

Rare Earth Elements—End Use and Recyclability



Scientific Investigations Report 2011–5094

Front Cover. Photograph of the Molycorp, Inc's Mountain Pass, Calif., mine. The Mountain Pass mine is one of the two largest rare earth mines in the world outside of China. Photograph by Dan Cordier, U.S. Geological Survey.

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By Thomas G. Goonan

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Conversion Factors

Multiply	By	To obtain
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)
kilogram (kg)	32.1507	ounce, troy
megagram (Mg); metric ton (t)	1.102	ton, short (2,000 lb)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$^{\circ}\text{C}=(^{\circ}\text{F}-32)/1.8$$

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By Thomas G. Goonan

Abstract

Rare earth elements are used in mature markets (such as catalysts, glassmaking, lighting, and metallurgy), which account for 59 percent of the total worldwide consumption of rare earth elements, and in newer, high-growth markets (such as battery alloys, ceramics, and permanent magnets), which account for 41 percent of the total worldwide consumption of rare earth elements. In mature market segments, lanthanum and cerium constitute about 80 percent of rare earth elements used, and in new market segments, dysprosium, neodymium, and praseodymium account for about 85 percent of rare earth elements used. Regardless of the end use, rare earth elements are not recycled in large quantities, but could be if recycling became mandated or very high prices of rare earth elements made recycling feasible.

Introduction

Rare earth elements (REEs) are not particularly rare in terms of abundance, but for many years remained rarely separated from each other owing to their similar chemical characteristics (Hurst, 2010). Although REEs (which are also known as the lanthanide series in the periodic table of elements) are widely distributed geographically, they are chiefly mined, concentrated, and separated in China. Semifabrication also takes place in China, so China is important to world production on several levels. The manufacture of assemblies that contain REEs is more broadly distributed.

World mine production of rare earth oxides (REOs) grew rapidly (about 7 percent per year) from 1990 through 2006 before decreasing in 2007 owing to worldwide economic conditions, with growth increasing but at a slower pace after 2007 (fig. 1). The growth in REO production directly correlates to the growth in REO consumption, which, in turn, has been tied to the general economic growth for the historic uses of REOs (catalysts for fluid cracking and catalytic converters for automobiles, glass and metallurgical industries, and phosphors) and the increase of high-technology uses tied mainly to alternative energy systems (such as batteries for hybrid cars) and permanent magnet applications for electric motors, stereo speakers, and wind turbine generators.

The U.S. Geological Survey is not a “principal statistical agency” and does not have a mandate to routinely collect end-use data from primary sources. End-use data are collected and (or) developed from and attributed to private communications with experts, published and Web site materials, and other third party sources. In this report, the tables and figures for REO end use by selected sectors are based on data in Bade (2010). REE statistics are usually reported as REO equivalents. The REE-to-REO ratio for each of the REEs is about 1:0.85. This makes the relative fractions of REOs in the end-use table closely approximate the relative REE end use (table 1). Regardless of the shortcomings of single-source data, the data in this report present a reasonable first approximation of the distribution of worldwide REO consumption by end use. Quantity data as detailed in this report are rounded to no more than three significant digits, and percentages are rounded to no more than two significant digits.

End Uses For Rare Earth Elements

In 2008, 129,000 metric tons (t) of REOs was consumed worldwide (Cordier and Hedrick, 2010). Mature applications (catalysts and the glass, lighting, and metallurgical industries, sectors that grow at the rate of growth for the general economy) consumed about 60 percent of the total, and the remaining 40 percent was consumed in developing, high-growth technologies (battery alloys, ceramics, magnets, and other sectors that grow at 4 to 10 percent per year) (Bade, 2010).

The distribution of REO consumption by type is not homogeneous among market sectors (table 1). However, REO consumption is split rather evenly among the following applications: glass industry (polishing, 68 percent; additives, 42 percent), 28,400 t; catalysts (fluid cracking, 72 percent; catalytic converters, 28 percent), 27,400 t; neodymium-iron-boron magnets, 26,300 t; metallurgy and alloys, 23,600 t; and other uses, 23,500 t (fig. 2; table 2). Figure 2 shows the distribution of REOs from end uses to the consumer product reservoir to various modes of disposition. Estimates are based on assumptions about previous production and consumer product life. There are no estimates for manufacturer-generated scrap. The estimates in figure 2 should not be taken as definitive because they are based on incomplete and anecdotal

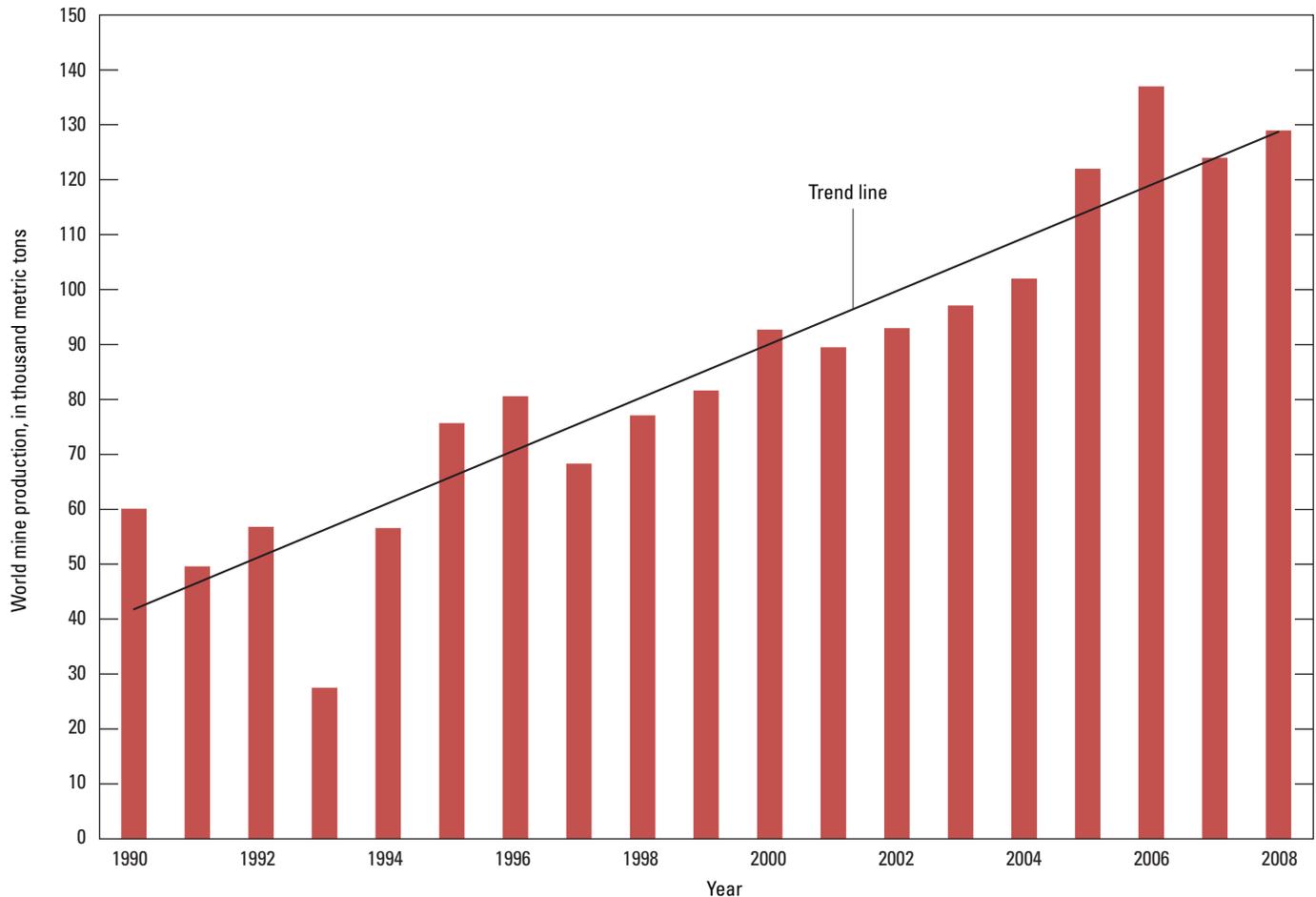


Figure 1. Chart showing world mine production of rare earth oxides from 1990 through 2008. Data are from Hedrick (1996–2009) and Cordier and Hedrick (2010).

information. What is important about disposition is that there is currently very little recycling of REOs. This suggests that the value of REOs that could potentially be recovered from recycling is insufficient to cover the cost to do so based on current technology, and possible future shortages that could cause sustained higher prices for these materials can likely be mitigated by this recycling potential. Indeed, Hitachi Ltd. of Japan is exploring recycling of REEs in response to Chinese REO export limitations (Clenfield and others, 2010). Kosaka Smelting and Refining (a subsidiary of Dowa Holdings) is in the process of developing the means to reclaim rare earths from electronic scrap (Tabuchi, 2010; Fast Company, 2011).

Mature Market Sectors

The mature REO end-use markets (catalysts, glass industry, metallurgy excluding battery alloy, and phosphors) consume mainly cerium (45 percent), lanthanum (39 percent), and yttrium (8.0 percent) oxides. Dysprosium, gadolinium,

neodymium, and praseodymium oxides and other REOs contribute the remaining 7.0 percent of total REOs consumed in these sectors.

Catalysts

Fluid cracking is one process in petroleum refining that converts a heavy hydrocarbon input into lighter hydrocarbon fractions. Fluid cracking depends on the control of temperature and pressure conditions and the presence of a suitable catalyst, which provides active physical reaction sites on which the desired reactions can take place. The catalyst is based on zeolite, a molecular sieve that has a great amount of reactive area within its own mineral structure. The zeolite is dealuminized, which increases the silicon-to-aluminum ratio but weakens the structure of the mineral. The former aluminum sites in the zeolite are repopulated with REOs through an ion exchange process. REO concentration in catalysts varies between 1.5 and 5.0 percent by weight and averages about

Table 1. Estimated worldwide end uses for rare earth elements in 2008, by amount of rare earth oxide in end use.

[Values are in metric tons of rare earth oxides and are rounded to three significant digits. Percentages are rounded to the nearest decimal. Values may not add to totals shown owing to independent rounding. CeO₂, cerium oxide; Dy₂O₃, dysprosium oxide; Eu₂O₃, europium oxide; Gd₂O₃, gadolinium oxide; La₂O₃, lanthanum oxide; Nd₂O₃, neodymium oxide; Pr₆O₁₁, praseodymium oxide; SmO, samarium oxide; Tb₆O₇, terbium oxide; Y₂O₃, yttrium oxide; REO, rare earth oxide; —, no consumption]

End uses	CeO ₂	La ₂ O ₃	Nd ₂ O ₃	Y ₂ O ₃	Pr ₆ O ₁₁	Dy ₂ O ₃	Gd ₂ O ₃	SmO	Tb ₆ O ₇	Eu ₂ O ₃	Other
	Quantity used, in metric tons										
Automobile catalytic converters	6,840	380	228	—	152	—	—	—	—	—	—
Ceramics	840	1,190	840	3,710	420	—	—	—	—	—	—
Fluid catalytic cracking	1,980	17,800	—	—	—	—	—	—	—	—	—
Glass additives	7,920	2,880	360	240	120	—	—	—	—	—	480
Metallurgy, except batteries	5,980	2,990	1,900	—	633	—	—	—	—	—	—
Neodymium magnets	—	—	18,200	—	6,140	1,310	525	—	53	—	—
Battery alloys	4,040	6,050	1,210	—	399	—	—	399	—	—	—
Phosphors	990	765	—	6,230	—	—	162	—	414	441	—
Glass polishing	10,700	5,170	—	—	574	—	—	—	—	—	—
Other	2,930	1,430	1,130	1,430	300	—	75	150	—	—	75
Total	42,200	38,700	23,900	11,600	8,740	1,310	762	549	467	441	555
Percentage of total REOs used											
Automobile catalytic converters	90.0	5.0	3.0	—	2.0	—	—	—	—	—	—
Ceramics	12.0	17.0	12.0	53.0	6.0	—	—	—	—	—	—
Fluid catalytic cracking	10.0	90.0	—	—	—	—	—	—	—	—	—
Glass additives	66.0	24.0	3.0	2.0	1.0	—	—	—	—	—	4.0
Metallurgy, except batteries	52.0	26.0	16.5	—	5.5	—	—	—	—	—	—
Neodymium magnets	—	—	69.4	—	23.4	5.0	2.0	—	0.2	—	—
Battery alloys	33.4	50.0	10.0	—	3.3	—	—	3.3	—	—	—
Phosphors	11.0	8.5	—	69.2	—	—	1.8	—	4.6	4.9	—
Glass polishing	65.1	31.4	—	—	3.5	—	—	—	—	—	—
Other	39.0	19.0	15.0	19.0	4.0	—	1.0	2.0	—	—	1.0
Total	32.7	29.9	18.5	9.0	6.8	1.0	0.6	0.4	0.4	0.3	0.4

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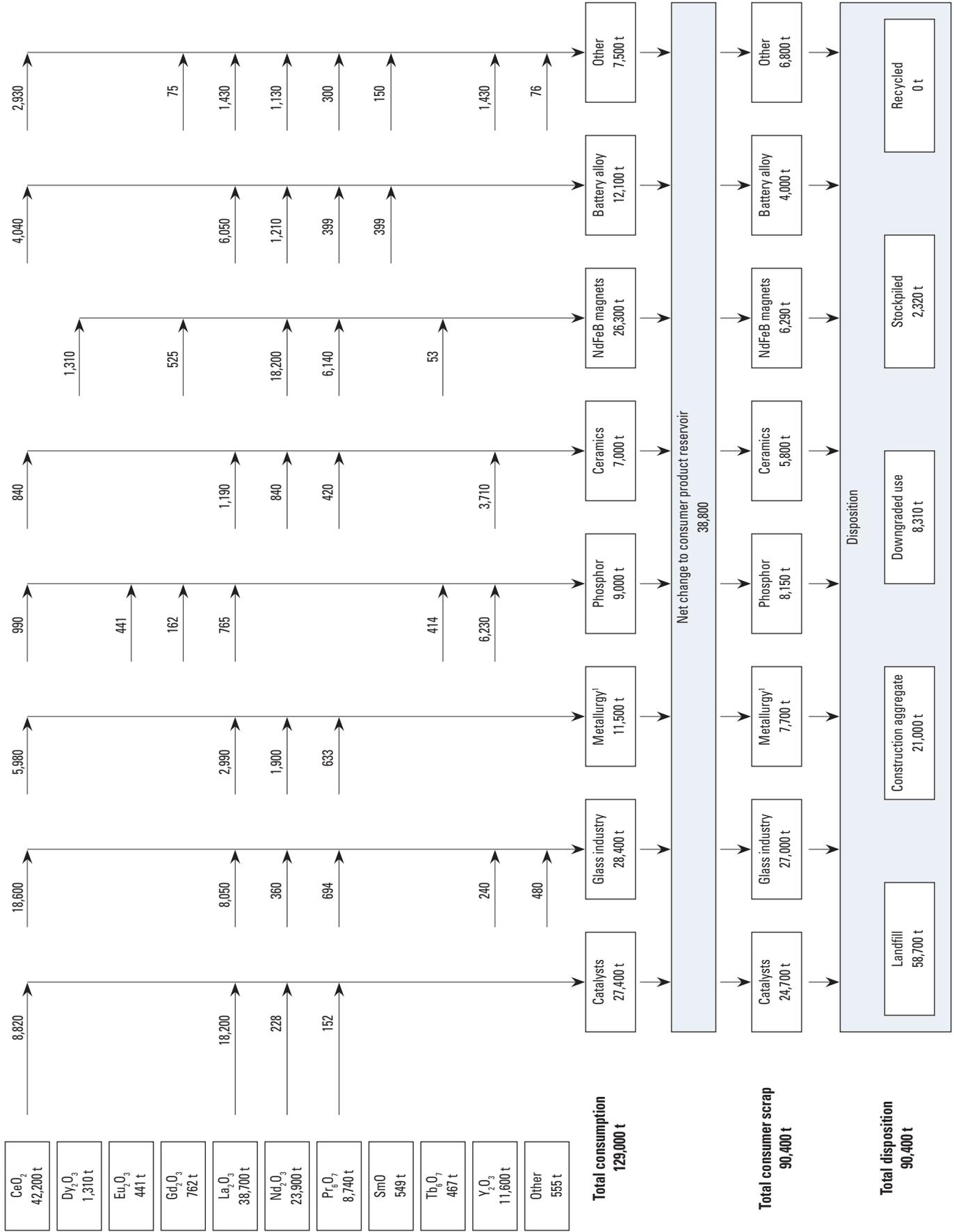


Table 2. Distribution of rare earth oxide consumption by market sector in 2008.

[Data are derived from Bade (2010). Values may not add to totals shown owing to independent rounding. —, no consumption]

Rare earth oxide	Catalysts	Ceramics	Glass industry	Metallurgy, except batteries	Neodymium magnets	Battery alloys	Phosphors	Other	Total
Cerium oxide	8,820	840	18,620	5,980	—	4,040	990	2,930	42,200
Dysprosium oxide	—	—	—	—	1,310	—	—	—	1,310
Europium oxide	—	—	—	—	—	—	441	—	441
Gadolinium oxide	—	—	—	—	525	—	162	75	762
Lanthanum oxide	18,180	1,190	8,050	2,990	—	6,050	765	1,430	38,700
Neodymium oxide	228	840	360	1,900	18,200	1,210	—	1,130	23,900
Praseodymium oxide	152	420	694	633	6,140	399	—	300	8,740
Samarium oxide	—	—	—	—	—	399	—	150	549
Terbium oxide	—	—	—	—	53	—	414	—	467
Yttrium oxide	—	3,710	240	—	—	—	6,230	1,430	11,600
Other oxides	—	—	480	—	—	—	—	75	555
Total	27,400	7,000	28,400	11,500	26,300	12,100	9,000	7,500	129,000

Figure 2 (facing page). Diagram showing the distribution of rare earth oxide consumption by market sector in 2008. Data are derived from Bade (2010). Values may not add to totals shown owing to independent rounding. CeO_2 , cerium oxide; Dy_2O_3 , dysprosium oxide; Eu_2O_3 , europium oxide; Gd_2O_3 , gadolinium

oxide; La_2O_3 , lanthanum oxide; Nd_2O_3 , neodymium oxide; Pr_6O_7 , praseodymium oxide; SmO , samarium oxide; Tb_6O_7 , terbium oxide; Y_2O_3 , yttrium oxide. The metallurgy end use does not include batteries, which are shown as a separate end use.

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3.5 percent (Du and others, 2009). As fluid cracking proceeds, catalyst contaminated with carbon is continually created and separated from the stream of light hydrocarbon products. The contaminated catalyst is regenerated and blended with a new catalyst at a 1:1 ratio and returned to the cracking area (Bulatov and Jirmov, 2009).

In 2008, 27,400 t of REOs was used as catalysts for fluid cracking (72 percent) and automobile catalytic converters (28 percent), of which lanthanum oxide contributed 66 percent; cerium oxide, 32 percent; neodymium oxide, 0.8 percent; and praseodymium oxide, 0.6 percent (fig. 3).

In 2008, catalysts accounted for 47 percent of the consumption of lanthanum oxide (18,200 t, of which 98 percent went to fluid cracking and 2.0 percent went to automobile catalysts), 21 percent of the consumption of cerium oxide (8,820 t, of which 78 percent went to automobile catalysts and 22 percent went to fluid cracking), 1.7 percent of the consumption of praseodymium oxide (152 t, 100 percent of which went to automobile catalysts), and 1.0 percent of the consumption of neodymium oxide (228 t, 100 percent of which went to automobile catalysts).

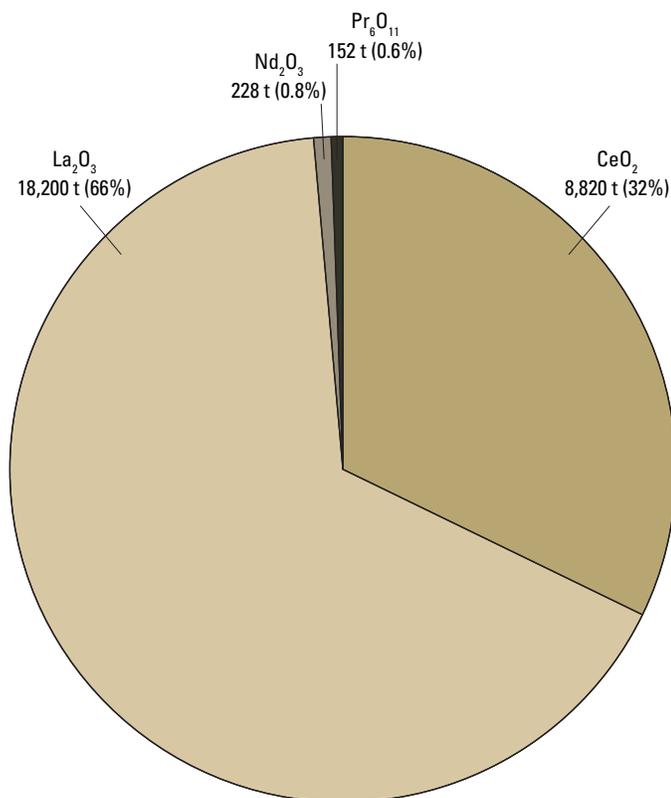


Figure 3. Pie chart showing the distribution of rare earth oxide consumption within the catalysts market sector in 2008. Data are derived from Bade (2010). CeO_2 , cerium oxide; La_2O_3 , lanthanum oxide; Nd_2O_3 , neodymium oxide; Pr_6O_{11} , praseodymium oxide.

Spent catalysts are generally considered to be hazardous wastes and as such incur higher disposal costs. Nevertheless, REOs are not recovered, but rather, depending on circumstances, are disposed in lined landfills, combined with other materials to make construction aggregates, or processed through cement kilns where they substitute for material and fuel inputs that would otherwise have to be extracted from the Earth.

With regard to automobile catalytic converters, REOs are not the major catalyst, but rather function as a protective coating for the major catalytic elements (palladium and platinum), which are generally more valuable and are used in much larger quantities for this end use. Very small amounts, if any, of the REOs used in catalysts are recycled within the processes that recover the major elements. The REOs separate to slag in these processes and are most likely a dissipative loss to construction aggregate or to landfills.

Growth in the demand for REOs that is generated by a catalyst's category of usage will likely be tied directly to worldwide growth in automobile production and fluid cracking. Growth is expected to depend upon general economic conditions and can vary by region.

Glass

REOs are added to glass to perform such functions as absorbing ultraviolet light, altering the refractive index, and coloring or decolorizing (AZoNano.com, 2009; Herbert, 2010; Rare-Earth-Technology, 2010). Yttrium is used with garnet to form yttrium-aluminum-garnet (YAG) lasers. Neodymium and other REEs are used as dopants to alter the properties of the YAG lasers (Anscombe, 2002; VLOC, 2002).

Polishing powder is sprayed on spinning glass where chemical dissolving and mechanical abrading agents work together to provide superior polished glass surfaces. Rare earth glass polishing powders at end-of-life contain 66 to 95 percent REOs in the following percentages: cerium oxide, 50 to 99 percent; lanthanum oxide, 0 to 35 percent; neodymium oxide, 0 to 15 percent; and praseodymium oxide, 0 to 5 percent. In 2008, 28,400 t of REOs was used in the glass industry, of which cerium oxide accounted for 65 percent; lanthanum oxide, 28 percent; praseodymium oxide, 2.4 percent; other oxides, 1.7 percent; neodymium oxide, 1.3 percent; and yttrium oxide, 0.9 percent (fig. 4).

In 2008, the glass industry accounted for 86 percent of the consumption of other REOs (480 t, of which 100 percent went to glass additives), 44 percent of the consumption of cerium oxide (18,600 t, of which 57 percent went to glass polishing and 43 percent went to glass additives), 21 percent of the consumption of lanthanum oxide (8,050 t, of which 64 percent went to glass polishing and 36 percent went to glass additives), 8 percent of the consumption of praseodymium oxide (694 t, of which 83 percent went to glass polishing and 17 percent went to glass additives), and 2 percent of the consumption of neodymium oxide (360 t, of which

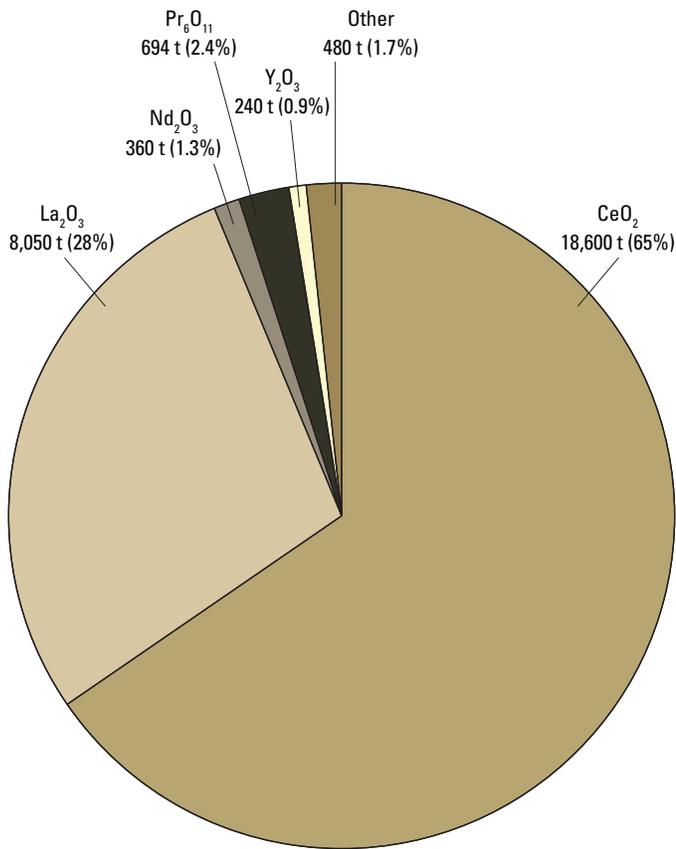


Figure 4. Pie chart showing the distribution of rare earth oxide consumption within the glass industry market sector in 2008. Data are derived from Bade (2010). CeO₂, cerium oxide; La₂O₃, lanthanum oxide; Nd₂O₃, neodymium oxide; Pr₆O₁₁, praseodymium oxide; Y₂O₃, yttrium oxide.

100 percent went to glass additives) and yttrium oxide (240 t, of which 100 percent went to glass additives).

Clear glass, which is unlikely to contain REEs, is recycled easily into containers, and clear glass cullet (crushed glass scrap) is highly prized in new clear glass production. Colored glass, some of which can contain REEs, is hand or machine sorted before becoming cullet. It can be recycled into colored glass under high quality control conditions, but is more likely to be used to manufacture color tile and glass fibers, as construction aggregate, or to be disposed of in a landfill (Container Recycling Institute, 2008; Earth911.com, 2010a,b).

Neodymium is used for the production of YAG lasers. No REE-bearing scrap material is recycled for use in this crystal-growing process. During production, 80 percent of the neodymium input is lost to a scrap material that contains as much as 5 percent neodymium oxide. This material, for lack of buyers, is sent to landfills (Michael Brennan, manager, YAG Crystal Growth, VLOC, written commun., January 25, 2001). Polishing powders can be regenerated with costly chemical processing (Xu and Peng, 2009).

Metallurgy (Excluding Battery Alloy)

REEs are added to aluminum, iron, steel, and other host metals in small quantities to improve selected physical properties of the resulting alloys. The rare earths are added as ferroalloys, master alloys, mischmetal (a mix of mostly cerium and lanthanum oxides), or metals.

In 2008, 11,500 t of REOs was used in this category, of which cerium oxide accounted for 52 percent; lanthanum oxide, 26 percent; neodymium oxide, 17 percent; and praseodymium oxide, 5.5 percent (fig. 5).

In 2008, the metallurgy sector (excluding battery alloy) accounted for 14 percent of the consumption of cerium oxide (5,980 t), 8.0 percent for neodymium oxide (1,990 t), 7.7 percent of the consumption of lanthanum oxide (2,990 t), and 7.2 percent of the consumption of praseodymium oxide (633 t).

The use of REEs in metallurgical alloys is generally dissipative because the rare earths congregate in low concentrations in the slag generated by melting scrap types that contain the rare earths. Slag is used as construction aggregate and (or) is disposed in landfills.

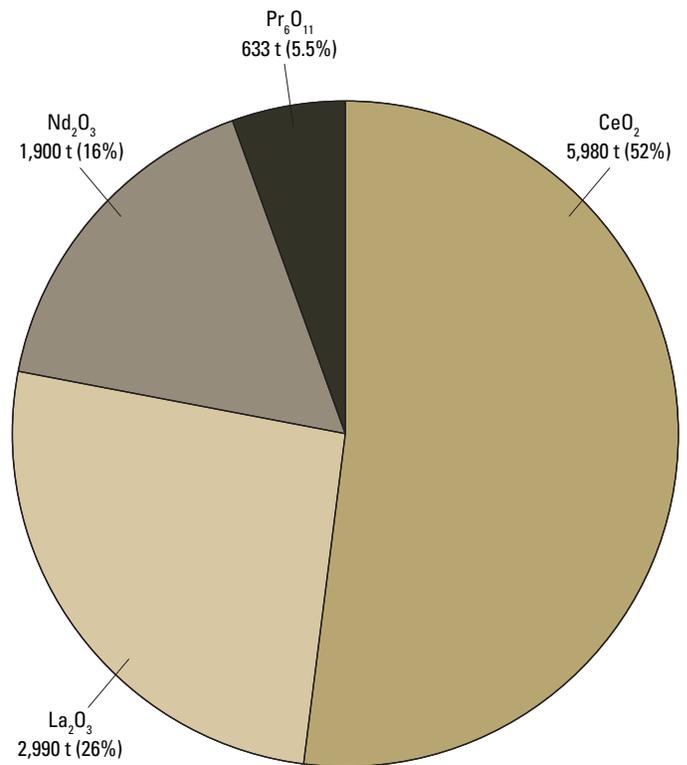


Figure 5. Pie chart showing the distribution of rare earth oxide consumption within the metallurgy industry market sector, excluding battery alloys, in 2008. Data are derived from Bade (2010). CeO₂, cerium oxide; La₂O₃, lanthanum oxide; Nd₂O₃, neodymium oxide; Pr₆O₁₁, praseodymium oxide.

Phosphors

Phosphors are used in cathode ray tube displays, fluorescent lamps, and other applications that require color in the light exhibited. Not all phosphors contain REEs, but many do. Phosphors convert incident radiation into light of designed color based on the properties of the elements included in the phosphor (Heyes, 1998).

In 2008, 9,000 t of REOs was used in this category, of which yttrium oxide contributed 69 percent; cerium oxide, 11 percent; lanthanum oxide, 8.5 percent; europium oxide, 4.9 percent; terbium oxide, 4.6 percent; and gadolinium oxide, 1.8 percent (fig. 6).

In 2008, phosphors accounted for 100 percent of the consumption of europium oxide (441 t), 89 percent of the consumption of terbium oxide (414 t), 54 percent of the consumption of yttrium oxide (6,230 t), 21 percent of the consumption of gadolinium oxide (162 t), 2.4 percent of the consumption of cerium oxide (990 t), and 2.0 percent of the consumption of lanthanum oxide (765 t).

Rhodia Group has estimated that, by 2015, recycled lamps will contain more than 250 t of REOs. Currently (2011), REOs as a constituent of the phosphor powder that can be recovered from recycled lamps is disposed in landfills. However, research efforts by Rhodia and others to economically recover this material continue (U.S. Department of Energy, 2009, p. 34141).

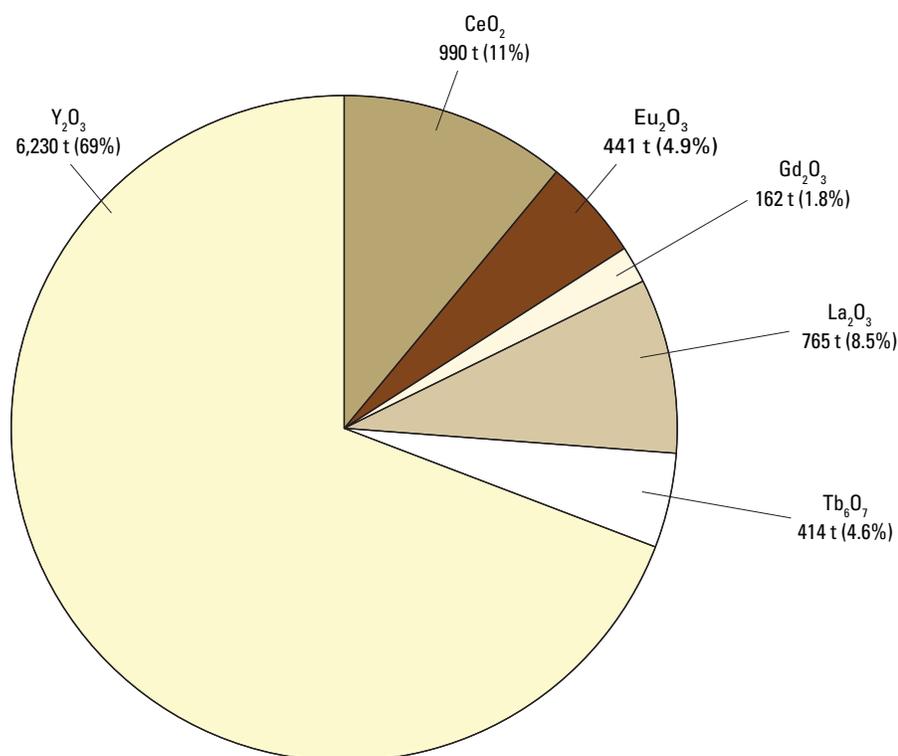


Figure 6. Pie chart showing the distribution of rare earth oxide consumption within the phosphor market sector in 2008. Data are derived from Bade (2010). CeO_2 , cerium oxide; Eu_2O_3 , europium oxide; Gd_2O_3 , gadolinium oxide; La_2O_3 , lanthanum oxide; Tb_6O_7 , terbium oxide; Y_2O_3 , yttrium oxide.

Developing Market Sectors

In developing high-technology market sectors, neodymium oxide accounted for 41 percent of REOs used in these sectors; lanthanum oxide, 16 percent; cerium oxide, 15 percent; praseodymium oxide, 14 percent; yttrium oxide, 10 percent; dysprosium oxide, 2.5 percent; and gadolinium and samarium oxides, 1.0 percent each.

Ceramics

REEs are added to ceramic glazes for color control (Campbell and Keane, 2010). Barium titanate powder, which is used in electronic applications, is doped with lanthanides to modify the properties of the titanate. Yttrium is used to make ferrites for high frequencies and to stabilize zirconia in oxygen sensors (Yoldjian, 1985).

In 2008, 7,000 t of REOs was used in this category, of which yttrium oxide accounted for 53 percent; lanthanum oxide, 17 percent; cerium and neodymium oxides, 12 percent each; and praseodymium oxide, 6.0 percent (fig. 7).

In 2008, ceramics accounted for 32 percent of the consumption of yttrium oxide (3,710 t), 4.8 percent of the consumption of praseodymium oxide (420 t), 3.5 percent of the consumption of neodymium oxide (840 t), 3.1 percent of the consumption of lanthanum oxide (1,190 t), and 2.0 percent

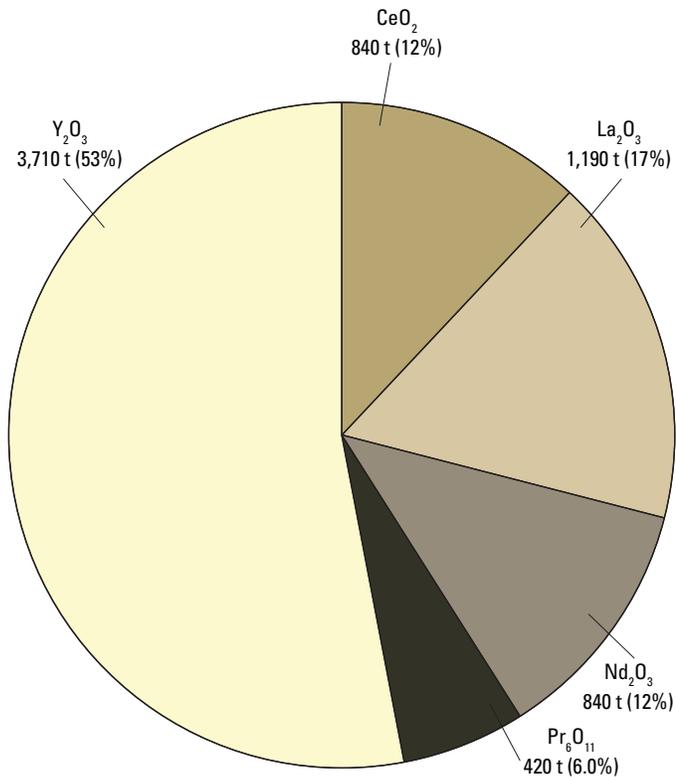


Figure 7. Pie chart showing the distribution of rare earth oxide consumption within the ceramics market sector in 2008. Data are derived from Bade (2010). CeO_2 , cerium oxide; La_2O_3 , lanthanum oxide; Nd_2O_3 , neodymium oxide; Pr_6O_{11} , praseodymium oxide; Y_2O_3 , yttrium oxide.

of the consumption of cerium oxide (840 t). Technology is available to recycle these materials, but little actual recycling occurs because the cost to separate the REEs is higher than the potential value of the materials (Lucchesi, 2010).

Neodymium-Iron-Boron Magnets

Because of their superior magnetic flux density, neodymium-iron-boron magnets are in high demand for small and large motors and generators. Small (servo) motors power disc drives in computers, windows in automobiles, and multitudes of other everyday applications. Larger motors, such as those in electric cars, can use up to 200 grams (g) of neodymium and 30 g of dysprosium per motor (Keane, 2009). Wind turbine generators can contain 1 t of neodymium per megawatt of electric capacity generated (Barton, 2009).

In 2008, 26,300 t of REOs was used in this category, of which neodymium oxide accounted for 69 percent; praseodymium oxide, 23 percent; dysprosium oxide, 5.0 percent; gadolinium oxide, 2.0 percent; and terbium oxide, 0.2 percent (fig. 8).

In 2008, the neodymium-iron-boron magnet category created 100 percent of the consumption of dysprosium oxide (1,310 t), 76 percent of the consumption of neodymium oxide (18,200 t), 70 percent of the consumption of praseodymium oxide (6,140 t), 69 percent of the consumption of gadolinium oxide (525 t), and 11 percent of the consumption of terbium oxide (53 t).

Neodymium-iron-boron magnets have the potential to be recycled, remanufactured, and reused because the magnets can be selectively disengaged from the assemblies in which they are used. Until recently, there had been no evidence of ongoing recovery activity (Walter Benecki, Walter Benecki LLC, written commun., January 26, 2011), partly because neodymium-iron-boron magnets often corrode with use, which increases the cost to recover useful elements, and partly because magnets that use plating materials (nickel) are more complex to recycle (Goodier, 2005). However, Hitachi has developed technologies to recycle rare earth magnets from hard disk drives and has successfully extracted rare earths from rare earth magnets (Hitachi, Ltd., 2010).

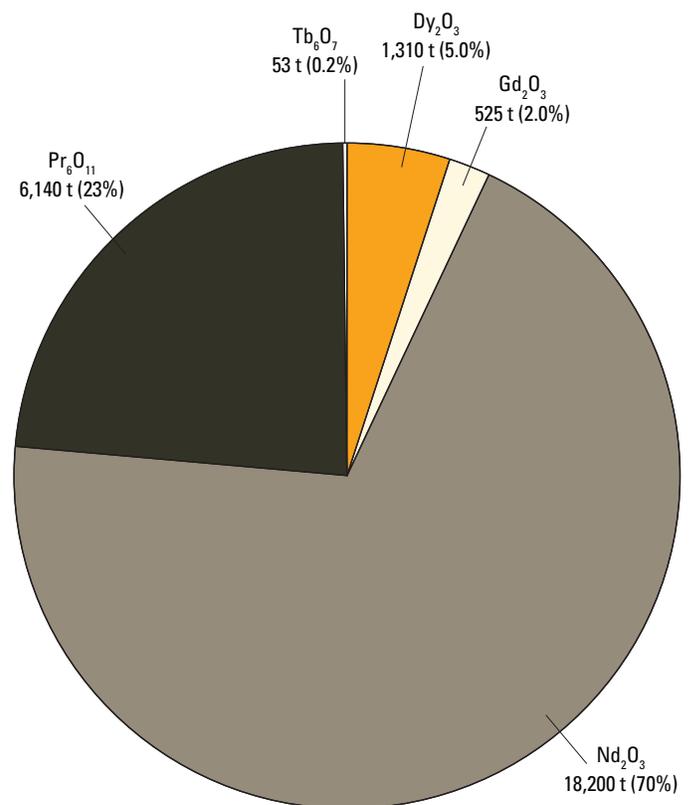


Figure 8. Pie chart showing the distribution of rare earth oxide consumption within the neodymium-iron-boron permanent magnet market sector in 2008. Data are derived from Bade (2010). CeO_2 , cerium oxide; Dy_2O_3 , dysprosium oxide; Nd_2O_3 , neodymium oxide; Pr_6O_{11} , praseodymium oxide; Tb_6O_7 , terbium oxide.

Battery Alloys

The negative electrode of nickel-metal-hydride (NiMH) rechargeable batteries comprises a variety of materials whose principal function is to store hydrogen within the lattice of the electrode. Some of these materials have REO participation, particularly the class called $RENi_5$, where the REO is mostly cerium or lanthanum oxide, with small amounts of other REOs included, depending on the nature of the mischmetal used in manufacture (Kopera, 2004).

In 2008, 12,100 t of REOs was used in this category, of which lanthanum oxide accounted for 50 percent (6,050 t); cerium oxide, 33 percent (4,040 t); neodymium oxide, 10 percent (1,210 t); and praseodymium and samarium oxides, 3.3 percent each (399 t) (fig. 9).

In 2008, the battery alloy category created 73 percent of the consumption of samarium oxide (399 t), 16 percent of the consumption of lanthanum oxide (6,050), 10 percent of the consumption of cerium oxide (4,040 t), 5.1 percent of the consumption of neodymium oxide (1,210 t); and 4.6 percent of the consumption of praseodymium oxide (399 t).

The $RENi_5$ chemistry is used almost exclusively in electric car batteries; the high growth rates expected for sales of electric cars have created concern about whether there is sufficient supply of REEs to cover the demand that electric car batteries would generate (fig. 10).

By yearend 2010, most of the hybrid and electric vehicles sold in the United States were powered by NiMH batteries. Lithium-ion batteries, which do not use REOs, are expected to replace the NiMH battery in electric vehicles sometime in the future (Anderson and Patiño-Echeverri, 2009). Future demand for the REEs used in the production of NiMH vehicle batteries is dependent upon acceptance by the public of electric vehicles as suitable substitutes for internal-combustion-powered vehicles, worldwide general economic growth, acceptance of lithium-ion batteries as a suitable substitute for NiMH batteries, and the technological response of NiMH battery manufacturers to the penetration of lithium-ion batteries into the electric vehicle battery market.

NiMH batteries can and are being recycled. A spent NiMH battery contains, by weight, 50 percent nickel, 33 percent REEs, 10 percent cobalt, 6 percent manganese, and 2 percent aluminum (Xu and Peng, 2009). The battery is pyrometallurgically recycled for the nickel and cobalt content, and the remainder separates to slag, which is landfilled or sold as construction aggregate.

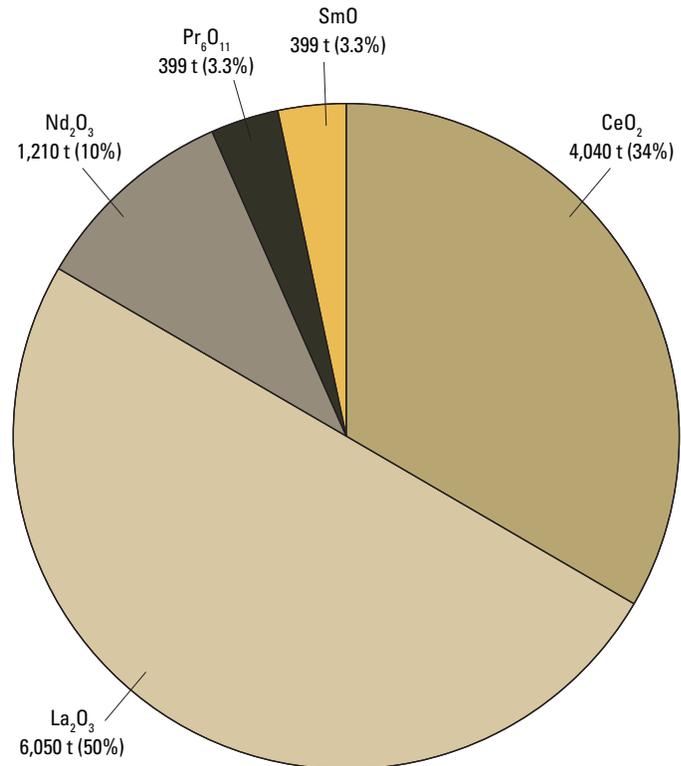


Figure 9. Pie chart showing the distribution of rare earth oxide consumption within the battery alloy market sector in 2008. Data are derived from Bade (2010). CeO_2 , cerium oxide; La_2O_3 , lanthanum oxide; Nd_2O_3 , neodymium oxide; Pr_6O_{11} , praseodymium oxide; SmO , samarium oxide.

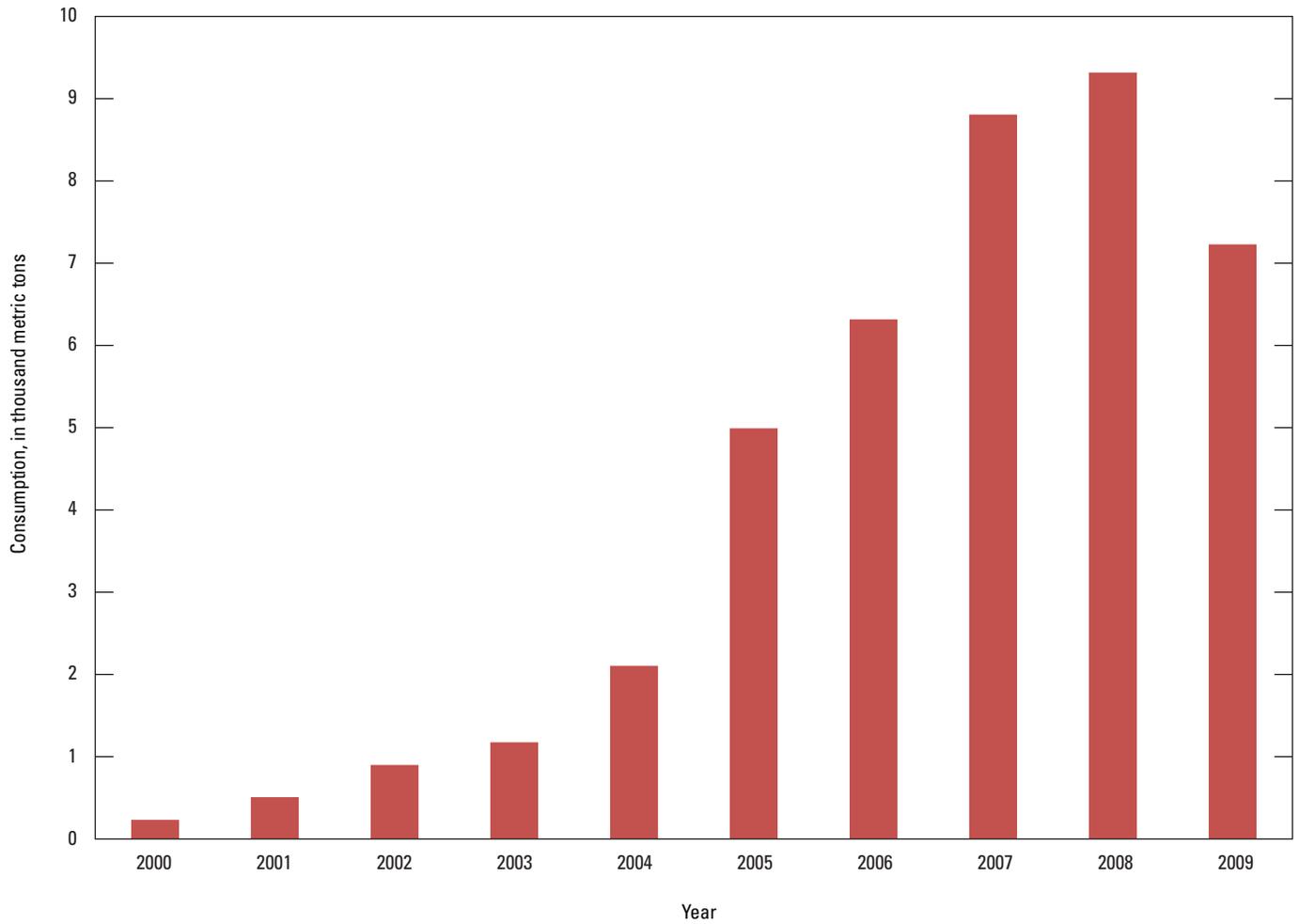


Figure 10. Chart showing demand for rare earth oxides associated with U.S. hybrid automobile sales from 2000 through 2009. Data are derived from Bade (2010).

Other (Unspecified)

The “other” category includes use of REEs in chemicals, military weapons and delivery systems, and satellite systems. In 2008, 7,500 t of REOs was used in this category, of which cerium oxide accounted for 39 percent (2,930 t); lanthanum and yttrium oxides, 19 percent (1,430 t) each; neodymium oxide, 15 percent (1,130 t); praseodymium oxide, 4.0 percent (300 t); samarium oxide, 2.0 percent (150 t); and gadolinium oxide and other REOs, 1.0 percent (75 t) each (fig. 11).

In 2008, the category of other, unspecified uses created 27 percent of the consumption of samarium oxide (150 t), 14 percent of the consumption of other REOs (75 t), 12 percent of the consumption of yttrium oxide (1,430 t), 9.8 percent of the consumption of gadolinium oxide (75 t), 6.9 percent of the consumption of cerium oxide (2,930 t), 4.7 percent of the consumption of neodymium oxide (1,130 t), 3.7 percent of the consumption of lanthanum oxide (1,430 t), and 3.4 percent of the consumption of praseodymium oxide (300 t).

Summary

In 2008, consumption of REOs was about 129,000 t, of which cerium oxide accounted for 33 percent; lanthanum

oxide, 30 percent; neodymium oxide, 18 percent; yttrium oxide, 9.0 percent; praseodymium oxide, 6.8 percent; dysprosium oxide, 1.0 percent; gadolinium oxide, 0.6 percent; and samarium oxide and other REOs, 1.6 percent combined. Cerium, lanthanum, and yttrium are used in market sectors that are driven by the growth of the general economy. Dysprosium, neodymium, and praseodymium are used in lower growth sectors, but most of their use is in the high-growth (8–10 percent per year) permanent magnet sector, which can be expanded to include batteries for electric cars, motors and generators for automobiles, and wind turbine generators.

In the event of REE shortages, whether by contraction of supply or expansion of demand, prices would likely increase and REE recycling activity can likely be expected also to increase from its current level of near-zero to a higher level where shortages are partially or wholly mitigated. There are ongoing research activities into reclaiming REEs from the scrap generated in the various end-use sectors (Schüler and others, 2011). Permanent magnet recycling seems to be the most promising from a technical standpoint, which could potentially benefit this high growth-rate sector. Replacement of NiMH batteries with lithium-ion batteries for electric cars can also potentially reduce the demand pressure on cerium, lanthanum, and neodymium, which are three of the six elements whose demand far exceeds the current supply (Bade, 2010).

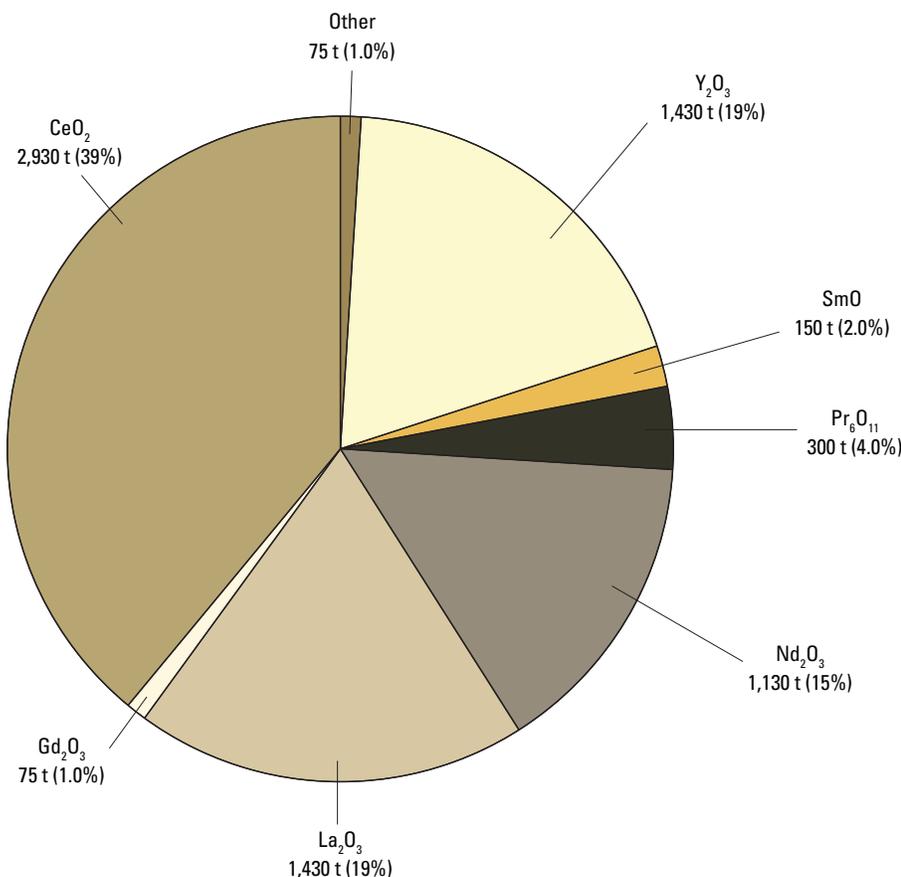


Figure 11. Pie chart showing the distribution of rare earth oxide consumption within unspecified market sectors in 2008. Data are derived from U.S. Department of Energy (2008), Hybrid Cars (2009), and Tasman Metals Ltd. (2010). CeO₂, cerium oxide; Gd₂O₃, gadolinium oxide; La₂O₃, lanthanum oxide; Nd₂O₃, neodymium oxide; Pr₆O₁₁, praseodymium oxide; SmO, samarium oxide; Y₂O₃, yttrium oxide.

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