

Rare earth element criticality and sustainable management

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Abstract. Rare earth elements (REEs) are critical for their functions in many clean energy technologies, but many of these technologies use REEs which are at risk of supply disruption. For this reason, scientific research on the problems surrounding the supply side of these rare earth elements (REE) has recently bloomed. Concerns about tighter supplies that might increase costs for producing the necessary green technology take the “criticality” of some of these elements as a warning sign.

In many papers, a cursory explanation of this criticality is given at most. In order to come up with management strategies that are able to help address the criticality of some of these elements, a scientific plausible picture should be given. The aim of this paper is do so by basing itself on a literature review of recent work.

Introduction

With the twenty-first session of the Conference of the Parties (COP21) having come to a global agreement, ambition to see the world shift away from fossil fuel and towards a low-carbon economy in the fight against climate change seems more vigorous than ever. Although considerable debate on the regional, seasonal, and diurnal character of projected future warming is still ongoing, nearly all scientists have recently agreed that future decades will be marked by a warming due to anthropogenic activities [1]. Besides cutting down on our forest consumption, major changes in our energy infrastructure are necessary to slow, and after 2050 halt, the rate of greenhouse gases emitted in the atmosphere.

A study [2] on the necessary energy infrastructure which would reduce world power demand by 30% provides an apprehension of the scope of the necessary near-future installment. In simpler terms, it would largely come down to ~3,800 000 5 MW wind turbines, ~49,000 300 MW solar PV power plants, ~1.7 billion 3 kW rooftop PV systems, ~5350 100 MW geothermal power plants, ~270 new 1300 MW hydroelectric power plants, ~720,000 0.75 MW wave devices, and ~490,000 1 MW tidal turbines. Rare earth elements (REEs) are critical for their functions in many clean energy technologies, but many of these technologies use REEs that are at risk of supply disruption. For this reason, scientific research on the problems surrounding the supply side of these rare earth elements (REE) has recently bloomed. Concerns about tighter supplies that might increase costs for producing the necessary green technology take the “criticality” of some of these elements as a big warning sign.

In many papers, a cursory explanation of this criticality is given at most. In order to come up with management strategies that are able to help address the criticality of some of these elements, a scientific plausible picture should be given. The aim of this paper is do so by basing itself on a literature review of recent work.

Rarity, scarcity and criticality

Worldwide annual demand of some of the REE is currently not balance with their demand. Take Dysprosium (Dy) and Neodymium (Nd): in the absence of efficient reuse and recycling or the development of technologies, an increase of more than 2600% and 700%, respectively, over the next 25 years should be realized (following a path consistent with stabilization at 450 ppm).

Production of these elements has increased by only a few percent each year, with a short term 12 percent growth annually as an exception. According to the study, much higher increases in production will be necessary in order to meet the expected future demand[3]. However, according to another study, geological reserves of Nd and Dy will likely not deplete for many hundred years ahead [4]. Worldwide annual demand of REEs currently lies around 136,000 tons [5].

There is no firm definition of “rare earth elements”. According to the IUPAC definition, “rare earth metals” (REMs) or “rare earth elements” are a family of 17 elements in the periodic table. They start with lanthanum (La) and end with lutetium (Lu), called all together the “lanthanides group” [6]. During our literature review, we’ve found that the definitions are sometimes used interchangeably, while other studies strictly refer to only rare earth elements, or rare metals, or critical metals. For the purpose of clarity, this article will partly adopt the definition according to IUPAC, but it will only refer to rare earth elements, and not rare earth metals.

Rare earth elements are, despite of their name, not rare in absolute terms. Reserves are more than 800 times the current annual production of 130 000 tons, which is by far more than the reserves of most other elements[7]. Especially the light rare earth elements (LREEs) are quite common, extracted in an easier way than the heavy rare earth elements (HREEs). In most cases, the real problem is thus not their absolute concentration.

Answering to the need for more clarity on the scarcity of rare earth elements, several studies on rare earth elements have appeared in recent years. A scientific overview of these studies is largely lacking from the literature, and different studies list different reasons as a result. Furthermore confusing is that the term “criticality” lacks a consistent definition throughout the literature.

Criticality according to [8] can be divided in roughly two dimensions, i.e. the supply risks that may turn into supply disruptions and the vulnerability to such a supply disruption. Another study [9] adds the level of inherent vulnerability to this definition, stating that criticality is generally defined as a dynamic, multidimensional characteristic of materials. In other words, criticality in its meaning of “state of being critical” can refer to something as being vital, absolutely essential as well as to something that is verging on the state of emergency. At the same time, [10] notes that ‘criticality’ of rare materials is a term strongly influenced by national policy, being predominantly used in reports of governments or consulting organizations. The ecological, political, social, ethical and technical aspects of criticality can be furthermore considered. Indeed, the criteria used to term a metal “critical” can vary from study to study [11].

As scientific publications on demand, supply and need for REEs are rapidly increasing, we also see a growth of scientific articles that see recycling of REEs as a significant (secondary) supply option ([12, 13, 4, 14]. Other studies are more critical, such as [15] who found that during the next decade, recycling of neodymium is unlikely to substantially contribute to global REE supply security. Likewise, opening new mines and mineral/metal extraction and processing facilities alone will likely not be able to fully address current and future shortages of critical elements [16]. While conventional options would probably include a “mixed approach” that would probably see governments investing in recycling techniques, other less conventional approaches are also considered. For example, [16]proposes that oceans hold a great potential as sources of rare earth elements and critical metals, while the American company Planetary Resources hopes to use robots to prospect asteroids and gather rare earth materials within the next decade[17].

However, as[18] already noted, what is missing from the analysis is a *discussion of the supply constraints emanating from economic, political and environmental realities*. Moreover, decent insight in the domains and several multidimensional characteristics of criticality of individual and/or groups of rare earth elements seems to be largely missing, while it is highly crucial for a convincing case for upgrading REE recycling. In the following part a summary of current studies on

REE criticality is provided in order to come to a more balanced view of which REEs are critical according to which factors.

Criticality of REE's

Geological factors.

REE's are not really "rare". Johann Gadolin suggested the term "rare earths" 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, REEs have an earthy appearance [19]. Although most of the rare earths are not geographically rare, the supplies of some of them are running out. Reserves of indium (In) for example may be used up in 13 years [20]. An example of a relatively rare REE in geographical sense is promethium (Pm), the rarest REE, which was not identified until 1945 [21]. According to another source, the only elements that are really scarce and even difficult to find, are europium (Eu), thulium (Tm) and lutetium (Lu)[19]. According to another study, neodymium is one of the more critical rare earth elements with respect to current availability [22]. These factors can be termed geographical. In a sense, all REEs could be commonly listed as critical because of a geographical factor, because unlike other minerals, REEs are mined in groups. To produce neodymium, for example, lanthanum, a more common element, must also be produced. Their high dispersion throughout the earth's crust has resulted in only a handful of locations with high enough concentrations for economically viable mining operations [23, 24]. However, this first classification strictly points at absolute scarcity at a given time, although knowing the global availability of particular resources in the ground is far from an exact science, since estimates are made on imperfect data [18].

Economic factors.

The HREE's are generally more valuable as their known exploitable deposits in the earth's crust are scarcer in comparison with the LREE's. Due to the highest relative price increase over the past years, dysprosium is considered as one of the most critical rare earth element in the short term [25], whereby the status of "critical" is thus economically motivated.

Naturally, criticality factors can be combined, and criticality due to economic and geographic factors is quite common. As [19] emphasize, it can be very difficult to find economically exploitable deposits and simple methods of extraction and separation due to the very similar properties of REEs. The balance can quickly alter though. Since demand is not static due to the evolving resource needs of emerging technologies, mining a certain element might not always be economically viable, making the element scarce on the market [18].

Strategic factors.

Another criticality factor is strategic. The worldwide value of products containing REE was calculated to be at least 1.5–2 trillion dollars, nearly 5% of the global gross national product [26]. In combination with the unique properties of REEs[27] and general lack of alternatives for their application in modern technologies [28], their strategic status immediately becomes clear. Indeed have concerns over supply placed REE among the list of "critical" or "strategic" elements in countries such as the United States of America (USA), the European Union (EU), Japan and even in the largest producer and holder of reserves, China [29]. REE's have been the topic of international trade disputes following the announcement of 35% reduction in raw export by China in 2011, which subsequently led to WTO case DS394[25]. This case sharply highlighted how growing demand has recently led to supply concerns, especially in and amongst resource-importing high-tech countries in Europe and North America [30]. However, if no new economically viable ores can be found, China will exhaust its reserves of HREE in the next 15 to 20 years [31], providing new market options for other countries. For now, though, the concerns over the export limitations of 2011, the global REE price rises and the dominance of China have not yet cooled down. Current global supply of REE comes mainly from China (around 87%, although estimates also vary per study). The remaining 13% is supplied by the USA, Australia, India, Brazil, Malaysia, and other countries [4]. Antimony (Sb) and indium are two examples of REEs that are strategically critical[32].

Technological factors.

A fourth factor is technological. For most industrial metals, the loss during a life cycle is 20–50%—or more. In the case of the rare earth elements, the loss per cycle is typically nearer 100 per cent, with a few exceptions [11]. The recycling rate of all rare earth elements is below 1%, mainly due to technological problems, inefficient collection, and a lack of incentives [12]. These are unacceptable numbers. Unfortunately, recycling of REE is only in the begin stages and unless legislated, significant contributions to the supply of REE are not likely to happen. It could become more viable if prices that would lie closer to their real market value would become the market norm, or if recycling becomes mandated by governments. [33].

Environmental factors.

Finally, environmental factors over the extraction of REE's have sprung up recently. Negative effects of REE mining on humans include metal accumulation through crops consumption [34] and the entering of REE's through air [35], which can lead to growth inhibition, cytogenetic effects, and organ-specific toxicity [36]. It was furthermore pointed out that REE's are accumulated in blood, brain and bone after entering into the human body [37]. Silica dust, radioactive thorium, deadly waste and smuggling were mentioned as posing threats to human and environmental health in the REE production centre in Inner Mongolia [25]. Not all countries might be willing to open mines at the expense of their environment.

Conclusions

Just like natural and engineering sciences, the social sciences and humanities have great potential to tackle supply security problems of rare earth elements, e.g. by providing sustainable resource management and end-of-life strategies of products containing REEs.

There are several factors in which a certain REE is or can become critical, and these factors can vary per individual element, shaping a complex reality for which not one single sustainable resource management strategy seems overall applicable. There's a stringent need for better understanding of the differences in stakeholders and environmental effects in order to take the discussion to the next level.

Recent articles tend to focus on substitution, recycling and new discovery/new mines [38, 15, 26, 39]. However, other common options falling under sustainable resource management include reduction, reuse, recovery and remanufacturing. The extend to which these might provide an answer to criticality should be further explored.

As mentioned before, recycling rates of REEs are still low. The impact of recycling has been explored by a number of authors, but a robust and accepted understanding of the future potential of recycling does not yet exist [40]. According to [39], the low recycle rates suggest that the value that could potentially be recovered from recycling is insufficient to cover the cost to do so based on current technology.

Reduce strategies might be possible in the near future, when nanotechnology might be able to replace various REEs over the longer term in many of the current uses by emulating their properties and thus reducing their quantities needed [19].

Remanufacturing certain products to make some of their parts realizing higher recovery rates is already explored by certain companies. Modular phones are an example of remanufactured products with higher recovery rates of certain metals.

In sum, when designing management strategies, we should not lose track of the whole life cycle of products containing REEs. Recycling of REEs from end-of-life electrical waste for example might be a partial solution for the supply problem of some REEs, as well as for the e-waste stream that ends up in countries like China and Nigeria.

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