

## Mapping the Product Life Cycle: Rare Earth Elements in Electronics

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**ABSTRACT** In this case, we map the issues that arise across the life cycle in “green” technologies such as wind turbines, electric cars, and electronics that are often hidden from the designers, manufacturers, and users of these technologies. We do this by focusing on some life cycle issues of using rare earth elements (REEs) in these technologies. We attend to the geopolitical issues of sourcing these rare earth materials, as well as the environmental and health effects of extracting them from the earth through mining and smelting and disposing or recycling them at life’s end. Our goal is to begin unpacking the difficult choices that manufacturers (and governments) must think through as they endeavor to improve both the design of sustainable technologies and the production of materials used in these products.

### KEY MESSAGE

Students will understand better how rare earth elements—as an example of the many materials now used to make products—raise a suite of interconnected environmental, health, and geopolitical issues through their extraction and end-of-life fate. Students will begin to think through the considerations that designers, companies, and governments face when trying to enhance the sustainability and social justice of products.

### INTRODUCTION

The design of products can have a huge effect on their sustainability. Selecting specific materials often results in damage from mining raw ingredients, harm to workers, and end-of-life waste. Are manufacturers obliged to think about the environmental and social impacts stemming from their choices of which materials to use in their products? Should companies think about where their materials are coming from, and what the effects are on local communities? Should economic cost be all-decisive in making decisions about materials?

One way to begin answering these questions is to map the product’s impacts across its life cycle, as well as the

industry structures, corporate decisions, and designer values that cause these consequences to be in the first place. This approach differs from life cycle assessment that is generally a highly technical calculus aimed at quantifying certain impacts. In contrast, life cycle mapping tries to trace the ways in which *production and design choices* lead to environmental effects, both destructive and favorable.

Rare earth elements (REEs) provide a window in the complex array of business, design, trade, and sustainability considerations that firms may hold. These materials are widely used in supposedly “clean technology” products like electronics and renewable energy systems. They may appear innocuous in helping make computer screens brightly colored, phones vibrate loudly, battery charges last longer, and wind turbines generate electricity, but their production, use, and end of life can create sizable ecological, health, and labor welfare costs in places from mines in California to electronic waste recycling villages in China. Whether corporations and designers decide to use REEs in their products, and where they source such materials from, can end up affecting endangered desert tortoises, Chinese miners, and national security. In turn, the effects of extracting or recycling REEs also depend on whether governments have stringent environmental regu-

latory standards in place or offer subsidies for the adoption of new recycling technologies.

In this case, we look at two life cycle phases—extraction and end of life—as examples of the effects that rare earths can have. Where do the materials in your phone come from? What happens to your phone once you dispose of it?

## CASE EXAMINATION

### *What Are REEs and What Are They Used For?*

REEs are a group of 15 lanthanide metals on the periodic table plus scandium and yttrium [1]. Their unique chemical and physical properties make them particularly attractive to industries. For example, because some REEs are powerful magnets, electronics manufacturers can design increasingly smaller, lighter technologies such as mobile phones, ultra-portable laptop computers, and electric car motors [2]. Rare earths are also used in numerous clean energy technologies, notably wind turbine generating units [3]. Rare earths help power rechargeable batteries. Some rare earths offer colorful phosphors for use in television and computer screens and energy efficient LED lights. As a result, rare earths have gained the aura of being highly sustainable materials.

The quantities of rare earths now consumed are not trivial. For example, some electric vehicles have small amounts, depending on their battery type: the Prius hybrid NiMH battery alone contains 10 pounds of lanthanum [4]. All cars have some REEs; the 87 million cars manufactured in 2013 accounted for roughly 30,000 tonnes of REEs [5]. Some (not all) wind turbines also contain REEs, ranging from 70 kg/MW for hybrid systems to 250 kg/MW for direct drive systems [5]. In iPhone, REEs are used in small amounts in screens, hard drives, speakers, and vibration units [6]. This may seem miniscule but over a billion iPhones alone have been sold as of 2016. Many more mobile phones and computers have been produced.

REEs are classified as “light” (Sc, La, Ce, Pr, Nd, Pm, Sm, Eu, and Gd; also known as the cerium group) and “heavy” (Y, Tb, Dy, Ho, Er, Tm, Yb, and Lu; also known as the yttrium group) based on their properties [7]. Light REEs are more common and easier to extract than heavy REEs. Rare earths are not found in their isolated elemental form in nature, and thus their separation and purification makes mining and processing challenging, expensive, and

polluting [2] (see pages 2-1 to 2-3 in Ref. [2] for more information about REE abundance and ores).

### *Where Are REEs Found?*

Rare earths, despite their name, are quite common throughout the earth’s crust but are usually found in small concentrations in mineral ores such as oxides [2]. REEs in their most concentrated natural form are found primarily in three mineral ores (of over 200 known REE-containing minerals). These mineral ores—bastnaesite, xenotime, and monzanite—are often but not always economically and technologically feasible for extraction. The most widespread ore is bastnaesite, a carbonate containing light REEs including cerium, lanthanum, and yttrium. Bastnaesite ore in the United States and China make up the majority of potentially extractable rare earths globally. Australia, Brazil, India, Malaysia, Sri Lanka, and China also have deposits of the second most common ore, monzanite [7].

Until the 1950s, South Africa was the leading producer of rare earths. Between the 1960s and 1980s, a mine in Mountain Pass, California, was the dominant global source before it closed down. Recently, Molycorps restarted this mine, which accounts for all U.S. production [8]. In the interim period, China rapidly became the largest extractor of rare earths, at times accounting for 95–97% of REEs worldwide, thus having a disproportionate influence on the availability of the materials [2]. Currently, partly in response to the geopolitical issues arising from China’s control, many countries around the world are exploring REE mining possibilities to protect their national security or to profit from a burgeoning market. With new mines coming online in the United States, Canada, Vietnam, and Australia, China’s control of the global markets has declined modestly to around 83% as of 2016 [9].

### *Mining and Refining REEs*

Extracting REEs creates environmental and geopolitical issues that manufacturers and designers must consider in deciding whether to use these materials. Mining and refining can significantly damage land, ecosystems, and local communities that depend on these resources for their livelihoods and well-being.

Miners typically choose above ground or open pit mines—instead of underground tunnels—to extract rare earth ore from the ground because these are by far the

cheapest method. Mining REEs is particularly destructive to the environment because they are found at low levels of concentration in minerals, thus forcing miners to remove vast quantities of ore simply to yield economically viable product. For example, at the Mountain Pass mine, rare earth oxides comprise only 7% by content, with the remainder being waste rock [2]. This means that larger land areas must be mined, often destroying habitats and diverting water streams that wildlife rely on. Miners must also remove a large amount of overburden, or rock and soil covering the more economically valuable ore. Storing these waste rocks next to the pit can result in ore debris, metals, and toxins being released into the soil, air, and water [3].

The next step is refining of the rare earth mineral to separate it from the materials it is bound to. Generally, refining happens close to the mining process to lessen transportation costs. The ore is pulverized into gravel and broken down further in a grinding mill so that the mineral grains get separated. This sand is then put through a floatation process in which, in the case of bastnaesite, toxic chemicals are added and bastnaesite floating on the top is then collected [7].

Once crushed, the ore requires further processing to recover the REE in its elemental form. This can happen in several ways, depending on the ore type. Because rare earths are incredibly stable, acids and/or high heat must be used to break up chemical bonds in order to separate the REE from the ore. The most common refining process is smelting where the metal is extracted by reacting ore in the furnace with highly poisonous oxidants and acids. This process often involves many steps, each generating its own waste stream: at the Mountain Pass Mine, refining involves 33 stages [2]. Finally, the REE is purified to a concentration high enough to sell. REEs are either sold as oxides, a powder form which can be packaged and shipped, or are further refined on-site to alloys for products.

#### *Mining Impacts in the United States and China*

Mining and refining rare earths cause many environmentally destructive effects that, by choosing to use REEs without demanding more sustainable practices, manufacturers tacitly endorse. The mines at Mountain Pass in the California Mojave Desert near Nevada and in China's Inner Mongolia province are vivid examples.

Rare earth ores at Mountain Pass were discovered in 1949, including a large vein of bastnaesite, which is an important source of cerium, used to make fluorescent lights, self cleaning ovens, and many other products [10]. By 1953, the Molybdenum Corporation of America (later renamed Molycorp) had built a mining complex sprawling over 222 acres. Initially, the mine supplied rare earths to the U.S. military to be stockpiled for future use. By 1965, the advent of color TV provided a new market for europium oxide, which is used as red phosphor. Soon the mine was producing a variety of REEs for the rapidly growing U.S. electronics industry. Between the 1960s and 1980s, Mountain Pass produced enough to satisfy U.S. demand, as well as a third of world demand [2]. Some heavy rare earths (e.g. dysprosium) still needed to be imported because they could not be mined in the United States; in fact, they generally came from Chinese mines.

In 1977, Union Oil Corporation of California (Unocal) acquired Molycorp. It halted production in 2002 due to increasingly intense competition from lower cost mines in China, as well as higher production costs, more stringent regulatory requirements, and difficulties in disposing of mine tailings [10]. In 2005, Chevron Corporation took over Unocal before selling the mine to a new company, Molycorp Minerals LLC. In 2011, the federal government granted a permit to Molycorp to reopen the mine, as the U.S. market revived in response to China's recent record in imposing quotas on its rare earths exports. The mine became operational again in 2014 and now supplies—in powder form—some of the REEs used in wind turbines and the iPhone and other electronics.

The mine has had a long history of pollution problems. Molycorp dumped tailings and other wastes from mining and refining these materials into a slurry behind a dam before the mine was closed in 2002 [11]. The acids, heavy metals, and radioactive elements from these wastes have leaked into local groundwater supplies [2]. Because some REEs are found in ores containing uranium, wastes can contain radioactive thorium and uranium; this was the case at Mountain Pass. In 1996, 300,000 gallons of wastewater spilled from a pipe breakage, contaminating the area around Ivanpah Dry Lake with radioactive materials and lead [12]. This threatened the delicate ecosystem in the nearby Mojave National Preserve, and potentially harmed endangered desert tortoises. This accident led to the discovery of 60-plus previous leakages and to federal investigations that eventually cost Molycorp millions of dollars

in fines and cleanup costs. At its peak, the mine produced 850 gallons of salty wastewater per minute, while smelting the ore released smoke containing greenhouse gases, heavy metals, sulfur, and other ore traces into the air [11].

Nonetheless, the new Molycorp mine claims to be producing REEs much more sustainably than before. Using new, sophisticated chemistry, it is striving to recover the same amount of REEs from half as much ore [11]. The company has asserted that it has at least eliminated the refinery's waste problem by finding a way to encapsulate toxic chemicals and radioactive materials. A new process "presses the water out of the tailings in order to reuse it. What's left is a paste, to which Molycorp adds cement and then lays out in a lined disposal site" [6]. In essence, this simply seals the waste, rather than preventing its generation. It is not yet clear whether this approach works in the longer term, since leaching from supposedly enclosed dumps can occur. Molycorp also planned to use heat and steam from natural gas for its energy, while setting up closed-loop systems to conserve water, and installing flue gas treatment technologies to reduce air emissions [11]. But, to date, these new technologies have not yet been fully implemented because of the difficult chemistry involved; moreover, Molycorp filed for bankruptcy in July 2015 as a result of lower global prices for rare earths [13].

Following a loss of interest by the U.S. government in maintaining its rare earth industry, China became the world's largest producer of REEs in the mid-1990s. The worst of the industry's environmental and health impacts are concentrated here. Rare earth mining began in China with the discovery of bastnaesite and monazite in Bayan Obo in the Inner Mongolia province during the 1930s [7]. Production began modestly in the 1950s before sharply accelerating in the 1980s in tandem with the rise of the global electronics industry. Between 1978 and 1989, production increased by 40% each year [7]. China came to see rare earths as a key commodity mineral in China's export economy, and accordingly began investing in an array of research institutes, a rare earths society, and supply chain mechanisms across several decades [14]. In 1992, Deng Xiaoping, chairman of the Communist Party, declared, "The Middle East has oil, China has rare earths" [7]. By 2010, China controlled an estimated 97% of the global market. Worldwide production more than doubled by 2011, while the United States and other countries' shares shrank to almost nothing [2].

Nonetheless, China still does not have the environmental regulations and monitoring now in place in the United States. This means that its mines produce rare earths at a much lower cost than competitors located in nations with stronger regulation and therefore can out-compete mines like Mountain Pass—with devastating consequences [6]. Mined ore from Bayan Obo is transported to Baotou, a town 120 km south of Bayan Obo, for processing. Decades of poor management mean that villages in and around Bayan Obo are now suffering greatly from water pollution [15]. The original tailings ponds, the largest in the world, were built in the 1950s. They do not protect groundwater from the sulfuric acid and thorium waste produced by the refining process [16]. According to villagers, by the 1980s, crops no longer grew and the polluted groundwater began to kill their livestock. Farmers were displaced and lost their livelihoods.

Villagers also began to experience high rates of cancer and birth defects [15]. While rare earths are not particularly toxic, thorium, if inhaled or ingested, can increase the risk of lung cancer and blood cancers. "Whole villages between the city of Baotou and the Yellow River in Inner Mongolia have been evacuated and resettled to apartment towers elsewhere after reports of high cancer rates and other health problems associated with the numerous rare earth refineries there" [16]. If contaminated groundwater reaches the Yellow River, as many as 150 million people may be exposed to its risks [16].

In the past few years, the Chinese government has belatedly moved to begin cleaning up the Baotou region and to strengthen environmental regulations. Nonetheless, who is in control of REE mining remains in question. Much mining is illegal and is also associated with extensive smuggling. Due to China's complex government structure (with local, province, and central authorities that often compete against each other for control), central authorities often struggle to oversee environmental law enforcement and industrial policies. Around 40% of Chinese production comes from illegal mines that do not pay royalties to the Chinese state [17]. Experts suggest that perhaps as 20,000–30,000 tons of rare earth oxides, roughly 15–30% of official production, were smuggled out of China each year in the late 2000s [17].

These tragic impacts raise many questions for product designers and manufacturers whose products include REEs. What responsibility do they have to require their suppliers to mitigate the harmful environmental impacts

of mining and refining these materials? What if their suppliers lack the power—or refuse—to meet their demands? What happens if certain (heavy) rare earths cannot be sourced from anywhere else except environmentally destructive mines in China? Do manufacturers have a responsibility to lobby for stricter regulation of REE mining and smelting in nations with weak environmental regulations? Do they have a responsibility to try to develop new designs that do not require the use of REEs? What should they do if the design alternatives raise consumer prices or provide less functionality for users?

#### *The Geopolitical Dimension: China's Trade Controls and Finding Substitutes*

Another issue that manufacturers must now think about when deciding whether to use rare earths in their products is the geopolitical situation arising from global trade in these materials. While geopolitical considerations have long influenced supply chain development and sourcing decisions, REEs illustrate the potential for so-called “energy critical” materials to become abruptly unavailable or very costly. China’s near-monopoly over rare earths trade—despite only having 37% of global reserves (as of 2016)—has meant that its trade policies can boomerang worldwide [18]. Companies increasingly fear that they will lose access to REEs, endangering their production and profits. Moreover, industrial countries such as the United States see China’s power as a possible threat to national security, since REEs are essential to modern military hardware.

Starting in 2006, China began imposing REE export quotas and duties, ostensibly to limit the ecological effects of its domestic extraction activities. In truth, China aimed to drive production of advanced technologies using REEs into its domestic economy [1]. In July 2010, for example, China reduced its exports by 72% for the rest of the year, leading to dramatic rises in prices. The price of neodymium increased from US\$42 to US\$283 per kilogram [19]. Later, in 2010, China was widely perceived to have temporarily stopped shipments going to Japan in response to a maritime incident [1]. Japan was largely dependent on China for its rare earth imports; in turn, many countries relied on the products that Japan exported.

As a result, multiple Congress hearings and Defense Department reviews occurred over whether the United States should revive its own rare earth extraction industry

[19]. Secretary of State Hillary Clinton described China’s behavior as a wake-up call. While national security arguments were made, environmental activists expressed strong concern that Congress could pass laws to relax regulatory protections in the name of national security. Indeed, in 2013, the House of Representatives passed a bill to ease the application and permit process for mining of “strategic minerals” [18]. Federal agencies would be required to decide on mining permits within 30 months of receiving applications, which would limit their capacity to investigate possible risks and undermine the ability of communities to respond to new mine proposals. The Obama government later decided to join Japan and the EU in a challenge at the World Trade Organization (WTO). In 2014, the WTO ruled that China’s attempts to regulate its REE exports infringed on international trade law, forcing China to eliminate its export quotas [19].

In contrast to other more traditional environmental life cycle issues, these issues raise questions for manufacturers that use rare earth materials in their products that relate to the geopolitics of sourcing: Should companies comply with China’s restrictions? Should they seek to develop new mines elsewhere? If they do, what steps should they take to mitigate the harmful environmental and health impacts of their mines and refineries? Or should they find alternatives to using rare earths in their products?

Not surprisingly, mining companies and governments worldwide have sought to open new mines in more politically stable places like Australia, the United States, and Canada [14, 20]. This can be challenging since many REEs are currently only needed in small amounts (e.g. just 200 tons for tellurium) and it is not economical to build mines just to produce this amount [20]. To date, a number of mines have come online, including the re-opened Mountain Pass mine. China has even begun investigating mining REEs around the world, including Greenland where melting ice is exposing land for exploration [18]. It remains unclear whether these mines are effectively managing their environmental effects.

But industries are also looking at how to reduce their use of rare earths, in terms of quantities or finding functional technological substitutes [19]. Wind turbine makers have developed a new magnet that does not need neodymium, while Honda recently engineered the world’s first hybrid car motor without using heavy rare earth metals [20]. Manufacturers can also find alternatives based on carbon nanotubes or

graphene for indium tin oxide in touchscreens. In the energy-efficient lighting sector, the ongoing transition to LEDs instead of compact fluorescent lamp (CFLs) is causing rare earth use to decline markedly. Nonetheless, it can be hard to find substitutes for rare earths that have extraordinary chemical properties. China will continue to wield tremendous power for decades to come. Another option, then, may be to mine existing products at the end of their lives for REEs and thereby better close the loop.

#### *End-of-Life Management*

This brings us to the other major life cycle stage where manufacturer and designer decisions can make an enormous difference as to the environmental outcome: the stage when products are taken out of use and either disposed of or recycled in some way. No product lasts forever. However, the electronics industry, in particular, emphasizes planned obsolescence as part of its business strategy [21]. Firms repeatedly introduce new models, features, software, and technologies to maintain their rapid rate of growth. This is why Apple, for instance, brings in a new iPhone generation every two years to entice consumers to keep buying. Because the new designs often increase the use of rare earths even as they shrink electronics further, it is important to recognize that accelerating model and feature turnover intensifies the need to think through and find ways to mitigate the harms that can be generated when such goods are thrown away, rather than being safely and effectively recycled.

As it stands now, the churn of products results in immense electronic waste, or “e-waste,” that is not reused [22]. The U.S. Environmental Protection Agency says that e-waste is growing two to three times faster than any other waste stream. Ruediger Kuhn, a leading expert, says that 49 million tons of e-wastes are produced each year, and only 10% is recycled [20]. In the United States, 25% of electronics are recycled, with only 8% of mobile devices being recycled [23]. Current estimates show that only 1% of REEs are recycled [24]. Many valuable materials in this waste, including REEs, are lost. Worse, much of this waste is returned to the earth in ways that may expose human and non-human life to carcinogenic, mutagenic, or endocrine disrupting toxins. A single computer may contain hundreds of toxic chemicals, including mercury, lead, and polyvinyl chloride [22].

Even where “old” phones and laptops *are* recycled, the conditions for recycling workers may be exploitative and ghastly. E-waste is often sent to developing countries for recycling because of cheap shipping and plentiful manual labor. Certain regions in India, China, and Nigeria, among others, have become centers for recycling over the past 20 years. The Silicon Valley Toxics Coalition, based in San Jose, California, has documented the conditions prevailing in these areas. In Guiyu, China, for example, workers typically smashed electronics with their hands, used highly toxic acids to extract metals from chips, and cooked circuit boards on fires [22]. Unrecyclable components formed piles of decaying waste around the villages. Much scientific evidence now suggests that recycling workers and villagers are suffering higher rates of respiratory illnesses, decreased lung function, and spontaneous abortions and premature births [25]. They manifest higher DNA damage than those living in non-recycling villages. Children and pregnant women are at particular risk: biomonitoring studies show that children contain elevated levels of chromium, lead, and other substances.

Given the global “scarcity” of rare earths (in terms of high economic feasibility and lack of industrial investment in mining facilities), recycling electronics could become an important new source of these materials. Currently, 35% of hard drives are shredded in the United States; if their magnets were extracted, 1,000 metric tons of neodymium could perhaps be recovered per year [26].

Nonetheless, the ways in which manufacturers have produced electronics make it difficult for recyclers to recover REEs. For example, phones have become even smaller and more complex: a phone used only 24 elements in 2000, whereas contemporary phones use over 60 elements [24]. Rare earths are increasingly integrated into devices and cannot be readily picked out. They may be dispersed across a screen, while batteries used to be removable but are no longer [24]. Because REEs are often used as additives in magnets or glass, their removal requires chemical reactions, not just physical dismantling. Simply shredding hard drives leads to a 90% loss of neodymium [24]. While LED lights are even more energy efficient than CFLs, their REEs cannot be removed. Ironically, it is much easier to remove REEs from their ores than from electronics.

Similar to the environmental and public health harms previously discussed, these problems should also be addressed by product designers and manufacturers, espe-

cially those involved in the design and production of green technologies. It is possible for manufacturers to design products that can be disassembled at low cost, or that permit REEs to be quickly and inexpensively removed [20]. Manufacturers have begun developing new technologies for extracting rare earths more efficiently and sustainably from discarded products. Typically, extracting REEs uses pyrometallurgical methods (heating e-waste, yielding air pollution, and GHGs) or chemical methods (using acids and solvents, creating toxic wastewater) [2]. In response to China limiting its exports, Japanese firms have invested \$1.2 billion in researching such techniques. Hitachi, for instance, has invented a process to scale up retrieval of magnets from its waste hard disk drives and air conditioners. The U.S. Department of Energy has funded numerous projects. In 2016, the Oak Ridge National Laboratory announced a process for putting hard drives on an assembly line, demagnetizing them, and separating magnets [26]. While magnets are the most easily removable REE source, other components could be treated similarly. It is also possible that rare earths could also be concentrated into modules that could be easily retrieved from end-of-life products and reused.

The problem is that developing these processes requires costly research and development as well as investment in construction and operation of the retrieval technologies. These added costs raise the cost that a would-be green manufacturer needs to pay to use recycled REEs in the production of new products, leading to prices higher than for the conventional version of the product. How can green manufacturers successfully surmount this hurdle? Can they do this without tax incentives and other government policies in place to offset the additional costs? Should governments step in to provide subsidies for developing and using new recycling technologies, thereby making recycling more economically feasible?

Alternatively, manufacturers could search for ways to reduce their REE use. As noted above, however, this may reduce functionality and will likely raise costs. Or manufacturers could build recycling systems to enable consumers to return their old products, thus greatly increasing take back rates. It has not been until the past decade that the electronics industry has had voluntary take-back programs or incentives. However, these continue to be unimpressive in their success rates. Government policies could help increase recycling by both investing in collection systems as a public resource, and mandating the take back of

electronics, wind turbines, electric cars, and other products containing REEs. The European Union does have a law that requires the take back and recycling of cars and electronics but extensive leakage occurs: wastes are still exported to developing countries and dumped there [27]. Still, take back is very unevenly mandated worldwide, with many gaps (e.g. wind turbines that are now obsolete). In turn, many consumers do not recycle their products because they are not motivated to. Could manufacturers change their marketing approach to make product “take back” more “hip”? And how?

Another possible solution to the end-of-product life disposal and recycling problem would be for manufacturers to stop pushing consumers to purchase products with REE content as often as they currently do (or for governments to provide incentives to manufacturers to improve product longevity). This would involve designing iPhones and other consumer electronics for durability to enable them to last longer, as well as moving away from the strategy of rolling out new models and features every year or two. Such a change would protect communities located near REE mines and electronics recycling centers (particularly in the developing world) by reducing the overall demand for the mining and smelting of REEs. Many environmentalists have argued long before that this is what is really needed to reduce the harmful impacts of our modern industrial system. However, this solution also suffers from a major drawback from the manufacturers’ perspective, namely that it might shrink the size of the market for its products over the long term. Consumers may also have a hard time getting used to the idea that “new” is not necessarily “better.”

Nevertheless, if any of these alternatives to the current system of using REEs in products can be successfully implemented, the resulting reduction in the demand for new REE supplies could weaken the move to build ecologically damaging mines in the first place.

## CASE STUDY QUESTIONS

Using REEs in sustainable technologies raises challenging issues. Whether it is wind turbines, electric cars, or iPhones, we are challenged to think about the complex web of life cycle costs and benefits of producing, using, and disposing of all the materials of which they are composed. Some questions you may want to consider are:



- What can mapping the life cycle of REEs add to our knowledge of product sustainability? What sorts of environmental and social problems exist? What are their root causes?
- What, and whose, are the key decisions that influence whether REEs can cause ecological and social harms?
- Where in the life cycle can the most effective interventions be made?
- What power can corporations—and governments—exert over the mining of key REEs?
- Why are there difficulties in recycling rare earths? Is improved recycling a panacea for REE problems?
- How could business be motivated to make long-lasting, upgradable products?
- What influence do consumers have to pressure companies to improve their behavior?
- Should governments take the lead in regulating REE mining and mandating REE take back?

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### SUPPORTING INFORMATION

Rare Earth Elements Case Slides (PPT).

### REFERENCES

1. Abraham DS. *The Elements of Power: Gadgets, Guns, and the Struggle for a Sustainable Future in the Rare Metal Age*. Haven: Yale University Press; 2015.
2. US Environmental Protection Agency. *Rare Earth Elements: A Review of Production, Processing, Recycling, and Associated Environmental Issues*. Report EPA 600/R-12/572. Cincinnati, OH. 2012. Available: <http://nepis.epa.gov/Adobe/PDF/P100EUBC.pdf>. Accessed 9 April 2017.
3. Haque N, Hughes A, Lim S, Vernon C. Rare earth elements: overview of mining, mineralogy, uses, sustainability and environmental impact. *Resources*. 2014;3(4): 614–635.

4. Farias S, Cammarata R. A Novel Approach to Synthesize Lanthanum Telluride Thermoelectric Thin Films in Ambient Conditions. In: *MRS Proceedings*, Vol. 1543. Cambridge University Press; 2013. pp. 113–118.

5. Barteková E. The Role of Rare Earth Supply Risk in Low-Carbon Technology Innovation. In: *Rare Earths Industry: Technological, Economic, and Environmental Implications*, 153; 2015.

6. Greene J. Digging for Rare Earths: The Mines Where iPhones Are Born. *CNET*. 2012. Available: [http://news.cnet.com/8301-13579\\_3-57520121-37/digging-for-rare-earths-the-mines-where-iphones-are-born/](http://news.cnet.com/8301-13579_3-57520121-37/digging-for-rare-earths-the-mines-where-iphones-are-born/). Accessed 9 April 2017.

7. Hurst C. China's Rare Earth Elements Industry: What Can the West Learn? Institute for the Analysis of Global Security. 2010. Available: <http://fms0.leavenworth.army.mil/documents/rareearth.pdf>. Accessed 9 April 2017.

8. Kyle W. A Visit to the Only American Mine for Rare Earth Metals. *The Atlantic*. 2012. Available: <https://www.theatlantic.com/technology/archive/2012/02/a-visit-to-the-only-american-mine-for-rare-earth-metals/253372/>. Accessed 9 April 2017.

9. US Geographical Survey. *Rare Earths Production and Use Data*. 2017. Available: [https://minerals.usgs.gov/minerals/pubs/commodity/rare\\_earths/mcs-2017-raree.pdf](https://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2017-raree.pdf). Accessed 9 April 2017.

10. Heffernan T. Why Rare-Earth Mining in the West is a Bust. *High Country News*. 16 June. 2015. Available: <http://www.hcn.org/issues/47.11/why-rare-earth-mining-in-the-west-is-a-bust>. Accessed 9 April 2017.

11. Thompson K. One American Mine Versus China's Rare Earths Dominance. *Popular Mechanics*. 2013. Available: <http://www.popularmechanics.com/science/a12794/one-american-mine-versus-chinas-rare-earths-dominance-14977835/>. Accessed 9 April 2017.

12. Cone M. Desert Lands Contaminated by Toxic Spills. *Los Angeles Times*. 24 April 1997.

13. Bomgardner M. The struggle to mine rare earths. *Chem Eng News*, 2015;93(30): 36–39.

14. Barteková E, Kemp R. National strategies for securing a stable supply of rare earths in different world regions. *Resour Policy*. 2016;49: 153–164.

15. Bronton C. Rare-Earth Mining in China Comes at a Heavy Cost for Local Villages. *The Guardian*. 7 August 2012. Available: <https://www.theguardian.com/environment/2012/aug/07/china-rare-earth-village-pollution>. Accessed 9 April 2017.

16. Bradsher K. China Tries to Clean Up Toxic Legacy of Its Rare Earth Riches. *New York Times*. 22 October 2013. B1.

17. Packey DJ, Kingsnorth D. The impact of unregulated ionic clay rare earth mining in China. *Resour Policy*. 2016;48: 112–116.

18. Raman S. Fossilizing renewable energies. *Sci Cult*. 2013;22(2): 172–180.



19. Ferris D. 5 Years after Crisis, *U.S. Remains Dependent on China's Rare Earth Element*. *E&E News*. 12 Jan 2015. Available: <http://www.eenews.net/stories/1060011478>. Accessed 9 April 2017.

20. Jones N. A Scarcity of Rare Metals Is Hindering Green Technologies. *Yale Environment* 360. 2013. Available: [http://e360.yale.edu/features/a\\_scarcity\\_of\\_rare\\_metals\\_is\\_hindering\\_green\\_technologies](http://e360.yale.edu/features/a_scarcity_of_rare_metals_is_hindering_green_technologies). Accessed 9 April 2017.

21. Slade D. *Made to Break*. Cambridge, MA: Harvard University Press; 2007.

22. Iles A. Mapping environmental justice in technology flows. *Global Environ Polit*. 2004;4(4): 76–107.

23. US Environmental Protection Agency. Statistics on the Management of Used and End-of-Life Electronics. 2012.

Available: <http://www.epa.gov/osw/conserves/materials/recycling/manage.htm>. Accessed 9 April 2017.

24. Marshall J. Why Rare Earth Recycling is Rare — and What We Can Do About It. *Ensia Magazine*. 2014. Available: <https://ensia.com/features/rare-earth-recycling/>. Accessed 7 April 2017.

25. Grant K, Goldizen F, Sly P, Brune M. Health consequences of exposure to e-waste: a systematic review. *Lancet Global Health*. 2013;1(6): e350–e361.

26. Recycling Today. DOE licenses rare earth magnet recycling process to Momentum Technologies. 2016. Available: <http://www.recyclingtoday.com/article/magnet-rare-earth-metals-doe/>. Accessed 7 April 2017.

27. Ongondo FO, Williams ID, Cherrett TJ. How are WEEE doing? A global review of the management of electrical and electronic wastes. *Waste Manage*. 2011;31(4): 714–730.