



Topic Insights

Rare Earth Permanent Magnets and Their Place in the Future Economy

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Due to their rising economic importance as an enabling technology for the energy transition from fossil fuels to renewables [1–3] and to their ubiquitous use in the miniaturization of electronic devices [2,4], permanent magnets are one of the key frontiers of technological development in the modern world.

Neodymium–iron–boron (Nd–Fe–B) (Coey, this issue; Liang et al., this issue) and samarium–cobalt (Sm–Co) (Coey, this issue; Liang et al., this issue) permanent magnets are at the forefront of new environmentally friendly technology developments, as are other rare earth magnet alloys (Insard and Kinast, this issue) and rare-earth-free/lean permanent magnets (Hadjipanayis et al., this issue; Kovacs et al., this issue; Rial et al., this issue).

Rare earth permanent magnets underpin the global adoption of wind turbine technologies [2,3] and of electric vehicles [1,2]. We sit on the cusp of a new global energy paradigm in which selected rare earth elements—rather than hydrocarbons—will help to “fuel” our future energy and transportation needs.

The use of rare earth permanent magnets in energy-transition technologies is clearly beneficial for the environment. However, concerns exist regarding upstream rare earth extraction methods, which can have negative environmental externalities—most notably, in the management of waste streams from the mining, processing, and separation of rare earth raw materials [5]. Nonetheless, while the ultimate societal impact of new-generation permanent magnet-based technologies is unknown, research in accelerating the adoption of rare earth and other permanent magnet-led technology continues to advance apace, and is the focus of this special issue of *Engineering*.

1. Recent changes in rare earths supply

Enabling a ready supply of rare earths at reasonable cost has already become a societal focus, with most rare earths being present on numerous “critical minerals” and/or “critical metals” lists issued by global and regional organizations [6]. A critical metal is a metal that has important economic uses, but also faces supply risks for geopolitical or sustainable development reasons [2,7]. For example, the concentration of rare earth mine production in China is seen as a geopolitical supply-risk factor for many

non-Chinese governments and industrial end-users [8], whereas the concerns surrounding radiation exposure at Lynas Corporation’s facilities in Malaysia are an example of a sustainable development (e.g., social and environmental)-related supply-risk factor [5]. Faced with such market constraints, the future potential for rare earths recycling [9–11] and thrifting or substitution [11] is becoming a clear research focus on the demand-side, with supply-side research aiming at the removal of one or more of the value-chain constraints in order to achieve greater, environmentally conscious, and “cleaner” rare earth procurement [12,13].

The rare earth elements, which number 21,39, and 57–71 on the periodic table, are not rare within nature, and are present in small concentrations within many rock types and on all continents [14–18]. In fact, they are about as abundant in the crust as the significantly more widely extracted base metals [12,19]. The known global resources and reserves of rare earth elements are relatively large, with the United States Geological Survey [20], for example, citing a figure of 1.2×10^8 t of known reserves—substantially more than the current mine production rate of 1.7×10^5 t·a⁻¹. This 706-to-1 ratio of production-to-known reserves compares favorably with other important industrial metals, such as copper, whose known reserves of 8.3×10^8 t and annual production of 2.1×10^7 t gives a ratio of 40-to-1 [21]. Such calculations also exclude the high likelihood of substantial further discoveries of mineral deposits, which has historically always been the case. In a Malthusian sense [22], the world will not “run out” of rare earths soon and, as such, the rare earths could potentially present a relatively sure footing upon which to build the new “green” economy, should the geopolitical and sustainable supply issues be overcome.

The above being said, the supply side of the rare earths industry remains complicated. First, although there are abundant rare earth resources, significant economic accumulations of rare earths where both the physical and chemical form and absolute concentration of rare earth minerals are sufficient to allow both extraction and processing to useable raw materials in an economically and an environmentally efficient manner are indeed rare [12,16,20]. Therefore, it has been pleasing to see the considerable advancement of our understanding of both the geology of rare earth deposits [14–17] and the required mineral processing techniques [23–27],

as well as significant further exploration efforts [18,28–30]. We have also seen the relatively successful development of a major new rare earth mine at Mount Weld in Western Australia, with associated separation facilities in Malaysia, all owned by Lynas Corporation [28,31]. In addition, there was a temporary—but ultimately failed—restart of the Mountain Pass mine in California [31]. Finally, there remains a relatively robust pipeline of rare earths mine projects, focused on both the light and heavy rare earths, all around the world, at different stages of development from exploration to feasibility study [14–18].

The other option for increasing rare earths supply is via secondary supply—that is, scrap supply, which is also known as recycling. At present, rare earth metals are essentially not recycled [9,32]; however, many efforts are underway to begin this process. Nonetheless, over the short to medium term, recycling cannot be the total solution we require. The minority economic status of rare earths means that we have mined relatively little of these metals, such that we could not sustain future demand based on even the most efficient recycling efforts. For example, the United States Geological Survey estimates that we have mined less than 3.3×10^6 t of rare earths since 1900 [33], which approximates all of the rare earths mined in history. This figure compares unfavorably with the known geological reserves of 1.2×10^8 t cited earlier [20], the current annual supply (and thus demand) of 1.7×10^5 t [20], and the current compound annual supply (and thus demand) growth rates of about 9.5% [20,33]. Furthermore, the difficulty in extracting rare earths for reuse from end-use product such as electronic goods means that much of these rare earths have been discarded to landfills or other very diffuse locations where end-of-life products end up [32]. Nonetheless, the present lack of recycling should not discourage investigations to increase rare earth recycling rates, such as the efforts by some authors in this special issue (Yin et al., this issue). Indeed, they suggest that increasing rare earth recycling rates is a matter of urgency. Again, by comparison, a “typical” industrial metal, such as copper, has a recycling rate of 33%, which is largely based on economic opportunity rather than on any specific environmental cause. With many governments expressing the desire to move to a recycling-based “circular economy” [34–39], rare earth recycling rates can only become a more urgent issue.

2. Recent changes in rare earths demand

Although rare earths are classified as critical metals, this has not been reflected in their prices in recent years, which have been historically low [30]. There are supply-and-demand reasons for these low prices. Most simply, on the supply side, the low prices are evidence of the widespread occurrence of the metals, as discussed above. From a demand perspective, the 2010–2012 price spike in rare earths [18,28–30], which was possibly among the greatest in commodity market history, led to significant demand destruction [28].

Rare earth demand statistics are extremely difficult to collate [30], so to illustrate the level of demand destruction, this article will use mine production data [33], making the reasonable assumption that rare earth secondary supply (from scrap) is still virtually nonexistent and that over longer time periods (such as a decade), the effects of stockpiling and “hardship” cancel out; thus, supply broadly equates to demand. With these assumptions, it is worth noting that in the ten-year period up to and including 2006, when rare earth prices were low, global supply (and assumedly demand) increased from 6.83×10^4 t·a⁻¹ in 1997 to 1.37×10^5 t in 2006—a 101% increase over the period [33]. The year 2006 represented a temporary period of peak production and demand, as rare earth prices began to increase, first

due to a broader commodities boom, and then specifically relating to the rare earths price spike from 2010 to 2012. However, ten years later, by 2015, production was 1.3×10^5 t—5% lower than in 2006, following the ructions of the price spike in 2010–2012 [33]. In the last few years, rare earths production (and perhaps demand) has increased rapidly to nearer 1.7×10^5 t·a⁻¹ [20]—an increase of nearly 25% in just a few years. There are clearly supply-side issues affecting these figures: first, the reduction of Chinese rare earth export quotas from 2005 [18,28,30]; and second, the start-up of Mount Weld from 2013 [28] and the start-up and closure of Mountain Pass between 2013 and 2015 [28]. However, it is clear overall that when the supply disappears, the demand disappears as well, and potentially vice versa.

It is unsurprising that close to the time of the price spike of 2010–2012, many research programs were launched around the Western world on the supply security, recycling, substitution, or thrifting of rare earths [40]. It is likely that we will continue to see the results of these efforts in the near future, as these research programs reach maturity; some are seen in this special issue. We have already seen the effective end of the use of rare earths as phosphors in lighting and displays, replaced by indium-based light-emitting diodes (LEDs) [28,41,42]. Although a direct link cannot be drawn between this demand change for rare earth phosphors and the 2010–2012 price spike, the price spike was likely a contextual factor. Overall, then, rare earths demand has not grown as robustly as was perhaps expected five to ten years ago [43].

The economic context for the use of rare earths is thus very different now, in comparison with just five years ago. Low prices make rare earths an affordable option for many technologies, and it is right that efforts should be directed toward end-use innovation, as many of the authors of the papers in this special issue do. A cheap and reliable supply of rare earths in the future will facilitate a much greater chance that the permanent magnet innovations discussed in this paper will enter the mainstream economy [32]. In addition, demand diversity is an under-recognized component of demand “creation” [32]. The largest metals markets are typified by broad demand patterns, with the metals being used across several key sectors, in several applications, and in thousands of products, utilizing several chemical or physical properties of the metal. For example, to the best of our knowledge, the largest demand sector for copper is the very broad category of “industrial equipment” (31%) [44], whereas the largest demand category for neodymium and dysprosium is the much more specific category of Nd–Fe–B magnets—at 76% and 100%, respectively [12,32]. Such diverse demand, as seen for copper, is critical for price stability, as is diverse supply. The innovations in this issue may help to stimulate this demand diversity by providing new and different uses for rare earth permanent magnets and, hopefully, beyond just magnets.

Nonetheless, the economically efficient use of rare earths in permanent magnets will continue to form one of the key downstream technological challenges, where the continuous improvement in permanent magnet performance, production efficiency, and sustainability has become a focus for research. Such factors can only serve to stimulate demand, whatever the supply-side conditions. Cost efficiency will remain a key focus of all stages of the rare earth value chain, as well as of the associated alloying metals that complement rare earth technologies, such as cobalt (Coe, this issue; Liang et al., this issue). Continuous cost improvements from “mine to magnet” will accelerate and bring forward permanent magnet demand and open new and emergent end-use markets, as indeed will stronger magnet performance and improved weight efficiency. On this note, we welcome a group of eight papers in this special issue of *Engineering*, which present some of the latest

research developments targeting an improved permanent magnet value chain.

In this issue, Coey discusses the perspective and prospects for rare earth permanent magnets, while reviewing the mineral economics of the rare earth elements and the historical development of permanent magnet technologies. Aside from the now-traditional deployment of permanent magnets in renewable energy and electric transportation, Coey identifies robotics as a major future end-use market opportunity as the automation of manufacturing processes gathers pace.

Yang et al. (this issue) discuss the structural and magnetic properties of nanocomposite NdFeB prepared by a rapid thermal processing technique. These authors propose that the performance of Nd₂Fe₁₄B/ α -Fe nanocomposite magnets will be further improved if a soft magnetic phase with a width in the critical dimension range can be formed to continuously surround the hard magnetic phase.

Liang et al. (this issue) investigate the structural properties associated with the magnetic anisotropy of amorphous Sm-Co films and highlight the significant potential for applications, both in information storage media and spintronic materials.

Yin et al. (this issue) investigate the potential for an efficient recycling process of Nd-Fe-B sludge for high-performance sintered magnets, with the aim of both reducing recycling cost and improving recycling efficiency at commercial scale.

Rial et al. (this issue) explore the optimization of magnet properties via alternative production processes for the rare-earth-free MnAl permanent magnet, with a focus on the relevance of nanostructuring and a short milling time to avoid high temperatures in the milling process.

Isnard and Kinast (this issue) provide a fundamental study of magnetic behavior with respect to temperature dependence through a neutron diffraction investigation of the DyFe₁₁Ti magnetic structure and its spin reorientations.

Kovacs et al. (this issue) report on a study of the computational design of rare-earth-reduced permanent magnets and present an overview on how the extrinsic magnetic properties of a virtual magnet, such as coercivity and energy density product, can be predicted from first principles including nanostructuring, grain boundary conditions, and (to a lesser extent) grain shape.

Finally, Hadjipanayis et al. (this issue) report on the use of ThMn₁₂-type alloys for permanent magnets and suggest that iron-rich compounds with the ThMn₁₂-type structure may address the demand for rare-earth-lean permanent magnets with high energy density.

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