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Strategic evaluations and mining process optimization towards a strong global REE supply chain

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ABSTRACT

Rare earth elements (REE) have turned from an inconspicuous group of raw materials to critical commodities in the last decade. The insatiable and continuously growing demand for rare earths combined with their small and opaque market has resulted in a global exploration boom that has led to the delineation of extensive resources on every continent. Nevertheless, the special boundary conditions that govern the REE industry require second thoughts and careful evaluations when it comes to the potential exploitation of such resources. Past mistakes, with respect to environmental impacts and uncertain investments, have resulted in an overall uncertainty whether the mining and beneficiation of rare earth elements can be a viable industry in a free market context. This paper attempts to record the erroneous practices of the past and use them as guidelines to strengthen the global REE supply-chain. Moreover, the paper focuses on the assessments that need to be made in order to optimize the mining process and reinforce the growth prospects of the market. An overall assessment tool for the mineability of rare earth deposits is also used to consolidate these evaluations and answer the question, if REE mining can be sustainable.

1. Introduction

It has been five years since the rare earth element crisis and price spike of 2011 when REE gained tremendous publicity and visibility to the general public (Massari & Ruberti, 2013). It was the time that China imposed export restrictions and the world became alarmed that the global high-tech market may suffer from supply restrictions. The crisis was intense but short-lived and the prices have decreased rapidly. Nevertheless, the world was startled, especially in REE importing countries which were and are still totally dependent on Chinese production and exports. Various studies published during the time of crises predicted supply chain disruption (Alonso et al.,

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2012; Humphries, 2012), thus initiating discussions and consultations.

Despite the fact that special market analysts had forecasted that demand may exceed supply (Alonso et al., 2012; Moss, Tzimas, Kara, Willis, & Kooroshy, 2011), we are already in 2016 and actual supply has not been short. Conversely, the forecast for the upcoming years indicates that there will be sufficient supply of rare earth elements to satisfy demand (Roskill, 2015). There is, of course, a disproportion in supply of the individual rare earth elements, not to mention the high demand for some critical rare earths. Neodymium demand, for example, could grow by as much as 700% over the next 25 years, while the respective demand for dysprosium could increase by 2.600% (Alonso et al., 2012). It should be mentioned that REE consist of 16 metallic elements which are generally divided into the Light Rare Earth Elements (LREE) and the Heavy Rare Earth Elements (HREE) with the HREE being much less abundant and far more critical. The attributions to these groups are not distinct but in general lanthanum to gadolinium are called LREE while terbium to lutetium are called HREE. With respect to criticality, a third classification is often introduced; the Critical Rare Earth Elements (CREE), taking into consideration the perspective of their individual supply and demand, as well as the cruciality of their applications and end uses (U.S. Department of Energy, 2011). At the time being, the list of CREE consists primarily of neodymium and dysprosium for which demand will remain in high levels or increase even more and secondarily of terbium, yttrium and europium (Binnemans & Jones, 2015).

The aforementioned crisis was sufficient to inflate a global treasure hunt by way of exploration for REE deposits, but despite the discovery of more than 400 potential projects worldwide and the fact that non-Chinese rare earth producers have entered the market, little has really changed. On the contrary, in mid-2015, the biggest REE mining company outside China, Molycorp, filed for bankruptcy within less than three years after having re-started operations. Hence, it has become apparent that the REE-industry is governed by a set of special boundary conditions which can determine the feasibility of any potential REE mining project. And thus, a sequence of questions was generated. Why non-Chinese suppliers cannot gain a significant market share? How is China dominating the REE market? Is this situation reversible?

The true meaning of the REE crisis was misconceived and wrong actions were taken. Without any doubt the market of rare earth elements is neither open nor transparent. Given the size of the market, only a few of the exploration projects will actually become rare earth mines over the next decade; which ones will go into production is difficult to predict. Many experts tried and still do try to find ways to break the Chinese monopoly. Some analysts express the opinion that there is not a problem in the mining of rare earths rather than in their refining process (Kennedy, 2015). Alternatively, many researchers and REE experts adopt the solution of urban mining and recycling of end-of-life products (Binnemans et al., 2013; ERECON, 2015). Moreover, solutions to the supply problem could be also found on the recovery of rare earths as by products from other kinds of deposits (Emsbo, McLaughlin, Breit, du Bray, & Koening, 2015) or from a multitude of industrial process residues (Binnemans, Jones, Blanpain, Van Gerven, & Pontikes, 2015). These secondary sources could ease the bottleneck of REE global supply, especially in countries that do not have economical and/or operational primary deposits on their territories.

In any case the primary mining sector remains the basic source of rare earth elements and plays a major role within the supply chain of the rare earth industry and thus its optimization shall contribute to strengthening the global REE sector. Hence, a thorough evaluation is made in this paper and an optimization of the rare earth mining process is introduced.

2. Methodology

To be able to solve the issues that aggravate the situation we need to find out what the real problems are. In this paper an attempt is made to spot and analyze past erroneous practices in order to find the answers to the aforementioned questions. Our conceptual approach involves the evaluation of former and current mistakes as well as an analysis of the status quo of the rare earth supply chain. The research is based on empirical and quantitative analysis of information, data and literature which are collected from various sources and are cross-checked. On the occasion of the problems that the REE industry is facing, data from active and future rare earth mining projects are utilized and analyzed with respect to the mining feasibility and environmental impact assessment of these projects. Furthermore, tangible criteria are defined that should be taken into account moving forward and strategic evaluations are made in this direction. These evaluations are thereafter combined with a set of standardized parameters and methodologies in order to optimize the mining process and strengthen the REE global supply chain. Finally, an assessment tool for the optimization of REE mining is illustrated with respect to the defined criteria and the necessity for a secure evaluation method for potential rare earth element mining projects. The structure of the assessment tool is described in detail and how it will contribute to the optimization of the overall REE mining process.

3. Past and current erroneous practices

3.1. *Misinterpretation of the crisis*

A critical assessment of the so-called rare earth crisis reveals a number of important lessons. To begin with, when the prices for any commodity increase by a factor of 10 or even higher in just a few months it is unlikely for these prices to hold there for a long time or even go up again (Knittel & Pindyck, 2013; Pindyck, 2004). Furthermore, there is no secure prediction model for if and when the prices will increase again. During the crisis and while the prices were high, investments appeared to be temptingly easy. This resulted in an exploration boom that multiplied the global rare earth resources and reserves. Speculators bought the stocks of many small mining companies that were fueled by inexperienced investors and that promised to develop new sources of rare earths around the world. In other words, China did try to exercise its monopoly while re-evaluating its long-term strategic plan regarding its domestic REE-industry. Consequently, the rest of the world became rightfully concerned and did roll up sleeves in an attempt to change the current status quo. The conditions changed yet again when the prices plummeted in a relatively short time (Fig. 1).

The prices of the individual REE are in 5-year lows but still above the 2005–2009 average. Cerium and lanthanum currently sell at or below cost. Expanding their production may gradually affect market prices for all the other LREE. For instance an increase in supply by REE separating companies in mid-2014 resulted in a further descending of the prices, especially for dysprosium oxide, praseodymium oxide, and neodymium (Mancheri, 2015). As a consequence, the viability of even major established producers is being challenged, not to mention the development prospects of potential REE-market entrants. Additional LREE suppliers have no chance to establish themselves in the market, and only few of the mines that can produce the above mentioned high-in-demand and commercially recoverable HREE, may start mining activities.

The fact that it takes a few years to advance from the exploration stage to the actual initiation of mining operations was for the benefit of many potential REE producers, since the fall in prices led to second thoughts and re-evaluation of the prospects of their projects. Nevertheless, some mining companies have acted quickly and opportunistically enough to have started mining operations in a shorter time than expected. Molycorp re-activated the only producing U.S. domestic rare earth mine at Mountain Pass. Simultaneously, Lynas extended their drilling program at Mount Weld in Australia and began operations at their concentration plant. Lynas' initial mining activities were completed in 2008, having mined and stockpiled 773.300 tons of ore (How We Mine Rare Earths, 2016). Despite the promising initial expectations however, the situation turned really bad due to a series of factors. Molycorp has incurred great debt and unable to make payments the company filed for bankruptcy in mid-2015. All activities at Mountain Pass ceased at this time. Lynas was facing similar problems and would have gone bust if it was not for a recapitalization in 2014. Despite being the major producer outside China now, the company is still struggling to sustain itself.

3.2. *Bad market analysis*

There are various possible explanations that can be put forward here, both economic and technical. One simple conclusion is that China exercises its monopolistic control to the non-Chinese industries' detriment. The REE market is indeed small and opaque and thus it is extremely difficult to predict its trends. Thus, the most obvious reason is the oversupply of REE in the market. The global consumption is of the order of 100.000–150.000 tons per annum (USGS, 2016) and the two new mines mentioned above would add approximately another 50.000 tons between them, which is actually the consumption of the world outside China. Hence, the supply shortage concerns and the insatiable demand for rare earths during and just after the crisis had turned into a glut on the marketplace.

The 16 rare earth elements share some interesting similarities but at the same time present extremely different characteristics and behaviors that do not at all allow substitutions between the individual elements (Zepf, 2013). In addition REE are not present in equal amounts in their host minerals. Taking into consideration the perspective of their individual supply and demand, as well as the cruciality of their applications and end uses the balance problem has been introduced and described in literature (Binnemans & Jones, 2015). A perfect match between demand and supply of REE would be ideal, yet the existing balance problem is significant enough to terminate any prospects of mining even before getting started.

Hence, the fact that both mines in the United States and Australia are rich in non-critical LREE has played a major role in their current economic situation. But even if their production regarded to high-valued REE, the only way for Molycorp and Lynas to sell the total of their planned production would

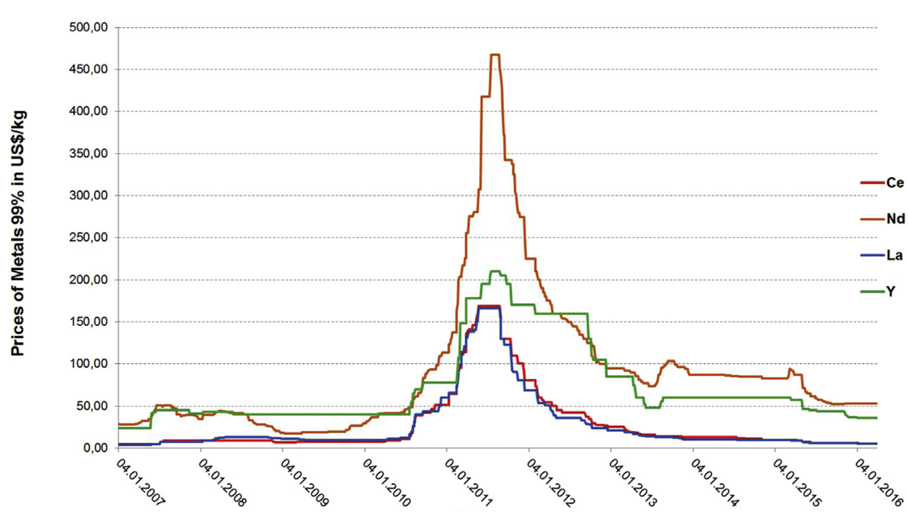

Fig. 1 – Metal prices development during the last 10 years for selected REE (Metal-pages, 2016).

be by marketing into China. This would place them in direct competition with a mature Chinese mining sector with much lower costs and thus far lower prices. However, it is not the mining costs that are determinative – it is the lowest overall cost to the sale point of the REE end product that is more important.

3.3. *The broken supply chain*

Refocusing from the supply and demand issue towards a more general view of the REE supply chain a larger problem appears: the lack of a fully integrated supply chain of rare earth elements outside China. To further highlight the significance of this issue, it must be pointed out that Molycorp was shipping all of its non-cerium and lanthanum oxides to China until recently for refining into high-value metals, alloys and then into valuable end-products (Kennedy, 2015). In addition to that, many non-Chinese end users are producing within China where they have security of both supply and processing expertise. The separation of REE is primarily a technical issue for the global REE-industry, with competency still centered mostly in China. Only a handful of separation plants are settled in the western world, such as the Molycorp facilities in Estonia, the Rhodia plant in France (which is now part of Belgian Solvay and supplying technology to Lynas) and the Lynas Advanced Materials Plant in Malaysia.

Hence there is a lesson to learn from this story, which could serve as an example of how not to act in the future regarding the handling of metals and minerals. Giving up mining activities combined with the know how in the processing and refining of rare earth elements has resulted in the disruption of the supply chain as well as in the loss of the intellectual capital for the world outside of China.

It is well known that China had implemented a well-thought, carefully-crafted, dynamic long-term strategic plan and took the lead in the REE market. It has taken decades and thousands of man-years to the Chinese to achieve their current capacities and capabilities. Yet, when there were no export restrictions and China sold REE at prices everyone was happy to pay then no one worried and the situation was simply ignored. Even after the alarm was sounded, mining and financial analysts faced towards the wrong direction by putting the most emphasis on potential junior rare earth producers who claimed that they would produce in the near term, from single mines, as much material as the Chinese are producing from a combination of numerous mines and refineries constructed and put into operation over a thirty-year period.

Latterly China lowered its domestic production of rare earths in an effort as claimed to control the depletion of Chinese reserves, abolish illegal mining and restrict environmental pollution. Simultaneously, as part of the Chinese governmental strategy to keep the lead in the market, they seek to invest in foreign exploration REE projects and try to lure more companies to move the value added manufacturing part of REE into China where they could still get supplies. After all, restrictions are upon exports, not upon consumption in China, nor upon exports of products made from rare earth elements.

3.4. *Environmental, social license and legislation issues*

On top of the above mentioned oversights, the REE industry is characterized by another drawback, namely environmental impacts. Environmental damage is caused mainly during mining and processing of rare earths. Starting at the point of mining, radioactivity is an important issue. Despite the abundance of numerous REE-bearing minerals only three of them are considered to be the principal REE mineral ores more feasible for the extraction of rare earth metals, namely; bastnaesite, monazite and xenotime; of theme monazite and xenotime ores with radioactive thorium. Bastnaesite is the least problematic source of REO, hardly containing any radioactive thorium. Furthermore, the separation and refinement of REE require the extensive use of hazardous chemicals. The wastes are radioactive and often end up in the ground water and are thus contaminating the surrounding ecosystems (Brumme, 2014). Moreover, rare earths have been used in agriculture as microelement fertilizers; as a result of this application more REE are moving into the ecosystems (Charalampides & Vatalis, 2015). In combination with the large-scale mining activities of REE resources, there have been substantial increases in the contamination levels of soil and water around the mining areas in China. Therefore, the presence of excessive contents of rare earth elements in soils may have serious impact on the surrounding ecosystems, groundwater and human health (Li, Chen, Chen, & Zhang, 2013).

The environmental pollution legacy that the REE industry has built in China over the last decades has raised public concerns and social arguments as regards to the exploitation of REE deposits all over the world. Rare earths have gained the reputation of dirty elements and authorities often hesitate over the development of REE mining projects. Lax compliance with the law in China has resulted in detrimental environmental effects as well as in illegal mining and smuggling of REE (Ali, 2014). Contrastingly, overly strict environmental regulations forced all rare earth mining and processing activities in the United States to stop, while processing plants also in Malaysia were closed down. Meanwhile, other countries are lacking proper legislation for the rare earth industry due to never having had industrial activities in this field in the past. This legislation gap in many countries has led to unnecessary delays and lengthy bureaucratic procedures. The regulatory framework malfunctions with regards to the establishment of refinery plants for the processing of rare earth elements as well. There is an obvious absence of national and international policy for rare earth cooperative that would strengthen the REE global supply chain.

4. Results

Judging from the list of arguments above it becomes apparent that the efforts to establish a REE value chain outside China has largely failed. This includes the attempts to establish an active mining sector in this field, while urban mining and recycling of rare earths are still on an early stage. The fundamentals of the REE sector have thus not changed, but may rather become even more strained. With its growing middle class and technological advances, China now consumes the majority of what it produces, in addition to having greatly reduced foreign exports in an effort to build reserves. This practically means that China will retain or even escalate export restrictions while selling at incomparably low prices, in a variation of a carrot and stick approach. Unless the geostrategic approach of China does not change – the rest of the industrialized world will ultimately need to disengage from the unilateral dependency – by establishing a functioning REE value chain outside China. This value chain should be based on the optimization of the mining sector, as well as on the establishment and amplification of a REE recycling policy. Some primary assessments to be made in this effort are described below.

4.1. REE market evaluation

The Chinese economy is changing from one that is export-driven to one that is consumer-driven (McKinsey & Company, 2012; Roskill, 2015). At the same time China wants to control both inflation and the value of its national currency. Thus, the Chinese government is implementing a strategic plan on its exports and will allow exports of REE as raw materials only so long as they are produced in excess of domestic needs. Taking into consideration that the abundance of HREE is significantly less, even in China, while their criticality and demand is higher than the respective of LREE, it is likely that the export balance between LREE and HREE will tilt in favor of light rare earths. Therefore surpluses will be found in most of the light rare earths, except may be of neodymium that could be in slight shortfall. However, secondary production of neodymium from scrap can make up any of this deficiency (Roskill, 2015). Recent research in the United States points out that the size and concentration of HREE as by products in some unmined U.S. phosphorites predominates over the world's richest rare earth deposits (Emsbo et al., 2015). This endowment, combined with the ease of extraction of rare earths from phosphorites, indicates that such deposits could be evaluated as a primary source of HREE with the potential to resolve the supply shortage. Moreover, growth in demand for HREE has somewhat declined since the crisis of 2011. Hence, the forecast for the next years indicates an unlikelihood of supply shortage for both LREE and HREE (Fig. 2).

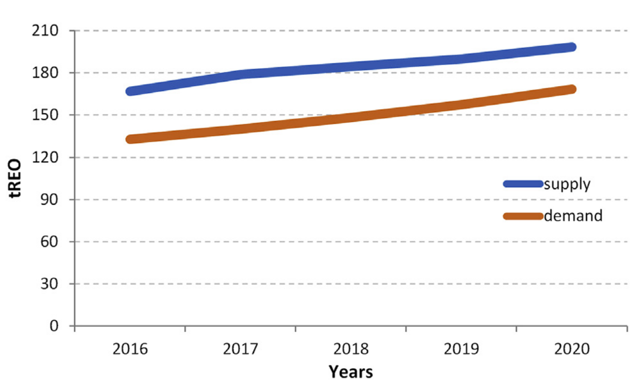

Fig. 2 – Rare earth overall supply/demand forecast (Roskill, 2015).

By all means, each one of the sixteen elements that are referred to as REE has its own individual demand drivers, challenges and technology innovations. Several up-to-date scientific publications indicate material flow analyzes of rare earth elements in significant commercial and industrial sectors (Guyonnet et al., 2015; Machacek, Richter, Habib, & Klossek, 2015; Rollat, Guyonnet, Planchon, & Tuduri, 2016). Thus, a generic model that makes assumptions for the entire group of REE will certainly not correspond well to the supply-demand balance of specific HREE such as dysprosium, terbium and yttrium. In some cases, some of these heavy rare earths may essentially no longer be exported from China in any form other than as components in end-products. Hence, before the risk of another REE supply disruption, sustainable and alternative solutions should be adopted; a proper classification of REE resources, the optimization of regulation frameworks as well as the enhancing of urban mining and recyclability of products that contain rare earth elements (ERECON, 2015).

4.2. REE resources classification

Besides market issues, there are more aspects to be considered regarding the value of rare earth ore deposits. Of the hundreds of potential REE projects, very few are in an advanced stage and may commence mining operations within foreseeable future. To our knowledge there are no projects – other than Mountain Pass and Mount Weld that have been mentioned above – close to entering mine construction or exploitation. Some of the resources are characterized as high-grade or large-volume deposits; however, this does not necessarily mean that they will have commercial success.

By terms of commerce, a good investment is considered to meet a growing demand for a material that is scarce. Admittedly, LREE are not rare or even hard to access. They are just currently too expensive to produce outside China – a hard lesson learned recently by Molycorp and Lynas. On the contrary, HREE are hard to find all around the world including China, where even there they are mined in low grade deposits, thus increasing their production costs significantly. This simply means that explored deposits containing high ratios of HREE can produce a commodity that may possibly compete with the Chinese production costs. When considering the commercial potential of a REE deposit grade and tonnage as tangible criteria needs to be accompanied by careful consideration of the balance of REE that is unique to every deposit. The only other commodity type where a similar "basket" of element concentrations is of fundamental concern is the group of platinum metals.

Another important issue concerns the concentration of thorium and uranium, which varies significantly for different rare earth ore bodies. The mining, separation, treatment and disposal of radioactive materials can result in high additional costs, as well as human health and environmental risks. Thus, for the sake of avoiding regulations and liabilities, ore deposits with low concentrations of radioactive elements are highly preferred. Such cases require a careful assessment to find the golden mean between viable mining and environmental protection.

For all the reasons raised above, an objective screening tool would be highly advantageous that will help to identify those REE resources that offer the greatest prospects for future exploitation (Fig. 3). Such an evaluation tool would of course, be dynamic and its result would only serve as tool to arrive at informed business decisions.

4.3. *Optimization of legislation instruments*

Either lax or strict, bad regulation practices of the past have played a major role in perpetuating the current situation. Research has advanced significantly but admittedly there is difficulty in improving practices, laws and policies at mining and processing operations of metals and minerals like REE that are vital to everyday-life commercial and industrial products. There is public perception that the extraction and beneficiation of rare earth elements is necessarily a "dirty business". However, proper design, operation and management of a mine (and related beneficiation industries) together with its associated pollution control systems can greatly reduce all environmental risks.

Furthermore, the recycling legislative framework is mostly based on weight percentages for the whole product. However, rare earths are contained in small quantities in products and thus this concept does not promote their recycling. Therefore regulations should be adjusted to emphasize the importance of minor metals including REE (ERECON, 2015).

Efforts have been made in recent years towards enacting efficient legislation frameworks that will strengthen the supply chain of REE. Nonetheless, all actions taken so far are posed by governments only in national level. The European Union is already on the right track of enacting effective and strict, yet flexible laws. Australia, Canada and the United States are in similar fashion. However, the regulations that govern the REE industry differ from country to country. In some countries, companies find ways to circumvent these legal restrictions through lobbying and in some cases, bribing. A globally accepted protocol is thus required to enforce regulations preventing the contamination of water, air and soil, plus the occurrence of mining accidents.

Meanwhile, the prices for the individual elements are currently set via contracts between sellers and buyers, which make future market trends difficult to predict. Therefore, long-term agreements which would set prices in a transparent manner may be required and are being demanded by an increasing number of REE importing parties (European Commission, 2014). A global REE stock exchange market could be the mean to establish such agreements; however, China could easily introduce distortions to its favor. For that, the World Trade Organisation (WTO) could pledge itself to ensure global free and fair trade of rare earth metals in the way it mediated the conflict over the export restrictions of China in 2009. It was the time when China was found to violate international trade rules, forcing the United States, European Union and Japan to lodge a complaint with the WTO. In 2014 the organization issued the dispute panel reports and forced China to compromise and re-evaluate its export quotas (WTO 2014). Nevertheless, it should be mentioned that the WTO did not resolve this conflict in a timely manner. The time and trade lost during mediation of this dispute contributed to the intensity of the 2010 crisis and 2011 price spike. Such issues call for the need to quicken the decision making procedures.

The rationale behind legislation must be the criticality of REE in combination with the protection of the environment and sustainable mining development. Furthermore, enabling and encouraging the building of processing plants, if possible, close to the mining sites, could further contribute to a sustainable rare earth supply chain.

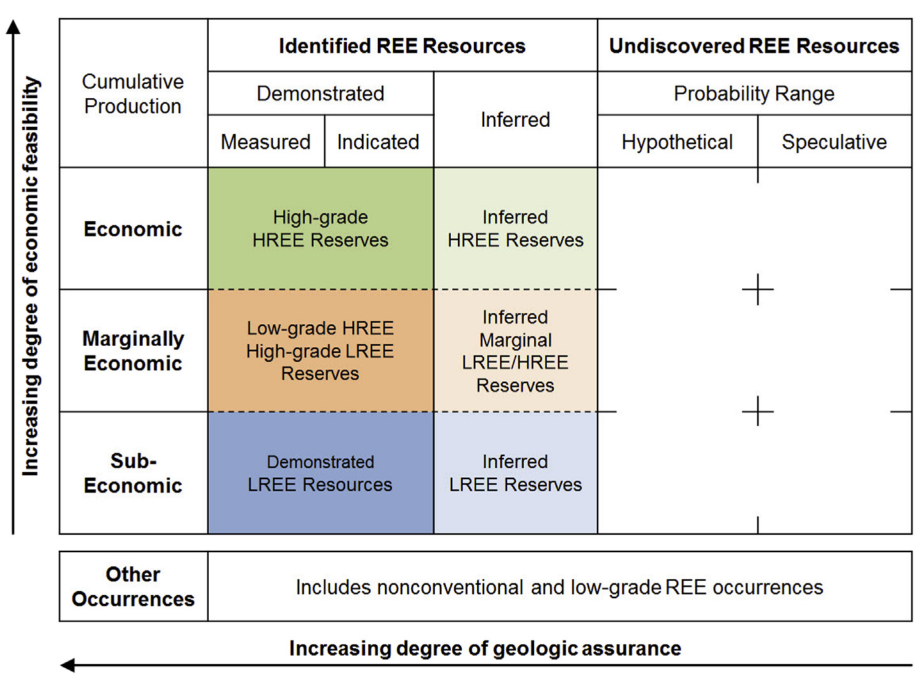

Fig. 3 – Diagram for REE resources (modified after McKelvey, 1972).

4.4. *Rare earth element value chain*

Rare earth elements are without any doubt valuable commodities; however, it is important to point out that the raw excavated ore and ore concentrates are the least valuable forms of the rare earth supply chain. Hence, the only way for REE to become of industrial value is by passing through the value chain until they are converted to high-valued components or finished products (Fig. 4). By taking into account the economic relevance of the complete REE value chain, the economic value of the REE oxides market, which currently is less than US$ 4 billion per annum globally (Roskill, 2015), turns into an industrial global market of all rare earth-dependent goods that exceeds US$7 trillion in value (Kennedy, 2015).

Here lies the secret of success of China – or, to express it differently – the reason for the failure of the rest of the world to compete. In the 1970s, China exported only concentrates of rare earths, while by the end of 1990s it began producing magnets, phosphors and polishing powders (Mancheri, 2015). Nowadays China is the only country that has developed a complete value chain – comprising of hundreds of independent companies dedicated to rare earth research and production, each providing highly differentiated technologies, processing, formulation, or component-specific applications. On the other hand some countries like Japan, Germany, France and the United States do not have a complete supply chain; they import concentrates and oxides, conducting further purification, they manufacture metals as well as other REE-based products and re-export them.

As standalone mining companies cannot replicate a complex REE value chain, this remains the biggest challenge on the path towards a strong and competitive REE-industry outside China. Rare earth oxides or raw material are useless to original equipment manufacturers. Such companies are not equipped to convert them into metals, alloys, and compounds. Thus, what end-customers in the western world require is a complete supply chain from mining to manufacturing that will adjust to their demands.

Efforts have already launched in state-level research centers of expertise around the world with regard to the separation and purification of the individual rare earth elements. The establishment of processing and refining plants in REE mining countries will give the opportunity for rare-earth containing products to be produced in and sourced from alternative value chains. The level of recycling and recovery from REE-containing waste is still limited but it is showing an upward trend. At the European Union level, research and technological development in relation to the recycling and recovery of REE are demonstrating progress (ERECON, 2015). Moreover, policy makers are implementing new strategies and governments are enacting laws for the strengthening of domestic REE supply chains.

Nonetheless, what could immensely contribute towards creating a robust REE industry is an international collaboration of countries that can join forces and build common intellectual capital. Chinese restrictions during the recent years have not only prompted other countries to appeal to the WTO as aforementioned; they were exhorted to cooperate as well. Since 2011 there have been several high level trilateral meetings and workshops between the United States, Japan and the European Union in order to discuss and implement strategies towards a stronger global rare earth supply chain.

5. Discussion

5.1. *In need of a proper mining optimization process*

The REE industry is in need of a strong value chain for rare earths and efforts are currently focusing on improving their refining process and establishing alternative sources of REE like urban mining, recycling of end-of-life products and recovery from secondary residues. The mining industry however, is the root to the rare earth industry. For that the optimization of the mining process can reinforce the prospects of the global REE supply chain.

The typical frame for a mining project evaluation includes the following; initial and advanced exploration, environmental studies, prefeasibility and feasibility studies and permitting. When the assessment process is completed and

Fig. 4 – The rare earth element complete supply chain.

financing is granted then mining activities can start. Several approaches, both linguistic and numerical have been presented in the past regarding the evaluation process of a potential mining project. Most of the schemes focus on determining only the proper surface or underground mining method, since there are so many possible choices and the process is far more complicated.

Nevertheless, as described in the previous paragraphs, there are special boundary conditions that govern the REE mining sector and which have to be carefully assessed. The abundance and distribution of radioactive elements, the deportment of REE between different ore and gangue minerals, as well as the treatment of tailings and their disposal are also important parameters that need assessments. All the above among other factors can determine the overall mineability of a rare earth ore deposit.

The bottom line is that none of the already known mining evaluation tools and mining method selection techniques are taking into consideration most of these criteria many of which are specific to the REE mining industry. Therefore it was decided to develop a new evaluation tool in order to consider the rare earth element industry specificities together with the standardized factors that determine the viability of mining investments.

5.2. *Assessment tool for the mineability of REE deposits*

This assessment tool is not only evaluating the mining method selection process but it identifies social, economic, environmental and technical impact factors. Based on the philosophy of previous linguistic and numerical approaches, this combined tool is based on a step-by-step numerical analytical hierarchical process with weighted criteria. The purpose of building such a tool is to adjust to the specifications of rare earth mining projects, optimize the overall mining procedure and contribute towards robust investment decisions.

The evaluation process has four successive stages. These four stages are proportioned and interconnected (Fig. 5). In the initial stage, the parameters are classified into categories and some critical factors are evaluated to ensure that the REE mining project has the perspectives to be further assessed. The second and third stages are considering the suitability of mining methods to the examined deposit, while the final stage draws in detail on the previous three stages and arrives at a well-founded recommendation.

Already during the preliminary stage of the assessment, tangible criteria are considered; this includes the type of rare earth elements that are found in the investigated ore deposit; the sociopolitical and legislation status of the country where the project is located; the recovery capability of REE; and the potential establishment of a REE value chain. Provided that the REE project does have the potentials to be further investigated, basic evaluations are made of the general criteria that regard to the spatial characteristics, the geological conditions and the geotechnical properties of the ore body. Subsequently, the main group of parameters are assessed among which are the REE specific criteria. These factors are economic, technical, environmental, sociopolitical and safety considerations. On the fourth and final stage the most suitable mining methods are chosen and final judgments are made on the viability of the rare earth project under consideration.

Each one of these parameters can affect or determine not only the selection of the most suitable mining method but also the overall mineability of any given examined REE mining project. The tool is able to adapt to changes of boundary conditions depending also on the input data. Further on, a sensitivity analysis model is implied to reveal the key factors that influence the assessment process the most.

6. Conclusions

The exploration boom during the recent years revealed abundant REE resources and it is certain that the world will not run out of these precious commodities. Nevertheless, the question is if these resources can turn into economic reserves where rare earths can be extracted at a reasonable price. The erroneous practices of the past and the misinterpretation of the crisis and price spike of 2011 have showed that more thorough evaluations are needed.

Without any doubt the supremacy of China is not only due to its REE reserves; it can be mainly attributed to its integrated rare earth value-adding chain that the rest of the world is lacking. Mining of rare earths while not having a value chain is an unsustainable industry. The value of rare earth elements is

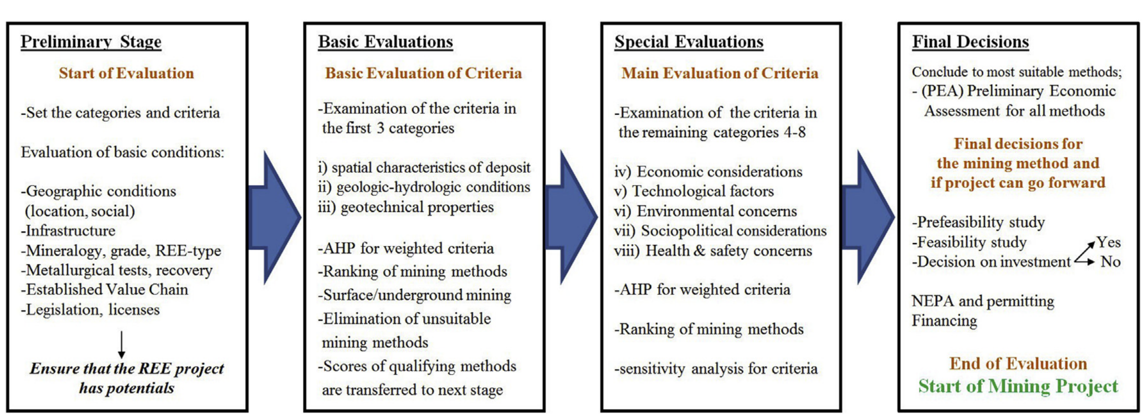

Fig. 5 – Structural description of the assessment tool in four successive stages.

based on their applicability and contribution to high-value end-products. The national viability of Japan, Germany, Korea, India, Canada and the United States among other countries greatly depends on them staying relevant in the area of material science and technology innovation. If the value chain of rare earths is not expanded to other countries then China will continue to capture technology and thus the viability of the aforementioned developed counties will be at risk.

After the initial misinterpretation of the REE crisis and the erroneous practices implemented in previous years, steps are now taken towards the right direction. The global REE supply chain can be reinforced from alternative sources including urban mining and recycling of end-of-life products such as waste electrical and electronic equipment (WEEE) which contain minor yet significant amounts of rare earth elements. Moreover, recovery from secondary residues can amplify the supply of CREE while the potential extraction of HREE from phosphorites can solve the balance problem for some of the HREE. Nevertheless, mining of rare earths remains the primary source and its optimization can contribute to a strong REE industry.

A tool for the objective assessment of REE resources is introduced in this contribution in order to select the most prospective deposits and to optimize the mining process in terms of economics. The assessment tool is dynamic and can adapt to the boundary conditions of the REE market. The continuous evolution in applications and alternation of end-uses of individual rare earth elements leads to a consequent change in their demand. This means that the market is likely to change fast enough to make a balance very difficult, if not impossible, to achieve. In addition, there are sociopolitical, technical, legislative and environmental issues that were mentioned and which have to be evaluated in order to further optimize the mining process.

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