



Assessing advanced rare earth element-bearing deposits for industrial demand in the EU



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ABSTRACT

This article examines proposed REE-product volume supply from six advanced rare earth-bearing mineral exploration projects, two of which in Greenland, for REE demand by industrial users in the EU. A methodology is developed which draws on supply chains and published feasibility studies, emphasizing timely data certainty as significant factor of exploration project feasibility. For 2014, our findings for the Greenlandic project exploration proposals reveal that Kvanefjeld would significantly exceed EU demand except for Eu, on which it would undersupply. In contrast, Kringslunde would undersupply on La, Ce and Pr, oversupply on Nd and Y, and on all heavy REE with the exception of Eu. Various disparities between the proposed REE supply from Australian, Canadian and South African projects and EU demand in 2014 are also noted.

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1. Introduction

The rare earth elements (REEs) are a group of elements summarized as lanthanides plus scandium (Sc) and yttrium (Y) (IUPAC, 2005). The lanthanides are commonly subdivided into two groups, yet a universally accepted division and definition is absent¹: Light Rare Earth Elements (LREE) comprising lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), and gadolinium (Gd) metals, and Heavy Rare Earth Elements (HREE) including terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), and yttrium (Y) metals. This division can be used for the benefit of reporting exploration projects by reducing the elements in the LREE category, and raising the comparatively higher valued HREE.

In this article, we exclude Pm, Tm, and Lu, and Sc due to no or insufficiently documented indication of their use in the REE end-use sectors. With the exception of ¹⁴⁷Pm, Pm cannot be identified for its

very small concentration levels in the entire crust since it generally does not form stable isotopes (Wall, 2014; Chakhmouradian and Wall, 2012, p. 334).

REEs are used mostly in minor portions for key functions in components of downstream end-products that enable, among other: reading, sending and storing energy codified in data (which allows for communicating across distances, lighting spaces, travelling, producing and storing energy, producing images with magnet resonance). Some of these products are made by firms in Europe² which are hereafter jointly referred to as European high-tech industry.³ Since the 2011 REE price peak, this industry is alerted to securing and diversifying REE supplies, including through firms which explore for new REE-bearing deposits. This applies specifically if the respective firm is without reliable access to REE-bearing minerals in China, where most REE-bearing mining and processing occurs today.

Low REE recycling rates (Binnemans and Jones, 2014) and growing

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¹ Other sources (such as Wall, 2014; Chakhmouradian and Wall, 2012) allocate the REE slightly differently, whereby in the different allocations it is mostly the dividing line between the SEG group (Sm–Eu–Gd) that is being contested. Flow sheet designers and process engineers refer to the SEG group as a third, medium REE group, ‘on the basis of initial segmentation during the separation process’ (Hatch, 2012, p. 341).

² A list of firms which are known to use or can be assumed to use REE in their manufacturing, either directly in the processes or as a portion in intermediate product, are listed in Appendix C.

³ We define ‘European high-tech industry’ by building on the Eurostat (2015) definition for high-technology products: Industries which partake – directly or indirectly e.g. as component suppliers to – in the manufacturing of products for aerospace, computers office machines, electronics telecommunications, pharmacy, scientific instruments, electrical machinery, chemistry, non-electrical machinery and armament. The intermediate REE-using industrial sectors can also be defined as high-tech industry.

demand for REE-using high-tech appliances necessitate mining of primary materials which involves changes in the affected environment with effects on, among other, human health (Izatt et al., 2014). At present, public acceptance for mining is comparatively low in densely populated European countries illustrated by a recent considerations of gold mining at Rosia Montana, Romania (Euromines, 2012; Reuters, 2012), and strict environmental regulations raising mining costs. This applies particularly to REE, which commonly occur in minerals associated with radioactive elements such as thorium and uranium.

Greenland appeared on the radar for REE-bearing mineral resources and reserves which are high in HREE as compared to the carbonatite⁴ deposits such as Bayan Obo and Mountain Pass, which are or have been mined for LREE (Chakhmouradian and Zaitsev, 2012; Verplanck and Van Gosen, 2011). A total of 13 REE-deposits⁵ are currently being explored in Greenland, of which two have reached, by means of a feasibility study, an advanced stage of exploration. These two projects are explored by two Australian registered firms and belong to the Ilímaussaq intrusive complex in South Greenland: Kuannersuit, or Kvanefjeld, and Killavaat Alannuat, or Kringlerne (by Greenlandic and Danish names, respectively). Public discourses on REE supply security and mining in the Arctic, have focused on these projects.

Also scholarly discourse has turned to supply strategies in the REE industry (Massari and Ruberti, 2013; Golev et al., 2014; Machacek and Fold, 2014), most recently with a focus on resilience in material supply chains (Sprecher et al., 2014; Mancheri, 2015) and security implications of rare earths (Kiggins, 2015). References to the rising number of exploration firms (Hatch, 2012; Van Gosen et al., 2014) and to the nature of these firms (Majuri, 2014), which propose to secure REE raw materials supplies (Sprecher et al., 2014) were made.

Guyonnet et al. (2015) provided a detailed material flow analysis with precise accounts of the methodology applied for deriving estimates and assumptions for REE flows. Their comparison of Kvanefjeld and Kringlerne with the Norra Kärr project in Sweden has them suggest Norra Kärr as the most likely European project to enter into REE production. The respective project advancement, measured by the state of data certainty reached by elaboration of a feasibility study, reaches beyond the immediate objective of their article.

However, the state of project advancement presents significant evidence for the progress of a project as it indirectly points to a timeframe for when a project could come into production and for an understanding of which projects are – due to having reached the same reporting status on their project – under competition of providing REE supplies in the timeframe. Further, chemical separation capacity defines whether REE products for industrial use from mined REE minerals can be produced, as highlighted in Guyonnet et al. (2015), jointly with suggestions that REE mining in Europe would stimulate capacity enlargement at the European chemical separation plants of Solvay and Silmet.

We would like to carry the discussion on estimating project feasibility and chemical separation capacity further by emphasizing that none of these occur within a vacuum of a European market, but more so within supply chains that operate across national and regional boundaries. With this background, we discuss how the proposed, advanced production plans for REE deposits in South

Greenland and in the rest of the world would meet REE volume demand of EU industries, in the context of global supply-demand dynamics and the Chinese REE market supremacy, given the absence of mining to complete a REE-supply chain within Europe. This is an issue that requires rigorous reflection and discussion since the securing of jobs and production in Europe is tied to access to primary raw materials and the down-stream products, including of REE (Dansk Industry, 2013; European Commission [EC], 2014).

We recognize that regulatory aspects, including obtaining a social licence to mine and process REE-bearing minerals, through stakeholder dialogue, carefully conducted environmental and social impact assessments need to be met alongside access to a technologically advanced and economically operable processing and chemical separation facility. All of these factors will influence decision-making as to whether an exploitation licence is to be granted to mine REE-containing minerals. These factors set aside; this paper contributes to the existing literature on the REE industry by unveiling questions as to the conceptualization of supply issues from a quantitative mineral volume perspective, at the early stage of applications for exploitation licences when mining plans are issued.

2. Methodology

We estimate REE production volumes in t REO from production plans of advanced REE exploration projects to compare these with estimates of REE demand in t REO of different REE-using industrial sectors in the EU. Comparisons with other, similarly advanced projects in other parts of the world are drawn. We apply the term 'supply chain' as opposed to 'value chain', since we limit our analysis to the account of material flows and exclude distributional effects such as from governance, which explores, in a snapshot, the influence of power exerted in transactions of materials, information and services, and affects material flows.

Our use of 'advanced REE exploration project' refers to the project status of a published feasibility study (FS).⁶ Two projects in Greenland and four projects in Australia, Canada and South Africa fulfil these requirements in September 2015, as depicted in Table 3. Kvanefjeld and Kringlerne in South Greenland are illustrated in Fig. 1. These deposits could be argued to have historical-jurisdictional ties to the EU through the Kingdom of Denmark of which Greenland is part, and its Overseas Countries and Territories status (OC) with the EU.⁷

2.1. Volume focus of potential REE supply from mining

The supply-demand comparison is conducted from a material (volume of individual REE) perspective, defined by the geology and the ore body, as established in the FS. We also acknowledge that production plans might involve REE-mining as co- and by-product and that mineral supply and demand is dynamic with numerous parameters influencing both supply and demand. However, this study disregards aspects associated with profitability. Our emphasis is on potential new mining projects and their proposed mineral volume capacity.

Exploration projects usually work with REE price forecasts

⁴ Carbonatites are defined as igneous rocks that contain more than 50% primary carbonate minerals (Chakhmouradian and Zaitsev, 2012).

⁵ Besides Kvanefjeld and Kringlerne, the further currently explored REE-deposits in Greenland are Motzfeldt Sø (associated with the Igaliko Complex), in Westgreenland there are Safartog, Qaqarsuk, Tikiusaaq, Nuaqornakavsak, as well as Bjørnedal and Milne Land in East Greenland (Thrane, Kalvig and Keulen, 2013). Further REE occurrences are located at Ivittut and Grønnedal-Ika, Nuaq/Karrat and Kap Simpson (GEUS, 2013). Charles et al. (2013) have provided an overview of the geological potential of REE in Europe and Greenland, however, with limits to their geological data.

⁶ This is in contrast to the use of 'advanced rare-earth projects' by Technology Metals Research (TMR), wherein projects are formally defined as a mineral resource or reserve, under the guidelines of a relevant scheme such as NI 43-101, the JORC Code or the SAMREC Code. This includes projects such as those owned by private companies that are not required to produce estimates under these guidelines, but which have reported adherence to the technical report format prescribed by one of these schemes (TMR, 2015).

⁷ 'Greenland enjoys a special relationship with the EU through its Overseas Countries and Territories status (OCT). The purpose of the Association of the OCTs with the EC is to promote social and economic development of the OCTs and establish close and economic relations with the EC.' (EC, 2012)

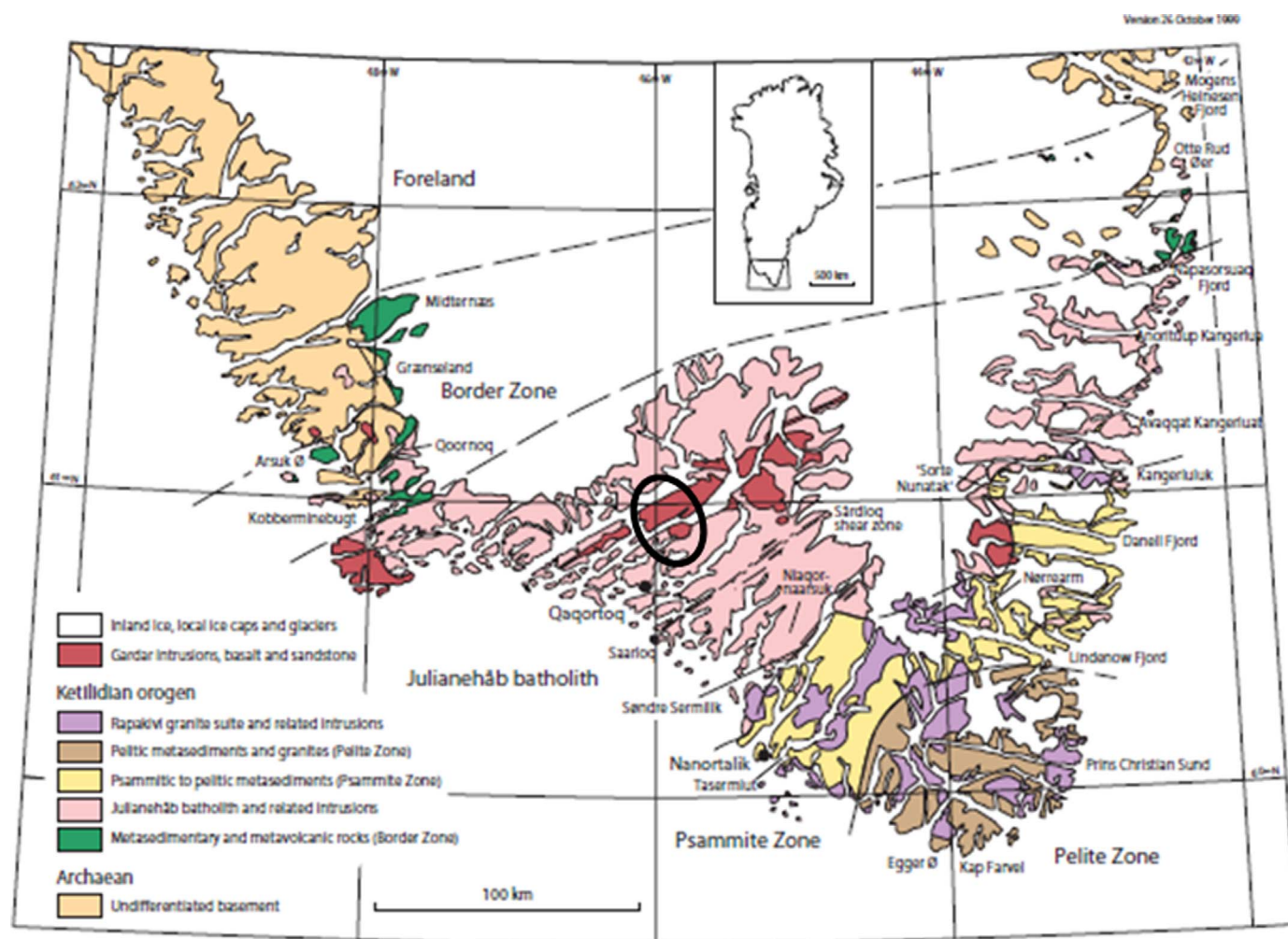


Fig. 1. Geological map of South Greenland with the two REE deposits of the Ilmaussaq intrusion circled.
Source: Garde (2007), simplified from Garde et al. (2002).

derived from historical price developments. Political discourses which we acknowledge as significant determinants in assessing whether REE-projects will be mined, since they influence REE prices and investor interest in financing mining, among other, also remain beyond the scope of this paper.

This mentioned, to obtain REE products (e.g. individual REE, such as Nd_2O_3) that can be used by intermediate industries, defined later on in this section, the mined REO⁸ need to be transformed to reach the chemical form and purity required. This includes gravitational and physical concentration, to produce a REO mineral concentrate from which impurities and hazardous (radioactive) elements are removed. Then, the solution undergoes chemical separation to achieve individual rare earth elements (REE). Golev et al. (2014) and Machacek and Fold (2014) provide a more detailed, however still simplified,

Table 1

Traceable REE-products in Eurostat.

Source: Eurostat, 2015a; average conversion factor from REO to REE with multiplication by 0.85 adapted from Guyonnet et al. (2015).

HS code	Eurostat (2015a) nomenclature	Av. conversion factor
28053010	Intermixtures or interalloys of rare-earth metals, Scandium and Yttrium	REE to REO 1.15
28053090	Rare-earth metals, Scandium and Yttrium (excl. Intermixtures and interalloys)	
28461000	Cerium compounds	
28469000	Compounds, inorganic or organic, of rare-earth metals, of Yttrium or of Scandium or of mixtures of these metals (excl. Cerium)	

⁸ Throughout this paper, we refer to rare earth oxides (REO) when the elements are contained in a mineral 'in-situ', in a deposit, through to when they have been mined and until, and inclusively, when they are physically beneficiated (through crushing, grinding, gravitational separation and flotation) into a mixed REO concentrate. Following the segment of chemical separation of this mixed REO concentrate into single (or individual) rare earth compounds (e.g. oxides, chlorides or nitrates) and into metals and alloys, they are addressed as rare earth elements (REE) or REE compounds. In some literature the single rare earth compounds in the state of oxides are also referred to as REO, however, to be clear as to which segment of the supply chain is addressed, in this article, REO will solely be used in reference to the upstream segments of processing up until chemical separation. The terms 'REE-deposit', 'REE-mineral', '(advanced) REE (exploration) project' achieve validity through the anticipation of REE products from REO processing for the 'REE-using industry'.

outline of these processes, while Gupta and Krishnamurthy (2005) elaborate in depth on REE processing.

We argue that our volume-based focus is a valid methodological choice in as far as geological conditions, e.g. the REE contained in the mineral of a particular rock type remain constant, and therefore constitute a suitable parameter for our analysis. Further, this focus appears to be a valid entry point for informing the discourse that portrays potential REE-mineral mining in Greenland as a source of supply for industrial use in the EU (EC, 2015).

2.2. Secondary REE supply from recycling of end-use products and processing tailings

Within the limits imposed by acceptable article length, our aim at adding to the discourse on REE-supply for European industries is limited to informing on potential REE product supplies from primary mining of REE-minerals from projects which have reached FS-stage. Certainly, any discussion of raw material markets and dynamics, including of REEs, particularly contextualized in securing supplies and enabling a circular economy would need to centre on both primary and secondary REE supply.

In this light, it needs highlighting that REE recycling has potential, both for its possibility to reduce the balancing problem (Binnemans et al., 2013b; Falconnet, 1985) amidst the manifold uncertainties associated with primary and secondary supply (Machacek et al., 2015), as demonstrated on various REE-product based studies (Bandara, et al., 2014; Binnemans et al., 2013a; Rademaker, Kleijn and Yang, 2013; Sprecher, Kleijn and Kramer, 2014), or e.g. of tailings from aluminium production, and more generally (Schüler et al., 2011) including from, what we summarize here broadly as ‘assessing the stocks of REE in our societies’ (Du and Graedel, 2011; Habib, et al., 2014; Mueller et al., 2015).

A discussion of balancing the proposed primary REE supply plans of junior mining firms with potential secondary supply, however, is beyond the focus of this article, but can be e.g. accessed in Machacek et al. (2015). Also beyond the focus of this article are discourses such as on the feedback control cycle (Wellmer and Dalheimer, 2012) and of methods applicable to assess resource lifetimes (Vaccari and Strigul, 2011).

Here we focus on beneficiation, the segments of the REE industry prior to chemical separation, hereafter referred to as ‘production’, even if the resulting mixed REE solution is not saleable to most REE-using industries. To contextualize these production volumes, we illustrate them in view of potential REE-mining and beneficiation by junior exploration firms in other parts of the world. This enables a discussion of potentially produced REE from Greenlandic and from other deposits and how these volumes match EU demand.

2.3. European share of global rare earth demand

In this paper we use REOs as a proxy for REE demand by different industrial sectors. To estimate demand of REOs by the European industry, we take a top-down and a bottom-up approach: We estimate the demand of REO per product to reach an estimate for each industrial sector which is then aggregated to represent European industry demand and requires contextualizing within global REE demand. Secondary sources which applied a

bottom-up or top-down approach derived a European share of global REE-use of 4 or 10%, respectively (Adamas Intelligence, 2014; European Rare Earths Competency Network [ERECON]⁹, 2014). We use this range as reference.

2.4. Identification of rare earth use

We classify REE uses¹⁰ according to intermediate industrial sectors, to align planned REE production with REE demand in the EU. Classifications are found to vary between six or nine categories, with differences arising from whether the category ‘metal alloys’ or ‘metallurgy’ comprises ‘batteries’, whether ‘catalysts’ are divided into ‘chemical catalysts’ and ‘automotive catalysts’, and whether ‘polishing’ and ‘ceramics’ and ‘glass’ are presented jointly. We opted for the most detailed categorization, depicted in Table 2, assuming that some sub-sectors, e.g. auto catalysts as compared to fuel cracking catalysts, are of comparatively higher significance to industries in the EU than e.g. to the U.S.

2.5. European rare earth demand

A Eurostat (2015a) query on EU-28 imports of REE products, as listed in Table 1, by volume (100 kgs) for January to December 2014 from USGS (2015)-denoted rare earth producing countries, Australia, Brazil, China, India, Malaysia, Russia, Thailand, U.S. and Vietnam provided data on European demand, accessible in Appendix A.1. Market dynamics are demonstrated in the annual demand growth of imports which averaged 3.2% from 2009 to 2014, also accessible in Appendix A.1.

Eurostat (2015a) provides several classifications for running a query on REE imports.¹¹ Under the Harmonized Commodity Description and Coding System, or Harmonized System (HS) of tariff nomenclature, data on REE trade is presented in the product group 284600, ‘Alkali or alkaline-earth metals; rare earth metals, scandium and yttrium, whether or not intermixed or inter-alloyed; mercury’ which summarizes the 15 elements and scandium and yttrium.¹² Appendix A.2 provides the results of this query and observational notes. However, throughout this article, we use the four HS codes as per CN8, as previously applied by Rech (2015), Guyonnet et al. (2015), EC (2014, p. 151) and Schüler et al. (2011):

Publicly accessible Eurostat data on REE imports is restricted in detail as it provides solely aggregates of REE imports, revealed by the names of the product categories. Further, the HS-nomenclature for rare earth products enables numerous interpretations as to the nature of the product. Two professionals working with rare earths responded to our request for clarification on whether the codes in Table 1 are rare earth elements (REE) or rare earth oxides (REO). Their educational/professional background seemingly influenced the interpretation of the nomenclature; however, both suggested that these HS codes represent REE according to their definitions.

Table 2

Total sectoral use of REE in the EU.

Source: Sectoral share allocations (in % as of 2010) are adopted from ERECON (2014), with an increase of the sectoral share of the category ‘Others’ to 7% to reach 100%. These EU sectoral share estimates align closely to those published in Guyonnet et al. (2015).

REE-using sector	EU sectoral share
Auto catalysts	27%
Glass additives	19%
Fluid cracking (FC) catalysts	16%
Others	7%
Batteries	6%
Ceramics	6%
Metallurgy	6%
Phosphors	6%
Magnets	4%
Polishing	3%
Total	100%

⁹ ERECON gathers 80 experts on REE to assess, evaluate and provide specifications on REE market dynamics.

¹⁰ REE uses can also be classified according to physical properties such as optical properties for colouring glass or ceramic, magnetic properties for miniaturizing electronic devices, joint optical and magnetic properties for recording densities such as erasable-rewriter laser systems, hydrogen storage properties for nickel-metal-hydride batteries and electrical and nuclear properties such as for superconductors or in nuclear energy control rods (Kirk-Othmer, 2005).

¹¹ The extent of classifications includes CN8, HS2-HS4, SITC, BEC since 1988 and HS6 since 1995; extra EU trade since 1999 by mode of transport with NSTR, and since 2000 by mode of transport with HS6 and HS2-HS4, adjusted EU-extra imports by tariff regime by CN8, HS6, HS2-HS4; EFTA trade since 1995 by SITC; traditional international trade database access (ComExt) (Eurostat, 2015a).

¹² Another of the many Eurostat (2015) query option for REE-imports is EU trade listed by the Standard International Trade Classification (SITC) under product group 525.95, ‘Compounds, inorganic or organic, of rare earth metals, of yttrium or of scandium or of mixtures of these metals’ (UNSTATS, 2015).

Table 3

Relative individual REE use in products.

Source: adapted from IZT (2011), Anderson and Taylor (2011), Roskill (2011), and EURARE (2012). 'x' indicates EURARE (2012), discrepancies with IZT (2011), indicated REE use in appliances.

REE end-use sectors	Weighting per element in % of total (100%)													
	LREE ^a							HREE						
	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Yb	Y	Other
Auto catalysts	5	90	2	3										
Glass additives	24	66	1	3									2	4
FC catalysts	90	10												
Others	19	39	4	15	2		2						19	
Batteries	50	33	3,3	10	3									
Ceramics	17	12	6	12			x			x	x		53	
Metallurgy	26	52	5,5	17									x	
Phosphors	8,5	11	x	x		5		5			x		69	
Magnets			24	70	1		2	1	1					
Polishing	32	65	3,5											

Note: We chose these sources over those of mining firm estimates of REE market use such as of Lynas (2010). Also, we excluded Pm and Tm from the table. We adapted individual REE use for the magnet sector with reductions in Dy-use (Cohen, 2014) and our assumptions as to effects on other REE (Dy use from 5% to 1%, increase in Tb from 0% to 1%, increase in Pr from 23% to 24% and increase by 1% of Nd), as well as added a 1%-share for Sm.

^a As described in the introduction, a universally accepted grouping of individual REE is currently inexistent.

The anonymized responses, and a third clarification which was provided during the review process, are provided in Appendix B.

We apply these four CN-8 codes also as REE compounds arguing that the nomenclature suggests the products in all four codes have undergone at least chemical separation. Therefore these products would have been purified from their original, impure state as REO (minerals) to intermediate REE compounds. We apply the average conversion factor derived from Guyonnet et al. (2015) for the Eurostat (2015a) data to enable a comparison of REO supply from potential new mines with REE demand as input into industrial processes and production of intermediate products in the EU.

2.6. Sectoral use of rare earth oxides

Table 3 depicts REE using intermediate-market sectors with an approximate per cent weighting of each REE use in the respective sector. The petrochemical industry, which is reflected by the sectors fuel cracking (FC) catalysts and auto catalysts, uses a high proportion of light rare earth elements (LREE), in particular lanthanum (La) for FC catalysts, and cerium (Ce) for automotive catalysts. Cerium oxide plays a pivotal role in polishing and as glass additive. Nickel-metal-hydride (NiMH) and lithium-ion (Li-ion) batteries require LREE, especially La and Ce (ZT, 2011, Anderson and Taylor, 2011, Roskill, 2011; EURARE, 2012).

On the case of Ce, we illustrate challenges in forecasting demand for each individual REE: The choice of battery technology in the automotive industry between REE-containing nickel-metal-hydride (NiMH) and lithium-ion (Li-ion) batteries, or (advanced) lead-based batteries will influence LREE demand. Forecasts suggest that (advanced) lead and REE-containing Li-ion batteries might be leading technologies in the automotive sector in the long term (EUROBAT, 2013).

A historical example of demand growth for the LREE Ce was the wide introduction of automotive catalysts for vehicle emission controls in the 1970s. In contrast, demand decreased for Ce as TV technology changed from cathode ray tubes (during 2007–2010) to liquid crystal display (LCD) and plasma display panel (PDP), which use comparably less Ce. Similarly, the market uptake of smart phones offset the Ce oxide demand decrease by the shift in the before described change in TV technology (IZT, 2011).

HREE are predominantly used by the magnet and phosphor sectors. Dy continues to be – with the exception of patented alternatives (e.g. for a Dy-free NdFeB magnet expected by Siemens in 2017 (Cohen,

2014)) – essential in manufacturing sintered neodymium–iron–boron (Nd–Fe–B) magnets, next to Gd and Tb. The extent of industrial choice of wind-turbine technology based on sintered Nd–Fe–B magnets will impact particularly Nd and Dy demand.

Eu and Tb are key to rare earth phosphor-based powders for fluorescent lamps and Eu in minor portions for LEDs or other potential future lighting technologies, such as screw-based remote-phosphor white LEDs as compared to typical white LEDs (Castilloux, 2014), next to yttrium. For instance, the rapid uptake of LED technology is expected to impact demand for HREE, as fluorescent lamp bulbs are phased-out sooner than anticipated (Cohen, 2014). Besides their use in these lamp types, yttrium is also essential in ceramics and other potential future applications (ZT, 2011, Anderson and Taylor, 2011, Roskill, 2011; EURARE, 2012). The chemical form and quality required of the REE influence the REE value. These parameters vary significantly in different REE sectors.

The relative weighted use of REE in percent of the total per REE end-use sector enabled – combined with European REE demand estimates from 2014, derived by allocating Eurostat (2015a) EU-28 REE imports to the sector use in percent provided by ERECON (2014) – an estimate on sectoral allocation of individual REE use in European industries. In addition, scoping interviews with informants of European REE-using high-tech firms have been conducive to understanding REE market dynamics. We estimate, drawing on Kingsnorth in Lifton (2015), that our error margin is in the range of 15%.

2.7. Potential REO supply from advanced projects

Estimates on the potential REO supply from exploration projects which have reached the state of FS, were derived in a three-step process. Exploration firms with rights to explore REE deposits in the world have been listed and sorted according to their stage of project development by means of publicly available reporting until September 2015, indicating the degree of reliability of the data produced on the geological deposit and thus, on the anticipated project. In most countries these reports are partial requirements in the application process for an exploitation lease, and for deposits in Greenland this is a mandatory requirement (Naalakkersuisut, 2015a).

Six REE projects have reached an advanced stage in their reporting of mineral occurrences, hereafter referred to as 'advanced REE projects', and listed in Table 4. Another four projects have reached pre-FSs, including Bear Lodge, USA, by current owner Rare Element Resources, Browns Range, Australia, by Northern Minerals

Table 4

Exploration firms with a feasibility study for a rare earth deposit.

Source: Project name, owner, ore, grade and TREO are derived from [TMR \(2015\)](#).

Project (Country)	Owner (Trade registration)	Ore MR (Mt) ^a	Grade TREO (wt%) ^a	TREO (Mt) ^b	Planned production TREO (tpa) ^c	Est. timing –production (year) ^d
Kuannersuit/Kvanefjeld (GRL)	Greenland Minerals and Energy Ltd. (ASX: GGG)	673	1.09	7340	23,000	2017
Killavaat Alannuat/Kringlerne ^e (GRL)	Rimbal Pty Ltd. (N/A - Privately owned)	4,300	0.65	28,058	9750	2016
Dubbo (Australia)	Alkane Resources (ASX: ALK)	73	0.89	0.651	4900	Q3 2017
Kipawa (Canada)	Matamec Explorations Inc. (TSX: V: MAT)	27	0.39	0.107	3700	Q4 2016
Nechalacho Basal (Canada)	Avalon Rare Metals Inc. (TSX: AVL)	126	1.43	1.799	10,000	2018
Steenkampskraal (South Africa)	Great Western Minerals Group Ltd. (TSX: GWG)	1	14.00	0.093	5000	(timeline) [*]

Note: Nechalacho Basal has been rounded up to 126 MR (Mt). Planned production volume of Kipawa has been rounded up to 3.700 TREO tpa.

^a Data based on reporting requirements of JORC, NI-43101 and SAMREC ([TMR, 2015](#)) or on provision by a private firm (such as of Tanbreez).^b Calculation is based on MR and TREO.^c Data from published firm reports.^d MT Højgaard's plant design allows for future treatment rates of up to 1.5 million tonnes per annum [Tanbreez \(2015\)](#), which has been confirmed by [Naalakkersuisut \(2015b\)](#).^e A delay in the permitting process for the project will lead to a delay in the mine facilities' construction (which takes on average 1.5 and 2 years), and thus, in the estimated timing of production.^{*} The indicated project timeline in the FS study refrains from a reference to a planned year of production start. Rather, it refers to a total construction period of 25 months and commercial production commencing in year 1 albeit at a lower production rate, all of which initiates upon receipt of the mining licence and depends on funding and economic feasibility.

Ltd., Ngualla, Tanzania, by Peak Resources Ltd., Nolans Bore in Australia by Arafura Resources Ltd. The Swedish REE deposit Norra Kärr is currently at the pre-FS stage, and consequently not included in this assessment of potential supply of REE from outside China ([Tasman Metals Ltd., 2015](#)).

[Table 4](#) shows that four of the projects are located in established mining countries however the degree of social acceptance and whether the firms are likely to obtain a social licence to mine remain uncertain. The data on planned production volumes was extracted from reports of the project owners. The deposits in Greenland are managed by the Australian registered junior exploration firms, Greenland Minerals and Energy Ltd (GMEL) and Tanbreez.

The mineralogy of each of the advanced REE projects is different and thus, the TREO varies from deposit to deposit with implications for the relative distribution of LREE and HREE, for the ease of chemical separation and REE production as by-product ([Rockstone Research, 2014](#)), as well as for the basket price,¹³ defined as USD/kg of REO contained in the deposits. We illustrate the differences in the relative distribution of LREE and HREE per project in [Fig. 4a, b](#). This relative distribution is of relevance for any REE project, including for the mines of Mt Weld (Lynas) and Mountain Pass (Molycorp), with both, while in operation,¹⁴ mostly producing LREE.

With relative in-situ TREO grades for the selected deposits collated by the Technology Metals Research ([TMR], May 2015) Advanced Rare-Earth Project Index, and indications on anticipated production as per project owner reports, we calculated volumes of rare earth oxides (t REO) to be produced per element. We assume that each of the REE-projects will materialize as proposed in their FS, that all of their production would be available to REE-using industrial sectors in the EU, and that each of these sectors would

need to meet its total REE demand from these projects.

2.8. Assessment of the methodological robustness and accuracy

On the demand side, we assume that imports of the four product group volumes represent the REE-volume demanded by industrial sectors in the EU. Such approach is robust and accurate since we are interested in quantitative inputs of REE to industrial processes rather than value-added within the EU by REE-use in industrial production.

Since dynamic market aspects are not within the ambit of this paper, our selection of 2014 import data on REE products into EU-28 member states as a baseline for our demand estimates is justifiable: This static, historical approach to prices which are assumed to stay unchanged in the future enables us to project similar demand patterns, ceteris paribus. Such methodology is in line with reports of the advanced REE projects.

We also use estimated EU sectoral shares for 2010 from [ERECON \(2014\)](#), see [Table 2](#). These sectoral shares might have fluctuated since 2010 in the aftermath of the price peaks of 2012 with effects for the LREE of Nd, Pr, Eu, and the HREE, Tb and Dy. While price dynamics are not the emphasis of this paper, it is worthwhile noting that the magnet and phosphor sector which mostly use these elements account for minor shares of EU sectoral use of REE.

We have not adjusted these shares as we can assume that substitutions with other elements are either impossible for functional losses, or would be commercially implemented over a longer timeframe, beyond 2014. In contrast, substitution or adaptation (through reduction) of LREE use e.g. as catalysts in processes such as FC, could be more rapidly implemented if processing costs are significantly raised by using LREE, and if their catalytic function could be provided cheaper by another element.¹⁵

The estimated timing for commercial production as indicated in [Table 4](#) is significant from the perspective of market saturation: With limited overall global market demand for REE, it is contested to which extent new mines with REE-bearing minerals that are

¹³ Lifton summarizes the criticism on the concept of basket price pointing to its fallacy of assuming '(...) that the mixed concentrate can be priced as if it is already separated and purified into individual rare earths in commercially (customer specified) forms and formats (blends) each and every one of which can be marketed into the infinite demand space in which the marketing plans were located' ([Investorintel, 2014](#)).

¹⁴ In August 2015, Molycorp announced that its Mountain Pass Rare Earth Facility was transitioned to a "care and maintenance" mode naming declining rare earth prices over the past four years as a reason. Yet, the firm planned to continue serving its customers with magnet materials and water treatment products from Estonia and China ([Molycorp, 2015](#)).

¹⁵ We remain, nonetheless, with the estimated shares provided by [ERECON \(2014\)](#), as adjusting the percentage to reflect sectoral market dynamics would require a sectoral survey which is beyond the scope of this article.

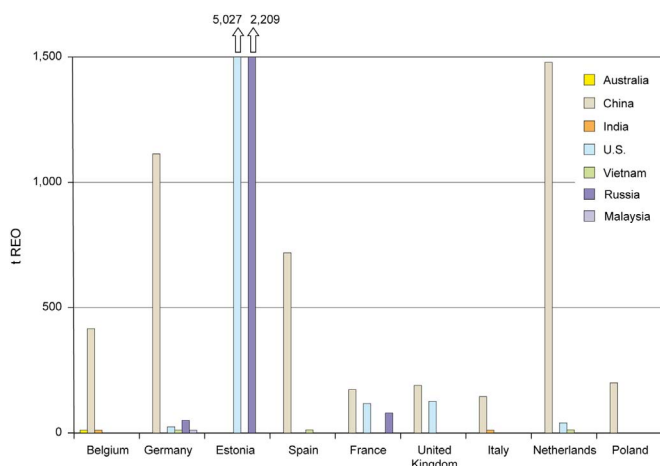


Fig. 2. Selected EU-28 countries importing REE products with totals in excess of 100 t REE from countries associated with REE production (as delineated by USGS, 2015). Eurostat data is most accurate for the EU, due to the 'Rotterdam effect' as described in Guyonnet et al. (2015), which explains that imports to the EU are accounted with the country at which the import occurred independent of whether they are re-exported to another country within the EU. This might be a partial explanation for the seemingly low volumes imported to France as compared to the high ranking of the Netherlands in this figure. Further, low imports to France might be due to the type of REE product visible in the Eurostat nomenclature which might not include some of the REE product types imported – such as from processing plants in China operated by the same REE-using firm. No REE were imported from Brazil or Thailand.

Source: adapted from Eurostat (2015a).

new for commercial exploitation will fill and/or substitute for mining in China. Timing of mining is essential as the first new mines will determine which other mines might still continue to pursue commercial mining in the future (e.g. based on their REO balance in the mineral deposit, demand of these specific REO-minerals and co-/by-products).

As always, estimated timing is dependent on numerous factors (most of which are beyond the scope of this paper) and therefore the project timelines to commercial production solely serve as guidelines without any influence in our calculations, since we refrain from a comparison of the effect of the commercialization of one project on another of the advanced projects.

In the following, we start by illustrating our assumptions as to the individual REE use per industrial sector. From there, we demonstrate how the commissioning of each of these proposed REE-mining projects would meet EU-28 industrial REE demand.

3. Results

The structure in this section follows the insights provided by the queried Eurostat (2015a) data on REE product imports into EU-28. First, we outline the EU countries which imported REE products from countries delineated as REE producers by USGS (2015) and second, we allocate the total Eurostat (2015a) volume of REE product imports in t REO according to industrial sector. Third, we illustrate the differential use of individual REE per industrial sector. Fourth, we combine demand and supply projections to illustrate how the REO production plans by the advanced REE projects respond to the EU-28 industrial demand of REE products for industrial production in 2014.

Eurostat (2015a) data suggests that more than 35% of the total EU-28 imports in 2014 of REE originated from China, close to 20% from Russia and more than 40% from the US. The EU imported 4594 t REE from China, of its total rare earth imports of 12,358 t (as

Table 5

Total sectoral use of REEs.

Source: Sectoral share allocations (in %) are adopted from ERECON (2014), with an increase of the sectoral share of the category 'Others' to 7% to reach a total of 100%. Differences in the totals arise from rounding.

REEs-using sector	EU sectoral share	t REE
Auto catalysts	27%	3337
Glass additives	19%	2348
FC catalysts	16%	1977
Others	7%	865
Batteries	6%	741
Ceramics	6%	741
Metallurgy	6%	741
Phosphors	6%	741
Magnets	4%	494
Polishing	3%	371
Total	100%	12,358

per Eurostat, 2015a). Fig. 2 depicts the EU-28 countries which reported each in total more than 100 t REE imports from rare earth producers in 2014 listed by USGS (2015). A total of 21 out of the EU-28 countries imported REE products, with Estonia, the Netherlands (assumably partially also due to the Rotterdam effect), Germany, Spain and Belgium, arranged in descendent order, among the top five, accounting for 90% of EU-28 imports.

We produced estimates on total REE volumes used by each European REE-using sector by allocating the Eurostat (2015a) total EU-28 imports of 12,358 t REE in 2014 among the individual sectors applying the percentage allocations of sectoral demand as proposed in ERECON (2014). Table 5 contains the results of this volume allocation.

The composition of REE use per industrial sector varies considerably in the EU, as illustrated in Fig. 3 on EU-28 REE imports of 2014. Total EU-28 demand of 12,358 t REO in 2014 represents a European share in the range of 4 to 10% of global use of REE (according to Adamas Intelligence, 2014 and ERECON, 2014 estimates). Three sectors account for largest REE demand in the EU – auto catalysts (27%), glass additives (19%) and fluid cracking catalysts (16%); each of these sectors are LREE dominated, whereby the ratio of Ce or La differs significantly among them, e.g. for auto catalysts and fluid cracking catalysts.

In contrast, TREE use for batteries, metallurgy, phosphors, and ceramics was equal to 645 t (each of 6%) REE or marginally greater for the sector 'others'. Magnets and polishing accounted for 4% and 3%, respectively, of 322 t and 430 t REO each, as illustrated in Fig. 4. At the global scale, REE use in magnets and phosphors adds the highest value to the REO. It might be surprising to see a low share of REE-use by magnets in Europe. This low share points to the geographical centre of magnet manufacturing in Asia, particularly China and Japan, with Europe as a minor (also demonstrated by Guyonnet et al., 2015), yet distinguished player due to quality high-precision, sintered and injection-bonded REE-magnet manufacturing.

The magnet and phosphor sectors use REE of highest value. This high valuation stems from a combination of factors: the use of large volumes of LREE (such as Nd), the cost involved in the chemical separation into individual REEs and in achieving high purity products, e.g. of HREE, and their essentiality for product performance, be it of protective or fluorescent properties, such as of Dy in sintered permanent magnets to maintain magnetic property stability over time at exposure to high temperature, or of Tb in REE-based phosphors to produce green spectra in fluorescent lamp bulbs. The high valuation of these REE is also due to their use in products that are in high demand (such as Nd in REE-based permanent magnets), and because they are, comparatively less common in host minerals.

Further, the HREE for phosphors need to be purified to up to 5 N, or 99.999% purity, which is essential to the achievement of

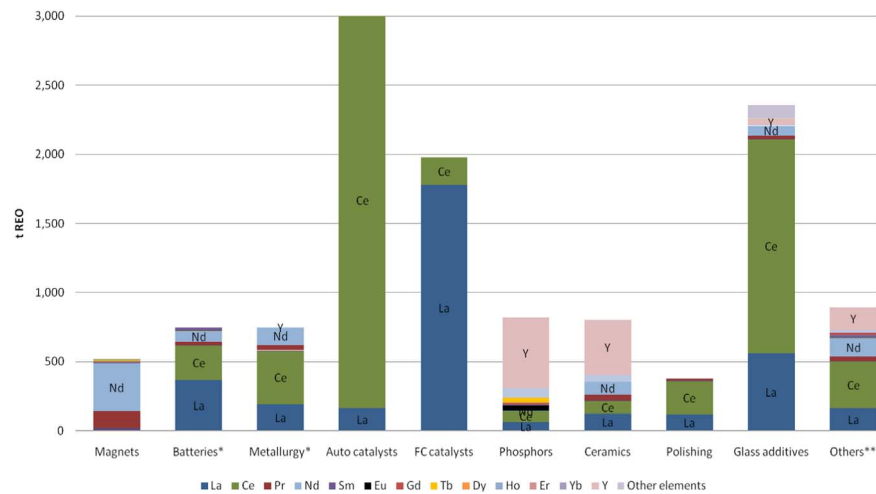


Fig. 3. Sectoral use of t REE in EU-28, 2014. Note: *Batteries and Metallurgy* appear jointly in ERECON (2014) as 'Metal Alloy' and have been divided in this figure according to equal shares as per Table 4. **We augmented the 'Others' sectoral share to 7%. Source: author.

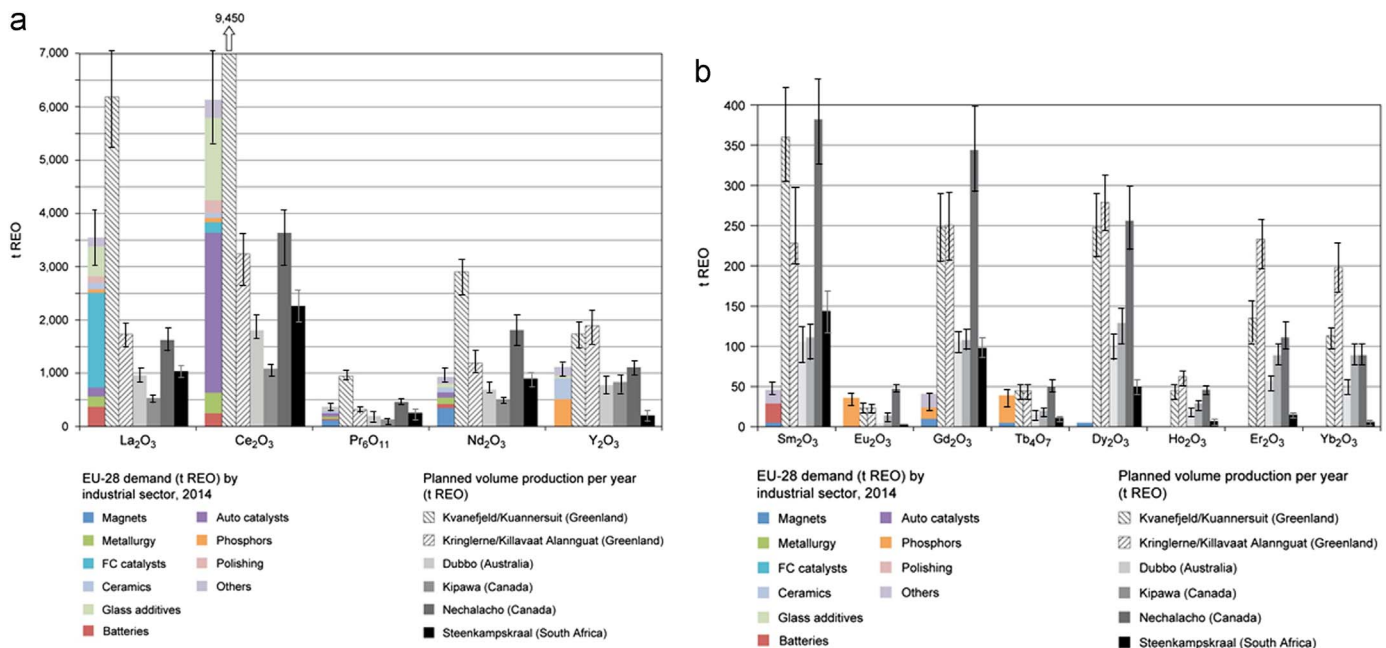


Fig. 4. (a) Estimated EU sectoral LREO volumes and Y used and plans of production by the selected projects.

Source: authors. Note: Data was derived from Eurostat (2015a) on EU-28 member states reported imports of REE in 2014 and allocated to REE-using sectors using the sectoral percentage shares provided in ERECON (2014). These selected projects are all planned to start between 2016 and 2019. The error bars indicate a bandwidth of $\pm 15\%$ for supply and demand respectively, and lean in their range on those usually applied by Kingsnorth, including in Lifton (2015). The error bars for proposed Ce_2O_3 from Kvanefeld are 8033 and 10,868 t REO. (b) Planned, selected LREO and HREO production and European sectoral demand in 2014. Note: We have used a classification which places Sm, Eu and Gd into the light group of REE, yet we illustrate them jointly with the HREE group, since the planned production and volume demand is significantly lower than of the other LREE shown in Fig. 4a. The error bars for supply and demand indicate a bandwidth of $\pm 15\%$, and lean in their range on those usually applied by Kingsnorth, including in Lifton (2015). Error bars up until 6 t REO have been excluded in the figure. Source: authors.

certain properties of light, and augments their value (Binnemans et al., 2013). In contrast, high prices of Nd, a LREE, reflect growing global demand for permanent magnets since the invention of Nd-Fe-B magnets in the mid-1980s. Table 3 shows Nd content of these magnets of about 60–70%. The industrial significance of these two sectors is reasoned from a high value perspective when marginal joint volume demand solely corresponds to about 10% of EU REE volume demand, or 1200 t REE.

Advanced REE-project plans were used for an indication on the production of individual REE illustrated in Fig. 4a and b. These volumes expressed in t REO are compared to estimated EU total

demand of REE (converted to REO) in 2014, as per Eurostat (2015a) CN-8 data on EU-28 imports of rare earth products in 2014 from REE producers stipulated by USGS (2015).

In the following, we compare the proposed individual REO production of the advanced projects with estimates of EU demand. This is certainly a hypothetical comparison as we cannot anticipate where mined REO minerals will be chemically separated and which firms will use these individual REE products, and thus, whether they will be available in the EU.

While the proposed production of the Kvanefeld project exceeds EU industrial demand for LREO in 2014 significantly, see Fig.

4a, the proposed Kringlerne project approaches EU demand of praseodymium oxide (Pr_6O_{11}), and exceeds demand for neodymium oxide (Nd_2O_3) and yttrium oxide (Y_2O_3), and undersupplies on lanthanum and cerium oxide (La_2O_3 , Ce_2O_3).

Of the other REE projects, Dubbo and Kipawa would undersupply on all of the EU LREE and Y demand, Nechalacho would undersupply on La_2O_3 and Ce_2O_3 , as would Steenkampskraal. On Pr_6O_{11} , and Nd_2O_3 , Nechalacho would oversupply, and it would come close to matching EU demand for Y_2O_3 . Steenkampskraal is anticipated to undersupply on Pr_6O_{11} and Y_2O_3 and comes close to match EU demand for Nd_2O_3 .

The projected production of HREO is illustrated in Fig. 4b. The proposed projects of Kvanefjeld and Kringlerne are expected to undersupply on europium oxide (Eu_2O_3) and oversupply on all other HREOs. It is also anticipated that all other projects will undersupply on Eu_2O_3 with the exception of Nechalacho, which is expected to oversupply on EU-demand on all HREOs. Dubbo, Kipawa and Steenkampskraal are projected to undersupply also on terbium oxide (Tb_4O_7) and oversupply on samarium oxide (Sm_2O_3), gadolinium oxide (Gd_2O_3) and dysprosium oxide (Dy_2O_3).

However, whether mined REE-containing minerals can in fact generate REE products according to industrial end-user specifications will depend on the access to knowledge and to a technologically advanced chemical separation facility which is operated economically. This unveils, among other, the question of available capacity:

Chemical separation capacities in Europe have been estimated to amount to between 3000 and 4000 Mtpa of LREE at Silmet in Estonia and between 5000 and 10,000 tpa of LREE and HREE by Solvay (ERECON, 2014). Whether and to which extent these estimated capacities would be available to any of the selected projects would need to be established and off-take agreements would need to be negotiated.

In May 2015, MarketWatch reported that China Non-Ferrous Metal Industry's Foreign Engineering and Construction Co. Ltd. (NFC) and GMEL are working under the terms of a 'Memorandum of Understanding'¹⁶ on cooperation for the separation of 'the critical rare earth concentrates from Kvanefjeld into high-purity individual rare earth oxides, and the subsequent product marketing to end-users globally'. These critical mixed rare earth concentrate comprises Nd, Pr, Eu, Tb, Dy and Y and an estimated volume of 7900 t REO (GMEL, 2015). If so negotiated, this concentrate could be chemically separated in China which could affect availability to industrial users around the world, including in the EU.

4. Discussion and considerations for policy

The restricted detail in REE product nomenclature of Eurostat has previously been uncovered by Massari and Ruberti (2013), and by Guyonnet et al. (2015, p. 3), and has been re-emphasized during our estimates of EU industrial demand. This lack of detail is astonishing given the politicized mineral criticality discourse for which the REE are flagship carriers. Arguably, heightened political concern about accessing REE supplies outside China would have incentivized a review of data collection on REE imports by different countries so that e.g. data on imports of each individual REE were accessible through Eurostat (2015a).

Also, estimates of sectoral European REE demand as published in ERECON (2014) would ideally reveal assumptions regarding percentages and t REO, describing also the sequence followed in deriving these. Transparency on data sources for the assumption would involve stipulating, if applicable, the number of interviewees and industrial sectors represented, and, the type of data provided, such as whether

absolute or relative indications were given.

In our comparison of advanced REE project proposals for individual REE product volumes with industrial demand for individual REE in the EU, we have depicted imbalances resulting from the mineral distribution in the earth's crust and industrial demand with implications for evaluating mineral deposit development:

- (1) None of the advanced project proposals will supply sufficient volumes of each individual REE to meet demand by different intermediate industrial sectors in the EU. This implies that sales on global market are needed to offset the imbalances.
- (2) Efforts to establish an integrated REE supply chain would need to be directed to particular intermediate industrial sectors, e.g. from mine to magnet,¹⁷ as mineralogy establishes specific deposits as more relevant to some industrial sectors than others.

It is noteworthy to emphasize that a balance between REE-bearing mineral composition and industrial demand could be approached through REE recycling from industrial process waste (tailings) and end-of-life products, particularly of those for which collection systems exist.

5. Conclusion

In this article we developed a methodology to assess production plans of advanced REE-bearing deposits for REE industrial demand, underpinned by several methodological choices:

- (1) a recognition of the *significance of time in reaching data certainty for a mineral exploration project* through the publication of a feasibility study, and
- (2) an *understanding of supply chain intricacies*, particularly of input and output from different industrial processes in the context of international trade in mineral products.

The novelty of these two explicit methodological choices lies, referring to point (1), in the significance attributed to data certainty attained on geological occurrences as compared to arguments driven by deposit location. Such approach enables an evaluation of mineral deposit potential in a global context, which we deem particularly important as supply chains are global and so needs to be the perspective taken on mineral deposit development.

In view of point (2), these intricacies associated with the supply chain are manifold: They challenge our data collection on mineral (material) flows from deposits through processing to intermediate and end-user industries, raising questions as to the detail needed in the REE product nomenclature applied in Eurostat, including for the possibility of tracing single elements as they enter intermediate industrial processes and exit these in components, and avoiding double-accounting of product flows (in imports/export statistics).

With these challenges revealed, we opted to focus on the interface of mineral beneficiation and REE sourcing by intermediate industries. This methodological choice stipulated statistics of REE products imported to the EU as the closest proxy to estimate input demand by intermediate industrial sectors. The emphasis on this supply chain interface and on imports provides for robust results, as it would be unfeasible to trace REE-content in components in export data with the current Eurostat REE product nomenclature. Similarly, a comparison of REE volume imports with exports would introduce more uncertainty.

¹⁷ Vertical integration has been pursued by some firms as a risk-managing strategy and marketed through a 'mine to magnet' narrative such as by GWMG (and of MolyCorp, 2015).

¹⁶ A memorandum of understanding commonly describes a non-binding agreement.

The comparison of proposed production from the Greenlandic deposits with estimated REE demand by intermediate industries in the EU provides evidence for divergences: The Kvanefeld project would significantly exceed REE demand of EU-28 countries in 2014 except for Eu, on which it would undersupply. In contrast, Krin-glerne would undersupply on La, Ce and Pr, oversupply on Nd and Y, and on all HREO with the exception of Eu. Similarly, divergences from the proposed production from the Australian, Canadian, and South African deposits with industrial REE-demand in the EU have been pinpointed.

We demonstrated that assessments of proposed REE-mineral mining projects need cross-evaluating with similarly advanced REE-bearing deposits in the world, since, from a volume perspective, deposit characteristics and a closely aligned plan of proposed supply with industrial demand of individual REE contribute to the feasibility of exploration projects.

Acknowledgement

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Appendix A.1

Eurostat (2015a) query on rare earth imports to EU-28 with 4 CN-8 codes

The data query can be replicated by following this input-tree accessible at

ec.europa.eu/eurostat/data/database

Data Navigation Tree > Database by themes > International trade > International trade detailed data (detail) > EU trade since 1988 by CN8 (DS-016890)

Our selected input values were:

Flow: Import

Indicators: Quantity in 100 kg

Partner: Australia, Brazil, China, India, Malaysia, Russia, Thailand, USA, Vietnam (as per USGS, 2015).

Period: Jan.–Dec., 2014

Product codes: presented in Table A1.

HS code	Eurostat (2015a) nomenclature
28053010	Intermixtures or interalloys of rare-earth metals, Scandium and Yttrium
28053090	Rare-earth metals, Scandium and Yttrium (excl. Intermixtures and interalloys)
28461000	Cerium compounds
28469000	Compounds, inorganic or organic, of rare-earth metals, of Yttrium or of Scandium or of mixtures of these metals (Excl. Cerium)

Reporter: individual countries (AT, BE, BG, CY, CZ, DE, DK, EE, ES, FI,

FR, GB, GR, HR, HU, IE, IT, LT, LU, LV, MT, NL, PL, PT, RO, SE, SI, SK) and EU-28.

The summarized data (cells of EU-28 countries which did not report any trade with the partner have been removed from the tables) from this query is available on the next page:

Last update 09.09.15

Extracted on 10.09.15

Note that the first two figures '28' for the group denominator has been removed in the product codes of Table A.1 on p. 31 for space limitations (Tables A2–A3).

Appendix A.2

Eurostat (2015b) query on rare earth imports to EU-28 and our observational notes.

The data query can be replicated by following this input-tree accessible at

ec.europa.eu/eurostat/data/database

Data Navigation Tree > Database by themes > International trade > International trade detailed data (detail) > EU trade since 1988 by HS2-HS4 (DS-016894).

Our selected input values were:

Flow: Import

Indicators: Quantity in 100 kg

Partner: Australia, Brazil, China, India, Malaysia, Russia, Thailand, USA, Vietnam (as per USGS, 2015).

Period: Jan.–Dec., 2014

Product: 28 – Inorganic chemicals; organic or inorganic compounds of precious metals or rare-earth metals, of radioactive elements or of isotopes > 2805 Alkali or alkaline-earth metals; rare-earth metals, Scandium and Yttrium, whether or not intermixed or inter-alloyed; mercury.

Reporter: individual countries (AT, BE, BG, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IT, LT, LU, LV, Malta, NL, PL, PT, RO, SE, SI, SK) and EU-28.

The summarized data (cells of EU-28 countries which did not report any trade with the partner have been removed from the table) from this query is available on the next page:

EU trade since 1988 by HS2-HS4 [DS-016894] (Table A4)

Last update	21.08.15
Extracted on	17.09.15

Observational notes on this HS2–HS4 query for January–December 2004 to 2014:

If this same query of HS2–HS4 code 2805 is run for a period of ten years (January to December between 2004 and 2014), the annual aggregates for EU-28¹⁸ of Eurostat (2015b) clearly reveal China as the major source of rare earth imports to Europe. Russia appears to be the only other continuous source to the European supply of rare earths and contributes with minor volumes. The U.S. also supplied small volumes to Europe, between 600 t and 5.300 t REO over the same period.

Other rare earth producers as listed by USGS (2015), namely Australia, Brazil, India, Malaysia, Russia, Thailand and Vietnam, seem to have supplied negligible volumes of rare earth products to Europe. For instance, Brazil supplied close to no rare earth volumes to Europe during 2012–2013 but the Netherlands imported minor volumes from the country in 2009, 2010 and 2014. From the statistics it appears that Belgium continuously

¹⁸ Please note that the data presentation in Eurostat takes into account that EU-27 had Croatia join in 2013 to form EU-28 and therefore data aggregates represent this change.

Table A1Adapted results from Eurostat (2015a) query on rare earth imports to EU-28¹.

Partner	Australia				China				India				United States			
Reporter / Code	053010	053090	461000	469000	053010	053090	461000	469000	053010	053090	461000	469000	053010	053090	461000	469000
BELGIUM 1	0	0	1	1	:	12	3.697	14	:	0	3	0	:	0	38	2
CZECH REPUBLIC 2	0	0	:	:	:	0	55	51	:	0	:	:	:	:	0	0
GERMANY 3	0	0	:	0	420	143	477	8.754	:	0	6	5	6	7	84	87
DENMARK	0	0	:	:	:	0	:	1	:	0	:	:	0	0	:	:
ESTONIA	0	0	:	:	:	:	:	:	:	0	:	:	:	:	2.350	41.361
SPAIN	0	0	:	:	2.698	50	2.166	1.429	:	0	5	:	0	0	0	73
EU28 4	0	0	1	1	5.985	1.349	13.442	19.174	1	0	14	5	82	87	3.608	42.877
FINLAND	0	0	:	:	:	:	4	:	:	0	:	:	:	:	0	0
FRANCE	0	0	:	:	400	3	:	1.140	:	0	:	0	10	2	:	997
UNITED KINGDOM	0	0	:	:	:	633	354	720	:	0	0	:	60	73	679	334
GREECE	0	0	:	:	:	:	14	:	:	0	:	:	:	:	6	:
HUNGARY	0	0	:	:	:	:	200	148	:	0	0	:	0	0	:	1
IRELAND	0	0	:	:	:	:	:	:	:	0	:	:	:	4	26	0
ITALY	0	0	:	:	73	3	785	460	1	0	:	:	:	0	74	0
LITHUANIA	0	0	:	:	:	2	:	:	:	0	:	:	:	:	0	:
LATVIA	0	0	:	:	:	:	:	:	:	0	:	:	:	:	1	0
NETHERLANDS	0	0	:	:	2.344	352	4.014	6.246	:	0	:	:	5	0	342	5
POLAND	0	0	:	:	:	0	1.667	138	:	0	0	:	0	:	2	2
PORTUGAL	0	0	:	:	:	:	:	11	:	0	:	:	:	:	0	:
ROMANIA	0	0	:	:	:	:	9	0	:	0	:	:	:	:	3	:
SWEDEN	0	0	:	:	50	:	:	62	:	0	:	:	1	1	3	15
SLOVENIA	0	0	:	:	:	151	:	:	:	0	:	:	:	0	0	0

Partner	Vietnam				Russia				Malaysia				Totals
Reporter / Code	053010	053090	461000	469000	053010	053090	461000	469000	053010	053090	461000	469000	
BELGIUM 1	:	:	:	:	:	:	:	0	:	:	:	:	3768
CZECH REPUBLIC 2	:	:	:	:	:	:	:	0	:	:	:	:	106
GERMANY 3	:	:	12	:	:	:	382	54	:	:	:	159	10.596
DENMARK	:	:	:	:	:	:	:	:	:	:	:	:	1
ESTONIA	:	:	:	:	:	:	:	19.206	:	:	:	:	62.917
SPAIN	:	:	:	10	:	:	:	19	:	:	:	:	6450
EU28 4	200	91	12	10	:	:	382	19.279	:	:	:	859	107.459
FINLAND	:	:	:	:	:	:	:	:	:	:	:	:	4
FRANCE	:	:	:	:	:	:	:	0	:	:	:	700	3.252
UNITED KINGDOM	:	91	:	:	:	:	0	0	:	:	:	:	2.944
GREECE	:	:	:	:	:	:	:	:	:	:	:	:	20
HUNGARY	:	:	:	:	:	:	:	:	:	:	:	:	349
IRELAND	:	:	:	:	:	:	:	:	:	:	:	:	30
ITALY	:	:	:	:	:	:	:	:	:	:	:	:	1.396
LITHUANIA	:	:	:	:	:	:	:	:	:	:	:	:	2
LATVIA	:	:	:	:	:	:	:	:	:	:	:	:	1
NETHERLANDS	200	:	:	:	:	:	:	:	:	:	:	:	13.508
POLAND	:	:	:	:	:	:	:	:	:	:	:	:	1.809
PORTUGAL	:	:	:	:	:	:	:	:	:	:	:	:	11
ROMANIA	:	:	:	:	:	:	:	:	:	:	:	:	12
SWEDEN	:	:	:	:	:	:	:	:	:	:	:	:	132
SLOVENIA	:	:	:	:	:	:	:	:	:	:	:	:	151

Color codes are used to facilitate the reported individual REE products imported from each individual partner (trading) country. Reporting countries are also color-coded according to the volumes imported, whereby yellow suggests higher volume imports of REE products and blue suggests marginal volume imports.

Clarifying notes on the data:

1 Belgium (and LUXBG => 1998)

2 Czech Republic (CS=>1992)

3 Germany (incl DD from 1991)

Brazil and Thailand have been excluded due to no indicated volume imports from these countries.

Table A2

EU-28 imports in 2014 from partners (Quantity in 100 kg)									
CN8	Australia	Brazil	China	India	Malaysia	Russia	Thailand	US	Vietnam
28053010	0	0	5,985	1	0	0	0	82	200
28053090	0	0	1,349	0	0	0	0	87	91
28461000	1	0	13,442	14	0	382	0	3,608	12
28469000	1	0	19,174	5	859	19,279	0	42,877	10
Totals in REE	2	0	39,950	20	859	19,661	0	46,654	313
Totals converted to REO (rounded)	2.3	0	45,943	23	988	22,610	0	53,652	360
Overall total	107,459 (corresponding to 10,745 t REE products, converted to 12,358 t REO)								
% of total	0.002	0.000	37	0.019	0.80	18	0	43	0.29

Advanced projects planned volume production (tpa REO)	La ₂ O ₃	Ce ₂ O ₃	Pr ₆ O ₁₁	Nd ₂ O ₃	Y ₂ O ₃
Dubbo	958	1,806	196	692	775
Kipawa	536	1,086	131	496	835
Kvanefjeld	6,188	9,450	945	2,903	1,733
Nechalacho	1,624	3,635	461	1,809	1,110
Steenkampsraal	1,038	2,264	256	899	207
Tanbreez	1,733	3,242	315	1,190	1,890

EU industrial sector demand (2014, in t REO)	La ₂ O ₃	Ce ₂ O ₃	Pr ₆ O ₁₁	Nd ₂ O ₃	Y ₂ O ₃
Magnets	-	-	119	346	0
Batteries	371	248	24	74	0
Metallurgy	193	386	41	122	0
Auto catalysts	167	3,003	67	100	0
FC catalysts	1,780	198	-	-	-
Phosphors	63	82	-	-	512
Ceramics	126	89	44	89	393
Polishing	119	241	13	-	0
Glass additives	564	1,550	23	70	47
Others	164	338	35	130	164

EU-28 imports (12,358 t REO)	3,547	6,135	366	931	1,116
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Table A3

EU trade since 1988 by CN8 [DS-016890]

Last update 24.01.2016

Extracted on 25.01.2016

Source of data Eurostat
Reporter EU28
Flow Import
Indicators Quantity in 100 kg

Partner	Product	Reporter / Period	Jan.-Dec. 2009	Jan.-Dec. 2010	Jan.-Dec. 2011	Jan.-Dec. 2012	Jan.-Dec. 2013	Jan.-Dec. 2014
China	28053010	EU28	5.020	8.665	2.726	3.606	6.073	5.985
	28053090		1.186	2.380	723	961	864	1.349
	28461000		60.343	57.738	27.747	35.996	9.695	13.254
	28469000		15.316	28.203	16.449	10.012	20.272	19.174
	Total imports		81.865	96.986	47.645	50.575	36.904	39.762
US	28053010		250	241	291	357	646	82
	28053090		43	52	29	56	59	87
	28461000		3.598	7.378	17.796	8.220	8.018	3.608
	28469000		5.198	7.315	28.536	12.190	34.580	42.877
	Total imports		9.089	14.986	46.652	20.823	43.303	46.654
Australia	28053010		0	0	0	0	0	0
	28053090		0	0	0	0	0	0
	28461000		0	160	0	1	162	1
	28469000		0	0	0	0	0	1
	Total imports		0	160	0	1	162	2

Table A3 (continued)

Brazil	28053010	0	0	0	0	0	0
	28053090	0	0	0	0	0	0
	28461000	0	209	0	0	0	0
	28469000	209	0	0	0	3	0
	Total imports	209	209	0	0	3	0
India	28053010	0	0	0	1	0	1
	28053090	540	770	720	0	0	0
	28461000	1.440	1	11	13	6	14
	28469000	0	2	33	165	131	5
	Total imports	1.980	773	764	179	137	20
Malaysia	28053010	0	0	0	0	0	0
	28053090	0	0	0	0	0	0
	28461000	0	0	14	5	0	0
	28469000	0	0	68	0	200	859
	Total imports	0	0	82	5	200	859
Russia	28053010	10	0	0	0	0	0
	28053090	0	0	10	0	0	0
	28461000	11	66	0	113	0	382
	28469000	1.947	414	15.993	42.506	16.446	19.279
	Total imports	1.968	480	16.003	42.619	16.446	19.661
Vietnam	28053010	0	198	28	160	60	200
	28053090	0	0	0	0	0	91
	28461000	0	0	20	120	0	12
	28469000	0	420	0	0	0	10
	Total imports	0	618	48	280	60	313
Thailand	28053010	0	0	0	0	0	0
	28053090	0	0	0	0	0	0
	28461000	0	0	0	3	0	0
	28469000	0	0	0	0	0	0
	Total imports	0	0	0	3	0	0
Total EU imports		95.111	114.212	111.194	114.485	97.215	107.271
			120	97	103	85	110
% change p.a.			20	-2	3	-15	10
av. % change over period				3,20			

imported minor volumes from India. Italy seems to be the only European country which imported rare earth volumes from Malaysia, and only in 2010. This Eurostat data also suggests that France and the Netherlands had what we consider to be 'trial' imports due to insignificant rare earth volumes and in non-consecutive mode, from Thailand. The Netherlands seem to source rare earths since 2011 in minor volumes from Vietnam while the UK reported a first import from the country in 2014.

Since the REE group does not distinguish among different REOs we cannot deduct from the available data which industries might use these REE imports (to define e.g. whether these industries are higher or lower value-adding industries to REE, e.g. producing magnets or phosphors or fluid cracking catalysts) and therefore assumed an allocation based on [BRECEN \(2014\)](#) estimates of sectoral shares of REE use. A feasible approach could include listing firms which operate in the sectors known to use REE to provide assumptions about which firms could potentially be REE-users (as provided in [Appendix C](#)).

Appendix B

Request for clarification on the interpretation of the Eurostat nomenclature

Request:

Dear (name of rare earth expert),

(Brief description of the project to which this enquiry is linked.)

Are you familiar with the below Eurostat Com Ext. HS CN8 nomenclature for the four rare earth product categories?

How would you categorize/allocate each of the four listed HS codes – as REE or REO?

HS code	Eurostat (2014) nomenclature
28053010	Intermixtures or interalloys of rare-earth metals, Scandium and Yttrium
28053090	Rare-earth metals, Scandium and Yttrium (excl. Intermixtures and interalloys)
28461000	Cerium compounds
28469000	Compounds, inorganic or organic, of rare-earth

Table A4

Partner	China (PRC)	U.S.	Brazil	India	Malaysia	Russia	Vietnam	Total
AUSTRIA	706	11	:	:	:	:	:	717
BELGIUM	6.431	837	:	24	3	132	:	7.427
BULGARIA	120	:	:	120	:	441	:	681
CZECH REPUBLIC	2.682	0	:	:	:	:	:	2.682
GERMANY	3.800	611	0	:	0	11.461	:	15.872
ESTONIA	930	0	:	:	:	519	:	1.449
SPAIN	9.200	0	:	:	:	:	:	9.200
FRANCE	15.601	632	:	:	:	1.498	:	17.731
UNITED KINGDOM	3.670	2.626	:	:	:	:	91	6.387
IRELAND	:	28	:	:	:	:	:	28
ITALY	2.001	49	:	1	:	:	:	2.051
LITHUANIA	2	:	:	:	:	:	:	2
NETHERLANDS	10.293	1.009	250	:	:	2.757	200	14.509
POLAND	1.385	0	:	:	:	:	:	1.385
SWEDEN	50	2	:	:	:	:	:	52
SLOVENIA	4.631	0	:	:	:	:	:	4.631
SLOVAKIA	1.120	8	:	:	:	:	:	1.128
EU28	62.622	5.813	250	145	3	16.808	291	85.932

Clarifying notes on the data provided:

1 Belgium (and LUXBG -> 1998)

2 Czech Republic (CS->1992)

3 Germany (incl DD from 1991)

4 EU-28 (AT, BE, BG, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IT, LT, LU, LV, MT, NL, PL, PT, RO, SE, SI, SK)

Australia and Thailand have been excluded due to no indicated volume imports from these countries.

EU-28 imports in 2014 from partners (Quantity in 100 kg)

HS2-HS4	Australia	Brazil	China	India	Malaysia	Russia	Thailand	US	Vietnam
Totals	0	250	62,913	145	3	16,808	0	5813	291
Overall total	86,223	corresponding to 8,622 t REE products (converted to 9,915 t REO)							
% share of imports	0	0,29	73	0,17	0,003	19	0	7	0,34

metals, of Yttrium or of Scandium or of mixtures of these metals (Excl. Cerium)

Thank you in advance for your reply.

Kind regards,

(Name of the paper's corresponding author and contact details)

Reply by Rare Earth Expert 1

From: (Rare Earth Expert 1) **Sent:** 13. august 2015 11:24 **To:** (Name of the paper's corresponding author) **Subject:** RE: Rare earths - Eurostat nomenclature

Dear (Name of the paper's author),

I am not familiar with the Eurostat Com Ext. HS CN8. However, most of the compounds listed in the 4 categories are not oxides, so I would not speak of REO (rare-earth oxides) but rather REE (rare-earth elements). For the first categories, one could also use the term REM (rare-earth metals).

Best regards,

(Rare Earth Expert 1)

From: (Name of the paper's corresponding author) **Sent:** 13 August 2015 11:33 **To:** (Rare Earth Expert 1) **Subject:** SV: Rare earths - Eurostat nomenclature

Dear (Rare Earth Expert 1),

Thank you for your prompt reply.

Could you please clarify why you would categorize the 4 categories as REE?

And when you are suggesting that REM is also a possibility of referring to the first categories of the four HS nomenclatures – do you mean all of the categories with the exception of cerium compounds?

Best regards,

(Name of the paper's corresponding author)

From: (Rare Earth Expert 1)

Sent: 13. august 2015 11:48

To: (Name of the paper's corresponding author)

Subject: RE: Rare earths - Eurostat nomenclature

Dear (Name of the paper's corresponding author),

I don't think that we understand each other.

I classify the 4 categories as REE because these are different types of compounds: metals, alloys, oxides, salts. REE is a general term for all types of compounds. REM are metals and alloys.

I must say that I am not interested in legal nomenclature.

Best regards,

(Rare Earth Expert 1)

Reply by Rare Earth Expert 2

From: (Rare Earth Expert 2)

Sent: 13 August 2015 13:59

To: (Name of the paper's corresponding author)

Cc: (Colleague of Rare Earth Expert 2)

Subject: AW: Rare earths - Eurostat nomenclature

Dear (Name of the paper's corresponding author),

Thank you for your question.

As "REO" (rare earth oxides), I would categorise those raw materials, which are still in situ (in the resource), freshly mined or only physically beneficiated into a concentrate (without chemical or thermal treatment).

As "REE" products, I would categorise those materials, which have been separated into single rare earth compounds.

These can be single rare earth compounds (oxides, chlorides,

nitrites), as well as their reduced metals and alloys.

... And I agree, the definition of single rare earth oxides is a bit unclear here, because often it is also referred to as REO.

So for us, all the listed Eurostat Nomenclature below deals with “REE” products.

Best regards

(Rare Earth Expert 2)

Comment by one Reviewer

‘Rare earth oxides can be pure. The original state is as REE minerals, then usually mixed REE compounds as intermediates, then purified REE oxides or metals.’

Appendix C

Selected examples of firms in industrial sectors that can be associated with REE use ([Tables C1–C3](#))

Table C1

Auto catalyst producers	
Solvay-Rhodia	Belgium-France UK
Johnson Matthey	
Source: Firm websites.	

Table C2

Fuel cracking catalyst manufacturers	
Haldor Topsoe	Denmark
Axens	France
Johnson Matthey	UK
Süd-Chemie	Germany
Grace Davidson	UK
BASF	Germany
Petroleum additive manufacturers	
Afton chemical	UK
Baker Hughes	UK
BASF	Germany
Chemtura	UK
Chevron Oronite	UK
Croda	UK
Evonik industries	Germany
Infineum	UK
Innospec fuel specialties	UK
Lubrizol	UK
Rhein Chemie	Germany
Total	France
Source: Additive Technical Committee (ATC)-Europe, 2015.	

Table C3

Glass polishing powder producer	
AMG Superalloys UK Ltd.	UK
Metal Alloy producers	
B.S.I. d.o.o. ¹	Bosnia-Herzegovina
Befesa Valer ¹	France
Climax Molybdenum B. V. ¹	UK
Elektrowerk Weisweiler GmbH ¹	Germany
Elkem asa ¹	Norway
Eramet Comilog Manganese ¹	France
Ferroatlantica SL ¹	Spain
Ferropem ¹	France
Fesil ¹	Norway
Finnfjord Smelteverk ¹	Norway
Glencore Intl AG ¹	Switzerland
Huta Laziska ¹	Poland
Jugohrom Ferroalloys Doo ¹	Macedonia
OFZ, a.s. ¹	Slovakia
RW Silicium GmbH ¹	Germany
Sadaci ¹	Belgium
Skopski Leguri Dooel ¹	Macedonia
Vargon Alloys AB ¹	Sweden
Treibacher Industrie AG	Austria
Outokumpu	Finland
5N Plus	UK
Advanced Alloys Services, Ltd.	UK
Amalgamated Metal Corporation	UK
Avon Metals Ltd.	UK
Cronimet Central Africa AG	Switzerland
Delta Products UK Ltd	UK
ENRC Marketing AG	Switzerland
Fondel Metals BV	The Netherlands
H.C. Starck GmbH	Germany
Indium Corporation of America	Italy
Jean Goldschmidt International SA	Belgium
Johnson Matthey Plc	UK
KGHM Polska Miedz S.A.	Poland
Less Common Metals Ltd	UK
Magnesium Elektron	UK
Molycorp Silmet AS	Estonia
Nordmet AS	Estonia
Rio Tinto Kennecott	UK
Scandinavian Steel AB	Sweden
Sims F. E. Mottram Ltd.	UK
Traxys Europe SA	Luxembourg
Umicore Precious Metals Refining	Belgium
Westbrook Resources Ltd	UK
William Rowland Ltd.	UK

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