

RARE EARTH ELEMENTS AND HIGH-TECH PRODUCTS

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Abstract

Rare earth elements are increasingly important for high technology products. The high-tech sector with the strongest demand for rare earths is the permanent magnet sector. Permanent NdFeB magnets are currently the strongest magnets on the market. The primary rare earths used for these magnets are Neodymium, Praseodymium (two “light” rare earths) and yttrium (a “heavy” rare earth). This paper discusses the main factors affecting the economics of rare earths in terms of supply and prices, as well as the high-tech applications that rely on rare earth magnets. The issue of rare earth recycling is discussed and also the inevitable reliance on primary (extracted) raw materials, given the strong increase of demand for rare earths and the duration of products in the economy, which significantly limits the relative contribution of end-of-life flows to supply through recycling. The latter emphasizes the importance of responsible supply, in particular from primary sources, which is one of the main action-areas of the circular economy.

Introduction

Within the list of mineral raw materials identified by the European Commission as “critical” for the EU (EC, 2017), rare earth elements (REE) are among those considered to present the highest levels of supply disruption risks, associated with high economic importance for the EU. Rare earth elements include the 15 Lanthanides (one of which is not stable; i.e., Promethium) and Yttrium. Rare earth elements are generally subdivided into light (LREE) and heavy elements (HREE) as follows (nomenclature adopted by EC, 2017):

- LREE: Cerium (Ce), Lanthanum (La), Neodymium (Nd), Praseodymium (Pr), Samarium (Sm) ;
- HREE: Dysprosium (Dy), Erbium (Er), Europium (Eu), Gadolinium (Gd), Holmium (Ho), Lutetium (Lu), Terbium (Tb), Thulium (Tm), Ytterbium (Yb), Yttrium (Y).

Due to their exceptional magnetic, luminescent, electrochemical and catalytic properties, REEs are essential to modern technologies. In its analysis of “raw materials for emerging technologies”, DERA (2016) identify magnets (Neodymium-Iron-Boron; NdFeB permanent magnets), electric vehicles and wind power as the primary emerging technologies that will dominate future demand for rare earths. While there has been emphasis on demand for energy storage (Nd and Pr for Nickel-Metal Hydride; NiMH batteries) and lighting (Y, Eu, Tb demand for fluorescent lamps), in recent years NiMH batteries have been largely replaced by lithium-ion batteries in electric and hybrid vehicles, laptop and desktop computers, etc. Between 2005 and 2015, the Li-ion battery market grew at a 14% compound average growth rate (CAGR; Avicenne Energy), at the expense of NiMH and NiCd batteries. In the lighting sector, fluorescent lights are progressively replaced by light-emitting diodes (LEDs) which use very small amounts of rare earths. LED lamps have significant advantages compared with fluorescent lamps: around twenty times more lumens are generated per gram of rare earth with a LED lamp than with a fluorescent lamp. The average lifetime of a fluorescent lamp is between 10 000 and 25 000 hours, compared with 40 000 to 50 000 hours for a LED lamp (Rollat et al., 2016).

Therefore, consistent with DERA (2016), the primary rare earth-consuming high-tech applications considered herein are in relation to permanent magnets. Other industrial sectors that use REEs but do not necessarily qualify as “high-tech” include catalysis, polishing powders, glass and ceramics, etc. This paper presents an overview of rare earth economics, discusses permanent magnet applications, potential recycling of rare earth elements from magnets and proposes some conclusions relevant to the application of circular economy concepts to rare earths.

An overview of rare earth economics

The geopolitical factor

The evolution of rare earth prices (Figure 1a and b) reflects major events in rare earth markets. The peak prices in 2011 seen in Figure 1 were the result of speculation linked to geopolitical tensions between China and Japan over ownership of the Senkaku Islands in the East China Sea. In reaction to this territorial dispute, China, which at that time was already responsible for 90% of the world REEs primary production, decided to reduce its export quotas of rare earth oxides (REO) and to stop exports to Japan. This triggered highly speculative reactions on trade markets. One result of the price hype was a realization by western governments of their vulnerability with respect to Chinese monopoly regarding mineral resource supply. In addition to rare earths, China is the main global producer of around 40 mineral raw materials, either at the mining stage or at the processing stage. Efforts at the European Union level regarding mineral criticality assessments can be linked pro parte to this particular event.

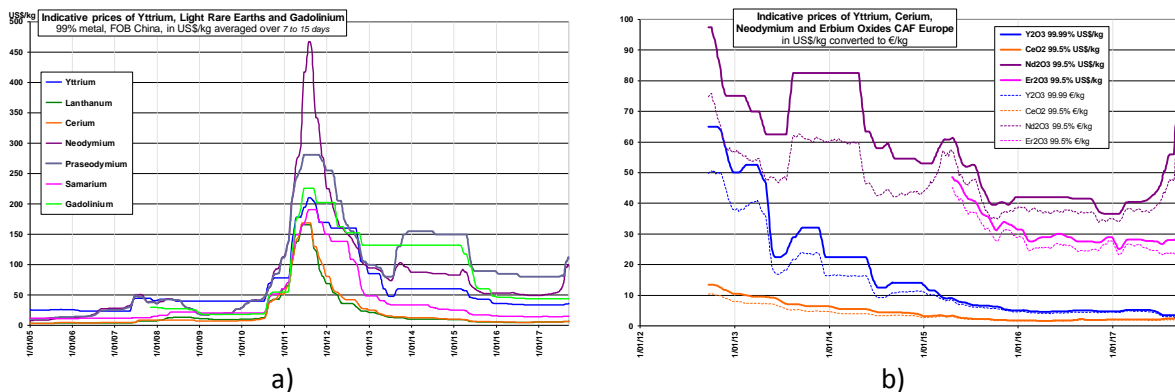


Figure 1 Evolution of rare earth prices from 2005 to 2018 (a) and since 2012 (b).

The technological factor

Following the 2011 price hype, prices subsided back to levels that are more in line with production costs, but prices have recently shown signs of revival (Figure 1b) in the case of certain rare earths that are used in NdFeB permanent magnets (Nd and Pr; +87% and +81% increase resp. between January and September 2017). These two rare earths have very similar properties and are closely associated in REO natural ores. According to D. Kingsnorth (IMCOA), rare earth oxide (REO) consumption in the permanent magnet sector increased from 24 000 tons in 2012 to 50 000 tons in 2016, thus representing 31% of global demand compared to 20% in 2012 (Figure 2).

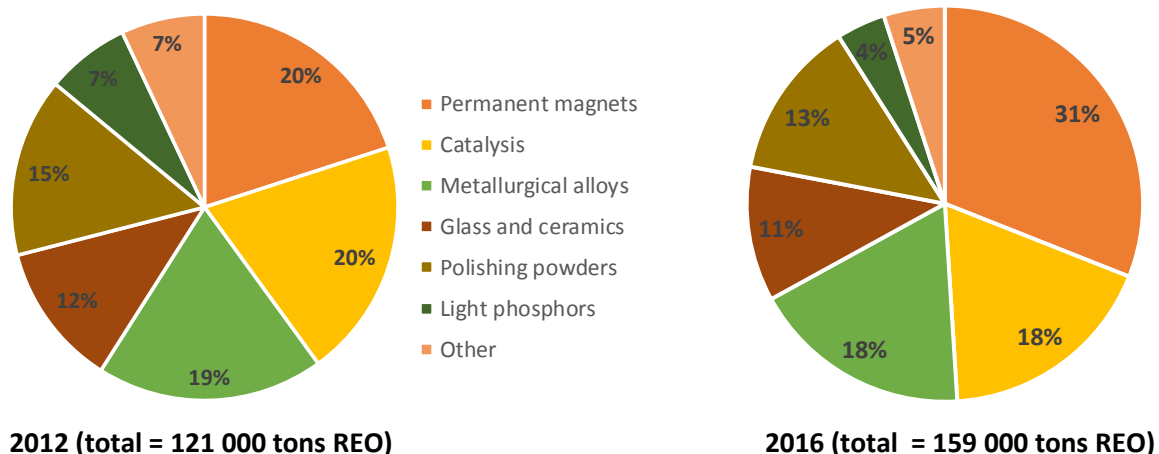


Figure 2 Evolution of REO consumption between 2012 and 2016 by industrial sector (Source: Roskill, 2015; IMCOA, 2017)

The substantial increase of rare earth consumption for permanent magnets is a consequence of the increasing number of technologies that use these magnets; from electric and hybrid vehicles to computer laptops and desktops, hard disk drives and renewable energy (especially wind power). As mentioned in the introduction, several other sectors have seen their consumption decrease (lighting and energy storage). In the near to intermediate future, the demand for REO (Figure 3) will be dominated by the development of permanent magnets. While this has affected the prices of the “light” rare earths; Nd and Pr, the heavy rare earth Dy has not been influenced because its use for increasing the Curie temperature in permanent magnets has been limited by its high price.

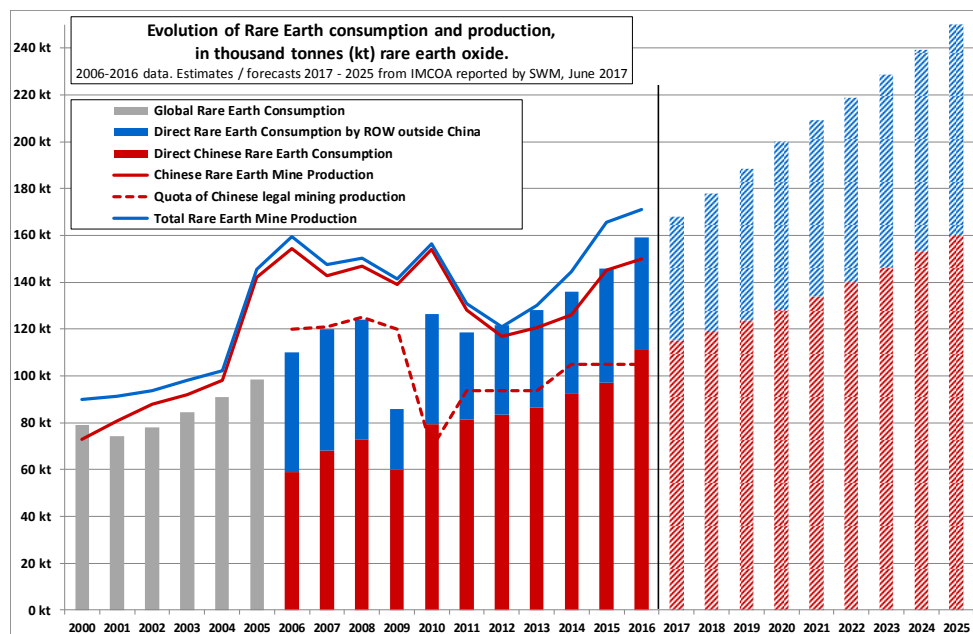


Figure 3 Historical and projected consumption of REO (Source: IMCOA, 2017).

The geological factor

As mentioned above, Nd and Pr are “light” rare earths. Even though most deposits contain all rare earth elements, the concentration of REEs varies with each type of mineralization but also between each individual ore body. Deposits that are relatively rich in light rare earths are much more common than deposits that are rich in heavy rare earths (currently limited to ion-exchange clays in southern China). Hence the higher prices of heavy rare earths. A typical distribution of rare earths in an average ore is: 50% Ce, 20-25% La, 12-20% Nd and 4-5% Pr. Following extraction, separation processes are used to produce individual REO. This distribution of rare earths in ores generates an imbalance between rare earth supply and demand (see, e.g., Binnemans et al., 2013): in order to obtain one ton of Nd, approximately two tons of Ce and at least as much La must be produced, which leads to an over-supply of Ce and La and directly affects prices. As emphasized by Binnemans et al. (2013), one solution to the imbalance problem is to recycle rare earths for which there is a strong demand, from end-of-life products (see below).

The fact that China provides more than 90% of global rare earth production is not entirely attributable to its geology. According to various estimates, the share of China in terms of rare earth geological resources is between 50 and 60% (Bru et al., 2015). There are currently many rare earth mining projects located outside China (Table 1).

Table 1 Main rare earth mining projects (not yet in operation) located outside China in 2017 (source: SNL)

Country	Project	Company	Production objective (kt REO/yr)	REO grade	Deposit type	Projected start date	Capex (M \$US)	Web site
Australia	Browns Range	Northern Minerals	3,25	0,63%	Hydrothermal	> 2018	314	http://northernminerals.com.au
Australia	Dubbo	Alkane Resources	4,9	0,89%	Alkaline igneous	2019	840	www.alkane.com.au
Australia	Nolans Bore	Arafura Resources	14	2,78%	Hydrothermal	> 2019	680	www.arultd.com
Australia	Yangibana	Hastings Technology Metals	5,5	1,27%	Carbonatite	2019	405	www.hastingstechmetals.com
Burundi	Gakara	Rainbow Rare Earths	5	54,30%	Seams	2017	10	http://rainbowrareearths.com
Malawi	Songwe Hill	Mkango Resources	2,8	1,60%	Carbonatite	2021	217	www.mkango.ca
Tanzania	Ngualla	Peak Resources	10,1	4,55%	Carbonatite	2019	400	www.peakresources.com.au
Greenland	Kvanefjeld	Greenland Minerals and Energy + Shenghe Resources	22,9	1,08%	Alkaline igneous	> 2018	1361	www.ggg.gl
Canada	Ashram	Commerce Resources Corp	16,9	1,88%	Carbonatite	N.A.	759	www.commerceresources.com
South Africa	Steenkampskraal	Steenkampskraal Thorium	5	14,90%	Hydrothermal	N.A.	119	www.thorium100.com
Madagascar	Tantalus	Tantalus Rare Earth AG	?	0,08%	Alkaline igneous	Suspended	?	www.tre-ag.com
Sweden	Norra Kärr	Leading Edge Materials	5,1	0,59%	Alkaline igneous	Suspended	378	http://leadingedgematerials.com

In Europe, the Swedish Norra Kärr project reports potential geological resources of around 33 000 tons Neodymium (metal), 12 000 tons Dysprosium and 90 000 tons Yttrium. But this project was suspended in 2016 by a decision of the Swedish Supreme Administrative Court, on the basis that potential environmental impacts of the projected mining facilities had not been sufficiently taken into account.

Also, the economic viability of rare earth mining projects outside China is jeopardized by fierce competition on prices, in particular due to Chinese exports from illegal mining activities (following the sources, Chinese rare earth output in 2016 from illegal mining was somewhere between 45 000 and 95 000 tons). Low prices explain why the Mountain Pass mine (Molycorp, US) had to file for bankruptcy in June 2015. The only other rare earth mine currently in activity outside China is the Mount Weld mine in Australia. This mine maintains its activity despite Chinese competition thanks to “off-take” contracts

between the owner (LYNAS) and Japanese industrial companies, whereby these companies guarantee a certain price for the mine's production.

The environmental factor

China's high share of rare earth production compared to its share of geological resources is explained in part by the lower environmental standards of Chinese extraction activities as opposed to mines in, e.g., western countries. But it is also the result of the poor "Social License to Operate" of the extractive industry in many western countries. This is particularly true for Europe, where surveys (see EC, 2016) show a low level of trust by the general public for mining and oil & gas industry companies, as compared to countries like China, Brazil, India, etc. However, with the development of a middle class, expectations with respect to environmental standards are also increasing in China. In 2017, an increased awareness of environmental issues brought Chinese authorities to enforce anti-pollution measures that led to the closure of several mines and a periodic shutdown of several metallurgical plants. Chinese authorities have expressed their aim to clamp down on illegal rare earth mining, which has had an influence on prices. According to the Chinese ministry of industry and technology (MIIT), China intends to limit its rare earth production to 140 kt in 2020 and its rare earth separation capacity to 200 kt.

The poor perception of the extractive industry by the general public in western countries jeopardizes the ability to offset the effects of Chinese monopoly. But the attitude of the general public in many European countries (e.g., France), is somewhat paradoxical. The public wants to benefit from the multiple high-tech applications that use rare earths (in particular magnets in, e.g., hard disk drives, portable phones, laptops and desktops, electric and non-electric vehicles, headphones and earphones, printers, scanners, etc.) but does not want the associated extractive activity. Recycling is often cited as the alternative to extraction but, as will be shown in section 4, recycling can only provide part of the solution.

High-tech applications of rare earths

As mentioned above, the primary rare earth application used in high-tech products is permanent NFeB magnets. These magnets are the most powerful on the market today. A measure of the strength of a magnet is its energy density (in Megagauss-Oersted; MGOe). Current NdFeB magnets have energy densities on the order of 60 MGOe, compared with, e.g., 7 MGOe in the case of AlNiCo magnets. Such high energy density has allowed the miniaturization of, e.g., electronic equipment. As indicated in Figure 4, current research on new magnet technologies such as iron nitride magnets might supplant rare earth magnets in years to come. The theoretical magnetic energy density for an iron nitride (Fe₁₆N₂) magnet is 130 MGOe, i.e., more than twice the maximum reported magnet energy density for a NdFeB magnet.

Rare earths used for the production of NdFeB magnets are primarily Nd and Pr, with some Dy and Tb. The global proportions of Pr, Nd, Tb and Dy in NdFeB magnets are on average 5%, 20%, 1%, 5% (gram REE per gram magnet) respectively. Dysprosium (or Tb) is added to NdFeB magnets to increase the Curie temperature, i.e., the temperature at which they lose their magnetic properties. Following the service temperature for which an application is designed, the magnets will require more or less Dy. For example in hard disk drives (HDDs), CD players and headphones, the proportion of Dy in magnets is between zero and 2% (gram Dy per gram magnet), while in hybrid electric motors it is closer to 10%. Due to the relatively high price of Dy, considerable research has been devoted to optimizing the quantities of Dy in magnets, while some manufacturers prefer to modify their technology in order to completely eliminate the need for Dy. For example Siemens, who aims world leadership in off-shore

wind power, announced in 2014 that it had developed new wind power generators without any Dy, by integrating a cooling system. According to certain authors approximately 14% of wind turbines are direct drive turbines that use NdFeB magnets. According to Castelloux (2014), the average Dy weight content in magnets should decrease from 2.3% in 2014 to around 1.9% in 2020.

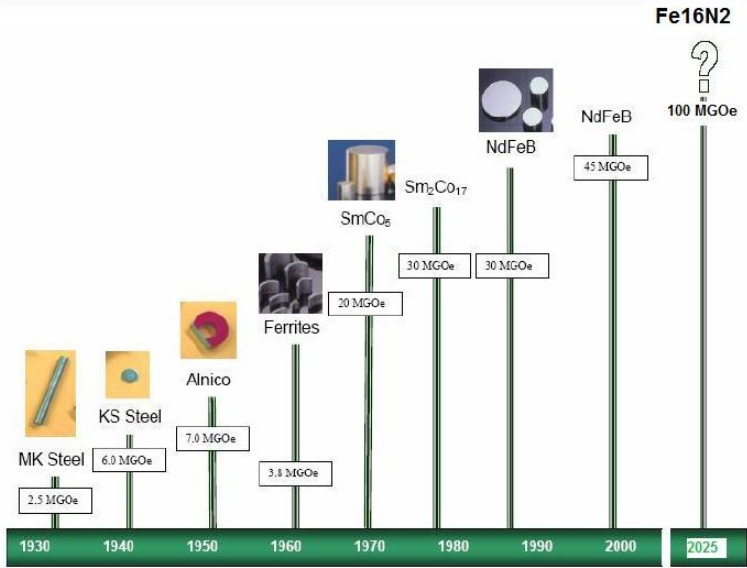


Figure 4 Different magnet technologies compared in terms of energy densities (in MGOe). (Source: leblogenergie)

Rare earth permanent magnets are gaining momentum in the electric vehicle market. For example in August 2017, the company Tesla Motors announced its intention to equip its Long Range Model 3 electric vehicle with NdFeB permanent magnets. Tesla’s decision to move away from alternative current (AC) induction motors was motivated by the fact that AC induction motors are larger, heavier, and less efficient, resulting in more draw on the lithium-ion battery pack compared to a permanent rare earth magnet motor. Tesla Motors initially chose the induction motor instead of the permanent magnet motor due to the high REE prices when its first electric vehicle was developed (the Model S). But as REE prices have fallen considerably since 2011, Tesla considers that the benefits of rare earth permanent magnet motors far exceed the elevated cost compared to the AC induction motor. The amount of Nd required per vehicle is on the order of 0.75 - 1.7 Kg. As Tesla plans to produce around 9.4 million vehicles of this type by 2020, the Nd requirement would be between 7 000 and 16 000 tons Nd metal for the requirements of this specific vehicle alone.

With respect to wind power, the generator of a 1 MW nominal power wind turbine can contain on the order of 600 Kg of NdFeB magnets (Zepf, 2013) with around 165 Kg Nd and 30 Kg Dy. The Indian government has recently announced its objective of reaching 175 GW energy production from renewable energy sources by 2022 (compared with 57 GW produced in 2017), with 60 GW energy production from wind power energy installed by the Danish company Vestas, which relies partly on NdFeB permanent magnets.

In a longer-range outlook, rare earths could be at the center of energy production from nuclear fusion. Scientists from MIT have recently announced that a collaboration between scientists at MIT and a private company will be able to transform fusion from an expensive science experiment into a viable commercial energy source and will put fusion power on the grid within 15 years. The technology relies on a newly available superconducting material: a steel tape coated with yttrium-barium-copper

oxide (YBCO) which has allowed scientists to produce smaller, more powerful magnets used to confine the plasma needed for the fusion reaction.

Recovery of rare earths: opportunities and limits

Rare earth recycling

Recycling of rare earths from end-of-life products presents several significant advantages as it:

- avoids many of the environmental emissions associated with primary ore extraction and processing; in particular emissions associated with radioactive elements (Thorium, Uranium) that are typically associated with rare earth deposits;
- helps address the balance problem presented above;
- provides a certain level of self-sufficiency to countries that do not have primary ore deposits.

While recycling operations for rare earth recovery from phosphors in fluorescent lamps are in operation or have existed in the past, the focus here is on rare earth magnets. It is worth noting however that the phosphor recycling operation that Solvay initiated in 2012 at its plant of Saint-Fons (France) was stopped in 2015 because it wasn't economically viable. This was due, on the one hand, to the low rare earth prices, but also to an insufficient fluorescent lamps collection rate.

A simplified recycling flow sheet for REE magnets is presented in Binnemans et al. (2013) which considers three different material flows: (i) swarf originating from magnet manufacturing, (ii) small magnets in end-of-life consumer products and (iii) large magnets in hybrid and electric vehicles or wind turbines. The authors underline that the re-use of magnets in their current form/shape is only possible for large, easily accessible magnets used in wind turbines or large electric motors in hybrid and electric vehicles. They provide an overview of different recycling methods for REE magnets, including hydrometallurgical and pyrometallurgical methods, each with their pros and cons, but underline that most efforts for REE recycling from magnets are still at an R&D lab scale stage, due essentially to technological difficulties.

BRGM is among the research groups currently working on ways to recycle rare earth magnets in WEEE (waste electrical and electronic equipment). Results of the Extrade project (Menad et al., 2016), supported by the French Science Agency (ANR), suggest that the best way to reduce the time of manual disassembly of the electronic devices containing NdFeB-type magnets is to recover the magnets still stuck on the stainless steel carrier at the stage of downstream valorization. Thermal treatment experiments show that the majority of the magnets present in the three investigated electronic devices (Figure 5) lose their magnetic properties when reaching the Curie temperature of 300-400°C in 15 to 20 minutes.

Pilot-scale trials on mechanical dismantling of hard-disk drives to recover the magnets yielded encouraging results: more than 87% of magnets were released without pulverizing them. For materials completely encased in metal, liberation of the magnets was difficult. While the initial energy required to "break in" to the casing and loosen it may be high, once liberation is initiated, it tends to propagate rapidly. Any exposed components are then quickly broken down, especially liberating plastic from metal. Physical and chemical techniques were developed to extract the magnet coating. Dissolution test results with weak acids showed that magnet-alloys were dissolved in 7 hours while the Ni or Zn coatings were not attacked. Oxalic acid was used to precipitate rare earths as oxalates, with an oxidation at 500 to 600°C (Seron et al., 2017).

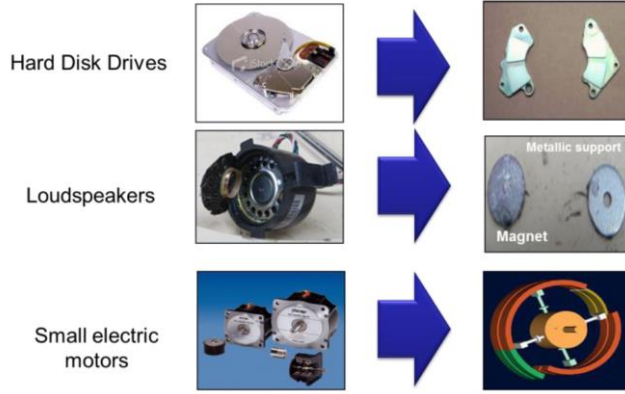


Figure 5 Electronic devices containing rare earth magnets studied as part of the Extrade project (Menad et al., 2016)

Limits to the contribution of rare earth recycling to supply

As illustrated by previous authors, there are thermodynamic limitations to multiple recycling cycles, as elements may be increasingly diluted and lose their functional properties. Other limitations include the efficiency and costs of end-of-life product collection schemes, the costs associated with the disassembly of products and constraints associated with recycling processes. But there is an additional constraint that is sometimes misunderstood by decision-makers and the general public and is related to the dynamic nature of the flows and stocks which constitute the “Urban Mine”. A fundamental difference between primary (extracted) and secondary (reused, recycled, ...) resources is that in the first case we address stocks (geological stocks in the subsurface) while in the second case we primarily address flows (end-of-life product flows). Flows are dynamic by nature and the dynamics must be taken into account for a realistic assessment of the potential of secondary resources in terms of their contribution to supply. The dynamics of demand for rare earths are one factor, while another one is the lifetime of products (which contain these metals) in the economy (in-use). It is worth reminding that before a product can become a recycled resource, it first has to be discarded.

This effect of value chain dynamics is particularly acute in the case of mineral raw materials for which demand is strongly increasing, as is the case for REEs. Historical mine production data from USGS suggest an annual growth rate of global REO mine production since the nineteen-sixties between 6% and 7% (with a lull over the period 2007-2012 in relation with the financial crisis). Let us assume that supply grows at a constant rate (noted α). If we know supply (noted s_0) at a given time (noted t_0), supply at any time “ t ” is given by:

$$S(t) = s_0(1+\alpha)^{t-t_0} \quad (1)$$

The flow of REEs from end-of-life (EOL) products at time “ t ” is equal to supply at time “ $t-LT$ ”, where LT is the lifetime of the products in the economy (assumed here to be homogeneous for the sake of simplicity):

$$EOL(t) = s_0(1+\alpha)^{t-t_0-LT} \quad (2)$$

The flow of recycled metal (Rec) takes into account the recycling rate (noted β):

$$Rec(t) = \beta s_0(1+\alpha)^{t-t_0-LT} \quad (3)$$

Therefore the relative contribution of recycled materials to supply is (RC):

$$RC = Rec(t) / S(t) = \beta / (1 + \alpha)^{LT} \quad (4)$$

Equation (4) depends only on the recycling rate, the supply growth-rate and the lifetime of products in the economy. It is illustrated in Figure 6 for a supply annual growth rate of 6% and for end-of-life recycling rates indicated along the y-axis (product lifetime = 0). Figure 6 shows for example that if the product lifetime is 20 years (as for, e.g., wind turbines; Rademaker et al., 2013), then the maximum contribution from recycling these end-of-life products cannot exceed around 40% of supply, even assuming a 100% recycling rate (which is unrealistic). The other 60% required for supply can only come from primary (extracted) sources, either produced domestically or else imported.

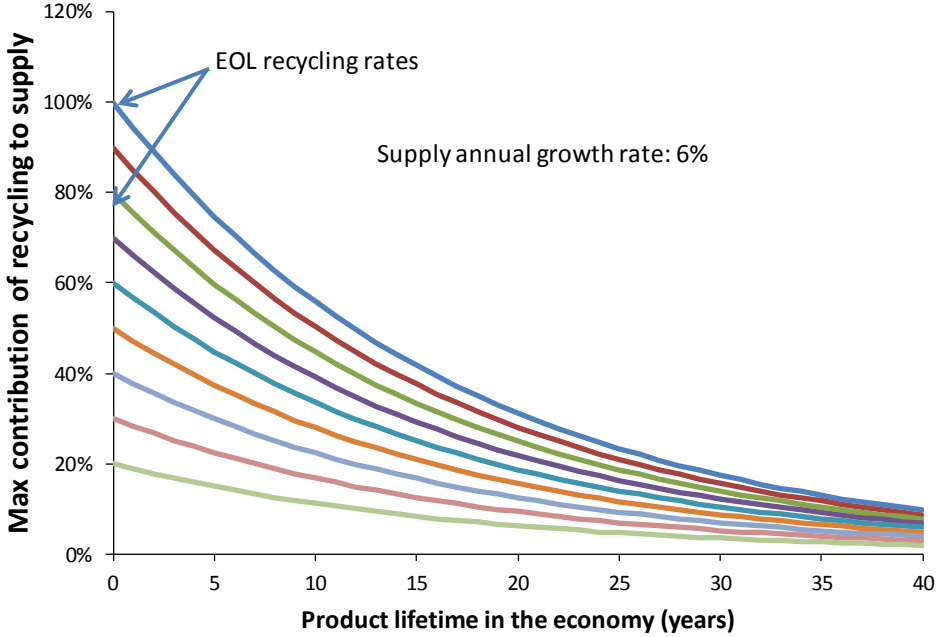


Figure 6 Maximum contribution of recycling to demand, as a function of EOL-RR and product lifetime, for a fixed demand annual growth rate of 6%

This effect of lifetime in the economy explains why the potential supply of Neodymium from recycled sources in Europe is expected to “pick-up” only after 2030, with the magnets from wind power generators entering end-of-life streams (Rademaker et al., 2013).

Conclusions

While rare earths are essential for certain high-tech products, a distinction should be introduced to distinguish those rare earths that enter the composition of permanent NdFeB magnets. In that respect the most important rare earths today are Nd, Pr and Dy. Terbium can be used in place of Dysprosium, but the current price of Tb is nearly 3 times higher than that of Dy. While future technologies may generate an increased demand for other rare earths, it should be reminded that industry adapts to scarcity and to high prices by reducing its needs and by substituting one element for another. For example, Gadolinium would be in high demand if there were a market for Gd-magnet refrigerators. But because of the low-level of Gd global supply (on the order of a couple of thousand tonnes per year), such technology is very unlikely to “take off”, despite its efficiency.

With respect to recycling, significant progress is needed in order to increase the recycled content of magnets above a few percent, as is currently the case. But whatever the progress in this area, the extraordinary increase in demand for rare earth magnets (associated with, e.g., the energy transition), combined with the lifetime of products in-use, implies that European supply will necessarily have to

rely on primary raw materials (extracted). These materials will either be extracted from European sources, as suggested by the 2nd pillar of the European Raw Materials Initiative (EC, 2008), or else imported; often from countries that apply much lower environmental standards than in Europe. The latter is in contradiction with the principles of the Circular Economy (Figure 7), which highlight the importance of sustainable supply as part of the action-area “Supply from economic actors”. This stresses the importance of responsible mining; in particular of environmental management all along the mine life cycle. The latter is one of the focuses of the EIT (European Institute of Technology) on Raw Materials.

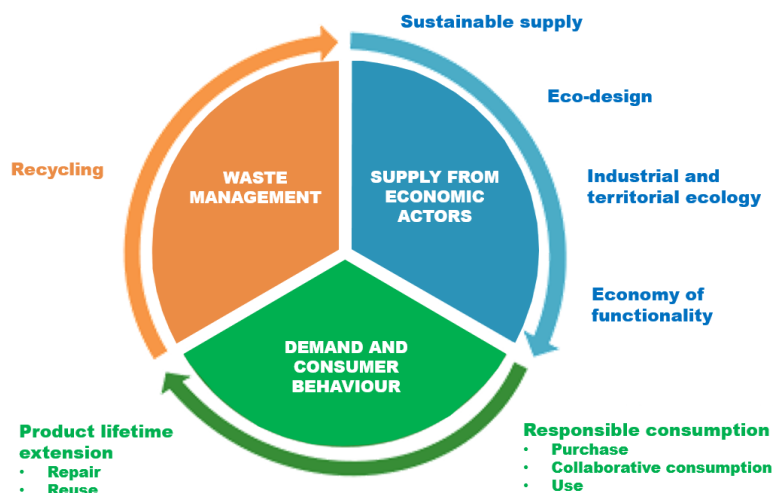


Figure 7 Principles of the circular economy according to the French Environmental Agency (ADEME, 2014): 3 action-areas and 7 pillars.

Conclusions:

The analysis presented above suggests the following:

- ▶ In the foreseeable future, the consumption of rare earths will be driven by demand for rare earth permanent magnets. These magnets are essential in the context of the energy transition.
- ▶ In terms of supply risks, the issue is “access to rare earths” rather than “geological scarcity”. Access is influenced by a variety of factors that are primarily geopolitical, economic and social (the extractive industry’s social license to operate).
- ▶ While it is essential to recycle in the context of the circular economy, it should be more widely recognized that if demand is increasing, as is the case for rare earths but also for a wide variety of other specialty and base metals, recycling can only provide part of the solution. The reliance on primary (extracted) mineral resources is inevitable (whether from domestic extraction or from imports).

Recommendations:

- ▶ Europe should take more responsibility for its own requirements in terms of mineral resources. Progress is required with respect to the sustainable supply of mineral raw materials. The particular issue of mining waste management remains extremely sensitive.

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