Supply-and-demand geoeconomic analysis of mineral resources of rare earth elements in the United States

by A. Nieto and M. Iannuzzi

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 global production of REEs and is reducing its export quotas. To predict the supply of rare earths in the United States based on future supply scenarios, a web-based database and geographic visualization tool was built. Five case scenarios with varying levels of REE demand were created by varying several economic conditions including (1) international trade policy, (2) greenhouse gas regulations, (3) environmental mining regulations and (4) tech applicability ratio of REEs. The most likely scenario, which is based on current international demand levels, indicates the importance of expediting the development of extractive operations of current REE resources within the United States. The results of the different case scenarios are supported by using dynamic geographic maps indicating the location of rare earth ore (REO) resources.

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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). The heavy REEs (HREEs) have atomic numbers greater than 65, while light REEs (LREEs) have atomic numbers between 57 and 64. In general, HREEs are scarcer than the LREEs and experience higher demand levels. 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 also have applied uses in the defense industry as components of lasers and night vision goggles (Hedrick, 2004).

Although rare earth ores are not that rare, since they can be found in a variety of mineral deposits, ore deposits with high concentrations of REEs are rare, with the majority of known deposits being located in China. The ores at these deposits consist of rare earth oxides (REOs) with varying grades of rare earth minerals (REMs) containing REEs. China has 48% of the world's known reserves of REEs. In 2009, the United States imported 51% of its total amount of petroleum products, with the highest percentage, 23.3%, coming from Canada (EIA, 2010). In contrast, the United States imported 100% of its rare earth needs, with 92% originating from China. 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, 2011).

Mineral deposits such as REM deposits are classified as either resources or reserves. A mineral deposit is classified by the quality of exploratory information known and the economic feasibility of its extraction and processing. Mineral resources can be further divided into three subcategories: measured, indicated and inferred. As seen in Fig. 1, along the vertical *y* axis, mineral resources transition from inferred to indicated to measured. The resource transitioning will occur as more quality and quantity exploratory information is improved. Mineral resources that are economically feasible for extraction and processing are classified as reserves and can be further divided into two subcategories, proved and probable. As seen in Fig. 1, mineral resources will transition respectively from indicated resources to probable reserves and from measured resources to proved reserves along the horizontal

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Figure 1

Reserves and resources designation's dependency on exploration information and economic feasibility (modified after Wood, 2010).

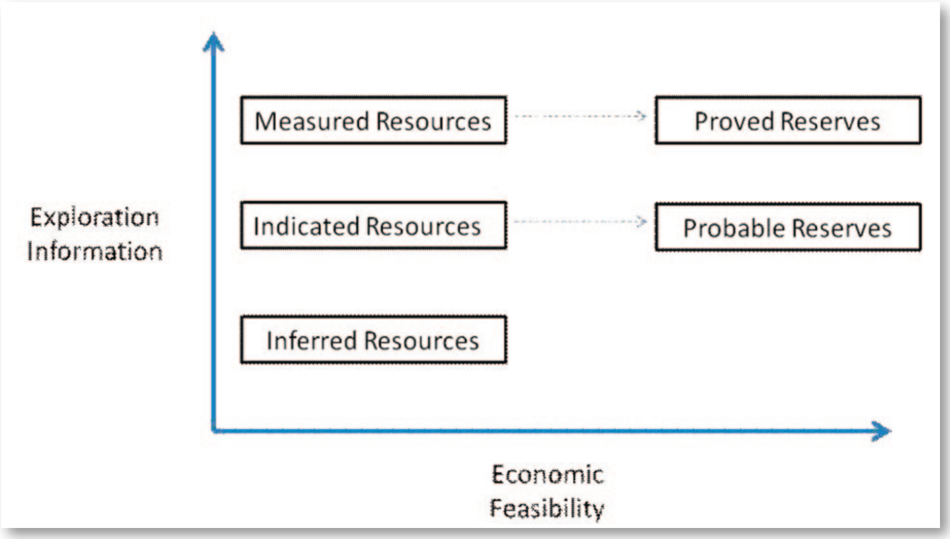
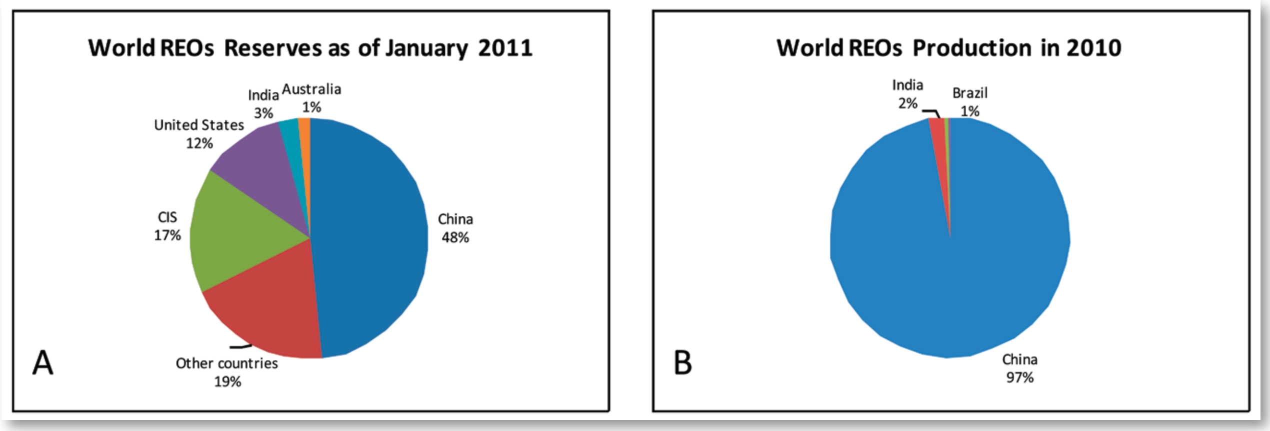


Figure 2

A) Pie chart showing the amount of REO reserves located in each country as a percentage of the global reserves. B) Pie chart showing the amount of REOs produced in each country as a percentage of the global production (Cordier, 2011).



x axis as extraction and processing of the ore becomes economically feasible.

Global reserves, production and consumption of REOs

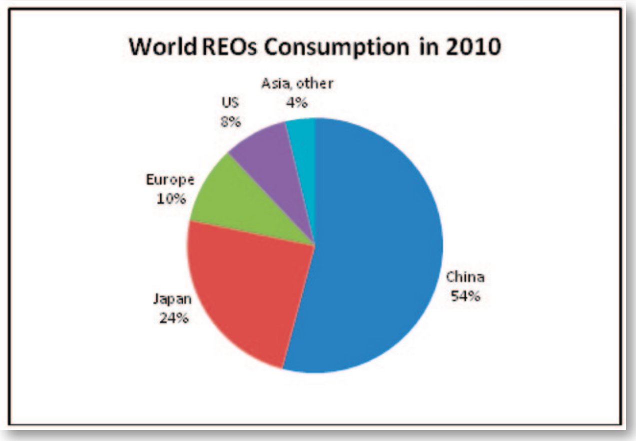
Current rare earth reserves are distributed among five major countries: China, Russia, the United States, India and Australia. Almost half of the rare earths' reserves are currently located in China. Russia and associated nations control about 17% of the global REO reserves, as seen in Fig. 2a. The United States controls about 12% of the global REO reserves, followed by India and Australia (Cordier, 2011).

Countries with REO reserves are not necessarily producing REEs. As depicted in Figs. 2a and 2b, while five countries report significant REO reserves, only three of those countries are producing REOs as of 2010. Between 1965 and 1984, United States mines dominated the production of REOs, with the Mountain Pass Mine in California producing the majority of REOs for the global market (Haxel et al., 2002). However, starting in 1991, China's ability to produce REOs at low cost prevented deposits in other countries from being developed competitively (Stone, 2009). When the Chinese mines began to dominate the rare earths industry, the rate of REO production increased significantly. From 1960 to 1990, the annual increase in the global REO production rate was approximately 2 kt/a (2,205 stpy). Once Chinese mines started producing REOs, the increase in production doubled to 4 kt/a (4,410 stpy). Between 2006 and 2009, the United States relied on China for almost 95% of the rare earth metals and compounds used in the United States (Cordier, 2011). In Fig. 2b, China's dominance of the current production of REEs is clearly displayed.

The global dependence on one country, China, for the production of REEs most certainly will lead to supply interruptions. Further, in November 2010, the Chinese government placed an export ban on REOs to Japan following an economic dispute (Bradsher, 2010). If the United States ever finds itself in an economic dispute with China, the U.S. demand for REEs would not be met, since the United States

Figure 3

Chart illustrating the consumption of REOs by country as a percentage of the global consumption (Lynas, 2010).



does not have a national stockpile or any REO producing mine running at full capacity (Cordier, 2011). Since 2011, the Chinese government has reduced the export quotas on REEs by 35% due to China's desire to improve environmental regulations and secure local demand (Bradsher, 2010). In addition to a reduction in the amount of REOs exported, Chinese export taxes on REEs have increased by 10% (Bradsher, 2010). A national rare earths stockpile is being created in China and may contain up to 100 kt (110,110 st) 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 kt (79,000 st) of rare earths (Lynas, 2010). The reduction of the export quota, increase in export taxes and development of a Chinese REE national stockpile has resulted in an increased price for REEs, improving the economic feasibility for other countries, such as the United States and Australia, to develop competitive REO mines.

Dependence on foreign REEs can be significantly reduced. As seen in Fig. 3, the consumption distribution is similar to the reserves distribution (Fig. 2a); thus, it is possible for the United States to provide enough REEs to support its demand. In 2010, consumers in the United States utilized 11 kt (12,000 st) of REOs (Cordier, 2011). Within the United States, there is a REO reserve base of 13 Mt (14.3 million st). If the historical records of domestic production and apparent consumption — production plus imports minus exports — of REOs are examined, it appears as if the United States can sufficiently supply itself with REOs, as shown in Fig. 4. Assuming demand remains constant, domestic reserves would provide enough rare earth reserves for the next 100 years. The United States stopped producing REOs in 2002, due to the relatively high environmental costs in the face of an aggressive production policy of REOs in China. In 2009, China started to change its REO supply policy from being a global supplier of REOs, to a protectionist policy based on the production and supply of REOs to secure China's domestic demand.

Per the U.S. demand and supply graph shown in Fig. 4, from 1964 until 1998, there was a strong correlation between domestic REO production and domestic apparent consumption. Until 1998, both indicators follow the same overall incremental tendencies. As the consumption or demand increases, production or supply should increase to meet the demand.

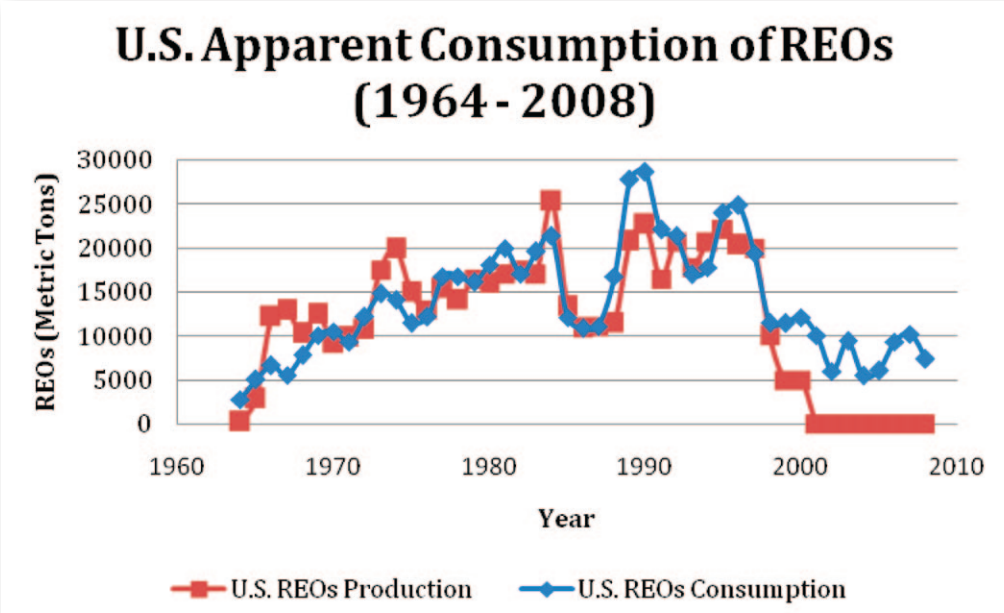
Penn State REE Deposits Database

The United States Geological Survey (USGS) has compiled two rare earth references. The first is a global database of rare earths and the second is a localized United States rare earths database (Orris and Grauch, 2002; Long et al., 2010). With these two references, a geographic visualization tool was created to help predict the future supply of REEs based on their location, status, number of years required to develop, deposit, type of REE and applications of the REE. This web tool, entitled "Penn State REEs' Deposits Database," is available as a public table at http://www.google.com/fusiontables/Home.

REEs' importance to green technologies and defense applications further increases the need for the United States to diversify its sources of REEs. Relying on China for 92% of the country's demand increases the risk of a supply interruption in the future. To secure the supply of REEs, the United States must develop domestic sources of REEs. The Penn

Figure 4

Apparent consumption and production of REOs in the United States versus time (1964 - 2008). Apparent consumption was calculated by subtracting the exports from the production and imports (USGS, 2010).



State REEs' Deposits Database helps to identify potential sources of REEs feasible for development.

Using data from USGS, the Penn State REEs' Deposits Database was created to predict the locations of future rare earths mines with the Google Fusion Table technology. Google Fusion Tables is a new web technology used for data management to host, manage, collaborate on, visualize and publish data online (Google, 2011). This technology allows for large datasets, such as the Penn State REEs' Deposits Database, to be mapped and dynamically filtered for query processes.

The Penn State REEs' Deposits Database includes the following fields describing each ore deposit: deposit name, latitude/longitude, country, state or province, estimated location, reserves/resources designation, 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 rock forming minerals, age, deposit type, host rock, company, comments and references.

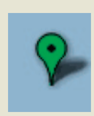
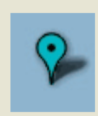
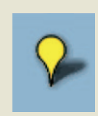
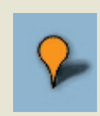
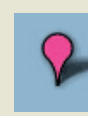
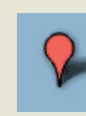
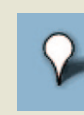
Five scenarios forecasting the future REE supply were created through filtering the information using this table tool. The base for this map is the Google Map with balloon place-marks indicating where the deposits are located. The color of the placemark represents the number of years needed to develop that location from a deposit to an active mine, as shown in Table 1. The number 9,999 indicates an unknown number of years required to develop the REEs mineral site.

Figure 5

United States' known rare earth deposits. Inferred resources of REEs are excluded from this map. Refer to Table 1 for a legend description.

Table 1

The legend for the REEs' Deposits Database. The colors represent the number of years needed to produce REEs from a given site. Black dots in the balloon represent deposits that are designated as reserves in lieu of resources.

Years needed to develop	0	3	5	7	10	15	9,999
Placemark							

Future supply scenarios

Five future supply scenarios with varying levels of demand forecasted the location of REE deposits using the Penn State REEs' Deposits Database on Google Fusion Tables. These scenarios include Scenario 1: low demand; Scenario 2: United States' current demand; Scenario 3: moderate demand; Scenario 4: high demand; Scenario 5: Japan's current demand.

Four conditions were used to develop the supply scenarios. They are as follows: (1) international trade policy, (2) greenhouse gas regulations, (3) environmental mining regulations and (4) REEs' applicability ratio. These variables were chosen based on their significant impact on the supply and demand curves of REE in the U.S. Using the Penn State 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 Fig. 6 displays the development of the five scenarios in Google Fusion Tables.

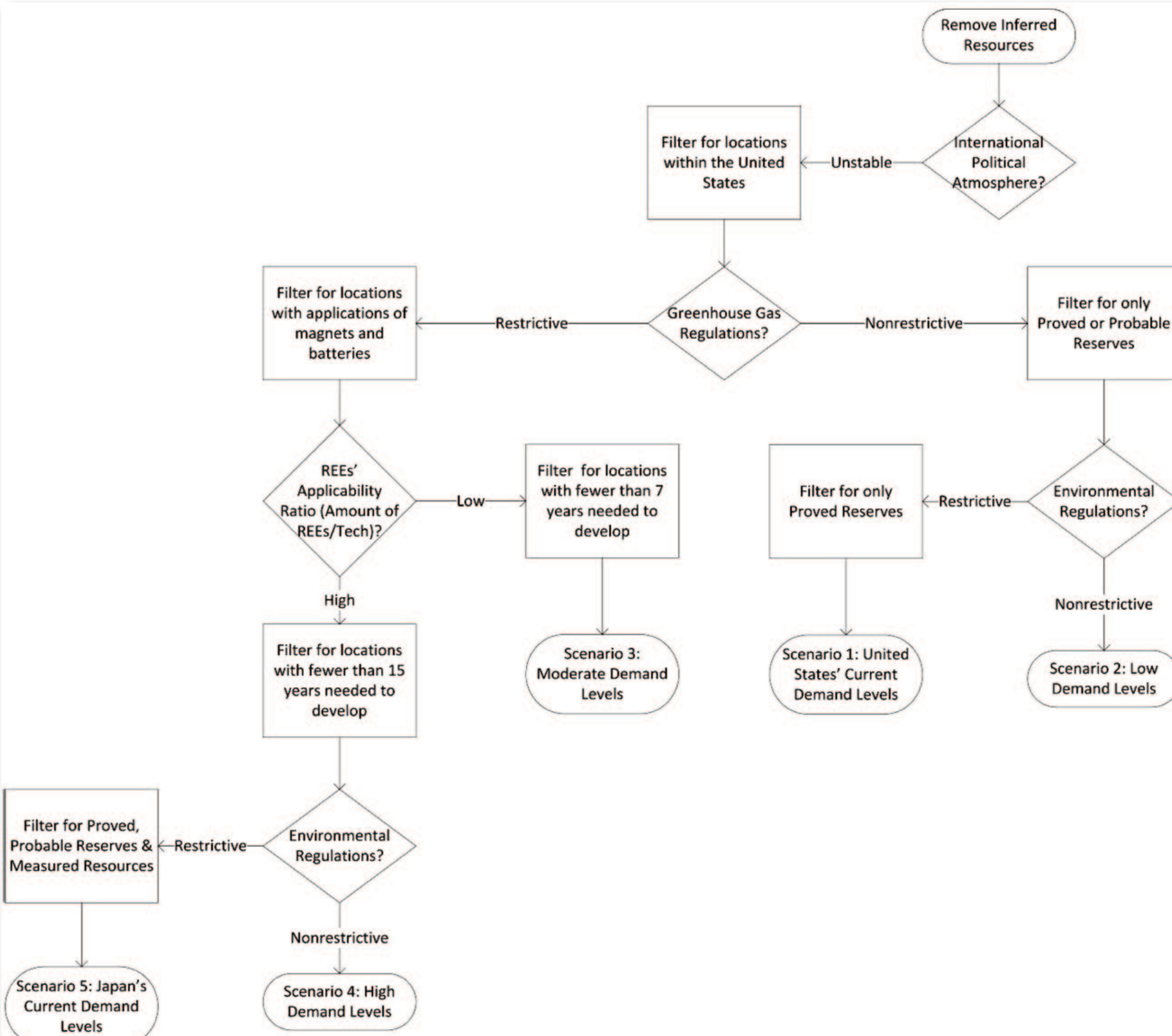
Before considering any of the four conditions, inferred mineral resources of REEs were filtered out of any possible scenario due to the lack of information describing these deposits. As more exploration data becomes available, REE-inferred mineral resources may be upgraded to indicated mineral resources in order to be included in future geoeconomic case scenarios.

The first condition considered for the first supply scenario is the stability of the current international trade policy. A stable international trade policy was defined by countries with significant rare earth deposits being willing to trade with countries without developed mines. Thus, with a stable international trade policy, all of the deposits across the world can be considered in the supply model. An unstable international trade policy is, therefore, classified as countries with significant rare earth deposits imposing export quotas preventing other countries from meeting their rare earth demand. With the extreme case of a disrupted international trade of REEs, the model is based on filtering the REE sites within the database to localize within the country of interest. Since the domestic deposits within the United States, shown in Fig. 5, have the potential to reduce dependence on foreign REEs once developed, the five future supply scenarios assume there is an unstable international trade policy and only consider deposits in the United States.

The second condition considers how restrictive green-

Figure 6

Flowchart illustrating future supply scenarios. Four conditions are considered to generate the supply scenarios: international trade policy, greenhouse gas regulations, environmental regulations and REEs' applicability ratio.



house gas (GHG) regulations will be in any given country, in this case the United States. Rare earths such as neodymium, lanthanum and dysprosium are necessary for a variety of green technologies such as wind turbines, biofuels, batteries, hybrid cars and electric vehicles. These elements are utilized to make permanent magnets used in wind turbines, in solar panels and in nickel metal hydride batteries used in electric cars. Therefore, the REE deposits able to produce these elements for both magnets and batteries will be the most critical site deposits to develop in the near future.

Currently, the United States does not have any regulations restricting the emission of carbon dioxide and other GHGs. Thus, the regulations are nonrestrictive. It is expected that this relaxed carbon dioxide emission scheme will create a relatively low demand for green technologies and their REE components. Thus, it will produce a relatively low demand for REEs in the United States. If GHG regulations continue to be as nonrestrictive as they are now, current proved reserves of REEs will be enough to supply the demand. On the other hand, if international GHG emission regulations were enacted, or the United States government decided to internally impose regulations, then the demand for REEs would increase, as they are key for the development of current green technologies. An increase in demand would increase the number of potential REE sites that would be feasible to develop.

The third condition being considered is based on determining the economic feasibility of developing new REE deposits for mining production in accordance with U.S. environmental regulations. If environmental regulations for rare earth mines are restrictive, production costs related to environmental control will increase, resulting in a reduced number of possible REE sites feasible for development. Only those few REE deposits with high concentrations of REEs and, thus, high profitability will be economically feasible to be exploited. On the other hand, if environmental regulations are less restrictive, it might be economical to open new mines from ore deposits with lower grades. To model this condition and to forecast supply of REEs, the geographic database was filtered using the reserves or resources designation.

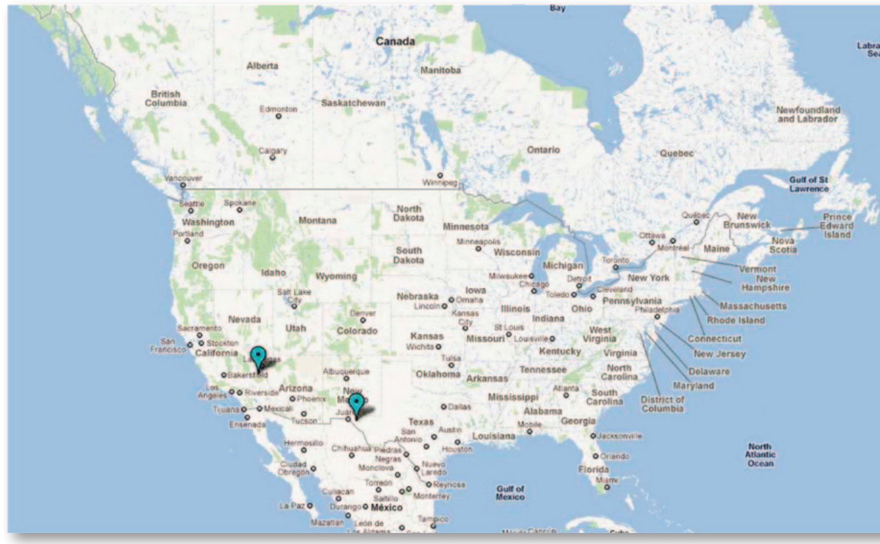


Figure 7

Scenario 1: Short-term resources of REEs in the U.S. considering an ongoing unstable international trade policy, nonrestrictive greenhouse gas regulations and restrictive environmental regulations. Refer to Table 1 for a legend.

The final condition considers REEs' applicability ratio. Applicability ratio is defined as the amount of REEs required to produce or develop a product within a given technology. The REEs' applicability ratio is expected to decrease as time progresses, as it is expected that materials research will advance the development of new products with equal or better properties and quality with less dependency on REEs. Materials research could develop new alternatives to fully replace the need for REEs. Alternative solutions and materials might significantly reduce the demand for REEs and, thus, decrease applicability ratios. As REEs' applicability ratio decreases, the demand will also decrease, bringing prices down. To account for low REE applicability ratios, only deposits within a development time less than or equal to seven years are considered in this scenario. In contrast, if the applicability ratio is increased, the demand will increase as well. Considering high applicability ratios, deposits with longer development times than seven years could still be feasible options.

The environmental, applicability and economic conditions reviewed above are used in the models to create five future supply scenarios with varying levels of demand: (1) United States' current demand levels; (2) low demand levels; (3) moderate demand levels; (4) high demand levels and (5) Japan's current levels.

Scenario 1: United States' current demand

The first scenario examines the United States' current demand levels with (1) an unstable international trade policy; (2) nonrestrictive greenhouse gas regulations and (3) restrictive environmental mining regulations. Under current United States Environmental Protection Agency (EPA) policy, there are restrictive environmental regulations on mining REEs. Restrictive environmental regulations will push the mining industry to spend more on environmental liability, remediation, closures, etc. Therefore, it probably would be economical to develop only proved reserves. The REEs' applicability ratio was not considered in this case, due to its minimal impact on the already limited alternatives. This scenario keeps the current relaxed greenhouse gas regulations and considers restrictive environmental regulations within the United States.

The current levels of U.S. demand predict only two deposits within the United States to be developed economically: Mountain Pass, CA and Round Top Mountain, TX. As depicted in Fig. 7, this scenario underlines the importance of the Mountain Pass Mine. Molycorp is in the process of restarting mining and processing operations and should be ready in 2012; currently, ore is being processed from stockpiles mined before 2002. While Mountain Pass has a large reserve base, these reserves are not enough to supply projected demand. Thus, if the conditions considered within this scenario remain unchanged, the demand for LREEs and, most significantly, of HREEs will outstrip the supply. Technology applications utilizing HREEs, such as lasers, silicon photovoltaic cells and the nuclear industry, will face severe supply deficiency if current levels of demand continue.

Scenario 2: low demand

The low demand scenario forecasts: (1) an unstable international trade policy; (2) nonrestrictive greenhouse gas regulations and (3) nonrestrictive environmental mining regulations. The unstable international trade policy specifies how the United States is focusing on developing domestic deposits. Nonrestrictive greenhouse gas regulations cause the REE demand to continue increasing 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. Therefore, mining companies can develop rare earth deposits with lower grades that possibly will require additional processing. In this scenario, several new potential ore sites are considered.

As seen in Fig. 8, this low demand scenario portrays 18 possible locations in the U.S. where rare earth mines could be established. Mountain Pass, CA and Round Top Mountain, TX are included in the outcome of possible REE resource locations. Quartz and clay are the dominant waste or gangue materials resulting from 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 is a group of mining deposits of REEs to be potentially mined as a byproduct. Most of these Idaho deposits are past REE producers. The geographic database used to run this case scenario contains more detailed information about tonnage and grade within these deposits. Per the results from this scenario, the Gallinas Mountains in New Mexico is the only deposit with a significant quantity of HREEs.

Scenario 3: moderate demand

This supply scenario inferring moderate levels of demand portrays (1) an unstable international trade policy; (2) restrictive greenhouse gas regulations and (3) a low REEs' applicability ratio. The restrictive greenhouse gas regulations will

Figure 8

Scenario 2: Mid-term resources of REEs in the U.S. considering an unstable international trade policy, nonrestrictive greenhouse gas regulations and nonrestrictive environmental regulations. Refer to Table 1 for a legend.

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 stem from future and ongoing research to find alternative solutions or materials to replace REEs and, thus, decreases the amount of REEs needed to produce each technology. This scenario also considers future environmental regulations.

As shown in Fig. 9, the moderate demand scenario portrays 17 possible locations where mines could be developed. It provides a similar view of potential REE ore resources to the low demand scenario without considering the Sheep Creek deposit in Idaho. The Sheep Creek deposit was not included in the moderate demand scenario, due to the unknown nature of the host minerals per the USGS report. Developing these deposits for mining would help secure the REE supply for green and high-tech applications within the United States.

Scenario 4: High demand

This scenario considers (1) an unstable international trade policy; (2) restrictive greenhouse gas regulations; (3) a high REEs' applicability ratio and (4) nonrestrictive environmental mining regulations. The high demand scenario, shown in Fig. 10, includes a high REEs' applicability ratio, which implies alternative materials to replace REEs were not found, resulting in an aggressive development of new extractive operations. The umbrella of feasible mines expands to cover those geologic deposits classified as measured and indicated REE resources that will require seven or more years to be fully developed.

In this scenario, there is a high level of demand stemming from restrictive greenhouse gas regulations and a high REEs' applicability ratio, allowing for a large number of possible locations to be developed into rare earth mines. Under this high-demand scenario, 39 potential mine locations appear feasible for development. Per the model, several known locations are found scattered throughout the United States (Fig. 10). Several western states have significant concentrations of REE deposits, including Idaho, Colorado and New Mexico. There is a group of rare earth ore 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 of the potential sites contain HREEs, including Hicks Dome, Gallinas Mountains, Elk Creek, Music Valley and Mineville Iron District. As expected, most of the potential geologic formations for REEs found under the conditions used for this case scenario contain mostly LREEs in the form of monazite as the dominant mineral. Mudstone and sandstone are the primary host rocks for the majority of these deposits. Ownership information for these sites is incomplete; this information is provided for approximately one-third of the given locations. Potential new ownership of the remaining two-thirds of the ore sites could be considered by rare earth entrepreneurs. Overall, this high-demand scenario leads to the development of several feasible potential REE locations.

Scenario 5: Japan's current demand

This final scenario forecasts (1) an unstable international trade policy, (2) restrictive greenhouse gas regulations, (3) a high REEs' applicability ratio and (4) restrictive environmental mining regulations. This scenario rep-

Figure 9

Scenario 3: Moderate demand levels - unstable international trade policy, restrictive greenhouse gases, low applicability ratio. Refer to Table 1 for a legend.

Figure 10

Scenario 4: High demand levels - unstable international trade policy, restrictive greenhouse gas regulations, high applicability ratio and nonrestrictive mining regulations. Refer to Table 1 for a legend.

resents Japan's current demand level just before 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 Japan may want to invest in wind energy and to continue driving its automotive industry towards hybrid and electric technology (Areddy, 2011b). Japan is one of the largest consumers of REEs, due to its car industry producing electric and hybrid-electric cars. Japanese companies must rely completely on imported REEs. With the Chinese government reducing the REEs export quotas, Japanese companies are forced to look elsewhere for sources of REEs. While Japanese scientists are intensively researching how to reduce the applicability of REEs and how to reduce the cost of recycling REEs, no feasible alternative solutions or new materials to replace REEs have been found yet, resulting in high REEs applicability ratios (Lynas, 2010).

Figure 11 displays the scenario for Japan's current level of demand, with 21 potential REE deposits, approximately half as many as in the high demand scenario. This scenario has been produced by targeting those REEs deposits that could be developed in 10 years or less. Carbonatite and phosphorite dominate the mineralogy of these deposits. Similar to the results of previous case scenarios, the majority of these deposits contain mostly LREEs. In order to fill the deficit between supply and demand of HREEs, alternative materials must be developed in addition to developing mines that are likely to contain HREEs.

Figure 11

Scenario 5: Japan's current demand levels - unstable international trade policy, restrictive greenhouse gas regulations, high applicability ratio and restrictive environmental mining regulations. Refer to Table 1 for a legend.

Comments

The Penn State REEs' Deposits Database is a geographic database and visualization tool developed by the authors. This visual database is mostly based on USGS rare earth data. It was created to analyze future supply scenarios. This new database can be used to identify domestic and global REE ore sites and potential new mine locations by anyone interested by searching for "Penn State REEs Deposits Database" on the Google Fusion Tables website. The database contains standardized information about the deposits, including deposit status, as shown in Fig. 1.

The five demand scenarios reviewed above determine the required supply that might be needed, showing the locations of known REE deposits based on specific conditions, such as greenhouse gas (GHG) regulations, environmental regulations and REEs' applicability ratio within the United States. In most scenarios, Mountain Pass, Round Top Mountain and Pea Ridge, all of which have plans to start 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. The moderate demand level is unlikely to occur, since it is based on a rapid and successful research of alternative new solutions and materials that could potentially decrease the REEs applicability ratios. The high-demand scenario predicts 39 deposits that could be developed considering restrictive GHG regulations, high applicability ratios and nonrestrictive environmental regulations pushed by high demands. The United States' current scenario indicates that Mountain Pass is one of two deposits that are feasible for production within the U.S. The actual future outlook probably looks similar to Japan's current scenario. There will be an increased demand for green technology and environmental regulations might be relaxed in some cases of rare earth extraction and production, considering that it is unlikely that any economical alternative to replace the use of REEs will be discovered within the next seven years. Under this scenario, there are approximately 21 REE deposits that could be developed into active mines. The majority of these deposits contain mostly LREEs without a significant presence of HREEs.

After examining the background information on REEs and the future supply scenarios, it is clear that the United States needs to focus on sustaining and securing the supply of REEs in the near future. Some sustainability tasks should be accomplished within the next five years, such as expediting the permitting process to develop domestic rare earth mines, strengthening international trade relationships, recycling of REEs and increasing research into alternative materials or solutions to replace REEs. Furthermore, the domestic inferred resources of REEs need to be further explored to better understand the extent of rare earth resources in the United States. ■

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