Heavy rare earths, permanent magnets, and renewable energies: An imminent crisis

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Abstract: This article sounds the alarm that a significant build-out of efficient lighting and renewable energy technologies may be endangered by shortages of rare earths and rare earth permanent magnets. At the moment, China is the predominant supplier of both and its recent rare earth industrial policies combined with its own growing demand for rare earths have caused widespread concern. To diversify supplies, new mining—outside of China—is needed. But what many observers of the “rare earth problem” overlook is that China also dominates in (1) the processing of rare earths, particularly the less abundant heavy rare earths, and (2) the supply chains for permanent magnets. Heavy rare earths and permanent magnets are critical for many renewable energy technologies, and it will require decades to develop new non-Chinese deposits, processing capacity, and supply chains. This article clarifies several misconceptions, evaluates frequently proposed solutions, and urges policy makers outside of China to undertake measures to avert a crisis, such as greater support for research and development and for the cultivation of intellectual capital.

Keywords: Rare earths Permanent magnets Renewable energies Energy security China Supply chains

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1. Introduction

In past years, many policy makers, scientists and other interested parties have urged reducing reliance on hydrocarbon energy sources in favor of renewable ones. Reasons for this range from concerns over global warming, oil price volatility and economic vulnerability, to the peaking of oil production or the general need for diversification in energy portfolios. Actually attaining the potential environmental, economic and political benefits of renewable energies will, however, require a massive build-out. This article sounds the alarm that one significant obstacle to this effort may be the scant supplies of certain critical materials: rare earth elements.[1] These are conventionally divided into two categories: the more common *light rare earths* and the less abundant *heavy rare earths*, which are particularly needed for efficient lighting applications and for the permanent magnets used in many renewable energy technologies.

Lately, the 'rare earth problem' has received considerable attention, and several publications have taken stock of the situation. These assessments include, but are not limited to, a flawed Wall Street Journal article belittling the possibility of shortages (Sternberg, 2014), a more accurate but overly optimistic report (Butler, 2014), as well as a rigorous evaluation (Golev et al., 2014). None of the recent reporting on rare earths accurately depicts the extent of the various challenges. In general, misconceptions about rare earths and rare earth-related industries are rampant.

Rare earths are the linchpin ingredients of many high technologies for a wide variety of uses—ranging in application from military and medicine to entertainment, communications and petroleum refining, through to lighting and renewable energies

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(US DOE, 2011)—and many analysts are prone to treating all industrial users as falling into one category and lumping the different types of rare earths together. As this article will demonstrate, some rare earths are 'rarer' than others and different technologies require different rare earths. Furthermore, many analysts either misunderstand or underestimate the potential heavy rare earth bottlenecks confronting efficient lighting and renewable energy technologies. Indeed, a common misperception is that an increase in global mining production will overcome rare earth supply shortages.

At the moment, the source of most rare earths is China. Thus, it is indisputable to say that diversification of suppliers is needed. However, as this article will also demonstrate, a more nuanced understanding of the problem is necessary: the issue is not just that most extraction of heavy rare earths occurs in China but, more importantly, China has a near-monopoly on processing capacity and on the supply chains for converting the raw elements into end products (Humphries, 2013). Whereas some extraction and processing of light rare earths does occur outside of China, for heavy rare earths it will take years—if not decades—to develop alternative supply chains.

This article seeks to serve as a wake-up call to renewable energy advocates, whether government officials, policy makers, industry decision-makers or simply concerned citizens. We begin by providing background information on rare earth elements and permanent magnets, clarify several ubiquitous misperceptions about rare earths and outline the risks of heavy reliance on a single supplier. We then review and assess the various methods for addressing shortages and present the main issues associated with developing rare earth supply chains outside of China. The article closes with a discussion of the implications and several policy recommendations.

2. Methods

The data for this article were collected in 2013 and 2014 from a wide variety of sources, including documents and reports from various governments, academic articles and research papers, industry specific publications, think tank reports and news media reporting. In-person and telephone interviews were also conducted with a number of experts, including geologists, material scientists, industry executives and government analysts.

3. Results

3.1. Critical rare Earths

The ‘rare earths’ category, depicted in Table 1, refers to 15 chemical elements (numbers 57–71 of the periodic table) collectively known as the lanthanide or lanthanoid series plus two additional metals, scandium and yttrium, that are closely related. Although many rare earths were discovered one-to-two centuries ago, their value has only recently been discerned. The “unique magnetic, luminescent, and electrochemical properties” of rare earths makes them almost indispensable to many of today's technologies (RETA, 2014); for example, when used as additives to permanent magnets, they endow resistance to demagnetization at high operating temperatures.

Table 1
Background on rare earths.

Atomic no.	Name	Type[a]	Selected applications[b]	Crustal abundance (ppm)[c]	Criticality to clean energy: short-term[d]	Criticality to clean energy: medium-term[d]
21	Scandium	N/A	metal alloys for aerospace industry	14	N/A	N/A
39	Yttrium	Heavy	Phosphors for fluorescent lighting and liquid crystal displays (LCDs)	21	Critical	Critical
57	Lanthanum	Light	Battery alloys, phosphors, fluid catalytic cracking catalyst for oil refineries, lasers	31	Near critical	Not critical
58	Cerium	Light	Nickel metal hydride (NiMH) batteries for hybrid/electric vehicles, phosphor powders	63	Near critical	Not critical
59	Praseodymium	Light	Permanent magnets, NiMH batteries, airport signal lenses, photographic filters	7.1	Not critical	Not critical
60	Neodymium	Light	Permanent magnets, glass and ceramic astronomical instruments, lasers	27	Critical	Critical
61	Promethium	Light	N/A	N/A	N/A	N/A
62	Samarium	Light	Permanent magnets, reactor control rods	4.7	Not critical	Not critical
63	Europium	Light[e]	Fluorescent lighting and LCDs	1.0	Critical	Critical
64	Gadolinium	Light	Nuclear fuel bundles, medical imaging, electronics	4	N/A	N/A
65	Terbium	Heavy	Lighting and display phosphors, permanent magnets	0.7	Critical	Critical
66	Dysprosium	Heavy	Permanent magnets, lasers, lighting	3.9	Critical	Critical
67	Holmium	Heavy	Magnets	0.83	N/A	N/A
68	Erbium	Heavy	Lasers, glass colorant	2.3	N/A	N/A
69	Thulium	Heavy	Magnets	0.3	N/A	N/A
70	Ytterbium	Heavy	Solar panels, fiber optics, lasers, stainless steel alloys, nuclear medicine	2	N/A	N/A
71	Lutetium	Heavy	X-ray phosphors	0.31	N/A	N/A

[a] USGS, 2014a.

[b] Selected applications compiled from US DOE (2011) and US EPA (2012).

[c] These figures indicate each rare earth element's abundance in the Earth's upper continental crust in parts per million (ppm), Rudnick and Gao (2003).

[d] US DOE (2011).

[e] The USGS (2014a) classifies europium as a light rare earth. However, it should be noted that some authorities consider the distinction between light and heavy earths as arbitrary (British Geological Survey, 2011). Europium, for example, is grouped with the heavy rare earths by the US DOE (2011), Molycorp (2012), and Alkane Resources (2013).

Several of the rare earths used in renewable energy technologies and efficient lighting applications are considered critical, that is, at risk for short- and mid-term shortages. The United States (US) Department of Energy (US DOE, 2011) assessed the criticality of various materials to clean energy applications according to a two-part schema: the importance of each individual material and

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the severity of the supply risks. Materials scoring high on both dimensions are considered “critical”, and those at medium or low risk are deemed, respectively, “near critical” or “not critical” (see Table 1). For both the short- (0–5 years) and medium-term (5–15 years) periods, five rare earth elements were placed in the critical category: dysprosium, neodymium, europium, yttrium, and terbium. Most of these are categorized as heavy rare earths: dysprosium, used in neodymium–iron–boron permanent magnets (for example, in wind turbines and electric vehicles); terbium, used primarily in lighting (terbium can also substitute for dysprosium, but is more expensive); and yttrium, used in lighting. Europium, used in lighting, lies between the light and heavy rare earths on the periodic table and is considered a heavy rare earth by some authorities (US DOE (US Department of Energy), 2011, Molycorp, 2012 and Alkane Resources, 2013) and as a light rare earth by others (USGS (US Geological

Survey), 2014a and USGS (US Geological Survey), 2014b). Neodymium, which is clearly categorized as a light rare earth, is used in electric vehicle motors and is the main rare earth component of neodymium–iron–boron permanent magnets.

3.2. Permanent magnets

Rare earth permanent magnets are particularly important for clean energy applications and, currently, China accounts for about 80 percent of global production (Benecki, 2013 and Dent, 2014). Permanent magnets are divided into two categories: samarium cobalt and neodymium–iron–boron. According to an executive in the permanent magnet industry interviewed for this article, the two types have similar properties, but offer different advantages and disadvantages. Samarium cobalt magnets perform better at higher temperatures, but are brittle, which limits magnet size and can cause problems with integration into certain applications, such as motors. Samarium cobalt magnets do not contain dysprosium, but there are supply and price concerns associated with cobalt (US DOE, 2011). These magnets are used for small, high-temperature applications and are typically not found in renewable energy technologies.

Neodymium–iron–boron magnets are even stronger than samarium cobalt magnets and, because their size is not as restricted, they are more suitable for large applications, such as wind turbines and other electricity generators. These magnets typically contain two to four percent of dysprosium to enhance their temperature resistance. The advantages offered by neodymium–iron–boron permanent magnet to renewable energies are not inconsequential. Depending on the system, permanent magnets can increase efficiency—upwards to 20 percent—which translates into lower costs and shorter payback periods. For example, at least two major benefits can be derived from replacing the mechanical gearboxes in wind turbines with direct-drive permanent magnet generators: first, the overall weight of the turbine is reduced, which thus reduces the costs of other components, such as the concrete and steel required to support heavy gearboxes; second, reducing the number of moving parts allows for greater efficiency and reliability (Hatch, 2014; see also Kleijn, 2012). The advantages of permanent magnet generators are particularly salient for offshore installations, where reliability is paramount due to the high costs of maintaining and repairing turbines.

Neodymium–iron–boron magnets are also used in other types of renewable energy technologies—such as underwater ocean and wave power (Dent, 2014). Additional potential applications that could use permanent magnets include small hydro applications, solar updraft towers (Hatch, 2008), geothermal drilling (Hatch, 2009), and heat pumps (rdmag.com, 2013). Several of these renewable energy technologies are in the prototype or testing stages. One factor that could impede their commercialization is the price of permanent magnets. Indeed: were the price lower, many existing renewable energy technologies could be re-designed around them, which could reap the same efficiency, size, reliability and, ultimately, cost benefits as they already produce for new technologies (Hatch, 2014).

3.3. Clearing up misconceptions about rare earths

As evidenced by the flawed recent reporting—even in publications such as the Wall Street Journal—misconceptions about rare earths abound and it is important that the public, particularly renewable energy advocates, achieves a more nuanced understanding.

The first major misconception related to rare earth elements stems from the word 'rare', which leads many observers to conclude that these elements are extremely scarce. However, as indicated in Table 1, rare earths differ in their abundance in the Earth's crust ('crustal abundance'). Some rare earths, such as terbium, thulium and europium, are scarce and others, such as cerium and yttrium, are more abundant than all precious metals (Chakhmouradian and Wall, 2012). Rare earth elements are found as part of the lattice structure of certain host minerals. For extraction of the rare earths to be economically feasible, the host minerals must contain sufficiently high quantities of rare earths. According to Bau (2014), a geoscientist specializing in rare earths, the rare earths show exceptionally coherent behavior due to their extremely similar physicochemical properties, which makes it difficult to separate the individual elements. In brief, a century ago, these elements were called rare because they were considered a rarity; nowadays, however, rare refers more to the difficulty in isolating single elements (Bau, 2014; for more on abundance, rare earth minerals and deposits, see Haxel et al., 2002 and Chakhmouradian and Wall, 2012).

A second major misconception is that the various rare earths are equally valuable; some are more valuable and critical, however, than others. The heavy rare earths are less common, not only occurring in far fewer deposits but also comprising just a fraction of the ore in which they are found: most ores are predominantly light rare earths (Dent, 2012 and Lifton, 2013). Moreover, the complex mineralogical composition of many heavy rare earth ores requires new and unproven extraction and beneficiation approaches (Bau, 2014; see also Oskin, 2013).

A third major misconception regarding rare earths is that China is the only country with substantial deposits. According to the most recent US Geological Survey USGS (2014b) data, global reserves total 140,000,000 t and are located in China (55,000,000 t), Brazil (22,000,000 t), the Commonwealth of Independent States (CIS) (19,000,000 t)[2], the US (13,000,000 t), India (3,100,000 t), and Australia (2,100,000 t), with the remaining 25,800,000 t spread among smaller reserves in Malaysia, Vietnam and other countries. China thus holds approximately 39 percent of the world's reserves. The category in which China more clearly predominates, however, is production. Global production is about 110,000 t per year (t/y), of which China supplies 100,000 t/y, or 90 percent. The other producers comprise the US (4000 t/y), India (2900 t/y), Russia (2400 t/y), and Australia (2000 t/y), with smaller amounts supplied by Brazil, Malaysia, and Vietnam.

Over the past few decades, China has pursued a concerted strategy to develop its refining and fabrication capacities and thus achieve the world's most integrated supply chain for permanent magnets and other products. At the moment, China is the *only* country with the capacity to process heavy rare earths (Lifton, 2012b). This means that many rare earths—and all heavy rare earths—extracted outside of China must be exported to China in order to enter value chains. Thus, the recent focus—by policy makers and the media—on finding non-China deposits of rare earths as the main solution for addressing shortages ignores an important issue: diversification will also require the development of non-China processing, separating and refining capacities and of non-China supply chains.

3.4. The risks of relying on a dominant supplier

Up until the mid-1980s, the Mountain Pass mine in California (US) produced 60 percent of the world's rare earths. The Mountain Pass mine closed in 2002, partly because of environmental problems and partly because it could not compete against lower-priced rare earths from China. Not only did China have lower labor costs, but several of its rare earth deposits were relatively easy to access and China had lax-to-nonexistent environmental regulations. With these cost advantages, China quickly became the world leader in mining.

For many years, China was considered a reliable supplier of rare earths, so manufacturers and end users alike, including the US Department of Defense, seemed unconcerned about its quasi-monopoly. This perception changed abruptly in the late 2000s when China began instituting significant reductions in its annual export quotas, which led to dramatic price hikes and alarmed importers around the world (Looney, 2011). Both the Chinese government and international industry analysts have provided various reasons for the Chinese government's decision to restrict quotas. First, the government is concerned about having sufficient future supplies for its own industries, despite the country's substantial reserves. Second, the government has recently begun asserting greater control over its rare earth industry, including cracking down on rogue production and theft, as well as implementing environmental protection measures. Third, whereas the global rare earth industry is lucrative, worth an estimated $1.3 billion in 2010, the end-use industries that require rare earths are worth a thousand-fold more: an estimated *$4.8 trillion* in 2010. Chinese officials have admitted that the quota restrictions are tied to the Chinese government's ambition to attract more end-use manufacturing industries: if manufacturers cannot be certain of Chinese exports of rare earths, then they might move their factories to China (Seaman, 2010).

Importers' concerns over China's intentions vis-à-vis rare earths were exacerbated in September 2010 when China used its control over supplies as a political tool to exert pressure on Japan during a dispute (Klare, 2012). In response to these indications that China could become an unreliable supplier, the European Union (EU), the US and Japan began holding joint “Trilateral Conference on Critical Materials” workshops, with Canada and Australia also as participants, to explore how to address potential shortages (Normile, 2010 and METI (Ministry of Economy, Trade and Industry of Japan), 2013). In 2011, the EU, the US and Japan filed a WTO complaint against China, and, in March 2014, the WTO found that China had violated international trade law by restricting overseas sales (Jolly, 2014).

To ensure energy security for oil and gas supplies, importing countries are exhorted to diversify and increase the number of suppliers (Yergin, 2006); the same holds true for other critical commodities, such as rare earths. Reliance on a single supplier—regardless of who it is—

carries risks. Thus, one of the prime recommendations of the Trilateral Conference was to find alternative sources of rare earths; other recommendations included searching for substitutes and increasing efficiencies (Trilateral EU-Japan-US Conference, 2011).

3.5. Addressing rare earth Shortages

Two ways of addressing potential rare earth shortages obtain: either *lessening dependence* on rare earths, by reducing the quantity needed, finding substitute materials, and/or changing the end-use products so that rare earths are no longer required; or *ensuring sufficient supplies* through new mining and recycling. Because of their importance to many renewable energy technologies, rare earth permanent magnets will receive special consideration in the next sections.

3.5.1. Substitution

For decades, research on rare earths and permanent magnets focused on optimization. Rare earths offer so many ideal characteristics that, far from seeking substitutes, scientists were exploring how to better deploy rare earths. After China's quota reductions, however, the search for alternative materials began to receive attention. For renewable energy and lighting applications, few comparable substitutes—that is, materials that deliver similar performance—have thus far been found.

Yttrium, terbium and europium are still the most important elements used in the phosphors for various types of fluorescent lamps, and demand for fluorescents will not decrease until light-emitting diode (LED) bulbs gain greater acceptance (US DOE, 2011). At the moment, few substitutes for these three materials in lighting are commercially available. In mid-2013, the University of Washington (US) announced the development of a silicon-based phosphor that could replace rare earths in LED bulbs, but, as with most other new discoveries, the technology is still in the experimental stage and whether or when the substitute will become a commercial product is unknown (Ma, 2013).

Yttrium is also used in high-temperature superconductors, which could replace permanent magnets, for example, in wind turbines; however, this switch would result in greater demand for yttrium. Terbium could substitute for dysprosium in permanent magnets, but terbium is even more expensive than dysprosium. Neodymium is the main rare earth component of rare earth permanent magnets (and such magnets constitute the primary use of neodymium) and, like the other four rare earths critical to clean energy and lighting applications, identifying comparable replacements has been problematic (US DOE, 2011). According to the US DOE (2011, 87), praseodymium “can be partially substituted for neodymium in magnets. However, the extent of this substitution is thought to be small (less than 5 percent) for high-performance magnets used in vehicles and wind turbines.” Partly because of the substitution difficulties, manufacturers and scientists have rather looked to reducing or eliminating rare earth content.

3.5.2. Reducing or eliminating rare earth content

In contrast to research on substitutes, research on ways of reducing rare earth dependence has yielded more promising results. Governments and manufacturers are—both independently and jointly—seeking to minimize or obviate the need for rare earths. For example, both the US DOE and Japan's Ministry of International Trade and Industry (MITI) are directly engaged in research as well as in supporting private research. As dysprosium is needed in magnets to enhance tolerance to heat, one method of reducing the need for dysprosium is to reduce the operating temperature of vehicles or of power generators. According to a permanent magnet industry executive interviewed for this article, while it may be possible to lower the temperature of underwater renewable energy applications (for example, in tidal systems), it is unlikely that wind turbines could be designed in a manner that would reduce the need for dysprosium. This is because the generation process itself produces high temperatures, and wind turbines are additionally heated through their exposure to sunshine.

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In terms of wind power, permanent magnets are found in systems that generate less than 7–10 MW of power. Turbines above 10 MW will likely require the use of superconducting generators rather than induction or permanent magnet generators, because of costs and weight (Constantinides, 2012). However, large scale deployment of 10 MW wind turbines is still in the future and may first play a role in offshore installations (see Smith Stegen and Seel, 2013). As noted above, greater deployment of superconductors will increase demand for yttrium. Thus, one type of dependence may just be exchanged for another.

In addition to reducing the need for rare earths, extensive research is being conducted on how to eliminate the need for rare earth magnets altogether. A recent advance, for example, was achieved by Mitsubishi, which created an electric motor that does not require rare earths; however, according to one analyst, the company admits “that the new motor is less efficient than conventional ones during acceleration but performs comparably after reaching what it calls stable speed (Bromby, 2012).”

In sum, significant game-changing breakthroughs have not yet materialized in research on either substituting or reducing/eliminating rare earth elements, and it could be years before this approach to potential shortages bears fruit. According to an industry report: “While every effort should be expended to find new and better materials and machine designs, this is a lengthy process. Invention defies mandated timelines. The process of discovery, scale-up and commercialization can easily consume 5–10 years (Constantinides, 2012, 7).” In the short-term (0–5 years), and most likely also in the medium-term (5–15 years), new supplies of non-Chinese rare earths will have to be part of the solution.

3.5.3. Re-opening mines

In past years, investors and policy-makers began re-evaluating mines outside of China which had been closed because they could not compete with China's low prices. Given recent higher prices, the Mountain Pass mine in the United States and the Steenkampskraal mine in South Africa appeared attractive again.

The Mountain Pass mine has changed hands several times over the past decades. From 1977 to 2008, the mine belonged to Union Oil/Unocal, which later became part of Chevron. (An interesting aside: in 2005, the China National Offshore Oil Corporation (CNOOC) attempted to purchase Unocal, which would have given it possession of Mountain Pass (Mancheri et al., 2013, 14)). Then, in 2008, Molycorp Minerals LLC purchased the mine, upgraded facilities (still ongoing) and re-opened it a few years later. Molycorp asserts that Mountain Pass will eventually be able to produce 19,050 t/y (Molycorp, 2013, 6). According to a Washington, D.C.-based rare earths expert, who was interviewed for this article, the company's actual production is unknown and, by analyzing Molycorp's data, this expert estimated 2013 production at close to 5000 t.

Mountain Pass contains primarily light rare earth ores: particularly rich in cerium and lanthanum, it also contains lesser amounts of the light rare earths neodymium and praseodymium and small amounts of the elements it categorizes as heavy rare earths: samarium, gadolinium, europium, yttrium, dysprosium and terbium (Molycorp, 2012). Molycorp aims to produce 7 t/y of dysprosium, which is precisely the quantity needed by the US military (Lifton, 2012a) meaning that other consumers of US-sourced dysprosium—from high technology to clean energy firms—would have to look elsewhere for supplies. In terms of separation capabilities, the Mountain Pass facilities can separate light rare earths but not heavy rare earths, which Molycorp carries out in China. This means that any dysprosium Molycorp generates would not be processed in the US: consumers would still be reliant on overseas intermediaries. Molycorp recently purchased a Chinese company with the technology to separate heavy rare earths and has announced it would like to build a processing plant outside of China (Smith, 2012), but the company has not made any concrete steps in this direction.

The Steenkampskraal mine in South Africa came online in the late 1950s/early 1960s, primarily producing thorium. Because the mine's ore also contains rare earths, including heavy rare earths, it is currently being refurbished as a rare earths mine. Its majority owner is a subsidiary of the Great Western Minerals Group (GWMG), which in 2010 received a 20-year mining permit. According to a 2014 status update, pilot plant testing for extracting rare earths has been preliminarily successful (GWMG, 2014).

In sum, re-opening mines is the most expedient way to quickly produce new sources of rare earths. However, although output from these mines is expected to increase global supplies, it will be insufficient to cover projected increases in demand (US DOE, 2011). Thus, diversified production of rare earth supplies in sufficient quantities to meet future demand will require new non-Chinese mining as well.

3.5.4. New onshore exploration and mining

Establishing a new mine is a costly, complex and lengthy process. The timespan for the development of an underground mine, from initial exploration to production, is approximately 12–13 years (US EPA, 2012). An open pit mine requires less time, but exerts greater environmental impact, which must also be factored into feasibility calculations. The greatest challenge of new mining is not constructing the mine itself, but developing the processing and separating facilities. No rare earth deposit is the same and the facilities must be custom-built to handle each deposit's unique mineralogical characteristics. Furthermore, as rare earths are almost always found together with uranium and thorium, the mining complex must be equipped to safely dispose of hazardous byproducts. One reason why some Chinese rare earths were so cheap is that the radioactive wastes were not properly treated (Jolly, 2014 and Golev et al., 2014).

The search for new deposits is partly driven by industry need and government concern, but also by eager investors. As a result, there is a high degree of speculation surrounding many ‘promising’ sites. To avoid adding to the hyperbole, we present only the US Geological Survey's (USGS, 2013) most recent information, which states that in addition to several sites in the US, assessments have been “underway in Australia, Brazil, Canada, China, Finland, Greenland, India, Kyrgyzstan, Madagascar, Malawi, Mozambique, South Africa, Sweden, Tanzania, Turkey, and Vietnam.” This number of potential new mines might seem encouraging; however, before a deposit can be considered economically feasible, rigorous criteria must be met and many initially auspicious cases fail. For example, GWMG conducted extensive exploration and drilling tests at a promising site in Utah and, after receiving disappointing results, opted not to engage in mining (US EPA, 2012). The same could happen for many of the other sites currently under consideration.

3.5.5. Seabed mining

Geological exploration and chemical analysis of manganese nodules indicate that the sea floor may be a source of rare earths, including the more critical neodymium and dysprosium. In comparison to land-based mines, such as Bayan Obo in China, initial exploration of seabed sources indicates they possess higher concentrations of heavy rare earths (Hein et al., 2013). Just as mining on land takes years to develop, commercial mining of seabed rare earths is presumably decades away from fruition.

3.5.6. Recycling

Rare earth recycling is more complex than reclamation of other types of metals. For example, recycled platinum supplies a significant portion of the platinum needed each year, often helping to avert shortages. Scientists hope that rare earth recycling will likewise fill demand gaps. However, whereas platinum is a native elemental metal found in pure form, the rare earths are not. Just as separating them from their host rock is difficult, the chemically-similar rare earths are also difficult to recover from used goods. Rare earths are “deeply embedded into other products” and “physical extraction often yields a small return on substantial effort” (Dent, 2012, 5).

Despite these issues, research into various aspects of recycling is ongoing, from finding the best methods for extracting materials to designing end products in a way that facilitates later reclamation. Such research is particularly emphasized in regions that have little hope for indigenous mining, such as in Japan and Europe. To paraphrase a German representative of the Fraunhofer Institute, used mobile phones constitute an urban mine (ZDF/ARTE, 2014).

Because of their cost and criticality status, scientists are particularly interested in reclaiming neodymium and dysprosium from end products such as permanent magnets. Although mobile phones might be one source, recycling from applications that use higher concentrations of rare earths, such as electric vehicles and wind turbines, is considered more likely to be economically feasible (Hoenderdaal, 2011). Even within this category, however, there are vast differences in the amount of rare earths used, for example: “A Toyota Prius uses 2.2 pounds of neodymium…and a new-generation windmill requires 1500 pounds of neodymium (US EPA, 2012: 5–2).” However, at least two obstacles confront such recycling. First, newly erected windmills will not be available for recycling for many years. Second, no “standard method of recycling rare earths” (Bonawandt, 2013) exists yet and research into their recovery has produced only incremental advances. Thus, rare earth recycling is a long-term endeavor.

In sum, interest and research into various methods for coping with potential shortages have been spurred by several inter-related factors. For example, policy-makers’ and manufacturers’ concern over potential shortages has fueled support for research into substitution, content reduction/elimination and recycling. Higher prices have encouraged financial investors and mining companies to re-open mothballed mines and fund new exploration—in the hopes of achieving a payoff. However, if prices were to drop, these profit-driven investments might end just as suddenly as they began; recognizing the precariousness of its position, Molycorp, for example, fears that Chinese producers might flood the market to drive out new mines. According to Molycorp, if prices drop because of “predatory pricing behavior” by “competitors, primarily various Chinese producers”, then this could “materially adversely affect our profitability” (Molycorp, 2012:10). Some observers believe that China would not engage in such behavior, if for no other reason than to protect its own prices, which have risen in recent years as its domestic consumption has soared (Humphries, 2013 and Lifton, 2013). Others, however, believe that China has sufficient stockpiles to flood the market for just long enough to shut down non-Chinese mines (Bau, 2014).

3.6. Supply chain development

As mentioned above, once the ore for rare earths is extracted, the individual streams of rare earths must be separated from each other and from the host ore in a series of procedures that are both costly and technically challenging. Whereas light rare earths can be processed outside of China, the more troublesome heavy rare earths are handled exclusively in China. At the moment, only one facility outside of China, Rhodia's La Rochelle plant in France, could potentially isolate heavy rare earths, including dysprosium. However, Rhodia, a subsidiary of the Solvay Group, reportedly plans to use the plant to recycle phosphors from light bulbs (Golev et al., 2014). Even if Rhodia were to focus on refining rare earths, its capacity of 9000 t/y would be insufficient to meet global demand (Lifton, 2012a and Lifton, 2012b). Before rare earths can be used in permanent magnets, they must be refined into metals, and then into alloys; only then are they ready for the magnet manufacturing process (for more on permanent magnet supply chains, see also Lifton, 2011 and Lifton, 2012c; GWMG, 2012; Humphries, 2013).

The US Magnetic Materials Association (USMMA) (2013) recently compiled an extensive (but not exhaustive) list of the companies and countries engaged worldwide in the various stages of the permanent magnet supply chain (mining→metals/alloys→magnet manufacturing). Under the mining heading (which they denote as *Oxides*), 10 percent of the world's mining takes place by a handful of companies outside of China. Only twelve companies comprise the *Metals, Alloys & Powders* category: China and Japan were indicated six times each, the US was mentioned twice, and the UK, Vietnam and Thailand each received one mention. [3] Under *Magnets*, the manufacturers were categorized into producers of samarium cobalt or neodymium–iron–boron magnets. Under samarium cobalt, 14 manufacturers were listed, with China mentioned nine times; Japan, three times; the US, twice; and Germany, Finland and Switzerland once each. Of the 41 firms listed as neodymium–iron–boron manufacturers, China was indicated 33 times; Japan, five; the US and Germany, twice each; and Finland and the UK, once each. According to Dent (2014), a rare earth expert and one of USMMA's co-founders, many neodymium–iron–boron magnet makers produce their own alloys; the real chokepoint is the supply of rare earth *metals,* as very few of these makers are located outside of China.

4. Discussion

Whereas experts in the minerals industry are mostly aware of China's strong position, many stakeholders in and advocates for renewable energy technologies are not. A recent spate of publications, which either falsely assure that there is no rare earth crisis or misinterpret/misrepresent the core problems, do not help. Indeed, many journalists, scholars and analysts seem to miss several important points. For example, Butler (2014) states that the Mountain Pass mine's potential to produce heavy rare earths is “an encouraging development for those US and foreign companies that rely solely on Chinese sources for their rare earth needs (35).” As one of the experts interviewed for this article observed: the small amount of heavy rare earths that the Mountain Pass mine may eventually produce would be but a “drop in the bucket”. Second, Butler does not seem to realize that any heavy rare earths extracted from the Mountain Pass mine will also have to be processed—and that capacity is currently lacking outside of China.

Golev et al. (2014) offer a far more informed and accurate report on the status of rare earth supply chains. However, even these authors overlook the timescale, and specifically, how long it will take to overcome the bottlenecks. Indeed, new mining and alternate supply chains will help, but *when*? Both mining and supply chain development require significant lead times. Perhaps the most flawed understanding of the rare earths crisis appeared in a January 2014 article in the Wall Street Journal titled “How the Great Rare-Earth Metals Crisis Vanished” (Sternberg, 2014), in which the author asserts that rare earth demand is declining and that new exploration combined with new developments in recycling and content reduction have resolved the emergency. This author entirely misses the fact that rare earths differ in their

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value and criticality, and that some are particularly difficult to process.

Such publications have muddled the discussion. In addition to raising awareness, this article also seeks to clarify several misconceptions of rare earths that have obscured the threats confronting renewable energy technologies. The main factual takeaways are thus:

- First, rare earths differ in their market demand, ease of mining, value and end uses. Dysprosium, for example, critical for clean energy applications, is more difficult to extract and process than many other rare earths and comparably more valuable.
- Second, the lead times for rare earth projects are daunting. It takes longer than a decade to bring an underground mine online.
- Third, although substitution, content reduction and recycling may eventually prove useful measures, they are years away from militating against shortages.
- Fourth, currently the only complete supply chain for heavy rare earths is in China.

5. Conclusions and policy implications

This article seeks to broaden awareness of a potential threat to a significant build-out of efficient lighting and renewable energy technologies: the almost monopolistic dominance of one country, China, over rare earth processing, particularly for heavy rare earths, and permanent magnet production. The policy implications of this dual dominance are significant. Innovation, which is clearly needed to catch up to China, is fostered by supporting ‘niche-level’ activities (Geels, 2010) such as research and development, laboratories and information exchange. Policy makers outside of China should clearly step up their support. Moreover, not only does China have a substantial head start regarding its heavy rare earth processing and permanent magnet industries, it has other ‘assets’ that are lacking elsewhere: technological know-how and intellectual capital. Technological know-how can be acquired, but intellectual capital—the engineers and scientists specialized in these fields—must be cultivated and developed.

There are several measures policy makers could implement to encourage a new generation of engineers and scientists, such as sponsoring scholarships, grant awards, and research competitions. Even at the secondary school level, policy makers could provide greater backing for teachers. As one of the experts interviewed for this article noted, a small investment in curriculum development, for example, in modules explaining the basics—as well as the constituent materials—of modern technologies could lay the groundwork for seeding future generations of scientists and engineers.

Once students have graduated and are established in their fields, there is still a need for synergy development. Outside of China, there are so few professionals that some experts have observed a lack of awareness and communication between different ends of the supply chains. Opportunities for cross-industry exchange could be enhanced through greater sponsorship of professional societies, themed conferences and meetings. The Japanese government has been particularly adept at encouraging its rare earth and critical materials industries, with the result that Japan has been responsible for many of the recent important developments in these fields (Hatch, 2014). Other countries would do well to emulate the Japanese model.

In sum, rare earth shortages are problematic for a wide array of industries, ranging from medicine to entertainment to communications. For the renewable energy industry, shortages of heavy rare earths and/or permanent magnets have implications for efficiency, reliability, size, and weight—all of which affect costs. Cost competitiveness has been one of the main bludgeons used against many renewable energy technologies vis-à-vis conventional energy technologies. If efforts are not made to avert such shortages, then one of the main challenges to a greater build-out of renewable power generation will persist.

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