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Environmental Life Cycle Perspective on Rare Earth Oxide Production

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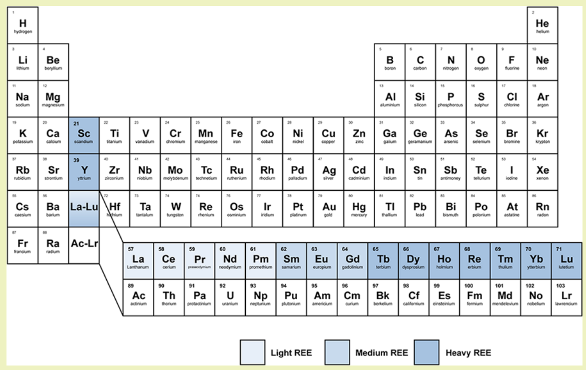
Supporting Information

ABSTRACT: Rare earth elements (REEs) are a collection of 17 chemical elements that are critical to the functionality of a host of modern commercial industries including emerging clean energy technologies, electronics, medical devices, and national defense applications. Despite their key importance in multiple industries, to-date there has been little emphasis on environmental systems analysis of REE production. Rapid growth in these industrial sectors could result in heightened global demand for REE. As such, assessing the broader ramifications of REE production on human health and the environment is crucial for guiding the sustainable development of these industries. In this study, life cycle assessment (LCA) is performed to evaluate the environmental impacts and resource intensity of producing rare earth oxides (REO) from the Bayan Obo mine located in Inner Mongolia, China. Analysis indicates that the mining, as well as extraction and roasting phase(s), had the greatest contribution to overall life cycle environmental impacts. Additionally, the results reveal that the production of heavy REO consumes over 20 times more primary energy as compared to steel (per unit mass). The high primary energy consumption and life cycle environmental impacts of REO production highlight the critical need for development of REE recycling operations and infrastructure.



KEYWORDS: *Rare earth elements, rare earth oxides, life cycle assessment, sustainability, critical materials, Bayan Obo*

INTRODUCTION

Rare earth elements (REEs) are a collection of 17 chemical elements composed of the 15 lanthanides as well as scandium (Sc) and yttrium (Y),[1] and are critical to the functionality of multiple modern commercial technologies[2] such as electric vehicles (batteries and magnets),[3] wind turbines (magnets),[4] fluorescent lighting (phosphors), catalytic converters, medical devices, and defense applications[5] (see Table 1). REEs are of significant national interest, as these chemical elements are pivotal for the development of emerging clean energy[6] technologies and are vital to the U.S. national security and economic well-being.[7]

REEs are a relatively abundant resource, however they are often widely dispersed and found in low concentrations, resulting in energy intensive and environmentally taxing mining, extraction, and refining processes.[9] REEs are often utilized for their special luminescent and magnetic properties.[10] However, because they are found in low concentrations, REEs are typically mined as coproducts of more concentrated materials. As such, REEs are typically more resource intensive and costly to recover, as compared to traditional ores such as iron or coal. In the past, the United States (U.S.) produced enough REEs to meet domestic demands, but now relies primarily on imports from China due to lower-cost labor and regulations.[9] In 2011, 95% of global rare earth oxides (REO) were produced in China;[11] the largest REE mine is located in Bayan Obo, Inner Mongolia,[9] see Figure 1.

In recent years, China has limited its export rate to meet growing internal demand for REEs.[13] Resultant global REE supply and demand dynamics[14] and monopolistic market conditions have raised significant U.S. economic and national security concerns, and have motivated efforts for rare earth mining and exploration in North America.[15] Additionally, there is ongoing interest in REE recycling as a means of mitigating REE resource scarcity and supply vulnerability.[16] However, the economic and technical viability of REE recycling remains uncertain, and the large time frame required for establishing recycling infrastructure limits its short-term effectiveness.

Prior research has focused on evaluating the projected demands and potential supply chain vulnerability of select REEs and REOs;[1,6,11,17] with specific attention to the political and economic implications of China's REE export policies and industrial regulations.[18] In a 2011 report, the U.S. Department of Energy (U.S. DOE) determined five REEs,

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Table 1. Overview REE Applications and End Uses[a]

element (atomic number)	classification	symbol	application and end uses
scandium (21)[b]	heavy	Sc	aerospace framework/components, high-intensity street lamps/additive in metal-halide lamps and mercury vapor-lamps, radioactive tracing agent in oil refineries
yttrium (39)	heavy	Y	TV sets, cancer treatment drugs, enhances strength of alloys, lasers, high temperature superconductors, microwave filters, energy-efficient light bulbs, spark plugs, gas mantles
lanthanum (57)	light	La	camera lenses, battery-electrodes, hydrogen storage, fluid catalysts for oil refineries
cerium (58)	light	Ce	catalytic converters, colored glass, steel production, chemical oxidizing agent
praseodymium (59)	light	Pr	magnets, welding goggles, lasers
neodymium (60)	light	Nd	permanent magnets, microphones, electric motors of hybrid automobiles, lasers
promethium (61)	light	Pm	nuclear batteries
samarium (62)	medium	Sm	cancer treatment, nuclear reactor control rods, X-ray lasers, masers, magnets
europium (63)	medium	Eu	color TV screens, fluorescent glass, genetic screening tests
gadolinium (64)	medium	Gd	shielding in nuclear reactors, nuclear marine propulsion, increases durability of alloys
terbium (65)	heavy	Tb	TV sets, fuel cells, sonar systems, florescence lamps, lasers
dysprosium (66)	heavy	Dy	commercial lighting, hard disk devices, transducers, magnets
holmium (67)	heavy	Ho	lasers, glass coloring, high-strength magnets
erbium (68)	heavy	Er	glass colorant, signal amplification for fiber optic cables, metallurgical uses
thulium (69)	heavy	Tm	high efficiency lasers, portable X-ray machines, high temperature superconductor
ytterbium (70)	heavy	Yb	improves stainless steel, lasers, ground monitoring devices
lutetium (71)	heavy	Lu	refining petroleum, LED light bulbs, integrated circuit manufacturing

[a]Adapted from refs 2 and 8. [b]REEs are listed in order of increasing atomic number.

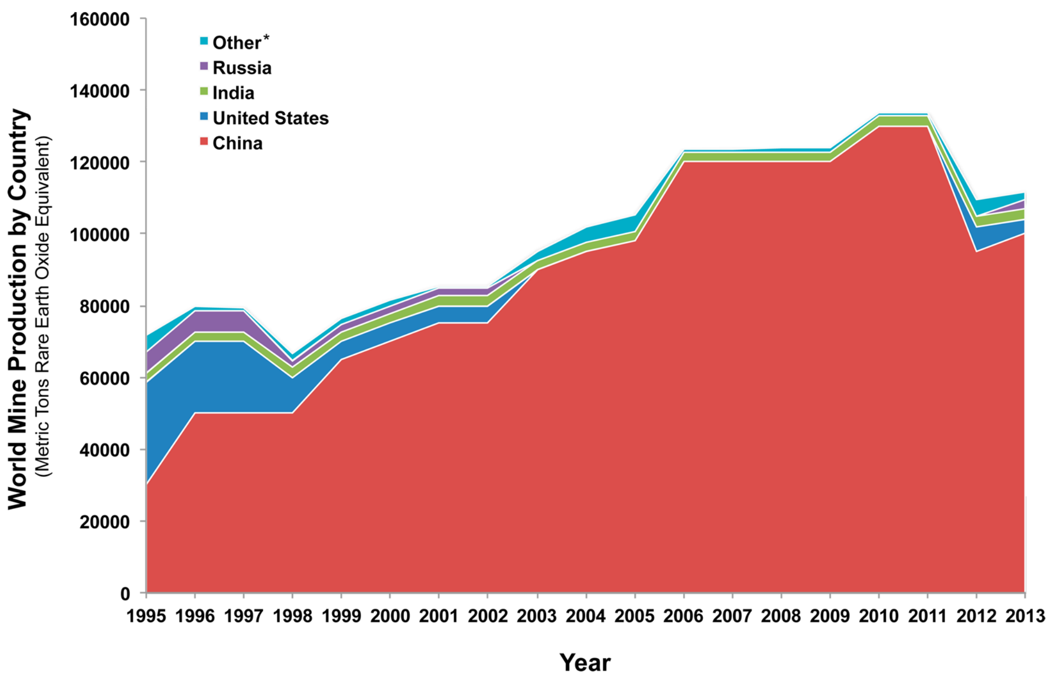

Figure 1. World REO production by country 1995 to 2013. World Mine Productivity for Russia includes data for the former Soviet Union. Data for World Mine Production was obtained from the United States Geologic Survey (USGS) Rare Earth Element Mineral Commodity Summaries, ref 12. Other (*) includes Australia, Brazil, Commonwealth of Independent States, Malaysia, Vietnam, Thailand, Sri Lanka, Congo (Kinshasa), Zaire, South Africa, and other countries.

dysprosium (Dy), europium (Eu), neodymium (Nd), terbium (Tb), and yttrium (Y) to be *Critical Materials* based on supply risk and importance to clean energy.[5] Alonso et al. utilized historical data to evaluate rare earth availability under different technological adoption and material demand scenarios.[17a] Du and Graedel analyzed the global in-use stock of rare earths using material flow analysis (MFA).[19] Their study concluded that if efficiently recycled, a significant amount of REEs could be added to the global market.[17b] The U.S. Geological Survey (USGS) determined that recycling of REEs is possible provided either (1) government legislation mandate the recycling of REEs or (2) elevated REEs prices make REE recycling economically feasible.[16b] A recent report by USGS summarized China's strategy for REE development and policy, including specific details regarding China plans to limit its exports, set specific output capacities, and ban mining of radioactive elements.[10] The Congressional Research Service (CRS) has compiled detailed and comprehensive information regarding REEs including major end uses of REEs, the role and application of rare earth metals in national defense, the production potential and global reserves of REEs, possible U.S. REE policy options/scenarios, and REE supply chain issues.[1]

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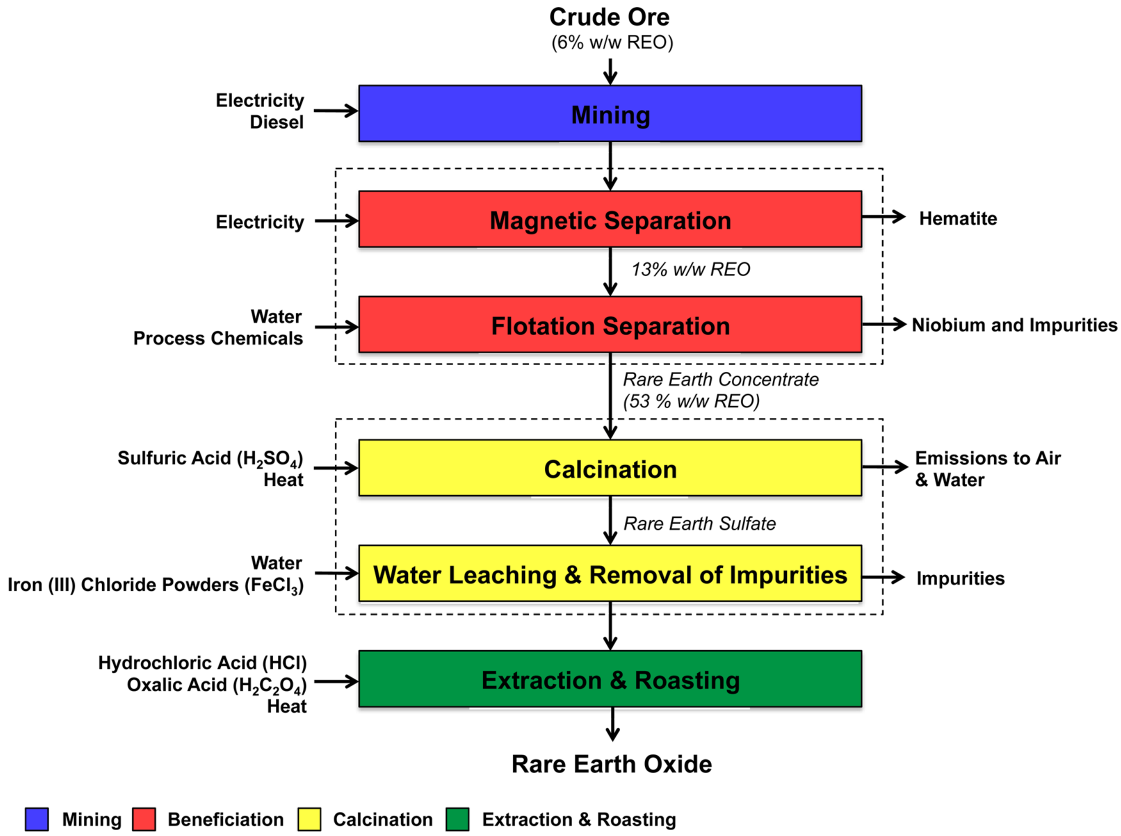

Figure 2. Rare earth oxide process chain.

To-date, there has been little emphasis on environmental systems analysis of REE production,[20] with only a handful of recent studies investigating the environmental impacts of REO/REE. Within Ecoinvent there exists a unit process for 60% REO concentrate produced from bastnasite; however, the unit process only extends to five REOs (La, Ce, Nd, Pr, and a Sm−Gd−Eu mixture), and utilizes economic allocation to partition the environmental impacts among REOs. Koltun and Tharumarajah performed a cradle-to-gate life cycle assessment (LCA) of REE production, and reported the impact of mass and market-based-allocation scheme(s) on the environmental profile of REEs.[21] Koltun and Tharumarajah found that for market-based allocation scandium, europium, terbium, and dysprosium had significantly larger carbon footprints relative to other REEs due to their higher market value(s). Sprecher et al. utilized LCA to quantify the environmental impacts of REO production under various technological adoption/use pathways, and investigated the environmental profile of NdFeB magnets under several different recycling scenarios.[22] Sprecher et al. found that the choice of recycling method had a significant impact on the environmental performance of NdFeB magnets, with manual dismantling and recycling of NdFeB magnets providing the greatest overall environmental benefits. More recently, Nuss and Eckelman performed a meta-analysis of the cradle-to-gate life cycle environmental impacts of 63 metals via synthesizing data from numerous commercial databases and peer-reviewed literature.[23] In the case of REEs, Nuss and Eckelman modified existing Ecoinvent REE processes and allocation procedures to reflect 2006−2010 REE market prices and more recent mine composition. Nuss and Eckelman found that for most metals, the majority of environmental impacts occurred during the purification and refining stages.

Prior reports have shown that REE extraction at Bayan Obo has brought the surrounding area serious environmental and health issues such as land depletion, water pollution, air pollution, and exposure to radioactive materials,[24] and highlights the importance of quantifying the human health and environmental impacts of REOs before their widespread adoption and use in multiple industries. Given the critical need for environmental sustainability assessments of rare earth element production, this work performs a LCA of REO production from the Bayan Obo mine located in Inner Mongolia, China. This work serves to add to the growing body of work on environmental impacts of REOs/REEs via providing a comprehensive understanding of the life cycle environmental profile of REOs produced in China, including details specific to China via Chinese REE industry reports. The following 15 rare earth oxides are evaluated in this study: cerium (Ce_2O_3), dysprosium (Dy_2O_3), erbium (Er_2O_3), europium (E_2O_3), gadolinium (Gd_2O_3), holmium (Ho_2O_3), lanthanum (La_2O_3), lutetium (Lu_2O_3), neodymium (Nd_2O_3), praseodymium (Pr_6O_{11}), samarium (Sm_2O_3), terbium (Tb_4O_7), thulium (Tm_2O_3), ytterbium (Yb_2O_3), and yttrium (Y_2O_3). The results of this work provide several important insights including (1) quantifying the environmental impacts of REO production on 10 key environmental sustainability and human health metrics; (2) identifying areas for process improvement in the REE supply chain; (3) environmental comparison of REO production to the primary production of several common metals. Furthermore, the analysis provided in this work can be synthesized with metallurgical and sustainability reports to provide a holistic understanding of the environmental sustainability of the growing REE and metals industry.

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■ EXPERIMENTAL SECTION

Process Description. Bayan Obo was chosen as the deposit for this analysis as it represents the largest REE producing mine in China.[9] In 2005, Bayan Obo produced 47% of China's REO and 45% of global REO.[25] Typical crude ore from Bayan Obo consists of iron, REEs, niobium, and other elements or impurities, with REO constituting approximately 5–6% weight per weight (w/w) of crude ore. Of the 5–6% w/w REO, the major components are cerium (50.0% w/w), lanthanum (23.0% w/w), and neodymium (18.5% w/w).[26] REEs exist in two mineral classes: (1) bastnäsite, a carbonate-fluoride class of minerals ($ReCO_3F$) and (2) monazite, a phosphate class of minerals ($RePO_4$).[27] Monazite can contain thorium and may be radioactive; as a result, China has plans to ban monazite mining containing radioactive elements.[10] In the Bayan Obo mine, the ore exists in a ratio of 7:3 bastnäsite to monazite by mass. A full summary of REO composition from Bayan Obo mine is in the Supporting Information. Process data for REO production was obtained from a review of technical and peer reviewed literature, first-principles of engineering, stoichiometric calculations, and published documents by the Ministry of Environmental Protection of China,[27,28] and best available engineering knowledge. Data on Bayan Obo's emission capturing systems is not available, and due to lack of publically available data concerning emissions for the REO production, it was assumed that mine meets the maximum allowable limits for emissions as regulated by China's Rare Earths Industry.[29]

The process chain for REO production includes mining followed by beneficiation, calcination, extraction, and roasting stages, see Figure 2. The first step in REO production is mining, wherein crude ore is blasted and transported for further refining. Crude ore abstracted from the Bayan Obo mine is composed of both monazite and bastnasite. The ore undergoes crushing and grinding until 90% of the input mass has a diameter of 0.074 mm.[27] It was assumed that gangue is backfilled into the mine, consistent with other published reports on REE mining operations.[30] However, due to data limitations, emissions for tailings are not included in the analysis. Power requirements for crushing and grinding were calculated utilizing the third theory equation developed by Fred C. Bond; details of the power requirement calculations are provided in the Supporting Information.[31] Diesel and electricity requirements for digging and dewatering during the mining phase were taken from U.S. average metal mining data,[32] and it was assumed that there was no loss of REEs during the mining phase. Although this is an optimistic assumption, it provides conservative lower estimate of life cycle environmental impacts of REO production. Post crushing, grinding, and dewatering, the tailings are subject to low intensity magnetic separation. Magnetic separation utilizes the difference in magnetism between iron and other minerals to extract the iron concentrate. The iron ore undergoes high intensity magnetic separation to produce high-quality iron concentrate. Iron and magnetic minerals are largely removed during magnetic separation, increasing the REO concentration in the crude ore to 13% REO by mass.[33] Following magnetic separation, further separation is achieved by flotation in a chemical solution, producing rare earth concentrates. Details concerning the chemicals utilized during flotation separation are in the Supporting Information. The recovery efficiency for REE in magnetic separations is 42–46%, the recovery efficiency for flotation is approximately 63%,[33,34] and the overall recovery efficiency for REE for both separation stages is 26–29%. After separations, the REO constitutes 53.71% w/w of the refined ore product.[34]

Post separations, rare earth concentrates undergo calcination. Several calcination methods exist to produce REO; however, the two most common methods are sulfuric acid (acid-based) and caustic soda (alkali-based). In China, the acid-based method is used for 90% of REE production.[16c] During acid-based calcination, rare earth ore is cracked with concentrated sulfuric acid (H_2SO_4) at 400–500 °C to produce rare earth sulfates. Excess H_2SO_4 is used during calcination, and any remaining H_2SO_4 volatizes or decomposes under the high temperature. Input data for the acid solution was obtained from rare earth technical articles, published documents by the Ministry of Environmental Protection of China,[27,28] and stoichiometric calculations. In the stoichiometric calculations, both REEs and other minerals or impurities are assumed to be involved in the reactions. In real operations, chemical requirements during calcination are subject to fluctuations due to varying crude ore compositions. The ratio of sulfuric acid to REE is crucial in the reaction steps, and depends on both the grade and temperature of the rare earth concentrate. This work considers a ratio of 1.4:1 sulfuric acid to REE on a mass basis at 450 °C, consistent with published literature, and a decomposition rate of 95–97% for REE.[28a] A summary of the chemical reactions during calcination is provided in the Supporting Information.

Following calcination, the rare earth sulfates are washed and filtered in a process referred to as water leaching, wherein water and chemicals are added in order to control the pH level and precipitate out impurities. In this step, the ratio of water to solids is about 7–15:1 on a mass basis.[27] Ferric chloride ($FeCl_3$) and calcium carbonate ($CaCO_3$) powders are added to precipitate impurities and control the pH. After water leaching, the $Re_2(SO_4)_3$ solution is sent to extraction and roasting stages. During extraction, the mixture is separated into Nd, and light, medium, and heavy REE. This separation is achieved with the use of paraffins and HCl, forming rare earth chlorides ($ReCl_3$). Next, $ReCl_3$ are precipitated with oxalic acid and then roasted to produce REO. This analysis assumes a ratio of oxalic acid to REE of 1.3:1 by mass,[35] with the overall recovery efficiency of REE during calcination and extraction exceeding 80%.[28a] Heat energy is provided via the combustion of coal, and is utilized during calcination and REO roasting. The disposal and treatment of radioactive materials/waste that may occur in the REO production chain is beyond the scope of this study and thus was not considered in the analysis; but merits further investigation. A review of radioactive emissions and exposure at the Bayan Obo mine and ore processing facilities, based on published literature, is provided in the Supporting Information.

Life Cycle Assessment. Life cycle assessment was conducted to quantify and track the environmental impacts of REO production from the Bayan Obo mine. The scope of the LCA is cradle-to-gate and the functional unit was chosen as 1 kg of REO. The developed LCA model translates process data including emissions, material, and energy flows into specific impacts on human health and the environment. In this work, the tool for reduction and assessment of chemicals (TRACI) was utilized to quantify the impact of REO production using eight environmental and human health metrics including ozone depletion, smog formation, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory effects, and ecotoxicity; whereas the Intergovernmental Panel for Climate Change (IPCC) 100 year global warming potential (GWP) characterization factors were utilized to quantify the carbon footprint of REO production, and the cumulative energy demand (CED) methodology was utilized to determine primary energy consumption. Life cycle data was obtained from the Ecoinvent database, and mass-based-allocation was performed to partition the environmental impacts among crude ore and REO, as well as allocate the environmental impact among light, medium, heavy, and neodymium REOs. Two alternative allocations schemes, (I) market-based and (II) exegetic-based allocation, were considered as a means to partition the environmental impacts among REOs. The results for market- as well as exergetic-based allocation are provided in the Supporting Information. It is important to note that allocation based on market-value is the preferred method of the metals industry.[23] When possible, Chinese-specific life cycle data was considered in the analysis; otherwise, European life cycle inventory (LCI) databases were used. The LCA results for REO production presented in this study provide a conservative benchmark for the environmental profile of REE. Furthermore, the LCI and LCA results can be extended/applied to evaluate the production of individual REE and REE-based technologies and products.

■ RESULTS

Figure 3 plots the primary energy consumption and greenhouse gas (GHG) emissions for producing light, medium, heavy REOs, as well as neodymium(III) oxide. Figure 3 shows that

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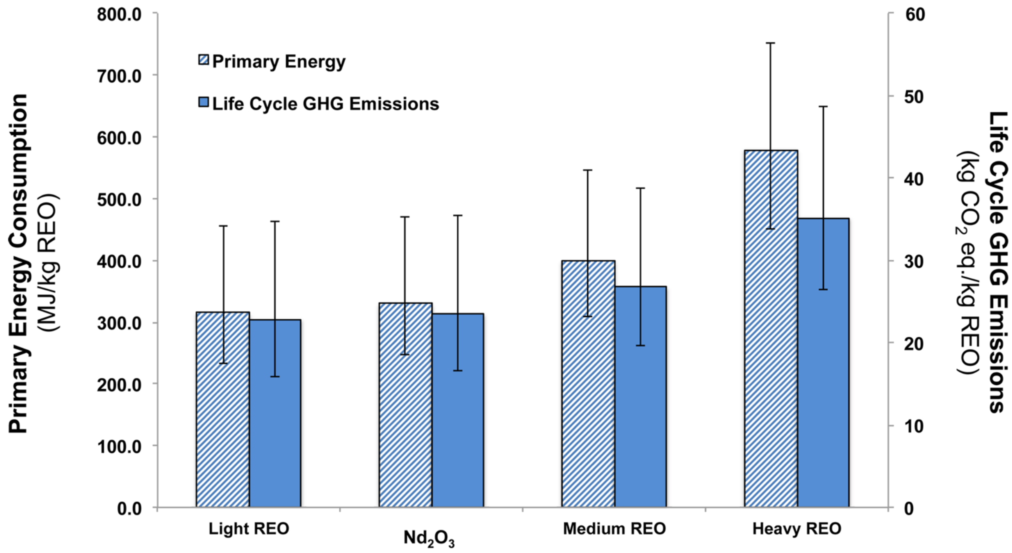

Figure 3. Life cycle greenhouse gas emissions and primary energy consumption for light, medium, and heavy rare earth oxides and neodymium(III) oxide. Error bars represent the 2.5th and 97.5th percentiles.

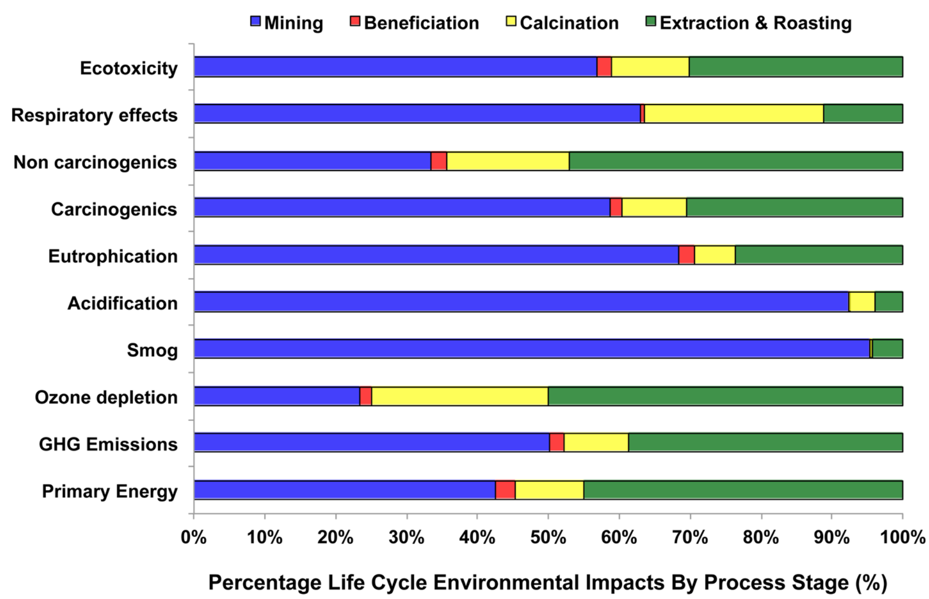

Figure 4. Contribution of life cycle impacts by process stage for the production of 1 kg of REO. 1 kg of REO consists of 79.5% w/w light REO, 1% medium REO, 0.9% w/w heavy REO, and 18.6% w/w neodymium(III) oxide.

the life cycle carbon footprint for REO range from 22.8 to 35.1 kg CO_2 eq/kg-REO and primary energy consumption ranges from 315 to 579 MJ/kg-REO for the different REO fractions. As shown from Figure 4, the magnitude of life cycle impacts increases from the light to the heavy REO fractions, due to additional chemicals and separations required for producing medium and heavy REOs. It is important to note that the results in Figure 3 do not consider the downstream processing and subsequent environmental impacts of converting REOs to REEs and final products; nevertheless, the analysis highlights the high carbon footprint and primary energy consumption of REO production. Due to data limitations, point estimates were used for data at process scale; however, uncertainty at the life cycle scale was captured via the use of Monte Carlo techniques to randomly sample from statistical distributions for environmental impact factors. The error bars presented in Figure 3 represent the 2.5th and 97.5th percentile for primary energy consumption and life cycle GHG emissions for the production of 1 kg of REO (light, medium, heavy, and neodymium(III) oxide), and are constructed via Monte Carlo simulation using 10 000 trials.

Figure 4 plots the percentage contribution of life cycle impacts by process stage for the production of 1 kg of REO. The results reveal that the mining as well as extraction and roasting stages contribute significantly to every environmental impact category. The large impacts from the roasting stage are due to the significant amount of heat required by this step, which is supplied by coal. The calcination stage contributes significantly to respiratory effects and ozone depletion categories, which is a consequence of the high amount of sulfuric acid required for the calcination process as well as hydrogen fluoride (HF) and sulfur dioxide (SO_2) emissions that occur during the chemical reactions. The extraction phase was found to be the main contributor to ozone depletion due to

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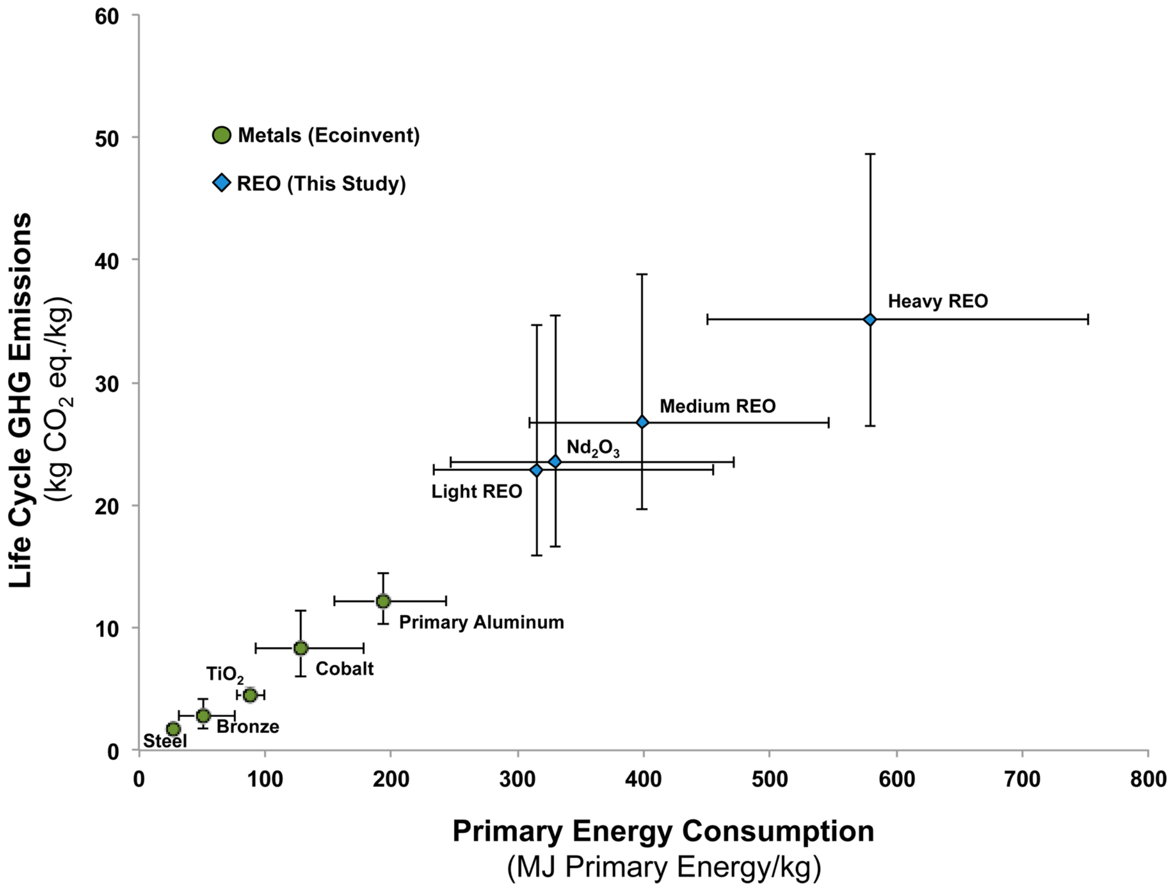

Figure 5. Environmental life cycle comparison of REO to common metals/ores. Average values are shown; error bars represent the 2.5th and 97.5th percentile. Environmental impacts for common ores and metals were obtained from the Ecoinvent database. Error bars for common ores and metals reflect 2.5th and 97.5th percentiles, and are constructed via Monte Carlo simulation using 10 000 trials.

the high upstream impacts of hydrochloric acid (HCl). Numerical values for the impact categories (magnitude of environmental impact) are provided in the Supporting Information.

To provide a broader understanding of the environmental profile of REOs, Figure 5 shows the life cycle carbon footprint and primary energy consumption for REO production against other common metals/ores. As shown in Figure 5, the production of light, medium, Nd_2O_3, and heavy REO consumes more primary energy and has higher life cycle GHG emissions as compared to steel, bronze, titanium dioxide, cobalt, or primary aluminum on an equal mass basis. It is important to note that these resources/materials are not comparable on a functional basis; nevertheless, this comparison highlights the high resource intensity of REO production. Additionally, although Figure 5 presents the environmental impacts of REO production, this work does not consider the energy or environmental impacts required for further downstream processing of REO to REE. As such, these results provide a conservative estimate for the environmental profile of REEs.

■ DISCUSSION

This work evaluates the environmental impacts of REO production from a life cycle perspective. Analysis indicates that the production of REO is energy intensive and environmentally taxing as compared to traditional materials. Production of heavy REO was found to consume over 20 times more primary energy as compared to steel (per unit mass). Additionally, the mining as well as extraction/roasting phases had the greatest overall contribution to life cycle impacts; therefore, process improvements during these stage(s) will be crucial for minimizing overall energy and environmental burdens. Additionally, although the production boundary of this study extends only to REO, further downstream processing of REO into REE and final products can only increase energy consumption and related environmental impacts. The high environmental impacts of REO identified in this study, are a potential source of concern, as the material demands for REOs are projected to increase in the near future due to their use in alternative energy technologies such as wind turbines and electric vehicles. The high upstream impacts of REO production are due, in part, to China's reliance on coal and other nonrenewable resources. Therefore, a shift toward renewable energy resources in China's power and electricity generation mix can significantly reduce the life cycle impacts of REO production. It is important to note that REO production is anticipated to increase in other parts of the world including Mountain Pass (California, USA), and Mount Weld (Australia), which have characteristically different energy systems, emissions standards, and different industrial situations as compared to China; thus the environmental profile of REO may be different for these locations. Additionally, it is important to note that the ion adsorption clay deposits of Southern China are currently the primary source for global heavy rare earth production. Moreover, these clays are less expensive and easier to exploit as compared to ore extraction and processing from

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Bayan Obo. As such, the environmental profile of heavy rare earths produced from these clays are likely different than the results presented in this work, and merits further investigation.

Recycling has emerged as a potential solution for increasing the global supply of REEs, thus helping to resolve issues of supply chain vulnerability and mitigate REE market price fluctuation.[36] Additionally, recycling of REE has the potential to significantly reduce the overall material and energy demands of REO production. However, current global average end-of-life functional recycling rate of REEs are less than 1%, and many technical and economic challenges must be overcome before recycling is feasible on a commercial scale.[37] To successfully implement REE recycling, comprehensive systems understanding of end-of-life flows must be established.[38] As is common with metal recycling, there is concern that undesirable trace elements could accumulate during the REE recycling process, thus potentially lowering the market value of the secondary REE.[39] Specifically, in the case of recycling NdFeB magnets, some loss of magnetism occurs due to contamination from the difficult to remove nickel casing.[16a] Though contamination is common in metal recycling, recycling of REE presents additional processing challenges. It has been suggested that it may be possible to recover REE from electronic waste (e-waste); however, most e-waste is processed on an international level and raises complex human rights and health issues.[17b,40] Shredding is typically used in the recycling process for e-waste; however, due to their magnetic properties, REE can attach to the shredder with past studies estimating that up to 80% can be lost during the recycling process.[22] As such, recycling of REE is technically challenging and is often not cost-effective.[41] Recycling of single components with high concentrations of REEs, such as magnets used in wind turbines and electricity vehicles batteries may reduce some of these technical and economic difficulties. Additionally, decomposition and recycling of fluorescent lamps may provide a source of secondary europium, terbium, and yttrium. However, due to their long life span and the likelihood of remanufacturing, wind turbines may not be a viable secondary source for REE.[42] Furthermore, many of the technologies that rely on REE such as electric vehicles, wind turbines, etc. are not at their end of life and thus not yet ready to be recycled. Thus, although recycling of REE may be a promising option for reducing the environmental burdens of REO production, it is not a panacea. Environmentally sound mining and primary processing, efficient use of material and resources along the supply chain, and increasing the life-span of products that use REEs may be effective measures to increase the environmental performance of commodities and services that rely on rare earth elements.

In recent years, several companies have initiated REE recycling; however, little information is available on these processes, and many are still undergoing research and development.[43] Additionally, these companies focus on one or two elements (dysprosium and/or neodymium) or specific products (fluorescent lamps and/or NdFeB magnets), and do not consider the full range of REE.[43] Nevertheless, the difficulty in recycling REE only highlights the need to design for recyclability, so that the burden is not solely on developing the recycling technology. Designing for recyclability, which also has its own set of challenges, will ensure that designers of the future have an array of secondary metals to choose from.[41,44] REE recycling is likely to be effective only in the long term, due to the large time frame required for establishing recycling infrastructure and for meeting the strict human health and environmental regulations inherent in metal recycling.[45] Material substitutes may reduce dependence on REE; however, the use of substitutes may compromise the efficiency, performance, and economics of the product/system, and in many cases no commercial available alternatives exist. Optimization of REE mining, extraction, separation,[46] and roasting processes, as well as developments in REE recycling will be crucial for reducing the environmental impacts and energy intensity of REE production. Future analysis should consider factors such as rebound effect,[47] price volatility, recycling trade-offs, societal implications,[48] and supply risk[49] in evaluating the sustainability of REEs.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Detailed information about Bayan Obo REE composition, crushing and grinding calculations, chemicals used during processing, emission requirements, and additional LCA results. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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