Quadrennial Technology Review 2015

## Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

# Technology Assessments




U.S. DEPARTMENT OF ENERGY

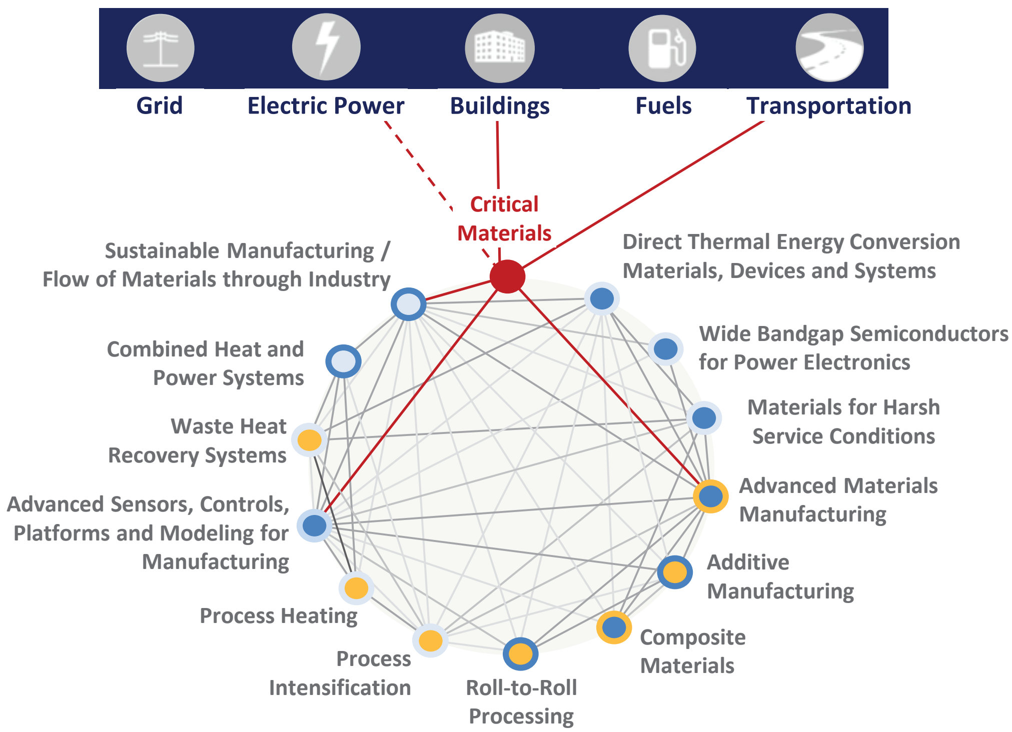
Quadrennial Technology Review 2015

# Critical Materials

## **Chapter 6:** Technology Assessments

*NOTE: This technology assessment is available as an appendix to the 2015 Quadrennial Technology Review (QTR). Critical Materials is one of fourteen manufacturing-focused technology assessments prepared in support of Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing. For context within the 2015 QTR, key connections between this technology assessment, other QTR technology chapters, and other Chapter 6 technology assessments are illustrated below.*

**Connections to other QTR Chapters and Technology Assessments**




**Representative Intra-Chapter Connections**

- **Sustainable Manufacturing:** materials substitution
- **Advanced Sensors, Controls, Platforms, and Modeling for Manufacturing:** models to minimize critical materials use
- **Advanced Materials Manufacturing:** computational techniques to develop critical material alternatives

**Representative Extra-Chapter Connections**

- **Electric Power:** permanent magnets for wind turbines
- **Buildings:** phosphors for LED lighting
- **Transportation:** dysprosium and other rare earths for motors; platinum for fuel cell catalysts

## Introduction to the Technology/System

Modern energy technologies—both new energy sources and novel ways to store, transmit, transform, and conserve energy—are enabled by the unique chemical and physical properties of a multitude of specific materials. The Department of Energy (DOE) determines a material's criticality by considering its importance to clean energy applications, as well as any supply challenges, such as a small global market, lack of supply diversity, market complexities caused by co-production, or geopolitical risks. This technology assessment will identify materials defined as critical by DOE for clean energy applications, and will describe technological approaches to optimize the supply chain to reduce criticality.

A materials shortage—exhibited through physical unavailability of a material, or high or volatile prices—may inhibit the widespread deployment of modern energy technologies, potentially causing adverse consequences to the economy, environment, security, and competitiveness of the United States. The potential impact of a materials shortage is illustrated when considering that each person in the United States requires 25,000 pounds of new nonfuel minerals to manufacture all of the products a person will use each year, including critical materials important for energy production and use.[1]

A variety of critical materials enable clean energy technologies such as photovoltaics, wind turbines, electric vehicles, and energy-efficient lighting (see Table 6.F.1). These clean energy technologies in turn reduce carbon pollution that contributes to climate change. As part of its efforts to advance a clean energy economy, DOE published a comprehensive Critical Materials Strategy to build on the Department's prior research and to inform future endeavors.[2] The Critical Materials Strategy examined the role of key materials in the clean energy economy, including criticality assessments, market analyses, and technology analyses to address critical materials challenges. Criticality assessments were performed by adapting an accepted methodology[3] of considering supply risk with societal importance for clean energy technologies. The most recent criticality assessment by DOE is shown in Figure 6.F.1a. As evidenced by comparing this assessment with a similar analysis performed by the European Commission (Figure 6.F.1b), the classification of a material strongly depends on how "criticality" is defined. Additional studies of material criticality exist, including those referenced here.[4,5]

**Table 6.F.1** Examples of Elements Important to Selected Clean Energy Applications.[6] An asterisk (*) denotes elements that were not considered in the DOE Critical Materials Strategy[7]

| **Application** | **Photovoltaics [2,8]** | | | **Wind** | **Vehicles** | | | **Lighting[9]** | |
|---|---|---|---|---|---|---|---|---|---|
| Technology | Silicon | CIGS | CdTe | Direct-Drive[10] | EV-NiMH[11] | EV-Li Ion[11] | Fuel Cells[12] | Fluorescent | LED |
| Carbon Abatement Potential Range[13] (MMTCE) | 5.11–18.46 | 1.24–10.28 | 1.98–11.61 | 4.29–19.57 | 2.31-3.82[15] | -0.01–0.00 | | -1.23–8.32[16] | 9.74–12.85 |
| Cerium | | | | | X | | X | X | X |
| Cobalt | | | | | X | X | X | | |
| Dysprosium | | | | X | X | X | | | |
| Europium | | | | | | | | X | X |
| Gallium | | X | | | | | | | X |
| Germanium* | | | | | | | | | X |
| Indium | | X | | | | | | | X |
| Lanthanum | | | | | X | | X | X | X |
| Lithium | | | | | | X | | | |
| Manganese | | | | | X | X | | X | |
| Neodymium | | | | X | X | X | | | |
| Nickel | X | | | | X | X | X | | X |
| Platinum Group Metals* | | | | | | | X | | |
| Praseodymium | | | | X | X | X | | | |
| Samarium | | | | | | | | | |
| Silver* | X | | | | | | | | X |
| Tellurium | | | X | | | | | | |
| Terbium | | | | X | X | X | | X | X |
| Tin* | X | | | | | | | | X |
| Yttrium | | | | | | | X | X | X |

Key: **MMTCE** = million metric tons of carbon equivalent avoided; **EV** = electric vehicles; **NiMH** = nickel metal hydride; **Li** = lithium.

**Figure 6.F.1a** Medium-Term (from 2015 to 2025) Criticality Matrix for Elements Important to Wind Turbines, Electric Vehicles, Photovoltaic Cells, and Fluorescent Lighting[16]

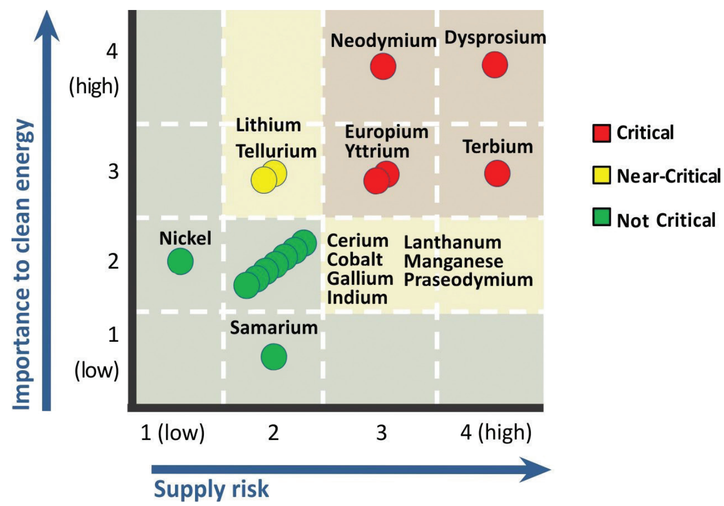



**Figure 6.F.1b** Criticality Ratings by the European Commission of Shortlisted Raw Materials.[17]

| High | High-Medium | Medium | Medium-Low | Low |
|---|---|---|---|---|
| REE: Dy, Eu, Tb, Y | Graphite | REE: La, Ce, Sm, Gd | Lithium | Nickel |
| REE: Pr, Nd | Rhenium | Cobalt | Molybdenum | Lead |
| Gallium | Hafnium | Tantalum | Selenium | Gold |
| Tellurium | Germanium | Niobium | Silver | Cadmium |
| | Platinum | Vanadium | | Copper |
| | Indium | Tin | | |
| | | Chromium | | |

## Technology Assessment and Potential

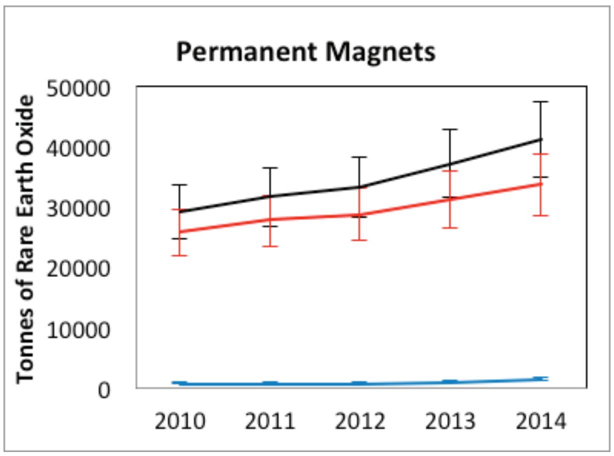
This section reviews the major trends that are driving future materials criticality within selected clean energy applications; namely, wind turbines, electric vehicles, and energy-efficiency lighting. Because these clean energy applications are enabled in part by the unique properties of rare earth elements (REEs), the section below entitled Major Trends in Selected Clean Energy Application Areas, focuses on those specific REEs utilized by permanent magnets (for wind turbines and electric vehicles) and phosphors (for energy-efficient fluorescent lighting). To address the challenges associated with critical materials, R&D opportunities include diversifying supply, developing substitutes, and improving reuse and recycling, as discussed in the next section Materials Supply Chain Challenges and Opportunities. As REEs are also distinctive in their particular supply chain risks, case studies of the REEs important to permanent magnets are examined. Finally, criticality is inherently dynamic, so additional key materials that may become critical in the future are also examined.

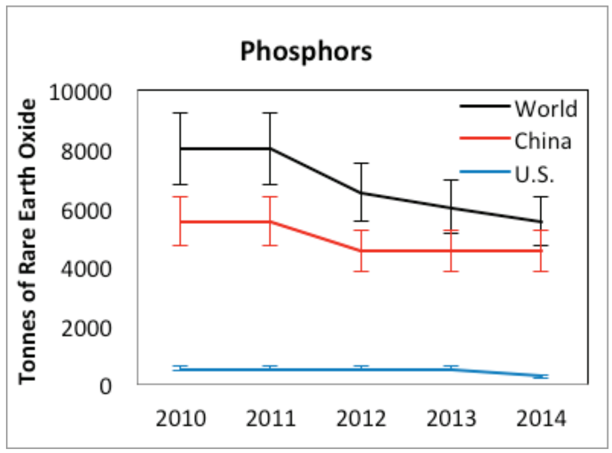
## Major Trends in Selected Clean Energy Application Areas

The functionality of many clean energy applications depend upon the unique properties of REEs. REEs represent an industry comprising $795 million in shipments and 1,050 workers in North America. The multitude of end-use products and technologies relying on REEs further constitutes $329.6 billion in economic output and 618,800 workers.[18] According to the United States Geological Survey 2015 Mineral Commodity Summary, the United States was 59% dependent on imports in 2014 to meet its domestic needs for REEs, 75% of which are imported solely from China.[19] Such a strong dependence on foreign imports has the potential to cause a shortage of materials required for national security,[20] such as the magnets containing REEs used for domestic fighter jets.[21] Further, REEs have a history of price volatility; for example, prices for REEs spiked more than tenfold from 2010 to 2011.[22,23]

The estimated demand of rare earth oxides for clean energy applications utilizing permanent magnets (such as for wind turbines and electric vehicles) and phosphors (for energy-efficient fluorescent lighting, lasers, cathode ray tubes, etc.) is shown in Figure 6.F.2.

**Figure 6.F.2** Estimated Demand of Rare Earth Oxides for Selected Clean Energy Applications.[24,25]




The estimated demand of rare earth oxides for all applications is shown in Table 6.F.2. The demand for rare earth oxides for fluid catalytic cracking catalysts (namely, lanthanum and cerium) fell in 2011 due to excessive prices, although the demand recovered by 2014 as prices decreased. Similarly for glass applications, the world demand for cerium fell by 40% due to high prices from 2008 to 2012, but is expected to increase in the near future due to lower prices. The demand for cerium for polishing applications has remained static, as high cerium prices and growing television size and demand are offset by the polishing recycling system installation and by new technologies that do not require polishing (liquid crystal displays and plasma display panels). For metal alloys, the increasing deployment of lithium ion batteries in electric vehicles may impact the demand of lanthanum (used in nickel metal-hydride batteries). The "other" category includes agriculture and water treatment applications, and demand for this category may increase with, for example, the development of cerium-based water treatment chemicals.

**Table 6.F.2** Estimated Demand of Rare Earth Oxides(In Metric Tons, With an Error of ±15%) for All Applications.[24] Note that "other" applications include agriculture, water purification, etc.

| Application | 2010 | | 2011 | | 2012 | | 2013 | | 2014 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | U.S. | World | U.S. | World | U.S. | World | U.S. | World | U.S. | World |
| Catalysts | 9,000 | 24,500 | 7,000 | 21,000 | 8,000 | 22,000 | 9,000 | 23,000 | 9,500 | 23,500 |
| Glass | 1,000 | 10,000 | 500 | 8,500 | 500 | 7,500 | 500 | 7,500 | 750 | 8,000 |
| Polishing | 1,000 | 19,000 | 1,000 | 16,000 | 1,000 | 16,000 | 1,500 | 17,000 | 2,000 | 19,000 |
| Metal Alloys | 1,000 | 22,000 | 500 | 20,000 | 500 | 23,000 | 1,500 | 24,000 | 1,250 | 25,000 |
| Magnets | 500 | 29,000 | 500 | 31,500 | 500 | 33,000 | 750 | 37,000 | 1,250 | 41,000 |
| Phosphors | 500 | 8,000 | 500 | 8,000 | 500 | 6,500 | 500 | 6,000 | 250 | 5,500 |
| Ceramics | 1,500 | 7,000 | 1,500 | 6,500 | 1,500 | 6,500 | 1,500 | 6,500 | 1,500 | 6,500 |
| Other | 500 | 7,000 | 500 | 6,000 | 1,500 | 7,000 | 1,500 | 7,000 | 2,000 | 7,500 |
| **Total** | **15,000** | **126,500** | **12,000** | **117,500** | **14,000** | **121,500** | **16,750** | **128,000** | **18,500** | **136,000** |

Estimated global rare earth oxides supply and demand are depicted in Table 6.F.3, indicating the strong role of China in supplying the world's demand for these important elements.

**Table 6.F.3** Estimated Global Rare Earth Oxides Supply and Demand (In Metric Tons, With an Error Of ±20%) Forecast for 2010-2020.[24] Note that "% of Global" includes the weighted average composition of the contribution from illegal mining.

| Year | Demand | | | Supply | | | | | Surplus/Deficit |
|---|---|---|---|---|---|---|---|---|---|
| | China | ROW | Global | China | | | ROW | Global | |
| | | | | Production Quota | Illegal Mining | % of Global | | | |
| 2010 | 79,500 | 47,000 | 126,500 | 89,200 | 25–30,000 | 95 | 5,000 | 122,500 | -5,000 |
| 2011 | 81,500 | 36,000 | 117,500 | 93,800 | 30–35,000 | 95 | 6,000 | 132,500 | 15,000 |
| 2012 | 83,500 | 38,000 | 121,500 | 93,800 | 35–40,000 | 95 | 8,000 | 140,000 | 27,500 |
| 2013 | 86,500 | 41,500 | 128,000 | 93,800 | 40–45,000 | 90 | 13,500 | 160,000 | 32,500 |
| 2014 | 92,250 | 43,750 | 136,000 | 105,000 | 45–50,000 | 85 | 18,500 | 170,000 | 35,000 |
| 2015 | 97,000 | 49,000 | 146,000 | 115,000 | 40–45,000 | 80 | 38,500 | 195,000 | 50,000 |
| *2020* | *132,000* | *78,000* | *210,000* | *165,000* | *50,000* | *75* | *87,000* | *300000* | *90,000* |

Key: **ROW** = rest of world

## Permanent Magnets for Wind Turbines and Electric Vehicles

Permanent magnets enable the conversion of energy between mechanical and electrical forms—an integral property to the functionality of the lightweight, high-power generators and motors found in wind turbines and electric vehicles. Magnetic energy density and temperature stability in permanent magnets are enhanced by the incorporation of additional REEs in small quantities, such as dysprosium, praseodymium, and terbium.[16,26] Common rare earth permanent magnet compounds are neodymium iron boron (NdFeB) for wind turbines and electric vehicles and samarium cobalt (SmCo) for certain niche applications, particularly in the defense sector.[16,26] The total mass of REEs used depends on the application and the manufacturer; in general, for neodymium, a wind turbine may contain up to several hundred kilograms and an electric drive vehicle may use up to a kilogram.[16]

The growing deployment of wind turbines and electric vehicles[28,29] contributes to the rising demand for these REEs.[30] For example, one study estimated that the demand for dysprosium and neodymium could increase by 700% and 2600%, respectively, over the next 25 years in a business-as-usual scenario.[31] Below are synopses of the major trends in these two applications that may influence the demand for REEs.

Two global trends are driving the growing incorporation of REEs into the permanent magnets found in wind turbine generators. First, the overall industry is transitioning towards larger, more powerful turbines to meet the demands for renewable energy.[32] These larger turbines are more likely to use rare earth permanent magnets, as these magnets can reduce the size and weight of the generator as compared to designs that do not use permanent magnets, such as induction or synchronous generators. A second trend is toward turbines that are capable of operating at slower speeds, allowing electricity generation at slower wind speeds than traditional high-speed turbines. The slowest turbine speeds are achieved through a direct-drive arrangement, where the rotating turbine blades are coupled directly to the generator, rather than through a series of gearing stages as in high-speed turbines. The direct-drive arrangement is more efficient and reduces maintenance requirements, two benefits that will be important to off-shore wind deployment[33] where maintenance can be difficult and expensive. However, the direct drive design also requires larger permanent magnets for a given power rating, demanding greater rare earth content—as much as several hundred kilograms of rare earth content per megawatt.[34] Siemens has announced that it will use direct drive technology for its forthcoming offshore units,[35] while GE continues to manufacture wind turbines with induction generators. Currently, the domestic wind turbine fleet uses negligible amounts of REEs—for example, of the more than 48,000 utility-scale units currently operating in the United States,[36] only 377 are direct drive units that employ REEs.[36,37] The low usage of REEs in the wind industry is due at least in part to their insufficient and uncertain supply, which has driven the market towards gearbox designs that are not as reliable and efficient as new designs employing significantly higher quantities of rare earth permanent magnets.

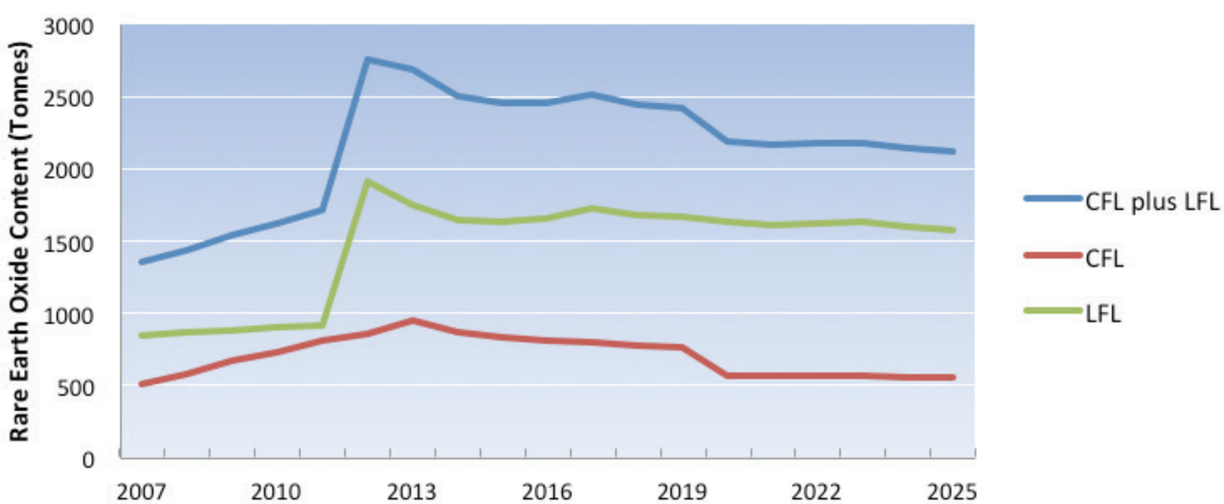
Permanent magnet demand is also driven by the growing demand for electric-drive vehicles. Nearly all mass-produced electric vehicles (including hybrid, plug-in hybrid, and all-electric vehicles) use rare earth permanent magnets in the motors that propel them during electric drive operation.[16] Total domestic sales of electric vehicles in the model year 2013 nearly doubled those of 2012.[38] In fact, the United States leads the global stock of plug-in hybrid electric vehicles, representing 70% of the global stock in 2012.[39] Aggressive deployment goals, such as the EV Everywhere Challenge to make plug-in electric vehicles as affordable and convenient as gasoline-powered vehicles in the United States by 2022,[40] will likely further drive sales, and therefore permanent magnet demand, in the future. Notably, Tesla employs induction motors rather than motors using rare earth permanent magnets, although induction motors pose unique technical challenges and are larger relative to motors using rare earth permanent magnets.[41]

## Phosphors for Energy-Efficient Lighting

Lighting is projected to account for approximately 11.8% of electricity use in U.S. buildings in 2015,[42] representing a significant opportunity to reduce overall electricity usage. The demand for more energy-efficient lighting is driving the transition from traditional incandescent bulbs towards energy-efficient fluorescent lamps, light emitting diodes (LEDs), organic light emitting diodes (OLEDs), and halogen incandescent lamps. These more efficient, spectrally complete, and visually pleasing lamps may utilize REEs to achieve various lighting effects. For example, fluorescent lamps require phosphors that may include lanthanum, cerium, europium, terbium, and yttrium. Further, REEs for phosphor applications must be extremely pure (99.999%) to achieve precise color characteristics, necessitating costly purification steps during their manufacture. In fact, fluorescent lighting is so dependent upon rare earths that DOE delayed the start date for energy conservation standards for particular types of lamps because of supply concerns, as the more efficient lighting technologies would increase the demand for rare earth element-containing phosphors.[43] LEDs, OLEDs and halogens use significantly less or no REEs as compared to fluorescent lamps;[16] however, LEDs and OLEDs may still employ other key materials such as gallium and indium for LED compound semiconductor materials.

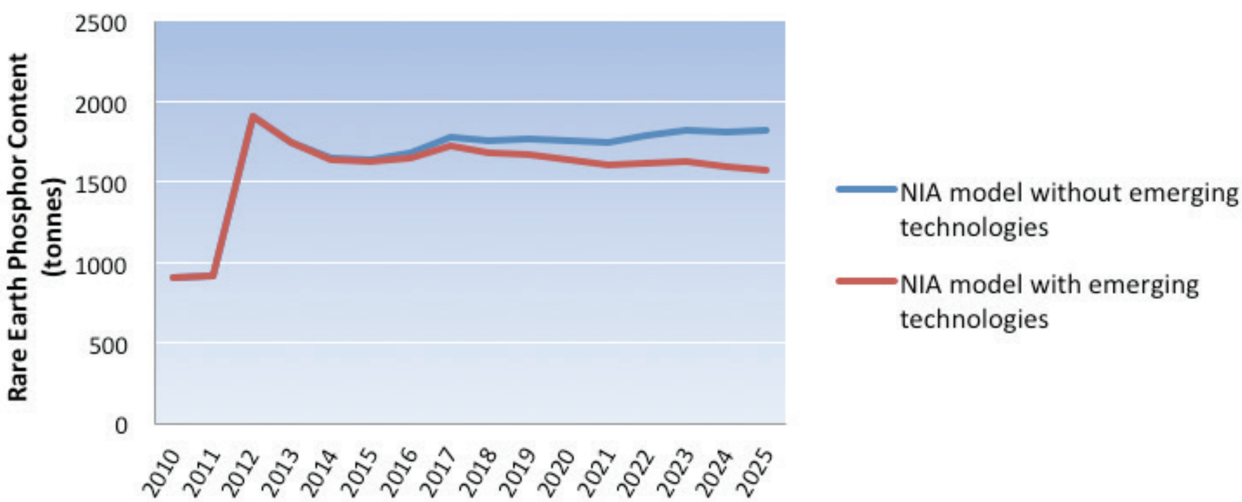
The demand of critical materials for energy-efficient lighting will be driven by the transition in lighting technologies. The first substitutes for traditional incandescent lamps have been fluorescent light bulbs, because they have achieved commercial availability at a price point attractive to consumers and meet the mandated energy efficiency standards. Therefore, the domestic demand for fluorescent lighting for phosphors containing rare earths was projected to nearly double between 2011 and 2013 (Figure 6.F.3). Since the U.S. lighting demand accounts for a significant share (20%) of the global market, this domestic demand peak may cause a noticeable peak in global phosphor demand.[16] There has already been some indication of tightening demand leading to higher prices, and several lighting manufacturers introduced rare earth surcharges in 2011.[44,45]

**Figure 6.F.3** Projected Rare Earth Oxide Content in Domestic Shipments of Compact and Linear Fluorescent Lights (CFL and LFL, Respectively).[16] Note that these projections were constructed prior to the granting of phase-out exceptions.[43]



Over time, the demand for LEDs, OLEDs, and halogen incandescent lamps is expected to grow, perhaps replacing the demand for fluorescent lighting and thus relaxing the demand for REEs for phosphors beyond 2013 (Figure 6.F.3). LED bulbs are already available on the consumer market, designed to fit directly into existing light sockets. Although these LED bulbs are competitively priced when considering the total life cycle, their demand is expected to grow further once their unit price declines to that of traditional incandescent or compact fluorescent light bulbs.[46,47] In fact, one estimate projects that LED lighting will account for the majority of installations by 2022 and 88% of all lumen-hours being produced for general illumination in 2030.[48] Halogen incandescent lamps that meet general service lighting standards are currently available at a price point between traditional incandescent lamps and compact fluorescent lamps, but halogen incandescent lamps are less efficient and do not last as long as compact fluorescent lights.

**Figure 6.F.4** Comparison of Domestic Rare Earth Oxide Demand from Linear Fluorescent Lamp Phosphors Under Different Assumptions for Emerging Technology Market Penetration.[16] Note that these projections were constructed prior to the granting of phase-out exceptions.[43]




## Materials Supply Chain Challenges and Opportunities

Major barriers exist along the entire supply chain of critical materials. REEs, for example, have supply chains that are notoriously challenging, as exemplified by permanent magnets (Table 6.F.4). The vast majority of this market is owned by a single supplier country, leaving significant supply chain gaps in the rest of the world. Market information is opaque, weighing down the best production estimates by world experts with large (±20%) margins of error[50] to account for smuggling and black markets. Illegal production may constitute an additional 40% of total production.[51,52] Financial constraints inhibit new entries to the rare earth element raw material market, as setting up a new mine and separation and processing facilities may cost on the order of $1 billion to enter this $2-3 billion market.[50,53] Perhaps for these reasons, the world's largest producer of REEs does so as by-products of iron ore deposit development.[54] However, some new capabilities have come on-line since 2011, improving the resilience of this supply chain: new mines in U.S.[55] and Australia[56] producing predominately lanthanum, cerium, praseodymium, and neodymium were opened; INFINIUM is performing some metal making;[57] Molycorp produces NdFeB and SmCo alloys for magnets;[58] Magnaquench produces NdFeB magnetic powders for bonded magnets;[59] a Hitachi plant in the U.S. produces NdFeB magnets on a small production scale;[60] and Intermetallic Japan produces sintered NdFeB magnets.[61] In June 2015, Molycorp filed voluntary petitions under Chapter 11 of the Bankruptcy Code in U.S. Bankruptcy Court to facilitate a financial restructuring of the company's $1.7 billion in debt.[62] In August, Molycorp made an additional announcement that rare earth production at the Mountain Pass facility would be suspended no later than October 20, 2015.[63] Suspending production at Mountain Pass will increase import dependence in future years.

Although spikes in the prices of REEs garnered significant attention around 2010,[64] the root cause of the criticality of REEs is in fact the lack of diversity in the supply chain. Thus, to fully address the challenges associated with these specific critical materials, a holistic view of the entire supply chain is required. A secure, sustainable supply chain needs to be developed to allow the invention, manufacture and deployment of clean energy technologies in the United States. This section considers diversifying supply, developing substitutes, and improving reuse and recycling for rare earth permanent magnets.

**Table 6.F.4** NdFeB Permanent Magnet Supply Chain Steps and Major Barriers to a Robust And Diverse Supply Chain.

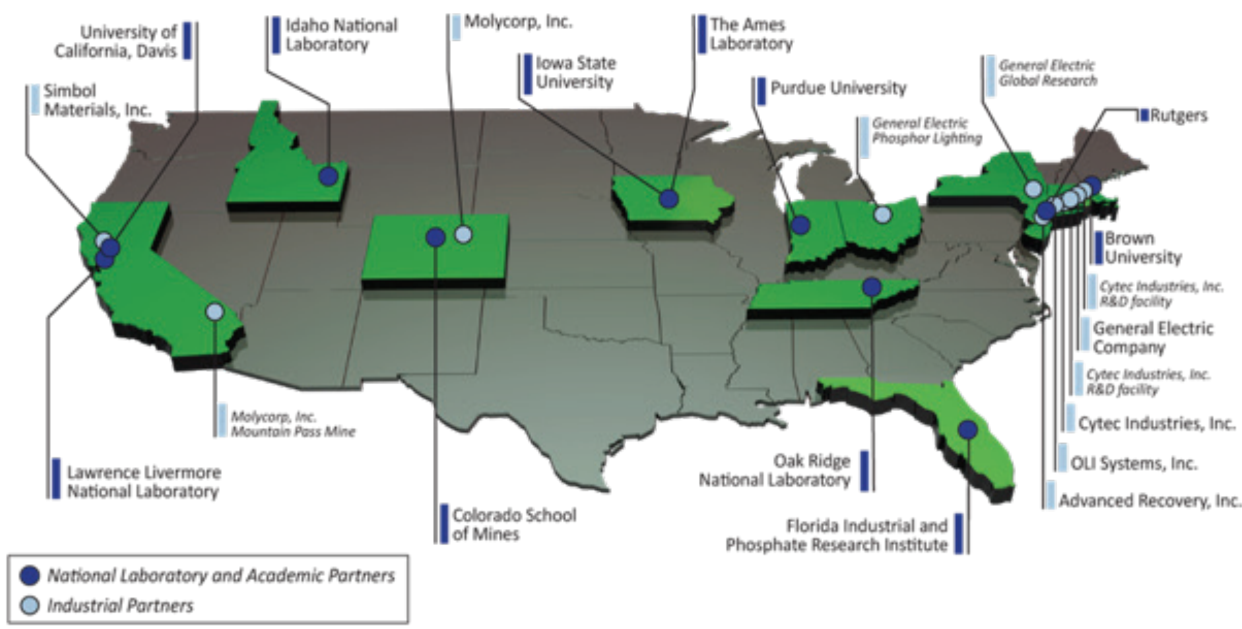
| Supply Chain Step | % in China | | Major Barriers |
|---|---|---|---|
| | 2010[65] | Current[24] | |
| 1. Mining, milling, and concentrating ores | 97% | 80–85% | ■ Significant capital expenditure and permitting time for new mines<br>■ Must work with given deposit geology |
| 2. Separations | 97% | 80–85% | ■ Extensive separations to isolate desired elements from those present in the ore (entire lanthanide series)<br>■ Significant capital expenditure<br>■ Loss of intellectual capital |
| 3. Refining metals | ~100% | >95% | ■ Lack of downstream consumers |
| 4. Forming alloys and magnet powders | 90% | >95% | ■ Lack of downstream consumers |
| 5. Manufacturing | 75% | >80% | ■ Intellectual property for sintered NdFeB magnets held in Japan by Hitachi |
| 6. Components (motors, generators) | Not available | Not available | ■ Secure upstream supply chain |
| 7. Recycling | Not available | Not available | ■ Financial uncertainty<br>■ Collection logistics<br>■ Technology<br>■ Uncertain markets for recycled materials |

To address critical materials challenges for the United States and other countries, there is a need to diversify supply, develop substitutes, and enhance reuse and recycling. Diversified global supply chains diffuse supply risk, and the United States must simultaneously facilitate domestic extraction, processing and manufacturing while encouraging other nations to expedite alternative supplies. The development of material and technology substitutes will also improve supply chain flexibility. Finally, recycling, re-use, and more efficient use will reduce the demand for newly extracted materials.[16] R&D can be an important contributor to all of these.

The DOE Critical Materials Institute (CMI) Energy Innovation Hub was established to conduct R&D to help assure supply chains of materials critical to clean energy technologies, with an aim to reduce the waste of critical rare earths within domestic manufacturing by 50% and reduce critical rare earths elements going to domestic landfills by 35%.[66,67] CMI partners are shown in Figure 6.F.5. Efforts within the DOE also include projects related to the batteries and magnets in electric vehicles[68] and the recovery of lithium from geothermal brines.[69] The Rare Earth Alternatives in Critical Technologies (REACT) program is funding early-stage technology alternatives that reduce or eliminate the dependence on rare earth materials by developing substitutes for rare earth permanent magnets in two key areas: electric vehicle motors and wind turbine generators.[70] The Joint Center for Energy Storage Research is working to enable next generation batteries and energy storage for the grid and for transportation by delivering electrical energy storage with five times the energy density and one-fifth the cost of today's commercial batteries within five years.[71] R&D is also being done to investigate the recovery of REEs from coal ash.[72]

**Figure 6.F.5** CMI Partners.

Credit: Critical Materials Institute




Other government agencies play active roles in the Federal response to critical materials challenges. The United States Geological Survey (USGS) provides an annual summary of rare earth activity in its Mineral Commodities Summaries report[73] and publishes on focused topics, such as recycling of REEs.[74] The Department of Defense maintains a stockpile of defense-related critical materials and closely monitors the rare earth materials market for projected shortfalls or failures to meet mission requirements,[64] and funds some research and development.[75] The National Science Foundation funds the Center for Resource Recovery and Recycling, an Industry & University Cooperative Research Program.[76] The Department of Commerce and Office of the U.S. Trade Representative review global trade policy. The Department of State reports on host government policies, private sector activities, and domestic markets. The Environmental Protection Agency establishes federal environmental standards for numerous activities, including mining.[64]

## Diversifying Supply

Diversifying the source of supply reduces the criticality of a material, moving it towards the left in the criticality matrix (Figure 6.F.1a). Three approaches to diversify supply are currently being investigated at CMI. One opportunity is to develop new, more efficient routes for chemical processing, since available technologies are expensive and polluting. Concentrated mixtures of REEs obtained from mining must be separated into purified rare earth oxides. Such separations are so technically difficult that industry continues to use essentially identical technologies to those developed over 50 years ago, leaving significant room for improvement based upon new science.[10] The development of new separations technologies is considered one of the grand challenges in the CMI. New techniques are needed that will cope with the fundamental similarity of the REEs, making possible efficient separations with minimal consumption of chemicals and energy. In the meantime, high processing costs have caused the migration of industry and expertise outside of the United States.[77] Domestic capabilities may be enabled in the future by improving the economics of solvent extractants and separation schemes through new technologies. One example of such new technologies is the development of more efficient ligands, which bind to specific rare earth metal ions in solution, allowing for their efficient extraction. To do this, CMI researchers are conducting both laboratory and computational experiments to develop game-changing technologies. One such effort has led to the doubling of the separation factor when trying to isolate neodymium from praseodymium in the laboratory, equivalent to a three-fold decrease in the separation equipment required for a processing plant. CMI researchers envision further improvements, and continue to work towards even higher separation factors.

Metal and alloy production should also be made more efficient (step 3 in Table 6.F.4). It is important to note that domestic production of metals and alloys are highly interdependent: the vast majority of domestic companies are not producing rare earth metals in the United States because, until the recent establishment of a single plant in North Carolina,[60] there were no domestic NdFeB magnet manufacturers.[78] (Conversely, the lack of domestic magnet manufacturing is due in part to insufficient supply of metals and powders, as well as significant intellectual property issues, which will be addressed further below.) INFINIUM, which was supported by a Small Business Innovation Research Grant from the DOE Advanced Manufacturing Office,[79] is now performing some metal making.

A diversified supply may also be achieved by considering the development of markets for co-produced abundant REEs. For example, lighter REEs (including cerium and lanthanum) account for 80-99% of a rare earth mineral deposit,[64] but represent a much smaller fraction of the total value of the deposit. For Mountain Pass, a mine owned by Molycorp in California, the value of cerium and lanthanum is ~25%.[80] This challenge, referred to as the balance problem,[81] is particularly relevant for Molycorp and Lynas mines, whose deposits tend to have significant cerium and lanthanum content.[16] CMI is currently researching novel applications for cerium and lanthanum to improve the economics of mining such deposits for heavy REEs, which are more valuable and useful for clean energy applications. One project examines the potential of cerium-containing alloys for structural or transportation applications. Such applications consume millions of tons of metal annually, and replacing even 1% of the metal consumed with a cerium-containing alloy would have a profound impact on the global demand for cerium.

Finally, the diversity of supply of REEs can be increased by both increasing the yield of existing ore processing and by finding ways to economically process new types of raw materials. One option for developing new raw materials involves leveraging non-traditional sources that happen to contain vast amounts of REEs at relatively dilute concentrations. For example, CMI researchers are investigating the potential of the phosphate fertilizer industry, where valuable REEs and uranium may be recovered as by-products from processing phosphate ores without disrupting production. The amounts of europium, dysprosium, terbium, and yttrium in phosphate rock processed globally each year would exceed annual global demand for these metals by more than an order of magnitude.[82] The technical challenge stems in part from the rather dilute concentrations of these metals in the phosphate rock, which are approximately one to two orders of magnitude less concentrated than typical rare earth element ores. Another project funded by DOE EERE is exploring geothermal brines for the production of lithium as a by-product of geothermal energy generation.[83] Finally, the Office of Fossil Energy is examining the feasibility of recovering REEs from coal ash,[84] tapping into a potentially vast non-traditional source. Other potential non-traditional sources of REEs include red muds and fracking fluids.

While DOE has focused primarily on technology solutions to material criticality, other agencies have investigated stockpiling as a way to diversify supply.[77] However, this approach is less applicable for rare earth permanent magnets because of the intensive processing and manufacturing required to transform stockpiled materials into a useful final product, especially with limited domestic capabilities.

### Developing Substitutes

Another way to reduce a material's criticality is to develop substitutes: although this does not directly reduce the supply risk of a material, substitutes can reduce the dependence of a clean energy technology on a particular material, moving it downward in the criticality matrix (Figure 1a). Substitutes may be made at both a material and manufacturing level, as will be discussed in this section.

One option for direct substitution is to develop new materials with similar functionality to the particular critical material. Although the commercialization of new materials typically requires 15-20 years,[85,86] NdFeB permanent magnets were developed from discovery to commercial production in three years.[87] This very fast commercialization remains highly unusual, so significant work is underway to understand success stories such as NdFeB and further speed the innovation cycles for new materials.[88] A promising methodology is to create tightly coupled feedback loops between high-throughput computation and experimentation, such as with the development of a MnBi permanent magnet (further detailed in section 5.0). Further, researchers at CMI are combining thermodynamic libraries with rapid synthesis and characterization capabilities to generate new magnetic compounds by combinatorial analysis.[89,90] The role of computational techniques in materials discovery and development is explored further in the *Advanced Materials Manufacturing* Technology Assessment.

A second opportunity to develop substitutes is to investigate new manufacturing routes.[16] In the case of NdFeB magnets, major intellectual property hurdles exist that inhibit potential manufacturers.[16] Exploring new routes to make magnets may allow for both new manufacturers and new manufacturing routes that reduce the use of critical materials and overall materials waste. For instance, researchers are investigating new additive manufacturing routes to develop exchange spring magnets,[91] which may double the energy density with half the rare earth element content as compared to commercial magnets.[92,93,94,95,96] CMI is also working to functionally modify sintered NdFeB magnets to minimize the use of dysprosium, and have shown that the coercivity (the magnetic field required to demagnetize the material) of commercially available sintered NdFeB may be enhanced by post-thermomagnetic processing in the presence of a high magnetic field. Manufacturers have also reported working on magnets that reduce or eliminate the use of dysprosium.[97]

Another approach for material substitution is to improve the properties of a potential material in order to create an economically viable substitute. Although some permanent magnet compounds may have magnetic strengths that are inferior to that of NdFeB, each alternative also has unique advantages. For example, ferrite magnets may have weaker magnetic strength, but they use abundant materials and are less costly to produce. SmCo and aluminum nickel cobalt (AlNiCo) both offer thermal stability superior to that of NdFeB.[98,99,100,101]

## System-Level Substitution

Substitution may also be made at the system level, thereby indirectly reducing the overall use of a critical material. For wind turbines, manufacturers may reduce the rare earth content through a range of design options. One option is the use of "hybrid drive" permanent magnet wind turbines, which use a permanent magnet generator in conjunction with a geared drive. Although these turbines operate at higher speeds than direct-drive turbines and require a more complicated gearing system, they reduce the required weight of the permanent magnet by 67% as compared to direct-drive turbines, reducing rare earth content commensurately. Hybrid drive turbines currently represent a small fraction of the wind turbine market, but could represent more than 50% of wind power generation over the next decade.[102]

Wind turbine manufacturers are also investigating options that drastically reduce or entirely eliminate the need for rare earth permanent magnets. One option is to reduce the operating temperature of the wind turbine so that the permanent magnets do not require the temperature stability enabled by dysprosium. To this end, Boulder Wind Power, with support from DOE Wind and Water Power Program's Next Generation Drivetrain Development Program, developed proof-of-concept designs for a unique "air core" stator for wind turbine drivetrains rated for 3-10 MW. The Boulder Wind Power advanced drivetrain enabled a cost of energy of less than $0.10/kWH in offshore applications by increasing the torque density by 70%, as compared to current state-of-the-art drivetrain technologies.[103] The elimination of dysprosium will reduce material costs and is part of a suite of innovations that the company is developing to lower production, installation, and operating costs compared to current wind turbines.[103] Another possibility is superconducting generator turbines, which do not use permanent magnets at all and show promise for turbines in the 10 MW+ range. Both American Superconductor and AML Superconductivity and Magnetics have developed sophisticated magnet systems for direct-drive superconducting generators.[104,105]

Electric vehicle manufacturers have explored several options to reduce or replace rare earth permanent magnet motors in vehicle designs. Some manufacturers are using induction motors,[106] which are larger than permanent magnet motors for a given power rating, but can provide advantages in the design, manufacture and operation.[107] Another option is to employ switched reluctance motors, which operate by electronically switching an electromagnetic stator field to drive an iron stator. Although switched reluctance motors have traditionally suffered from noise and vibration problems, advances in electronic control and precision machining of motor parts have made them more viable.[16] The DOE Vehicle Technologies Office *Advanced Power Electronics and Electronic Motors* program is developing alternatives to rare earth permanent magnet motors, such as AlNiCo for automotive traction motors and other industrial and commercial motors.[108] Within the Rare Earth Alternatives in Critical Technologies program at ARPA-E, projects focused on electric motors are seeking to design and prototype a 100 kW continuous and 200 kW peak electric vehicle traction motor that contains no REEs, yet meets or exceeds the performance of current rare earth element magnet motors.[109] Additional projects within this program focused on superconductors for 10 MW wind generators, aiming to increase in-field tape performance fourfold, enabling superconductor-based wind generators to compete in price and performance with rare-earth-element-based wind generators.[110]

## Improve Reuse and Recycling

The final pillar for reducing material criticality is to close the supply chain at the end of its useful life. Less than 1% of end-of-life products containing REEs are recycled,[111] due to an array of challenges described below. However, recycling of the critical materials that currently feed into clean energy products and their manufacture may ensure that the deployment of such products is not limited by materials supply.

One potentially large recycling stream for NdFeB permanent magnets is from the computer hard drives used in data centers. More than 33,000 metric tons of neodymium are produced each year for magnet manufacturing.[24] While a large number of products are recycled for their steel and aluminum content, less than 1% of magnets contained within consumer products are recycled, in part because the drives are shredded and the parts containing REEs are lost in the scrap.[112] However, if these magnets were reused or recycled, then this would increase the supply of both neodymium and NdFeB permanent magnets for use in clean energy technologies. Note that, although solid-state drives are gaining popularity, most data centers use and will continue to use traditional disc-based drives for the near future, as the cost per byte stored and the total storage volume are significantly greater for solid-state drives.[113]

To illustrate the magnitude of the permanent magnet waste stream from hard drives, consider a few examples of hard drive turnover in modern data centers:

- Facebook's data storage has grown threefold in the last year to around 300 petabytes (1 petabyte = $10^{15}$ bytes), increasing at 600 terabytes (1 terabyte = $10^{12}$ bytes) per day.[114]
- Amazon strives for 11 nines of reliability (99.999999999) for data, necessitating a significant number of hard drives for redundant data storage.[115]
- The National Security Administration (NSA) Utah Data Center will be able to handle unprecedented quantities of data, with estimates ranging from 5 zetabytes (1 zetabyte = $10^{21}$ bytes) to yottabytes (1 yottabyte = $10^{24}$ bytes).[116] The largest hard drive is currently 8 terabytes, so 5 zetabytes would require a minimum of 625 million hard drives.[116]
- Approximately one-third of the hard drive population is replaced annually.[117]

As an agency whose mission focuses on developing technology solutions, DOE concentrates on the technical challenges associated with recycling. Challenges for recycling rare earth permanent magnets from expired hard drives include: locating and extracting the magnets in a cost-effective manner[118] (such devices are not currently designed for disassembly[112]), processes to separate REEs from within the components (varied compositions and impurity levels may alter the recycling process), and the re-insertion of recycled materials back into the supply chain. The Center for Resource Recovery and Recycling (an NSF Industry/University Cooperative Research Center) is investigating cost-effective methodologies to separate rare earth permanent magnets from steel scrap and recover the rare earth metals by acid dissolution.[119] Recycling rare earth permanent magnets from other sources, such as wind turbines and electric vehicle motors, may become relevant once these technologies are widely deployed, enabling an economic recycling industry.

Additional non-technical challenges also exist: first, the value of this waste stream may be complicated by the fact that hard drive size is decreasing over time; whereas, for example, magnet size in wind turbines may increase with increasing turbine power. Second, recycling permanent magnets is challenging not because of chemical processing, but because collecting hard drive disks and isolating the permanent magnets in a cost-efficient manner is challenging. Finally, data centers prefer to shred hard drive disks for data security, further complicating magnet collection.

## What are the Next Critical Materials?

Material criticality is dynamic—while REEs are a challenge today, other materials may become critical in the future.[120] Consider the political unrest in Zaire in the 1970s and 1980s, which led to a shortage of cobalt, a vital element in the SmCo permanent magnets used in domestic aerospace and defense industries.[121] The cobalt shortage contributed to the development of substitutes, in turn assisting the development of NdFeB permanent magnets.[122] Another case study of dynamic criticality is that of tellurium, which DOE considered near-critical in 2011 for its use in cadmium telluride photovoltaic cells. However, a more recent analysis, which includes continued improvements in tellurium recovery and device efficiency and decreased thickness of the absorber layer, indicates that tellurium supply and demand may be less of a concern than earlier assessments indicated.[123]

Vigilant scrutiny of potential material criticality is required to avoid future materials supply disruptions. Since price is an incomplete indicator of criticality, current efforts focus on the root causes of potential supply disruptions: lack of diversity in supply chains, market complexities associated with co-production, slow demand response due to long development times for various steps in the supply chain, and other factors identified earlier. For example, CMI is currently re-assessing the criticality of energy-relevant materials and developing models to better understand the economic, environmental, and technical relationships along supply chains, as well as the potential impacts of CMI research on supply chains.[124] The DOE is supporting Argonne National Laboratory to develop a dynamic agent-based model that includes interacting agents at five NdFeB magnet supply chain stages consisting of mining, metal refining, magnet production, final product production and demand.[125] A version of this model is currently being applied to helium markets. In addition, DOE is supporting Argonne, Idaho, and Oak Ridge National Laboratories to develop a white paper that explores the vulnerabilities of energy supply chains at the systems level, considering temporal, spatial, and network dynamics. The Department of Defense assesses the potential for domestic challenges with strategic and critical non-fuel minerals every two years,[126] and recently reported on a risk mitigation strategy for REEs.[127] As part of a new Sustainable Chemistry, Engineering, and Materials cross-directorate initiative, the National Science Foundation is prioritizing the discovery of new science and engineering to allow for a safe, stable, and sustainable supply of chemicals and materials sufficient to meet future global demand.[128] GE, the first company to publish the results of a corporate criticality assessment,[129,130] continues to update its analysis.[131] Researchers at Yale University have conducted elemental life cycle analyses to characterize rates of recycling and loss, revealing criticalities in the substitute materials for 62 different metals.[132] The British Geological Survey last updated their Risk List, which provides a quick indication of the relative supply risk of a variety of elements, in 2012.[133] The European Commission has evaluated the criticality of 41 raw materials not produced in Europe yet essential to its current and future economic vitality,[134] and recently updated this analysis with additional materials and data;[135] and Germany has conducted their own study of the minerals necessary for the production of technologies that generate electricity, heat, and fuels from renewable sources up to 2050.[136]

**Table 6.F.6** Key Materials for Other Energy Technologies.

| Technology | Key Elements |
|---|---|
| Catalytic converters | Platinum, palladium, rhodium, cerium, lanthanum |
| Fuel cells | Platinum, palladium, rhodium, lanthanum, cobalt, cerium, yttrium, gadolinium |
| Gas turbines | Yttrium, rhenium, hafnium |
| Batteries for electric vehicles and storage | Lithium, vanadium, graphite, cerium, cobalt, manganese, nickel, terbium |
| Hydrogen electrolysis | Platinum, palladium, rhodium |
| Nuclear power | Indium, cobalt, gadolinium |
| Thermoelectrics | Tellurium, bismuth, cerium, cobalt, lanthanum, lead, tellurium, ytterbium |
| Vehicle light-weighting | Magnesium, titanium, gadolinium |

When considering other energy technologies, some key materials have emerged as candidates for criticality in the near-term (Table 6.F.6).[3,16,137,138] Further, materials essential to the manufacture of clean energy technologies, but are not present in the final products, may also require oversight. Examples of such manufacturing materials include tungsten,[139] bismuth,[140] helium,[5] and catalytic materials for chemical production.[3]

Finally, there are materials that complicate the supply chains of other materials due to their over-abundance, known as the balance problem (above). For example, cerium and lanthanum are currently produced in excess of their demand because of their over-abundance in domestic rare earth deposits. Thus, mining for valuable heavy REEs (such as dysprosium) results in the saturation of the cerium and lanthanum supply chains. Toxic materials may also be considered overly abundant in minute quantities, creating supply chain challenges for manufacturers.

For example, when the European Union restricted the use of certain hazardous substances[141] such as lead, this created a market for lead-free solder and bearings that replace lead with bismuth. However, bismuth has potential supply chain risks, primarily due to the concentration of its production.[140] Further, bismuth is a secondary product from lead mining, so a reduction in primary lead production may reduce the supply of bismuth.

## Program Considerations to Support R&D

### R&D Goals, Strategies, Pathways, and Enabling Science Activities

A variety of technical challenges and opportunities exist in the field of critical materials. To start, a comprehensive understanding of the intricate life cycles of materials will aid in the identification of supply chain bottlenecks. An increased understanding of the basic materials properties, such as the role of f-orbital electrons in the unique properties of REEs, is necessary to transform the full materials lifecycle. Current computational tools face severe limitations when attempting to model the behavior of f-electrons for properties such as magnetism or luminescence. The development of substitutes is challenging, as finding candidate materials requires exploring a large composition and phase space. Improving these computational tools and methods, combined with rationally designed experiments, may enhance the discovery of comparable substitutes and process modeling to optimize performance.[142,143] Innovations in the separation and processing of complex ore bodies into the high-purity critical materials may facilitate more selective, efficient, economical, and environmentally-friendly solutions to critical materials supply needs. A redesign of existing energy systems, including a consideration of end-of-life recovery, could dramatically reduce or even eliminate the need for critical materials, thus creating a disruptive technology based on replacement or reduction.

### DOE R&D Partnerships and Stakeholder Engagement

DOE co-chairs an *Interagency Working Group on Critical and Strategic Minerals Supply Chains* with the White House Office of Science and Technology Policy. This group examines issues including market risk, critical materials in emerging high-growth industries and opportunities for long-term benefit through innovation, and works to develop a coordinated, cross-government critical materials agenda.[16] Such interagency collaboration enables DOE to charter the direction of its own activities. This group recently engaged stakeholders through a request for information to solicit feedback from industry, academia, research laboratories, government agencies, and other stakeholders on issues related to demand, supply and supply chain structure, R&D, and technology transitions related to raw materials (including, but not limited to, minerals and gases) used in the U.S. economy.[144]

International cooperation on critical materials challenges can help all countries achieve their clean energy goals, and DOE has thus organized several workshops with the European Union (EU), Japan, Australia and Canada to identify possible research and development collaborations. The most recent of these meetings was the Annual Trilateral U.S.-EU-Japan workshop, where more than 70 participants discussed common challenges and potential collaborations in critical materials for clean energy applications (Figure 6.F.6). [145] DOE is also pursuing international information sharing to help improve transparency in critical materials markets, and ongoing engagement with international partners through dialogues and collaborative institutions is important.[16]

**Figure 6.F.6** A Panoramic View of Workshop Attendees from the United States, the European Union, Japan, and Other Countries.

Credit: Critical Materials Institute

## Risk and Uncertainty, and Other Considerations

A material's criticality depends on its risk of supply disruption and its societal importance;[3] thus, uncertainties associated with critical materials arise from dynamic market forces. Many challenges may be addressed by conducting research and development aimed at diversifying supply, developing substitutes, and improving recycling. However, some challenges elude this holistic approach, as briefly outlined in this section.

Lacking rare earth element supply diversity is a prominent risk for the United States, which is heavily dependent on relatively few foreign suppliers for all products along the rare earth permanent magnet supply chain. Potential supply disruptions may arise from a small global market, market complexities caused by co-production, and geopolitical risk. New mining projects may also face regulatory uncertainty, creating challenges with capital financing and production timelines. Illegal mining creates deposits that are uneconomical to develop because the illegal activities target the high-grade portions, rather than developing the entire resource as a portfolio of grade qualities.[146] Further, illegal mining and black markets also increase the opaqueness of markets.

Fluctuating demand may also cause market instabilities. For example, increasing deployment of clean energy technologies could substantially increase the demand for key materials that may be required for other technologies, creating competition between sectors. Competition may also be caused by applications employing critical materials at different rates and with different price sensitivities—for example, increasing demand for billions of small rare earth permanent magnets in handbags (low price sensitivity) may drive up the individual metal price through a significant leverage of unit sales, complicating the economics for very large magnets for wind turbines (high price sensitivity). Alternatively, reduced demand due to improved substitutes, recycling techniques, or use efficiency may further destabilize small global markets by creating material extraction environments that are uneconomical. Technology development and tax incentives (such as investment and production tax credits) may also alter demand or create demand uncertainty.

Some critical materials have no substitute, making supply disruptions even more inhibitive. The uniqueness of a material may also arise from the early stages of product development, as many industry sectors ignore materials criticality, instead designing devices to optimize performance and cost. The high-performance materials adopted at the laboratory scale may be imbedded into early prototypes, making them integral to the final commercialized product.

## Case Studies

### Development of Manganese Bismuth-Based Permanent Magnet[147]

Manganese bismuth (MnBi) is being explored as an alternative to the permanent magnets containing REEs, such as neodymium iron boron (NdFeB) and samarium cobalt (SmCo), for medium temperature applications (423-473 K). MnBi has unique properties: its coercivity increases with increasing temperature over the temperature range of 150–550 K,[148,149] whereas the coercivity of most magnetic materials decreases with temperature.[150] In practice, the maximum theoretical energy product of a single-phase MnBi is higher than magnets such as ferrite and AlNiCo, but is only half of that of NdFeB and SmCo. To best utilize MnBi's unique high temperature properties, MnBi should be used as a hard phase to be exchange-coupled with a soft phase, so that the remnant magnetization can be improved while the coercivity is maintained, resulting in an increased maximum energy product.

The technological challenges for developing a MnBi-based exchange-coupled magnet are threefold: prepare high purity MnBi compound in large quantity, encourage exchange coupling between MnBi and soft phases such as Fe and Co, and fabricate bulk nanocomposite magnet with fine grain size, uniform phase distribution, and a high degree of texture. Supported by the ARPA-E REACT program, a team of scientists across eleven organizations has made significant progress on these challenges.

- Large quantities of high purity MnBi single-phase particles can be produced. Each batch weighs about 8 lbs, with average particle sizes ranging from 0.5 to 2 µm.
- Instead of fabricating particles by melt spinning, which is an inefficient and expensive method, a conventional thermal-mechanical treatment that is compatible with the current industrial practice has been developed.[151]
- Under the guidance of theoretical calculation, the exchange coupling of a MnBi and Co double-layer thin film exhibited an energy product of about 25 MGOe. In parallel to this thin film effort, MnBi-Co core-shell particles were also synthesized by colloidal synthesis, where the Co layer can be controlled to ~20 nm and the overall magnetization exceeded 80 emu/g.[152] After alignment, the energy product of the powder reached 12.1 MGOe, and that of the sintered bulk magnet reached 8.6 MGOe at room temperature.[153] In comparison, Table 6.F.7 shows commercially available magnets and the typical energy product ranges for these materials.

**Table 6.F.7** Typical Energy Product Ranges of Commercially Available Magnets (at Room Temperature)

| Magnet material | Typical Energy Product Range (MGOe) |
|---|---|
| Aluminum-nickel-cobalt | 1-8 |
| Ferrite | 3-4 |
| Samarium-Cobalt | 15-30 |
| Neodymium-Iron-Boron | 25-50 |

## Demonstration of New 30-Stage Solvent Extraction Separation Processes for Critical Materials

Separating a complex mixture of REEs into pure, individual components is extraordinarily difficult and expensive because the adjacent REEs have nearly identical ionic radii and chemical properties. CMI is developing and evaluating new solvent extraction (SX) processes that have the potential to significantly improve the economics of recovery and/or separations of the REE, thereby addressing a major gap in the domestic REE supply chain. A newly installed solvent extraction demonstration facility located at Idaho National Lab is now being utilized for engineering-scale evaluations of candidate separation systems (Figure 6.F.7).

**Figure 6.F.7** Solvent Extraction Demonstration Facility Located at Idaho National Lab.

Credit: Idaho National Laboratory

Highlights of this work include:

- Initial process testing in the demonstration facility focused on the separation of heavy REE (elements holmium through lutetium) and yttrium (Y) from middle REE (elements samarium through dysprosium). Significant quantities of Y occur in rare earth ores, and that Y behaves very much like the heavy REE in SX schemes. A simulated feed concentrate consisting of 60 wt % gadolinium (Gd, representative of middle REE), 30 wt % Y, and 10 wt % holmium (Ho, representative of heavy REE) has been used in the tests to study the middle/heavy/Y cut. Less than 2% of the Gd was found in the Ho/Y (heavy) product, and well under 1% of the Ho/Y remained in the Gd raffinate (or middle product) using the industry standard extractant.
- A new extractant, developed by industrial partner Cytec, will be tested next to demonstrate that significant savings can be achieved in acid and base consumption, a major cost component, when compared to the industry standard conditions.

New extractants are currently being designed by computational molecular modeling in the CMI. In the future, these new extractants will be tested in the demonstration facility to dramatically reduce equipment size and processing costs, ultimately reducing costs for the production of purified REE for clean energy applications.

## Fluorescent Lighting with Greatly Reduced Critical Rare Earth Content

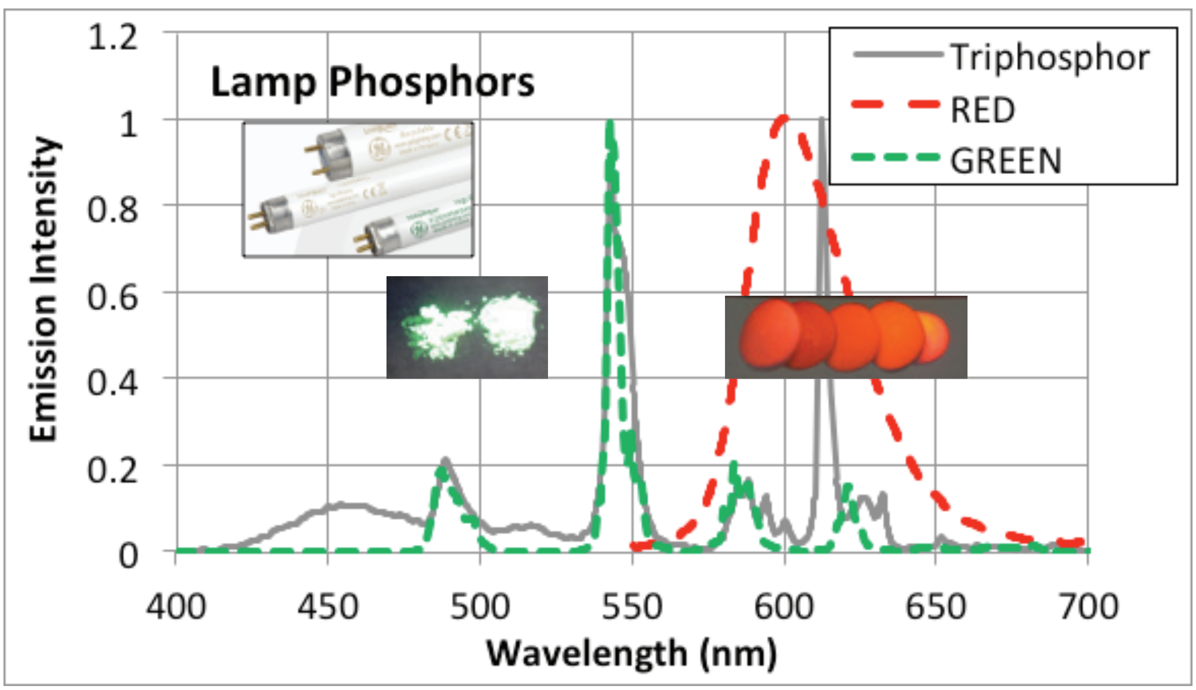
The phosphors in fluorescent lighting currently consume 500 metric tons of critical rare earth oxides in the United States, including Europium, Terbium, Yttrium, and Lanthanum (Eu, Tb, Y, and La). While LED lighting will likely eventually replace fluorescent tubes, low-cost linear fluorescent lighting is expected to remain a dominant feature in our infrastructure for more than a decade into the future. It is both prudent and necessary to replace the current triphosphor blend discovered over 30 years ago (based on a mixture of blue, green and red emitters), with alternatives having very low or zero rare earth usage. General Electric (GE), Lawrence Livermore National Laboratory (LLNL) and Oak Ridge National Laboratory (ORNL) are working together through the Critical Materials Institute to reduce the amount of REEs required for fluorescent lighting products.

Highlights of this work include:

- The CMI team has identified a green phosphor which reduces the Tb content by 90% and eliminates La and a red phosphor which eliminates both Eu and Y. These proposed phosphors appear to meet stringent requirements of long lamp survivability, high efficiency, precise color rendition (Figure 6.F.8), and low-cost. The commercially available blue phosphor has inherently low rare earth content and need not be replaced.
- The feasibility of utilizing these developed phosphors for commercial lighting will be assessed by evaluating chemical issues related to slurry compatibility and to improve the fabrication procedures.

**Figure 6.F.8** Emission Properties of the Developed Red and Green Phosphors (See Lower Two Photographs), as Compared to a Commercial Triphosphor Blend Commonly Used in Linear Fluorescent Lamps (Upper Photograph).

Credit: Critical Materials Institute



## High-Value Recycling Technology

Rare earth magnets are manufactured in significant quantities for use in consumer products and industrial machinery; for example, nearly 1 billion computer hard disc drives (HDDs) containing rare earth are manufactured annually, half of which are deployed in data centers. Many HDDs are recycled annually by shredding, an efficient and cost-effective recycling method for large volumes of materials. However, shredding also complicates the separation of outputs—of the various components contained within a large format (3.5”) HDD (~75.7% aluminum, ~13.3% steel, ~1.9% magnets, ~5.7% permalloy and ~3.4% printed circuit boards), only aluminum and steel are primarily recycled. Fully recycling the remaining components may allow the recovery of valuable materials, such as rare earths (neodymium, praseodymium and dysprosium), copper, silver, and gold.

CMI is developing cost-effective recycling technology, reclaiming the maximum value from end-of-life products. Within CMI, Oak Ridge National Laboratory (ORNL) researchers are partnering with Lawrence Livermore National Laboratory (LLNL), Idaho National Laboratory (INL), Colorado School of Mines (CSM), and others to develop technologies to recycle HDDs.

Highlights of this work include:

- CMI has developed an efficient 5-step process for HDD recycling: sorting by size, aligning, shearing off the printed circuit boards, punching out magnets, and separating the process outputs.
- The CMI system separately recovers magnets, their permalloy brackets, printed circuit boards, aluminum and steel from millions of HDDs, while destroying the data storage media to ensure data security.

The economic viability of recycling complex, high technology products like HDDs must be demonstrated to ensure commercial adoption. CMI’s process enables material specific revenue streams: magnets are recovered intact, enabling direct reuse, alternate uses (resized or reshaped magnets) or processing back to rare earth metal. Direct reuse of premium magnets avoids significant energy and environment costs, as compared to reprocessing. The CMI goal is recycling 1 HDD/sec, totaling >5 million HDDs/system annually.

## Endnotes


1 “Do we take minerals for granted?” U.S. Geological Survey: Mineral Resources Program. http://minerals.usgs.gov/granted.html

2 U.S. DOE, “The Department of Energy’s Critical Materials Strategy.” 2010 and 2011. Available at: http://energy.gov/epsa/initiatives/department-energy-s-critical-materials-strategy

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4 Zepf V., Simmons J., Reller A., Ashfield M., and Rennie C., “Materials critical to the energy industry: an introduction.” 2nd edition. London: BP, 2014. http://www.bp.com/content/dam/bp/pdf/sustainability/group-reports/ESC_Materials_handbook_BP_Apr2014.pdf

5 American Physical Society (APS) and the Materials Research Society (MRS), “Energy Critical Elements: Securing Materials for Emerging Technologies.” Washington, DC: APS Panel on Public Affairs, 2011. Available at: https://www.aps.org/policy/reports/popa-reports/upload/elementsreport.pdf

6 Eggert R.G., Brown M., Jordan B., Lee S.K., Muta T., Smith B.. “Material Criticality for Clean Energy Technology: Medium-Term Assessment.” Draft report. Critical Materials Institute, October 2014.

7 U.S. DOE, “The Department of Energy’s Critical Materials Strategy.” 2010 and 2011. Available at: http://energy.gov/epsa/initiatives/department-energy-s-critical-materials-strategy. Note that the Critical Materials Strategy did not consider fuel cells or light emitting diodes (LEDs).

8 Moss R.L., Tzimas, E., Willis P., Arendorf J., Tercero Espinoza L., et al., “Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector.” Luxembourg: Publications Office of the European Union, 2013. Available at: https://setis.ec.europa.eu/sites/default/files/reports/JRC-report-Critical-Metals-Energy-Sector.pdf

9 Lighting materials include elements that provide important properties to commercially viable Compact Fluorescent Lamps (lamps and phosphors) and LED (semiconductor chips and phosphors) technologies, as discussed in:

- U.S. DOE, “The Department of Energy’s Critical Materials Strategy.” 2011. Available at: http://energy.gov/epsa/initiatives/department-energy-s-critical-materials-strategy

- Moss R.L., Tzimas, E., Willis P., Arendorf J., Tercero Espinoza L., et al., “Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector.” Luxembourg: Publications Office of the European Union, 2013. Available at: https://setis.ec.europa.eu/sites/default/files/reports/JRC-report-Critical-Metals-Energy-Sector.pdf
- U.S. Geological Survey, “Byproduct Metals and Rare-Earth Elements Used in the Production of Light-Emitting Diodes—Overview of Principal Sources of Supply and Material Requirements for Selected Markets.” 2012. Available at: http://pubs.usgs.gov/sir/2012/5215/

[10] Constantinides, S., "The demand for rare earth materials in permanent magnets." Presented at the 51st Annual Conference of Metallurgists, Niagara Falls, Ontario, October 2012.

[11] Vehicles materials are based on those materials which provide important properties to batteries and permanent magnets, as discussed in:

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[13] MMTCE avoided from deploying the given technology with respect to a reference technology in a given scenario. Range represents the highest and lowest estimates calculated from various scenarios. Source: Own calculations based on Energy Information Administration Annual Energy Outlook (AEO) 2014. High case assumes in 2030 a: 50%/50% split of the total solar market for CdTe/CIGS (high case for silicon assumes an 85% solar market share), and 75% of onshore wind from direct drive in addition to the assumptions of AEO’s GHG25 scenario; 100,000 BEV, 217,000 PHEV, 840,000 HEV, and 7,000 FCV vehicles sold per year, respectively, in addition to AEO’s HWOP scenario. Low case assumes in 2030: 10%/5% split of the total solar market for CdTe/CIGS (low case for silicon assumes it has been totally replaced by CdTe/CIGS panels by 2030), respectively, and 15% of onshore wind from direct drive in addition to the assumptions of AEO’s LEG scenario; 62,000 BEV, 140,000 PHEV, 648,000 HEV, and 6,000 FCV vehicles sold per year, respectively, in addition to AEO’s LEG scenario. Lighting estimates are based on McKinsey and Company, “Lighting the Way: Perspectives on the Global Lighting Market,” 2012. Available at: http://www.2012.smartlighting.org/pdf/MCKINSEY_LIGHTING_THE_WAY_AHEAD.pdf

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# Acronyms

| | |
|---|---|
| **CdTe** | Cadmium telluride |
| **CFL** | Compact fluorescent lighting |
| **CIGS** | Copper indium gallium selenide |
| **CMI** | Critical Materials Institute |
| **emu/g** | Electromagnetic units/gram |
| **EV** | Electric vehicle |
| **HDD** | Hard disc drive |
| **LFL** | Linear fluorescent lighting |
| **LED** | Light emitting diode |
| **MGOe** | Mega-Gauss-Oersted |
| **MnBi** | Manganese bismuth |
| **MMTCE** | Million metric tons of carbon equivalent |
| **NdFeB** | Neodymium iron boron |
| **NiMH** | Nickel metal hydride |
| **OLED** | Organic light emitting diode |
| **REACT** | Rare Earth Alternatives in Critical Technologies |
| **REE** | Rare earth element |
| **REO** | Rare earth oxide |
| **SmCo** | Samarium cobalt |
| **SX** | Solvent extraction |
| **USGS** | United States Geological Survey |

# Glossary

| | |
|---|---|
| **Coercivity** | The resistance of a material to demagnetization |
| **CIGS PV** | A thin-film photovoltaic cell based on copper indium gallium selenide (CIGS) |
| **CdTe PV** | A thin-film photovoltaic cell based on cadmium telluride (CdTe) |
| **emu/g** | Unit that expresses the mass magnetization of a material, where 1 emu/g = 1 Amp-meter$^2$/kilogram |

| | |
|---|---|
| **Energy product (in reference to magnets)** | The amount of energy stored in a magnet; can be expressed in units of MGOe |
| **Exchange-coupled magnet** | Composites of hard and soft magnetic materials, known as exchange spring magnets, are being developed as substitutes for rare earth permanent magnets. Hard magnets have a large coercivity. Soft magnets have a small coercivity, but are easily magnetized. Careful control of the architecture of the hard-soft composite can enable exchange spring coupling of the materials, creating enhanced magnetic properties. |
| **Ligand (in inorganic chemistry)** | The atoms or groups of atoms joined to a central metal atom to form an inorganic coordination complex. Most metal-containing compounds and metalloids are coordination complexes. |
| **Permanent magnet** | A magnet that retains its magnetism in the absence of a magnetic field or current. Examples of permanent magnets include samarium cobalt (SmCo) and neodymium iron boride (NdFeB) |
| **Rare earth element (REE)** | Includes the 15 elements in the lanthanide series on the periodic table (elements with atomic numbers 57-71). Scandium and yttrium are also included as rare earth elements as they are often found in ore deposits with the lanthanides. |
| **Rare earth oxide** | An oxide of a rare earth element. REE production is often represented in terms of rare earth oxides (REO), as many REE materials are often sold in oxide form (e.g., cerium is commonly available as cerium oxide, or $CeO_2$). |
| **Separation factor** | A measure of the ability of a system to separate two solutes. A higher separation factor represents a higher separation efficiency, typically corresponding to fewer separation stages. |