Miner Econ (2014) 27:21–31
DOI 10.1007/s13563-014-0043-y

ORIGINAL PAPER

Rare earth metals: a strategic concern

Gary A. Campbell

Received: 30 September 2013 / Accepted: 19 March 2014 / Published online: 11 April 2014

Abstract Rare earth metals are important inputs into the development and manufacturing of many green and high-tech products. It is an international strategic concern that much of the supply chain for rare earth metals is based in China. This paper looks at issues involving the availability of rare earth metals, its use, China's involvement, and pricing to better understand the strategic issues and their impact. It is concluded that the major need is to develop rare earth metal processing and use capacity outside of China. However, this will not be easy to do because of economic and social factors.

Keywords Bastnäsite ore · Green technology · Monazite ore · Rare earth metals · Strategic resources

Introduction

Rare earth metals have moved from obscurity to very public prominence in recent years as the availability and strategic concerns about rare earth metals have grown dramatically. Well into the 1980s, rare earth metals were not considered a major strategic concern for businesses or governments (Maull 1984). Rare earth metals were largely used in low-valued, low-purity mixtures and were readily available from the large Mountain Pass Mine in the USA (bastnäsite ore) and monazite ore sites in locations like Australia and Malaysia. By the early 1990s, production of rare earth metals had become much more concentrated as monazite sources were phased out and replaced by the expansion of bastnäsite ore production in China. Higher purity uses of rare earths metals had become more substantial by this time requiring specialized processing skills that limited the potential suppliers. The role of China in the market was growing rapidly, but rare earth metals were still not considered a major strategic concern (Nappi 1993). By the late 1990s and 2000s, this view had changed radically as rare earth metals became highlighted as a significant strategic concern (National Research Council 2008; U.S. Department of Energy 2010; European Commission Enterprise and Industry 2010). There are several reasons for this change in view. Rare earth metals are proving to be vital inputs for developing green technologies and evolving high-tech uses, including the military, with ever-growing demand. There are limited sites today where rare earth metals are mined commercially. This limit has led to the mining and processing of rare earth metals to be largely a monopoly of China. Rare earth metals are mined together with other metals leading to supply complications that do not respond quickly to price changes.

G. A. Campbell (✉)
School of Business and Economics, Michigan Technological University, Houghton, MI 49931, USA
e-mail: gacampbe@mtu.edu

Events during the 2008–2013 time period have intensified the market and strategic concerns about the usage of rare earth metals. China began limiting its production and export quotas of rare earth metals and raising taxes on exports. The reasons given by the Chinese government for these actions were to increase environmental protection and to promote the capture of more of the value-added of rare earth production domestically, specifically in new green technologies where it has a goal to be a world leader (Information Office of the State Council 2012). In addition, the Chinese government has been seen as willing to use rare earth export restrictions for political purposes. China has been accused by Japan of restricting rare earth supplies to Japan during a political confrontation over a disputed territory in September 2010. As a consequence, the demand for specific rare earth metals has surged at times because of the additional demands created by stockpiling and speculation in response to uncertainty of supplies in the future. Accordingly, the Chinese domestic price and international market price of rare earth products have seen rapid and dramatic increases over short periods of time. The market situation and prices of rare earths are complicated further by the mixing of the individual metals in varying proportions in the source minerals and by the need often to mine rare earths with other mineral products as a by-product because of the limited options in commercial deposits.

These events have led to a number of actions: investment speculation in rare earth metals, the seeking and opening of alternative rare earth metal sources, and calls by governments around the world to intervene into the market of rare earths to protect perceived strategic and industrial interests. This new strategic concern about rare earth metals is clearly illustrated by the number of papers and studies written about rare earth use and supplies (examples include Hurst 2010; Parthemore 2011; Massari and Ruberti 2012). The aims of this paper are to evaluate the evolving market of rare earths and its behavior and to examine the likely trends of the market as it moves forward. In particular, why has China emerged as the dominant force in the rare earth supply chain and is it likely to continue in the future? Is there a need for other governments to intervene and implement policies to address the situation or will the market handle it adequately? In other words, are rare earth metals really the strategic problem they have been made out to be or has the case been overstated? The paper has five sections. The first section explains the sources of rare earth metals. The second section provides a brief overview of the evolving use of rare earth metals. The third section examines the role of China in the market for rare earth metals. The fourth section provides an analysis of the pricing of rare earth metals and its behavior. The fifth section puts all the parts together to provide insights into the behavior of the rare earth metal market and what it means for those producing and using rare earth metals. The paper ends with its conclusions and recommendations.

Availability of rare earth metals

Rare earth metals are chemically similar metals that consist of the 15-lanthanide metals plus the closely related metals yttrium and scandium. Commercially, the metals are often divided into "light" (the first seven lanthanides) and "heavy" (the remaining lanthanides and yttrium). These metals have a variety of uses as a group or as individual metals. The significance of use of the individual metals varies greatly. The close chemical similarity of the rare earth metals causes them always to be concentrated together in the crust. Although rare earth metals are reasonably common in the crust (more common than many of the other metals we use commercially), they tend not to be highly concentrated in any particular source so commercial deposits are uncommon. Often, rare earth metals are produced as a by-product of a more plentiful product (like iron ore and heavy sands). Within a commercial rare earth deposit, the individual rare earth metals are highly variable in how much of each metal is present in the host minerals. The percentage can vary from 50 % to a trace/zero amount.

There are several commercial mineral sources for rare earth metals. Two important mineral sources for rare earth metals are bastnäsite and monazite. These two minerals consist mainly of the light rare earth metals (especially cerium, lanthanum, and neodymium). Monazite has been recovered as a by-product of heavy sands mining in Australia and as a by-product of tin placer mining in Southeast Asia. The commercial use of stand-alone monazite was phased out in the 1990s because of the cost of handling excess radioactive thorium created by processing the mineral relative to the cost of the abundant bastnäsite. Bastnäsite was produced as the main product at the Mountain Pass Mine in California and as by-product of iron ore mining in Bayan Obo, China (Bayan Obo also has monazite present with the associated thorium problem). Mountain Pass halted production during the 2002–2010 period because of China's ability to meet the world's demand for rare earth metals at a lower cost from its by-product production associated with its large iron ore industry, apparent less concern about the environmental cost of recovering rare earths, and less concern about short-term profitability. The minerals xenotine, loparite, and others are small commercial sources of rare earth metals. Ion absorption minerals (clays) are processed in small amounts as commercial sources of heavy rare earth metals in China.

After mining, the rare earth metals found in the minerals must be concentrated since rare earth metals make up a small portion of the ore raw material. Unprocessed rare earth material has little commercial value as a bulk mixture. The concentrate is then processed to create low-purity rare earth mixed compounds, high-purity oxides, or pure metals (out of fluorides). Each additional step of processing requires sophisticated and difficult technology because of the high chemical and physical similarities between the metals. There is a wide range of variation in the types of rare earth products that are demanded by users leading to the need for many processed forms of rare earth products in limited quantities. The result is significant value-added for each additional step of processing done and high cost for high purity.

An important factor associated with the mining and processing of rare earth metals is the damage to the environment that it can cause. The mining of rare earth metals involves creating radioactive waste (from the thorium present in the ores) that can contaminate water and air. Leaching techniques are often used with the mining of heavy rare earth metals and require the use of acid and other damaging liquids. The result is acid and heavy metal waste problems. The processing of rare earth metals involves the use of toxic chemicals that must be controlled and disposed of properly. Problems with waste control and disposal were contributing factors in the closure of facilities like Mountain Pass Mine in the USA and processing facilities in Malaysia. Part of the reason China has captured so much of the production and processing of rare earth metals has been the past willingness to accept environmental damage in lieu of paying higher preventive costs relative to producers elsewhere.

The market economics of producing rare earth metals is very complex. The initial mining of rare earth minerals is often as a by-product of another mineral product. This means that while much of the cost of the initial mining may be paid by the main product operation, the potential supply of the by-product rare earth metals depends on the output of the main product and is independent of the market of rare earth metals. The dominance of China's production of rare earth metals is due in part to the low cost of producing bastnäsite from its iron ore mining and the high level of steel production in China. Excess rare earth material from the iron ore mining operations can simply be stockpiled and processed later as needed. Stockpiled material from the Mountain Pass Mine was still being processed even after the mine had ceased operations.

Within the rare earth minerals, the individual rare earth metals are concentrated as a group. Individual metals must be separated from the other metals present for high value uses. The individual rare earth metals are found in very different proportions in the original minerals. These proportions are independent of how much of each metal is actually demanded in the market place. Accordingly, it is possible to produce too much of some of the metals and too little of others relative to the market demands. The heavy rare earth metals are largely absent in bastnäsite and monazite so other mineral sources must be mined separately in small and costly operations to supply them. The high market concentration of the mining output of rare earth metals and the difficulty of processing the raw material create significant market power for the few suppliers. The complexity of these interwoven relationships means that understanding price trends and their impact can be difficult.

High prices and concerns about China's policies have changed the supply scene in recent years. Mountain Pass Mine in California (operated by Molycorp), once the world's largest source of bastnäsite, has been restarted (Molycorp 2013). The processing of stockpiled material began in 2009. Mining was started again in December 2010 and had passed 19,000 mt per year by mid-2013. Molycorp has also made a major investment in upgrading and expanding associated processing facilities with the mine. Mt. Weld in Australia (operated by Lynas) has begun producing and has reached its phase 1 goal of 11,000 mt per year (Lynas 2013). Higher levels of output are planned. A new and controversial processing facility in Malaysia (Lynas Advanced Materials Plant) has begun to receive and process material from Mt. Weld mine.

It is estimated that currently China holds only 23 % (China's estimate, Information Office of the State Council, 2012) to 36 % (USA's estimate, Humphries 2010) of the world's available and potential reserves of rare earth materials. A commissioned study by the U.S. Geological Survey (2010) determined that there are enough potential sources of commercial rare earth metals in the USA and around the world to meet future needs. Recent events have caused a strong interest in finding new sources of rare earths, particularly for the "heavy" rare earths that are not readily available from current commercial sources. Examples include potential sites at Thor Lake in Canada and Norra Kärr in Sweden that are high in heavy rare earths and low in radioactive waste. Other potential mining sites include Nolans Bore (Australia), Kvanefield (Greenland), Hoidas Lake (Canada), Strange Lake (Canada), and Steenkampskraal (South Africa) (Tien 2013). The growing demand for thorium for some national nuclear programs (suitable for nuclear power needs but not weapons) has made monazite a potential option again as well. Processing facilities are also very limited outside of China. The difficulty of getting new processing facilities approved and opened outside of China as illustrated recently in Malaysia may be a greater problem for diversifying supply then finding raw material to mine (Mining Engineering 2012).

The use of rare earth metals

Initially, industrial uses of rare earth metals were typically low-purity mixtures of the metals, often left in the original ratios found in the source minerals. This type of use avoided the difficult and expensive problems of separating and purifying the individual metals and of the wide variability in the amount of each metal found in the commercial ore sources. The disadvantage was the low value of the mixtures. Over time, usage of rare earth metals has shifted to higher purity, separated materials. The end uses of rare earth metals include the following: catalysts for automobile converters and petroleum refining; metallurgical uses for alloying, glass polishing, and ceramics; screen phosphors; and permanent magnets. The direct demand for rare earth metals varies across countries depending on what products are being produced domestically and what is being imported. It also changes over time as industries evolve. Most of the world consumes rare earth metals in the indirect form of imports of components and final products because the processing of rare earth metals has become concentrated in a few locations. In the case of the USA, the direct apparent consumption of rare earths peaked in 1996. By 2008, apparent consumption of rare earths had dropped to 30 % of the amount for 1996 (see Fig. 1). This shift is an indication of a movement in the USA away from the use of rare earth metals to make final products to importing final products that contain rare earth metals. This trend is not limited to the USA by any means.

For the USA, the largest direct use (62 % in 2012) of rare earth metals is as catalyst materials for refining petroleum,

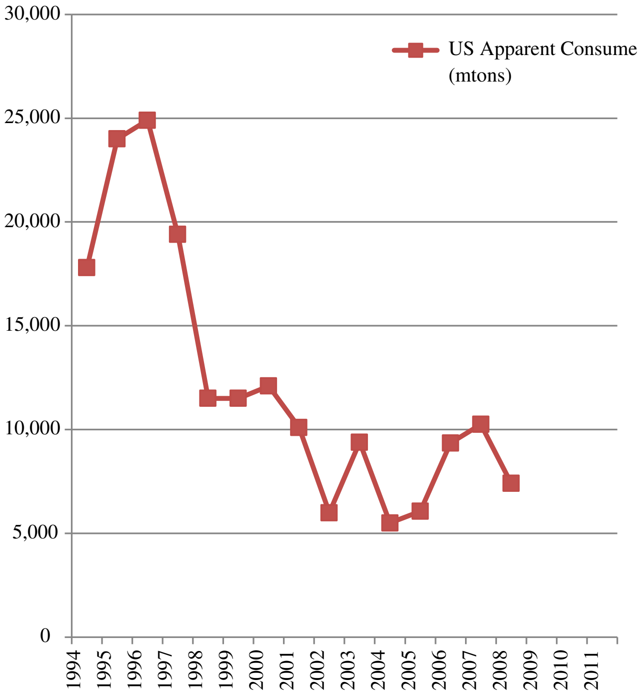

Fig. 1 US apparent consumption, 1994–2008 (U.S. Geological Survey 2013)

chemical processes, and converters for cars (U.S. Geological Survey 2013). Catalysts consist of the most common and lowest cost of the individual rare earth metals (lanthanum and cerium). This makes the USA one of the largest users of rare earth metals for catalysts as compared with the rest of the world. Catalysts are of relatively low value.

The USA has little capacity for producing products like permanent magnets, metal alloys, and phosphors that use rare earth metals as compared to China and Japan. Hitachi Metals announced in 2011 that they were planning to produce permanent magnets in China Grove, North Carolina which will provide a domestic source of permanent magnets for the USA. The significant uses of rare earth metals by value are in permanent magnets and phosphors because of their need for high-purity and less available rare earth metals (praseodymium, neodymium, europium, gadolinium, and terbium). The specialized uses of rare earth metals for permanent magnets and metal alloys are significant in green and high-tech products and the variety of applications are growing rapidly.

Despite the importance of the uses of rare earth metals, the metals themselves are used in small amounts across many uses. In 2011, the total mining output for all rare earths was approximately 111,000 metric tons. This compares to 16.1 million metric tons for the much less common (by crustal abundance) copper. Rare earth metals are largely used in alloys as well. The small amounts and alloying use make it very difficult to recycle rare earth metals commercially. Recycling accounts for less than 1 % of the supply and is not an important source of the metals.

It is hard to generalize the future consumption trends for rare earth metals because of the variety of metals involved and the newness of many of the uses. However, it seems likely that the consumption of rare earths will increase as the use of green technologies and high-tech applications expand. This would indicate that a period of significant increase in consumption of rare earth metals is ahead as the products move into mass production. Individual rare earth metals are consumed in different products and in different quantities. The available supplies of individual rare earth metals are determined by the percentages present in the ores being mined. This means that supplies of the individual metals may not and will not match up with the desired levels of consumption needed. Even with adequate levels of rare earth metal production in general, some individual metals can be in short supply. This is particularly likely for several of the heavy rare earth metals that are used in green and high-tech uses. These heavy rare earth metals are not present to any degree in the bastnäsite and monazite minerals that are presently being mined. The commercial sources of heavy rare earth metals are small ion adsorption clay mines in southern China. Indications are that heavy rare earth metals like dysprosium, europium, and terbium could provide supply concerns as the demand for their use grows. Increasingly, the USA and other countries are not involved in the direct use of rare earth metals (except for catalysts) but import the final products.

China and rare earth metals

Increasingly, the focus of the market of rare earth metals is on China and its decisions about how to develop its rare earth resources. China began producing rare earth metals in the 1950s. In 1992, Deng Xiaoping urged the exporting of rare earth metals as a way to generate needed revenue and international currency. China became a significant world producer during the 1990s and was the dominant world producer by the 2000s. Most of the rare earth production comes from Baotou, Inner Mongolia (over 80 %) in association with iron ore mining (Chen (2010). This production is mainly of light rare earth metals. A small amount of heavy rare earth metals are produced in Jiangxi and the surrounding southern provinces. Strong domestic competition and little environmental protection allowed China to push down the prices of rare earth metals to the point where producers elsewhere were not able to compete. China dominates the production of rare earth metals along the complete length of the supply chain: 97 % of mine production, 97 % of oxides, 90 % of metal alloys, 75 % of neodymium permanent magnets, and 60 % of samarium permanent magnets (Humphries 2010). On the other side of the market, China has become a significant user of rare earth metals. Consumption has grown significantly since 2004 and accounts for 70 % of the world's total consumption of rare earth metals. The main area of growth has been in new materials developed for emerging green and high-tech products.

There is widespread concern internationally about the degree of control that China has over the supply chain of rare earth metals. For example, the USA has little capacity to process rare earth metals directly and must depend on the importation of rare earth metals in intermediate and final products. The direct use of rare earth metals by the USA has dropped dramatically during the 1985–2011 period. In this period, Mountain Pass Mine and most of the processing facilities of rare earth metals in the USA closed down. This is reflected by the steep decline in apparent consumption of rare earth metals in the USA since the late 1990s (Fig. 1). The USA has only two facilities to make samarium-cobalt permanent magnets and none to make neodymium-iron-boron magnets (Humphries 2010) although this will change with Hitachi Metals' new facility in North Carolina.

The large increase (and in recent years rapid) in the production and consumption of rare earth metals has created problems for China as well. The boom in rare earth metals has led to numerous small, unsanctioned operations, smuggling, and hoarding within China that are outside the government's regulation, especially in the small mines in the south that produce heavy rare earth metals. The mining and processing of rare earth metals has significant environmental impacts that are often not mitigated especially with the rapid uncontrolled growth in recent years. The waste material is radioactive (thorium). Hazardous chemicals are used to process the material and must be disposed of properly, but the waste is often simply dumped into the local environment. The large-scale production and exporting of rare earth metals is also rapidly depleting the rare earth reserves of China just as their own demand is rapidly increasing from new green technology industries.

In response to the growing importance of the market of rare earth metals, the government of China designated rare earth metals "strategic commodities" in 2007. With this new emphasis, China's government has introduced a variety of programs to bring rare earth metal mining and processing more under its control (Chen 2010). It placed tariffs on rare earth metal exports, and these tariffs have risen steadily since 2006. It has reduced annual export quotas for rare earth metals and prohibited the exportation of some rare earth compounds. In 2012, the quota was set at 31,130 metric tons out of the roughly 130,000 tons of projected annual production. China's government has restricted the export of processing technology. It has tried to consolidate the mining and industry of rare earth metals into a few larger state-controlled firms. In 2012, rules were passed to close small mines (20,000 metric tons per year) and smelters (2,000 metric tons per year). Foreign investment in rare earth mining is also prohibited although it is allowed for processing and production facilities. It is estimated by the Chinese government that this would reduce capacity by 20 %. Other efforts to coordinate industry activity among the main producers have been made (trade association, metal exchange, etc.). China has introduced efforts to improve the environmental protection performance of rare earth metal mining and processing through requiring improved standards and slowing the introduction of new facilities until the existing ones meet the new standards. Efforts have been made to encourage the domestic use of rare earth metals for green technology products instead of being exported. Rare earth metals are cheaper and more available domestically than outside the country. The price differential and uncertainty of the export quota has already caused some outside processors and users to move their facilities into China. The FOB price includes the VAT (13 %), export tax (15–25 %), and the quota impact. It is hoped by the government that goals of more stable (and higher) rare earth metal prices, more value-added through leadership in green technologies and products, and more protection of the environment and rare earth metal reserves can be achieved through these actions.

The rare earth metal policies of China have significant implications for the international market for rare earth metals (Wübbeke 2013). A major international fear is the possible manipulation of export quotas, tariffs, and production of rare earth metals by the Chinese government to push up international rare earth metal prices and to force users of rare earth metals to move their facilities to China where China would realize more of the value-added of the use of rare earth metals. The Chinese government counters by arguing the goal is to improve environmental compliance and industry performance although they do support the domestic use of rare earth metals as a goal. A dispute with Japan that led to an alleged halt to the shipments of rare earth metals to Japan also raised concerns about political risks in the market of rare earth metals due to the high concentration in China. In response, the USA, European Union, and Japan filed a complaint against China for its behavior in the international markets for rare earths and other minor metals with the World Trade Organization (WTO) in July 2012. In October 2013, the WTO ruled against China although a sharp drop in the demand of rare earths had already reduced fears and concerns.

Chinese companies have also been involved in providing funding for new projects elsewhere in the world creating concern about China trying to control outside sources as well. However, analysis by Moran (2010) argues that this investment is helping to create more supply and competition in the rare earth metal markets than would otherwise occur and is not increasing the overall market power of China. The increasing domestic demand for rare earth metals in China could soon surpass its ability to produce rare earth metals domestically and new sources need to be developed. China is helping to fund new sources that are not controlled by the existing concentrated industry outside of China. Even so, an effort by China Non-Ferrous Metal Mining Company to buy controlling interest in Lynas (and Mt. Weld) was stopped by the Australian government in 2009.

Prices

The price behavior of rare earth metals is directly affected by several important production factors. First, rare earth metals have a derived demand (Tilton 1985). Rare earth metals are demanded as an input of production for making a final good and not for their own sake. It is only the desired characteristics that the rare earth metals can bring to a good that drives the demand. As is typical for material inputs of production, rare earth metals make up a small share of the final cost of the product and can be hard to substitute away from in the short run because of technical considerations for production. These factors tend to make the derived demand for material inputs of production to be insensitive to price in the short run since demand will not change in response to price changes in the short run unless the changes are large. Some applications of individual rare earth metals may be more susceptible to substitution than others because individual rare earth metals are very similar and may be directly substituted for each other in some cases (neodymium for samarium in permanent magnets for example), making them somewhat more sensitive to price changes than otherwise.

Second, rare earth metals are mined together as joint products. They are always mined together but are present in very different individual proportions. The proportion of rare earth metals for Mountain Pass and Bayan Obo is similar and consists mainly of the light metals cerium and lanthanum with smaller amounts of praseodymium. The other metals are present in very small or trace amounts. There is no reason for the market demand for individual rare earth metals to match up with the mineral proportions although there will be some correlation since the most common and cheapest rare earth metals are most likely to find uses and vice versa. Changing the mined quantity of rare earth ores will change the availability of the individual rare earth metals by a fixed proportion. This can lead to overproduction or underproduction of some of the rare earth metals relative to market conditions. An example of this type of disequilibrium was seen for samarium in the late 1980s. There was a surge in the demand for samarium-cobalt permanent magnets. Samarium makes up a very small percent of commercial rare earth minerals (0.8 %) so there was no corresponding surge in samarium production. The market price rose rapidly. The solution was to move to the alternate neodymium-iron-boron permanent magnet. Neodymium is present in much greater quantities in commercial rare earth minerals (12–18 %), and the supply can be increased more readily. The price of samarium dropped back to its presurge level quickly with only a small increase in neodymium prices (Campbell 1996).

Third, rare earth minerals can be mined commercially alone (Mountain Pass) or as a by-product from mining another mineral product (Banyan Obo). Rare earth production as a by-product of mining other minerals like iron ore and ilmenite has a significant impact on market pricing behavior (Brooks 1965). The production of the main product is independent of the market for the by-product rare earth metals. The production of the main product determines the quantity of by-product material that is potentially available for use. The degree of separation from the by-product(s) needed to produce the main product commercially and the cost of additional processing required for the commercial use of the by-product will determine the cost of extracting the by-product. Market forces then establish how much of the potential by-product material will be processed. Therefore, the market has a limited ability in the short run to change the level of the output. It depends significantly on the situation of the main product market. One reason for the resulting monopoly of rare earth mining by China was the large supply of by-product rare earth metals produced in association with the large iron ore mining operations in Bayan Obo in competition with the production by the main product rare earth mine at Mountain Pass.

Fourth, the near monopoly position of China in mining and processing rare earth metals has had an obvious market impact. The goals and actions of the Chinese government have led to the short-run reduction of rare earth metals on world markets at a time when rare earth metals are increasingly demanded for new materials used in high-tech and green technologies. This situation led to shortages and dramatically higher prices given the price inelastic nature of the supply and demand for rare earth metals. The run-up of rare earth metal prices over 2009–2012 was staggering, from at least 700 to 3,000 % depending on the metal. This is indicative of a market where short-run supply and demand is very price inelastic as predicted. The existing available alternative sources of rare earth metals were very limited. The reduction in export quotas by the Chinese government reduced supplies for which there were no immediate alternatives. This can change in time but not immediately. There were also reports of hoarding and stockpiling by Chinese producers in anticipation of even higher prices that created domestic shortages and increased the pressure for higher quotas. In addition, the stockpiling of rare earth metals for speculative/insurance purposes increased the demand even further worldwide. The rare earth metal prices continued to rise until a market response to the shortage occurred. The very high prices brought about a significant reduction in the consumption of rare earths as users finally responded to the sharp price increases. Demand also decreased with the weaker global economy as much of the demand for rare earth metals is driven by industrial output. This response continued as China enacted policies to try to

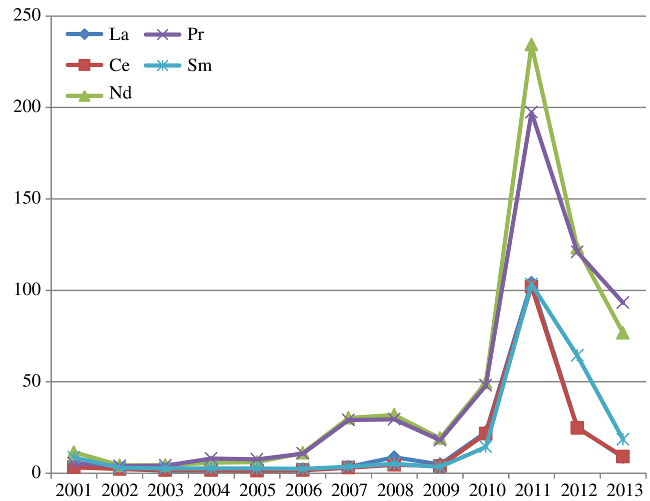

Fig. 2 Annual prices for selected light rare earth metals, 2001–2013 (Lynas 2014)

stabilize the rare earth prices as they dropped in the late 2011 through early 2013, by 80 % for the light metals and 50–60 % for the heavier metals.

Price trends of individual rare earth metals can be used to see if any identifiable patterns may be found that would give insights into market behavior. Price data is difficult to get and use for rare earth metals. Rare earth metals are processed and sold in many forms (that change frequently) leading to difficulties in creating a consistent price time series. The international market for rare earth metals and their products is very concentrated, and pricing information is very limited as well. The analysis here makes use of pricing information for the commonly sold oxides made available by Lynas (2014). Figures 2 (light rare earth metals) and 3 (heavy rare earth metals) show annual prices for selected rare earth metal oxides for 2001–2013. Two figures are used because of the scale differences in price.

One factor of interest is how closely rare earth metal prices move together. A high level of correlation would suggest broader factors at work like market concentration, general speculation, global economic conditions, and industrial policies. A lower level of correlation would suggest that prices are moving more in response to individual market supply and demand conditions than general market conditions. Correlations between the price of lanthanum oxide and selected other rare earth oxides over the time period of 2001–2013 are shown in Table 1. A second correlation for the years 2001–2010 is also done for a comparison because of the large increase in price of all the metals in 2011 (Table 1).

The results show a great deal of similarity in behavior over 2001–2013. The correlation between the prices of lanthanum oxide and the other rare earth metal oxides-cerium, neodymium, praseodymium, samarium, dysprosium, europium, and terbium is high. There is some variation between the light and heavy rare earths. Terbium and europium oxide have the lowest correlations at 0.824 and 0.820. The prices moved very much together. Once 2011–2013 is dropped from the time series, other variations between prices can be checked. The real outlier is terbium at 0.554 (caused by a price drop in 2009). The next lowest is europium at 0.818.

A look at monthly price trends for the Chinese domestic price during 2011–2013 shows some variation, especially between light and heavy metals (Table 2). Here, europium is the outlier at 0.529. This result suggests that the Chinese domestic prices are being influenced by individual supply

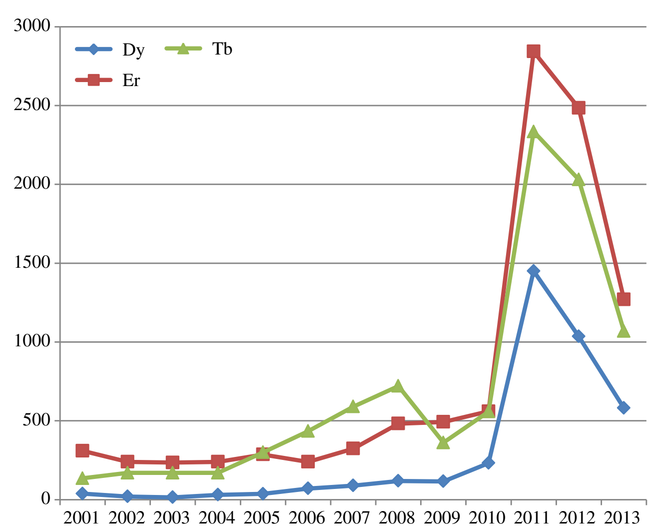

Fig. 3 Prices for selected heavy rare earth metals, 2001–2013 (Lynas 2014)

Table 1 Price correlations of rare earth metals

	Ce	Nd	Pr	Sm	Dy	Tb	Er
La correlation (2001–2013)	0.999	0.941	0.891	0.927	0.873	0.824	0.820
La correlation (2001–2010)	0.981	0.883	0.890	0.989	0.933	0.554	0.818

and demand factors as well as general trends in the monthly price. However, when the prices are adjusted to an annual rate for the years 2009–2013, the variation largely disappears. These results suggest that the individual factors are quickly outweighed by the general market trends.

However, the extent that price changed for each metal did vary greatly. Some of the oxide prices showed a much higher rate of price increase (lanthanum, cerium, praseodymium, dysprosium) than others (neodymium, samarium, europium, and terbium). This is an interesting result given the anecdotal evidence for underproduction of some of the heavy rare earths. With the exception of dysprosium, the price increases are greatest with the more commonly used light metals instead of the heavy metals (see Table 3). Noteworthy is the fact that the two key metals for permanent magnets (neodymium and samarium) were not the ones with the highest jump in price either. Despite the concern expressed by analyst/industry about shortages, the price data shows that it is the more common light metals that show the most sign of shortages, not the rarer, heavy metals (with the exception of dysprosium). It is easy to be impressed by the absolute price increases of the very expensive heavy metals, but it is the cheaper light metals that have had the largest percent increases.

Another useful comparison is to look at how price changes vary between the Chinese domestic price and the international price. This was done for the period of 2009 through 2012 (Table 4). In three cases (lanthanum, cerium, and samarium), the international price increase was much less than in China. Otherwise, the changes were roughly the same. Again, the outliers were lighter metals with lanthanum and cerium being the most common of the rare earth metals in the commercial minerals.

One should not draw too strong of conclusions from looking at a small sample of price behavior, but some interesting possibilities can be raised. During the measured time period, the international rare earth metal prices tended to move up and down together. However, there are individual differences as well. This is also the case for the Chinese domestic prices, particularly between the light and heavy metals that are mined separately. These results suggest that the price movement in general is based on factors common across all the rare earth metals, but there is some influence from individual market supply-demand factors as well. This influence is particularly noticeable for some of the heavy rare earth metals. This would indicate a greater market importance for supply-demand conditions for these metal prices and, therefore, more chance for shortages and surpluses.

Table 2 Correlations for Chinese domestic prices

	Ce	Nd	Pr	Sm	Dy	Tb	Er
La correlation (monthly)	0.980	0.926	0.861	0.883	0.875	0.860	0.529
La correlation (annual)	0.996	0.976	0.871	0.965	0.995	0.985	0.988

Table 3 Percent increase of international prices from 2001 to 2011

	La	Ce	Nd	Pr	Sm	Dy	Tb	Er
% Increase	4,000	3,100	2,000	3,700	1,200	3,800	900	1,700

Differences in individual metal markets do seem to be reflected in how much international prices go up or down. These differences can be quite significant (compare lanthanum and terbium in Table 3 for example). A possible reason for this is the difference in short-run price elasticity of demand (how much prices must change to bring about a market adjustment). One reason may be that users are more willing to accept higher price increases for the lower cost light metals than the more expensive heavy metals. Another reason may be differences in substitution possibilities. For example, neodymium and samarium are used in high-valued permanent magnets, but they also showed lesser price increases as compared to some metals used in less valuable products. The two metals, however, are substitutes for each other and allow some flexibility in use as discussed earlier in the paper. If price elasticity is the factor, the results suggest that the more common light metals have been less responsive to price than the less common, heavy metals in the studied time period (with the notable exception of dysprosium which showed a pattern of short supply).

Analysis of the situation

Rare earth metals have taken on new strategic value and concern in the twenty-first century as materials needed for new technologies and products. Accordingly, questions are being raised by businesses and governments around the world about what needs to be done about the market of rare earth metals in response to the current situation. From the

Table 4 Comparison of price increases, 2009–2012

	La	Ce	Nd	Pr	Sm	Dy	Tb	Er
% International	500	900	1,100	900	580	1,240	580	630
% China	2,100	2,600	1,200	1,100	3,040	1,250	580	650

discussion of the market situation, there are three main themes that need to be addressed in answering these questions: Will there be enough rare earths to meet demand, particularly heavy rare earth metals? Is the supply of rare earth metals too concentrated? What will be China's impact on the market?

The U.S. Geological Survey (2010) reported that there are ample potentially commercial sites for rare earths geologically. Much of this potential is outside of China. However, the problem is more about whether or not the sites can be developed. As noted earlier, the mining and processing of rare earths is very damaging environmentally unless strict and costly measures are taken. One of the contributing factors to the closure of Mountain Pass Mine in 2002 was radioactive water spills. The opening of a new large processing facility in Malaysia by Lynas faced difficulties because of past environmental damage from rare earth processing in the country (Mining Engineering 2012). It is apparent that a large part of the question about the supply of rare earths and the concentration of the production will be about the willingness of communities to allow the production of rare earths and not just the physical resources available for use. One reason China has its commanding control of the production of rare earths is its willingness in the past to accept the environmental damage associated with it.

Another difficulty for mining rare earth metals outside of China is dealing with the by-production nature of China's production. Most of the mining of rare earths done in China is as a by-product of large iron ore mining operations. This type of production typically has a cost advantage over main product mining of rare earths. During extended periods of low prices (historically common for rare earth metals, Campbell 1996), it is hard for main product mines to compete (Mountain Pass Mine for example). A by-product producer like China is better able to continue to produce since some of the costs are being met by the iron ore operations. Most of the new projected mining sites would be main product production.

These production conditions have led to the use of China's rare earth resources instead of others. The result is that China has only 23–35 % of the world's potential future supply of rare earths but accounts for over 90 % of mining output. Clearly, sites outside of China will need to be developed to meet the growing demand for rare earths, especially since China's own demand (70 % of the total) in the future could outgrow its domestic production and make it an importer of rare earth materials (Tse 2011). However, past market conditions have clearly favored production in China.

Due to the nature of mining and processing rare earths, market concentration on the supply side has always been an issue (before China, it was the USA). On the mining side, there are limited sites. On the processing side, there is the need for very specialized skills and limited output of numerous products. Historical pricing trends tend to support the view of market concentration and the use of market power (Campbell 1996). Recent consolidations in the rare earth processing industry (as an example: Molycorp's takeover of Neo Material Technologies in 2012) suggest that just expanding the locations that rare earth metals are mined will not be enough to alter the importance of China in the rare earth industry and the degree of market power present outside of China. What is important is the diversification of the processing and use of rare earth metals, and the market is having difficulty moving away from China.

Given the importance of China in all aspects of the supply chain of rare earth metals and the likelihood it will keep that importance for some time, what is the likely impact that China will have on the future development of the rare earth metal market? A key concern is that China will negatively impact the international market as it follows its own domestic policies. The Chinese government has already been accused of a willingness to use rare earth supplies as a bargaining factor in international affairs (Japan) and to meet domestic goals (improved environmental protection and more control of output). Chinese policy is clearly aimed at making the domestic use of rare earth metals a priority over the international market. The aim of the policy is for China to be a large user of rare earth metals (consuming all of its own domestic production) with special emphasis on green technologies for the value-added. However, international users of rare earth metals are still attracted to China for its low cost of mining, processing, and manufacturing. When faced with the choice between short-run cost savings in China versus long-run diversity benefits, companies are choosing short-run cost savings in many cases.

Conclusions and recommendations

An analysis of the market of rare earth metals shows a challenging market for its participants. Market conditions tend to favor a concentrated industry centered on China with severe hurdles to be overcome for global diversification to occur, especially in processing. Pricing behavior shows a market where low price elasticities of demand and supply can lead to volatile swings in prices. Consumption of rare earth metals is also dependent on trends in other industries because of its derived demand nature. Recent experience suggests that users are able to respond quicker to price changes than suppliers, indicating that users are more likely to make the necessary adjustments to bring supply-demand into balance in the short run than suppliers who will take a longer to respond.

Should other governments follow the lead of China and develop policies to manage the production and use of rare earth metals in their country or just let the market operate freely? Should rare earth metals be of explicit strategic concern instead of being left to the markets? For many countries like the USA, there is little capacity in any aspect of the supply chain of rare earth metals, not just mining. The USA is a significant producer of catalysts from cerium and lanthanum material available domestically or imported but largely depends on imports for permanent magnets, phosphors, and other key products although some new capacity is being created. This situation is typical outside of China although some countries like Japan have significant processing capacity without mining resources. Additional mining of rare earth metals without additional processing is not enough to improve the situation adequately. Accordingly, government programs solely to promote rare earth mining are not the solution.

Strategically, what needs to be done over time is to diversify the supply chain of rare earth metals outside of China. Even the Chinese government supports this goal (at least for mining and early-staged processing). Chinese companies are active investors outside of China as they seek to create new sources because of the belief that China will need to be an importer in the near future as consumption in China grows in response to new and expanding industries. However, this change would probably involve higher processing costs initially and face strong public opposition to the increased environmental damage and risk such production would entail. The ability to diversify outside of China, therefore, depends on the willingness of others outside of China to face the cost and environmental risk of producing rare earth metals and their products. The easiest solution (not necessarily the best) is to avoid these problems by continuing to let China handle the production and processing of rare earth metals with China retaining the control that it has over the market.

Given the difficulty for a government to create a complete supply chain, market forces would seem to be the best response to the situation. However, in the past, that approach has led to China's strong market position. Interestingly, much of the development of the industry of rare earth metals in China has been market-driven, and it is only within the last few years that the government has stepped in to try to control it. Despite the rhetoric and panics at times, China has been a force that has maintained low prices and supply in the market in the past. Even the more restrictive behavior in recent years has not prevented users from getting the needed supplies (the restrictive quota in 2010 was not completely used because of insufficient demand). A bigger concern seems to be the growing possibility that China will become the dominant producer of key products that use rare earth metals in green, high-tech, and military applications. China's government is very open that this a major aim of its policies about rare earth metals.

The important need is the products that use rare earth metals, not the metals themselves. It would not be strategically sound to let any one region be the dominant producer of these vital products for advancement in many key industries. The market will develop rare earth resources and processing capacity outside of China if the need is there and if there are adequate resources and skills to do that. The demand needs to be there as well and that requires much more effort in development and investment. The promotion of viable industries in green technologies and high-tech applications outside of China would be the area of most effective use of government policy toward rare earth metals. Such an investment will be costly and long term and is less likely to be achieved solely by the market place. Government policy can offset some of the financial risk for the private sector seeking to develop these types of industries in order to offset some of the strategic risk for the country of being too dependent on one source.

References

Brooks D (1965) Supply and competition in minor metals. Resources for the future. The John Hopkins Press, Baltimore

Campbell GA (1996) Economic relationships and market trends of the rare earths. J Miner Policy Bus Environ 12(2):2–11

Chen Z (2010) Outline on the development and policies of China rare earth industry. Office of the Chinese Society of Rare Earths, Beijing

European Commission Enterprise and Industry (2010) Critical materials for the EU. Report of the Ad-hoc Working Group on defining critical raw materials, Brussels

Humphries M (2010) Rare earth elements: the global supply chain. Congressional Research Service R41347, Washington DC. Available at: www.crs.gov

Hurst C (2010) China's rare earth elements industry: what can the West learn? Institute for the Analysis of Global Security, Washington DC

Information Office of the State Council (2012) Situation and policies of China's rare earth industry, Beijing. Accessed at: news.xinhuanet.com/English/business

Lynas (2013) Annual report, Sydney. Available at: www.lynascorp.com

Lynas (2014) What are their prices? Sydney. Accessed at: www.lynascorp.com

Massari S, Ruberti M (2012) Rare earth elements as critical raw materials. Focus on international markets and future strategies. Resour Policy 38(1):36–43

Maull HW (1984) Energy, minerals & Western security. The John Hopkins University Press, Baltimore

Mining Engineering (2012) Lynas' processing plan halted. 64 (8), 56

Molycorp (2013) Year in review: 2012. Greenwood Village. Available at: www.mo;ycorp.com

Moran TH (2010) China's strategy to secure natural resources: risks, dangers, and opportunities. Peterson Institute for International Economics, Washington DC

Nappi C (1993) China and Western nonferrous metal markets: threats or opportunities. Centre for Resources Studies, Queen's University, Kingston, Canada

National Research Council (2008) Minerals, critical minerals, and the U.S. economy. The National Academies Press, Washington, D.C

Parthemore C (2011) Elements of security: mitigating the risks of U.S. dependence on critical minerals. Center for a New American Security, Washington. Available at: www.cnas.org

Tien JC (2013) China's rare earth minerals: reserves, supply and demand. Min Eng 65(12):44–49

Tilton JE (1985) In: Vogely W (ed) The metals. Economics of the mineral industries, 4th edn. American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, pp 383–415

Tse P-K (2011) China's rare-earth industry. U.S. Geological Survey. Open-File Report 2011-1042. , Washington DC. Available at: minerals.usgs.gov/minerals/pubs/mcs

U.S. Department of Energy (2010) Critical materials strategy, Washington DC. Available at: www.energy.gov

U.S. Geological Survey (2010) The principal rare earth elements deposits of the United States—a summary of domestic deposits and a global perspective. Scientific Investigations Report 2010-5220, Washington DC. Available at: minerals.usgs.gov/minerals/pubs/mcs

U.S. Geological Survey (2013) Rare earths. Mineral commodity summaries, Washington DC. Available at: minerals.usgs.gov/minerals/pubs/mcs

Wübbeke J (2013) Rare earth elements in China: policies and narratives of reinventing an industry. Resour Policy 38(3): 384–394