Global Neodymium and Praseodymium Mining and Processing

Environmental and Social Impacts

Carrie Snyder, More Than Sustainability
CC-BY-SA 4.0



https://www.shutterstock.com/image-photo/neodymium-stone-part-rare-earth-group-1902037270

Global Neodymium and Praseodymium Mining and Processing: Environmental and Social Impacts © 2023 by More Than Sustainability is licensed under CC BY-SA 4.0

About This Presentation

- **Rare Earth Elements (REEs) are normally discussed as a group in the literature** because they are often found together in ores, have some shared chemical properties, and are processed together to separate out the individual elements.
- **Wherever possible, I have attempted to find data specifically about Praseodymium (Pr) and Neodymium (Nd), or at the least, "light" REE (LREE) elements, of which Pr and Nd are a part and are co-present with in ores.**
- While the US originally produced the majority of the world's REEs out of Mountain Pass mine in California in the 1960's through the 1990's, it was shut down in 1998 due to ongoing environmental issues[1].
- **The more recent sustainability information for Pr and Nd** —not to mention the most relevant, as NdFeB magnets were only invented in 1982—**now centers around China, which had a virtual monopoly on REE production for many years, and today still contributes the over half of REE mining and the majority of REE processing.**
- In particular, **the Bayan Obo mine in Inner Mongolia, which will be discussed in this presentation, has been a primary source of Pr and Nd production to date**. (Note this situation is in contrast to other elements like copper, where there are many mines are spread throughout the world.)
- More recently, the Mountain Pass REE mine in California reopened in 2017[1], and new mines such as Mount Weld in Australia (which opened in 2011) have come online. **These, and other future mines, will contribute to the REE sustainability story going forward. But they, too, do and will face similar difficult sustainability challenges to that of China**, as you'll see in this presentation.
- **One of the challenges with researching sustainability issues in China is the lack of information.** As the REE LCA researchers, Klingelhöfer et al stated in 2022[27], "The exploitation of REEs is still in the hands of a few countries, first and foremost China. Therefore, obtaining data is difficult for independent and open- ended research is difficult, which is necessary for research on the environmental and health risks of REE use and production." **To that end, this presentation relies also in part on the personal stories collected by journalists and activist groups to help tell the Pr and Nd sustainability story.**

Global Neodymium and Praseodymium Mining and Processing: Environmental and Social Impacts © 2023 by More Than Sustainability is lice

Neodymium and Praseodymium: Chemistry and Ores

- Unlike copper—which has been mined and used by humans for thousands of years—**praseodymium (Pr) and neodymium (Nd) are relatively new to human use, having only been discovered in 1885**[2] after originally being thought to be one element. Praseodymium means "green twin" in Greek, and neodymium means "new twin"[2]
- **The most common use today of Nd (and Pr as well)—permanent magnets—was invented in 1982**[3]
- **Nd and Pr are in the lanthanide series of the periodic table, and in particular are part of what are called the "light" rare earth elements (LREEs)**[4]. The entire lanthanide series (which—plus yttrium and sometimes scandium—are known as the Rare Earth Elements (REEs))
- The REEs differ from other metals in that their valence occurs in an inner subshell rather than the outermost one[4]. **This gives the REEs unusual and useful chemical and physical properties, such as unique magnetic and/or optical properties**[5]**, but this same structure also makes them very difficult to separate from each other**[4]
- Interestingly, **despite their name, all REEs—except promethium—are not particularly rare**[6]
- **REEs are usually found together, but never in a pure form—rather in combined mineral ores.** "Metals like gold and copper are generally found clustered together in massive, readily-exploitable deposits, however, the geologic chemistry of rare earths tends to result in sparse distribution within mineral deposits"[3]
- **The two most common ores containing Nd, Pr and other LREEs are bastnäsite and monazite**[7]**.** Pr is present in smaller quantities than Nd in these same ores
- **Overall, lanthanum (La) and cerium (Ce), along with Pr and Nd, are the four most typical elements in a LREE deposit, comprising 80-90% of the total mass**[7]. These must then be separated from other elements—and from each other—during processing
- While there are over 200 different types of REE ore, bastnäsite, monazite, and xenotime (which contains heavy REEs) constitute almost 95% of the world's REE reserves[8]

Global Neodymium and Praseodymium Mining and Processing: Environmental and Social Impacts © 2023 by More Than Sustainability is licensed under CC BY-SA 4.0

China Mines and Produces the Majority of the World's REEs

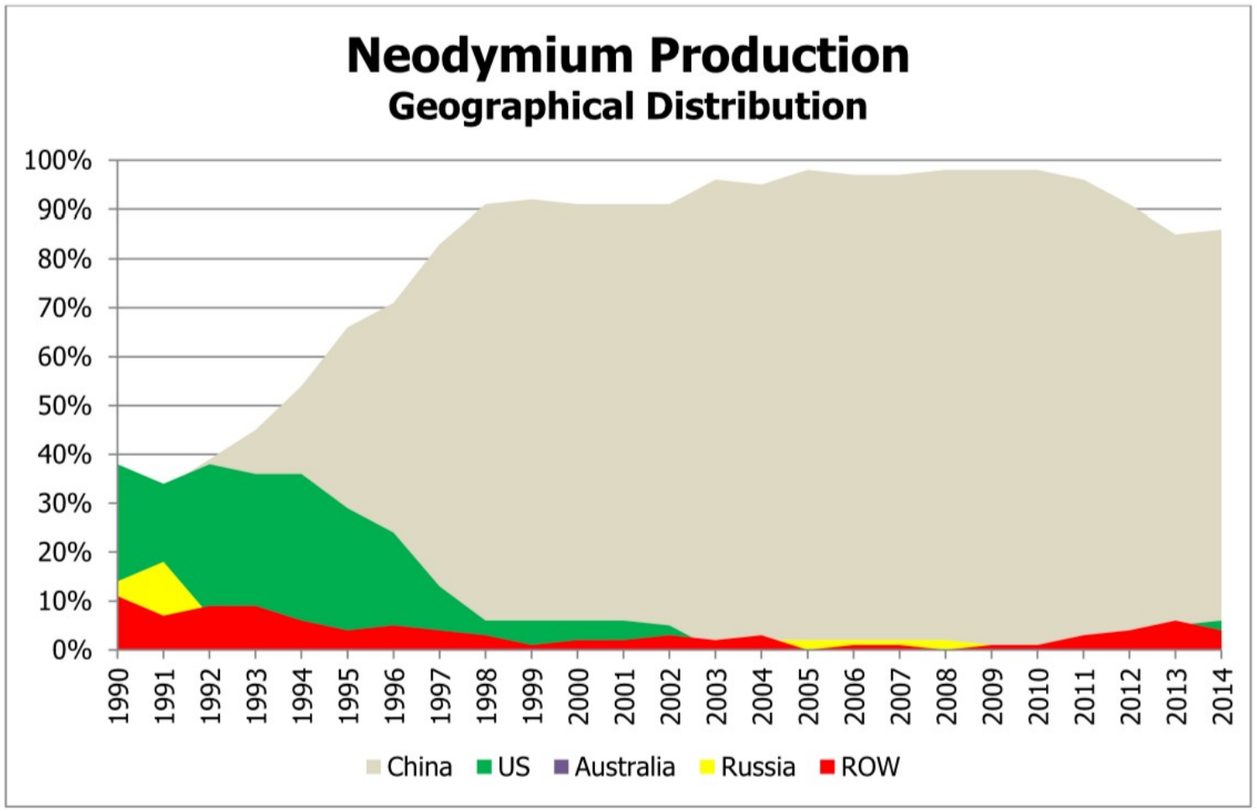


Figure 10: Geographical distribution of neodymium primary production, 1990-2014, based on data from the BGS archives, Habib et al (2014) and the USGS REE mineral summary (2015)

- As of 2017, while REE deposits had been found in 34 countries, only 6 at that time were (formally) actively mining REEs[8]
- **Most recently, Nd (and other REE) mining has been dominated by China** (see graph)[9]
- Despite the Chinese share of mining of REEs overall falling from 92% in 2010 to 58% in 2020**, as of 2021 China was still responsible for 85% of the refining of REEs**[10]

Global Neodymium and Praseodymium Mining and Processing: Environmental and Social Impacts © 2023 by More Than Sustainability is licensed under CC BY-SA 4.0

Nd and Pr: From Ore to Magnet

- **REE ore contains anywhere from 0.1-12% REEs, but each element needs to be processed to 98-99.99% purity[11] for most applications including electronics**
- Permanent magnets today are usually made of a combination of (primarily) Nd, Iron (Fe), and Boron (B), called NdFeB magnets for short
- PrFeB magnets perform nearly as well[12], and the addition of Pr may increase the magnet's resistance to corrosion[3]. But pure PrFeB magnets are unlikely to be produced because Pr is less abundant than Nd[12]
- In practice, a combination of Nd and Pr is used in magnets for applications where the cost and effort of separating them is not required[13]
- Overall, **Nd likely the most critical REE in the future[12], because of its unique, hard-to-substitute[14] contribution as permanent magnets to the functionality of electronics, wind turbines, and hybrid vehicle batteries**. Pr, conversely, is not generally considered a critical element[12]

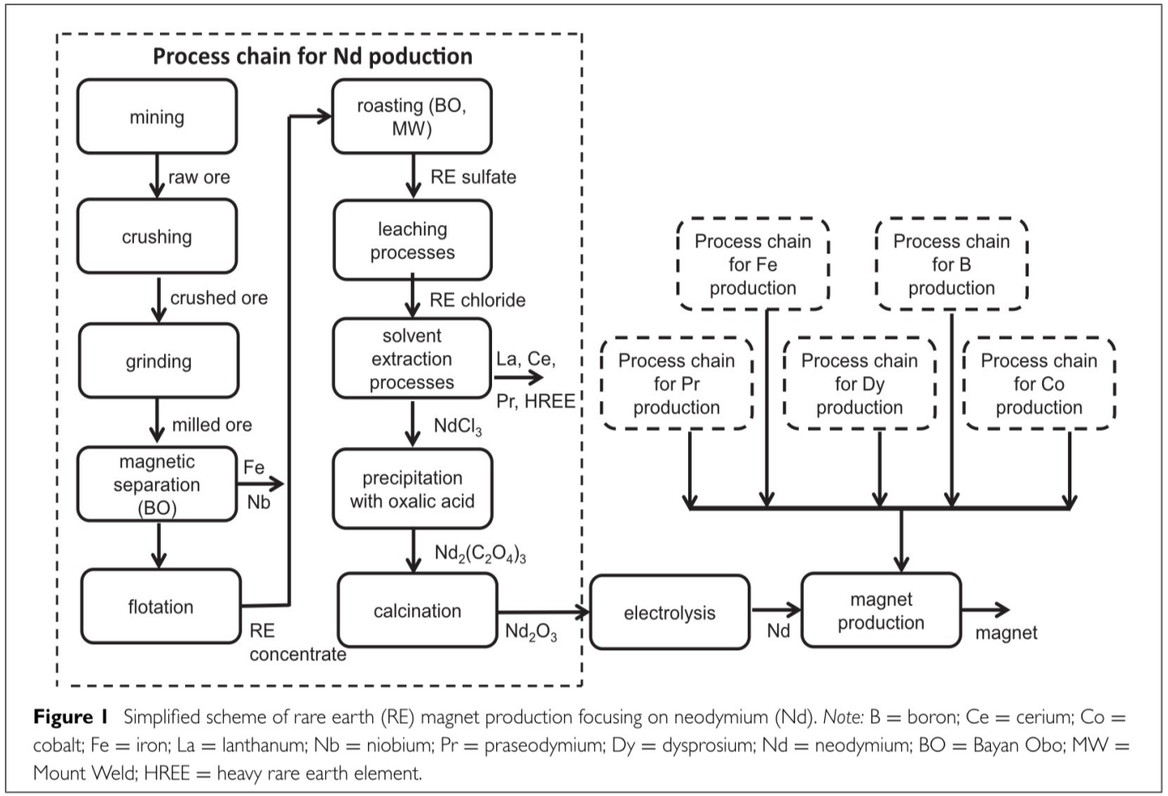


Figure 1 Simplified scheme of rare earth (RE) magnet production focusing on neodymium (Nd). *Note:* B = boron; Ce = cerium; Co = cobalt; Fe = iron; La = lanthanum; Nb = niobium; Pr = praseodymium; Dy = dysprosium; Nd = neodymium; BO = Bayan Obo; MW = Mount Weld; HREE = heavy rare earth element.

A summary of the production process for Nd[26]

Global Neodymium and Praseodymium Mining and Processing: Environmental and Social Impacts © 2023 by More Than Sustainability is licensed under CC BY-SA 4.0

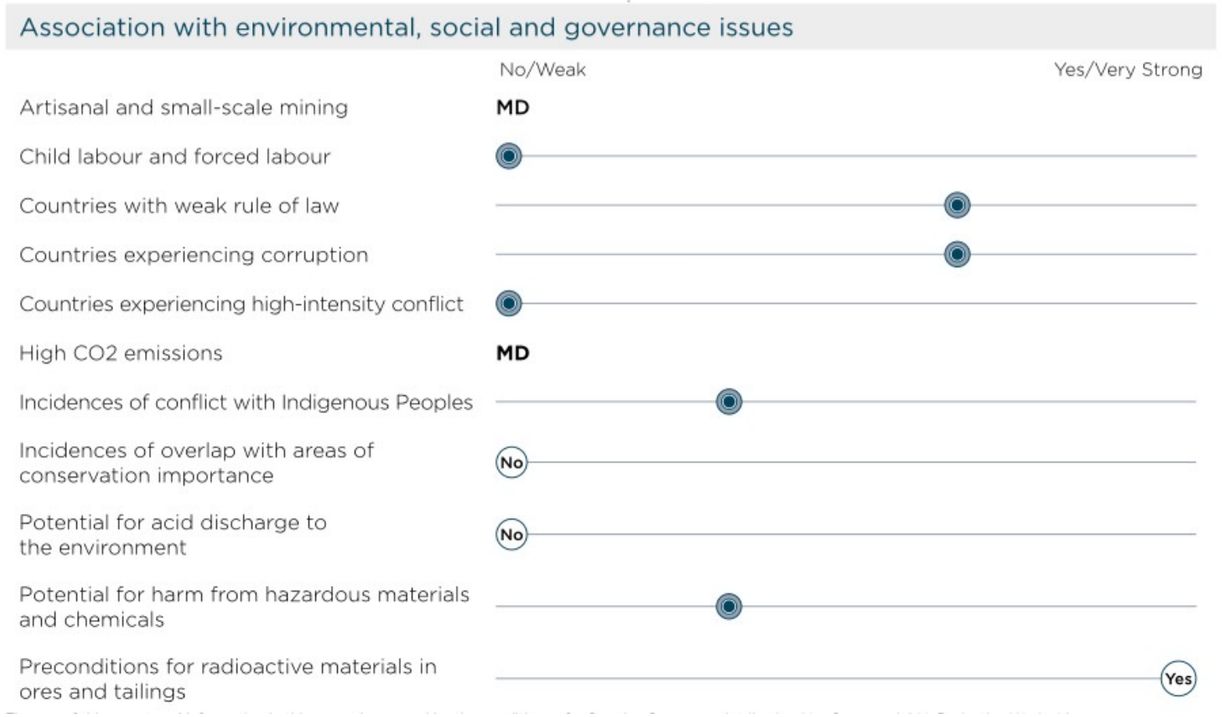
Processing Requirements and Risks

- To give you a sense of the input materials involved in this processing, at Bayan Obo, a primary LREE mining site in China, it's estimated that **the extraction of 1 ton (t) of REE requires**:
  - 4.41 t of sulfuric acid
  - 12.32 t of sodium chloride
  - 1.64 t of sodium hydroxide
  - 1.17 t of hydrochloric acid
  - 1.90 t of water, and
  - the grinding of almost 50 t of mineral ore[1]
- Some of this chemical processing is done outside in the environment, in what is called a tailings lake
- **Because rare earths are extremely similar chemically, they tend to stick together, requiring a complex and expensive process generating large quantities of waste**[1]
- Another serious problem* unavoidably exists for processing bastnäsite and monazite ores: **the ores are regularly are found in combination with Uranium (U) and/or Thorium (Th), radioactive elements that are in quantities too low to be economically extracted but high enough to present a danger to humans exposed to them**[15,16,2]. These radioactive elements are present in the ore until the later stages of refinement
- **For example, the tailings lake for Bayan Obo—which processes ores and stores mining waste, and is about three times the size of Central Park in NYC**[17]**—is estimated to contain 70,000 tonnes of thorium**[18]
- **The newly reopened Mountain Pass mine in California also mines LREE ore mixed with radioactive elements.** In fact, it was originally closed in 1998 after US federal investigation found that 60 spills—some unreported—occurred between 1984 and 1998, and in all, about 600,000 gallons of wastewater containing thorium flowed onto the desert floor[19].
- For its reopening, more controls have been put in place at Mountain Pass to try to manage these risks. But even at the newer facilities, **the tailings lakes, which continue to grow as mining continues, have a high potential for environmental damage should accidental releases occur**[15].

Global Neodymium and Praseodymium Mining and Processing: Environmental and Social Impacts © 2023 by More Than Sustainability is licensed under CC BY-SA 4.0

Sustainability Concerns for Nd and Pr

According to the Responsible Minerals Initiative's Material Change report, **REEs have above average sustainability risks in being mined and produced in countries with weak rule of law, countries experiencing corruption, as well as having very strong preconditions for radioactive materials in ores and tailings**.[21].



- Although this is evolving as other countries begin and ramp up more REE mining, geopolitical risk—namely, China's virtual monopoly on REE mining and processing—has been the biggest overall risk associated with REEs[20].
- In the opinion of a BBC reporter, "Arguably, what makes neodymium, and cerium, scarce enough to be profitable are the hugely hazardous and toxic process needed to extract them from ore and to refine them into usable products... **It could be argued that China's dominance of the rare earth market is less about geology and far more about the country's willingness to take an environmental hit that other nations shy away from.**"[22]

Global Neodymium and Praseodymium Mining and Processing: Environmental and Social Impacts © 2023 by More Than Sustainability is licensed under CC BY-SA 4.0

Bayan Obo, Inner Mongolia, China[28]

Because China features so predominantly in all REE production—including Nd and Pr—most of the sustainability impacts in recent years have come from China, and in particular, from the primary LREE mining site at Bayan Obo[18]





Global Neodymium and Praseodymium Mining and Processing: Environmental and Social Impacts © 2023 by More Than Sustainability is licensed under CC BY-SA 4.0

LREE Mining and Processing at Bayan Obo, Inner Mongolia, China

- **The Bayan Obo mine accounted for 45 percent of the world's rare earth production in 2019[1], which includes the production of both Nd and Pr.**
- After being mined in the mountains, excavated materials are then transported to a massive outdoor tailings "lake" in the city of Baotou. Here, other chemicals are added to the lake, consisting of black sludge 20m deep,[23] to begin to extract the REEs[24]. It is also where the remaining waste materials are permanently stored.
- Unfortunately, the tailings lake was not built on an impermeable layer[18] now present at more regulated mining sites, **but risks would exist regardless. The lake 35m above the Yellow River[15], and the entire area is situated on an active fault zone**[18]. And as stated before, the tailings lake contains significant amounts of radioactive thorium[18], and emits solvents vapors like sulfuric acid into the air[23]
- **The leakage of the tailings lake into the ground are almost certainly the cause of local "cancer villages"**[18]. A local farmer tells that in the late 1980s, goats and horses started to develop odd growths, only then to die suddenly. Later, the men and women developed issues with their jaws, and too, began to fall severely ill and be ultimately diagnosed with cancer. He mentioned that **in one nearby village, 30-40% of the villagers got cancer**[18]
- Over time, the Chinese government has been more publicly admitting to the environmental damage caused by REE mining and processing. Interestingly, **China implemented a tax on the export of rare earths in 2011, stating that the reason for the resulting limited exports was to conserve a limited resource and to reduce mining pollution; however the World Trade Organization ruled against China in 2014 and subsequently the tax was repealed**[2]

Global Neodymium and Praseodymium Mining and Processing: Environmental and Social Impacts © 2023 by More Than Sustainability is licensed under CC BY-SA 4.0

The Unclear Impacts of REEs Directly on Environmental and Human Health

- **Given the co-presence of radioactive elements during the mining and some of the processing steps for many REE ores, there are clear negative effects on humans and the environment. However, to what extent the impacts are from the radioactive elements, the REEs themselves, or the chemicals used to process them (especially outdoors in tailing ponds) is unclear.**
- Scientists note there is a lot we don't know yet formally about the direct impact of REEs themselves (which may be released into the environment during mining and processing) on human and other life, as REEs are relatively new elements in widespread human exposure and use.
- **In the health research, REEs are often considered to be emerging chemicals, and "like most emerging chemicals:**
  - **(1) they are currently unregulated in humans and the environment,**
  - **(2) they are not routinely monitored in environmental and public health programs,**
  - **(3) they are micropollutants detectable with analytical equipment with very low detection limits; and**
  - **(4) their mechanisms of environmental and human toxicity are poorly understood"**[29].
- Over time, we may discover more risks directly related to REE exposure during mining and processing

Global Neodymium and Praseodymium Mining and Processing: Environmental and Social Impacts © 2023 by More Than Sustainability is licensed under CC BY-SA 4.0

Benefits from Recycling Neodymium and Praseodymium

- REEs have what is called the "balance problem", where large quantities of less desired REEs (such as La and Ce) have to also processed/produced in order to isolate the more desirable REEs like Nd. By targeting Nd and Pr in secondary production (e.g. through recycling end of life devices), the balance problem could be reduced[31]
- **Recycling of REEs has the potential to reduce sustainability impacts: data indicates roughly a 60% reduction in environmental burdens through recycling for rare earths**[30]. See the diagram for a comparison between REE primary and secondary production impacts
- **For NdFeB magnet-to-magnet recycling (based on a study for electric motors), the benefits are significant, estimated at 64-96% in various environmental categories**[25]

Table 4.2. Summary of the major burdens and impacts of primary and secondary production of rare earths.

	Primary production	Secondary production
Mining	High risks where regulatory structures are either absent or poorly implemented. High risks for illegal and unofficial mining. Potential for significant release of dusts, thorium and uranium. Substantial reduction in risk possible through effective regulation.	Not applicable.
Processing of ores and secondary materials	Significant use of caustic agents and solvents, potentially contaminating land and drinking water. Controllable via regulation.	High risk where informal processing is carried out, with particular concern over the dismantling and processing of e-waste. This may affect workers, their families and neighbours. Substantially lower relative to primary production in well-regulated environments.
Smelting	Emissions to air from power generation and fuel use (SO_2, NO_x, PM_{10}, CO_2). Emissions can be closely controlled, both to air and water.	Similar types of impact to those from primary production. However, energy and other savings of around 50% seem achievable. This figure may rise as recycling technology advances assuming that recycling innovation keeps pace with developments in battery technologies.
Transport	Very largely dependent on proximity of operations to the Chinese centres of rare earth production for the foreseeable future.	Potentially significant given that there will be possibly few centres equipped for rare earth recovery, leading to the movement of secondary materials over significant distances, dependent on any barriers to trade that may exist.
Overall burdens	Substantial variation in overall burdens through differences in the regulatory framework and enforcement, ore quality and fuels used, especially for power production.	Significant variation possible, again through differences in regulatory framework and enforcement and fuels used for power production.
Trends	Increasing burdens as ore grades decline. Reduced burdens through advances in the regulatory environment.	Reduced burdens through advances in the regulatory environment and advances in knowledge and optimisation of recycling technologies for the rare earths. Increased burdens where secondary materials are exported to countries that lack efficient processing infrastructure.

Global Neodymium and Praseodymium Mining and Processing: Environmental and Social Impacts © 2023 by More Than Sustainability is licensed under CC BY-SA 4.0

Summary

- Unlike an element like copper—which has been mined and used by humans for thousands of years—praseodymium (Pr) and neodymium (Nd) are relatively new to human use, and some of their sustainability impacts are still being discovered
- Pr and Nd, like the other rare earth elements (REEs), have unusual (and useful) chemical and physical properties, but these same properties also makes the REEs very difficult to separate from each other
- As such, REE production is complex, expensive, and generates a massive amount of dangerous waste; most of which (like in many mining operations) is stored outside in what are called tailings lakes
- In addition, most ores with Nd and Pr are co-present with radioactive elements, which present significant human and environmental health risks
- Unlike many other metals, there relatively few mines producing REEs like Nd and Pr; most mining still comes out of China, and the majority of production happens there
- Bayan Obo in China mines and produces of a large amount of the world's Nd and Pr supply, even as other countries' mines come online. Unfortunately it also has an extremely poor environmental record, including being connected to the creation of local "cancer villages"
- Recycling Nd and Pr offers great promise in helping reduce environmental and human impact

Global Neodymium and Praseodymium Mining and Processing: Environmental and Social Impacts © 2023 by More Than Sustainability is licensed under CC BY-SA 4.0

Thank you

Global Neodymium and Praseodymium Mining and Processing: Environmental and Social Impacts © 2023 by More Than Sustainability is licensed under CC BY-SA 4.0

References (1 of 3)

[1] Gramling, C. (2023, January 11). Rare earth mining may be key to our renewable energy future. But at what cost? https://www.sciencenews.org/article/rare-earth-mining-renewable-energy-future

[2] Voncken, J. H. L. (2016). The rare earth elements: An introduction. Springer. https://link.springer.com/book/10.1007/978-3-319-26809-5

[3] Hart, M. (2013). Evaluating United States and world consumption of neodymium, dysprosium, terbium, and praseodymium in final products. Colorado School of Mines. https://repository.mines.edu/handle/11124/77777

[4] Weber, R. J., & Reisman, D. J. (2012). Rare earth elements: A review of production, processing, recycling, and associated environmental issues. US EPA Region, 8, 189–200. https://www.clu-in.org/download/issues/mining/weber-presentation.pdf

[5] Van Gosen, B. S., Verplanck, P. L., Seal II, R. R., Long, K. R., & Gambogi, J. (2017). Rare-earth elements (No. 1411339916). US Geological Survey. https://doi.org/10.3133/pp1802O

[6] Leal Filho, W., Kotter, R., Özuyar, P. G., Abubakar, I. R., Eustachio, J. H. P. P., & Matandirotya, N. R. (2023). Understanding Rare Earth Elements as Critical Raw Materials. Sustainability, 15(3), Article 3. https://doi.org/10.3390/su15031919

[7] Moir, A. (2010). The Chemistry, Economics and Politics of Neodymium. http://large.stanford.edu/courses/2010/ph240/moir2/

[8] Mat Suli, L., Ibrahim, W., Abdul Aziz, B., Deraman, M. R., & Ismail, N. (2017). A Review of Rare Earth Mineral Processing Technology. Chemical Engineering Research Bulletin, 19, 20. https://doi.org/10.3329/cerb.v19i0.33773

[9] Crock, W. D. (2016). Mapping stocks and flows of neodymium: An assessment of neodymium production and consumption in the Netherlands in 2010 and 2030. https://repository.tudelft.nl/islandora/object/uuid%3A4929a4c4-5df2-4005-8792-2fd377ec68c8

[10] Mining.com. (2021). Rare earth elements: Where in the world are they? https://www.mining.com/web/rare-earth-elements-where-in-the-world-are-they/

[11] Talens Peiró, L., & Villalba Méndez, G. (2013). Material and Energy Requirement for Rare Earth Production. JOM, 65(10), 1327–1340. https://doi.org/10.1007/s11837-013-0719-8

[12] Binnemans, K., Jones, P. T., Müller, T., & Yurramendi, L. (2018). Rare Earths and the Balance Problem: How to Deal with Changing Markets? Journal of Sustainable Metallurgy, 4(1), 126–146. https://doi.org/10.1007/s40831-018-0162-8

Global Neodymium and Praseodymium Mining and Processing: Environmental and Social Impacts © 2023 by More Than Sustainability is licensed under CC BY-SA 4.0

References (2 of 3)

[13] Alonso, E., Pineault, D. G., Gambogi, J., & Nassar, N. T. (2023). Mapping first to final uses for rare earth elements, globally and in the United States. Journal of Industrial Ecology, 27(1), 312–322. https://doi.org/10.1111/jiec.13354

[14] Chen, A. (2019, February 15). Where will the materials for our clean energy future come from? The Verge. https://www.theverge.com/2019/2/15/18226210/energy-renewables-materials-mining-environment-neodymium-copper-lithium-cobalt

[15] Zapp, P., Schreiber, A., Marx, J., & Kuckshinrichs, W. (2022). Environmental impacts of rare earth production. MRS Bulletin, 47(3), 267–275. https://doi.org/10.1557/s43577-022-00286-6

[16] Shirazi, A., Shirazy, A., Pour, A. B., Hezarkhani, A., & Khakmardan, S. (2022). Investigation of Environmental and Biological Effects of Rare Earth Elements (REEs) with a Special Focus on Industrial and Mining Pollutions in Iran: A Review. Advances in Geological and Geotechnical Engineering Research, 4(1), 1–10. https://10.30564/agger.v4i1.4102

[17] Ives, M. (2013). Boom in Mining Rare Earths Poses Mounting Toxic Risks. Yale E360. https://e360.yale.edu/features/boom_in_mining_rare_earths_poses_mounting_toxic_risksin

[18] China Water Risk. (2016). Rare Earths: Shades Of Grey. https://chinawaterrisk.org/wp-content/uploads/2016/08/China-Water-Risk-Report-Rare-Earths-Shades-Of-Grey-2016-Eng.pdf

[19] Ali, S. (2014). Social and Environmental Impact of the Rare Earth Industries. Resources, 3, 123–134. https://doi.org/10.3390/resources3010123

[20] Gemechu, E. D., Helbig, C., Sonnemann, G., Thorenz, A., & Tuma, A. (2016). Import-based Indicator for the Geopolitical Supply Risk of Raw Materials in Life Cycle Sustainability Assessments. Journal of Industrial Ecology, 20(1), 154–165. https://doi.org/10.1111/jiec.12279

[21] Responsible Minerals Initiative, & Drive Sustainability. (n.d.). Material Change. Retrieved from https://www.responsiblemineralsinitiative.org/minerals-due-diligence/other-minerals/

[22] Maughan, T. (2015). The dystopian lake filled by the world's tech lust. https://www.bbc.com/future/article/20150402-the-worst-place-on-earth

[23] Martin, A., & Iles, A. (2021). The ethics of rare earth elements over time and space. In Ethics of chemistry: From poison gas to climate engineering (pp. 317–346). World Scientific. https://doi.org/10.1142/9789811233548_0012

Global Neodymium and Praseodymium Mining and Processing: Environmental and Social Impacts © 2023 by More Than Sustainability is licensed under CC BY-SA 4.0

References (3 of 3)

[24] Standaert, M. (2019). China Wrestles with the Toxic Aftermath of Rare Earth Mining. Yale E360. https://e360.yale.edu/features/china-wrestles-with-the-toxic-aftermath-of-rare-earth-mining

[25] Jin, H., Afiuny, P., Dove, S., Furlan, G., Zakotnik, M., Yih, Y., & Sutherland, J. W. (2018). Life cycle assessment of neodymium-iron-boron magnet-to-magnet recycling for electric vehicle motors. Environmental Science & Technology, 52(6), 3796–3802. https://doi.org/10.1021/acs.est.7b05442

[26] Wulf, C., Zapp, P., Schreiber, A., Marx, J., & Schlör, H. (2017). Lessons learned from a life cycle sustainability assessment of rare earth permanent magnets. Journal of Industrial Ecology, 21(6), 1578–1590. https://doi.org/10.1111/jiec.12575

[27] Klingelhöfer, D., Braun, M., Dröge, J., Fischer, A., Brüggmann, D., & Groneberg, D. A. (2022). Environmental and health-related research on application and production of rare earth elements under scrutiny. Globalization and Health, 18(1), 86. https://doi.org/10.1186/s12992-022-00879-5

[28] Google Earth. (2023). Mine near Bayan Obo, Inner Mongolia, China [Map].

[29] Gwenzi, W., Mangori, L., Danha, C., Chaukura, N., Dunjana, N., & Sanganyado, E. (2018). Sources, behaviour, and environmental and human health risks of high-technology rare earth elements as emerging contaminants. Science of the Total Environment, 636, 299–313. https://doi.org/10.1016/j.scitotenv.2018.04.235

[30] Holland, M. (2020), "Reducing the health risks of the copper, rare earth and cobalt industries: Transition to a circular low-carbon economy", OECD Green Growth Papers, No. 2020/03, OECD Publishing, Paris. https://www.oecd-ilibrary.org/environment/reducing-the-health-risks-of-the-copper-rare-earth-and-cobalt-industries_88ce1db4-en

[31] Binnemans, K., Jones, P. T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., & Buchert, M. (2013). Recycling of rare earths: A critical review. Journal of Cleaner Production, 51, 1–22. https://doi.org/10.1016/j.jclepro.2012.12.037

Global Neodymium and Praseodymium Mining and Processing: Environmental and Social Impacts © 2023 by More Than Sustainability is licensed under CC BY-SA 4.0