Rare Earth Minerals – Our Most Strategic Mineral

Introduction

Simply put, rare earth minerals run your life. We need these elements for LCD screens, lasers, headphones, microphones, smartphones, space rockets, satellites, and even in some modern cancer treatment drugs. Rare earth elements have certain properties that make them extremely useful. Their use in wind turbines and electric vehicles means they have become a key part of developing clean energy technology, helping with slowing climate change. However, there is reason to worry about how they are sourced. If we don't act now, there will be problems in meeting the required demand in the future. Restricting the exports of rare earths would be a good way of inflicting economic pain on geopolitical rivals. Even if mining companies wanted to extract rare earths in an environmentally friendly way, the market incentives are simply not there. This paper will discuss the rare earths this country needs, and which countries controls them and why. Securing essential minerals supply is a social, environmental, and geopolitical problem that needs to be solved. Highly magnetic elements are essential for energy conversion. Rare earth magnets help make electric vehicle motors and wind turbines lighter and more efficient. The International Energy Agency (IEA) predicts that demand for rare earths will rise by more than three-fold by 2040 without concerted government policy and seven-fold in the sustainable development scenario due to the renewable energy language embedded in the Inflation Reduction Act. Unfortunately, there is a tremendous mismatch between the world's climate goals and the availability or critical minerals.

According to the US Geological Survey, these rare earths can be found virtually everywhere but that doesn't mean they are easily obtainable. The economics of mining them is not exactly straightforward. Typically, rare earths are co-produced with other minerals simply because they are co-located. Currently, the economics of extracting rare earths are driven by the price of the co-located metal.

Reserves

Rare earth elements include the 14 lanthanides as well as lanthanum and often yttrium. Most of the elements are not very rare and occur widely dispersed in a variety of rocks. Availability of rare earths is somewhat limited, since their concentration levels in many ores are quite low (typically less than 5% by weight). An economically viable source needs to contain more than 5% rare earths, unless they are mined with another product which allows economic recovery of ore bodies with concentrations of as little as 0.5% by weight.

Of the 83 naturally occurring elements, the 16 naturally occurring rare-earth elements fall into the 50th percentile of the elemental abundances. Rare earths elements are not present in equal amounts in rare earth elements. They are generally divided into the light rare earth elements and the heavy rare earth elements, with the heavy variety being much less abundant and thus much more valuable.

Sources

Rare-earth ore deposits are found all over the world. The major ores are in China, the United States, Australia, and Russia, while other viable ore bodies are found in Canada, India, South Africa, and southeast Asia. The major minerals contained in these ore bodies are bastnasite (fluorocarbonate), monazite (phosphate), loparite, and laterite clays.

Chinese deposits accounted for about 80% of the rare earths mined in the world (105,000 tons of rare-earth oxide in 2017). About 94% of the rare earths mined in China are from bastnasite deposits. The major deposit is located at Bayan Obo, Inner Mongolia (83%), while smaller deposits are mined in Shandong (8%) and Sichuan (3%) provinces. About 3% comes from laterite (ion absorption) clays located in Jiangxi and Guangdong provinces in southern China, while the remaining 3% is produced at a variety of locations.

China's monopoly allowed it to raise prices by hundreds of percent for various rare-earth materials from 2009 to 2011 and to impose export quotas on many of these products. This brought about by changing dynamics of the rare-earth markets. Mining of bastnasite resumed at Mountain Pass, California, in 2011 after a nine-year pause in mining. Mining of monazite began that same year at Mount Weld, Australia. At the same time, loparite was being mined in Russia, while monazite was mined in India, Vietnam, Thailand, and Malaysia. Those and other mining operations brought a new equilibrium between demand and supply in which China was still the major supplier of rare-earth minerals, but manufacturers either sought alternative sources, used less, or recycled more rare earths.

As of 2017, known world reserves of rare-earth minerals amounted to some 120 million metric tons of contained REO. China has the largest fraction (37%), followed by Brazil and Vietnam (18% each), Russia (15%), and the remaining countries (12%). With reserves this large, the world would not run out of rare earths for more than 900 years if demand for the minerals would remain at 2017 levels. However, demand for rare earths is rising at a rate of about 10% per year. If demand continues to grow at this rate and no recycling of produced rare earths is undertaken, known world reserves likely will likely be exhausted sometime after the mid-21st century.

Recycling Rare Earth Elements

Considering both the limited reserves and high value of the rare-earth metals, recycling these elements from consumer products that reach the end of their useful life is expected to become essential from a sustainability standpoint. Currently, only scrap metal, magnet materials, and compounds used in the manufacture of phosphors and catalysts are recycled. However, products that contain relatively large amounts of rare earths could be recycled immediately using existing techniques. These include rechargeable nickel–metal hydride batteries that contain a few grams to a few kilograms of $LaNi_5$-based alloys as a hydrogen absorber as well as large $SmCo_5$- and $Nd_2Fe_{14}B$- based permanent magnets. All these materials hold 25–30% by weight light lanthanides—much more than even the best rare-earth-containing ore. However, most consumer electronic devices contain only small amounts of rare earths. For example, a hard drive's spindle magnet contains only a few grams of $Nd_2Fe_{14}B$. A speaker magnet of a cellular phone makes up less than 0.1% of the total mass of the telephone. A compact fluorescent lamp has just a fraction of a gram of lanthanide metals in the phosphor. Considering the complexity of many modern electronic devices, recycling of rare earths must be done simultaneously with recycling of other valuable resources and potentially dangerous substances. These include precious metals (such as silver, gold, and palladium), nonferrous metals (such as aluminum, cobalt, nickel, copper, gallium, and zinc), carcinogens (such as cadmium), poisonous elements (such as mercury, lead, and beryllium), plastics, glass, and ceramics. Several scientific and engineering issues need to be resolved to create consumer products that are easily recyclable at the end of their life and to make recycling of rare earths both economical.

Minerals and Ores

The content of the individual rare-earth elements varies considerably from each mining operation. The minerals and ores are generally classified as “light” or “heavy”; in the former group most of the elements present are the light-atomic-weight elements (i.e., lanthanum, cerium, praseodymium, neodymium, samarium, and europium), whereas most of the elements in the latter group are the heavy-atomic-weight elements (i.e., gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium, plus yttrium, which is considered to be a member of the heavy group because it is found in the ores with the heavy lanthanides).

Of the approximately 160 minerals that are known to contain rare earths, only four are currently mined for their rare earths: bastnasite, laterite clays, monazite, and loparite. Except for laterite clays, these minerals are good sources of light lanthanides and lanthanum and account for about 95% of the rare earths in use. Laterite clays are a commercial source of the heavy lanthanides and yttrium.

Other minerals that have been used as a source of rare earths are apatite, euxenite, gadolinite, and xenotime. Allanite, fluorite, perovskite, sphene, and zircon have the potential to be future sources of rare earths.

Bastnasite - Bastnasite, a fluorocarbonate, is the principal source of rare earths. About 94% of the rare earths used in the world come from mines in Mountain Pass, California, U.S.; Bayan Obo, Inner Mongolia, China; Shandong province, China; and Sichuan province, China. The Bayan Obo deposit is slightly richer in praseodymium and neodymium than the Mountain Pass bastnasite is, primarily at the expense of the lanthanum content, which is 10% greater in the Mountain Pass ore.

Laterite clays - The laterite clays (also known as ion-absorption clays) are primarily composed of silica, alumina, and ferric oxide; those that also contain viable amounts of rare earths are found only in Jiangxi province of southeast China. Of the Jiangxi deposits, the clays located near Longnan are quite rich in the heavy lanthanides and yttrium. The clays at Xunwu have a most unusual distribution of rare earths, being rich in lanthanum and neodymium with a reasonably high yttrium content. These clays are the main source of heavy elements used in rare-earth-containing products—e.g., dysprosium in $Nd_2Fe_{14}B$ permanent magnets.

Monazite - Monazite, a phosphate, is the third most important ore source of rare earths. However, it contributes only a small fraction to the mined rare earths. There were two reasons for this change: first, it is more costly to process monazite from the ore body to a rare-earth concentrate than to process bastnasite; second, monazite contains a significant amount of radioactive thorium dioxide (ThO_2) compared with bastnasite, and consequently, special EH&S procedures in handling and storage are needed.

Monazite is widely distributed; in addition to Australia, it is found in India, Brazil, Malaysia, countries of the Commonwealth of Independent States, the United States, Thailand, Sri Lanka, the Democratic Republic of the Congo, South Korea, and South Africa.

Loparite - Loparite is a complex mineral that is mined primarily for its titanium, niobium, and tantalum content, with the rare earths extracted from the ore as a by-product. This ore is found mainly in the Kola Peninsula in northwest Russia and in Paraguay.

Xenotime - Xenotime is a phosphate mineral, like monazite except enriched in the heavy lanthanides and yttrium. Because of its high concentrations of yttrium and heavy lanthanides, xenotime is used as a source material for the individual rare-earth elements rather than being used as a mixture of heavy rare earths. The major producer of xenotime is Malaysia; deposits are also reported to exist in Norway and Brazil.

Processing Ores

All rare-earth ores contain less than 10% rare earth oxides (REO) and must be upgraded to about 60% to be processed further. They are first ground to a powder and then separated from the other materials in the ore body by various standard processes that include magnetic and/or electrostatic separation and flotation.

Separation Chemistry

The rare-earth separation processes in use today were developed by Oak Ridge National Laboratory and at Ames Laboratory using an ion-exchange process. Both laboratories showed that the ion-exchange process would work at least on a small scale for separating rare earths. In the 1950s the Ames group showed that it was possible to separate kilograms of high-purity (>99.99%) individual rare-earth elements. This was the beginning of the modern rare-earth industry in which large quantities of high-purity rare-earth elements became available for electronic, magnetic, phosphor, and optical applications.

Argonne National Laboratory and Oak Ridge National Laboratory developed the liquid-liquid solvent extraction method for separating rare earths in the mid-1950s. This method is used by all rare-earth producers to separate mixtures into the individual elements with purities ranging from 95 to 99.9%. The ion-exchange process is much slower, but higher purities of more than 99.99999% can be attained. For optical and phosphor-grade materials, where extremely high purities are required, the individual rare-earth element is initially purified by solvent extraction up to about 99.9% purity, and then it is further processed by ion exchange to reach the purity required for the given application.

Preparation of the Metals

There are several different processes of preparing the individual rare-earth metals, depending upon the given metal's melting, and boiling points and the required purity of the metal for a given application. For high-purity metals (99% or better), the calciothermic and electrolytic processes are used for the low-melting lanthanides (lanthanum, cerium, praseodymium, and neodymium), the calciothermic process for the high-melting metals (scandium, yttrium, gadolinium, terbium, dysprosium, holmium, erbium, and lutetium, and another process (the so-called lanthanothermic process) for high-vapor-pressure metals (samarium, europium, thulium, and ytterbium). All three methods are used to prepare commercial-grade metals (95–98% pure).

Metallic and Complex Compounds

Among the many rare-earth intermetallic compounds that form, a few stand out because of their unusual applications or interesting science. The main applications include permanent magnets, rechargeable batteries, electron guns, microkelvin cooling, magnetostriction, and giant magnetocaloric effect. The two applications that have been extensively commercialized are permanent magnets and rechargeable batteries.

Permanent magnets - The most prominent rare-earth intermetallic compound is $Nd_2Fe_{14}B$, which is ferromagnetic and, with proper heat treatment, becomes the hardest magnetic material known. Hence, this intermetallic compound is used as a permanent magnet in many applications. Its main uses are in electric motors (e.g., the modern automobile contains up to 35 electric motors), spindles for computer hard disk drives, speakers for cell phones and portable media players, direct-drive wind turbines, actuators, and MRI units. $SmCo_5$ and Sm_2Co_{17} are also permanent magnets. Both have higher Curie (magnetic ordering) temperatures than Nd2Fe14B but are not quite as strongly magnetic.

Rechargeable batteries - Another important compound, which is a hydrogen absorber used in green energy, is $LaNi_5$. It is a main component in nickel–metal hydride rechargeable batteries, which are used in hybrid and all-electric motor vehicles. $LaNi_5$ absorbs and dissolves hydrogen quite readily near room temperature, absorbing six hydrogen atoms per $LaNi_5$ molecule at modest hydrogen pressure. This is one of the major rare-earth markets.

Recent Developments

The Defense Department recently financed the construction of rare earths separation facility in Texas. The government's concern is China's dominance of the critical mineral supply chain. Rare earth elements are vital to making magnets used in military equipment such as lasers and guidance systems. These metals are also necessary in the production of electric vehicles, wind turbines, fiber optic cables and consumer electronics. China mines approximately half of the world's rare earth metals and refines roughly 90% of these metals according to the International Energy Agency. At present, the United States has no commercial processing facility which is raising concerns that the US could lose complete access to these critical minerals if trade with China deteriorates. Along with this proposed Texas separation plant, a deal with Australia for refined rare earth minerals, the United States' strategic vulnerability on the mining and production of these minerals would come to an end. The US Defense Department is also separately funding a rare earth processing project at the only rare earth mine in the US, located in California. These Defense Department funded projects will help provide new source of refined and separated rare earth metals for US manufacturing of semiconductors and other electronic devices, in addition to permanent magnet electric motors.