREEs are scarcer than LREEs. In the United States, 92 deposits contain LREEs and 88 deposits contain HREEs. If the tonnage and grade of these deposits are examined, LREEs are clearly more prevalent as compared to HREEs.

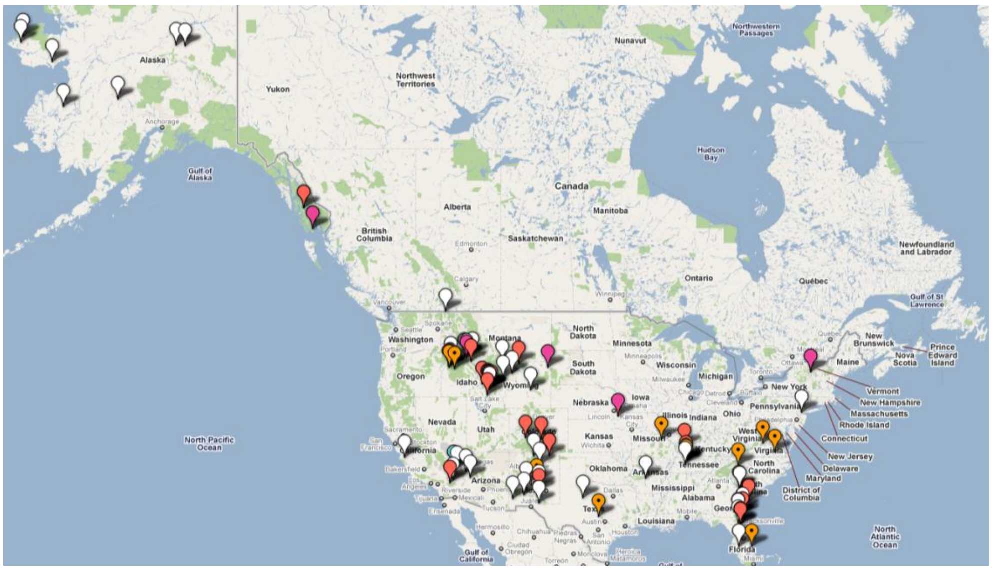


Figure 6-11. A screen capture of all deposits containing HREEs in the United States. Refer to Table 5-2 for a legend.

Figure 6-12. A screen capture of all deposits containing LREEs in the United States. Refer to Table 5-2 for a legend.

Six deposits in the United States contain only HREEs as shown by Figure 6-13. Of those six deposits, four of them are inferred resources and lack exploration information. The Gallinas Mountains in New Mexico has the shortest development time, seven years. This deposit is relatively small and probably would not support the United States' demand of HREEs for a significant period of time.

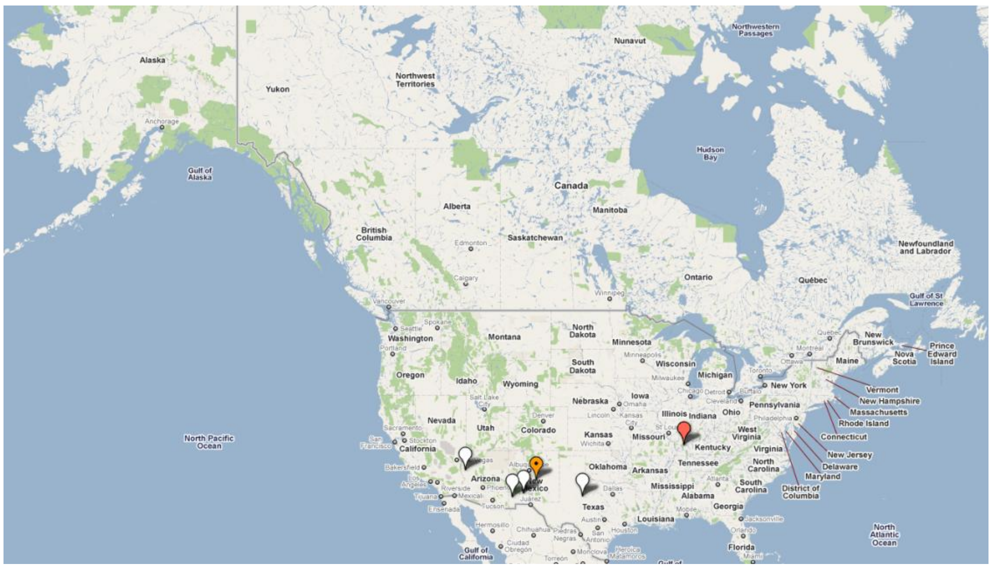


Figure 6-13. A screen capture of the REEs' deposits in the United States with only HREEs. Refer to Table 5-2 for a legend.

Eleven deposits in the United States contain a majority of HREEs and some LREEs (Figure 6-14). These mines will probably be profitable to develop, because the production of a variety of REEs provides a wider profit base. Unfortunately, most of these deposits have a development time of ten years.

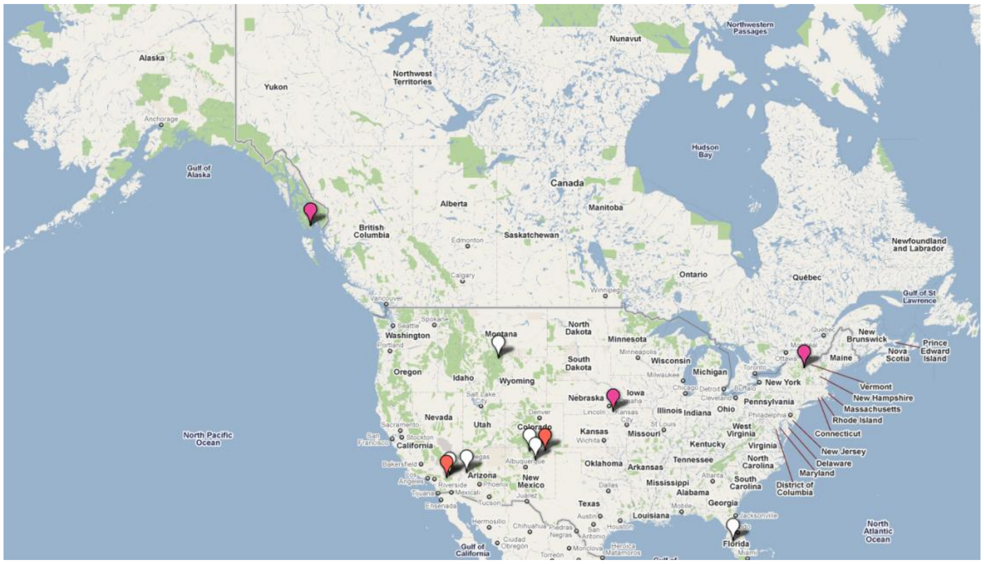


Figure 6-14. A screen capture of Heavy/Light REEs' deposits in the U.S., those deposits containing mostly HREEs and some LREEs. Refer to Table 5-2 for a legend.

Fortunately, 71 deposits with a majority of LREEs and some HREEs can be developed more quickly (Figure 6-15). Light/Heavy deposits are located throughout the continental United States and in Alaska. As discussed in the scenarios section, there are a significant amount of deposits in Idaho and along the East Coast. These deposits should support the demand for HREEs while the HREEs mines are being established.

HREEs are typically found with LREEs but in smaller quantities than LREEs as shown by the large number of LREEs/HREEs deposits in Figure 6-15. The United States should invest in finding alternative materials for HREEs due to their limited domestic supply. While these alternative materials are being researched, the United States can import HREEs from Thor Lake in Canada or Mount Weld in Australia.

Figure 6-15. A screen capture of Light/Heavy REEs' deposits in the United States, those deposits containing mostly LREEs and some HREEs. Refer to Table 5-2 for a legend

Critical Deposits

Background

While HREEs' deposits are considered scarce, there is a small group of REEs identified by the U.S. Department of Energy (DOE) as "critical" to the United States (DOE, 2010). The critical elements include dysprosium (Dy), neodymium (Nd), europium (Eu), yttrium (Y), and terbium (Tb); three of them (Dy, Tb, Y) are HREEs. In addition to identifying critical elements, the DOE report outlined a plan to develop an integrated research agenda, improve the information available on REEs, and work with international partners to reduce the possibility of supply disruptions (DOE, 2010). This plan intends to diversify the global supply chain, develop substitutes, and improve recycling, reuse, and use of REEs.

To establish which elements are critical, all REEs were assessed on their importance to clean energy and their supply risk. Importance to clean energy was defined by the importance of the elements to magnets, batteries, and phosphors as well as the possibility of substituting the element for an alternative material (DOE, 2010). Supply risk was defined by the ability of the global supply to meet demand, other technology demands on the element, political, regulatory and social factors, and if a country or company has a monopoly over the production of the element in question (DOE, 2010). Experts evaluated each element on a qualitative basis and then plotted the elements onto a critically matrix for both the short term outlook (0-5 years) and the medium term outlook (5-15 years). Moving from the short term outlook to the medium term outlook, all of the elements were either downgraded in criticality or remained in the same category. Since rare earths' mines have lengthy development times, as much as ten years, the REEs' Deposits Database examined the medium term criticality matrix, shown in Figure 6-16. Dysprosium, used in permanent magnets or lasers, was identified as the most critical element with global demand exceeding supply in as little as five years in the future.

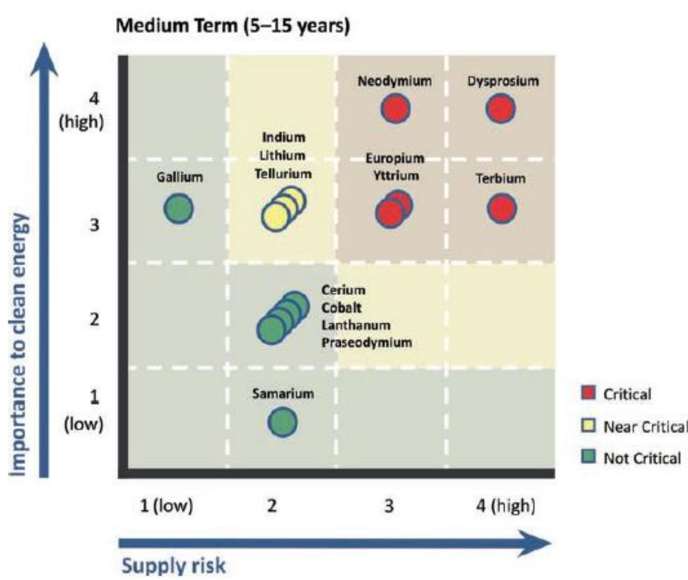


Figure 6-16. The medium term outlook criticality matrix as identified by the DOE. **Source: DOE, 2010**

In Google Fusion Tables, it is easy to identify the deposits containing one specific element in the United State by applying two additive filters: "COUNTRY = United States of

America" and "REEs contains X element." However, in order to view the mines in the United States containing any one of the five critical elements (Nd, Dy, Eu, Y, or Tb), a multi-step process was required. If the filters of "REEs contains Nd" and "REEs contains Dy" and "REEs contains Eu" and "REEs contains Y" and "REEs contains Tb" were applied, only deposits containing all five elements will be displayed. It was the goal of this query to identify deposits containing any one or more of the critical elements. The workflow required for this operation is shown in Figure 6-17.

All Critical REEs Deposits

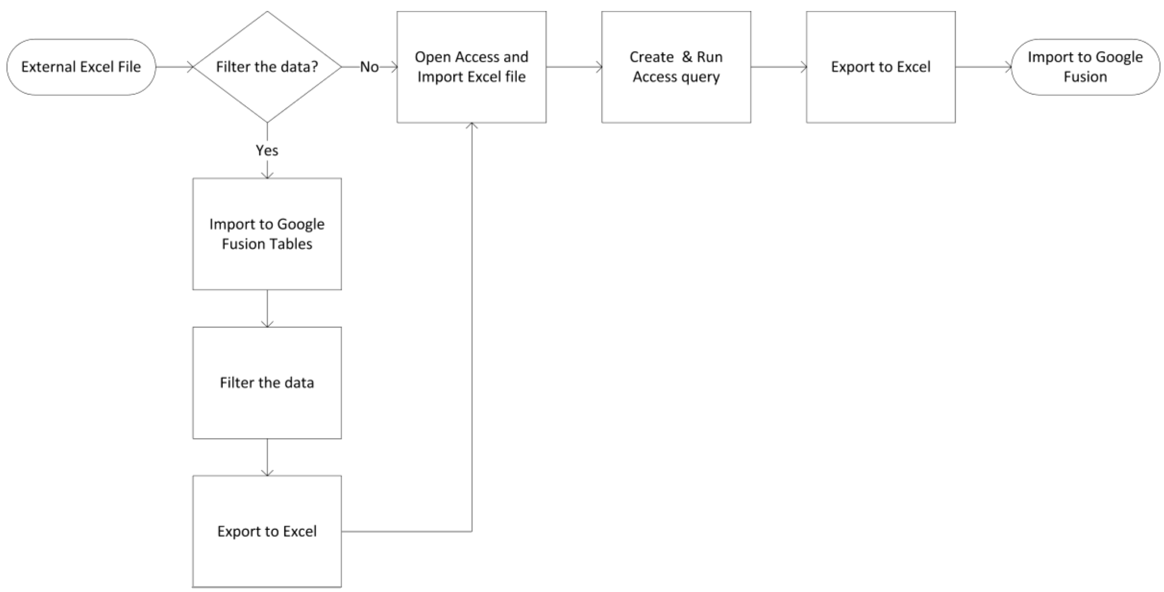


Figure 6-17. The workflow process to identify deposits with any one of the critical REEs. A combination of Microsoft Excel, Google Fusion Tables, and Microsoft Access was used.

To identify all mines containing any one of the critical REEs, a multistep process was followed (Figure 6-17). First, a Google Fusion Tables filter was applied to view only deposits in the United States: "COUNTRY = United States of America." Then, the United States dataset was exported to Excel and saved as an .xls file. A new database was created in Microsoft Access.

Then, the .xls file was imported into Access as a table. A query to find deposits containing any of the five elements was created in the design view. The query was "Like "*Nd*" Or Like "*Dy*" Or Like "*Eu*" Or Like "*Y*" Or Like "*Tb*"." The asterisks before and after each element are wild card symbols. Wild card symbols indicate anything can be listed before or after the critical element as long as the critical element is listed. The Access critical deposit table was exported back into Excel and imported into the Google Fusion Tables to yield the map shown in Figure 6-18.

Of the 91 critical deposits, 55 are inferred resources with minimal information and are denoted by the white placemarks in Figure 6-18. Further exploration is required to accurately assess these sites. Alaska in particular should be explored with drilling and other sampling techniques to gather additional information about the quantity and quality of REEs at these locations. When the inferred resources are removed, the map is altered to Figure 6-19.

Figure 6-18. A screen capture of critical REEs' deposits containing any one of the critical REEs: Nd, Dy, Eu, Y, or Tb. Refer to Table 5-2 for a legend.

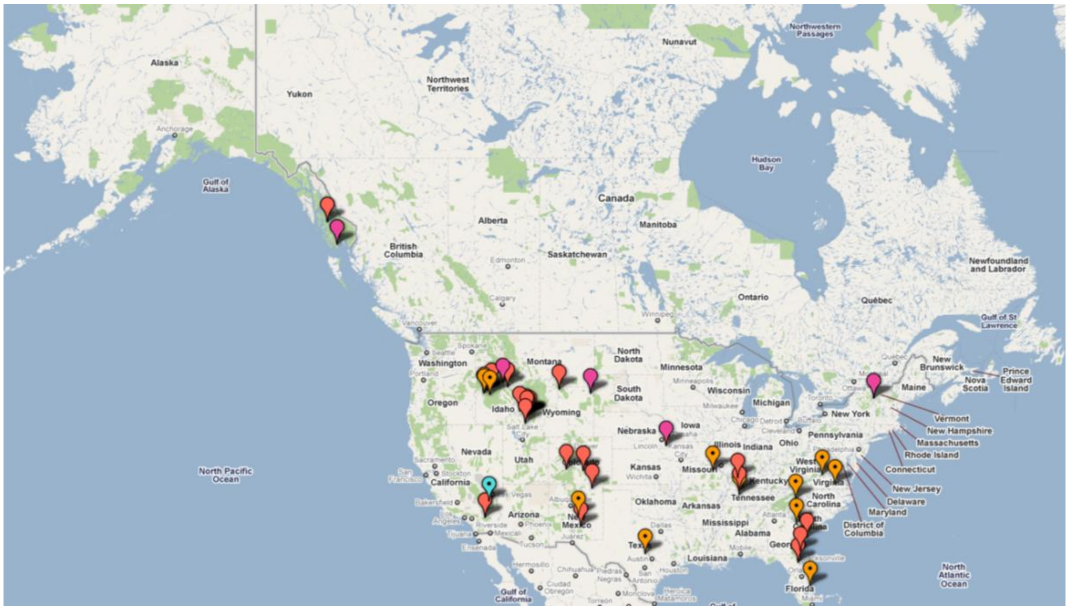


Figure 6-19. A screen capture of critical REEs' deposits excluding inferred resources containing any one of the critical elements: Nd, Dy, Eu, Y, or Tb. Refer to Table 5-2 for a legend.

There are three areas where the critical deposits are clustered. The most concentrated cluster of deposits is in Idaho. However, much of Idaho is covered by protected national forests where environmental regulations are restrictive. These protected lands could complicate the establishment of a rare earths' mine. Along the east coast, there are several placer reserves but these deposits are located close to urban areas. To develop these deposits, the general public would need to be educated about mining REEs to overcome resistance to developing mines near a populated area. The Not-In-My-Backyard (NIMBY) mentality must be overcome. Also, there are a few promising deposits in the southwest corner of the United States. These will be significant because they are not located near urban centers or on protected land.

Dy Deposits

Dy is the most critical element, and there are 17 deposits with Dy in the United States, as shown in Figure 6-20. A small cluster of deposits in southern California includes the Mountain Pass deposit and the Music Valley deposit. Otherwise, Dy deposits are spread fairly evenly throughout the country without any significant geographic patterns. Four deposits are considered reserves and can be developed within seven years. The grades of these deposits vary widely from 0.01% REO at Iron Hill to 16% REO at Music Valley.

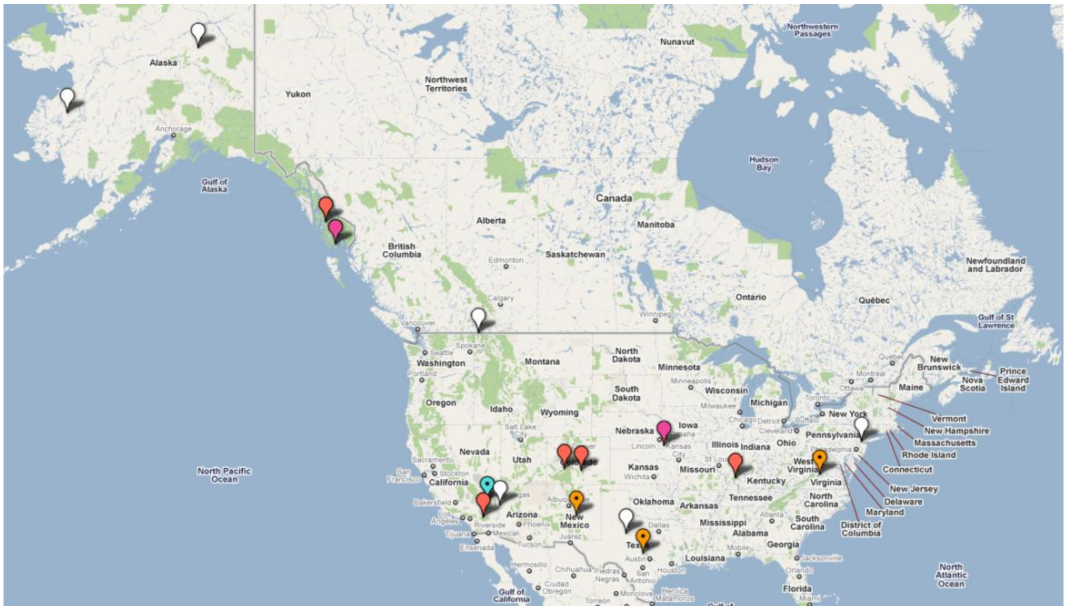


Figure 6-20. A screen capture of rare earths' deposits in the United States containing Dy. Refer to Table 5-2 for a legend.

Nd Deposits

Nd is used in both wind turbines and hybrid or electric vehicles either as permanent magnets or NiMH batteries. This element is located in 74 deposits in the United States and has a cluster pattern as shown in Figure 6-21. There are a significant number of deposits in Idaho, Wyoming, and Montana area with the majority being probable reserves or inferred resources. Another cluster of shoreline placer deposits occurs in the southeastern corner of the United States, and these deposits have a reserves/resources designation of either indicated or inferred resources. Carbonatite deposits are clustered in Colorado and California. More exploration of the inferred resources in Alaska and Montana would help to determine if supply will be able keep up with demand.

Figure 6-21. A screen capture of rare earths' deposits in the United States containing Nd. Refer to Table 5-2 for a legend.

Eu Deposits

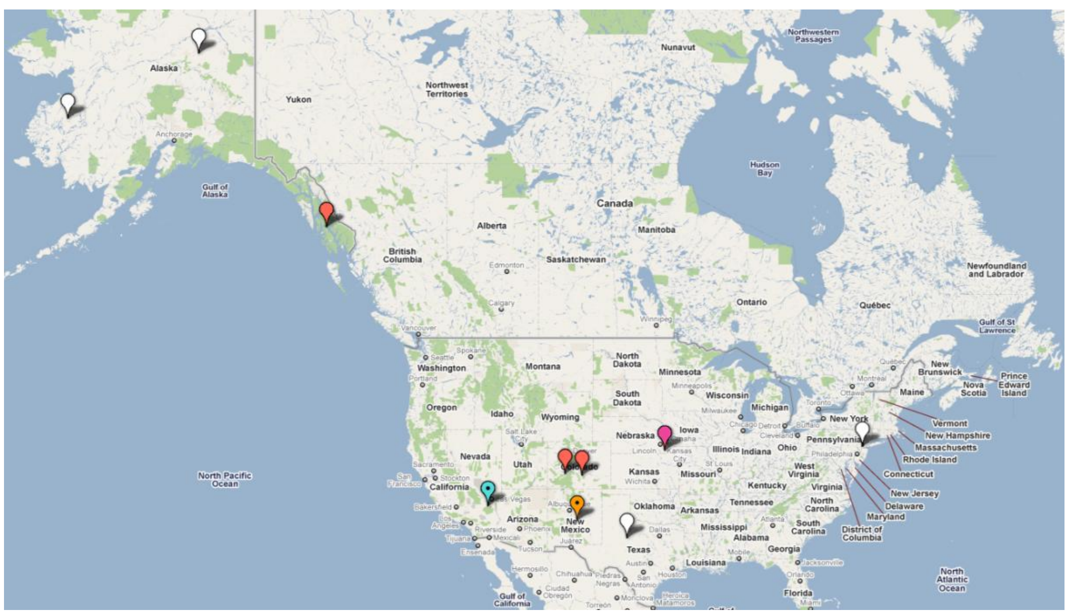


Figure 6-22. A screen capture of rare earths' deposits in the United States containing Eu. Refer to Table 5-2 for a legend.

Eu, used in fluorescent light bulbs, is found at only10 deposits in the United States as shown in Figure 6-22. Besides Mountain Pass, the deposit with the shortest development time is the Gallinas Mountains in New Mexico. It produced about 65 tons of bastnasite concentrate in the 1950s and is a relatively small deposit. It could play a crucial role, because the exact location of the deposit is known and the ore has a grade of 2.95% REO. Elk Creek in Nebraska is another deposit to potentially produce Eu. Quantum Rare Earth Developments Corporation owns Elk Creek and began extensive assay testing in 2010 (Long et al, 2010). While there are relatively few deposits with Eu, there are a couple of deposits that can be developed quickly.

Y Deposits

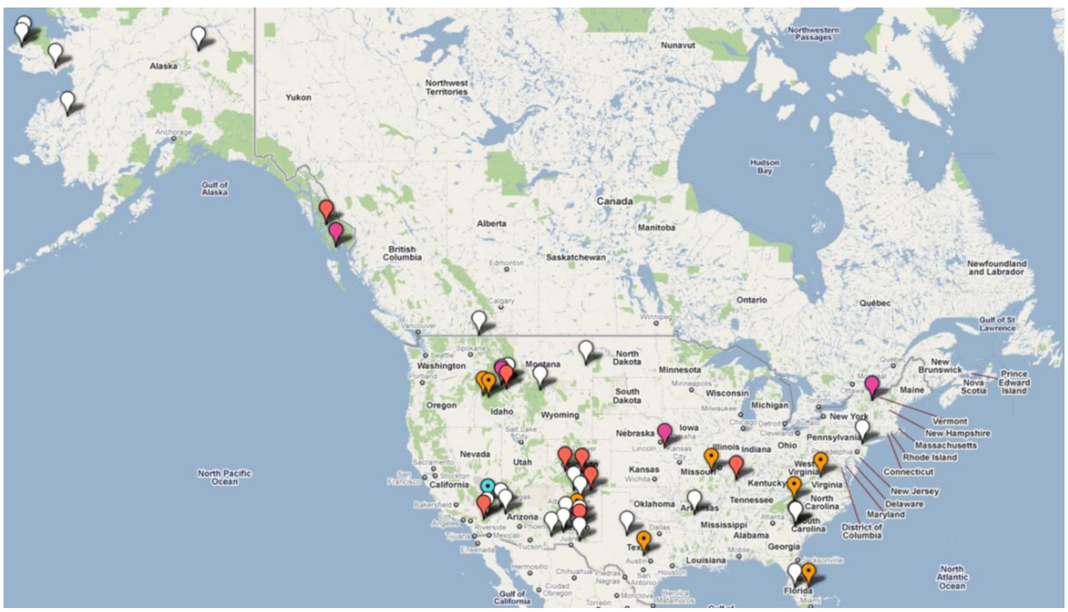


Figure 6-23. A screen capture of rare earths' deposits in the United States containing Y. Refer to Table 5-2 for a legend.

Y is located at 47 locations in the United States, as shown in Figure 6-23. About 50% of these deposits are inferred resources with minimal information on tonnage and grade, and the remaining 50% are evenly divided among probable reserves, measured or indicated resources. Ten locations were identified in New Mexico, and the majority of these deposits were uncertain of deposit type and lacking in company information. In Missouri, Y can be found in the Pea Ridge deposit. Pea Ridge plans to start mining the tailings from a previous iron mine by 2012.

Eventually, rare earths will be produced as a byproduct of the iron production (Boyle, 2011). The ore at Pea Ridge contains monazite and xenotime as well as other minerals such as magnetite, a mineral used to produce magnets. While the future supply of Y looks secure; it is very important to clean technology, so Y is classified as a critical REE.

Tb Deposits

Figure 6-24. A screen capture of rare earths' deposits in the United States containing Tb. Refer to Table 5-2 for a legend.

In the United States, there are 64 deposits containing Tb, a HREE, as shown in Figure 6-24. There are two clusters of Tb deposits: one in the northwest United States and one in the southeast. Many of the deposits highlighted by the other critical elements also contain Tb, because it is found in monazite and xenotime. Monazite and xenotime contain Nd and Y as well as other non-critical REEs. The group of four deposits in western Tennessee has quartz and sand as the host rocks. Salmon Bay in Alaska is an indicated resource and contains parisite, bastnasite, and monazite.

The United States will be facing shortages for critical REEs such as dysprosium and europium if more sources are not established in the next 5 to 15 years. The critical elements were identified based on the importance to green technology and the supply risk. Mountain Pass will be producing critical elements by 2012 when it is fully re-established. Other important deposits include Pea Ridge in Missouri and Gallinas Mountains in New Mexico.

Chapter 7

Results and Conclusions

REEs are critical to both green technology and the defense industry. Unfortunately, the United States is not prepared to meet the demand for REEs due to the time needed to establish a rare earths' mine. The United States has the rare earths' resources needed to meet its demand; this conclusion is drawn after understanding how the United States consumed only 11,000 tones in 2010 and has 13,000,000 tones of REOs in reserves (Lynas, 2010; USGS, 2011). The United States needs to develop additional domestic mines and processing plants and expedite the process to establish these mines. A geographic visualization tool of the locations of the rare earths' deposits such as the one introduced in this thesis will be key to identify current supply conditions and trends and identify the deposits to develop into active mines.

Conclusion 1: Expedite the Development of Domestic Rare Earths' Mines

A significant amount of time is required to establish a rare earths' mine and this time is extended in the United States because of permitting delays. While the potential environmental impacts need to be carefully examined, time is a critical element in preventing a REEs shortage. To reduce the delays caused by permits, the regulatory agencies may require a larger workforce. Another suggestion would be to simplify the permitting process by eliminating some of the extraneous agencies or creating one agency to oversee all aspects of the REEs' mining industry.

Mountain Pass, Pea Ridge, and Bear Lodge deposits in the United States would directly benefit from fewer permitting delays. Mountain Pass mine is the largest known REEs reserves in the United States with about 25,000 tones of REOs and should begin mining new ore in 2012.

This deposit contains mostly bastnasite and monazite minerals, and Molycorp plans to improve recovery to about 90% (Kara et al, 2010). Molycorp has to apply environmental controls to prevent thorium from leaking into the ground water system. Two other domestic developing deposits are Pea Ridge in Missouri and Bear Lodge in Wyoming. These deposits underwent active exploration and drilling to determine the grade and tonnage during 2010. Pea Ridge is expected to start mining the tailings from a previous operation in 2012. At the time of publication of this thesis, there is no specific date for the opening of the Bear Lodge Mountains mine. The first step to securing the REEs' supply is expediting the permitting process in the United States to allow REEs' mines to develop more quickly.

Conclusion 2: Strengthen Trade Relationships with Canada and Australia

The United States should diversify its sources of REEs imports by strengthening relationships with Australia and Canada. Both Australia and Canada ranked first and second, respectively, in Behre Dolbear's ranking of best countries for mining investment. While Australia contains only 1% of the world's REEs reserves and Canada does not contain any significant percentage, these two countries will be able to assist in the short term until domestic mines are established.

Mount Weld and Nolan's Bore are the two most advanced REEs' projects in Australia. Mount Weld is a carbonatite deposit with about 21,000 tonnes of REOs and is in the process of being established in Western Australia. Lynas Corporation controls this location and plans to build a concentration plant 1.5 km from the open pit mine (Lynas, 2010). Mount Weld contains mostly LREEs and a low amount of thorium oxide, less than 0.3%. Already Lynas has several clients with four supply contracts and two letters of intent signed (Lynas, 2010). In the Northern Territory, Nolan's Bore is in the site-selection phase, because the pre-feasibility studies revealed

REEs' grades exceeding 10% in places. Nolan's Bore owned by Arafura Resources Ltd. is a slightly smaller deposit than Mount Weld with 20,000 tonnes REOs (Kara et al, 2010). Nolan's Bore has some HREEs such as Er, Ho, Tm, and Yb but Mount Weld does not.

In Canada, the Thor Lake and Elliot Lake are developing REEs' deposits. Thor Lake is a small deposit located in the Northwest Territories with a majority of HREEs and a smaller percentage of LREEs. Avalon Rare Metals have been extensively exploring the area and may establish a mine there soon. Elliot Lake is being developed near the United States-Canada border. The tonnage and grade information on this deposit indicates as much as 100 Mt of REOs with a grade of about 0.01%. Two companies have investment in various parts of this deposit: Denison Mines and SM Yttrium Canada Ltd and Rio Algom. Uranium is also contained at this location, so there is a possibility of radioactive tailings. With four developing REEs' deposits between Canada and Australia, a reasonable step to secure the future REEs' would be for the United States to strengthen trade relationships with these countries.

Conclusion 3: Recycling & Research Relating to Alternatives and Reduction in Applicability Ratio

Even if new sources of REEs are developed and the supply of REEs is secured for the near future, eventually there will not be any REOs available to mine. There are two possible solutions to this dilemma. One solution would be to create a closed material loop and introduce recycling and reuse of REEs. Creating recycling facilities and other infrastructure such as centers where people could deposit electronics containing REEs would be crucial to the success of this option. Also, the general public would need to be educated about the importance of recycling their electronics. Without the cooperation of the public, a recycling program will not be successful.

Another solution would be to develop new technologies and alternative materials to economically substitute REEs. These alternatives would need to have the same chemical and physical behaviors produced by REEs in green technology and other applications. Also, the alternatives would need to be economically synthesized on a large scale. China and Japan have the best rare earths research facilities and their scientists are attempting to find alternative solutions. However, at this point, no feasible solution has been found. Further research and funding is required to fully investigate new options.

Research regarding REEs' applications should be investigated as well. The applicability ratio or the amount of REEs required for each application, such as 10 kg of lanthanum per hybrid-electric vehicle, could be reduced if a technological advancement were discovered relating to the manufacturing of REEs' applications. This applicability ratio reduction would increase the longevity of the rare earths' mines as a smaller amount of REEs would be needed for the same amount of goods. If the production rate at the rare earths' mines could be reduced, then the current supply of REEs could be used further in the future than originally estimated. It is important for the United States to invest in domestic research in order to maintain and support the knowledge base.

Conclusion 4: Future Supply Scenarios Results

Five scenarios with varying levels of demand (low, United States' current, moderate, high, and Japan's current levels) were created to predict the future supply locations of REEs. The scenarios were based on four variables: (1) international political atmosphere; (2) greenhouse gas regulations; (3) environmental mining regulations; and (4) REEs' applicability ratio (amount of REEs needed per application). The international political atmosphere determines where the REEs will originate. All of the scenarios assumed an unstable international atmosphere, so deposits' locations were filtered to be within the United States. Restrictive GHG regulations would cause an increase in demand for magnets and batteries, and nonrestrictive GHG regulations would cause the the current level of demand to be maintained. Restrictive environmental mining regulations cause mining companies to develop only deposits with high grades. If the environmental mining regulations are nonrestrictive, then lower grade REMs can be mined. For low applicability ratios, only mines with a short development time will be developed, because the longevity of the mines will be increased. Conversely, if there are high applicability ratios, rare earths' mines will be developed further into the future.

A geographic visualization tool, the REEs' Deposits Database, was created to analyze the scenarios using Google Fusion Tables and based on the USGS database of Rare Earth Element Mines, Deposits and Occurrences (Orris and Grauch, 2002). This database can now be used by analysts at the USGS and DOE to identify where mines should be developed as well as people interested in investing in REEs. Google Fusion Tables provides tools to filter, import/export, and share the dataset, but lacks ability to filter based on "OR" function and a legend to explain the placemarks. The REEs' Deposit Database provides information about the REEs found within the REMs at each location and the applications where the REEs may be used. Also, there is a standardized status field (Reserves/Resources Designation) and a time estimate for how long it would take to establish a mine (Years Needed to Develop).

Several important results were concluded after the geographic analysis of the scenarios. In most scenarios, Mountain Pass and Pea Ridge, both with plans of beginning production within the next few years, are highlighted as important deposits. The low demand scenario yielded 18 deposits requiring three to seven years to develop and a couple of potential mine clusters in Idaho. With the current demand level in the United States, only one reserve seems feasible to develop, Mountain Pass. The moderate demand level is unlikely to occur because a decrease in applicability ratio requires extensive research. The high demand level scenario predicts 39 deposits that could be developed if there are restrictive GHG regulations, high applicability ratio, and nonrestrictive environmental regulations due to a high level of demand. Japan's current situation limits the amount of deposits from the high demand scenario with restrictive environmental mining regulations allowing for a ten year development time and is the most likely to occur.

The geographical analysis of the HREEs deposits showed a majority of deposits containing both LREEs and HREEs in the United States. HREEs are scarcer but experience a higher demand than LREEs. Typically these deposits had a higher amount of LREEs than HREEs. The United States does not have large reserves of HREEs and research should be concentrated in finding HREEs alternatives.

The REEs' Deposits Database also developed maps plotting the deposits containing REEs identified by the DOE as critical: Dy, Nd, Eu, Y, and Tb. Many of the deposits were located in the western states. Many of the deposits along the east coast are located too close to urban centers to be developed. Dy is the most critical element, and the United States has 17 deposits containing Dy spread throughout the country. Deposits containing Nd, used for wind turbines and hybrid-electric vehicles, are concentrated in Idaho, Wyoming, and Montana. The fewest number of deposits, 10, contain Eu. Despite the low numbers of deposits, a few of these deposits can be developed quickly. The Gallinas Mountains in New Mexico contains Eu and has produced it in the past. Y is found at 47 locations including Pea Ridge. Tb can be found clustered in the northwest and southeast corners including several in western Tennessee.

Summary

After a thorough investigation of the current supply and demand REEs relationship, several conclusions can be drawn. The development of domestic rare earths' mines within the United States must be expedited to reduce permitting delays. International trade relations with Australia and Canada should be strengthened as both countries are developing REEs' projects. A recycling program could close the material loop and reduce the need for new rare earths' mines. Research must be performed to identify materials to substitute REEs and reduce the applicability ratio in green technologies. The geographic visualization tool of REEs' Deposits Database in Google Fusion Tables identified potential mine locations for five future supply scenarios. Mountain Pass and Pea Ridge were identified as important mines under development. Idaho and other western states contain the majority of feasible deposits to develop. There are probably not enough resources in the United States containing HREEs to support the domestic demand. While there are five REEs identified as critical due to supply risk and importance to green technology, there are many deposits containing these elements in the United States. United States' government, mining industry, and scientists need to act immediately to secure the REEs' supply in the future.

Appendix A: REMs, REEs, Applications table

This table shows the relationship between mineral, element, and application. The bolded minerals are more common.

Mineral	*Elements*	*Light or Heavy*	*Application*	*Reference*
Aeschynite	Y, Nd	Heavy/Light	Phosphors, Ceramics, Magnets, Batteries	http://www.mindat.org/min-39.html
Allanite	**La, Ce**	**Light**	**Petroleum refining, Batteries, Phosphors, Auto catalysts, Glass additives, Polishing compounds, Metal alloys**	http://rruff.geo.arizona.edu/doclib/cm/vol31/CM31_159.pdf
Ancylite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.handbookofmineralogy.org/pdfs/ancylitela.pdf
Apatite	Ce, La, Nd, Sm, Gd	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining, Magnets	http://pubs.acs.org/doi/abs/10.1021/ac00227a023
Astrophyllite	Ce, Nd, Gd, Yb, Sm, Dy	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining, Magnets, Lasers, Silicon photovoltaic cells	http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6VHG-42MFFS2-C&_user=209810&_coverDate=04/30/2001&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1562462223&_rerunOrigin=google&_acct=C000014439&_version=1&_u
Baddeleyite	Ce, La	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.springerlink.com/content/m242631p6823634h/
Bariopyrochlore	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.handbookofmineralogy.org/pdfs/bariopyrochlore.pdf
Bastnasite	**Y, Eu, Gd, Dy, Er, Tm, Lu**	**Heavy**	**Phosphors, Ceramics, Magnets, Lasers, Alloys, Nuclear industry**	Chevron Mining Inc, 2008
Brannerite	Y, Ce	Heavy/Light	Phosphors, Ceramics, Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Petroleum refining	http://www.minsocam.org/ammin/AM39/AM39_109.pdf
Britholite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://rruff.info/uploads/CM37_1239.pdf
Brockite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.mindat.org/min-780.html
Burbankite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.handbookofmineralogy.org/pdfs/burbankite.pdf
Carbocernaite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.handbookofmineralogy.org/pdfs/carbocernaite.pdf
Caysichite	Y, Gd	Heavy	Phosphors, Ceramics, Magnets	http://www.mindat.org/min-922.html
Cerianite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.mindat.org/min-929.html
Ceriopyrochlore	Ce, Y, Nd	Light/Heavy	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining, Ceramics, Magnets	http://webmineral.com/data/Ceriopyrochlore-(Ce).shtml

Mineral	*Elements*	*Light or Heavy*	*Application*	*Reference*
Cerite	**La, Ce**	**Light**	**Petroleum refining, Batteries, Phosphors, Auto catalysts, Glass additives, Polishing compounds, Metal alloys**	http://www.mindat.org/min-931.html
Chevkinite	Ce, La	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://webmineral.com/data/Chevkinite-(Ce).shtml
Churchite	Y	Heavy	Phosphors, Ceramics	http://webmineral.com/data/Churchite-(Y).shtml
Collophane	Ce, La	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	Mineralolgy and Geology of Rare Earths in China by Peishan Zhang, Yang Xueming, Tao Kejie, Google Books
Columbite	Y, Ce, La, Gd, Yb	Light	Phosphors, Ceramics, Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Petroleum refining, Magnets, Lasers, Silicon photovoltaic cells	http://minmag.geoscienceworld.org/cgi/reprint/74/4/691
Cordylite	Ce, La	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://webmineral.com/data/Cordylite-(Ce).shtml
Crandallite	Y, Ce, Nd, La, Sm, Pr	Heavy/Light	Phosphors, Ceramics, Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Petroleum refining, Magnets	http://eurjmin.geoscienceworld.org/cgi/content/full/12/6/1229
Daqingshanite	Ce, La	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://webmineral.com/data/Daqingshanite-(Ce).shtml
Davidite	La, Ce, Y	Light/Heavy	Petroleum refining, Batteries, Phosphors, Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Ceramics	http://www.handbookofmineralogy.org/pdfs/daviditece.pdf
Eudialyte	Ce, La, Y, Nd, Pr, Gd	Light/Heavy	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining, Ceramics, Magnets	http://rruff.info/uploads/CM25_755.pdf
Euxenite	**Yb**	**Heavy**	**Lasers, Silicon photovoltaic cells**	Chevron Mining Inc, 2008
Fergusonite	**Y, Dy**	**Heavy**	**Phosphors, Ceramics, Magnets, Lasers**	Chevron Mining Inc, 2008
Fersmite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.handbookofmineralogy.org/pdfs/fersmite.pdf
Florencite	Ce, La, Nd, Sm	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining, Magnets	http://www.handbookofmineralogy.org/pdfs/florencitece.pdf
Fluocerite	Ce, La	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.wolframalpha.com/input/?i=fluocerite-(Ce)
Fluorite	La, Ce, Pr	Light	Petroleum refining, Batteries, Phosphors, Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Magnets	http://www.minsocam.org/ammin/AM33/AM33_64.pdf
Formanite	Y	Heavy	Phosphors, Ceramics	http://www.mindat.org/min-1582.html
Gadolinite	**Ho, Y, Gd, Dy**	**Heavy**	Phosphors, Ceramics, Magnets, Lasers	Chevron Mining Inc, 2008
Gagarinite	Y	Heavy	Phosphors, Ceramics	http://webmineral.com/data/Gagarinite-(Y).shtml
Gorceixite	Ce, La, Nd, Sm, Pr, Y, Gd	Light/Heavy	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining, Magnets, Ceramics	http://www.minsocam.org/ammin/AM43/AM43_688.pdf

Mineral	*Elements*	*Light or Heavy*	*Application*	*Reference*
Goyazite	Nd, Ce, La	Light	Magnets, Batteries, Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.mindat.org/min-1787.html
Hellandite	Ce, Y, La, Nd, Sm	Light/Heavy	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining, Ceramics, Magnets	http://webmineral.com/data/Hellandite-(Y).shtml
Hingganite	Y	Heavy	Phosphors, Ceramics	http://www.wolframalpha.com/entities/minerals/hingganit
Huanghoite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://webmineral.com/data/Huanghoite-(Ce).shtml
Hydroxyapatite	Y, Eu, Ce	Heavy/Light	Phosphors, Ceramics, Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Petroleum refining	http://www.springerlink.com/content/r038524231k8p672/
Iimorite	Y	Heavy	Phosphors, Ceramics	http://www.mindat.org/gallery.php?loc=1745&min=2006
Joaquinite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.mindat.org/min-2099.html
Kainosite	Y, Ce	Heavy/Light	Phosphors, Ceramics, Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Petroleum refining	http://webmineral.com/data/Kainosite-(Y).shtml
Kamphaugite	Y, Nd, Sm, Gd, Dy, Er	Heavy/Light	Phosphors, Ceramics, Magnets, Batteries, Lasers	http://eurjmin.geoscienceworld.org/cgi/reprint/5/4/679.pdf
Karnasurtite	La, Ce	Light	Petroleum refining, Batteries, Phosphors, Auto catalysts, Glass additives, Polishing compounds, Metal alloys	http://webmineral.com/data/Karnasurtite-(Ce).shtml
Keivite	Yb	Heavy	Lasers, Silicon photovoltaic cells	http://rruff.info/Keiviite-(Y)
Kuliokite	Y, La, Ce, Pr, Nd, Sm	Heavy/Light	Phosphors, Ceramics, Petroleum refining, Batteries, Phosphors, Auto catalysts, Glass additivies, Polishing compounds, Metal alloys, Magnets	http://webmineral.com/data/Kuliokite-(Y).shtml
Lavenite	Y, Yb, Ce, Gd, La, Eu, Er	Heavy/Light	Phosphors, Ceramics, Lasers, Silicon photovoltaic cells, Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Petroleum refining, Magnets	http://webmineral.com/data/Lavenite.shtml
Lessingite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.mindat.org/show.php?id=7152&ld=2
Leucophanite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.mindat.org/min-2383.html
Loparite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.mindat.org/min-2432.html
Lovchorrite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://encyclopedia2.thefreedictionary.com/Lovchorrite
Lushite	Ce, La	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://eurekamag.com/keyword/l/182/lueshite.php
Miserite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.mindat.org/min-2727.html

Mineral	*Elements*	*Light or Heavy*	*Application*	*Reference*
Monazite	**La, Ce, Pr, Nd, Sm, Tb**	**Light/Heavy**	**Petroleum refining, Batteries, Phosphors, Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Magnets**	Chevron Mining Inc, 2008
Mosandrite	Ce, Y	Light/Heavy	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining, Ceramics	http://webmineral.com/data/Mosandrite.shtml
Parisite	Ce, La, Nd	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining, Magnets	http://webmineral.com/data/Parisite-(Nd).shtml
Perovskite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://tin.er.usgs.gov/carbonatite/carbonatite.php?mineral=perovskite-(ce)
Plumbopyrochlore	Y	Heavy	Phosphors, Ceramics	http://webmineral.com/data/Plumbopyrochlore.shtml
Polycrase	Y	Heavy	Phosphors, Ceramics	http://www.mindat.org/min-3257.html
Polylithionite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.minsocam.org/ammin/AM70/AM70_1127.pdf
Pyrochlore	Nd	Light	Magnets, Batteries	http://pubs.acs.org/doi/abs/10.1021/cm9003917
Rhabdophane	La, Ce, Nd	Light	Petroleum refining, Batteries, Phosphors, Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Magnets	http://webmineral.com/data/Rhabdophane-(Nd).shtml
Rinkite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://webmineral.com/data/Rinkite.shtml
Rosenbuschite	Y, Ce	Heavy/Light	Phosphors, Ceramics, Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Petroleum refining	http://rruff.geo.arizona.edu/doclib/cm/vol41/CM41_1203.pdf
Sahamalite	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://webmineral.com/data/Sahamalite-(Ce).shtml
Samarskite	**Y, Ce**	**Heavy/Light**	**Phosphors, Ceramics, Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Petroleum refining**	Chevron Mining Inc, 2008
Steenstrupine	Ce	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://webmineral.com/data/Steenstrupine-(Ce).shtml
Stillwellite	Ce, La	Light	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining	http://www.handbookofmineralogy.org/pdfs/stillwellitece.pdf
Synchysite	Ce, Nd, Y	Light/Heavy	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining, Magnets, Ceramics	http://www.handbookofmineralogy.org/pdfs/synchysitece.pdf

Mineral	*Elements*	*Light or Heavy*	*Application*	*Reference*
Tengerite	Y	Heavy	Phosphors, Ceramics	http://www.mindat.org/min-3910.html
Thalenite	Y	Heavy	Phosphors, Ceramics	http://webmineral.com/data/Thalenite-(Y).shtml
Thorite	Y	Heavy	Phosphors, Ceramics	http://www.minerals.net/mineral/silicate/neso/zircon/thori
Titanite	Y, Ce	Heavy/Light	Phosphors, Ceramics, Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Petroleum refining	http://www.mindat.org/min-3977.html
Vesuvianite	Ce, La, Nd, Y, Sm, Gd	Light/Heavy	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining, Magnets, Ceramics	http://www.minsocam.org/ammin/AM51/AM51_381.pdf
Wohlerite	Nd	Light	Magnets, Batteries	http://webmineral.com/data/Wohlerite.shtml
Xenotime	**Y, Tb, Yb**	**Heavy**	**Phosphors, Ceramics, Magnets, Lasers, Silicon photovoltaic cells**	Chevron Mining Inc, 2008
Yttrialite	Y	Heavy	Phosphors, Ceramics	http://webmineral.com/data/Yttrialite-(Y).shtml
Yttrotantalite	Y	Heavy	Phosphors, Ceramics	http://webmineral.com/data/Yttrotantalite-(Y).shtml
Zirkelite	Ce, Nd, Y, Sm, Gd	Light/Heavy	Auto catalysts, Glass additives, Polishing compounds, Metal alloys, Batteries, Phosphors, Petroleum refining, Magnets, Ceramics	http://rruff.geo.arizona.edu/doclib/mm/vol62/MM62_837.pdf

References

Ames Laboratory. (2002). “Rare Earth Metals Archive.” U.S. Department of Energy. Iowa State University. Retrieved February 25, 2011, from http://www.ameslab.gov/dmse/rem/archive

Areddy, J. (2011a). “China moves to strengthen grip over supply of rare-earth metals.” Proquest. *Wall Street Journal*. 06 Feb 2011. Retrieved March 1, 2011, from http://search.proquest.com/docview/849405220?accountid=13158

Areddy, J. (2011b). “Rare Earths Stay Hot.” Proquest. *Wall Street Journal*. 22 March 2011. Retrieved April 1, 2011, from http://ezaccess.libraries.psu.edu/login?url=http://search.proquest.com/docview/858020856?accountid=13158

Avalon Rare Metals. “General Geology and Mineralization.” Retrieved April 2, 2011, from http://avalonraremetals.com/projects/thor_lake/thor_geology

Bautista, R. G., & Mishra, B. (2000). Rare Earths and Actinides: Science, Technology and Applications IV (pp 12). Warrendale, Pennsylvania: TMS.

Behre Dolbear Group Inc. (2011). “2011 Ranking of Countries for Mining Investment or “Where Not to Invest.”” Retrieved January 15, 2011, from http://www.dolbear.com/announcements/asdf

Boyle, R. (2011). “My Visit to An American Rare Earth Metals Mine: The electronic future is buried under the ground in Missouri.” *Popular Science*. Retrieved March 11, 2011, from http://www.popsci.com/technology/article/2011-03/rare-earth-mine

Bradsher, K. (2010, December 29). “China to Tighten Limits on Rare Earth Exports.” The New York Times, pp. B2. Retrieved March 1, 2011, from http://www.nytimes.com/2010/12/29/business/global/29rare.html?scp=1&sq=China%20to%20Tighten%20Limits%20on%20Rare%20Earth%20Exports&st=Search

Bryce, R. (2009). “The Lanthanides, China, and High-Tech Autos.” Toyota. Retrieved November 15, 2010, from http://www.toyota.com/esq/pdf/Robert_Bryce_Toyota_ESQ.pdf

Campbell, M., & Keane, C. “Rare Earth Colorants.” *Ceramics Today*. Retrieved November 15, 2010, from, http://www.ceramicstoday.com/articles/lanthanides.htm

Castor, B., & Hedrick, J. B. (2006). “Rare Earth Elements (pp 769-792).” *Industrial Minerals and Rocks*. Edited by J. E. Kogel, N. C. Trivedi, & J. M. Barker. Society for Mining, Metallurgy and Exploration. Retrieved November 15, 2010, from http://www.rareelementresources.com/i/pdf/RareEarths-CastorHedrickIMAR7.pdf

Castor, S. B. (2008). "Rare Earth Deposits of North America." *Resource Geology.* Vol. 58, No. 4: 337-347. Retrieved March 1, 2011, from http://onlinelibrary.wiley.com/doi/10.1111/j.1751-3928.2008.00068.x/full

Chevron Mining, Inc. (2008). "The Blue Marble: Where the Elements We Use Come From." Poster.

Civic Impulse, LLC. (2011). "H.R. 502: Clean Energy Technology Manufacturing and Export Assistance Act of 2011." Retrieved March 17, 2011, from, http://www.govtrack.us/congress/bill.xpd?bill=h112-502

Civic Impulse, LLC. (2011). "H.R. 618: Rare Earths and Critical Materials Revitalization Act of 2011." Retrieved March 17, 2011, from http://www.govtrack.us/congress/bill.xpd?bill=h112-618

Civic Impulse, LLC. (2011). "H.R. 952: Energy Critical Elements Renewal Act of 2011." Retrieved March 17, 2011, from http://www.govtrack.us/congress/bill.xpd?bill=h112-952

Coppel, E. (2011). "Rare Earth Metals and U.S. National Security." American Security Project. Retrieved February 8, 2011, from http://americansecurityproject.org/wp-content/uploads/2011/02/Rare-Earth-Metals-and-US-Security-FINAL.pdf

Cordier, D. (2011a). "Rare Earths." U.S. Geological Survey, Mineral Commodity Summaries. Retrieved March 5, 2011, from http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2011-raree.pdf

Cordier, D. (2011b). Telephone interview. 7 April 2011.

DOD. (2010). "Annual Report to Congress: Military and Security Developments Involving the People's Republic of China 2010." Office of the Secretary of Defense. Retrieved February 8, 2011, from http://www.defense.gov/pubs/pdfs/2010_CMPR_Final.pdf

DOE. (2010). "Critical Materials Strategy." Retrieved March 15, 2011, from www.energy.gov/news/documents/criticalmaterialsstrategy.pdf

Drew, L., Qingrun, M., & Weijun, S. (1991). "The Geology of the Bayan Obo Iron-Rare-Earth-Niobium Deposits, Inner Mongolia, China." *Materials Science Forum*. 70-72: 13-32. Retrieved March 1, 2011, from http://www.scientific.net/MSF.70-72.13

EIA. (2010). "How dependent are we on foreign oil?" Retrieved March 13, 2011, from http://www.eia.doe.gov/energy_in_brief/foreign_oil_dependence.cfm

Fifarek, B. J., Veloso, F. M., & Davidson, C. I. (2008). "Offshoring technology innovation: A case study of rare-earth technology." *Journal of Operations Management*. 26, 2: 222-238. Retrieved April 2, 2011, from http://www.andrew.cmu.edu/user/fveloso/offshoring.pdf

Google. (2011). “Google Fusion Tables, Beta.” Retrieved November 30, 2010, from http://www.google.com/fusiontables

Govtrack.us. (2011). “A Civic Project to Track Congress.” Retrieved March 16, 2011, from http://www.govtrack.us/

Haxel, G. B., Hedrick, J. B., & Orris, G. J. (2002). “Rare Earth Elements – Critical Resources for High Technology.” U.G. Geological Survey. Fact Sheet 087-02. Retrieved September 13, 2010, from http://pubs.usgs.gov/fs/2002/fs087-02

Hedrick, J. B. (2004). “Rare Earth in Selected U.S. Defense Applications.” USGS. 40th Forum on the Geology of Industrial Minerals. Retrieved December 10, 2011, from http://www.molycorp.com/pdf/RARE%20EARTHS%20IN%20SELECTED%20U%20S%20%20DEFENSE%20APPLICATIONS.pdf

Humphries, M. (2010). “Rare Earth Elements: The Global Supply Chain.” Congressional Research Service. Retrieved March 11, 2011, from http://www.energy.psu.edu/oeo/ree/reports/Congressional_Research_REE_20100930.pdf

Investopedia.com (2003). “Economics Basics: Demand and Supply.” Retrieved March 11, 2011, from http://www.investopedia.com/university/economics/economics3.asp

Jaffe, R., Price, J., Ceder, G., Eggert, R., Graedel, T., Gschneider, K., … Slakey, F. (2011). “Energy Critical Elements: Securing Materials for Emerging Technologies.” American Physical Society. Materials Research Society. Retrieved March 15, 2011, from http://www.aps.org/policy/reports/popa-reports/loader.cfm?csModule=security/getfile&PageID=236337

Jones, A. P., Wall, F., & Williams, C. T. (1996). <u>Rare Earth Minerals: Chemistry, Origin and Ore Deposits (pp 77, 294)</u>. New York: Chapman & Hall.

Kara, H., Chapman, A., Crichton, T., Willis, P., & Morley, N. (2010). “Lanthanide Resources and Alternatives: A report for Department for Transport and Department for Business, Innovation and Skills.” Okdene Hollins Research & Consulting. Retrieved March 11, 2011, from http://www.slideshare.net/RareEarthsRareMetals/oakdene-hollins-research-and-consulting-lanthanide-resources-and-alternatives

Lifton, J. (2010). “The Battle Over Rare Earth Metals.” *Journal of Energy Security*. January 2010 Issue. Retrieved March 20, 2011, from http://www.ensec.org/index.php?option=com_content&view=article&id=228:the-battle-over-rare-earth-metals&catid=102:issuecontent&Itemid=355

Long, K.R., Van Gosen, B.S., Foley, N.K., & Cordier, D. (2010). “The principal rare earth elements deposits of the United States—A summary of domestic deposits and a global perspective: U.S. Geological Survey Scientific Investigations Report 2010–5220.” Retrieved December 20, 2011, from http://pubs.usgs.gov/sir/2010/5220/.

Lynas Corporation Ltd. (2010). "Will There Be Sufficient Rare Earths To Meet Demand From Clean Energy Technology?" International Minor Metals Conference. Retrieved January 5, 2011, from http://www.lynascorp.com/content/upload/files/Presentations/MMTA_APRIL_2010.pdf

Mitchell, R. H. (2004). "Mineralogical and Experimental Constraints on the Origins of Niobium Mineralization in Carbonatites." In R. L. Linnen & I. M. Samson (Eds.), Rare-Element Geochemistry and Mineral Deposits (pp 201). Ontario: Geological Association of Canada.

Molycorp. (2011). "Molycorp Minerals: The Rare Earth Company." Retrieved December 10, 2010, from www.molycorp.com

Nebler, J. (2007). "Giant Bayan Obo REE-Fe-Nb Ore Deposit of Inner Mongolia, China." Retrieved March 1, 2011, from http://www.geo.tu-freiberg.de/oberseminar/os06_07/J%F6rg%20Ne%DFler.pdf

Orris, G. J., & Grauch, R. I. (2002). "Rare Earth Element Mines, Deposits, and Occurrences." USGS Open-File Report 02-189. Retrieved September 1, 2010, from http://pubs.usgs.gov/of/2002/of02-189/

Papp, J. F., Bray, E. L., Edelstein, D. L., Fenton, M. D., Guberman, D. E., Hedrick, J. B.,… Tolcin, A. C. (2008). "Factors that influence the price of Al, Cd, Co, Cu, Fe, Ni, Pb, Rare Earth Elements, and Zn." U.S. Geological Survey Open-File Report 2008-1356. Retrieved September 1, 2010, from http://pubs.usgs.gov/of/2008/1356/

Richards, B. S. (2006). "Luminescent layers for enhanced silicon solar cell performance: Down-conversion." *Solar Energy Materials & Solar Cells*. Retrieved October 15, 2010, from www.elsevier.com/locate/solmat

Roth, R., & Ross, K. (2009). "Extending the Google Maps API For Event Animation Mashups." *Cartographic Perspectives.* Number 64: 21 – 40. Retrieved March 15, 2011 from http://www.geovista.psu.edu/publications/2009/RothRoss_2009_CP.pdf

Sahr, R. C. (2009). "Consumer Price Index (CPI) Conversion Factors 1774 to estimated 2019 to Convert to Dollars of 1998." Oregon State University. Retrieved March 31, 2011, from http://oregonstate.edu/cla/polisci/faculty-research/sahr/cv1998.pdf

Samson, I. M., & Wood, S. A. (2004). "The Rare Earth Elements: Behaviour in Hydrothermal Fluids and Concentration in Hydrothermal Mineral Deposits, Exclusive of Alkaline Settings." In R. L. Linnen & I. M. Samson (Eds.), Rare-Element Geochemistry and Mineral Deposits (pp 269-298). Ontario: Geological Association of Canada.

Smith, M. (2010). "Rare Earth Minerals and 21st Century Industry." Written Testimony: House Science and Technology Committee, Subcommittee on Investigations and Oversight. Retrieved March 20, 2011, from http://gop.science.house.gov/Media/hearings/oversight10/mar16/Smith.pdf

Stone, R. (2009). “As China’s Rare Earth R&D Becomes Ever More Rarefied, Others Tremble.” *Science*. Volume 325: 1336-1337. Retrieved September 15, 2010, from http://www.sciencemag.org/content/325/5946/1336.full

Tse, P. (2011). “China’s Rare-Earth Industry.” USGS. Open-File Report 2011-1042. Retrieved April 2, 2011, from http://files.eesi.org/usgs_china_030011.pdf

USGS. (2010). Rare earths statistics, in Kelly, T.D., and Matos, G.R., comps., “Historical statistics for mineral and material commodities in the United States: U.S. Geological Survey Data Series 140.” Retrieved March 11, 2011, from http://pubs.usgs.gov/ds/2005/140/.

USGS. (2011). “Appendix C – Reserves and Resources. Part A – Resource/Reserve Classification for Minerals.” Retrieved March 13, 2011, from http://minerals.usgs.gov/minerals/pubs/mcs/2011/mcsapp2011.pdf

Wood, T. (2010). “Mineral Economics for Investors.” San Francisco Hard Assets Investment Conference. Retrieved March 30, 2011, from http://www.minefund.com/wordpress/wp-content/uploads/misc/MineralEconomics_V7.html

World Bank Group. (2011). “GDP (current US$)” Retrieved March 31, 2011, from http://data.worldbank.org/indicator/NY.GDP.MKTP.CD/countries

ACADEMIC VITA

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EDUCATION

The Pennsylvania State University **Anticipated May 2011**
Bachelor of Science: Environmental Systems Engineering University Park, PA
Minors: Watersheds and Water Resources
Geographic Information Science

Passed the Fundamentals of Engineering Exam in October 2010

Schreyer Honors College – Honors Thesis: "Supply and Demand of Rare Earth Minerals Based on Geographic Information Using Google Earth as a Platform"
Thesis Supervisor: Dr. Antonio Nieto

EXPERIENCE

Intern – Chevron Global Upstream Health, Environment and Safety
May 2010 – Aug. 2010 in Houston, TX
- Compiled and analyzed qualitative environmental data from 14 global business units in Microsoft Excel 2007
- Revised the environmental gap assessment questionnaire; Saved the company up to $50,000 by performing analysis typically contracted out
- Assisted in tracking behavioral based safety observations

Intern – Chevron Mining, Inc.
May 2009 – Aug. 2009 in Questa, NM
- Initiated and completed a water quality study
- Catalogued a database of 110 potential environmental impacts of the mine in Microsoft Access 2007
- Downloaded and inspected data from air and weather monitors

Researcher – Women in Science and Engineering Research
Jan. 2008 – May 2009 in University Park, PA
- Collaborated with a research team to design poroU.S. hydrogels for the production of biohydrogen
- Published: Iannuzzi, M.A; Reber, R.; Lentz, D.M. and Hedden, R.C.; "USANS Study of Porosity and Water Content in Sponge-Like Hydrogels." *Polymer*. April 2010.

LEADERSHIP

Secretary – Society of Environmental Systems Engineers
- Organized club communications, including the website
- Networked with alumni and learned about job opportunities in the environmental field

Newman Catholic Student Association

- Led an accountability small group and managed four other groups
- Volunteered to visit residents at the local nursing home

HONORS

Dean's List (Fall 2007 – Fall 2010)
Chevron Intern Scholarship (2009-2011)
Murrysville Garden Club Scholarship (2007-2011)
John and Elizabeth Holmes Teas Scholarship (2010-2011)
Wood Honors Scholarship (2009-2010)
Franz Centennial Mineral Engineering Scholarship (2009-2010)
Charmbury Geo-Environmental Scholarship (2008-2009)
Matthew J. Wilson Scholarship (2007-2008)
Gold Award (Highest Award in Girl Scouts of America)
National Honors Society (2005-2007)