Critical Materials: Technology Assessment

Contents

1. 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. These materials are considered “critical” if they have or may have supply challenges, such as a small global market, lack of supply diversity, market complexities caused by co-production, or geopolitical risks. The Department of Energy defines a material’s criticality by considering its importance to clean energy applications, as well as any supply challenges. This technology assessment will identify materials defined as critical by the Department of Energy 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 they use each year, including those of particular interest in the Department of Energy.[1] A variety of critical materials enable clean energy technologies such as wind turbines, electric vehicles, and energy-efficient lighting (see Table 1). These clean energy technologies in turn reduce carbon pollution that contributes to climate change.

A special class of minerals critical to clean energy technologies, rare earth elements, represents an industry comprised of $795 million in shipments and 1,050 workers in North America. The multitude of end-use products and technologies relying on rare earth elements further constitutes $329.6 billion in economic output and 618,800 workers.[2] The United States is currently 59% dependent on imports to meet its domestic needs for rare earth elements, 75% of which is imported solely from China.[3] Such a strong dependence on foreign imports has the potential to drive a shortage of materials required for national security,[4] such as the magnets containing rare earth elements used for domestic fighter jets.[5] Further, rare earth elements have a history of price volatility: the prices for rare earth elements increased more than ten-fold from 2010 to 2011.[6, 7] Although prices have largely recovered from this price shock, fears of future price volatility have led some manufacturers to reduce their usage of rare earth elements, rather than taking advantage of the unique properties that could contribute to developing and deploying clean-energy technologies.

Table 1. Examples of elements important to selected clean energy applications.[8] An asterisk (*) denotes elements that were not considered in the Department of Energy Critical Materials Strategy.[9] (Note that the Critical Materials

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[1] USGS website, http://minerals.usgs.gov/granted.html

[2] RETA The economic benefits of the North America Rare Earths Industry

[3] USGS. Import reliance is defined as estimated consumption minus production of mineral concentrate, because of insufficient data available to determine stock changes and unattributed imports and exports of rare earth materials. Production of concentrate was based on Molycorp's production.

[4] Kent Hughes Butts. Is China’s Consumption a Threat to United States Security? Center for Strategic Leadership Issue Paper, vol 7-11, Jul 2011. http://www.csl.army.mil

[5] Exclusive: U.S. waived laws to keep F-35 on track with China-made parts http://www.reuters.com/article/2014/01/03/us-lockheed-f-idUSBREA020VA20140103

[6] http://www.nytimes.com/interactive/2013/10/22/business/a-bubble-bursts.html?_r=0

[7] 5 years after crisis, U.S. remains dependent on China's rare earth elements. Energy Wire. David Ferris, January 12, 2015

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

Strategy did not consider fuel cells and light emitting diodes (LEDs).) EV = electric vehicles, NiMH = nickel metal hydride, and Li = lithium.

	Wind	Vehicles			Lighting	
Element	**Direct Drive**	**EV-NiMH**	**EV-Li ion**	**Fuel Cells**	**Fluorescent**	**LED**
Cerium		X			X	X
Cobalt		X	X			
Dysprosium	X	X	X			
Europium					X	X
Gallium						X
Germanium*						X
Indium						X
Lanthanum		X			X	
Lithium			X			
Manganese			X			
Neodymium	X	X	X			
Nickel		X	X			X
Platinum*				X		
Praseodymium		X				
Samarium	X	X	X			
Silver*						X
Tellurium						
Terbium					X	
Tin*						X
Yttrium					X	X

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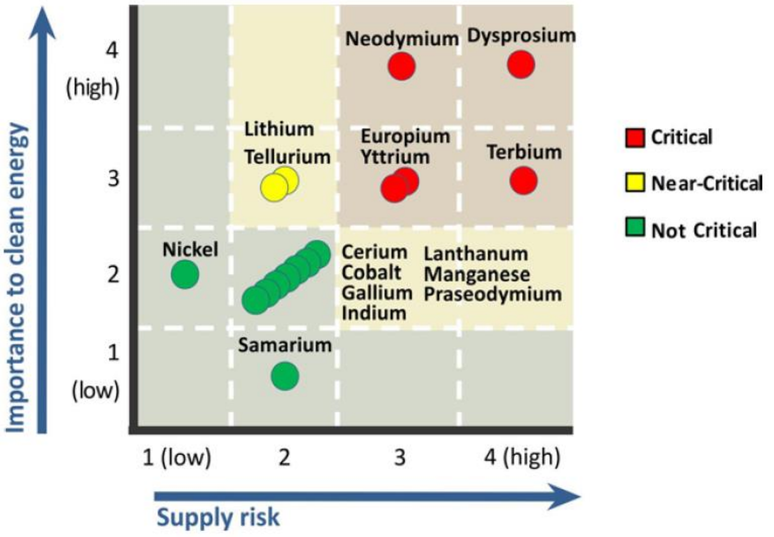
[9] Critical Materials Strategy. The Department of Energy, 2010 and 2011.

As part of its efforts to advance a clean energy economy, the Department of Energy authored a comprehensive Critical Materials Strategy to build on the Department's prior research and to inform future endeavors.[10] 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[11] by considering supply risk with societal importance for clean energy technologies. The most recent criticality assessment by the Department of Energy is shown in Figure 1, along with a similar analysis performed by the European Commission. As evidenced by the charts in Figure 1, the criticality of a material strongly depends on how criticality is defined. Additional studies of material criticality exist, including those referenced here.[12, 13]



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		

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[10] Critical Materials Strategy. The Department of Energy, 2010 and 2011

[11] Minerals, Critical Minerals, and the U.S. Economy. National Research Council, 2008.

[12] Materials critical to the energy industry, 2nd edition. www.bp.com/energysustainabilitychallenge

[13] Energy Critical Elements: Securing Materials for Emerging Technologies. APS, MRS. http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0CCgQFjAB&url=http%3A%2F%2Fwww.aps.org%2Fpolicy%2Freports%2Fpopa-reports%2Fupload%2Felementsreport.pdf&ei=cwi4VPy6GdOOyASH-YDABw&usg=AFQjCNF5ImiE6LsA8b0-n7umyzmfikZ2bA&sig2=x74OHGrBF9WPvN0wGy68Kw&bvm=bv.83640239,d.aWw&cad=rja

Figure 1. (top) Medium-term (from 2015 to 2025) criticality matrix for elements important to wind turbines, electric vehicles, photovoltaic cells, and fluorescent lighting. [14] (bottom) Criticality ratings of shortlisted raw materials.[15]

2. Technology Assessment and Potential

This section reviews the major trends within selected clean energy applications that are driving future materials criticality. A research and development strategy is introduced, which optimizes the supply chain by diversifying supply, developing substitutes, and improving reuse and recycling. This chapter focuses on rare earth elements because of their unique properties that enable clean energy technologies (put another way, substitution may be extremely difficult) and because of their particular supply chain risks. However, criticality is dynamic, so other key materials that may become critical in the future will also be considered in this section.

2.1 Major Trends in Selected Clean Energy Application Areas

The functionality of clean energy applications such as permanent magnets (such as for wind turbines and electric vehicles) and phosphors depend in many cases upon the unique properties of rare earth elements. The estimated demand of rare earth oxides for these applications is shown in Figure 2, and for additional applications in Table 2. Permanent magnets and phosphors for clean energy applications, and their impact on rare earth element criticality, are detailed here.

Figure 2. Estimated demand of rare earth oxides for selected clean energy applications.[16]

Table 2. Estimated demand of rare earth oxides for all applications.[17]

Table 3. Preliminary global rare earth oxides supply and demand forecast for 2010-2020.[18] Note that data is in tons of rare earth oxides (with an error of ±20%), and that the data for 2020 is preliminary.

2.1.1 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 rare earth elements, such as dysprosium, praseodymium, and terbium.[19, 20] 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.[21, 22] The total mass of rare earth elements used depends

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[14] Critical Materials Strategy. The Department of Energy, 2011.

[15] http://setis.ec.europa.eu/system/files/Critical%20Metals%20Decarbonisation.pdf

[16] Dudley Kingsnorth. DO NOT DISTRIBUTE.

[17] Dudley Kingsnorth. DO NOT DISTRIBUTE.

[18] Dudley Kingsnorth. DO NOT DISTRIBUTE.

[19] Critical Materials Strategy. The Department of Energy, 2010

[20] London, I.M. 2010. "The delicate supply balance and growing demand for rare earths." Slideshow presented at Magnetics Economic Policy Photovoltaic Manufacturing Symposium, Washington, DC, July 29, 2011.

[21] Critical Materials Strategy. The Department of Energy, 2010

[22] Electron Energy Corporation. 2010. "Response to Department of Energy request for information." June 7, 2011.

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.[23]

The growing deployment of wind turbines and electric vehicles[24, 25] contributes to the rising demand for these rare earth elements.[26] 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.[27] Below are synopses of the major trends in these two applications that may influence the demand for rare earth elements.

Two global trends are driving the growing incorporation of rare earth elements into the permanent magnets found in wind turbine generators. First, the overall industry is transitioning towards larger, more powerful turbines to meet the demands of high-power renewable energy.[28] 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[29] 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.[30] Siemens has announced that it will use direct drive technology for its forthcoming offshore units,[31] while GE continues to manufacture wind turbines with induction generators.

Currently, the domestic wind turbine fleet uses negligible amounts of rare earth elements—for example, of the more than 48,000 utility-scale units currently operating in the United States,[32] only 377[33] are direct drive units that employ rare earth elements.[34] The low usage of rare earth elements 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 rare earth elements.

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[23] Critical Materials Strategy. The Department of Energy, 2010

[24] IEA, Energy Technology Perspectives.

[25] IEA, World Energy Outlook.

[26] The Role of Chemical Sciences in Finding Alternatives to Critical Resources Workshop. The National Academy of Sciences, Sep 29-30, 2011.

[27] Alonso, et al. Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. Environmental Science & Technology 3406-3414 (2012).

[28] Revolution Now http://cms.doe.gov/sites/prod/files/2014/10/f18/revolution_now_updated_charts_and_text_october_2014_1.pdf

[29] http://energy.gov/eere/wind/offshore-wind-advanced-technology-demonstration-projects

[30] Md. Rabiul Islam, Youguang Guo, and Jianguo Zhu, “A review of offshore wind turbine nacelle: Technical challenges, and research and developmental trends,” Renewable and Sustainable Energy Reviews 33, 161-176 (2014).

[31] http://www.energy.siemens.com/hq/en/renewable-energy/wind-power/platforms/

[32] AWEA U.S. Wind Industry Annual Market Report Year Ending 2013.

[33] AWEA.

[34] 278 of the direct drive turbines are >1 MW. AWEA counted the 100 kW Northern Power Systems turbines in their utility-scale classification up until 2011.

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.[35] Total domestic sales of electric vehicles in the model year 2013 nearly doubled those of 2012.[36] In fact, the United States leads the global stock of plug-in hybrid electric vehicles, representing 70% of the global stock in 2012.[37] 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,[38] 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, Tesla may have chosen this technology in part due to supply chain concerns.

2.1.2 Phosphors for Energy-Efficient Lighting

Lighting is projected to account for approximately 11.8% of electricity use in U.S. buildings in 2015,[39] 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. However, these more efficient, spectrally complete, and visually pleasing lamps may utilize rare earth elements to achieve various lighting effects. For example, fluorescent lamps require phosphors that may include lanthanum, cerium, europium, terbium and yttrium. Further, rare earth elements 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 the Department of Energy delayed the phase-out date for a particular type of fluorescent lamp because of supply concerns.[40] LEDs, OLEDs and halogens use significantly less or no rare earth elements as compared to fluorescent lamps;[41] 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 the rare earths was projected to nearly double between 2011 and 2013 (Figure 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.[42] There has already been some

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[35] Critical Materials Strategy. The Department of Energy, 2011
[36] http://energy.gov/sites/prod/files/2014/02/f8/eveverywhere_road_to_success.pdf
[37] http://www.cleanenergyministerial.org/Portals/2/pdfs/EVI_GEO_2013_FINAL_150dpi.pdf
[38] http://energy.gov/articles/president-obama-launches-ev-everywhere-challenge-part-energy-department-s-clean-energy
[39] http://buildingsdatabook.eren.doe.gov/docs/DataBooks/2011_BEDB.pdf
[40] http://energy.gov/sites/prod/files/oha/EE/EXC-12-0001thru03.pdf
[41] Critical Materials Strategy. The Department of Energy, 2011
[42] Critical Materials Strategy. The Department of Energy, 2011

indication of tightening demand leading to higher prices, and several lighting manufacturers introduced rare earth surcharges in 2011.[43, 44]

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 rare earth elements for phosphors beyond 2013. LED bulbs are already available on the consumer market, designed to fit directly into existing light sockets. These LED bulbs are competitively priced when considering the total life cycle, although their demand is expected to grow further once their unit price declines to that of traditional incandescent or compact fluorescent light bulbs.[45, 46] 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.

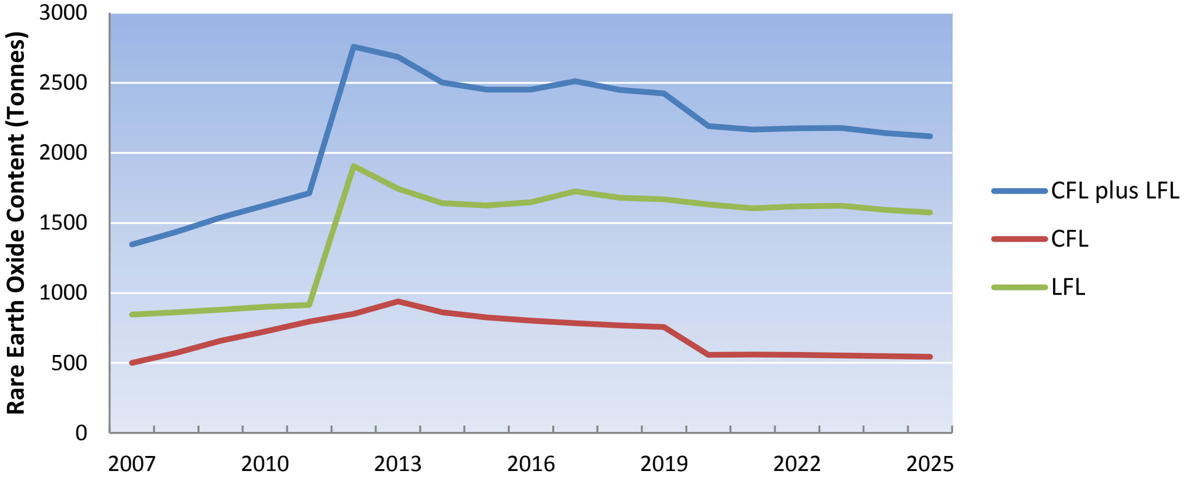

Figure 3. Projected rare earth oxide content in domestic shipments of compact and linear fluorescent lights (CFL and LFL, respectively).[47]

Retrofits into existing linear fluorescent lamp fixtures are complicated by differences in bulb dimensions, fixture design, and lighting characteristics. Likely, LEDs will be used in new commercial and industrial buildings at a much higher rate than in retrofitting existing buildings, as new buildings could be designed with the unique characteristics of LED lighting in mind. However, even a modest transition from linear fluorescent lamps to LEDs will reduce domestic demand for rare earth elements in phosphors, as shown in Figure 4. The DOE employed a model used for the 2009 National Impact Assessment of U.S. lighting standards, and considered the effect of adoption and deployment of emerging technologies, such as LEDs.[48] By 2025, accelerated adoption and deployment of emerging technologies will reduce the rare earth element demand by 13.5% as compared to a business-as-usual scenario. This difference highlights the impact of technology transitions on material demand over time.

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[43] GE (General Electric). 2010. "Response to DOE request for information."

[44] Sylvania. 2011. "Rare earth phosphor crisis." Sylvania. Accessed October 17, 2010. http://www.sylvania.com/Phosphors/

[45] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2014_web.pdf

[46] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mfg_roadmap_aug2014.pdf

[47] Critical Materials Strategy. The Department of Energy, 2011

[48] For a detailed description of the model, see http://www1.eere.energy.gov/buildings/appliance_standards/residential/incandescent_lamps_standards_final_rule_tsd.html.

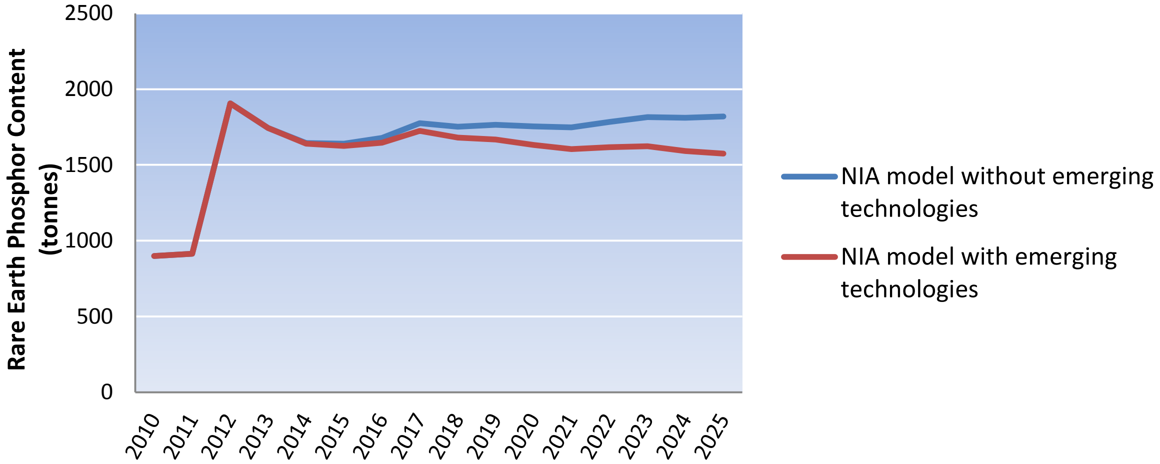

Figure 4. Comparison of domestic rare earth oxide demand from linear fluorescent lamp phosphors under different assumptions for emerging technology market penetration.[49]

2.2 Materials Supply Chain Challenges and Opportunities

Major barriers exist along the entire supply chain of critical materials. Rare earth elements, for example, have supply chains that are notoriously challenging, as exemplified by permanent magnets (Table 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.[53, 54] Perhaps for these reasons, the world's largest producer of rare earth elements does so as by-products of iron ore deposit development. Although spikes in the prices of rare earth elements garnered significant attention around 2010,[55] the root cause of the criticality of rare earth elements is in fact the lack of diversity in the supply chain. To fully address the challenges associated with these specific critical materials, a holistic view of the entire supply chain is required. A secure, sustainable domestic supply chain needs to be developed to allow the invention, manufacturing 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.

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[49] Critical Materials Strategy. The Department of Energy, 2011

[50] http://investorintel.com/wp-content/uploads/2013/08/AusIMM-CMC-2013-DJK-Final-InvestorIntel.pdf

[51] "Supplies of rare earth materials are still far from secure" http://theconversation.com/supplies-of-rare-earth-materials-are-still-far-from-secure-33156

[52] Rare earth market outlook: supply, demand, and pricing from 2014-2020. Chapter 7: Unregulated rare earth mining and processing. Adams Intelligence: Critical Metals and Minerals Research. October 1, 2014.

[53] http://www.molycorp.com/investors

[54] http://investorintel.com/wp-content/uploads/2013/08/AusIMM-CMC-2013-DJK-Final-InvestorIntel.pdf

[55] Mark Humphries. "Rare earth elements: the global supply chain." Congressional Research Service, December 16, 2013.

Table 4. NdFeB permanent magnet supply chain steps and major barriers.

Supply chain step	**% in China**		**Major barriers**	**Updates since 2011**	**DOE R&D Investments since 2011**
	2010[56]	**Current[57]**			
1. Mining, milling, and concentrating ores	97%	80-85%	• Significant capital expenditure and permitting time for new mines • Must work with given deposit geology	New mines in U.S.[58] and Australia,[59] which produce predominately light rare earth elements	• CMI • GTO Mineral Recovery
2. Separations	97%	80-85%	• Extensive separations to isolate desired elements from those present in the ore (entire lanthanide series) • Significant capital expenditure • Loss of intellectual capital		• CMI
3. Refining metals	~100%	>95%	• Lack of downstream consumers	INFINIUM is doing some metal making[60]	• CMI • INFINIUM SBIR
4. Forming alloys and magnet powders	90%	>95%	• Lack of downstream consumers		• CMI • VTO SBIR • ARPA-E REACT
5. Manufacturing	75%	>80%	• Intellectual property for sintered NdFeB magnets held in Japan by Hitachi	New Hitachi plant in U.S. for NeFeB magnets,[61] but small production scale	• CMI
6. Components (motors, generators)	Not available	Not available	• Secure upstream supply chain		• ARPA-E REACT
7. Recycling	Not available	Not available	• Financial uncertainty • Collection logistics • Technology • Uncertain markets for recyclates	No clear outlet market for materials collected for recycling	• CMI

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[56] GAO. 2010. Rare Earth Materials in the Defense Supply Chain: Briefing for Congressional Committees, April 1. Washington, DC: United States Government Accountability Office, April 14. http://www.gao.gov/products/GAO-10-617R.

[57] Dudley Kingsnorth, "The Rare Earths Industry: Marking Time," March 2014, and "Australian Critical Materials Initiative," 2014, both published by Curtin University, Bentley, Western Australia.

[58] http://www.molycorp.com/about-us/our-facilities/molycorp-mountain-pass/

[59] http://www.miningaustralia.com.au/news/lynas-wins-full-operating-licence-for-its-lamp

[60] http://www.infiniummetals.com/

[61] http://www.hitachi-metals.co.jp/e/ir/ir-news/20111221e.pdf

This section references a variety of major research and development efforts related to critical materials supported by the Department of Energy. The Department of Energy's strategy for addressing critical materials challenges rests on diversifying supply, developing substitutes, and enhancing 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.[62]

Within Energy Efficiency and Renewable Energy (EERE), the Critical Materials Institute (CMI) Energy Innovation Hub is working to assure supply chains of materials critical to clean energy technologies, with an aim to reduce loss of critical rare earths within domestic manufacturing by 50 percent and reduce critical rare earths elements going to domestic landfills by 35 percent.[63,64] CMI partners are shown in Figure 5. Additional efforts within EERE include projects related to the batteries and magnets in electric vehicles (Vehicles Technology Office, VTO) and the recovery of lithium from geothermal brines (Geothermal Technology Office, GTO). The Rare Earth Alternatives in Critical Technologies (REACT) program with the Advanced Research Projects Agency-Energy (ARPA-E) 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. The Joint Center for Energy Storage Research is the Energy Innovation Hub for Battery and Energy Storage within Basic Energy Sciences, aiming 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. Within Fossil Energy, the National Energy Technology Laboratory is investigating the recovery of rare earth elements from coal ash.

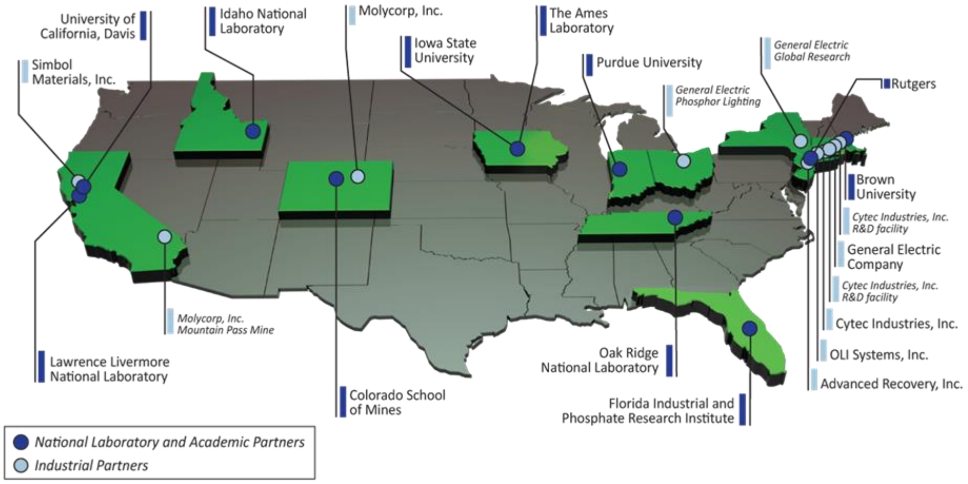

Figure 5. CMI partners.

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[62] Critical Materials Strategy. The Department of Energy, 2011

[63] Danielson testimony before SENR Jan 28 2014

[64] CMI First Annual Review Report

Note that other government agencies play active roles in the Federal response to critical materials challenges, in addition to interagency work (discussed in Section 3). The United States Geological Survey (USGS), housed within the Department of the Interior, provides an annual summary of rare earth activity in its Mineral Commodities Summaries report[65] and publishes on focused topics, such as the recycling of rare earths.[66] The Department of Defense maintains a stockpile of defense-related critical materials and closely monitors the rare earth materials market for any projected shortfalls or failures to meet mission requirements.[67] 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.[68]

2.2.1 Diversifying Supply

Diversifying the source of supply reduces the criticality of a material, moving it leftward in the criticality matrix (Figure 1). 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 rare earth elements 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.[69] The development of new separations technologies is considered one of the grand challenges in the CMI. New science is needed that will overcome the fundamental similarity of the rare earth elements, 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.[70] 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 2). 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, [71] there were no domestic NdFeB magnet

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[65] http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2014-raree.pdf

[66] U.S. Department of the Interior, USGS, Rare Earth Elements- End Use and Recyclability, Scientific Investigations Report 2011-5094.

[67] Mark Humphries. “Rare earth elements: the global supply chain.” Congressional Research Service, December 16, 2013.

[68] Mark Humphries. “Rare earth elements: the global supply chain.” Congressional Research Service, December 16, 2013.

[69] Steve Constantinides, “Demand for rare earth materials in permanent magnets,” COM 2012, Niagara Fall, Canada, October 1-2 (2012).

[70] Valerie Bailey Grasso. “Rare Earth Elements in National Defense: Background, Oversight Issues, and Options for Congress.” Congressional Research Service, September 17, 2013.

[71] http://www.hitachi-metals.co.jp/e/ir/ir-news/20111221e.pdf

manufacturers.[72] (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 in Section 2.2.2.) INFINIUM, which was supported by a Small Business Innovation Research Grant from the Advanced Manufacturing Office (INFINIUM was then Metal Oxide Separation Technologies, Inc.),[73] is now performing some metal making.

A diversified supply may also be achieved by considering the development of markets for co-produced abundant rare earth elements. For example, lighter rare earth elements (including cerium and lanthanum) account for 80-99% of a rare earth mineral deposit,[74] but represent only a fraction of the total value of the deposit—for Mt. Pass, a mine owned by Molycorp in California, the value of cerium and lanthanum is ~25%.[75] This challenge, referred to as the balance problem,[76] is particularly relevant for Molycorp and Lynas mines, whose deposits tend to have significant cerium and lanthanum content.[77] CMI is currently researching novel applications for cerium and lanthanum to improve the economics of mining such deposits for heavy rare earth elements, 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 one percent of the metal consumed with a cerium-containing alloy would have profound impact on the global demand for cerium.

Finally, the diversity of supply of rare earth elements 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 the non-traditional sources that happen to contain vast amounts of rare earth elements at relatively dilute concentrations. For example, CMI researchers are investigating the potential of the phosphate fertilizer industry, where valuable rare earth elements 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 satisfy annual global demand for these metals by more than an order of magnitude.[78] 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 the Department of Energy is exploring geothermal brines for the production of lithium as a by-product of geothermal energy generation.[79] Finally, NETL is examining the feasibility of recovering rare earth elements from coal ash,[80] tapping into a potentially vast non-traditional source.

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[72] Domestic SmCo magnet producers include Electron Energy Corporation and Arnold Magnetics, but SmCo magnets are currently not used in significant quantities for wind or motor applications.

[73] https://www.sbir.gov/sbirsearch/detail/390437

[74] Mark Humphries. "Rare earth elements: the global supply chain." Congressional Research Service, December 16, 2013.

[75] http://www.metal-pages.com/metalprices/rareearths/

[76] Binnemans, K.; Jones, P. T.; Acker, K. V.; Blanpain, B.; Mishra, B.; Apelian, D. Rare-Earth Economics: The Balance Problem. *Journal of Metals* **2013**, *65*, 846–848.

[77] Critical Materials Strategy. The Department of Energy, 2011

[78] Chen, M.; Graedel, T. E. The potential for mining trace elements from phosphate rock. *Journal of Cleaner Production,* **2014;** doi:10.1016/j.jclepro.2014.12.042

[79] http://energy.gov/sites/prod/files/2014/10/f18/Mineral%20Recovery%20Project%20Descriptions.pdf

[80] http://www.netl.doe.gov/newsroom/news-releases/news-details?id=ccda1fcb-4cc7-423a-a441-97d0d0f8262f

While the Department of Energy has focused on technology solutions to material criticality, other agencies have investigated stockpiling as one way to diversify supply.[81] 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.

2.2.2 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 importance of a material to clean energy, moving it downward in the criticality matrix (Figure 1). Developing substitutes recognizes that additional mining will not solve all materials criticality. For example, the supply of heavy rare earth elements, such as dysprosium, will not be significantly increased through domestic mining because the earth's crust within the borders of the United States is not endowed with minerals that contain significant fractions of these elements (Table 5).

Table 5. Relative dysprosium oxide (Dy_2O_3) content in domestic deposits.[82]

Domestic Deposit	Total Rare Earth Oxide (TREO, weight %)	Relative Dy_2O_3 Content of TREO (%)
Mountain Pass (CA)	6.57	0.05
Bear Lodge (WY)	2.68	0.42
Bokan (AK)	0.61	4.25
Round Top (TX)	0.063	5.61

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,[83] NdFeB permanent magnets were developed from discovery to commercial production in three years.[84] This astonishingly fast commercialization remains highly unusual, so significant work is underway to understand success stories such as NdFeB and further speed the innovation cycle for new materials.[85] 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 combinatory analysis.[86, 87]

A second opportunity to develop substitutes is to investigate new manufacturing routes.[88] In the case of NdFeB magnets, major intellectual property hurdles exist that inhibit potential manufacturers.[89]

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[81] Valerie Bailey Grasso. "Rare Earth Elements in National Defense: Background, Oversight Issues, and Options for Congress." Congressional Research Service, September 17, 2013.

[82] Tech Metal Research. http://www.techmetalsresearch.com/

[83] http://motresearch.bus.sfu.ca/Papers/RP_proofs_CGT_March_2006.pdf; National Academies' "Materials In the New Millennium"

[84] http://www.japanprize.jp/data/prize/commemorative_lec_2012_e.pdf#page=13&view=Fit

[85] http://www.whitehouse.gov/sites/default/files/microsites/ostp/materials_genome_initiative-final.pdf

[86] Rainer Schmid-Fetzer. Phase diagrams: the beginning of wisdom. Journal of Phase Equilibria and Diffusion, DOI: 10.1007/s11669-014-0343-5 (2014).

[87] Larry Kaufman, John Ågren. CALPHAD, first and second generation—birth of the materials genome. Scripta Materialia 70 (2014) 3–6.

[88] Critical Materials Strategy. The Department of Energy, 2011

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, CMI researchers are investigating new additive manufacturing routes to develop exchange spring magnets,[90] which may double the energy density with half the rare earth element content, as compared to commercial magnets,[91, 92, 93, 94, 95] and to functionally modify sintered NdFeB magnets to minimize the use of dysprosium. Manufacturers have also reported working on magnets that reduce or eliminate the use of dysprosium.[96]

Improving the insufficient properties of a potential material may 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 cheaper to produce. SmCo and aluminum nickel cobalt (AlNiCo) both offer thermal stability superior to that of NdFeB.[97, 98, 99,100] Further, CMI researchers have shown that the coercivity of commercially-available sintered NdFeB may be enhanced by post-thermomagnetic processing in the presence of a high magnetic field.

2.2.2.1 Systems-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 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, corresponding to reduced rare earth content. 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.[101]

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

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[89] Critical Materials Strategy. The Department of Energy, 2011

[90] Vayre Benjamin, Vignat Frederic, and Villeneuve Francois, "Metallic additive manufacturing: state-of-the-art review and prospects," Mechanics & Industry, 13 (2), 89-96 (2012); DOI: 10.1051/meca/2012003; http://www.ornl.gov/science-discovery/advanced-materials/research-areas/materials-synthesis-from-atoms-to-systems/additive-manufacturing

[91] "The exchange-spring magnet: a new material principle for permanent magnets" E.F. Kneller and R. Hawig, Magnetics, IEEE Transactions on 27, 3588-3560 (1991).

[92] "Nucleation field and energy product of aligned two-phase magnets-progress towards the `1 MJ/m3 magnet" R. Skomski and J.M.D. Coey, Magnetics, IEEE Transactions on 29, 2860-2862 (1993).

[93] "Exchange-coupled FePt nanoparticle assembly" H. Zeng, et al., Appl. Phys. Lett. 80, 2583-2585 (2002).

[94] "Nanocomposite exchange-spring magnet synthesized by gas phase method: From isotropic to anisotropic" X. Liu, et al., Appl. Phys. Lett. 98, - (2011).

[95] "Rational design of the exchange-spring permanent magnet" J.S. Jiang and S.D. Bader, J. Phys. Cond. Matt. 26, 064214 (2014).

[96] http://articles.sae.org/11988/

[97] Steve Constantinides, "Novel Permanent Magnets and Their Uses," Presented at the MRS Conference and Exposition, San Francisco, May 1995.

[98] Advances in nanostructured permanent magnets research" P. Narayan and J.P. Liu, J. Phys. D: Appl. Phys. 46, 043001 (2013).

[99] "Hard Magnetic Materials: A Perspective" J.M.D. Coey, Magnetics, IEEE Transactions on 47, 4671-4681 (2011).

[100] J.M.D. Coey, Magnetism and Magnetic Materials (Cambridge University Press, New York, 2010).

[101] Constantinides 2011 (DOE CMS)

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. The elimination of dysprosium will reduce material costs and is part of a suite of innovations that the company expects to dramatically lower production, installation and operating costs compared to current wind turbines. [102] 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.[103, 104]

Electric vehicles manufacturers have explored several options to reduce or replace rare earth permanent magnet motors in vehicle designs. Some manufacturers have reconsidered induction motors,[105] which are larger than permanent magnet motors for a given power rating, but are easier to cool and potentially more efficient. 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.[106] The Vehicles Technology 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.[107] 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 rare earth elements, yet meets or exceeds the performance of current rare earth element magnet motors.[108] Additional projects within this program focused on superconductors for 10 MW wind generators, aiming to increase in-field tape performance four-fold such that superconductor-based wind generators may compete in price and performance with rare earth element-based wind generators.[109]

2.2.3 Enhancing Reuse and Recycling

The final pillar for reducing material criticality is to close the supply chain at the end of its useful life. One report observed that less than 1% of end-of-life products containing rare earth elements are recycled. One potentially large waste stream for NdFeB permanent magnets is from the computer hard drives used in data centers. More than 21,000 metric tons of neodymium is produced each year for

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[102] Advanced Gearless Drivetrain - Phase I Technical Report http://www.osti.gov/scitech/biblio/1050994/

[103] http://www.amsc.com/documents/seatitan-10-mw-wind-turbine-data-sheet/, http://www.power-technology.com/features/featurethe-worlds-biggest-wind-turbines-4154395/, http://www.windpowermonthly.com/article/1150731/amsc-completes-sea-titan-turbine-design

[104] http://amlsuperconductivity.com/new-superconducting-magnet-will-lead-to-next-generation-of-wind-turbine-generators/

[105] http://www.teslamotors.com/roadster/technology/motor

[106] Critical Materials Strategy. The Department of Energy, 2011

[107] http://energy.gov/sites/prod/files/2014/04/f15/2013_apeem_report.pdf

[108] Lei Gu, W. Wang, **B. Fahimi**, M. Kiani, " A novel high energy density double salient exterior rotor permanent magnet machine, accepted for publication in *IEEE Transactions on Magnetics*.

[109] Y. Liu, Y. Yao, Y. Chen, N. D. Khatri, J. Liu, E. Galtsyan, C. Lei, and V. Selvamanickam, "Electromagnetic properties of (Gd,Y)Ba2Cu3Ox superconducting tapes with high levels of Zr addition", IEEE Transactions on Applied Superconductivity, Issue Number: 6601804, 2003

magnet manufacturing. 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.[110] To illustrate the magnitude of this waste stream, consider a few examples of hard drive turnover in modern data centers:

- Facebook's data storage has grown three-fold in the last year to around 300 petabytes (10^{15} bytes), increasing at 600 terabytes (10^{12} bytes) per day[111]
- Amazon strives for 11 nines of reliability (99.999999999) for data, which requires a significant number of hard drives for this redundant data storage[112]
- NSA's Utah Datacenter will be able to handle historic quantities of data, with estimates ranging from 5 zetabytes (1 zetabyte = 10^{21} bytes) to yottabytes (1 yottabyte = 10^{24} bytes)[113] (for reference, the largest hard drive is currently 8 terabytes, so 5 zetabytes would require 625 million hard drives)
- Approximately one-third of the hard drive population is replaced annually[114]

Even with this significant waste stream, hard drive recycling has unique challenges. First, decreasing hard drive size is opposite to, for example, increasing wind turbine size, which may complicate the value of this waste stream for this particular application. Second, recycling permanent magnets is challenging not because of chemical processing, but because of collecting hard drive disks and isolating the permanent magnets in a cost-efficient manner. Finally, data centers prefer to shred hard drive disks for data security, further complicating magnet collection.

The Department of Energy focuses on developing technology solutions to enable recycling from consumer and household products, such as hard drives and light bulbs. Reusing or recycling these recovered magnets may then increase the supply of both neodymium and NdFeB permanent magnets for use in clean energy technologies. Challenges associated with the research and development of recycling rare earth permanent magnets from expired hard drives are: locating and extracting the magnets in a cost-effective manner (such devices are not designed for disassembly),[115] processes to separate rare earth elements from within the components (varied compositions and impurity levels may later the recycling process), and the re-insertion of recycled materials back into the supply chain. Recycling rare earth permanent magnets from other sources, such as wind turbines and electric vehicle motors, will become relevant once these technologies are widely deployed, enabling an economical recycling industry.

2.3 What are the Next Critical Materials?

Material criticality is dynamic—while rare earth elements are a challenge today, markets will adapt.[116] Consider the political unrest in Zaire in the 1970s and 1980s, which led to a shortage of cobalt, a vital

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[110] http://www.unep.org/resourcepanel/Publications/MetalRecycling/tabid/106143/Default.aspx

[111] https://code.facebook.com/posts/229861827208629/scaling-the-facebook-data-warehouse-to-300-pb/

[112] https://blog.cloudsecurityalliance.org/2010/05/24/amazon-aws-11-9s-of-reliability/

[113] http://www.forbes.com/sites/kashmirhill/2013/07/24/blueprints-of-nsa-data-center-in-utah-suggest-its-storage-capacity-is-less-impressive-than-thought/

[114] Conversations between Tim McIntyre and Seagate, Western Digital, Google, Amazon, and other stakeholders

[115] Oak Ridge National Laboratory, a member of CMI, is filing 2 of 5 patent disclosures on this topic.

[116] The Role of Chemical Sciences in Finding Alternatives to Critical Resources Workshop. The National Academy of Sciences, Sep 29-30, 2011.

element in the SmCo permanent magnets used in domestic aerospace and defense industries.[117] The cobalt shortage contributed to the development of substitutes, in turn assisting the development of NdFeB permanent magnets.[118] Another case study of dynamic criticality is that of tellurium, which was considered near-critical in 2011 by the Department of Energy 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 availability may be more abundant than originally thought.[119]

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.[120] Energy Policy and Systems Analysis, within the Department of Energy, 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.[121] A version of this model is currently being applied to helium markets. In addition, Energy Policy and Systems Analysis 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 annually assesses the potential for domestic challenges with strategic and critical non-fuel minerals,[122] and recently reported on a risk mitigation strategy for rare earth elements.[123] 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.[124] GE, the first company to publish the results of a corporate criticality assessment,[125, 126] continues to publish on their analysis.[127]

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[117] http://www.cbo.gov/sites/default/files/doc29-entire.pdf

[118] http://spontaneousmaterials.com/Papers/REPMW.pdf

[119] Y. Houari, et al. A system dynamics model of tellurium availability for CdTe PV. Prog. Photovolt: Res. Appl. 22, 129 (2014).

[120] Review Article, Published on 06 Nov 2014 Life-Cycle Assessment of the Production of Rare-Earth Elements for Energy Applications: A Review Julio Navarro and Fu Zhao Frontiers in Energy Research. doi: 10.3389/fenrg.2014.00045

[121] Riddle, M et. al., Global Critical Materials Markets: An Agent-based Modeling Approach, Resources Policy, to appear.

[122] Office of the Under Secretary of Defense for Acquisition, Technology and Logistics. Strategic and Critical Materials 2013 Report on Stockpile Requirements. http://www.strategicmaterials.dla.mil/Report%20Library/2013%20NDS%20Requirements%20Report.pdf

[123] Office of the Under Secretary of Defense for Acquisition, Technology and Logistics. Diversification of supply chain and reclamation activities related to rare earths.

[124] White, et al. The Nation Science Foundation's investment in sustainable chemistry, engineering, and materials. ACS Sustainable Chemistry & Engineering 1 871-877 (2013).

[125] Duclos, S.J., et al. Design in an Era of Constrained Resources. Mechanical Engineering, 132 (9) p.36-40 (2010).

[126] GE. Response to the U.S. Department of Energy Request for Information. May 24, 2011.

[127] Anthony Ku, Stephen Hung. Manage Raw Material Supply Risks. American Institute of Chemical Engineers, September 2014, p. 28.

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.[128] 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.[129] The European Commission has evaluated the criticality of 41 raw materials not produced in Europe yet essential to its current and future economic vitality,[130] and recently updated this analysis with additional materials and data;[131] and Germany has conducted their own study for the minerals necessary to the production of technologies that generate electricity, heat, and fuels from renewable sources up to 2050.[132]

When considering future clean energy technologies, some key materials have emerged as candidates for criticality in the near-term (Table 6).[133, 134, 135] 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,[136] bismuth,[137] helium,[138] and catalytic materials for chemical production.[139]

Table 6. Key materials for future clean energy technologies

Technology	Key elements
Grid storage batteries	Lithium, vanadium
Fuel cells	Platinum group metals, lanthanum, cobalt, cerium, yttrium
Nuclear power	Indium, cobalt, gadolinium
Vehicle light-weighting	Magnesium, titanium
Gas turbines	Yttrium
Catalytic converters	Platinum group metals, cerium
Photovoltaic cells	Indium, gallium, tellurium, silver, ruthenium
Thermoelectrics	Tellurium, various rare earth elements

Finally, “anacritical” materials may also complicate the supply chains of other materials due to their over-abundance. 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 rare earth elements (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

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[128] Graedel, et al. On the materials basis of modern society. PNAS, DOI 10.1073.

[129] http://www.bgs.ac.uk/mineralsuk/statistics/risklist.html

[130] European Commission. Critical Raw Materials for the EU. http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/crm-report-on-critical-raw-materials_en.pdf

[131] http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm

[132] http://wupperinst.org/uploads/tx_wupperinst/KRESSE_Endbericht_Summary.pdf

[133] Critical Materials Strategy. The Department of Energy, 2011

[134] ECS Transactions, 33 (17) 3-11 (2011) (solar materials); Nanoscape Volume 7, Issue 1, Summer 2010 www.nanoscape.northwestern.edu)(thermoelectrics)

[135] Minerals, Critical Minerals, and the U.S. Economy. National Research Council, 2008.

[136] http://www.rand.org/content/dam/rand/pubs/research_reports/RR100/RR133/RAND_RR133.pdf

[137] http://minerals.usgs.gov/minerals/pubs/commodity/bismuth/mcs-2014-bismu.pdf

[138] http://www.aps.org/policy/reports/popa-reports/upload/elementsreport.pdf

[139] Minerals, Critical Minerals, and the U.S. Economy. National Research Council, 2008

hazardous substances[140] such as lead, this created a market for lead-free solder and bearings that replace lead with bismuth. However, bismuth has supply chain issues, primarily due to its production overseas.[141] Further, bismuth is a secondary product from lead mining, so a reduction in primary lead production may reduce the supply of bismuth.

3. Program Considerations to Support R&D

3.1 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 lifecycle of materials will aid the identification of supply chain bottlenecks. An increased understanding of the basic materials properties, such as the role of *f*-electrons in the unique properties of rare earth elements, 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 candidate materials cover a large composition and phase space to explore. 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.

3.2 DOE R&D partnerships and stakeholder engagement

The Department of Energy 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. [144] Further, such interagency collaboration enables the Department of Energy 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.[145]

The Department of Energy also recognizes that international cooperation on critical materials challenges can help all countries achieve their clean energy goals; and as such, has organized several workshops with the European Union (EU), Japan, Australia and Canada to identify possible research and

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[140] http://www.rohsguide.com/

[141] http://minerals.usgs.gov/minerals/pubs/commodity/bismuth/mcs-2014-bismu.pdf

[142] https://www.ameslab.gov/node/9102

[143] National Science and Technology Council, *Materials Genome Initiative for Global Competitiveness*, 2011. http://www.whitehouse.gov/sites/default/files/microsites/ostp/materials_genome_initiative-final.pdf

[144] Critical Materials Strategy. The Department of Energy, 2011

[145] OSTP RFI, https://www.federalregister.gov/articles/2014/07/22/2014-17192/critical-and-strategic-materials-supply-chains

development collaborations. The most recent of these meetings was the Annual Trilateral U.S.-EU-Japan conference, where more than 70 participants discussed common challenges and potential collaborations in critical materials for clean energy applications (Figure 6).[146] The Department of Energy is also pursuing international information sharing to help improve transparency in critical materials markets, and will continue to engage international partners through dialogues and collaborative institutions. [147]

Figure 6. A panoramic view of workshop attendees from the United States, the European Union, Japan, and other countries. Photo courtesy of Critical Materials Institute.

4. Risk and Uncertainty, and Other Considerations

A material's criticality depends on its risk of supply disruption and its societal importance;[148] 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 (Sections 1 and 2). Potential supply disruptions may arise from a small global market, market complexities caused by co-production, and geopolitical risk.

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. 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.

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.

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[146] http://energy.gov/epsa/downloads/annual-trilateral-us-eu-japan-conference-critical-materials-clean-energy-future

[147] Critical Materials Strategy. The Department of Energy, 2011

[148] Minerals, Critical Minerals, and the U.S. Economy. National Research Council, 2008.

Recycling is driven predominately by regulation, and uncertain regulation may destabilize markets. Examples of regulations relevant to critical materials include mining permit processing and requirements regarding radioactive elements found in minerals containing rare earth elements.

5. Sidebars and Case Studies

5.1 Development of MnBi-Based Permanent Magnet (Jun Cui)

J Cui[1], M J Kramer[2], D D Johnson[2], M Marinescu[3], I Takeuchi[4], Z. Chaudhry[5], J P Liu[6], S Ren[7], Y-K Hong[8], S Jin[9], S-G Kim[10], G. Hadjipanais[11]
[1] Energy and Environment Directorate, Pacific Northwest National Laboratory, Richland, WA 99354
[2] Division of Materials Sci. and Eng., Ames Laboratory, Ames, IA 50011
[3] Electron Energy Corporation, Landisville, PA 17538
[4] Dept. Materials Sci. and Eng., University of Maryland, College Park, MD 20742
[5] United Technologies Research Center, East Harford, CT 06108
[6] Dept. Physics, University of Texas at Arlington, Arlington, TX 76019
[7] Dept. Chemistry, University of Kansas, Lawrence, KS 66045
[8] Dept. Electrical and Computer Eng., University of Alabama, Tuscaloosa, AL 35487
[9] Dept. Mechanical & Aerospace Eng., University of California San Diego, La Jolla, CA 92093
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MnBi is an attractive alternative to the permanent magnets containing rare earth elements, especially the ones for medium temperature applications (423~473 K) such as NdFeB-Dy and SmCo. MnBi has unique temperature properties: its coercivity increases with increasing temperature, reaching a maximum of 2.6 T at 523 K.[149] The large coercivity is attributed to MnBi's large magnetocrystalline anisotropy (1.6×10^6 J/m^3).[150] MnBi has relatively low magnetization. Its room temperature saturation magnetization is about 75 emu/g or 8.4 kG with 5 T field.[151] The corresponding maximum theoretical energy product $(BH)_{max}$ is about 17.6 MGOe. In practice, a single-phase MnBi should exceed 12 MGOe, which is competitive compared to magnets such as ferrite and AlNiCo, but is only half of what NdFeB and SmCo magnets can offer at 473 K. To best utilize MnBi's unique high temperature properties, MnBi should be used a hard phase to be exchange-coupled with a soft phase, so that the remanent magnetization can be improved to >10 kG while coercivity is maintained at >10 kOe. The corresponding $(BH)_{max}$ entitlement is 25 MGOe.

The challenges for developing a MnBi-based exchange-coupled magnet are three-fold: 1) how to prepare high purity MnBi compound in large quantity, 2) how to encourage exchange

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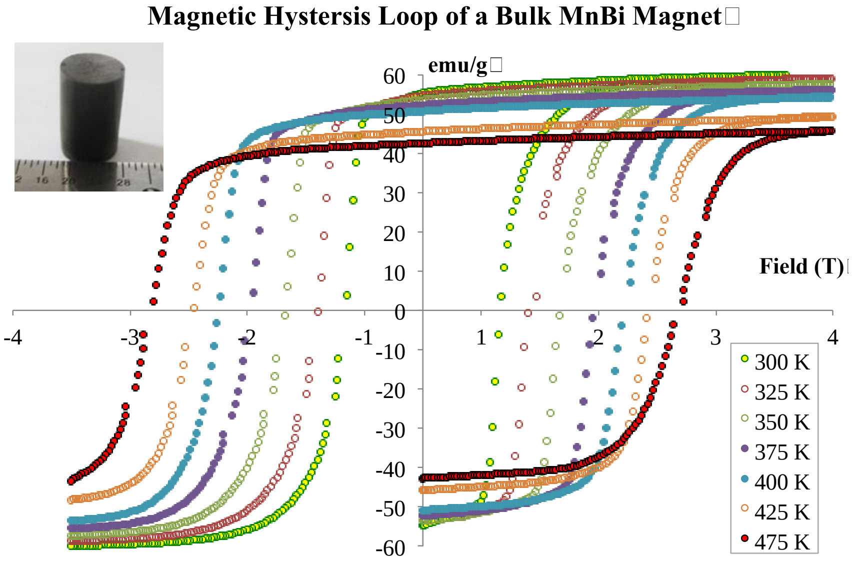
[149] Y.B. Yang, X.G. Chen, S. Guo, A.R. Yan, Q.Z. Huang, M.M. Wu, D.F. Chen, Y.C. Yang, J.B. Yang, Temperature dependences of structure and coercivity for melt-spun MnBi compound, J Magn Magn Mater, 330 (2013) 106-110. J.B. Yang, K. Kamaraju, W.B. Yelon, W.J. James, Q. Cai, A. Bollero, Magnetic properties of the MnBi intermetallic compound, Appl Phys Lett, 79 (2001) 1846-1848.

[150] X. Guo, X. Chen, Z. Altounian, J.O. Stromolsen, Magnetic-Properties of Mnbi Prepared by Rapid Solidification, Phys Rev B, 46 (1992) 14578-14582.

[151] J. Cui, J.P. Choi, G. Li, E. Polikarpov, et. al. Development of MnBi permanent magnet: Neutron diffraction of MnBi powder, J. Appl. Phys. (2014) 115(17), 17A743

coupling between MnBi and soft phases such as Fe and Co, and 3) how to fabricate bulk nanocomposite magnet with fine grain size, uniform phase distribution, and high degree of texture. Supported by ARPA-E REACT program, a team of scientist involving eleven organizations worked on these challenges in the past three years and made significant progress.

Highlights of the achievements are 1) Large quantity of high purity MnBi single-phase particles can be routinely prepared. Each batch weighs about 8 lbs; the average particle size ranges from 0.5 to 2 µm; and the magnetization of the powder at 2.3 T field is about 70 emu/g. What makes this achievement significant is that the method is not based on the melt-spinning method which has limited productivity and higher cost, rather, it is based on conventional thermal-mechanical treatment that is compatible with the current industrial practice.[152] 2) Under the guidance of theoretical calculation, the exchange coupling of MnBi and Co was successfully demonstrated using thin film method. The fabricated double-layer film exhibits an energy product about 25 MGOe. In parallel to the thin film effort, MnBi-Co core-shell particles were synthesized using a colloidal synthesis method. The Co layer can be controlled to ~20 nm and the overall magnetization exceeded 80 emu/g.[153] 3) 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.[154]



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[152] J. Cui, J P Choi, G Li, E Polikarpov, J Darsell, N Overman, M Olszta, D. Schreiber, M Bowden, T Droubay, M J Kramer, N A Zarkevich, L L Wang, D D Johnson, M Marinescu, I Takeuchi, Q Z Huang, H Wu, H. Reeve, N V Vuong, and J P Liu, "Thermal stability of MnBi magnetic materials", J. Phys. Cond. Matt, 26, 064212, 2014.

[152] J. Cui, J.P. Choi, E. Polikarpov, M. E. Bowden, W. Xie, G. Li, Z Nie, N. Zarkevich, M. Kramer, D. Johnson, "Effect of Compositions and heat treatment on magnetic properties of MnBi", Acta Meta. 79 (2014) 374-381.

[153] H. Cui, J. Shen, W. Manube, W. Qin, J. Cui, S. Ren, "Synthesis and Characterization of Rare-Earth-Free Magnetic Manganese Bismuth Nanocrystals", J. Mats, Chem. A., Submitted.

[154] V. Vuong Nguyen, N. Poudyal, X. B. Liu, J. Ping Liu, K. Sun, M. J. Kramer, J. Cui, "Novel processing of high-performance MnBi magnets", Mater. Res. Express, 1 (2014), 036108.

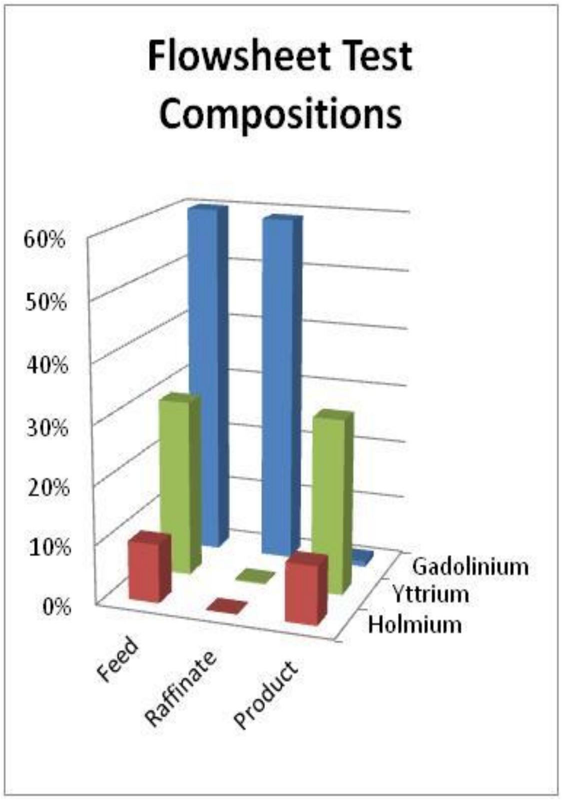
Fig 1. Hysteresis loops of MnBi bulk magnet at different tempeatures. The picture of the bulk magnet is shown on the top left corner.

5.2 Demonstration of New Solvent Extraction Separation Processes for Critical Materials in 30-Stage Test Facility (Bruce Moyer)

Separating a complex mixture of rare earth elements (REE) into pure, individual components is extraordinarily difficult and expensive because the adjacent lanthanides have nearly identical ionic radii and chemical properties. The Critical Materials Institute (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 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.

Initial process testing in the demonstration facility focused on the separation of heavy REE (Ho thru Lu) and yttrium (Y) from the middle REE (Sm thru Dy). Note that 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 % Gd (representative of the middle-REE), 30 wt % Y, and 10 wt % Ho (representative of the heavy REE) has been used in the tests to study the middle/heavy/Y cut. Results were good, with less than 2% of the Gd reporting to the Ho/Y (heavy) product and well under 1% of the Ho & Y remaining in the Gd raffinate (or middle product) using the industry standard extractant. A new extractant, developed by our 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.

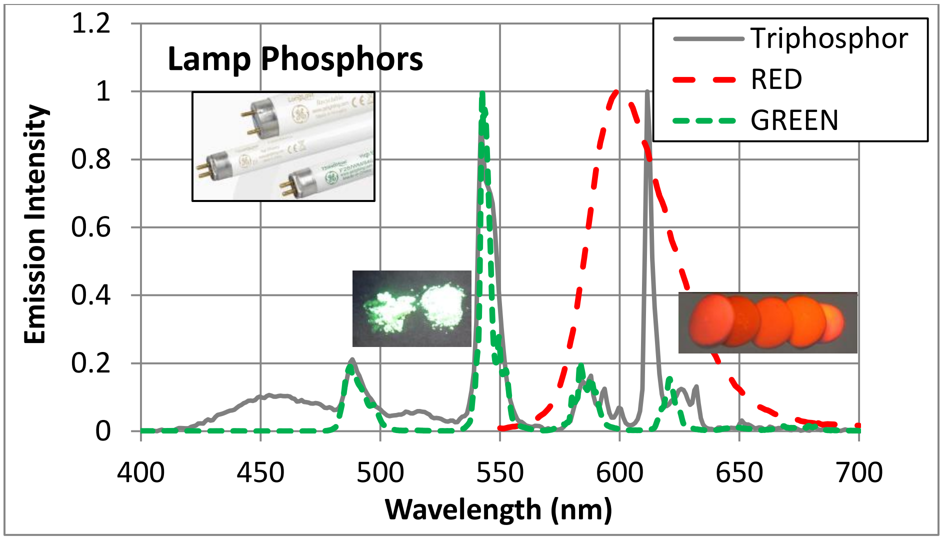
New extractants are currently being designed by computational molecular modeling in the CMI. In the future, these designer extractants will be tested in the demonstration facility to dramatically reduce equipment size and processing costs, ultimately reducing costs for the production of purified REE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



5.3 Fluorescent Lighting With Greatly Reduced Critical Rare Earth Content (Tom Lagrasso)

General Electric, Lawrence Livermore National Laboratory and Oak Ridge National Laboratory

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 replace fluorescent tubes eventually, low-cost linear fluorescent lighting is expected to remain a dominant feature in our infrastructure for more than a decade to come. 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. The GE, LLNL, ORNL Team has identified a GREEN phosphor which reduces the Tb content by 90% and eliminates La, while the RED phosphor eliminates both Eu and Y. These proposed phosphors appear to meet stringent requirements of long lamp survivability, high efficiency, precise color rendition (see plot below), and low-cost; the BLUE phosphor has inherently low rare earth content and need not be replaced. At this juncture, the fundamental physics of these phosphors is compelling, and we are therefore taking the next steps and assessing their feasibility for commercial lighting by evaluating chemical issues related to slurry compatibility, and by improving the synthetic procedures.


Lamp Phosphors
Emission Intensity
Wavelength (nm)
1.2
1
0.8
0.6
0.4
0.2
0
400
450
500
550
600
650
700
Triphosphor
RED
GREEN

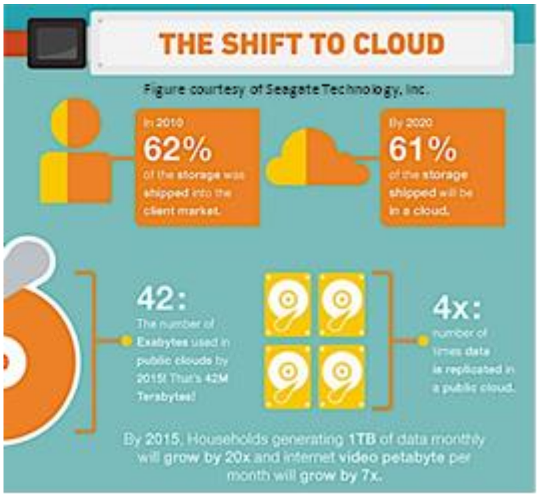
5.4 High-Value Recycling Technology (Tim McIntyre)

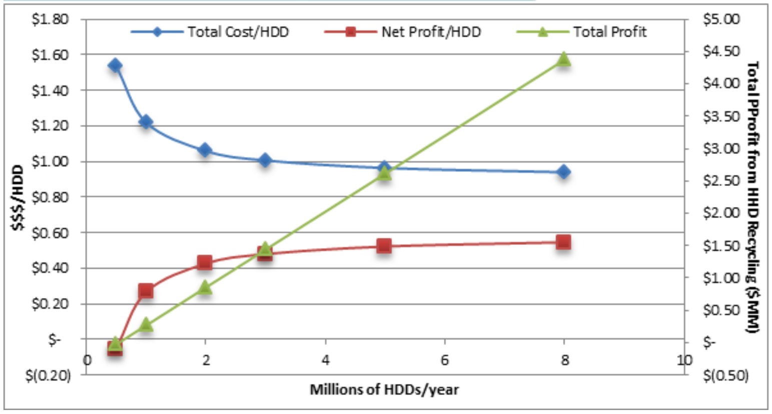
Rare earth magnets are manufactured in very large quantities for use in consumer products and industrial machinery. Computer hard disc drives (HDDs) and electric motors are among many items containing rare earth magnets. Approaching 1 billion HDDs are manufactured annually with ~50% deployed in data centers. Similarly, a very large number of HDDs are recycled annually by shredding. Shredding is efficient and cost effective for large material volumes but complicates separation of outputs. Large format (3.5”) HDDs consists of ~75.7% aluminum, ~13.3% steel, ~1.9% magnets, ~5.7% permalloy and ~3.4% printed circuit boards. Largely, aluminum and steel are recycled.

The Critical Materials Institute (CMI), an Energy Innovation Hub, is developing cost effective recycling technology, reclaiming maximum value from end-of-life products. Oak Ridge National Laboratory (ORNL) researchers, and their partners from Lawrence Livermore National Laboratory, Idaho National Laboratory, Colorado School of Mines, and others are developing technology to recycle HDDs with an efficient 5-step process: sorting by size; aligning; shearing off the printed circuit boards; punching out magnets; and separating the process outputs. Recycling high-tech products offers great benefit because of valuable materials they contain, such as rare earths (neodymium, praseodymium and dysprosium), copper, silver, gold, etc. Co-location with data centers is key as estimates suggest >100 million HDDs could be recycled.

The ORNL system separately recovers magnets, their peramalloy brackets, printed circuit boards, aluminum and steel from millions of HDDs. During the recycling process, data storage media are destroyed to ensure data security. Our recycling effort eliminates disposal of valuable materials into landfills.

The economic viability of recycling complex, high technology products like HDDs must be demonstrated to ensure commercial adoption. ORNL’s process enables material specific revenue streams. Magnets are recovered intact enabling options: direct reuse, alternate uses (resized or reshaped magnets) or processing back to rare earth metal. Direct reuse of premium magnets vs. reprocessing avoids significant energy and environment costs. Current market prices for aluminum, steel, magnets (not direct reuse), permalloy and printed circuit boards, produce ~$1.49/HDD. Enterprise recycling cost estimates, including capital (amortized), O&M (including co-location) and acquisition totals ~$0.95/HDD. Our goal is recycling 1 HDD/sec; >5 million HDDs/system annually. Scrap and specialty metal prices continue to rise, ensuring the economic viability.


THE SHIFT TO CLOUD
Figure courtesy of Seagate Technology, Inc.
In 2010
62%
of the storage was shipped into the client market.
By 2020
61%
of the storage shipped will be in a cloud.
42:
The number of Exabytes used in public clouds by 2015! That's 42M Terabytes!
4x:
number of times data is replicated in a public cloud.
By 2015, Households generating 1TB of data monthly will grow by 20x and internet video petabyte per month will grow by 7x.


Total Cost/HDD
Net Profit/HDD
Total Profit
$$$/HDD
$1.80
$1.60
$1.40
$1.20
$1.00
$0.80
$0.60
$0.40
$0.20
$-
$(0.20)
0
2
4
6
8
10
Millions of HDDs/year
Total PProfit from HHD Recycling ($MM)
$5.00
$4.50
$4.00
$3.50
$3.00
$2.50
$2.00
$1.50
$1.00
$0.50
$-
$(0.50)