R

The Important Role of Dysprosium in Modern Permanent Magnets

Introduction

Dysprosium is one of a group of elements called the Rare Earths. Rare earth elements consist of the Lanthanide series of 15 elements plus yttrium and scandium. Yttrium and scandium are included because of similar chemical behavior. The rare earths are divided into light and heavy based on atomic weight and the unique chemical and magnetic properties of each of these categories. Dysprosium (Figure 1) is considered a heavy rare earth element (HREE).

One of the more important uses for dysprosium is in neodymium-iron-boron (Neo) permanent magnets to improve the magnets' resistance to demagnetization, and by extension, its high temperature performance. Neo magnets have become essential for a wide range of consumer, transportation, power generation, defense, aerospace, medical, industrial and other products. Along with terbium (Tb), Dysprosium (Dy) is also used in magnetostrictive devices, but by far the greater usage is in permanent magnets.

Figure 1: Dysprosium Metal(1)

The demand for Dy has been outstripping its supply. An effect of this continuing shortage is likely to be a slowing of the commercial rollout or a redesigning of a number of Clean Energy applications, including electric traction drives for vehicles and permanent magnet generators for wind turbines. The shortage and associated high prices are also upsetting the market for commercial and industrial motors and products made using them.

Background

Among the many figures of merit for permanent magnets two are of great importance regarding use of Dy. One key characteristic of a permanent magnet is its resistance to demagnetization, which is quantified by the value of Intrinsic Coercivity (H_{cJ} or H_{ci}). Substituting Dy for a portion of the neodymium (Nd) in Neo magnets increases the room temperature value of H_{cJ} and also reduces the rate at which it falls with increasing temperature. Thus Dy-containing Neo magnets have greater resistance to demagnetization over a wider temperature range. The downside of adding Dy is a drop in Residual Induction (B_r). The second key characteristic, Energy Product, is proportional to the square of B_r. Therefore, even a small drop in B_r results in significantly lower magnet strength.

For applications such as motors and generators, resistance to demagnetization is a critical performance objective and the amount of Dy is dictated, not only by demagnetizing stress, but also by the expected maximum temperature of the application. Grades of Neo are most often denoted by a suffix indicating the minimum H_{cJ} (at 20 °C) and a corresponding recommended maximum operating temperature.

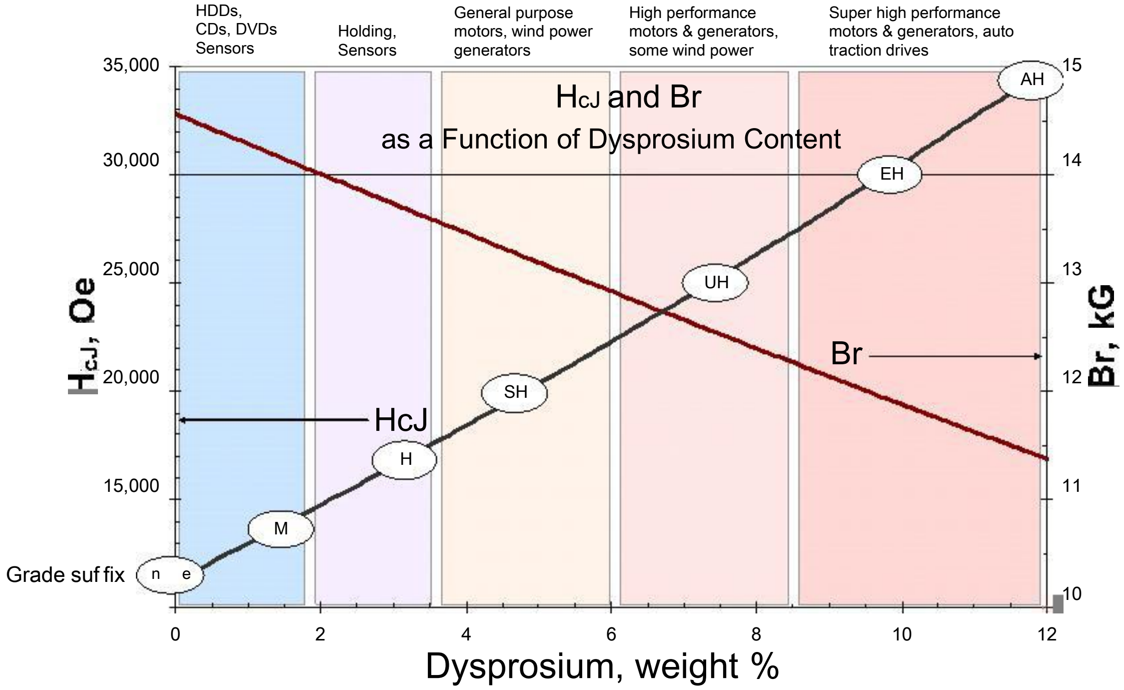


Figure 2: Intrinsic Coercivity (H_{cJ}) and Residual Induction (B_r) as a Function of Dysprosium Content

These notations are shown in Figure 2. At the top of the chart are some typical applications. Letters in ovals along the H_{cJ} curve are suffixes denoting minimum H_{cJ} of Neo magnets. For example, "SH" magnets have a minimum H_{cJ} of 20,000 Oe (1590 kA/m). The Dy percentages shown in Figure 2 are typical for materials where all the Dy is added to the starting alloy. Despite recent improvements in alloying and processing, considerable dysprosium is still required for high temperature applications. Increased demand for higher Dy grades of Neo magnets is one reason why Dy has been in short supply and why prices have stayed relatively higher even after the pricing bubble collapsed. (Efforts to reduce dysprosium will be discussed later).

A list of applications and most likely Dy content (traditional alloying) is shown in Table 1. Two green energy applications are Wind Power, in which designs have used 4 to 5% Dy to resist demagnetization at the operating temperature seen in the generators (up to 150 °C), and hybrid or full electric vehicle traction drives (EVs), in which demagnetization stress can be severe, especially along the leading and trailing edges of the magnets thus requiring Dy as high as 11%. Recent introduction of dysprosium diffusion - more accurately HRE diffusion since terbium can also be used - is permitting reduction of HRE content from 4+% Dy for SH grades to ~2% while 8-11% grades are reduced to 4-5%.

Many questions might come to mind such as the following.

Table 1: Approximate Dy content of Neo magnets in these applications - typical from 1985 to 2011. New or refined technologies are permitting reduced percentages. The new requirements are not yet well established.

Applications	Grade Suffix	Typical Dy Weight %
High Temperature Motors and Generators Hybrid & Electric Traction Drives	EH, AH	8.5 to 11.0
Commercial and Industrial Generators Wave Guides: TWT, Undulators, Wigglers	UH	6.5
Electric Bicycles Energy Storage Systems Magnetic Braking Magnetically Levitated transportation Motors, industrial, general auto, etc Pipe Inspection Systems Relays and Switches Reprographics Torque-coupled drives Wind Power Generators	SH	4.2
Gauges Hysteresis Clutch Magnetic Separation	H	2.8
Acoustic Transducers HDD, CD, DVD Magnetic Refrigeration MRI Sensors	M	1.4
Advertising Latches Toys	(no suffix)	<0.5

Is there enough dysprosium to supply the growing demand for neo magnets?
What and where are the principle sources of dysprosium?
What are the issues regarding dependability of supply?
Are there alternative technologies that could further relieve the demand for Dy?
Are there magnet materials that can successfully use less or no dysprosium?
What efforts have been expended to develop magnets with less dysprosium?

Discussion

Rare earths are mined from ore containing one or more minerals, a summary of which is presented in Table 2.(2) The light REEs such as La, Ce, Nd and Pr are available in high percentages in Bastnasite (carbonatite) ores and in the phosphate ore Monazite. Heavy rare earth elements (HREEs) such as Dy, Tb, and Eu are primarily found in Xenotime, Fergusonite, zircons and Placer Sand deposits of these and other minerals.

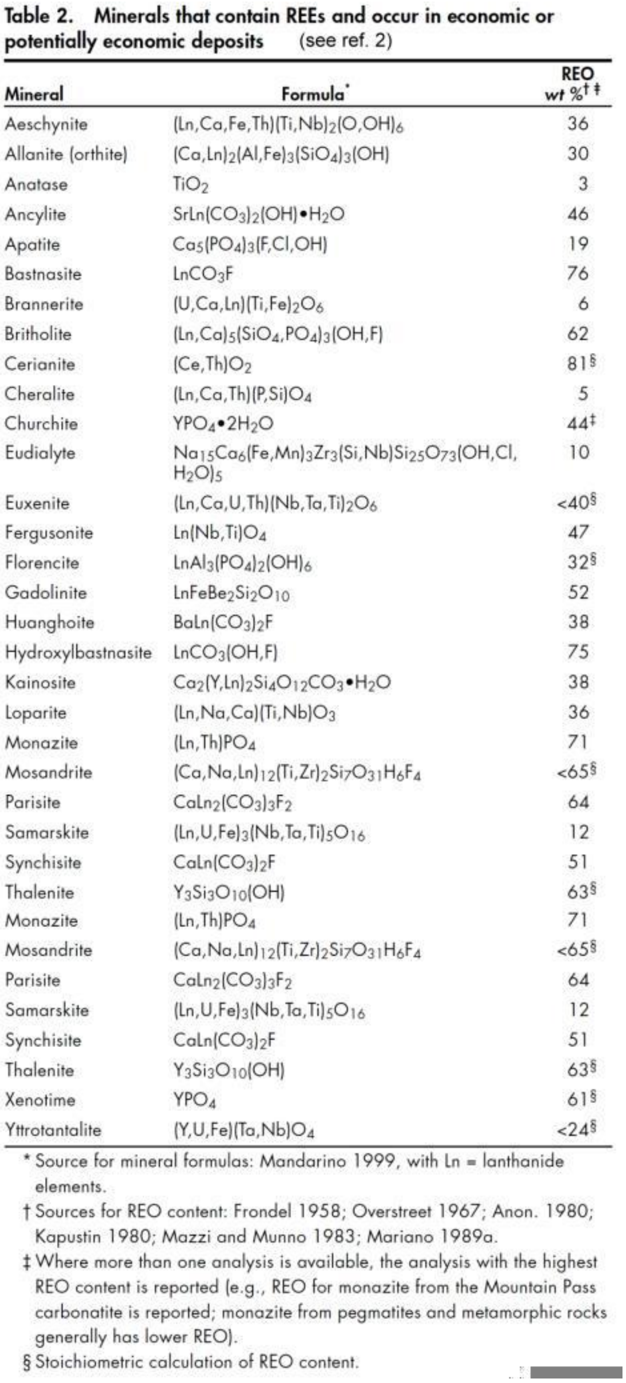


Table 2. Minerals that contain REEs and occur in economic or potentially economic deposits (see ref. 2)

Mineral	Formula*	REO wt %†‡
Aeschynite	$(Ln,Ca,Fe,Th)(Ti,Nb)_2(O,OH)_6$	36
Allanite (orthite)	$(Ca,Ln)_2(Al,Fe)_3(SiO_4)_3(OH)$	30
Anatase	TiO_2	3
Ancylite	$SrLn(CO_3)_2(OH)\bullet H_2O$	46
Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$	19
Bastnasite	$LnCO_3F$	76
Brannerite	$(U,Ca,Ln)(Ti,Fe)_2O_6$	6
Britholite	$(Ln,Ca)_5(SiO_4,PO_4)_3(OH,F)$	62
Cerianite	$(Ce,Th)O_2$	81§
Cheralite	$(Ln,Ca,Th)(P,Si)O_4$	5
Churchite	$YPO_4\bullet 2H_2O$	44‡
Eudialyte	$Na_{15}Ca_6(Fe,Mn)_3Zr_3(Si,Nb)Si_{25}O_{73}(OH,Cl,H_2O)_5$	10
Euxenite	$(Ln,Ca,U,Th)(Nb,Ta,Ti)_2O_6$	<40§
Fergusonite	$Ln(Nb,Ti)O_4$	47
Florencite	$LnAl_3(PO_4)_2(OH)_6$	32§
Gadolinite	$LnFeBe_2Si_2O_{10}$	52
Huanghoite	$BaLn(CO_3)_2F$	38
Hydroxylbastnasite	$LnCO_3(OH,F)$	75
Kainosite	$Ca_2(Y,Ln)_2Si_4O_{12}CO_3\bullet H_2O$	38
Loparite	$(Ln,Na,Ca)(Ti,Nb)O_3$	36
Monazite	$(Ln,Th)PO_4$	71
Mosandrite	$(Ca,Na,Ln)_{12}(Ti,Zr)_2Si_7O_{31}H_6F_4$	<65§
Parisite	$CaLn_2(CO_3)_3F_2$	64
Samarskite	$(Ln,U,Fe)_3(Nb,Ta,Ti)_5O_{16}$	12
Synchisite	$CaLn(CO_3)_2F$	51
Thalenite	$Y_3Si_3O_{10}(OH)$	63§
Monazite	$(Ln,Th)PO_4$	71
Mosandrite	$(Ca,Na,Ln)_{12}(Ti,Zr)_2Si_7O_{31}H_6F_4$	<65§
Parisite	$CaLn_2(CO_3)_3F_2$	64
Samarskite	$(Ln,U,Fe)_3(Nb,Ta,Ti)_5O_{16}$	12
Synchisite	$CaLn(CO_3)_2F$	51
Thalenite	$Y_3Si_3O_{10}(OH)$	63§
Xenotime	YPO_4	61§
Yttrotantalite	$(Y,U,Fe)(Ta,Nb)O_4$	<24§

* Source for mineral formulas: Mandarino 1999, with Ln = lanthanide elements.

† Sources for REO content: Frondel 1958; Overstreet 1967; Anon. 1980; Kapustin 1980; Mazzi and Munno 1983; Mariano 1989a.

‡ Where more than one analysis is available, the analysis with the highest REO content is reported (e.g., REO for monazite from the Mountain Pass carbonatite is reported; monazite from pegmatites and metamorphic rocks generally has lower REO).

§ Stoichiometric calculation of REO content.

Rare earth elements (REEs) are almost always accompanied by thorium and/or uranium. Ores containing greater percentages of HREEs contain greater amounts of thorium and uranium. Dealing with issues of permitting, processing, storing and disposing of radioactive components of the ore is costly but has been and can continue to be effectively managed.

The one major exception to radioactive components being in the HREE ore is ionic adsorption clay principally of southern China. These clay deposits exhibit very low thorium and uranium content. The deposits also lie on or near the surface of the land thereby providing ready access for even the most modest mining efforts. The rare earths, though present in low percentages (<0.5%), can be easily separated. This has led to many small mining companies, often just families, performing crude concentration of the ore with frequent contamination of the surrounding land and waterways. As there have been so many small, unlicensed miners, much of the processed material enters the black market avoiding taxes, quotas and regulation. Attempts have been underway by the Chinese government to curtail unlicensed mining and the accompanying poor environmental practices.

What is the current supply of Dy? Accurate data from within China has been difficult to obtain largely due to the size of the black market which has reputedly contributed between 5 and 50% of all REEs (including the HREEs) since 2005 when rare earth prices started to rise. Further, approximately 80 percent of magnet production takes place within China at one of over 300 neo magnet manufacturers. Crude estimates can be derived from product manufacturing data and these have been separately reported(3,14).

In December of 2010, the DOE issued its report on critical materials(4), updating it on December 27, 2011(11). Table 4-2 of the report from 2011 presented estimated future production of Dy, identified new sources and calculated supply for year 2015. Additional sources not shown in this table may be developed for introduction in 2016 and beyond although some of the sources listed are unlikely to contribute, at least in the near future. For example: Molycorp has just (2-Sep-2015) announced cessation of operations at Mountain Pass; GWMG has declared bankruptcy; and Avalon has been unable to obtain financing for continued development. There are mining companies which are continuing efforts to develop their properties, but the investment community is reluctant to provide financial support.

Market demand is exceeding supply and has resulted in rapid and extreme price changes for REEs especially for Dy. The rare earth market has been "closed", meaning that contracts are private and prices, settled on by the buyer and seller, are only approximately known by the public. Metal-Pages™ (www.metal-pages.com) tracks and publishes these prices; Asian Metals (www.asianmetal.com) publishes similar data. If these published prices are used even only as a guide, we see a substantial bubble in pricing over the past few years followed by a precipitous drop. In addition to price volatility, there has been a difference between prices for Chinese domestic purchasers and sales for export ("FOB China" sales) – a spread encouraged, if not actually caused, by export tariffs. (Export tariffs have now - spring 2015 - been replaced with a resource tax). Dy reached a low export price in 2003 of $28.50 per kg of metal. A kg of metal fetched a peak price of $3,410 in early 2011, 120x greater than in

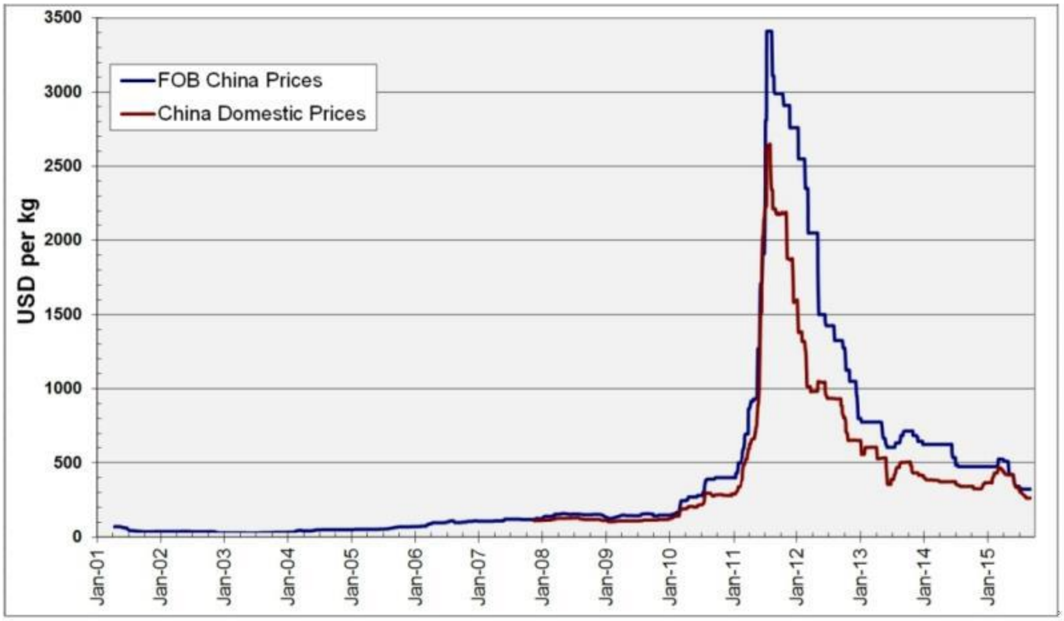


Figure 3: Price of dysprosium metal as reported by Metal Pages, both domestic China and exported product

year 2003. The price for dysprosium has retrenched considerably since its high in mid-year 2011, but is still well above 2003 pricing.

Domestic China Dy pricing had remained consistently lower over this period reaching a peak price in mid-2011 that was ~22% lower than the export price. In addition to a moderation in pricing, there were spot offerings of Dy – sellers wishing to off-load stock after the market bubble burst. This buying and selling of stock is representative of another facet of the shortage of a material: the entry into the market of commodities traders. The strategic nature of Dy has led government agencies (e.g. Japan Oil, Gas, and Metals National Corporation [JOGMEC] and the US Defense Logistics Agency [DLA]) to stockpile or consider establishing strategic inventories of rare earths in oxide, metal or alloy form. Even the Chinese government has established a stockpile program, although this is at least in part an attempt to stabilize prices by regulating supply. The pricing differential between within and outside of China is diminishing due to the elimination of export tariffs.

Is there adequate Dy to satisfy demand? Some crude calculations follow based on published production. The natural abundance of Dy is 2.8% of all the rare earths in the crust of the earth, but is present at much lower fractions in bastnasite and monazite ores, those most often mined (e.g. Bayan Obo, China; Mount Weld, Australia; Mtn. Pass, California). Dysprosium is present at only slightly higher percentages in monazite (phosphate-type ore) such as at Mount Weld (Lynas). Of the mined ores, dysprosium is ~1.5% of all the rare earths produced. Neodymium (Nd) is about 18.8% of all rare earths in the crust of the earth, but about 15% of currently mined ores. With minor sacrifice in Br and energy product, praseodymium (Pr) can be used to substitute for a portion of the Nd in Neo magnets and is available at between 4 and 5% of all REEs in these ores. At a ratio of (Nd+Pr)-20: Dy-1.5 and with Neo magnets containing about 32% total rare earth content, Dy can therefore be present at up to 2.2% of the magnet alloy and be in balance with production of the raw materials. Average consumption in Neo magnets has been reported to be ~2.0%, therefore approximately in balance with supply – which is what one should expect since if the material is not available, the magnets can't be made.

However, newer and growing applications for wind power generators, hybrid or full electric traction drive vehicles (commercial as well as military), and high performance motors and generators are increasing the average Dy content from the 2.0% range up to as high as 3% which is beyond the natural abundance and availability and at the same time the overall demand for Neo magnets is growing. This is likely to result in Dy pricing remaining high and supplies tight. Industry has responded since 2011 by:

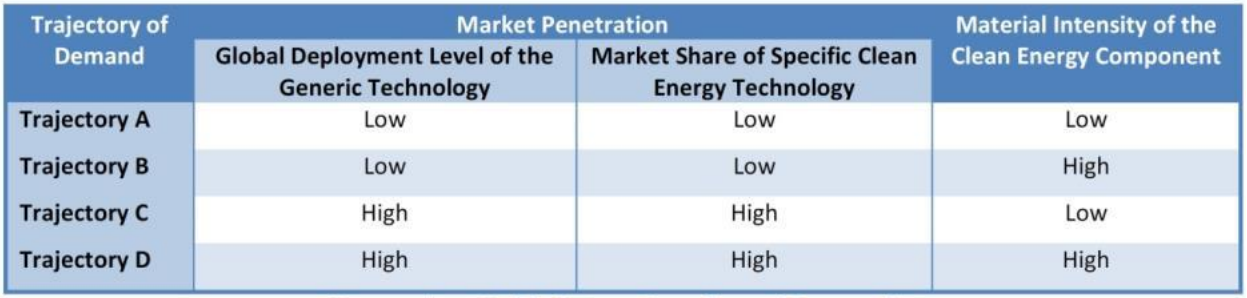
- Wind Power Generators: Slowing the introduction of products which are dependent upon Neo magnets, e.g., generation 4 permanent magnet wind power generators, although that constraint now seems (mid-2015) to be easing due to the reduction in pricing of the REEs coupled with technologies to reduce the dysprosium content requirement for wind from 4-5% down to ~2%
- Transportation: Converting to alternative technologies such as induction instead of PM motors. HEV and BEV vehicle sales are growing, but at about half the earlier forecast rate. The majority of traction drive motors remain the permanent magnet type due to better efficiency, but the most successful BEV to-date has been the Tesla which uses an induction motor coupled with Li-ion batteries.
- Using alternate permanent magnet materials: Ferrite, La-Co-ferrite, samarium-cobalt (SmCo)
- Long-term material supply contracts: for example, Siemens–Lynas and JOGMEC–Lynas

- Establishing secondary or tertiary sources of supply: for example, Shin-Etsu’s factory in Vietnam with access to Lynas REO or formation of JVs with companies within China such as Hitachi-San Huan
- Backward integrating into the mining and material processing industry through funding or IP investment and resource or company acquisition – or – forward integrating from mining to magnet manufacture such as the strategy of Molycorp and Great Western Materials Group (GWMG) prior to their bankruptcies

The current main source of dysprosium is, as mentioned earlier, the ionic clays of southern China. China has said that this resource has an expected life of between 15 and 25 years at current rates of consumption. Search is underway for additional sites containing HREEs and with manageable amounts of accompanying radioactive elements. Current producing sources contain primarily thorium and have been limited in output (e.g. Lehat Perak, Malaysia and Orissa, India). The KazAtomProm mining operation in Kazakhstan is a former uranium mining operation and is being brought back into production to obtain the rare earths. Numerous other mining operations are planned including those of Avalon Rare Metals (Nechalacho), Rare Element Resources (Bear Lodge), Ucore Rare Metals (Bokan Mountain), Lynas (Malawi), the Dubbo Zirconia Project (Alkane Resources Ltd.), and more. Further and periodically updated information can be found at the USGS website (5) and at the TechMetals Research (6) website.

The DOE Critical Materials Strategy (11) includes several charts for raw material supply and demand. The chart for dysprosium is presented here as DOE Figure 4.4 accompanied by DOE Figure 4.1 which explains the Trajectory assumptions. In trajectories B, C and D a shortage of dysprosium is predicted.

Table 4-1. Assumptions to Estimate Future Trajectories of Material Demand



Trajectory of Demand	Market Penetration		Material Intensity of the Clean Energy Component
	Global Deployment Level of the Generic Technology	Market Share of Specific Clean Energy Technology	
Trajectory A	Low	Low	Low
Trajectory B	Low	Low	High
Trajectory C	High	High	Low
Trajectory D	High	High	High

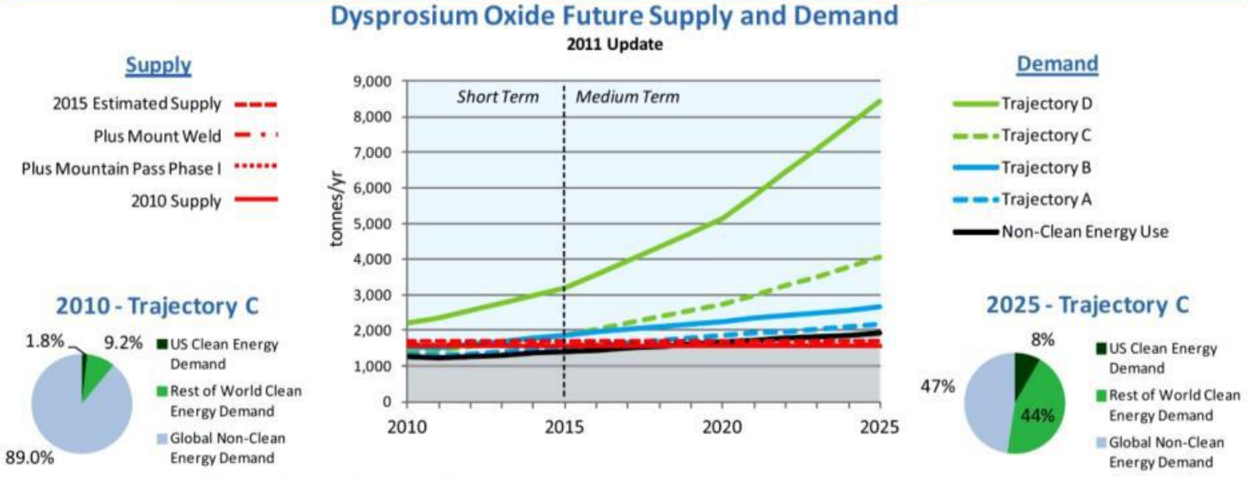


Figure 4-4. Future Demand and Supply for Dysprosium Oxide

The US Department of Energy (DOE) continues to rank dysprosium as a critical material. Their Figures ES-1 and ES-2 from page 116 of the 2011 Critical Materials Report(11) (see below) present key materials from both Supply Risk Assessment and Importance to Clean Energy for both the short- and medium-term time frames. Some relief is expected in supplies of neodymium and Neo magnets remain critical to the clean initiatives of wind power and electric drive vehicles, but the clean (green) energy applications require more HREEs, especially dysprosium.

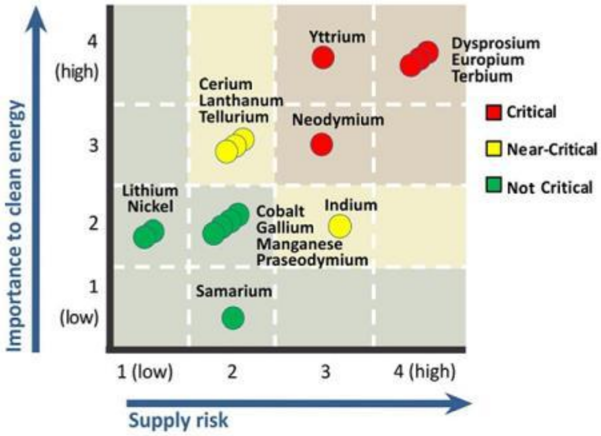


Figure ES-1. Short-Term (Present–2015) Criticality Matrix

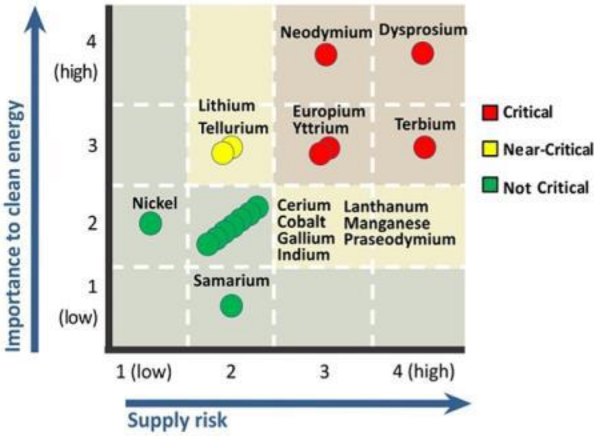


Figure ES-2. Medium-Term (2015–2025) Criticality Matrix

Earlier it was mentioned that conversion to alternative technologies is taking place to avoid business disruption which had resulted from rapid price changes and lack of dependable supply of Dy. What are some of these technologies? Wind power has already grown rapidly to become a major consumer of rare earth magnets. In 2010 China installed 49.5% of all wind power installed globally (7,15) and 25% of that is reported to have used direct drive permanent magnet generators. During 2010, 18.9 GW (gigawatts) of wind turbines were installed in China, which would have consumed approximately 15% of the dysprosium produced the same year (i.e., published, non-black market). An additional 7% of available Dy was used in the ROW (rest-of-world) wind power totaling 22% of Dy being used for wind power generators. Larger towers (3.5 MW and up) are designed primarily for off-shore installations where tower construction and maintenance are more costly. Fewer towers, each with greater output, lower the cost of power generation. Offshore wind power installations have often experienced less public resistance and some of the most dependable wind sources are off-shore. In 2015, these larger towers grew to a rating of 6 to 8 megawatts (MW) using direct drive generators and utilizing about 500 kg of Neo magnets per MW output. (For more information, see references 15 and 16). In addition to wind power, tidal current power generation is being developed and installed and these also use Neo magnets(16).

In the transportation market, traction drives using permanent magnets have been shown to be more efficient over a larger rpm range. To maximize battery performance and extend driving range, the more efficient PM traction drive is desirable. On the other hand, induction drives have been used for several years, are well proven and less sensitive to the high temperatures observed during operation (up to 200 °C in hot climates or after heavy use). Alternative designs that show promise are axial drives and drives using a hybrid technology (somewhere between induction and PM designs). Oak Ridge National Laboratory, a USA Department of Energy laboratory, is spearheading the DOE effort on drive technology(12, 13).

Efforts to minimize dysprosium usage may result in lower percentages of Dy. One technique is the dysprosium (or HREE) diffusion method of Shin-Etsu, Hitachi, Vacuumschmelze and others. Another method is exemplified by Daido's use of melt-spun, nanostructured Neo material – nano-structuring increases intrinsic coercivity without the use of dysprosium – but there are limits to this feature wherein above about 16,000 Oe (1275 kA/m) dysprosium is still required to increase H_{cJ}. A third method is more finely milled and more uniformly fine powder alloy particles which results in a 30% increase in H_{cj} of the no-dysprosium magnets. For examples, see patents of Showa-Denko (17). Despite the improvements, considerable dysprosium is required for high temperature applications.

HRE diffusion methods do nothing to mitigate loss of flux of the magnets which occurs with increasing temperature. A neo magnet capable of performing at 200 °C because of HRE diffusion still loses 19.8% of Br and ~36% of the energy product between 20 and 200 °C, assuming a reversible temperature coefficient of induction of -0.11%/°C. In contrast, SmCo 2:17 magnets lose only 6.3% of Br and ~12% of energy product. Thus at about 150 °C, SmCo starts to outperform Neo in energy product and the advantage of SmCo increases as temperature climbs to 200 and above.

Improved materials are also being sought that minimize the use of dysprosium while retaining high resistance to demagnetization. One method is to diffuse (by heating) dysprosium into previously manufactured magnets having low base levels of dysprosium in order to put the additional Dy into the microstructure where it will have the greatest effect on intrinsic coercivity (H_{cJ}). This is being advertised by both Shin-Etsu and Hitachi and both companies have introduced new series of magnets with reduced Dy content.

Numerous industrial and laboratory projects are underway attempting to discover new magnet materials that don't require dysprosium – perhaps no rare earths at all. At least a dozen projects have been funded but have not as yet (Sept 2015) resulted in commercially viable product. Most of the projects have now lost their funding with no commercialization.

Another approach is to moderate the temperature of the application thus obviating the need for high coercivity. Additionally, designs using more readily available materials are also possible. Numerous motor manufacturers are engaged in improving designs utilizing La-Co-ferrite magnets, alternative motor structures (e.g. axial drives) and more sophisticated drive algorithms using electrically complex applied power.

Samarium Cobalt magnets, which represent an exceptionally good high temperature performance material, will find increasing use in key applications. While Sm is available in greater quantities than Dy, it is available in lower quantities than Nd and thus SmCo magnets are best applied to high power density, high temperature applications. There has been an excess of Sm available 2003 through the present (2015). Estimates are that SmCo magnet production could at least double (possibly triple) without distorting the supply situation. And the more Neo magnets that are produced, the more samarium becomes available to make SmCo. Concerns regarding supply and pricing of cobalt are covered in reference 3. The use of cobalt in soft and permanent magnets is at a rate of 6 to 7% of the overall cobalt market and, while there is some price volatility, unlike the rare earths, cobalt is widely geographically mined, processed and readily available.

Much of the growth in consumption of dysprosium and other magnet rare earths is due in large part to the improvement in standard of living for several billion persons in developing countries. Most of this population cannot afford an enclosed car or truck, but many can now afford an electric bike – a vehicle that uses between 60 and 350 grams of Neo magnet per motor for either assisted propulsion or full drive power. It has been reported that over 20 million of these bikes were sold in China in 2009 and that the market size was growing. According to Bloomberg, there were 120 million electric bikes in use in China in 2010 (8) and other sources list comparable quantities(9, 10). As pointed out in Table 1, these motors require over 4% dysprosium when using conventional Neo magnets.

Summary

Use of dysprosium is forecast to increase to the extent it is available. Shortage of dysprosium is likely to constrain use of permanent magnet devices in several key applications. The selling price of dysprosium will remain sensitive to the supply-demand dynamic.

Owners of potential new sources for dysprosium face many challenges in proving economic viability before mining and processing begin. Among these challenges are low ore grade, quantifying rates of recovery, permitting and, where they exist, management of radioactive byproducts. Further the investment community has been disappointed in the financial situation at Molycorp and Lynas. There is a strong reluctance to invest in other RE ventures.

While every effort should be expended to find new and better magnet compositions and machine designs, this is a lengthy process. Invention defies mandated timelines. Subsequent to discovery, the process of scale-up, process optimization and commercialization can easily consume 5 to 10 years.

Efforts must also be expended to maximize manufacturing yield, optimize application of the magnet materials – use only where the specific magnetic properties are required and only to the extent required - and to recycle materials both from the manufacturing process and from reclaimed commercial product.

Addendum: this is an update produced in September 2015 of an earlier white paper (2012).
While the market issues have remained essentially unchanged, there have been changes in government policies, applications and in technology - and more change is expected. The reader is urged to treat this white paper as an introduction and to seek out additional and more current information.

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