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Rare earth elements as critical raw materials: Focus on international markets and future strategies

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A B S T R A C T

Supply of some critical raw materials by European industry is becoming more and more difficult. After the case of natural textile fibres, in particular cotton, and timber, over the last few years the problem of rare earths (REs) availability has also risen. The 97% of the global supply of rare earth metals (REMs) is produced by China, that has recently done copious cuts of its exports, apparently in order to protect its environment. This fact has greatly increased the REs prices, causing tension and uncertainty among the world hi-tech markets. Many of these materials, in fact, have very few effective substitutes and low recycling rates too. In addition, their natural reserves of rare earths are concentrated in a small number of countries (China, Brazil, US, Russia, Democratic Republic of Congo). REMs are a group of 17 elements particularly used in many new electronic and advanced components: such as fuel cells, mobile phones, displays, hi-capacity batteries, permanent magnets for wind power generation, green energy devices, etc. Many analysts foresee much more requests in the next decades.

Introduction

In June 2010, the European Commission published a list of 14 raw materials (metals or group of metals) that are *critical* for many important emerging technologies of its regional industries, highlighting their vulnerability, due to possible political tensions or shortages. In fact, the same Commission labels a raw material as "critical" when – after having carefully evaluated the political and economic situation of the producing countries, the level of supply concentration, the potential for substitution and the recycling rate – its impacts on the economy, due to a possible supply contraction, are much higher than other raw materials (European Commission, 2010).

In this list, there are 12 materials (antimony, beryllium, cobalt, fluorspar, gallium, germanium, graphite, indium, magnesium, niobium, tantalum and tungsten) and two groups of other elements: PGMs (platinum group metals, which include iridium, osmium, palladium, platinum, rhodium and ruthenium) and rare earths (REs) group (European Commission, 2011).

Lately, the most critical situation seems to be that of REs – for the EU high import dependency rate, low substitution and low recycling rate – did not produced within the European members, except the limited capacity of Estonia (Chen, 2011). In fact, although their industrial demand is relatively small (in terms of tonnes), they are essential for many expanding high-technology applications. Moreover, while global consumption of rare earth elements (REEs) has registered a steady and significant increase, their supply has drastically diminished.

To face this crucial situation, the Commission, already in 2008, launched the "European Raw Materials Initiative" (Commission of the EC, 2008) suggesting an integrated strategy based on the following three principles: (1) enforcing deeper links and co-operation contracts with producer countries, particularly in Africa, by improving foreign investment agreements; (2) encouraging and promoting internal mining potential; (3) developing more efficient recycling policies (European Commission, 2010). Monitoring and proactive measures are thus necessary, particularly, for those strategic materials, like REs, to which EU has high import dependency and increasingly difficult to access (Tiess, 2010).

Even the US Department of Energy (DOE) wrote, in the same year, a technical document (US DoE, 2010) in order to determine a long-term strategy for those materials and others that, like the REs, may be considered critical for the national economy, because they have high and imminent risk of supply interruption.

Since a few years ago, in fact, many producing and emerging countries, rich in REs resources, have applied protectionist policies, reducing the exports to EU, in order to protect their national

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downstream industries. China, for example, that dominates the world market of REs minerals (97%, with about 30% of the reserves), has steadily increased export taxes on REEs, drastically restricting their export quotas in recent years: from about 50,150 t exported in 2009 to a little more than 30,250 t in 2010, with a decrease of about 40% (Kingsnorth, 2010a; Lynas Corp., 2011). Already in 1992, the Chinese President Deng Xiaoping proudly said, that ''If the Middle East has oil, China has the rare earths'' (Keller, 2011).

It is known that, according to the IUPAC definition, ''rare earth metals'' (REMs, or ''rare earth elements'', REEs) are a family of 17 elements in the periodic table. They start with lanthanum (atomic no. 57) and end with lutetium (atomic no. 71), called all together ''lanthanides group''. The scandium (atomic no. 21) and yttrium (atomic no. 39), having similar physical and chemical properties (*lanthanide contraction*), are also included in this family. In fact, they often occur together in nature. Based on their location in the periodic table and their atomic weights, it is possible to classify these elements into *light* REs or LREEs (lanthanum, cerium, praseodymium, neodymium, promethium and samarium, with atomic no. 57–62) and *heavy* REs or HREEs (europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium atomic no. 63–71) (IUPAC, 2005). All of them can be found in nature, in form of compounds, except promethium, which is obtained by synthetic methods.

The aim of this note is to illustrate the current situation of international markets, the availability of these strategic resources, the critical points of their supply, the possibility for substitution and recycling, the environmental problems related to their extraction and the possible solutions to enhance their future supply security for the European countries.

Reserves and production

Despite of their name, REs are not very rare indeed, especially the LREEs, extracted in a more common and easier way than the ''heavies''. In fact, the term ''rare earths'' was misleadingly suggested – after chemist Carl Axel Arrhenius (1757–1824), student of the Swedish chemist Berzelius, had discovered them in 1787 in the dumps of the Ytterby (Sweden) quarries – by Johann Gadolin in 1794: ''rare'' because, when the first REEs were discovered, he thought that they were present only in small amounts in the Earth's crust, and ''earths'' because, as oxides, REs have an earthy appearance (Long et al., 2010).

For example, cerium (6.6×10^{-3}% by weight in the Earth's crust; 25° element for what concerns plenty) has a similar abundance to that of Cu and it is about four times more abundant than Pb. Even the two least abundant REEs (Tm, Lu) are nearly 200 times more common ($\sim$0.5 ppm) than gold (US Geological Survey, 2002; Naumov, 2008). The real problem, then, is not their absolute concentration (10–500 ppm by weight) but the relative one: in fact, it is very difficult to find economically exploitable deposits and, as we will see, simple methods of extraction and separation due to their very similar properties. The only elements, that are really scarce (upper crust abundance $\leq$ 1 ppm) and even difficult to find, are europium, thulium and lutetium (Taylor and Mclennan, 1985).

They are globally traded on the basis of their content of oxides expressed in terms of a specific RE oxide (REO) or as total RE oxides (TREOs). For some applications, the requested percentage of purity of single element in these oxides can get to 99.99% or even 99.999% (''five nines'' products in a particular crystallographic structure) (King, 2011).

The principal commercial sources of REOs are *monazite* (a phosphate mineral of Ce and other LREE, like Nd, Y and Th; general formula $LaPO_3$; where La is a lanthanide), *bastnaesite* (a family of three carbonate-fluoride minerals, i.e. $LaCO_3F$,), *xenotime* (an anhydrous phosphate mineral, whose major component is YPO_4 and other HREE) and *loparite* (an oxide mineral of the *perovskite* class). The last one, as it contains considerable radioactive thorium, is no longer an attractive RE source. Most of these REEs are contained in only a few minerals (bastnaesite, monazite and xenotime) and flotation methods are used to produce REOs from these ores; other REOs (50%) are produced from heavy mineral sands and gangue by physical concentration methods or using a cationic collector, such as fatty acids or alkyl sulphate and phosphate esters (Bulatovic, 2010).

Typically, in most of these minerals, the percentage composition of the individual RE elements follows the Oddo–Harkins law: that is, an odd–even relationship according to which the elements of the periodic table with an even atomic number are usually more abundant than their odd-numbered neighbours (Kilbourn, 1993). For this reason, the concentrations of the heavier REEs are smaller than those of the lighter REEs (Uchida et al., 2006).

REs minerals are quite plentiful in the earth crust and it seems there are reserves in thirty-four countries: six countries in Europe (among all, Russia Estonia and Greenland), fourteen in Asia, ten in Africa, and then USA, Canada, Brazil and Australia (Chen, 2011).

According to the US Geological Survey (US Department of the Interior, 2011), in 2010, the whole world REOs reserves were about 110 million tonnes: China ranks the first position, with more than 60% (55 million tons); CIS (Commonwealth of Independence States—former Soviet Union) is the second, with about 17% (19 million tons); United States are the third, with a quota of about 12% (13 million tons); then follow India (3.1 million tons), Australia (1.6 million tons), Brazil (0.48 million tons), Malaysia (0.3 million tons) and other countries (22 million tons, 20% of total).

Until the 1980s, the mine of Mountain Pass (Southern California, USA) was the largest site of REs in the world. It was opened by Molycorp in the early 1950s which invested millions of dollars in researching potential uses for REEs. It was productive until 2002, when problems of groundwater pollution and the importation of low cost minerals from China greatly lowered the production, limited to a few oxides that must be processed in Asia to be converted into REMs (Fifarek et al., 2008). Other interesting sites in the United States are Lemhi Pass and Diamond Creek (Idaho) and the Bokan Mountain (Alaska) (Long et al., 2010).

A group of researchers of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) have identified huge deposits of REEs in the sedimentary mud of the seabed of the Pacific Ocean: according to some valutations, these reserves are about 100 billion tons: thousand times bigger than those on the dry land. The problem is that these resources are very deep (from 3500 to 6000 m) and their extraction currently meets serious technical and, above all, economic difficulties (Kato et al., 2011).

The largest producer is China: in 2010, 130,000 t of REOs on a world estimated production of 134,000 ones, equal to 97% of them, came from there (US Department of the Interior, 2011). Today, many of these reserves (principally based on bastnaesite's Northern deposits) are located in the regions of Inner Mongolia (Bayan Obo mine), Shangdong, Jiangxi, Guangdong, Hunan, Guangxi, Fujian, Sichuan (Hurst, 2010). Most of these mines are unlicensed and unregulated, taking advantage of low wages and causing serious environmental problems (Pui-Kwan, 2011).

Other producing countries are India (in 2010, 2700 t of REOs from illmenite and monazite minerals), Brazil (550 t from illmenite) and Malaysia (350 t from cassiterite). The main consumer countries are USA, Europe, Japan, Corea and China (US Department of the Interior, 2011).

At the moment there is a negative difference between the actual production of REs and their estimated demand: in 2010,