



Alternative value chains for rare earths: The Anglo-deposit developers



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ARTICLE INFO

Article history:

Received 5 July 2014

Received in revised form

30 September 2014

Accepted 30 September 2014

Keywords:

Global value chain

Rare earth

Filament

Upgrading

Industry

ABSTRACT

The 2011 peak in rare earth element (REE) prices revealed a vast knowledge gap on the REE-based industry considered to be almost monopolized by Chinese players. A global value chain (GVC) framework is used to provide an understanding of value-adding segments of REE in their transformation from mine to market but inquiries on the currently most-advanced company strategies for alternative REE supplies form the cornerstone of this paper. The Anglo-REE deposit developer strategies are aligned with the value-adding segments and different approaches to integration and co-optation of REE processing competence are uncovered. On this basis the significance of alternative Anglo-REE-developer supplies is discussed and positioned in the perspective of Chinese industrial upgrading.

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Introduction

In the third quarter of 2011, free-on-board China prices for products of rare earth elements (REE), a group of 17 non-ferrous metals, surged by up to +600 per cent, caused by Chinese reductions in export quotas and exacerbated by territorial disputes between China and the second largest-REE market, Japan (Metal-pages 2011–2012; Hatch, 2012 and Kingsnorth, 2012). Responses by REE-using markets included varying combinations of stock-piling, end-user firm requests for product redesigns to reduce and substitute REE, and interest in alternative supply of REE via exploration for non-Chinese deposits and recycling.

The Chinese market dominance did not appear overnight: from the mid-1980s to the early 1990s, the Chinese share of global REE production increased significantly from 20 to 60 per cent while the US share remained in the range from 30 and 36 per cent. This share was exceeded between 1992 and 1995 when China took over the majority of global production from the US Mountain Pass mine (Hedrick, 1997; Castor and Hedrick, 2006). Other players included Australia, and smaller actors in Brazil and South Africa which were outcompeted from the mid-1990s until 2000s when China reached 95 per cent of the global production share and Mountain Pass operations ceased. Russia and India remained the only other REE producers next to a small contribution by Malaysia (Castor and Hedrick, 2006).

China also emerged as the largest geographical market for REE, increasingly producing larger shares (68 per cent in 2011) for domestic consumption and augmenting the value-added in its REE products (Kingsnorth, 2012). The remaining part of Asia (with Japan as the single largest market) ranked second with 16 per cent of total world consumption in 2011 while the US market ranked third with 10 per cent and Europe and other countries consumption was even smaller at around six per cent (Kingsnorth, 2012); hence, most of the REE production and consumption occurs in Asia today. In spite of high unit prices, the total REE market value is low compared to other mineral and commodity markets: in 2012, it was estimated between USD 4 and 6 billion with a total global REE demand of 115,000 t Rare Earth Oxides (REO) with an estimated annual variation of about 15 per cent (Kingsnorth, 2013). REE are mostly used in minor proportions in final end-use products (Kingsnorth, 2012) but they are highly important for both industrialized and emerging economies due to the potential of REE for value added and employment (both directly and indirectly) and induced value creation in new industries (American Chemistry Council (ACC), 2014).

The use of REE in a number of industries (including so-called strategic industries), their importance in high-tech applications and their value-adding potential make them targets of geopolitical interest. In 1992, the Chinese leader Deng Xiaoping suggested that China should become 'the Middle East for REE' and the advances China has made in this industry are surely remarkable: it has monopolized the market by high production volumes and steadily increased the value-added in its REE products by using a set of quotas and duties for production and exports. The system created a two-tier market of lower prices within China and higher prices outside for the same product with the aim to relocate foreign players' downstream production capacity to China. Already in

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2005, the effects of a steep export quota reduction triggered the creation of a black market in China while non-Chinese actors started questioning the organization and dynamics of the industry, the applications relying on REE, and alternative options to resource access (Tse, 2011).

Several research contributions have investigated these trends and processes which require interdisciplinary knowledge to understand the intricate weaving of explanatory factors derived from mining, geochemistry, metallurgy and economics. The contributions focus on criticality of issues involving the global REE market and REE industrial sectors (Korinek and Kim, 2010; Hatch, 2012; Hansen, 2012; Kingsnorth, 2013; Packey, 2013), REE geology and criticality (Eggert, 2011; Chakhmouradian and Wall, 2012; Massari and Ruberti, 2013; Nieto et al., 2013), Chinese industrial policy (Wübbeke, 2013) and the implications of the monopoly for different REE-using industries (Degeorges, 2012; GAO, 2010; Hurst, 2010; Adachi et al., 2010; Kramer, 2010), including specific intermediate products and industries such as magnets (Eggert, 2010; Zepf, 2013). A further stream of research has emerged on aspects related to recycling (Du and Graedel, 2011; Schüler et al., 2011; Binnemans et al., 2013; Harris and Walton, 2013; Habib and Wenzel, 2014) while some contributions address organizational aspects of supply chains (ACC, 2014; Zepf, 2013; Humphries, 2012; Walker, 2010; Eriksson and Olsson, 2011; USDOE, 2011; EU, 2010).

However, the implications derived from the complexity of the REE value chain for the end-user industries and critical appraisals of efforts by REE consumers to encourage alternative supply chains of REE have so far been omitted in academic discussions. The recent contribution on rare earth market developments by Packey (2013) provides a good overview of the industry including insights on two Anglophone REE-miners; while the contribution on REE supply chains by Golev et al. (2014) depicts some of the major non-Chinese actors and is a significant advance towards a more comprehensive understanding of the industry, yet their analytical focus is on geological and recycling aspects of the REEs. In this paper we document the integration strategies of three Anglophone, non-Chinese REE deposit developers, arguably the most advanced projects in terms of providing alternative routes of REE product supply today (Hykawy, 2014a; Kingsnorth, 2012; Lifton, 2012; Silver, 2012). We illuminate their different forms of co-operation and integration with Canadian, Chinese, European and US actors – some of which depend on Chinese REE supply today. Our findings are based on data from an empirical data set of interviews with European REE industry players which were conducted between May 2013 and January 2014 and supplemented with data from the annual reports of the three Anglo-REE-deposit developers.

The paper is structured into five sections. In the next section we describe the input–output structure of the global value chain of REE by depicting the main value-adding segments that transform the REE and we point to specific intermediate and end-user industry requirements of REE. In *Section New supply chains? The rise of Anglo-REE-deposit developers* we delineate the Anglo-REE-deposit developer strategies towards establishing alternative sources of REE supply. Our discussion in *Section Maneuvering between Chinese control of raw materials and efforts to upgrade REE-based filaments: Any changes in global supply patterns?* revolves around the construct of the GVC, the identified periods in the transition of the Anglo-REE-deposit developers and implications of these findings for REE-using industries. The paper continues with the *Section Policy considerations* and ends with the *Section conclusion*.

Upstream processes and products in the REE value chain

Rare earth elements (REE) are a group of 17 transition metals comprising 15 non-ferrous elements of the lanthanides (atomic

number 57–71) and also including yttrium (atomic number 39) and scandium (atomic number 21) (Kirk-Othmer, 2005; Ulmanns, 2005). Albeit having chemical similarities, REE display significant differences in their physical properties namely in their reactions to light, electricity and magnetism (Kirk-Othmer, 2005; Ulmanns, 2005). A multitude of appliances from consumer to industrial use appreciate these properties (Roskill, 2011).

REE occur in mineral and not in elemental form, as for example gold. More than 200 different minerals contain REE (Kanazawa and Kamitani, 2006; BGS, 2011), yet only four minerals, namely bastnaesite, monazite, xenotime, and loparite, and ion-adsorption clays, have to date been dominantly used for commercial exploitation (Roskill, 2011 and Walker, 2010). REE-bearing minerals are normally biased towards containing more light REE or heavy REE (BGS, 2011) and the 9 intermediate industries according to our classification (see Fig. 1) demand individual REE from either group or both (Roskill, 2011, Eurare, 2014). Some compositions of REE-containing geological deposits bear geochemical advantages for further processing such as comparably easier and more economically feasible flow sheets (which will be put into context below). As a result, separation from certain REE-bearing minerals will be easier due to factors such as comparably lower content of hazardous, radioactive elements and feasibility of REE production as by-product (BGS, 2011; Rockstone Research, 2014). In addition, the consistency of mineralization will impact tonnage and grade and some deposits are more advantageous due to more favorable and balanced REE distribution; profitability is also influenced by infrastructure and jurisdiction (Rockstone Research, 2014).

By volume and value, the magnet sector is currently the most important within the rare earth industry (Kingsnorth, 2010 and Roskill, 2011). The use of REE in the catalyst market sector is characterized by high volume and comparatively low value as this sector predominantly absorbs light REE. On the contrary, the phosphor market sector rare earth ore consumption in 2008 revealed low volume and high value, due to absorption of predominantly heavy REE.

In comparison to other mineral commodities, the production of REE entails higher complexity and capital intensity since equal focus is required on both mining and chemical processing (Lynas Annual Report, 2013). This is reflected in the so-called ‘balancing problem’ which summarizes these challenges faced by the REE industry due to REE occurrence in mineral form and the need to separate the REE jointly even if particular industries require only a number of the elements at a time (Falconnet, 1985).

Fig. 2 illustrates the upstream segments of the GVC of REE. *Exploration* is a precondition to finding suitable and commercially viable deposits for exploitation which depends on knowledge about the deposit composition. Thus, value input in form of investments in equipment and labor will result in area surveys, detailed geological maps and rock and mineral samples to be used for laboratory determination of compositional characteristics. The data generated serves the elaboration of flow sheets needed in the forthcoming processing stages. Each REE-mineral bearing rock is different and thus, requires a specific, adjusted flow sheet. The process from resource establishment over preparation of flow sheets, documentation for mining permissions (including progressive feasibility studies and environmental impact assessment) to mine construction is lengthy and can take several years up to a decade and more (Kingsnorth, 2012). Therefore, *mining* does not react rapidly to market demand and large mineral volumes might be mined and come onto the market when market demand has already changed (Falconnet, 1985 and Geoviden, 2012).

In the first (mineral) processing step which usually takes place at the mine, a *beneficiation* is performed by means of crushing, milling and concentration technology, relying on physical processes such as gravity concentration, magnetic and electric separation and flotation techniques. The output from this first processing

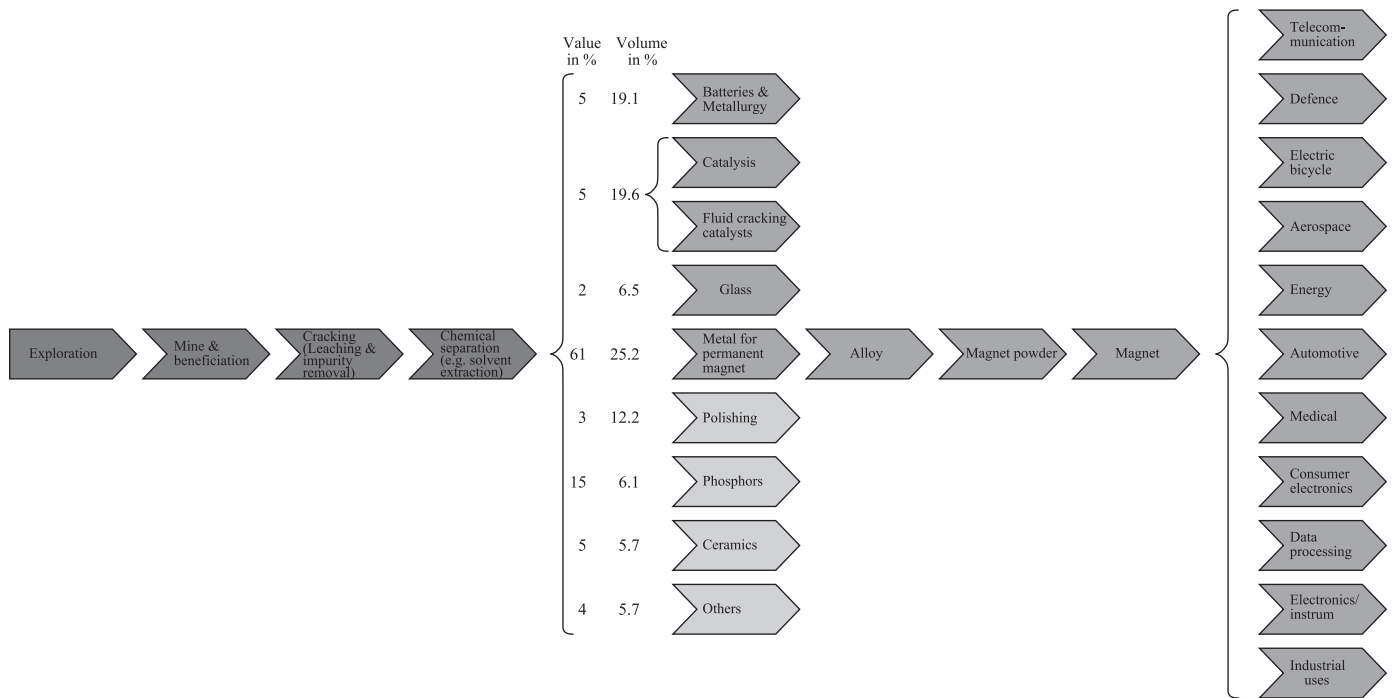


Fig. 1. Upstream and downstream parts of GVC for REE. The figure depicts the four upstream segments of the GVC. A simplified filament of REE-based magnets is also illustrated as the acquisitions pursued as part of the strategies of the three Anglo-mine developers reach beyond the four upstream segments into this particular filament. For reasons of clarity, the filaments of the other intermediate industries are not included. The fourth segment of the GVC, chemical separation, forms part of the chemical industry. Source: compiled by the authors; volume and value percentages based on individual REE (t REO) consumption of 2013 expressed in per cent of the overall market are derived from [Kingsnorth, 2014](#).

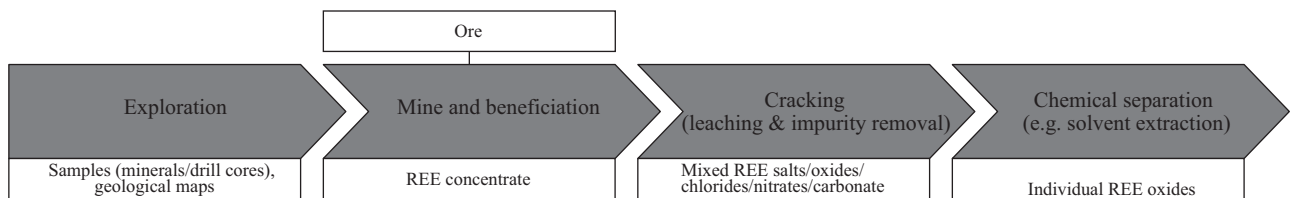


Fig. 2. Upstream part of the GVC of REE consisting of four segments. Source: adapted from [Lifton, 2013](#); [Roskill, 2011](#).

step is a *rare earth mineral concentrate*. This concentrate undergoes a process which we refer to as *cracking*, also known as dissolution, whereby a chemical leaching process takes place. The chemical leach can be preceded by a number of cracking or pyrometallurgical steps that could change the leach feed to the form that can be leached. This process results in an aqueous solution of *mixed rare earth elements*, in the same general proportions as found in the deposit. This solution is further processed/precipitated as mixed hydroxides or carbonates in order to facilitate transport and *remove impurities and hazardous elements*, including thorium (Th) and uranium (U) at typically <5 ppm (parts per million/five grams per 1000 grams), to adjust the pH.¹ At some point during precipitation and selective dissolution, U and Th will leave the solvent extraction circuit and become radioactive waste, preferably of as low levels as possible. U and Th are used as indicators for the presence of other so-called daughter products, such as Th-232, which is indicative of Ra-228 and Th-232. The radioactive elements can remain part of a REE concentrate. Once they are liberated, they act as individual elements. For instance,

U-235 daughter, which is AC-227 behaves like lanthanum and remains with the REE.

The next multi-step process is *chemical separation*. This process is a real bottleneck since very few players, including two European-based firms and a couple of Japanese firms are capable to control the separation outside China ([Interview 1 with Solvay, 2013](#)). The processing technologies applied on an industrial scale are solvent extraction and ion exchange.² The separation intensity differs for light REE and heavy REEs ([Hatch, 2012](#) and [Kingsnorth, 2012](#)). La–Ce–Pr–Nd are easy to separate as a group because of promethium (Pm), a radioactive element without long-lived or stable isotopes ([Belli et al. 2007](#) in [Chakhmouradian and Wall, 2012](#)) that does not occur with other REE. The heavy REE are more difficult to separate since more specialization and knowledge are needed ([Interview 1 with Solvay, 2013](#)). Even if the process is not any longer patent-protected and it is simple to explain, successful heavy REE separation depends on technically advanced solvent use and requires that the operating conditions are tightly controlled ([Interview 1 with Solvay](#)). As of early 2014, only one

¹ Some Th and U are removed during all the purification steps (precipitation, selective dissolution), but due to the strong extraction of Zr4+, Th4+, UO22+ and Fe3+ (pH50 values of lower than –0.4) these metals will be extracted together with the heavy rare earth fraction (pH50 values between –0.4 and –0.24) (Email communication with respondent of [Mintek, 2013](#)).

² Another separation technology was used by the US mining firm Molycorp, who used to produce the majority of REE until Chinese competition took over with lower cost solvent extraction technology ([Interview 1 with Solvay, 2013](#)).

European player and one Japanese player were able to separate the heavy REE besides some of the Chinese companies (Interview 1 with Solvay, 2013). A typical plant has a multitude of mixer-settlers (also referred to as batteries) which are very costly and thus present a barrier to entry to this industry. The separation process technology can be visualized as “a pair of scissors, that (...) cut between two elements, as many cuts you want to do, as many batteries you need to operate” (Interview 1 with Solvay, 2013 and Solvay 2014b). The results of this REE separation are intermediate products, *individual rare earth oxides* (REO) also referred to as separated REE or rare earth compounds, such as neodymium oxide (Nd_2O_3) or lanthanum oxide (La_2O_3), which still contain proportions of other REE, e.g. 0.1 per cent Ce, 0.01 per cent Y. The aim of maximizing purity of REE oxides is to reach the specifications set out by the end-users of these separated REE and the refining chemical separation plant will need to be configured to these levels in order to manufacture saleable products (Mintek, 2013). The specifications required from the REE product are tested by the customer in a qualification process, which can take a few weeks up to a year (Lynas Annual Report, 2013). Hence, the individual REE oxides are further refined to reach purity levels in the range from 99 to 99.999 per cent, depending on intermediate industry requirements (Hykawy, 2014b; Roskill, 2011). For instance, in this paper, we present the filament of REE-based permanent magnets which includes the downstream processing by the Great Western Minerals Group (GWMG) and Molycorp, two of the Anglo-REE-deposit developers, we address in the next section. Several processing steps are required to obtain the material magnet producers require as input (see Fig. 1). The first segment in this REE-permanent magnet filament is the *metal making* process. The individual REO are fed into the process which can involve amongst others molten salt electrolysis and electrolysis of rare earth bearing ionic liquids, producing *high purity rare earth metals*, such as Nd metal, or *alloys of rare earth elements*, such as mischmetal (La–Ce, La–Ce–Pr or La–Ce–Pr–Nd) used in the iron and steel industry and in the production of La-rich battery alloys (Kingsnorth, 2014), lighter flints or ferro-alloys (GWMG, 2012; Roskill, 2011). Another output of the metal making process can be didymium (Pr–Nd) supplied to magnet alloy producers. Residues such as SEG (Sm–Eu–Gd) and the heavier fractions are sold on for further separation (Roskill, 2011). High purity rare earth metals and other metals are then used to *produce specialist alloys*, or so-called “super alloys” of aluminum or permanent magnet alloys such as NdFeB or SmCo (Roskill, 2011).

Of the four segments in this part of the GVC for REE, chemical separation adds the highest value, especially with the refining (commonly referred to as formulation) of rare earth oxides to end-user requirements. Therefore value-adding objectives mostly focus on this segment. This is clearly exemplified by the trends followed by China:

- less than 10 per cent of total REE production was in the form of separated REE before 1990 whereas it exceeded 60 per cent in 2011 (Roskill, 2011);
- exports included primarily mixed REE mineral concentrates until the early 1990s but thereafter shifted to separated REE oxides and metal (Kingsnorth, 2012);
- just before the end of the century, exports of REE-containing product were mainly made up by magnets, phosphors and polishing powders (Kingsnorth, 2012) but after the turn of the century, exports started to include advanced REE-containing products including computers, batteries, mobile phones and LCDs (Kingsnorth, 2012).

Japanese industries are high value-adding users of REE and Hitachi Metals controls the sintered REE magnet market through

ownership of the patents for the high performance Neodymium–Iron–Boron (NdFeB) magnets (China Daily, 2013). Producers of NdFeB magnets without patent licenses cannot export their products to markets in which the patents apply (China Daily, 2013). After China and Japan, the USA has the third largest REE demand, with a 10 per cent share of the global REE market (equivalent to a total demand of 10,500 t REO) with most emphasis on REE use in catalysts in 2011 (Kingsnorth, 2012). The North American rare earth industry counts about 1000 employees and is also small in its directly generated output of about USD 800 million yet indirect output of the industry totaled almost two billion including approximately 6000 jobs (American Chemistry Council (ACC), 2014). Furthermore, downstream activities induced by REE are valued at about USD 300 billion with employment created for about 619,000 people (ACC, 2014). These activities include the use of rare earth products as input into magnetic powders, catalysts, metallurgy, polishing powders, phosphor powders, glass additives and ceramics and in alloys for batteries or sensors in intermediate industries, which then are used in a multitude of end-using economic sectors ranging from renewable energy, transport (automotive and aerospace), information technology, consumer appliance and the medical industry. Europe and other REE-using markets are even smaller and count for 6500 t REO, or six per cent of global REE demand in 2011 (Kingsnorth, 2012). The European rare earth industry is limited to a few players, yet the value-adding potential is large, as depicted by the example of the USA. In the next section, we explore how REE competences from across the world have been linked via co-operation or integration by the Anglo-REE-deposit developers with the aim of creating alternative supply chains.

New supply chains? The rise of Anglo-REE-deposit developers

In the wake of the REE crisis and industry calls for alternative supplies to diversify supply chains and increase resilience against exogenous factors to their production, the closest alternative appeared to be the re-opening of previous mines. The first we discuss is the Mountain Pass mine, owned by *Molycorp Inc.* (hereafter “Molycorp”), an American mining corporation with headquarters in Colorado, USA. The firm is present at 26 locations in 11 countries, and counts more than 2700 employees; it is listed on the New York Stock Exchange. Production includes rare earth metals, rare earth alloys (such as NdFeB and SmCo alloys) and rare metals such as niobium and tantalum.

In the 1950s Molycorp produced REE as Molybdenum Corporation of America and supplied most of the global demand for Europium oxide, which was in high demand with the development of red phosphor for color television in the 1960s. Up until the 1980s, Molycorp had met the majority of global demand of light and heavy REE. In 1998, against fierce Chinese competition and production-related environmental hazards, REE separation operations were suspended. In the period until 2002 REE concentrates were recovered from past inventories, but almost 10 years after mine closure, Molycorp re-commenced with new production capabilities (Kingsnorth, 2014) and with a number of integration processes in an attempt to build an alternative to the Chinese supply of REE products:

In 2011, Molycorp acquired Estonian based AS Silmet, one of two European REE processors producing rare earth oxide and rare metals and now known as Molycorp Silmet. In the same year, Santoku America Inc. in Tolleson, Arizona, the only US specialty metal and alloy producer was acquired; it is now known as Molycorp Materials and Alloys (MMA). Molycorp also announced a joint venture (JV) named Intermetallics Japan with Japanese Daido Steel, Ltd., the Mitsubishi Corporation and Dr. Masato Sagawa, the co-inventor of

sintered NdFeB magnet manufacture. The JV licensed technology from Intermetallics, Inc., making it independent of the use of patents held by other magnet companies and allowing for the manufacture of permanent rare earth magnets that deliver greater performance with less reliance on dysprosium, one of the REE considered critical (Molycorp, 2013b; European Commission (EC), 2014).

In 2012, Molycorp Canada was established with the acquisition of Canadian Neo Material Technologies (NMT), which in 2005 had been formed in a merger between the majority shareholder Magnequench and Canadian Advanced Material Resources (AMR) Technologies. The 2012 acquisition of NMT added former AMR light and heavy REE separation capabilities in China via two other JVs, namely Zibo (ZAMR) from light mixed rare earth carbonate and/or chloride including zirconium, and Jiangyin (JAMR) from ion adsorption clays. Former AMR processing competence in China dates back to the 1990s when AMR had increased its stake of 80 per cent in ZAMR to 85 per cent in 2001 and from initial 60 per cent in JAMR to 90 per cent. In 2006, NMT increased its shareholding in ZAMR to 95 per cent, reaching maximum allowable foreign shareholding. In addition, AMR sales expertise of oxides and phosphor products in China, and the alloy, magnet powder and magnet production facility in Korat, Thailand, were added to the portfolio of Molycorp (2013c).

In addition, the 2012 acquisition of NMT added the Magnequench patented magnet powder portfolio used to produce bonded NdFeB magnets to the product portfolio of Molycorp. Magnequench was a unit of the Delphi Automotive Systems Energy & Engine Management Systems division of General Motors (GM). The company emerged from an agreement of GM with Sumitomo (today part of Hitachi) and the Chinese Academy of Sciences. The three parties had jointly developed a magnet with the up to today highest available energy product containing neodymium ($\text{Nd}_2\text{Fe}_{14}\text{B}$ magnet) in 1983 and divided patents to this magnet according to production methods – one using a sinter process and making sintered magnets, the other using a quenching process, making bonded magnets. The latter suited automotive applications of GM better and Magnequench was founded – “Magne” for magnet, “quench” for quick cooling (Interview with Magnequench, 2013). In 1986, GM commercialized NdFeB powder and bonded NdFeB magnet production with a plant in Indiana, US. However, during the automotive industry crisis in 1995, US Magnequench was acquired by two Chinese state owned enterprises (China National Nonferrous Metals Import and Export Corporation, a subsidiary of China National Nonferrous Metals Industry Corp. and San Huan New Materials and Hightech, Inc.) and a US investment firm (Molycorp, 2013d). Following the expiry of the acquisition agreement to maintain employment at the US powder production site for six years, the US powder production was closed, an alloy producer in Tianjin was acquired and production was relocated to China. The Magnequench technology centre in North Carolina, US, which was established in 1999 was closed in 2004 as an office was opened in Singapore (Molycorp, 2013d).

In 2013, all key production facilities were operational at Mountain Pass and production for customers started (Molycorp, 2013a). Custom engineered materials from 13 different REE, plus yttrium, with purity levels of up to 6 N (99.9999%), and from six other metals (niobium, tantalum, gallium, indium, rhenium, and zirconium) at purity levels of up to 8 N (99.999999%) are produced (Molycorp, 2013e). In 2012, the largest markets (in terms of revenues for Molycorp) were Japan second ranked by China and Europe, and North America as third ranked. Largest customers were Japanese Hitachi Metals Ltd., Mitsubishi Unimetals USA, W.R. Grace & Co. – Conn., and Japanese Chuden Rare Earth Co. Ltd. (Molycorp, 2012).

The other, non-Chinese alternative of REE supply has been established by Lynas Corporation Limited (hereafter “Lynas”), a public-registered company in Western Australia and listed on the

Australian Securities Exchange (Lynas, 2014a). Until the early-1990s, Australia produced and exported significant volumes of REE concentrates, mostly to France and other European producers (Hoatson, Jaireth and Mieztis, 2011). Increased sensitivity to radioactive substances significantly increased disposal costs for Th and prevented a major French REE concentrate importer (Rhône-Poulenc, which we turn to later in this section) to continue REE processing (Hoatson, Jaireth and Mieztis, 2011). The activities of Lynas are focused on the development of rare earth deposits with Mt Weld Holdings Pty Ltd. and on integrated extraction and processing of rare earth minerals with Mt Weld Mining Pty Ltd., the mine and beneficiation plant and Lynas Malaysia Sdn Bhd, the latter being an Advanced Materials Plant (LAMP) for chemical separation. Lynas also holds a title to the Kangankunde Rare Earth deposit in Malawi but has not developed it further due to unsolved issues regarding its title (Lynas Annual Report, 2013). With a view to implement a supply chain focused on extracting and processing REE minerals, Lynas entered into several agreements:

In 2006, Lynas signed an agreement for a five year supply of cerium and heavy REE product to Rhodia. The company was a French specialty chemical firm and a spun off from Rhône-Poulenc in 1997. Today it counts five rare earth plants: one each in France, Japan and the US, and two in China (Interview 1 with Solvay, 2013). From the mid-1980s to the late 1990s, when the REE market was centered on pure carbonites and pure oxides, Rhodia was the “king of the world” in separation technology (Interview 1 with Solvay, 2013). It was the first firm to implement the now commonly applied solvent extraction technology for the REE chemical separation on an industrial scale; the plant at La Rochelle, France, continues to be in operation. In 2000, Rhodia formed a JV and acquired a 45 per cent stake in China-based Founder with capacity for REE chemical separation into REO and REE chloride (Roskill, 2011). The company has since then been renamed to Liyang Rhodia Founder Rare Earth New Material Co. In 2004, Rhodia increased its shares in Liyang to 70 per cent and a year later to 95 per cent, the maximum allowable foreign shareholding. Rhodia also has majority shareholdings in Baotou Rhodia with chemical separation capacity for REO and REE metals (Roskill, 2011). In 2007 Rhodia acquired W.R. Grace & Co. alumina wash coat business for auto catalysis. The company also signed a memorandum of understanding with French nuclear energy group Areva with the aim to identify and develop unworked deposits of uranium and REE (Roskill, 2011). In 2010, Rhodia entered into an agreement with Belgian Umicore, a specialist in recycling, to recycle rechargeable Nickel Metal hydride (NiMH) batteries.

In 2011, Rhodia was acquired by Solvay, a Belgian specialty chemicals firm (Nicholson, 2011), which ventured into fluorescent light recycling, as discussed in-depth by Golev et al. (2014). Value adding to REE products by Solvay has shifted from a focus on separation to a focus on formulation, which refers to the refining of the REE products derived from the chemical separation segment in order to better meet customer quality requirements. These are the highly profitable specialty markets (Interview 1 with Solvay, 2013). Profitable separation in-house is not anymore always an option: “there are really periods when you better process the separated elements rather than separate yourself” (Interview 1 with Solvay, 2013).

In 2009, Lynas received a bid by the state-owned China Non-Ferrous Metal Mining (Group) Co. for a 51.6 per cent stake but the bid was blocked by the Foreign Investment Review Board of Australia on grounds of national security concerns (Kirchner, 2014). In 2011, Sojitz Corporation, a trading corporation and conglomerate with headquarters in Japan, invested in Lynas with financial support by the state-run Japan, Oil, Gas and Metals National Corporation ([JOGMEC], 2014). The investment is conditional on access to materials from the mine. In the same year, Lynas signed several other agreements for supply to end-users

(manufacturers), including BASF, the largest chemical firm headquartered in Germany. A letter of intent was also approved with the Drive Technologies Division of German Siemens, the largest European engineering firm, to form a JV for NdFeB magnets for energy-efficient drive applications and wind-turbine generators; Lynas holds 45 per cent. Under the agreement, Lynas supplies predominantly a combined Nd-Pr metal to the JV, through a long term supply contract (Lynas Corp. Ltd., 2011). Also in 2011, Rhodia (now Solvay) and Lynas prolonged their agreement from 2006 with 10 years, adding a commitment by Rhodia to technically support the planned chemical separation facility Lynas Advanced Materials Plant (LAMP) in Malaysia.

In 2012, the Atomic Energy Licensing Board in Malaysia issued a temporary operating license which enabled Lynas to ship REE concentrate from Western Australia to Malaysia where the material undergoes cracking and leaching, production and product finishing. In 2013, Lynas constructed a concentration plant at Mt Weld and LAMP was completed with a phase one production capacity of 11,000 tpa (tons per annum) REO. A special purpose company was established by the Japanese trading conglomerate, Sojitz Corporation, and JOGMEC for the construction and commissioning of phase two at Mt Weld and LAMP which is adding an additional capacity of 11,000 tpa (Lynas Annual Report, 2013). This investment is conditional on the allocation of at least 8500 tpa to the Japanese market for 10 years (Reuters, 2010).

Until current low market prices rise again, LAMP remains optimized at 11,000 tpa rare earth oxides (Lynas Annual Report, 2013). The output consists of lanthanum-cerium carbonate (joint and separated), samarium-europium-gadolinium and heavy REE carbonate plus three synthetic material products (Lynas, 2014b). Lynas announced a minimum price schedule in 2013 which was, according to the company, supported by customers that aim to prevent REE price peaks and ensure supply security. Lynas also registered an international brand, Rare Earths Direct, to promote quality and continuity of supply for all its REE products. In its Annual Report (2013), the Anglo-REE-processor states its continuous work on product testing with potential customers from agriculture and the construction industry. REE products are shipped from LAMP for auto-catalysts to customers in Europe and Japan, for magnets to China and from there to Japan, and for fluid cracking catalysts (FCC) to the US (Lynas Annual Report, 2013).

Our third case is *Great Western Minerals Group Ltd.* (hereafter “GWMG”), a multinational exploration and mineral deposit development company with headquarters in Saskatoon, Canada, listed at the Toronto stock exchange, yet not operational at the time of writing. From original exploration and mineral property development with focus on diamonds, GWMG refocused its core business to provide an integrated REE supply chain in 2005. In the transformation from a rare earth explorer to a rare earth producer, GWMG acquired and entered into collaboration with numerous firms, counting nine wholly-owned subsidiaries, including Rare Earth Extraction Co. Ltd. (Rareco) and Steenkampskraal Monazite Mine (Pty) Ltd. (SMM) operating the Steenkampskraal REE deposit in South Africa, and three partly-owned subsidiaries in 2013. The Steenkampskraal monazite mine mainly produced monazite concentrate from which customers in Europe and North America extracted thorium as a nuclear fuel source (GWMG, 2014a) while REE were a by-product during the mine operations from 1950 to 1963 (Jepson, 2012). With a change in nuclear technology from thorium to uranium, the Steenkampskraal mine was abandoned in the early 1960s (Jepson, 2012). GWMG holds two other active material subsidiaries: Less Common Metals (LCM) and the JV for chemical separation in South Africa with Chinese Ganzhou Qiangdong Rare Earth Group Ltd. (GWGQD). GWMG also holds interests in three inactive rare earth exploration properties, namely Hoidas Lake and Douglas River in Saskatchewan, Canada and Red Wine in Labrador, Canada (GWMG, 2014a).

The development path of GWMG towards an integrated supply chain of REE included the acquisition of downstream value adding alloy and metal making through Great Western Technologies Inc. (GWTI) in the USA in 2005. However, the facility was closed in March 2014 as market demand for GWTI's NiMH battery alloys remained low in the US market (GWMG, 2012). In 2008 GWMG acquired the rare earth magnet alloy producer Less Common Metals (LCM) in the UK. LCM produces a fifth of the global supply of SmCo alloys and NdFeB alloys both mainly used by the permanent magnet industry. The demand by permanent magnet manufacturers in Europe and Japan for supply of rare earth metals and alloys independent of China induced further investment in LCM to ensure expansion of alloy production including the development of metal making capacity. This expansion program is synchronised with projected output from the Steenkampskraal mine in which GWMG bought a controlling interest in 2008 (Jepson, 2012). The beneficiation at the mine is envisaged to produce a mineral concentrate and thorium in addition to other radioactive materials which will be removed and stored. The cracking will result in a mixed REE chloride and if required for transport, a mixed REE carbonate (GWMG, 2012).

In 2011, GWMG finalized the acquisition of the South African Steenkampskraal monazite mine through Rareco (see above). In the same year, GWMG established a JV with Chinese Ganzhou Qiangdong Rare Earth Group Ltd. (GQD), referred to as GWMGQD, in which 25 per cent is owned by GQD while the majority of shares are owned by GWMG (2012). GWMG signed a letter in which German Vacuumsmelze GmbH & Co. KG, the largest sintered REE-magnet producer in Europe, specified its intent to negotiate the purchase of a minimum of 50% of its REE material needs from LCM (GWMG, 2014b). In the same year, GWMG also entered into agreements with the Japanese Aichi Steel Group, a member of the Toyota Group of Companies, and Electron Energy. In 2013, sales by LCM totaled USD 16.7 million and accounted for more than 95 per cent of total GWMG sales; revenue stemmed from permanent magnet manufacturers, the main market for LCM. LCM sales depend entirely on foreign customers: the company sold 60 per cent of its products in Europe, 30 per cent in the Far East (primarily Japan) and 10 per cent in the US in 2013.

In January 2014, GWMG successfully produced mixed REE carbonate from Steenkampskraal ore in mini pilot plant testing at Mintek, a mineral processor in South Africa (GWMG, 2014a). In the future it is planned that GWMGQD will separate the mixed REE chloride into 14 individual REE products and yttrium mainly for LCM processing (GWMG, 2012). Other selected oxides may be processed into other chemicals, such as carbonates, and sold to potential JVs according to future off-take agreements with the remainder sold in the open market (GWMG, 2012). GWMG is also assessing opportunities to have separation completed on a tolling basis by third parties intended to generate cash flow (GWMG, 2014a).

To recapitulate: the strategies of two of the companies can be divided into three distinct historical periods. The first period reaches back to the 1980s and is marked by a build-up of processing competence and resource access in China via shareholdings in local businesses. It was followed-up by share increases in these firms during the early to mid-1990s. Rhodia, (which is now part of Belgian Solvay and supplying technology to Lynas) enters into a 45 per cent shareholding with Liyang Founder Rare Earth New Material Co. in 2000 in addition to its shareholding in Baotou Rhodia. Around the same time, Canadian Advanced Material Resources Technologies (AMR), now part of Molycorp Canada, increases its original shareholding of 80 per cent in the rare earth processing plant at Zibo to 85 per cent and from initial 60 per cent in Jiangyin to 90 per cent.

The second period takes place in the years around 2005 when the first Chinese consolidation efforts take effect and two of the companies acquire the highest possible shareholdings in the Chinese companies they have invested in. Rhodia acquires 70 per cent of

Liyang in 2004 and 95 per cent in 2005 and enters into a five year supply agreement with Lynas in 2006. Magnequench, now part of Molycorp Canada, merges in 2005 with AMR Technologies to form Neo Material Technologies (NMT) and gains access to REE chemical processing in China via the JVs of AMR in Zibo (ZAMR) and Jiangyin (JAMR). In 2006, NMT augments its shareholding in Zibo to the maximum allowable of 95 per cent.

The third period is characterized by acquisitions and mergers outside China to acquire further REE industry competence and to enter into agreements with large volume end-users immediately following the 2011 REE price peak. Lynas prolongs its agreement with Rhodia to supply REE for a 10 year period with the addition of a commitment by Rhodia to technically support the construction of the Lynas advanced material plant in Malaysia in 2011. In the same year, Lynas enters into a JV for magnet production with majority shareholder Siemens, and into an agreement with BASF. Molycorp completes an acquisition of Estonian AS Silmet for both its chemical separation expertise and for the possibility to source additional REE ore from Russian Solikamsk Magnesium Works in 2010. Two years later, US Molycorp acquires Canadian NMT and thereby consolidates its upstream part of the value chain through shareholdings in REE separation in China (ZAMR and JAMR) and secures an alternative Thai down-stream powder and magnet processing filament as well as the bonded magnet patented technology. In effect, both Molycorp and Lynas are constructing alternative REE supply chains outside China. While Molycorp also has a REE supply chain within China, Lynas has no (apparent) formal links.

The strategy of GWMG differs somewhat as the re-orientation towards REE and integration processes of the Anglo-REE-developer begins in 2005 (the second phase above) with the acquisition of alloy and metal making competence through Great Western Technologies Inc. in the USA. Roughly corresponding in time and geography to our third depicted phase, in 2008, GWMG acquires UK-based LCM Ltd. for magnet alloy making competence. The group thus consolidates its business strategy to serve predominantly permanent magnet producers. The described intentions of a backward move in their value chain to increase metal making competence at LCM illustrates their strategic objective to increase the resilience of their business, providing an alternative source of REE metals and alloys. Yet, at the chemical separation segment, GWMG requires Chinese competence. It is the first company building an alternative REE supply chain to enter into a JV with a Chinese firm for separation competence to be installed close to their Steenkampskraal mine.

The three strategies to construct alternative supply of REE have seen the vertical integration of different players into the supply chains of US-based Molycorp and Canadian-based GWMG while Australian-based Lynas appears to rely on looser forms of collaboration through agreements (illustrated in Fig. 3). Its partner of collaboration for further processing of REE, Solvay, already expresses an interest in the company controlled ore in the second period, in contrast to Molycorp that acquires chemical separation competence in the third period. Neither does Lynas enter downstream processing after chemical separation, contrary to Molycorp and GWMG. Yet, downstream processing at GWMG ends at REE alloys for sintered and bonded REE magnets while Molycorp offers both magnetic powders for bonded REE magnets and sells ready-made bonded REE magnets from Thailand and China. At Solvay we observe strong efforts towards achieving recycling objectives in an attempt to strengthen their market position.

Maneuvering between Chinese control of raw materials and efforts to upgrade REE-based filaments: Any changes in global supply patterns?

In the previous sections we depicted the input–output structure of the GVC for REE and explained the complex processing and

value-adding steps. The ‘balancing problem’ (Falconnet, 1985) points to the unique REE characteristics, namely that all 17 REE need to be mined and jointly enter chemical separation in order to meet demand for particular REE. We depict a GVC of REE with four segments – exploration, mining (and beneficiation), cracking, and chemical separation – followed by filaments that are tied to specific end-user industries with unique and distinct quality criteria. This ‘filamentation’ allows us to outline value-adding segments in the intermediate industries (such as magnet producers, auto-catalyst producers) and end-user industries (such as automotive or electronics) and facilitates an assessment of the value-adding potential of the REE industry and its many ‘off-springs’ downstream the chemical separation segment.

This insight provides a background for an understanding of the general organization of the REE-based industries and the context for the strategic pathways followed by the three Anglo-REE-mine developers that we examine in this paper. We are able to relate their strategies to the value-adding segments in the GVC for REE and – when applicable – to the filament of permanent magnets. We focus on these companies for two reasons:

- 1) Molycorp and Lynas are in an advanced project status, while GWMG is well advanced in commissioning the mine, although we recognize that combined REE-deposit developments and integration by mine developers also take place in many other places such as India, Kazakhstan, Vietnam, Russia, and Brazil (Chen, 2011), and
- 2) they are highly relevant for the REE market in Japan and for the REE markets of US and Europe as they are working towards creating alternative supply chains of REE.

The performance of these Anglo-REE-deposit developers is closely observed by more than 200 mostly junior mining companies across the world. These companies surged particularly in the aftermath of the 2011 REE price peaks and are now in different project phases but all are trying to raise capital in order to continue development (Hatch, 2012). It appears crucial for the continued financing of these projects that at least one of the Anglo-REE-deposit developers succeeds to establish a vertically integrated supply chain that is economically resilient against dominant Chinese industrial policy, i.e. the ambitions to maintain control over the world market for REE while upgrading domestic activities in the filaments to include higher value added segments. The remaining part of this section will discuss this issue.

Continued economic growth in China (and the other BRIC countries) will result in structural change from the primary to the tertiary sector and among industries within the secondary sector. The accompanying social change related to higher skills and wages will most likely lead to higher use of REE-based goods, e.g. increasing demand for high-tech appliances both by industry and consumers. Higher mobility of goods and labor would similarly lead to increased demand for more and cleaner energy in turn resulting in growth of the REE intermediate and end-user industries in the energy and transportation filaments.

According to UNCTAD (2013), industrial upgrading is becoming a necessity for China for two reasons. First, large parts of the growth-generating workforce enabled by the one-child policy of the 1970s becomes dependent on social transfers. Second, increases in local income might reduce incentives for foreign firms to invest into China, particularly in manufacturing (Naughton, 2007). As part of this general trend, China is insistently trying to increase the value-added of its REE-based industries. Chinese competence embodied in the REE chemical separation segment is a cornerstone for industrial upgrading and provides a platform for upgrading in other REE intermediate and end-user industries. At the same time intermediate industries downstream of the

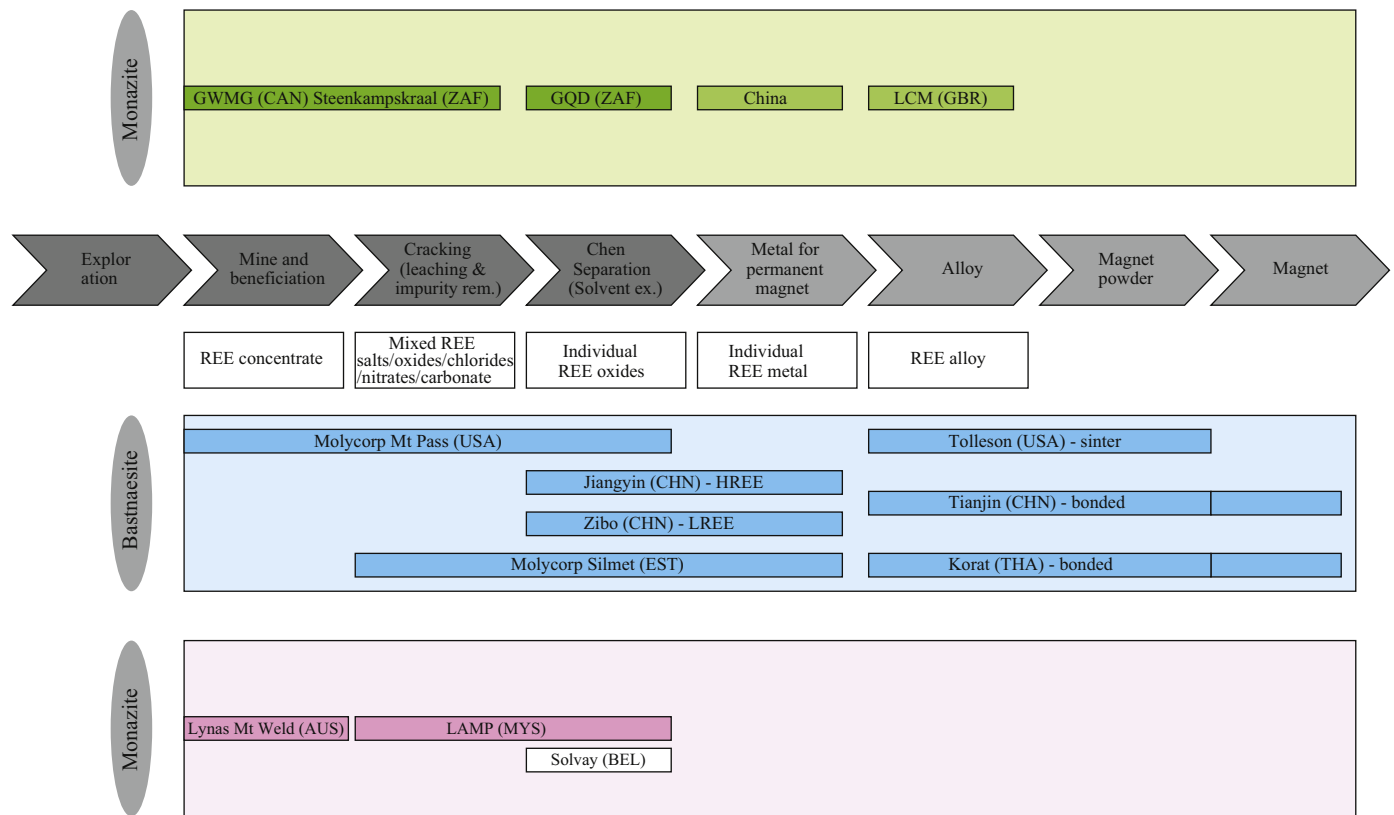


Fig. 3. Components of alternative REE supply chains (including the magnet filament). Source: authors based on data from the annual reports of the three companies and interviews.

chemical separation segment require different purities of the REE products. Hence, certain REE products need further processing and refining while others can be sold in less pure forms. For instance, applications that use chemical and structural properties of REE require less pure REE, e.g. as in metallurgy, catalysis (petrochemical industry and cars), glass and ceramics. Applications using physical properties of REE including optical, magnetic, combined optical and magnetic, hydrogen storage, electrical and nuclear properties and nuclear energy require high purity (> 99.99% and more) REE before used in for instance magnets, phosphors, rechargeable batteries, electrical components, nuclear fuel or control rods (Walker, 2010, Roskill, 2011, Kirk-Othmer, 2005). As we have mentioned above (see also Fig. 2), value-adding potential is highest in the magnet and phosphor filaments followed by alloys e.g. for batteries. Besides consisting of high-value adding segments, the magnet filament also absorbs a considerable volume of REE production. The phosphor filament is amongst the smallest volume users of REE, yet it includes the highest value-added segments.

However, the Chinese REE chemical separation segment has a strong foundation in the production of traditional, less pure REE of less value used in metallurgy, petrochemical industry and glass. For example, the state-owned China Petrochemical Corporation (2012–2014) (Sinopec Group) with its business in traditional petrochemicals ranks as high as third in terms of chemical sales among the global top 50 players of the chemical industry (C&EN, 2013) – but in many ways the company is to catch-up with its competitors in the top of the list, BASF and Dow Chemical, who both have diversified into different industrial sectors (C&EN, 2013; CEFIC, 2013). This type of advanced diversification strategy is also visible in the case of European-based Solvay which is active across six different global industries – one of which handles REE (C&EN, 2013 and ICIS, 2014a, 2014b).

China has gradually moved into higher-value added REE products with its export-oriented, REE-based products (Kingsnorth, 2012). The market of catalysis (e.g. for polybutadiene rubber used for tires) is moving into China now (Interview 2 with Solvay, 2014a). Phosphor production moved into China 10 years ago (yet patents for phosphor powder compositions are often held elsewhere) and a lot of polishing and glass manufacturing is already taking place in China (Interview 2 with Solvay, 2014a). Yet production for high-quality REE products destined for exports still relies on high-value added component inputs from outside China, such as from Japan (Interview 2 with Solvay, 2014a). A similar traditional position also seems to be the case for magnet production in China where the production process of injection molding (with the highest value added in the filament for bonded magnetic components) has not been fully established yet (Khan, 2014; Machacek and Fold, 2014).

Hence, the strategies of the Anglo-REE deposit developers to construct alternative REE supply chains is situated between Chinese ambitions to upgrade their own domestic REE-based industries and the continued control of the world market for raw materials – truly a challenging and delicate task.

Policy considerations

In any case it is relevant to consider the implications for REE-based intermediate and end-user industries outside China if the three companies discussed should succeed in their endeavors. The volumes will be insignificant in relation to Chinese production and consumption but sufficiently interesting for the actors operating on the Japanese market (the second largest REE market) and the smaller markets of the US and the EU. Japanese geographical diversification of supply chains of REE has been extended to South-east Asia, Pacific, India and Kazakhstan, and is

also reaching into the EU and the US (Roskill, 2011). However, alternative access to REE-resources for industry actors in the EU and US is highly dependent on the successes of the Anglo-REE-deposit developers even though products will primarily consist of light REEs. We see a twofold significance of the alternative supply chains:

- (1) If China continues to further limit access to REE the alternative supply could constitute a solid backbone for retaining high value-adding segments of REE-based intermediate and end-user industries in Europe and the US, despite preferential treatment by Chinese authorities such as tax incentives offered by the Investment Promotion Bureau (2014) to support enterprises and attract competences to the Baotou Rare Earth Hi-tech Zone (Baotou National Rare Earth High-Tech Industrial Development Zone Investment Promotion Bureau, 2014). We assume that the preservation of these segments will positively affect technological development, innovation and employment generated by these intermediate and end-user industries in Europe and the US. In addition, incentives for the REE-based intermediate and end-user industries to move production and technology into China will be primarily motivated by access to a growing Chinese market rather than by securing access to resources. Thus, we anticipate a continued ability to protect proprietary technology by the European and US companies and a somewhat reduced bargaining power of enterprises in China aspiring to acquire access to skills and new technologies that could facilitate further industrial upgrading.
- (2) State involvement carries the current two-tier pricing system in which REE products sold inside China are significantly cheaper than REE products sold outside and might be maintained although under increasing pressure from Chinese industrial companies and associations. The two-tier pricing system can be viewed as an effort to facilitate downstream development, yet internal frictions in the Chinese market between right and non-right holders of production and export quota challenged the system and enhanced internal redistribution. The 2011 REE price peak both nourished illegal mining and sales of REE, and significantly changed the threshold for market entry, awakening the interest by profit-seeking junior exploration firms and stimulating technological development (for REE exploitation, processing and (partial) REE substitution) over the past years. Yet, we have observed a lack in the financing of several REE junior exploration firms recently. (Hatch, 2012; TMR, 2014) Two observations are pertinent regarding these contrasting trends: First, diversification of supply and (partial) substitution of REE in products in turn facilitated by research and development including extensive product tests might occur over the mid- to long-term. The choice of these diversification strategies depends on the importance of REE content in the final product in terms of volume, product performance and substitutability. Second, as long as adequate quantities of REE are supplied from China, diversification will arguably be more strongly driven by geopolitical concerns. Thus, while robust data to inform and motivate diversification will become available over the mid- to long-term, potential investors in REE junior exploration projects will take decisions on options for REE upstream development based on current disclosed information (see Majury, 2013). This information will not inform about long term effects of available REE for the downstream part of the GVC. These effects would include issues such as potential REE-facilitated innovations in high-tech industries and impacts on induced employment, i.e. issues that are much closer to the interest of the public realm. Thus, potential public benefits from alternative upstream development of GVC for REE will only be reaped if current information disclosure meets investor long-term interest.

In the meantime, industry consolidation efforts within China may lead to more controlled material flows amongst state-owned enterprises and their satellites, in turn resulting in less accessible REE-containing ore for foreign firms involved in JVs. Finally, increases in Chinese domestic consumption of REE-based products enabled by the production of high-tech goods which might stimulate domestic consumer trust and interest may lead to decreases in available REE (intermediate) products on the world market. Hence, the alternative supply remains important for reasons of Chinese state-ownership structures as part of its REE industry organization. Even though prices of selected REE products are announced in the [Baotou rare earth product exchange \(2014\)](#) which are to enhance market transparency, state ownership structures will continue to influence industry dynamics (Bloomberg, 2014).

State involvement in the GVC of REE is also prevalent in the rest of the world. It is most common in the form of 1) foreign investment review boards which agree or object to foreign bids in REE deposit development and mining, 2) monitoring of mergers and acquisitions involving REE intermediate and end-user industries, and 3) government support for diversification of REE supply chains (and for REE recycling). Excluding Japan, which already has government involvement in securing alternative REE supply chains, we find it worthwhile for other countries and regional groupings to reconsider whether public involvement in integrated mining projects would be appropriate when market responses (reflected in significant share price falls of both Molycorp and Lynas over the first three quarters of 2014, at the time of writing) are counterproductive for the efforts to create alternative supply chains of REE. If favored, the question is, obviously, to identify the most efficient locus for intervention. We address this issue in the remaining part of this section.

The bottleneck for the establishment of alternative REE supply chains is (as discussed in section two) at the chemical separation segment which requires both high capital expenditures (CAPEX) and operating expenditures (OPEX) as well as cross-cutting knowledge of mineralogy, geology, chemistry and metallurgy. CAPEX is made up by the expenses associated with the purchase of both batteries³ and annex equipment for the liquid–liquid extraction (commonly referred to as solvent extraction (SX)), and induced equipment (e.g. for specific effluent treatment) (Solway, 2014b). The OPEX is derived from the use of solvents and energy, solvent losses, handling and storage of radioactive material, effluent treatment and taxes for discharge streams (Solway, 2014b). Overall, the cost structure of the SX process is primarily determined by the choice of the solvent followed by the selected technology and the number and fixed sequence of REE to be individually separated (Solway, 2014b).

One way to minimize CAPEX is to establish what is denoted as a tolling station. Such a centralized facility would provide chemical separation services by processing a mixed REE solution (salts/oxides/chlorides/nitrates) from numerous suppliers into individual REEs while complying with the quality requirements of potential buyers. Both the technological and economic feasibility of a tolling separation facility must be critically reviewed. Thus, it is important to comprehend the REE-bearing ore that constitutes the basis of the mixed REE solution which is fed into the tolling facility. Does it originate from one of the four already commercially processed ore types (bastnaesite, monazite, xenotime, loparite) or from non-commercialized sources (such as lujavrite or kakortokite)? In the latter case additional economic risk is added as new and specific

³ Batteries are the essential equipment to run the SX process and their purchase is influenced by decisions on the number and volume of stages which will be conducted in the batteries, the material fed into the batteries and the need for annex equipment linked to the solvent characteristics (Solway, 2014b).

processes need to be developed. Further consideration is needed on how the tolling separation facility organizes the risks of the REE-input suppliers, the risks of the potential separated REE-procuring customers and its own risks. As these risks are determined in confidential contracts they can only be addressed generically:

First, the mixed REE solution supplier may be contractually obliged to contribute locked-in capital for the tolling facility while also being locked-in to deliver the mixed REE solution. Presumably the delivery of specific volumes of mixed REE solutions will need to be agreed upon with the tolling separation operator in order to allow for the same proportional blending of different mixed REE solutions. Compliance with these specifications is necessary to produce a homogenous feedstock for the chemical separation plant over a defined period of time. In turn, highly sophisticated and customized software will facilitate adequate blending and process control.

Thus, second, it could be that the seller of the mixed REE solution (either the original owner of the mixed REE solution or the tolling facility), or the buyer of separated REE (or both) will carry the risk of a binding REE purchase from the tolling separation independent of current market prices. Here it would be interesting to know how a mixed REE solution feedstock originating from both commercial and non-previously commercially processed REE-bearing ore will affect the solvent choice in the separation process and the division of risk in the contracts among the parties.

Recently allocated funds by the US Army Research Laboratory, part of the US Department of Defense, to support REE upstream development is highly notable in respect of the potential of state support to the establishment of a tolling station. The purpose is to test the commercialized SX technology with different flow-sheets on a lab-scale to extract and separate the REE (Innovation Metals Corp (IMC), 2011–2013). A third-party process-engineering facility in Canada is planned to operate a pilot plant which at the outset will be fed with heavy REE-rich concentrates from non-Chinese sources (IMC, 2011–2013). Besides developing this pilot plant, IMC also runs a parallel project concerned with the development of a SX-separation tolling facility that is planned to be located in Canada or in the USA (IMC, 2011–2013). Since 2011, the company has conducted research in China that demonstrates the technological feasibility of tolling with the mixed REE solution fed into the centralized tolling facility. IMC would offer the supplier(s) to carry out chemical separation into individual REE products with two options: either to sell the individual REE back to the mixed REE solution supplier or to sell the individual REE directly at the market (IMC, 2011–2013). The recent US funding and US legislative proposals (Bill H.R. 4883 and S. 2006, proposing a 'National Rare Earth Cooperative Act of 2014') suggest that the USA may become the preferred location of these facilities (Congress, 2014a, 2014b).

In Australia and South Africa, supportive initiatives are more generic and grounded in research and development conducted by national research agencies, such as the Australian national science agency (CSIRO, 2012), the Australian nuclear science and technology organisation (ANSTO, 2014) and the South African Mintek (2011). These agencies host pilot plant capabilities for mineral processing technologies. Outside China, ANSTO and Mintek share the market for metallurgical test work of REE flotation and chemical separation. Numerous regional and national initiatives conduct research on critical materials with either a material-based or an awareness-raising approach, informing about the downstream parts of the GVC for REE. In the countries focused on in this paper, notable examples are the US Critical Material Institute (CMI), CSM and Ames Laboratory under the US Department of Energy, and the Australian Critical Materials Initiative (CMI, 2014; Curtin University, 2014).

To which extent governments or other interested parties should support alternative REE supplies is a question of national

economic development and national sovereignty objectives. The need for government intervention in the REE industry has (as mentioned above) been dismissed by Zachmann (2010) who argues for reliance on the efficiency of market self-regulation. Building on Hurst (2010) and Worstall (2010), he suggests that REE-using industries should focus on diversifying their REE supply. He continues to argue that '(...) the willingness to pay for diversification [such as sourcing REE from different non-Chinese processing sites and/or investment in establishing value chains from re-opened mines or new REE deposits] largely depends on private information about the individual companies' cost of decreasing REE consumption.' (Zachmann, 2010, p. 3) However, complete reliance on self-regulation seems like an over-optimistic confidence in the virtues of market efficiency (see Tukker, 2014). We find that the market externalities outlined in this section, the geographically concentrated market in consuming countries (primarily China and Japan) and the heavy state involvement in both of these countries suggest some form of intervention is unavoidable and indeed warranted: an additional argument lies in the assumption that a liquid market of REE products will form. This is perceived to be impeded by both (generally) comparably small REE volume demand and strict purity requirements by industrial consumers which imply prolonged testing and therefore prohibit spot sales. The recent US funding of upstream initiatives described earlier seems to follow aspects of this line of argumentation.

One of the issues at stake is the value-adding potential offered by alternative REE supplies which would feed into numerous intermediate industries that again serve as key nodal points in several other GVCs. Yet, the value-adding potential by the REE industry obviously cannot be clarified in the abstract but needs a thorough examination of individual REE products and their involvement in flows to numerous intermediate industries and further on to a multitude of end-user industries. We would, however, assume that Japanese government involvement in the establishment of new and alternative channels for REE resource access is mainly due to the economic importance of its electronics industry in which high-value adding activities are enabled by many physical REE properties including miniaturization. Does Japan rely more strongly on REE products for its economy than the US and the EU? Again, what is needed is an investigation of the numerous intermediate good producing industries and end-user industries, including many high-tech industries such as production of technologies for renewable energy generation, the automotive industry and the defense industry. Findings presented by for instance Sturgeon and Kawakami (2010) on electronics and by Humphrey (2003); Sturgeon, Van Biesebeek and Gereffi (2008) and Wad (2008) on the automotive industry present solid analyses of GVC dynamics but their scope excludes REE use in these industries. Further research is needed to inform this discussion.

Conclusion

In this paper we map the GVC of REE and depict the strategies of three Anglo-REE deposit developers who seek to establish alternative supplies to the dominant Chinese REE industry. We present their strategies with reference to the value-adding segments of the GVC of REE and transcend into the REE magnet filament for explanatory purposes. Three historically distinct periods which align with the Chinese transformation of the REE industry are observable: intensified increases in shareholdings in their joint ventures in China in the first two periods followed by a third period after the 2011 price peaks characterized by mergers and acquisitions as well as negotiations of off-take agreements outside China. Whereas Molycorp and GWMG pursue acquisitions, Lynas enters into lose agreements possibly influenced by the

Japanese government support of its operations at the time. These strategies aim to succeed in a market dominated by China which strives for further industrial upgrading. We point to the upgrading potential in the GVC segment of chemical separation and illustrate the differences in length of downstream integration pursued by the three Anglo-REE-deposit developers: the alternative supply chain of Molycorp reaches down to REE-based magnet production while GWMG will lean into REE alloy production and aims to strengthen capacity in the previous metal-making segment. In contrast, Lynas pursues integration down to the chemical separation segment only, potentially downstream to formulation through Solvay.

Against the background of strong Asian presence in the REE industry, we critically reflect on the value of the efforts by the three Anglo-REE-deposit developers. We conclude that the value-adding potential inherent to REE downstream processing following chemical separation is significant from the perspective of indirect value-adding possibilities enabled by REE-containing components. These value-adding opportunities can take the shape of innovations related to product performance which might support the upgrading of firms, employment in the many industries which absorb REE-containing components, and opportunities for research and development which frequently are higher in the geographical and institutional proximity of production sites as ideas can be applied and tested easier. With our illustration of a simplified GVC for REE and a simplified REE-permanent magnet filament, we argue for further research that follows the REE-containing ore to intermediate industries and final end-products to derive specific data on value-adding dimensions of REE-using (globally-organised) industries and of their importance to national economies.

Acknowledgments

We are thankful to the Geocenter Denmark Grant number 4/2012 for funding the research under which this article was produced. The research benefitted greatly from the support and facilitation of interdisciplinary approaches by the University of Copenhagen and the Geological Survey of Denmark and Greenland. We are particularly grateful for the information our informants and respondents shared with us. Without their input, we could not have obtained the insights on which our argument and analysis are constructed. Further, we would like to thank Professor Daniel J. Packey for his general comments and Professor Dudley J. Kingsnorth for his in-depth comments on an earlier version of this paper.

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