The Ethics of Rare Earth Elements Over Time and Space

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Abstract: Rare earths are a critical resource for contemporary societies. Among their diverse uses, they are key components of sustainability technologies such as wind turbines and electric vehicles. While rare earths can help societies transition away from fossil fuels to renewable energy and conserve energy, their extraction, processing, and use creates serious environmental and social effects around the world, especially in China. We argue that environmental justice and intergenerational justice concepts can provide an ethical framework for navigating this green energy bargain. We survey the environmental and social effects that rare earth production causes and the changing geography of production that means these effects are being distributed worldwide, both in and beyond China. Finally, we consider several strategies that miners, manufacturers, designers, and users can use to achieve greater environmental justice and intergenerational justice, now and for the future.

Keywords: *Rare earths, environmental justice, intergenerational justice, mining, recycling.*

1. Introduction

The multi-billion-dollar rare earth industry supplies a critical resource for contemporary societies. Rare earth elements (REEs), also known as rare earth metals, are a group of 15 lanthanide metals on the periodic table plus scandium and yttrium, as defined by the International Union of Pure and Applied Chemistry. REEs have become extremely important for manufacturing a wide range of products in consumer, industrial, military, and medical markets. They are also key components in electric vehicles, wind turbines, energy-efficient light bulbs, and other sustainability technologies, making them important for mitigating climate change by helping societies transition away from fossil fuels to renewable energy and conserve energy.

Mining for REEs creates serious threats to the environment and the well-being of communities adjacent to mines. As with mining other raw materials,

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the extraction of rare earth ore from the Earth has major ecological and public health impacts. Removing large amounts of earth can scar the landscape for generations and limit alternative land uses such as agriculture. Extraction and processing of rare earth materials generates large amounts of waste and releases toxins into the air, water, and soil. People living and working near mining sites face an increased risk of developing cancers and other serious illnesses due to contaminated drinking water and food. Mining can also introduce and exacerbate social conflicts over how resources are controlled, accessed, and profited from.

For chemists, engineers, product designers, and business managers who want to contribute to products for society that can help transition away from fossil fuels, REEs are extremely important. A number of REEs are required to manufacture wind turbines and electric vehicles, but obtaining these elements can have a considerable negative impact on the people and communities involved in REE production chains, creating what may be considered a 'green energy bargain' (Phadke 2018). In addition to the environmental and social costs borne by the communities who host rare earth mining operations, the consumption of REE resources is accelerating at rates that may be unsustainable. In order to meet growing demand for sustainability technologies like wind turbines and electric vehicles, current generations are expected to use more and more of these critical resources. At some point, future generations may lose out if they cannot readily obtain these resources due to reserves being exhausted. The climate-saving benefits of REEs could be distributed unevenly across time, with current and near-future generations benefiting the most. On the other hand, using REEs today could help ensure future generations avoid severe climate impacts. In this article, we argue that downstream decision-makers must consider the ethics of REE use from the standpoint of environmental justice and intergenerational justice, which together offer guidance in navigating this green energy bargain.

We begin this case with an overview of the various end uses for REEs. We then review the environmental and social impacts associated with mining and processing REEs, before turning to discuss the ethics of extracting and using REEs. Here, we argue that environmental justice and intergenerational equity direct our attention to specific ethical requirements for those who produce or use REEs. The next section applies the concepts of environmental justice and intergenerational justice to understand where moral hazards concentrate in the changing geography of rare earth mining and processing. Finally, we discuss strategies for reducing moral hazard to advance environmental justice and intergenerational justice.

2. Uses of Rare Earths

The 17 elements commonly referred to as REEs have many end-uses. Their exceptional magnetic, phosphorescent, and catalytic properties make them a valuable component of materials used in manufacturing high-technology consumer products (Balaram 2019). For example, the rare earths neodymium and dysprosium are often alloyed to form magnets that resist demagnetization at high temperatures, which is essential for any heat-generating electronic device such as laptop computers, televisions, flat screens, cell phones, portable DVD players and more. REEs also have end uses in the medical and defense industries, from devices like x-rays and MRI machines, to the military's jet fighter engines, missile guidance and antimissile defense systems, space-based satellites, and communication systems (Machacek & Fold 2014).

Although metals and alloys used to make rare earth magnets are one of the largest rare earth products, the REEs are transformed into a diverse array of materials for many different consumer, industrial, and military applications. REEs lend unique properties to steel and aluminum and have enabled innovations in glass. For instance, the realization of rare-earth-doped glasses has enabled numerous innovations in the chemical formulation of both commercial glasses and new functional glasses. These glasses include filters and lenses, light-sensitive and photochromic glasses, coloring and decoloring agents, X-ray and gamma-ray absorbing glasses, glass with luminescence and fluorescence effects, and communication fibres (Locardi & Guadagnino, 1992). Glass materials containing rare earth elements have been central to dramatic light-based innovations like semiconductor lasers, also called laser diodes (Tanabe 2015).

In addition, the unique catalytic performance of the REEs make them a critical resource for industrial applications requiring catalysts. Catalysts comprise a large share of REE end uses, which includes petroleum refining, the catalytic combustion of fossil fuels, automotive engine emissions control, and the purification of industrial waste, air, and solids. In particular, lanthanum and cerium are used in petroleum refining to make gasoline, which constitutes the largest end-use of REEs in the United States (US DOE 2011). These REEs ultimately make the fluid catalytic cracking process more efficient, which increases the gasoline yield per unit of catalyst (Sadeghbeigi 2012).

More recently, REEs have received increased attention for their use in sustainability technologies that can help wean societies from dependence on fossil fuels. For example, REEs are used to create red (Eu and Y), and blue (Eu) phosphors for energy-efficient light emitting diodes (LEDs), which can provide better energy savings for buildings than incandescent and fluorescent lights. The quantities of REE used to make LEDs are one to two orders of magnitude lower than that required for these other lighting technologies. Thus, expanding the markets of LEDs is not likely to increase REE demand (Ku *et al*. 2015).

Wind turbines and electric vehicles, however, are expected to have a large impact on demand for rare earths, despite their relatively small share of total REE end uses. Electric vehicles rely heavily on dysprosium and neodymium. The hard, magnetic alloy neodymium iron boron (NdFeB) has enabled the development of compact, torque- and power-dense electric traction motors, which has led to greater deployment of hybrid electric vehicles such as the Toyota Prius, and of battery electric vehicles like the Nissan Leaf (Widmer *et al*. 2015). The addition of dysprosium, a heavy rare earth element, to the NdFeB alloy increases its ability to withstand de-magnetization in high temperatures, making it possible for the alloy to perform despite heat-generating vehicle traction. The nickel metal hydride (NiMH) batteries in many electric vehicles also contain cerium and lanthanum. However, some industry analysts expect electric vehicle manufacturers will soon transition to lithium-ion batteries, which would reduce REE demand from electric vehicles because lithium ion batteries do not require REEs (DOE 2011).

Certain kinds of wind turbines also use dysprosium and neodymium. Unlike smaller, onshore wind turbines that use rotating gearboxes, larger offshore turbines use direct drive technology. This involves a generator composed of a ring of NdFeB. By some estimates, a wind turbine that generates 3.5 megawatts of electricity contains about 600 kilograms, or 1,300 pounds, of rare-earth metals (Alonso *et al*. 2012).

Expanding offshore wind capacity and growing electric vehicles sales could therefore lead to greater demand for REEs. Some analysts emphasize that the magnet sector, generally, will become the leading user of REEs based on mass (US Geological Survey 2018). Others predict electric vehicles will be the biggest driver (Alonso *et al*. 2012). As the market for electric vehicles grows, the demand for dysprosium and neodymium could increase by more than 700% and 2600%, respectively, assuming a decarbonization path of electrifying 80% of automobile sales (*i.e.* hybrid electric vehicles, plug-in hybrids, and battery electric vehicles) by 2035 in line with the goal of limiting average global temperature to 2 °C (*ibid.*). Whereas conventional fossil-fuel powered cars may use about one pound of REEs for small motorized components like windshield wipers, the various motors and batteries of an electric vehicle can require nearly 10 times more REE materials than conventional cars (*ibid.*). Using more electricity from wind power will also add to the demand for Nd and Dy. Recent estimates for deploying 80 gigawatts of offshore wind power by 2050 in the US predict the industry's REE demand will increase from about 1,200 tons a year in 2020, to nearly 3,000 tons per year by mid-century (Fishman & Graedel 2019).

These trends pose the question of whether the rate at which REEs are being used now and in the foreseeable future might deplete reserves. Rare earths are not geologically rare, but they are hard to find at levels that make it economically viable to mine (Chakhmouradian & Wall 2012). For example, cerium and yttrium are the 25th and 30th most abundant elements by mass – far exceeding tin, molybdenum, and gold. But other rare earths are less abundant by mass and more geographically dispersed. Usually, REEs are mined as a by-product of extracting another valuable mineral. REE-only mines are very rare. Although there are over 200 mineral ores containing individual rare earths, only 20 of these have been commercially mined, suggesting the economic and technical difficulties.

Many government and scientific agency reports have viewed rare earths as a 'critical' resource in relation to anxieties about China's strategically powerful control over REE supplies. Nasser *et al.* (2015) project that all individual rare earths would take a century to deplete at the rates of use of known reserves as of 2008. If the use rates of a few REEs do rise dramatically, depletion time could speed up by a few decades. Yet rare earths are arguably not yet an issue for most future generations, as there are many other resources for which depletion is on the horizon within decades, such as copper.

The key question is whether actual *supplies* of rare earths are accurately known and whether these supplies can be accessed. The answer is not clear for the long term. New reserves can be found, while existing reserves may be made more accessible through technological advances. For example, known reserves of rare earth ores grew from 88 million tons in 2008 to 130 million in 2014, indicating the importance of exploration work for estimating supplies accurately (Zepf 2016). In addition, REEs escape from supply chains in large quantities because their recovery for recycling is so low (Darcy *et al.* 2013). Most rare earths eventually end up in landfills or elsewhere once products reach the end of their lifetime. Wind turbines, for example, are hardly recycled at present. If rare earths can be recovered at high levels, this will stretch actual supplies more and change the extent to which growing demand for REEs will be met by more mining.

3. Environmental and Social Impacts of REE Production

The environmental and social impacts of REE mining begin during exploration and continue after a mine's closure. During the initial prospecting phase, mining companies must obtain access rights for local land and resources in order to secure project finance. Companies may negotiate access rights for local land and resources with government officials but fail to seek local people's permission (Handelsman 2002). In complex systems of land ownership, what is considered legal property is only one approach to determining who has rights to access land and other resources. When governments and mining companies do not recognize the rules of traditional land tenure systems, there may be lasting conflict. For instance, on Bougainville Island in Papua New Guinea, villagers refused to sell their land for the giant Panguna copper mine. Instead, property negotiations were made according to Australian law and the government expropriated villagers' land to the mining company, Rio Tinto (Denoon 2000). Villagers continued to protest the mining operation over land rights, pollution, and the lack of economic benefit for local people. The conflict escalated into a civil war in the 1990s, in which 15,000 to 20,000 people died (*ibid*.). Rio Tinto was forced to close the mine, and in 2018 the Bougainville government imposed an indefinite moratorium on renewing the company's license due to fears that violent civil conflict would erupt again (Davidson 2018).

After exploration, once a site has secure investment and access to land and resources, mining begins. Different methods can be used to excavate ore deposits from the landscape: open pit mining (removing earth from the landscape), underground mining (involving digging tunnels), or in-situ leach mining (using strong acids to dissolving the ore in the ground so it may be pumped out). REEs typically come from open pit mines, since most REEs are byproducts from other mining operations, as is the case at the most prominent operating mines producing REEs, including the Bayan Obo in Inner Mongolia (the largest REE source in China), the Mount Weld mine in Australia, and the Mountain Pass mine in the US (before it halted production).[1] The significant amount of soil, rock, and other debris dug out may be dumped back into the open pit once the mine is closed, but often it is dumped elsewhere, forming human-made mountains that alter a landscape's sense of place, topography, geology, and ecology (Francaviglia 1992, pp. 137-142).

Removing earth is extremely water-, chemical-, and energy-intensive, resulting in large amounts of waste. Water, electricity, and diesel are needed to run the equipment for blasting, drilling, dredging, and pumping material out of the deposit. Chemical blasting agents and lubricating oil are also used to help move and loosen the earth. In the process, metallic and radioactive dusts, asbestos-like minerals, and exhaust from machinery or generators and a variety of chemicals get released into the air and soil. Excessive amounts of ammonia and nitrogen compounds may leak into the groundwater during the mining-process. Cadmium and lead may also be released into the environment.

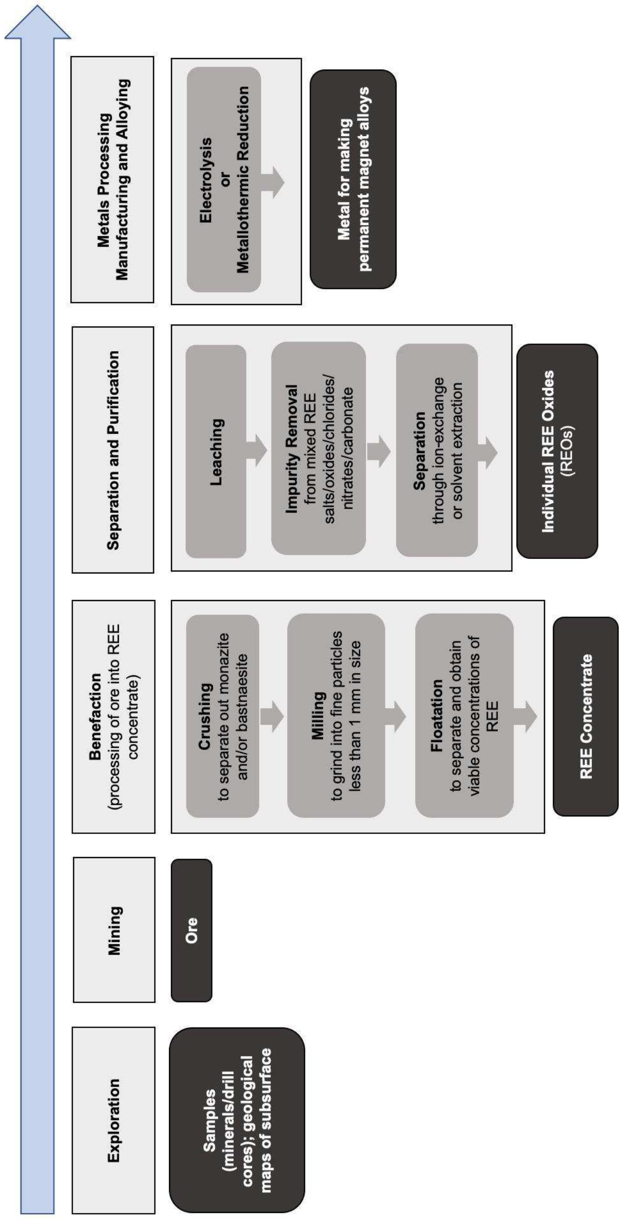

Figure 1. Rare earth production stages and outputs (adapted from Department of Energy 2017).

Rare earths are not found in their isolated elemental form in nature, and thus their separation and purification make processing challenging, expensive, and polluting. After mining, the REEs must be separated and purified into rare earth oxides through a series of water-, chemical-, and energy-intensive processes (Figure 1). First, the ores are crushed, milled, and separated through froth floatation into dissolved concentrates. To purify these concentrates, there is a second round of processing via complex chemical reactions: dissolved concentrate passes through hundreds of liquid-containing chambers designed to pull out desirable elements or compounds using extraction agents (hydrochloric acid) and precipitating agents (ammonium bicarbonate $(NH_4)HCO_3$ or NaOH precipitation), followed by solvent extraction (*e.g.*, $(C_{16}H_{35}O_3P)$ and HCl) and precipitation steps using ammonium bicarbonate and oxalic acid $(C_2H_2O_4)$.[2] The precipitate oxalates are filtered out and roasted to form a concentrate of rare earth oxides (REO). For most industrial applications, the rare-earth material is supplied as oxides (*e.g.* for automotive catalysis) or in the form of a material obtained from merging oxides with two or more elements to make metals and alloys. However, the final form in which REEs are sold depends on the application. For instance, in the 1970s and 1980s most REE exports from China were mineral concentrates and then mixed REE chemicals (British Geological Survey 2011). Separated REE oxides and metals were in greater demand in the 1990s. Since the 2000s, REE magnets, phosphors and polishing powders have dominated REE trade. The diversity of final forms poses challenges for REE recovery and recycling as discussed later in this article.

One of the greatest sources of harm to environmental and human health comes from the production of mine tailings. Tailings are finely ground residual liquid wastes created by separating out the undesired material from the ores, which can include toxic metals, fluorine, and radionuclides, as well as leftover processing chemicals. These dangerous byproducts require careful storage and disposal. Typically, tailings ponds are constructed to hold this toxic wastewater and prevent it from seeping underground. All tailings at the REE mining operation in Bayan Obo, in the Inner Mongolia Province of China, collect in a tailing pond that is over fifty-years-old with a 20-meter thick sludge layer composed of raw ore, iron, niobium, and other substances (Schreiber *et al*. 2016). Left in open air, these ponds emit solvent vapors like sulphuric acid. Moreover, if the tailing ponds leak, their drainage goes on to contaminate other watersheds and soil. Local communities exposed to tailings by drinking water and by eating locally grown food are at greater risk of developing certain illness and premature death.

Water and land contamination from tailings can last hundreds of years, damaging land-based livelihoods for generations. Baotou, China, is a city known as the 'rare-earth capital of the world' because it lies 120 kilometers south of Bayan Obo and is the main processing site. There, leakage from tailings ponds has displaced productive farmland and contaminated crops. By the 1990s, crops in nearby villages were failing, causing farmers to accept that crops would no longer grow and animals could not survive in the area (Bontron 2012). Ten years later, the area population had dropped from 2,000 to 300 people (*ibid*.). According to a New York Times journalist, "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" (Bradsher 2013). If contaminated groundwater reaches the Yellow River, as many as 150 million people may also be exposed to its risks.

A number of factors will affect the degree of pollution a local community experiences, including fuel sources, the makeup of an area's business cluster, and local permitting and waste regulations. The solvent extraction processes itself varies little from place to place in terms of material efficiencies and chemical usage (Schreiber *et al*. 2016). However, some energy mixes emit more harmful emissions than others, with emissions from coal fired power plants producing the greatest amount of hazardous emissions. In addition, a mining site may attract other polluting industries to the area. For instance, in Baotou, an investigation into mining pollution in the surrounding area by the municipal environmental protection agency found that REE mining and processing facilities had caused the pollution originally, but the problem had been exacerbated by the dozens of factories and industrial services that had been built near the REE processing facilities and the fossil-fuel power station (Bontron 2012). By contrast, this kind of business clustering would be more difficult to achieve in places with strict environmental permitting.

The existence and scope of hazardous waste regulations also determines the impacts of mining pollution. For instance, in Sweden, a mining operation's tailings must be treated and stored in a special facility, with any radioactive waste stored separately. In contrast, China has relatively weak environmental standards when it comes to rare earth mining. Due to China's complex government structure in which local, province, and central authorities often compete against each other for control, enforcing environmental law is a struggle (Packney & Kingsnorth 2016). Bayan Obo's radioactive sludge is also stored separately, but in an open facility (Schreiber *et al*. 2016). This means there may still be exposure to the sludge's radioactive elements, such as thorium, which can cause cancers of the pancreas and lungs and leukemia.

Finally, human rights abuses can be substantial across all stages of a mining operation. Human rights are a set of civil, political, economic, social, and cultural rights articulated in the 1948 Universal Declaration of Rights that have been accepted by most governments as well as by the International Labor Organisation (ILO) (Handelsman 2002). Mining companies have often been criticized for their complicity in human rights abuses related to their treatment of local and indigenous people in mining operations, including negotiation of land access and resettlement of local people. Labor abuses are prevalent as well, including child labor, modern slavery, violating worker rights to organize, and racial and sexual discrimination. The use of security forces to protect mining operations is also a major contributor to human rights abuses and in many cases has fueled conflict in areas already affected by unrest, economic deprivation, and weak governance. Mining companies often turn to police, mercenaries, and private companies for security. When these forces are empowered to commit human rights violations for control over resources, and the host government lacks the means or will to intervene, violent conflict may grow and persist.

4. Ethics in the REE Value Chain

Given the environmental and social impacts outlined in the previous section, what are the ethics of REE production and use? Two concepts of justice are useful here: environmental justice and intergenerational justice. Below, we define both concepts and the moral obligations they raise for those involved in REE value chains, before turning to a discussion of potential strategies for developing REE use in the next section.

The concept of environmental justice emerged from activists and researchers in the US who have shown that the negative environmental effects of industrial activity (*e.g.* air pollution, water and soil contamination from hazardous waste) tend to concentrate in disadvantaged communities (according to race and/or income) (Szasz & Meuner 1997, Schlosberg 2013). In ethical terms, environmental justice invokes the principle of distributive justice by calling for greater fairness in the distribution of risks and benefits of industrial activity – not by re-distributing harm to other groups, but by reducing harm in the communities that endure a greater share of harm than other groups. Examining environmental justice in global value chains raises a number of questions about where risk is produced in the global economy (Iles 2004). This requires recognizing those who have been injured (*e.g.* a community or certain groups of workers) versus those who are responsible (*e.g.* corporations or states), and determining what actions or remedies are necessary to address the injustice as well as who has the power to carry this out (*e.g.* government, industry, civil society, or international organizations) (Schlosberg 2013). In other words, who is generating harm, and who is exposed to this harm? Who should take responsibility for the harm, and what should be done for those who have been harmed?

Environmental justice suggests that chemists and others scientists, product designers, and business managers all have a moral obligation to understand the geography of their REE supplies and act to source REEs responsibly. This requires understanding the changing geography of RRE mining and processing. REEs can be found worldwide, but as with most mineral resources, geology is not the primary factor shaping where mining occurs. Both REE supply and demand has been concentrated in China for many decades. China is not only a major producer of REEs, but also a major industrial consumer of REEs. This means that many of the environmental injustices associated with how REEs are extracted and used in the manufacturing sector concentrate in the Chinese communities which host mining, waste disposal, and manufacturing plants. In recent years, the Chinese government has been developing a practical guidance to facilitate the development of 'Green Mines', which focuses on increasing financial support to the different levels of government interested in implementing environmental and efficiency performance standards for upgrading existing mines and building new mines (Dolega & Schüler 2018). However, the Green Mines standard is a management standard applied during mine construction and retrofit, and lacks the influence of strict environmental regulation and enforcement. Moreover, its application is concentrated in Eastern China (Lei *et al*. 2016), whereas most REE mining is in China's northern Inner Mongolia region.

However, as REE mining projects have been expanding outside of China, so too has the map of environmental injustices associated with REE production and industrial use. New REE mining projects have sprung up around the world to capitalize on rapidly increasing REE prices, as the Chinese government has reduced the availability of REE supplies in other countries first through a series of export taxes and export quotas, choosing to promote state-owned mining companies that specialize in REE extraction and processing (Phadke 2018). Investors and governments have argued that diversification of REE mining will reduce dependency on Chinese-sourced REEs (Worstall 2010). Outside of China, notable projects emerged in Australia, the United States, and Malaysia soon after China restricted supplies (Haque *et al*. 2014), with a growing number of projects coming on line in recent years in Burma/Myanmar, Vietnam, Brazil, Russia, and India (Figure 2). In 2007, Lynas Corporation began mining its Mount Weld deposit in Western Australia, the richest known deposit of rare earths outside of China, and is now the world's only significant rare earths producer outside of China. The US Mountain Pass mine in southern California also temporarily reopened under new management in response to China's trade policies, with a new wastewater system to manage tailings closer to the mine site and avoid the piping of wastewater. Investors are also eying potential REE projects in Vietnam, Brazil, Russia, India, Canada, South Africa, Malawi, Kazakhstan, and other countries, although proposed projects must first be proven to be viable through exploration, and even after that, commercial production will not come online until the late 2020s (US Geological Survey 2018).

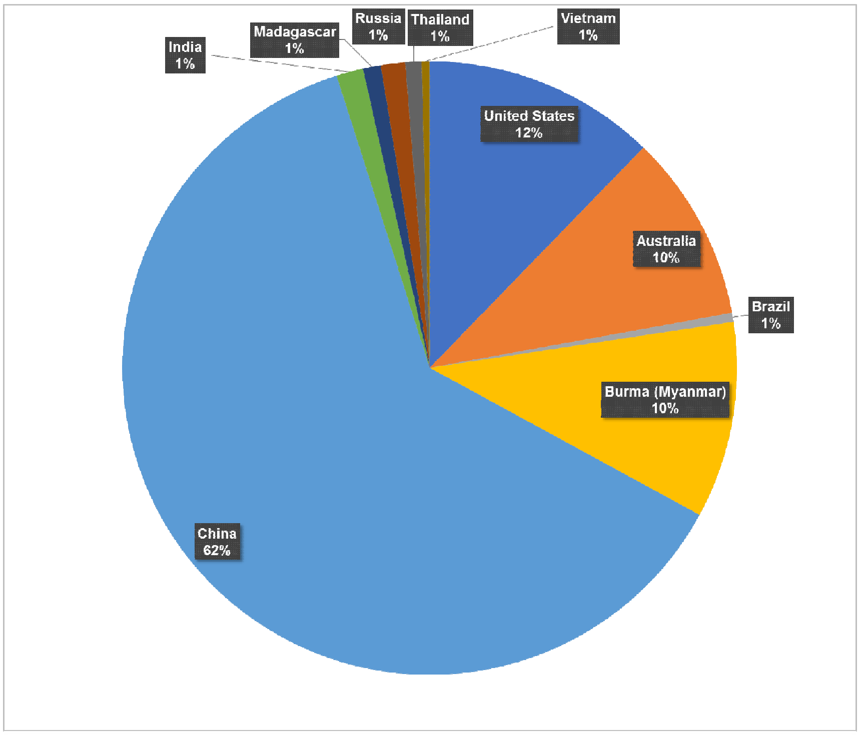

Figure 2. Rare earth production by country in 2019 (based on USGS 2020).

After answering the question of who is being harmed by REE production, remedying environmental injustice entails negotiating rights, remedies, and responsibilities. Solutions depend importantly on where the injustice takes places. In countries that have strong environmental and public health laws, remedies to environmental injustice may center on ensuring existing laws are being followed. In countries with insufficient legal protections to offer those communities and the environments impacted by mining, companies will need to either disengage from suppliers associated with serious impacts or increase their involvement in the supplier's operations to ensure REEs are not causing environmental injustices. In either case, companies who are REE consumers have an obligation to avoid creating harm, and the diverse geography of REE extraction and production requires a strong management system that can detect where environmental injustices are taking place.

The demands of intergenerational justice add further complexity to managing REE value chains ethically. Existing REE-based businesses have already caused great damage that will reverberate across future generations. How should future generations be taken into account given REE use is projected to grow? The concept of intergenerational justice extends the timeframe in which we consider the moral claims of actors impacted by REEs, beyond those who are currently alive. Intergenerational justice asks the question, how are future generations impacted by the actions of current generations? Whereas environmental justice focuses our attention on the existing unfair distribution of risk across space and social groups, intergenerational justice focuses on fairness in the future. This idea is becoming prominent in climate change activism. For instance, movements like Extinction Rebellion and Fridays for Future, as well as lawsuits led by school-age children and young adults, argue that their opportunities for their future lives have been imperiled by insufficient government action now and in the past.

Examining intergenerational justice requires identifying what obligations people today owe to people in future, often referred to as 'intergenerational equity'. One proposal for intergenerational equity is that present generations must preserve the opportunities for future generations to live well (Curren & Metzger 2017). But what standard of well-being should be attained? How far into the future are present generations obliged to consider? Do present generations have obligations to future generations only in their own society/nation/community, or do their obligations extend to future peoples everywhere? Must current generations safeguard the state of the world they inherited, or must they work to make it better (Spjikers 2018)? Is it enough if present generations pass on the capabilities needed to achieve well-being, such as technological innovation or knowledge for repairing or replacing what has been destroyed? For instance, is it ethical for current generations to deplete rare earth resources now, so long as they develop innovations that enable these materials to be manufactured, substituted, or reused in the future? Or is it ethical to deplete these resources in the next 20 years so long as doing so dramatically reduces the risk of climate change effects that cause societies to suffer in the longer term?

Given that present generations inherited the world from previous generations, should present generations also focus on addressing the wrongs generated by oppressive and environmentally harmful forces of colonialism, slavery, and capitalism (Shelton 2008, Brown-Weiss 1989)? In other words, how can intergenerational justice be realized in full without addressing the injustices inherited from previous generations?

The authors of the famous Brundtland Report attempted to answer some of these questions by defining sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). In the context of mining, processing, and using materials, the Brundtland definition suggests that intergenerational equity can be achieved if industrial activities can proceed without hampering the ability of future people to live in the environment from which the resource was taken.

In practice, this definition of intergenerational equity means adhering to environmental laws, labor laws, and human rights law; or, in cases where such laws are weak or poorly enforced, a variety of industry best practice standards or codes of conduct can provide guidance. Civil society organizations (*e.g.* Amnesty International), international governance organizations (the Global Compact, the OECD), and industry associations (*e.g.* the International Council on Mining and Minerals) have put forward numerous codes of conduct for the mining industry. Typically these codes require certain impacts to be measured, monitored, and reduced, according to internationally accepted definitions of labor rights and human rights as defined by the 1948 Universal Declaration of Rights, the International Labor Organisation (ILO), and the UN Guiding Principles on Business and Human Rights (UNGP), which is the global authoritative standard on business and human rights.

However, formal laws and codes of conduct may not go far enough to ensure the well-being of future generations. Legal institutions typically struggle to define the rights of local communities and indigenous peoples compared to those for workers because such definitions require cultural-specificity and often entail engaging in ongoing controversies over how nation states have defined the sovereignty of local people and indigenous groups. In other words, formal laws and codes offer little guidance for ensuring intergenerational justice for local communities and indigenous groups in places where there are disputes about how much control these communities have over land, natural resources, and the wealth created by developing the natural resources.

In addition, in situations where a mining company does not adhere to formal environmental laws that prevent or remediate toxic pollution, such pollution may endure for generations. In such situations, some argue that industrialized nations have an obligation to pay for remediation through foreign aid and anticipatory reparations to the communities harmed by destructive industrial practices (Westin 1992). In this view, societies where the consumption of REEs takes place must compensate the REE host societies, and such payments can be used to ensure that current and future generations in those host societies live well. This reasoning is strongest in situations where production costs would be substantially higher (and thus corporate or government profits much lower) if the minerals came from the consumer countries with strong regulations. As one government official in China's Longnan County in Jiangxi Province – the center of REE mining in China – explained, "[Technology] companies have benefited from using our rare earth resources, they should bear a part of the responsibility and join the process of cleaning up the environment [...]. We have made huge sacrifices to extract the resources they need" (Standaert 2019). Yet realizing intergenerational equity in this case depends importantly on how the host government uses foreign aid payments within its territory. Cleanup of tailings pollution, for example, is extremely difficult and can take upwards of decades to 100 years before local environmental systems recover. In the meantime, local communities suffer from the loss of livelihoods as well as from potential health impacts from exposure to pollution.

Another challenge in enacting intergenerational equity is determining how the removal of a resource from a particular community impacts future generations. Mining permanently pulls resources from underground and relocates those resources elsewhere. For future generations, the inability to access that resource may fundamentally hamper their ability to achieve well-being. For instance, consuming highly desirable REEs now could mean they are not available for future generations who may require them for their livelihood, be it in the form of technologies like wind turbines, electric cars, or technologies we do not yet have that address some not-yet-identified need. This possibility raises additional questions about REE management, such as whether existing and known REE stocks should be managed in some equitable fashion to meet unknown future needs? If so, how should present generations estimate the amount needed for future generations and the proper threshold depletion rate that must be observed in order to prevent scarcity later on? How should present generations balance the need to take extreme climate interventions now (like switching to all-electric cars in a short time) against the possible longer term benefits and losses (such as preventing a 4°C world from happening, in which much of the world may become uninhabitable due to heat, sea level rise, and other effects)? Answering these questions requires giving those whose descendants may be most harmed by REE mining a say in how decision-making about where and how REE extraction takes place.

These challenges suggest the need to take a more expansive view of intergenerational equity – one that goes beyond the definition of the Brundtland Report to include the politically unpopular propositions of redistributing the wealth created by REE mining more equitably and empowering those impacted by REE mining in decision-making about REE activities. The Brundtland definition of sustainable development emphasizes intergenerational equity in terms of preventing or correcting environmental damages in mining communities, without attending to re-distribution and empowerment. Many mining communities oppose mining on the grounds that they are completely left out in decision-making and wealth creation. Typically, the process of licensing and permitting an area for mining is carried out by governments who control access to underground minerals. Governments then require mining companies to pay concessionary fees to prospect minerals and royalties on any mineral earnings. These economic gains may be shared with the community (as described above in the case of the Alaska Permanent Fund) or used to benefit a larger public. For instance, in the case of Botswana, government mining revenue paid for schools, roads, hospitals, and other public infrastructure (Poteete 2009). The Alaska Permanent Fund (APF) is another example of how wealth re-distribution may be addressed in extractive industries (Devarajan *et al*. 2011). The APF is a state-owned corporation that collects revenues generated by Alaska's oil and gas leases and manages these assets through reinvestment. Earnings from these investments are distributed among Alaskan households, and a quarter of the principal (25%) is reserved for future generations. The APF trustees have the authority to distribute dividends accordingly, such that all Alaskans benefit economically from the use of public resources.

But redistribution arrangements alone do not address the need to empower citizens to advance intergenerational justice. Decision-making about how and whether the resource can be used requires open and inclusive decision-making processes in which communities are empowered to determine whether and how resource should be exploited at all, or limited to certain uses (*e.g.* some communities may question the use of raw materials for military applications) instead of indiscriminately in international commodity markets, and how the benefits of exploited resources should be distributed fairly between current and future generations. Of course, such an approach raises further questions of procedural justice, such as who should participate in decision-making about resource access and use. These complex questions will vary by context. Local communities may be united in fundamentally opposing mining activities, especially when those activities threaten to displace local people. But there are numerous cases in which communities look to mining for a combination of economic opportunities and self-determination (Bryceson 2018). For example, as mentioned before, government and mining companies ignored villagers' opposition to the use of land for mining in the Bougainville Island of Papua New Guinea, and violent conflict ensued for decades rendering the mine inoperable (Denoon 2000). Similar conflicts have arisen over mining in many developing countries of the Global South where national governments have deliberately implemented mining regulations and policies for the exclusive interests of large-scale mining companies, while making small-scale mining illegal (Moretti & Garrett 2018). In Bougainville, this conflict is ongoing, but recent developments have empowered local people in mining decisions. The Bougainville Island Mining Act of 2015 contains legal provisions for local elder councils and village assemblies to designate and regulate small-scale gold mining, giving local landowners the power to veto any mining licenses as well as to create 'community mining areas' for smaller-scale mining (O'Faircheallaigh *et al*. 2016).

The important point here is that intergenerational equity requires going beyond the standard of assuring environmental protection. Determining the criteria for extracting REEs will undoubtedly entail conflicts between different beliefs about who should control resources, and whether extraction is justified at all, or for specific markets only – such as for renewable energy technologies – and whether some amount of a resource should be preserved for a community's descendants, who may need them more.

5. Strategies to Advance Environmental and Intergenerational Justice

For chemists, product designers, and business managers working upstream, what strategies are available for extracting non-renewable, depletable REEs in a way that does not create new – or exacerbate existing – environmental injustices, nor impair the opportunities of future generations to live well? Given the lack of existing examples that would satisfy the requirements of environmental justice and intergenerational justice, we discuss some promising strategies and their shortcomings. Calls for 'sustainable mining' have fallen short despite more stringent regulations and industry codes that aim to protect the environment, human rights, and workers. Societies must therefore go beyond sustainable mining protocols and also wrestle honestly with the challenges of figuring out how to meet intergenerational justice claims when it comes to REE use here and now.

5.1 Reducing and replacing REEs

Some large industries that use REEs discovered during the 2010 supply scare that they could do without some of them. When the price of lanthanum soared, oil refinery operators temporarily stopped using this rare earth even though it improves refining efficiency. The glassmaking industry largely abandoned using cerium for polishing. More may be done to find designs that keep REE use to the minimum. However, many REEs needed for high-technology products have no or low potential for adequate substitution with other materials (Graedel *et al*. 2015). For example, dysprosium (used in permanent magnets in computers and wind turbines), europium and yttrium (used in flat panel displays), and thulium and ytterbium (used in laser technologies) do not have straightforward substitutes available. The lack of replacements suggests sharply increasing recycling is one strategy for REE supply chains, which requires implementing a circular flow of REE material through different stages in a product's lifecycle, from design, to end-of-life collection, to separation and recycling.

5.2 Innovations to REE manufacturing and bypass mining

Some industries that rely on REEs are looking for ways to bypass mining entirely by extracting REEs from other materials. For example, the US could someday obtain these elements as byproducts from power plant coal ash and coal mining waste. And the problem of radioactive material mixed in with ores could end up being positive: If thorium-based nuclear plants prove viable, expanded thorium mining would also turn up usable rare earth minerals. However, insofar as such innovations rely on energy production that poses significant risks to local communities, these approaches cannot satisfy the requirements of environmental justice, let alone intergenerational justice.

5.3 Circular economies for REE recovery and recycling

Recovering and recycling rare earth metals is one possible way of avoiding the ongoing environmental and intergenerational injustices of mining. However, only a very small proportion of REEs becomes recycled from products, some estimating less than 1% (Binnemans *et al*. 2013).

One reason is that the amount of rare earth elements that can be recovered from electronics, medical devices, and similar applications is very small, often less than one gram (Bonawandt 2013). Typically, recycling requires that rare earths be separated from metals and alloys created with REEs. For instance, the Japanese mining company Dowa began harvesting circuit boards, hard drives, computer chips and other components for rare earth metals by cutting these components into 2 cm squares, smelting them at 1,400° C, which enables separation of the various components. For every 300 tons of e-waste smelted, the harvestable rare earth material is only about 150 grams. Although REEs are valuable, Dowa would not be profitable were it not for other materials, such as gold, silicon, *etc.* (Tabuchi 2010).

Another issue is that there is no standard method of recycling REEs, and the processes for doing so are considerably costly and environmentally hazardous – some on par with mining. Several efforts are underway to make REE recycling more efficient (Harler 2018). Researchers working under the US Department of Energy's Critical Materials Institute have focused on developing a single-step process to recover REEs from scrap magnets in order to recover the ores from hard drives, magnetic resonance imaging machines, cell phones, and hybrid cars (ORNL 2019). For instance, using membrane solvent extraction, about 3 kilograms of magnets can yield about 1 kilogram of rare earth metals. Other US researchers have been improving an older method of isolating REEs from magnets and scrap metals using molten magnesium (Bonawandt 2013). Researchers in Belgium are using ionic liquids to separate REEs from magnets, a process that uses trihexyl(tetradecyl)phosphonium chloride to transform metals like iron, cobalt, magnesium, and copper into a liquid phase, leaving the rare earths behind in an aqueous state. Researchers at Japanese car manufacturer Honda have found a way to extract rare earths from nickel-metal hydride batteries from hybrid vehicles by using molten salt, and claim as much as 80 percent of REEs being recycled. In addition to these separation challenges, there are also challenges in handling reclaimed REEs due to their air reactivity, which can render them into oxides if left out in the open for too long.

Manufacturing blended REE materials is one alternative to the challenges of purification and the relatively small amounts of pure REE that can be recovered from many products. For instance, scientists and engineers working at Momentum Technologies and the DOE's Critical Materials Institute are producing a blended REE product from recovered hard drives and other technology waste (Harler 2018). After extracting iron and boron, the recovered rare earth metal product includes a mixture of neodymium, dysprosium, and praseodymium. Technology companies and other manufacturers may be willing to take this blended product that combines all three REEs as long as the material meets manufacturing requirements.

One strategy for enhancing the profitability would be to target REE recovery and recycling initiatives in supply chains with much larger REE quantities. For instance, it may be more profitable to work with the REEs in specific supply chains, such as sustainability technologies like wind turbines and electric cars or specific consumer electronics. Some argue that recycling of e-waste will have little impact on REE supplies until there is enough material in the recycling stream to keep up with REE demand. This assumes that manufacturers' only recourse is to wait for a steady flow of recycled REEs to become available for purchase on the world market. However, the recycling of REEs can also be pursued at the firm or industry level through a circular economy approach. The term 'circular economy' refers to 'close the loop' business models that replace the 'take-make-dispose' models, or what some now call the 'linear economy'.

Individual firms could take a product-centric approach to closing the loop for REE reuse as well. A closed-loop system developed internally would keep REEs and other materials in circulation for as long as possible. This would mean that downstream manufacturers, product designers, engineers, and business take control of their upstream REE supply chains, re-circulating REEs rather than purchasing mined REEs or waiting for a sizable market of recycled REEs to develop. Such product-centric design approaches require attention to disassembly: designers and engineers must understand how complex products break down into component parts and how particular materials behave in order to design products for easy separation. For instance, the circuit board of an electronic product may be redesigned so that its metals are easily removed from other plastic, aluminum, and steel parts. Product-centric recycling systems must be designed by those with knowledge of the chemical and physical properties of waste containing REEs, physical separation methods, physical and chemical recycling methods, as well as the thermodynamics of a specific plant's processing to assess material performance with regard to energy efficiency, durability, and manufacturing compatibility, in addition to recyclability (UNEP 2013, Kaya 2016). Liberation modeling is an important tool in this regard because it focuses on defining recyclate grades in a way that allows a common language to develop among engineers, policy specialists, and environmentalists about the trade-offs of different design approaches (UNEP 2013).

Policymaking has an important role to play here. Product-centric design for a circular economy must be undertaken in collaboration with policymakers as well as planning and recycling professionals who can help design collection systems for waste products and discourage informal or illegal disposal. Producer-responsibility laws, recycling targets, and other policy-based incentives can help to incentivize circular economy innovations from specific manufacturers and entire industries. For instance, the 2012 European Parliament law to reduce electronic waste requires member states to collect 45 tons of e-waste for every 100 tons of electronic goods sold in the previous three years, which has pushed companies and governments to develop better collection systems. In 2015, the European Commission launched its Action Plan on the Circular Economy, which aims to go further by pushing companies to re-design products to be durable and made with materials that can be re-used again and again.

In theory, a circular economy would keep harmful material from entering waste streams and reduce the environmental injustices created by e-waste. Instead, companies would assume responsibility and control over the entire lifecycle of all its products materials. Whether this happens in practice remains to be seen. Recycling value chains have created serious global environmental injustices, especially for the discarding and trading of electronics. Collecting and processing of electronic waste like mobile phones, computers, monitors, and televisions is dangerous and expensive to do safely (Amuzu 2018). Countries that accept e-waste from the United States, Europe, Japan, South Korea, and Australia usually lack the means to handle the materials safely (Iles 2004). E-waste workers, including children, are exposed to toxic fumes from smelting electronic parts and using acid baths to recover the valuable components, with little to no protective gear. Processing of scrap that contains lead, phthalates, chlorinated dioxins, and more, creates poor air and water quality for the entire community.

In terms of intergenerational equity, closing the loop on products that use REEs would help preserve the availability of REEs for future generations but it would raise new questions about intergenerational equity for the communities where REEs were originally mined. Thus, even if REE recycling provides a way to avoid new mining in the future, what forms of intergenerational equity are available to communities where lives and livelihoods have become negatively impacted by REE mining or workers who have become dependent upon REE mining despite its pollution, human rights and labor abuses?

6. Conclusion

In conclusion, we have shown that participants in the REE sector have a moral obligation to use these materials in an ethical manner by advancing environmental justice and intergenerational justice. REE value chains are complex, with rare earths feeding into many different end-uses. The increasing demand for REEs has encouraged investors to expand the geography of REE mining to avoid dependency on Chinese imports subject to price spikes. The large-scale mining industry's poor record of environmental destruction and human rights abuses will continue in order to meet REE demand unless more ethical strategies are developed for sourcing REEs. One of the best ways for REE users to advance environmental justice and intergenerational justice is to make REE reclamation a product-centric circular economy. However, consumer products represent only one segment of the REE sector. Where possible, product designers, material scientists, and engineers should fully take into account the risks and limitations of relying on such resources and design new products to reduce the use of REEs.

Notes

1 One significant exception is ion adsorption clays in southern China, where most of Chinese dysprosium originates, which use the in-situ leach mining approach (see note 2).

[2] This general process is not used in the in-situ method in southern China, where an ammonium sulfate solution is pumped into the clay deposit to leach out the REEs into a solution, which is then pumped back to the surface and the REE salts are precipitated from the solution by addition of ammonium carbonate (British Geological Survey 2011).

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