Energy and Economic Growth
Applied Research Programme

Rare earth metals: Options for a more sustainable future

Energy Insight

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Preface

The Applied Research Programme on Energy and Economic Growth (EEG) produces cuttingedge research on the links between energy and economic growth, working closely with policy makers in Sub-Saharan Africa and South Asia to build more sustainable, efficient, reliable and equitable energy systems.

EEG's objective is to build a body of evidence around how sector reforms, innovative technologies and practicable actions can enhance the economic impacts of large-scale electricity infrastructure in low-income countries. By pioneering research, harnessing best practice and strengthening institutional capacity in low-income countries, EEG aims to promote evidence-based programming, and ultimately, help bring the benefits of modern energy services to poorer people.

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Introduction: rare earth metals as a binding constraint to global climate policy

Rare earth metals (REMs) are integral to the manufacture of the technologies required for the transition to a low-carbon economy. With growing demand for clean technologies that rely on REMs, such as wind turbines and batteries for electric vehicles (EVs), global commodities companies are scrambling to increase their share of the REM market (The Economist, 2018a). This Energy Insight explores the current market conditions for REMs, and how their scarcity and China's global monopoly on supply may present a binding constraint to meeting our global climate change commitments.

REMs can be divided into two 'types': light rare earths, which are more commonly found in nature, and heavy rare earths, which are mostly used in clean technology applications (Smith Stegen, 2015). Also known as rare earth elements, REMs such as neodymium (Nd), dysprosium (Dy), and their periodic neighbours are used in the manufacture of a wide range of technologies, including batteries, smartphones, and military equipment. Crucially, their strong magnetic properties, high electrical conductivity, lightness, and efficiency make them critical to magnets that are used in wind turbines, electric car batteries, energy-efficient light bulbs, and efficiency motors/generators. To date, no substitute has been found to match REMs' weight and efficiency.

Until recently, there has been an adequate supply of REMs to meet global demand (de Koning *et al.*, 2018). As we transition to low-carbon energy and transportation systems, demand for REMs will increase drastically, and it is not clear that supply can match it.

The following section explores the available literature on projected demand for REM, particularly from clean technologies, and more specifically from EVs. Section 3 discusses the status of possible alternative supplies and substitutes for increasing supply and reducing the demand for REMs. Section 4 concludes with overarching comments on the role of the public and private sectors in overcoming REM supply bottlenecks to ensure a low-carbon future.

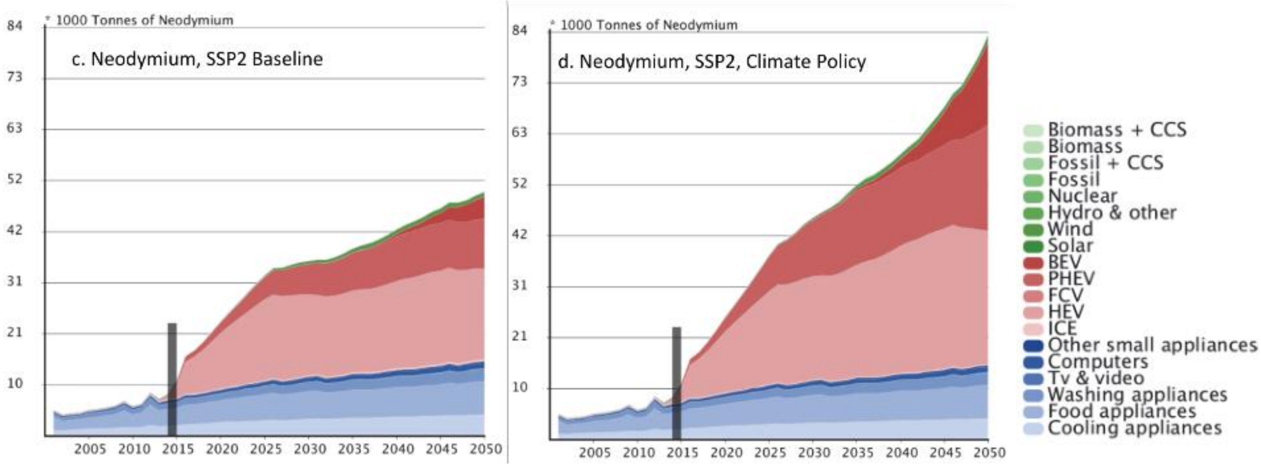
REM demand could outgrow available supply

Most of the clean technology demand for REMs is projected to come from growth in EVs (Deetman *et al.* 2018). As countries commit to reducing greenhouse gas emissions and climate policies start to be implemented, demand for EVs is growing rapidly. According to the International Energy Agency (2017), EVs surpassed 2 million units in 2016, up 60% from 2016. The IEA has set a target of 140 million EVs on the road by 2030, to reach a 2°C scenario. The European Union has a combined target of 8–9 million EVs on the road by 2020, while India has committed to the ambitious target of having 30% of all new vehicles coming onto its roads be electric by 2030 (Amsterdam Roundtable Foundation and McKinsey & Company, 2014).

Demand for magnets containing REMs for EVs is projected to more than double by 2020 (Pavel *et al.*, 2018). This could lead to supply risks for many REMs. By 2020, global electric road transport could require up to 75% of available dysprosium, for example. To secure an adequate supply of the limited resources, road transport will need to compete with other applications, such as high-tech and energy-devices (Pavel *et al*., 2018)

Climate policies are predicted to boost demand for neodymium by at least 60% by 2050, compared to a baseline scenario (Deetman *et al*., 2018). Neodymium is used in many clean technologies, including wind turbines, but as shown in Figure 1, most growth in demand will come from clean cars. Depending on the metal content required for clean technologies (i.e. on how efficient we can make the use of REMs within the magnets that use them), it is likely that the demand for REMs will exceed supply.

Figure 1: Demand projections for neodymium in the baseline scenario and in its corresponding 2°C climate policy scenario (in tonnes/yr) (from Deetman *et al.*, 2018).



Note in figure from Deetman *et al*. (2008): green represents all electricity generation technologies, red represents all car types, and blue is used for appliances. The dark bar in 2015 represents the current total annual consumption estimates for neodymium. The study only addresses three categories of demand, thus the bar gives a feeling for the size of the 'rest' of the demand (e.g. construction, medical applications, etc.).

MIT's Randolph Kirchain, Elisa Alonso, and Frank Field (2012) predicted that there would need to be an increase of neodymium and dysprosium of over 700% and 2,600%, respectively, in the next two decades in order for clean technologies to contribute significantly to a reduction in greenhouse gases (Alonso *et al.*, 2012). The supply of these metals was increasing at 6% a year in 2012, and was already under threat. In order to meet demand for clean technologies, supply would need to increase 8% and 14% per year, respectively.

What is more, the costs and environmental impacts of REM extraction can be high, particularly as REMs being prospected are found in more complex and less concentrated ore forms. The extraction process is complex and highly polluting. Lee and Wen (2018) estimated the net environmental costs of REM production in China in 2015 were $14.8 billion, which will increase to $16 billion by 2025 under a baseline scenario. Lee and Wen note that only with the strictest environmental regulations and tackling of illegal mining could environmental impacts be reduced. Such measures, however, would likely tighten the supply of REMs and increase market volatility.

Efforts to transition to a green economy would benefit from a more comprehensive understanding of the limitations and diversification options of these natural resources.

Meeting increasing demand for REMs could be challenging

Securing adequate supply of REMs is particularly challenging, because they are not commonly found in sufficient concentrations to be mined profitably (Smith Stegen, 2015). China currently holds a near monopoly on supply. Until 2011, China mined 94–97% of REMs globally. While efforts have increased in America and Europe to find alternative supplies, which has reduced China's monopoly to around 80–85% in 2018, there are still no clear avenues for diversifying supply.

China's effective monopoly on REMs can have substantial impacts on the liquidity and stability of global markets more broadly. In 2010, China halted the export of rare earth exports to Japan, leading to a 30-fold increase in the price by the summer of 2011. The price subsequently plummeted to less than half that price.

In 2016, China moved to acquire one-third of the cobalt shipped by the largest producer of this REM, likely contributing to the price jump from $26,500 to $90,000 a tonne. Observers noted that this supply may be required for China to fulfil its plan to step up EV production, but other sources note the motive could be continued control over REM markets (The Economist, 2018b).

Figure 2 shows the evolution of REMs primary production over time, per country. As at late 2015, Harmer and Nex reported that there were 53 REM development projects outside of China. Developing these sources could reduce China's global monopoly to approximately 70% of the market and potentially provide enough REMs to meet global demand, although it is unclear if the authors include the demand from clean technologies in this assessment. Furthermore, these developments will not come online until market forces make them profitable enough, which could delay the diversification of the market for another decade.

Figure 2: Primary production of rare earth elements over time, per country (from Sprecher *et al.*, 2017)

Importantly, China is not just the main country sourcing and extracting REMs, but also the country with the highest processing capacity for turning these elements into the end products that are needed in clean energy technology (Smith Stegen, 2015). Diversification of the supply chain is likely to be critical in order to avoid bottlenecks in the near future and to mitigate the risks associated with a single supplier, including security implications for other countries.

The following section reviews the current status of REM supply and demand to meet the needs of growing markets. Options for meeting demand include the development of new mines, recycling, substitution at the component or technology level, and more efficient use of the metals within magnets. However, many of these options show limited potential, and questions remain as to how the gap can be met.

New extraction sources

China is not the only country with substantial deposits of REMs. China does, however, significantly dominate the production markets. The following table shows the US Geological Survey summary of the world's mine production and existing reserves in 2017 (Geological Survey (USGS), 2018). As at 2015, China was the only country with the capacity to process heavy REMs, which means many extracted REMs have to be imported to China in order to be processed and to enter the supply chain (Smith Stegen, 2015).

World mine production and reserves of REMs (USGS, 2018)

Country	Mine production (tonnes)		Reserves (million tonnes)
	2016	**2017**	
United States			1.4
Australia	15000	20000	2.4
Brazil	2200	2000	22
Canada			0.83
China	105000	105000	44
Greenland			1.5
India	1500	1500	6.9
Malawi			0.14
Malaysia	300	300	0.03
Russia	2800	3000	18
South Africa			0.86
Thailand	1600	1600	
Vietnam	220	100	22
World total (rounded)	**129000**	**130000**	**120**

Developing resources outside of China will reduce the risk in supply chains, but for independent supply chains to emerge this has to involve both the development of mines to extract REMs, and the development of the processing of the REMs. Mines like Mountain Pass in California or the Steenjampskraal mine in South Africa, which both closed in the early 2000s, are in the process of being explored for reopening. However, an attempt to do this in Mountain Pass went bust in 2015, and it is reported that this mine has now been bought by a Chinese-owned consortium (The Economist, 2018b). Reopening old mines or developing new ones is not projected to meet all the demand that will come from new technologies, and thus recycling and reduction of demand need to be considered (Smith Stegen, 2015).

Recycling

REMs can be recycled from primary ores, end-of-life products, landfill, and scrap. Approximately 75–100% of REMs has been recovered in lab experiments, but there are no large-scale industrial activities that aim to recycle REMs (Zhou *et al.*, 2016). Recycling REMs is a complex process, and separating them from host products often yields a small return on substantial effort (Smith Stegen, 2015).

Nonetheless, there are some initiatives that are trying to recover REMs from fluorescent lightbulbs, consumer electronics, household appliances, and hybrid cars. Currently, only about 1% of REMs are recycled, meaning there is space for growth. Public research and development investment in the recycling of REMs could strengthen technological capability and provide economic opportunities.

Efficiency and substitution: unlikely short-term demand management solutions to the global squeeze

Beyond recycling, there are four main options to reduce the demand for REMs, according to Pavel *et al*. (2018):

- reducing the quantity of REMs within products;
- substituting REMs with other materials;
- reducing demand for the magnets containing REMs; and
- reducing demand for the motors that use REMs.

There are few or no alternatives to neodymium magnets that use REMs, so these are unlikely to be substituted for alternative materials in the near future. Instead, most ongoing research in this area focuses on reducing the quantity of REMs within these magnets. Studies suggest that the quantity of dysprosium in magnets for EVs could be reduced from 7–9% currently to 5% by 2020, and down to 2.5% in subsequent years (Pavel *et al*., 2018).

There are also several alternative motor concepts being developed that use very small quantities of REMS or are completely REM-free. The development of these alternatives depend on market conditions, cost-effectiveness, and the specific requirements of the EVs being developed, so it may take some time for them to come to market. Nonetheless, given the number of prototypes available today, it is expected that REM-free motors could be produced within five years of reaching the conceptual stage (Pavel *et al.*, 2018).

While these technological developments may alleviate the demand for REMs, it is unlikely that REMs will be fully substituted in the near future. The precise rate of substitution remains unclear due to lack of incentives and the high uncertainty of future technological and economic development.

Conclusions: responding to likely imbalances in REM markets

Demand for REMs will continue to increase significantly, driven by the transition to a low-carbon economy. If we cannot find ways to use or replace REMs, diversify our sources, and ultimately reduce reliance, the lack of REMs will be a major constraint in achieving our global climate targets.

Lengthy lead times are required to open new extraction sources, so any new supply will take time to enter the global markets. Supply and demand imbalances will likely continue to persist over the coming decades.

Efforts should focus on developing new technologies to substitute or reduce the use of REMs in the magnets and motors that will power the green economy, and on creating policy and market environments for their uptake.

Governments can support this transition through providing incentives for technological advancements. For example, after the 2010 China embargo, the US Department of Energy established a competition to support research into increasing the efficiency of REM application in green technology products, providing $150 million in investments (Gholz, 2014). Efforts such as these can support long-term transformation in the market.

There is also ample space for the private sector to innovate and capitalise on opportunities that support the green economy transition. Private investment will be particularly important to increase production. REMs have until now been scarce in the global market because they have been uneconomic to mine in most places outside of China. As demand for EVs increases, the economically attractive opportunities to mine REMs in other countries will grow with it.

Meeting global emissions reduction targets will be near impossible if the supply of REMs is not diversified, increased, and utilised more efficiently. Investment in research and development by both the public and private sectors will be critical to overcoming the REM supply bottleneck, and strengthening our capacity to transition to a low-carbon economy.

References

Alonso, E., Sherman, A.M., Wallington, T.J., Everson, M.P., Field, F.R., Roth, R., and Kirchain, R.E. (2012) 'Evaluating rare earth element availability: a case with revolutionary demand from clean technologies', *Environ. Sci. Technol.* 46, 3406–3414.

Amsterdam Roundtable Foundation and McKinsey & Company (2014) 'EVolution: Electric vehicles in Europe – Gearing up for a new phase?', Amsterdam Round Tables and McKinsey & Company, www.mckinsey.com/~/media/McKinsey/Locations/Europe%20and%20Middle%20East/Netherlands/Our%20Insights/Electric%20vehicles%20in%20Europe%20Gearing%20up%20for%20a%20new%20phase/Electric%20vehicles%20in%20Europe%20Gearing%20up%20for%20a%20new%20phase.ashx

de Koning, A., Kleijn, R., Huppes, G., Sprecher, B., van Engelen, G., and Tukker, A. (2018) 'Metal supply constraints for a low-carbon economy?' *Resources, Conservation and Recycling*, 129(October 2017), 202–208. https://doi.org/10.1016/j.resconrec.2017.10.040

Deetman, S., Pauliuk, S., Van Vuuren, D. P., Van Der Voet, E., and Tukker, A. (2018) 'Scenarios for Demand Growth of Metals in Electricity Generation Technologies, Cars, and Electronic Appliances', *Environmental Science and Technology*, 52(8), 4950–4959. https://doi.org/10.1021/acs.est.7b05549

Gholz, E. 2014 'Rare Earth Elements and National Security'. Energy Report, Council on Foreign Relations. https://cfrd8-files.cfr.org/sites/default/files/pdf/2014/10/Energy%20Report_Gholz.pdf

Harmer, R. E., and Nex, P. A. M. (2016) 'Rare Earth Deposits of Africa', *Episodes*, 39(2), 381. https://doi.org/10.18814/epiiugs/2016/v39i2/95784

International Energy Agency (2017) 'Global EV Outlook 2017, Beyond one million electric cars'. https://webstore.iea.org/download/direct/291?fileName=GlobalEVOutlook2017.pdf

Lee, J. C. K., and Wen, Z. (2018) 'Pathways for greening the supply of rare earth elements in China', *Nature Sustainability*, 1(10), 598–605. https://doi.org/10.1038/s41893-018-0154-5

Pavel, C. C., Thiel, C., Degreif, S., Blagoeva, D., Buchert, M., Schüler, D., and Tzimas, E. (2017) 'Role of substitution in mitigating the supply pressure of rare earths in electric road transport applications', *Sustainable Materials and Technologies*, 12, 62–72. https://doi.org/10.1016/j.susmat.2017.01.003

Sprecher, B., Daigo, I., Spekkink, W., Vos, M., Kleijn, R., Murakami, S., and Kramer, G. J. (2017) 'Novel Indicators for the Quantification of Resilience in Critical Material Supply Chains, with a 2010 Rare Earth Crisis Case Study', *Environmental Science and Technology*, 51(7), 3860–3870. https://doi.org/10.1021/acs.est.6b05751

Smith Stegen, K. (2015) 'Heavy rare earths, permanent magnets, and renewable energies: An imminent crisis', *Energy Policy*, 79, 1–8. https://doi.org/10.1016/j.enpol.2014.12.015

The Economist (2018a) 'Clean could get dirty: A scramble for the minerals used in renewable energy is under way'. www.economist.com/special-report/2018/03/15/a-scramble-for-the-minerals-used-in-renewable-energy-is-under-way.

The Economist (2018b) 'Goblin Metals: What if China corners the cobalt market?' www.economist.com/finance-and-economics/2018/03/24/what-if-china-corners-the-cobalt-market

USGS (2018) 'U.S. Geological Survey, Mineral Commodity Summaries, January 2018. Rare Earths'.

Zhou, B., Li, Z., Zhao, Y., Zhang, C., and Wei, Y. (2016) 'Rare Earth Elements supply vs. clean energy technologies: new problems to be solve', *Gospodarka Surowcami Mineralnymi*, 32(4), 29–44. https://doi.org/10.1515/gospo-2016-0039

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Iliana is a consultant at Oxford Policy Management specialising in climate change policy, water resources management, and disaster risk management. She obtained a DPhil from the University of Oxford's Environmental Change Institute. She carried out her undergraduate degree at the School of Civil Engineering and the Environment at the University of Southampton, graduating from the MEnvSci (Hons) in Environmental Sciences. She carried out her Masters in Climate Science and Policy at Columbia University's Earth Institute in New York City, where she also worked as a Research Assistant for both the Columbia Climate Centre and the Centre for International Earth Science Information Network. Prior to starting her doctoral studies, Iliana worked in the Environmental Statistics Department at the United Nations Department of Economic and Social Affairs in New York City and at the Environment Directorate of the European Commission in Brussels, and was then appointed as a senior consultant for the United Nations Development Programme in Mexico City, where she worked directly with the Mexican Environment Ministry.

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