Examining the rare-earth elements (REE) supply–demand balance for future global wind power scenarios

Per Kalvig and Erika Machacek

Rare-earth elements (REE) are considered Critical Raw Materials (CRM; EC 2018; US Department of the Interior 2018) and essential in the technological transformation of the energy sector into carbon-free technologies such as wind turbines, electrified transport and LED-lights. The new technologies have led to swiftly expanding markets for REE products, in which China has achieved a monopolistic role in all segments of the REE value chains. Political strategies aimed to establish REE supplies outside China are currently being implemented within the EU and in other Western countries in order to ensure an adequate future REE supply. However, new REE value chains outside China have not yet materialised.

The aim of this paper is to assess whether the global REE supply from present and potential mines can keep pace with the REE demand for the expanding offshore wind energy sector (Fig. 1). A successful development of this sector outside China relies on an adequate supply of particularly neodymium (Nd) and to some extent praseodymium (Pr), terbium (Tb) and dysprosium (Dy), used in permanent magnets for windmill generators. In 2015, about 82% of the global Nd-oxide production was used in the permanent magnets

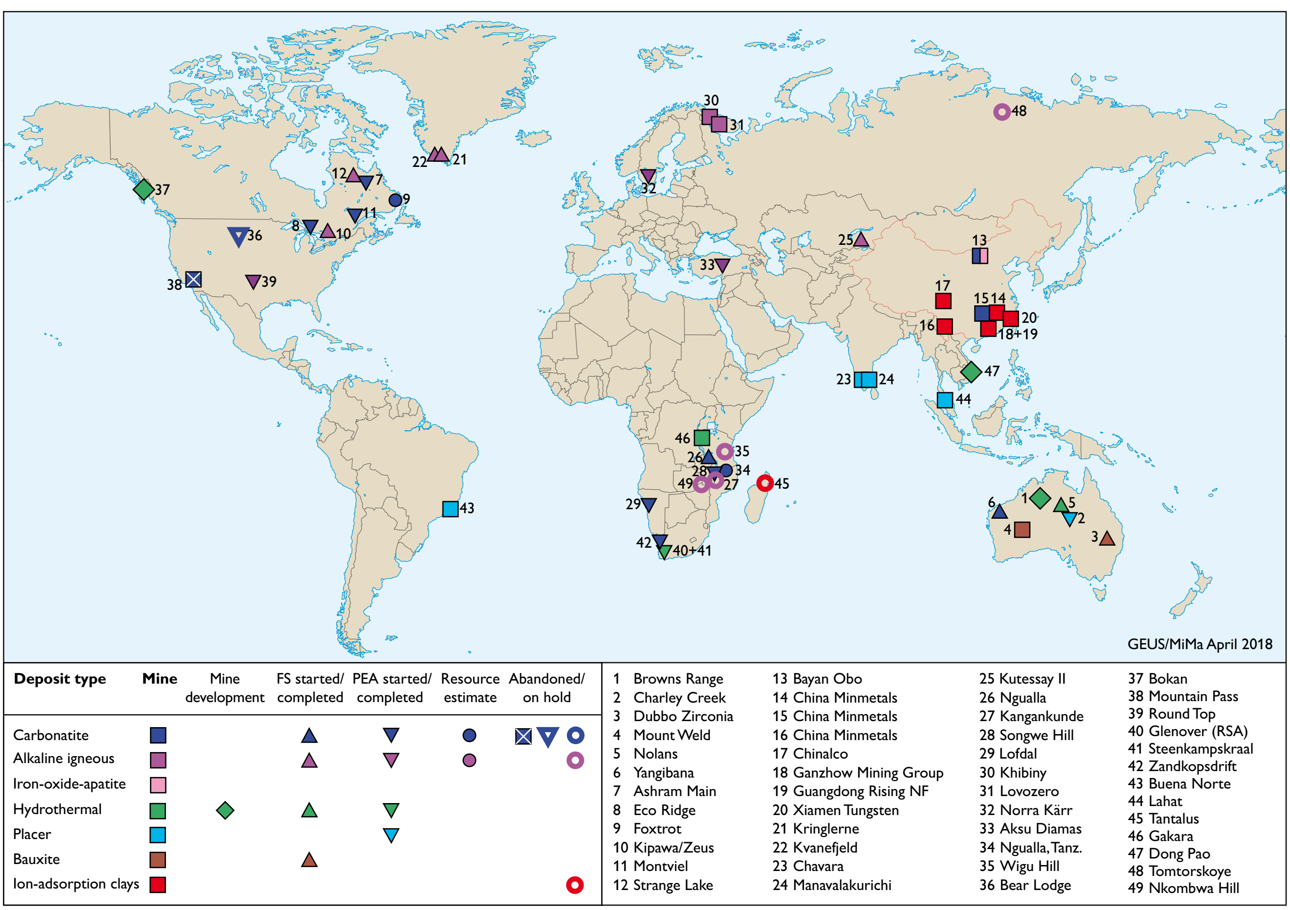
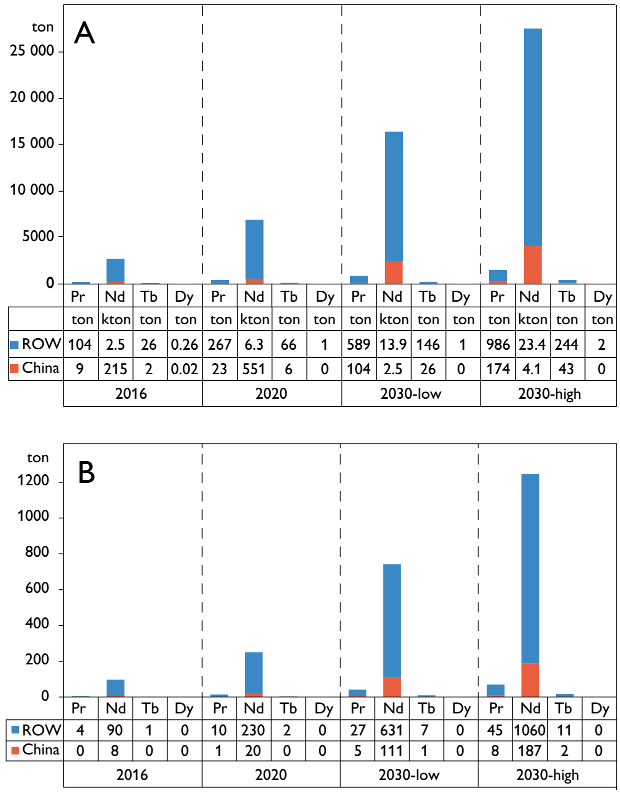


Fig. 1. Global rare-earth element mines and advanced exploration projects. **FS**: Feasibility study. **PEA**: Pre-economic assessment.



A

	2016				2020				2030-low				2030-high			
	Pr	Nd	Tb	Dy	Pr	Nd	Tb	Dy	Pr	Nd	Tb	Dy	Pr	Nd	Tb	Dy
	ton	kton	ton	ton	ton	kton	ton	ton	ton	kton	ton	ton	ton	kton	ton	ton
ROW	104	2.5	26	0.26	267	6.3	66	1	589	13.9	146	1	986	23.4	244	2
China	9	215	2	0.02	23	551	6	0	104	2.5	26	0	174	4.1	43	0

B

	2016				2020				2030-low				2030-high			
	Pr	Nd	Tb	Dy	Pr	Nd	Tb	Dy	Pr	Nd	Tb	Dy	Pr	Nd	Tb	Dy
ROW	4	90	1	0	10	230	2	0	27	631	7	0	45	1060	11	0
China	0	8	0	0	1	20	0	0	5	111	1	0	8	187	2	0

Fig. 2. Rare-earth metal demand by wind energy deployment in China and the ROW in 2016, and forecasts for 2020 and 2030. **A**: assuming that all offshore wind technology is centred on REE-based permanent magnets. **B**: assuming that only a small share of offshore wind technology uses REE-based permanent magnets, and differentiating between varying REE uses per PM generator technology. Note: Both figures show cumulated (forecasted) individual REE use by examined wind energy technology in the respective year. **ROW**: the rest of the world.

production (Adamas 2016). Here we evaluate the future supply and demand situations for Nd, Pr, Tb and Dy in the global wind energy sector in the form of three scenarios, one for 2020 and two for 2030 based on high and low demand. The balance is discussed. Our assessment reflects the challenge caused by limited insight into the REE supply chains inside China, and the figures presented in this paper are therefore only indicative.

Scenarios for future global REE demand of the wind energy sector

In 2016, the Global Wind Energy Council reported a total global wind power capacity of 487 GW (GWEC 2016), of which the offshore capacity amounted to 3% according to the Global Status Report 2017 for Renewables. Due to the

Table 1. Forecast scenarios for installed global offshore wind energy capacity in 2020 and 2030

Wind energy capacity scenarios	Global total	Global offshore	
	From GWEC (2016a)	assumptions, this survey	offshore capacity % REE permanent magnets installed capacity
Forecast 2020	739 GW	5% = 37 GW	5% = 1.85 GW
Forecast 2030 low	1260 GW	7% = 88 GW	10% = 8.80 GW
Forecast 2030 high	2110 GW	7% = 148 GW	10% = 14.80 GW

otherwise very high maintenance costs of the offshore wind energy, it depends in part on direct-drive and hybrid wind turbine technologies that use REE-based permanent magnet (PM) or high-temperature superconducting (HTS) generators (Barteková 2016). This is why the offshore wind energy sector is the focus of this study.

Our scenarios solely deal with technologies using permanent magnets in which Nd is vital. Barteková (2016) specifies the consumption of total rare-earth element oxides (TREO) for the individual types of magnets used in wind turbines and indicates the individual REE used. The REO content per magnet varies by generator design between *c.* 23–35%, highest in the permanent magnet of a direct-drive synchronous generator (PMSG-DD), and lowest in hybrid single and multistage synchronous generators (PMSG-SG and PMSG-MG). The relative magnet weight proportions of the four REOs are about 95% Nd, 4% Pr, 0.99% Tb and 0.01% Dy (Barteková 2016).

In order to estimate the future REO-demand of the sector, the following assumptions about the wind energy technology are made based on Barteková (2016, p. 158), who reported that in 2014 the REE-based permanent magnet technology accounted for 4% of the offshore wind technology, equally divided between direct-drive and hybrid generator designs. For our 2016 baseline scenario, we (i) increased this share to 5%, (ii) maintained the equal split between direct-drive and hybrid generator technologies, and (iii) subdivided the hybrid generator designs equally into single and multistage gearbox designs. Further, we assume that in 2016, China held 8% and the rest of the world (ROW) 92% of the global offshore wind capacity.

From the 2016 baseline scenario, we developed three scenarios: (1) the REO use in the total global offshore wind energy capacity in 2020, and (2, 3) low and high forecasts of the same in 2030. We set the regional offshore shares to 85% for ROW and 15% for China. See details in Table 1.

Our scenarios are based on the estimates by GWEC (2016) for 2020, 2030-low, and 2030-high global wind energy capacity. It is important to note the large variability in the underlying assumptions. The most significant parameter is the share of REE-based permanent magnets deployed in offshore installations. For instance, if all offshore technology capacity would employ REE-based permanent magnet technology and 75% of this was installed with the highest REE-using direct-drive design, this would result in the consumption 16 400–27 500 tons Nd-oxide in 2030 (Fig. 2A). In contrast, the wind-turbine sector will demand only about 740–1250 tons Nd-oxide (Fig. 2B) for the alternative technology split-up outlined in Table 1.

Scenarios for the future global REE supply

In 2016, the primary global production of total rare-earth oxides (TREO) amounted to 129 000 tons, of which China produced 83%, Australia 11%, Russia 2%, Brazil 1%, India 1% and Malaysia, Thailand, and Vietnam still less (USGS 2017). Although the TREO supply figures for 2016 reported by different sources are rather similar (USGS 2018: 23 680 tons; Adamas 2016: 24 377 tons), there are major discrepancies at national level. This partly stems from the assumed contributions of the non-reported market which may account for 25–30% (Roskill 2016) and from uncertainties pertaining to production and smelting quota (Adamas, personal communications 2018). This study applies the figures for for 2016 from USGS (2018), and contribution from non-reported production is not considered. The 2016 supplies of Pr, Nd, Dy and Tb from China and seven ROW countries are shown in Figs 3A, B. The official Chinese production quota for 2016 was set to 105 000 tons TREO (Machacek & Kalvig 2017); our estimate of the regional REO production is based on Kingsnorth (2016) and shown in Fig. 3A. Given that no scheduled production quotas for 2020 and 2030 are available, our China 2020 and 2030 supply scenarios are arbitrarily set to an increase of 5% p.a., reflecting the anticipated growth in demand (Dutta *et al.* 2016), the potential for higher capacity on existing plants, as well as continued efforts to transform the informal sector into to a formal one.

The ROW supply in the 2020 and 2030 scenarios is developed as follows: of the recorded 320 REE exploration projects outside China, 99 are reported to be active (S&P-database 2017). Our search revealed that 31 of these projects, located in 12 countries, have reached an advanced stage (Fig. 1). These 31 projects are divided into four classes of development, which are in turn translated into expected production start-ups in 2020, 2025, 2030 and 2035.

The estimates of relative REO grades and targeted production of Pr, Nd, Tb and Dy are based on TMR (2015) and company data. Where relative grade data are not available, our estimate is based on the actual REE mineralogy. According to these data, new REO productions in Australia, USA, and Vietnam are expected in 2020. In 2030, REO will also

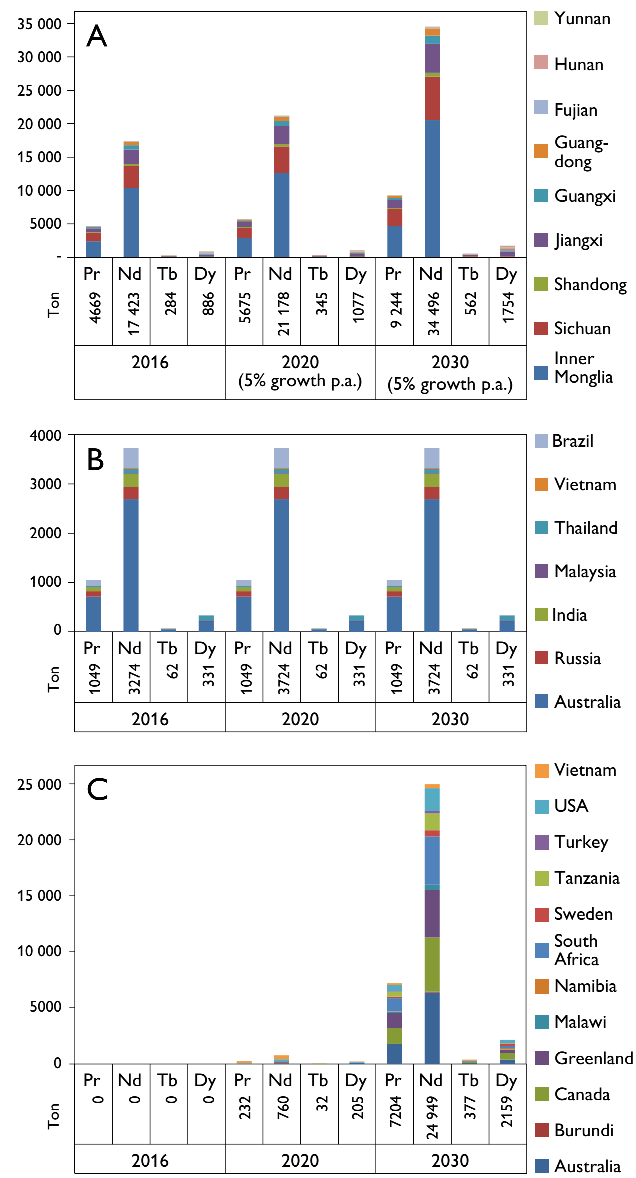


Fig. 3. Current and future REE production scenarios. **A**: Current and forecasted Chinese production of praseodymium, neodymium, terbium and dysprosium in seven regions. Forecast assumes a general 5% annual increase. **B**: Current and forecasted production of praseodymium, neodymium, terbium and dysprosium in ROW. Forecast assumes a static production. **C**: Forecasted production of praseodymium, neodymium, terbium and dysprosium from 31 advanced REE projects outside China.

be supplied by Canada, Greenland, Malawi, Namibia, South Africa, Sweden, Tanzania and Turkey (Figs 1, 3C). The scenarios indicate ROW-TREO productions of 6920 tons in 2020 and 154 075 tons in 2030 (Fig. 3C).

Discussion and summary

We demonstrate here that the level of detail applied to estimates of the future use of different types of generators and their relative shares allow for great variance in the current and forecast REE demand by the wind energy sector. Against this background, our ROW scenario for 2020 points to a Nd demand by the wind energy sector within a wide range of 230–6300 tons (Fig. 2), while our ROW supply forecast for Nd-oxide from both current and new mines is around 4500 tons. A top-down approach indicates that the REE-based permanent magnets for the wind sector absorb 10%, equivalent to about 4000 tons TREO (Lucas *et al.* 2015). Adamas (2016) estimates that Nd-oxide accounts for *c.* 73% of the TREO in the permanent magnets for the wind sector. In effect this means that in 2020, the total Nd-oxide supply for the wind energy sector would be roughly 3000 tons Nd-oxide, i.e. in the middle range of the forecasted global demand for this purpose.

For the 2030 low scenario and with REE technology applied in some but not all offshore technology, the global Nd-oxide demand by the wind sector is forecasted to *c.* 740 tons and for the 2030 high scenario close to 1250 tons. If it is assumed that all offshore technology will draw on REE use, these figures increase to 16 400 and 27 500 tons, respectively. Our global supply forecast of Nd-oxide in 2030 from current operations is about 35 000 tons from China and 3700 tons from ROW, to which advanced ROW REE projects could contribute an additional *c.* 25 000 tons if all projects go into production. If the 10% share of the REE-based permanent magnet sector as well as a stable demand for REE-based permanent magnets from the wind sector are maintained, about 450 tons Nd-oxide could be made available by ROW suppliers in 2020, and 2900 tons in 2030. However, in the scenarios based on generator technologies that consume a higher percentage of REE-based magnets, the estimated ROW supply is inadequate and an additional Nd-oxide supply will be required, e.g. from Chinese REE operators.

This study shows that there are currently significant uncertainties in trying to determine both the current REE demand and supply in the wind sector and in building scenarios for 2020 and 2030. Given that Nd-Dy permanent magnets represent a fast-growing sector, there is a need to establish a comprehensive, research-based and harmonised framework for precise estimates of the future supply and demand scenarios for REE-based permanent magnets.

References

Adamas 2016: Rare Earth Market Outlook: supply, demand, and pricing from 2016 through 2025 Report, 822 pp. Adamas Intelligence.

Barteková, E. 2016: The role of rare earth supply risk in low-carbon technology innovation. In: Borges De Lima, I. & Leal Filho, W. (eds): Rare earths industry: technological, economic, and environmental implications. Amsterdam: Elsevier, 437 pp.

Dutta, T., Kim, K-H, Uchimiya, M., Kwon, E.E., Jeon, B-H, Deep, A. & Yun, S-T. 2016: Global demand for rare earth resources and strategies for green mining. Environmental Research **150**, 182–190.

EC 2018: Report on Critical Raw Materials and the Circular Economy, 69 pp. Commission Staff Working Document. SWD(2018) 36 final.

GWEC 2016: Global Wind Energy Outlook 2016. Fried, L. *et al.* (eds), 44 pp. GWEC and Institute for Sustainable Futures, University of Technology Sydney.

Kingsnorth, D.J. 2016: Curtin University publication on the rare earth industry in 2016.

Lucas, J., Lucas, P., Le Mercier, T., Rollat, A. & Davenport, W. 2015: Rare-earth-based permanent magnets preparation and uses, 231–249. In: Rare Earths. Amsterdam: Elsevier.

Machacek, E. & Kalvig, P. (eds) 2017: Road map for REE material supply autonomy in Europe. EURARE, European REE market survey (component D1.2). 141 pp + appendix.

Roskill Informations Services Ltd. 2016: Rare Earths: Global industry, markets and outlook to 2026, 396 pp. Roskill Reports on Metals and Minerals, 16th revised edition.

S&P-database 2017: S&P Global Market Intelligence Metals & Mining Database 2017.

Technology Metals Research (TMR) 2015: Advanced Rare-Earth Projects: *http://www.techmetalsresearch.com/metrics-indices/tmr-advanced-rare-earth-projects-index/* (accessed 9 February, 2018).

US Department of the Interior 2018: Draft List of Critical Minerals. Feb 16, Notices. Federal Register **83**(33), 7065–7068.

USGS 2018: Mineral Commodity Summaries. US Geological Survey.

Authors' address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. E-mail: *pka@geus.dk*.