

## Rare Earth Elements – a Novelty in Energy Security

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### ABSTRACT

This study analyses the role of rare earth elements (REE) as critical resources for the energy security. This research presents the developments in the global REE extraction, i.e. the dominance of the Republic of China, which attempts to maintain and control its monopoly. The typical and novel uses of rare earth metals were presented in various applications, such as in advanced electronic and information technologies utilised in the aerospace and energy industries. Bearing in mind their vital importance to the manufacturing of high-tech products, the REE deposits are of strategic importance for the USA, the Republic of China and for the European Union. Striving to maintain the independence of raw materials, the USA is focused on the search for raw materials on its territory and furthermore on waiving the legal restrictions with respect to their extraction. China is primarily occupied with maintaining the monopoly and control over the global market of critical raw materials, including REE. The activities within the European Union concentrate on the exploration in search for the REE deposits in Europe and ensuring the continuity of supplies by maintaining good diplomatic relations with partners – the USA and Japan. In addition, extensive REE recycling initiatives are being undertaken in the EU. Further rare earth metals extraction is anticipated to extend to the outer space. However, developing the economically viable methods of extraction remains the major challenge faced by space mining, given that it requires establishing an expensive, permanent space infrastructure. What is more, mining and processing of rare earth metals raises serious environmental concerns, as it involves such hazards as radioactive products, toxic chemical compounds and waste generation. With respect to the environmental protection, this study also addresses the issues of REE substitutes and recycling. It is concluded that the environmental protection practices regarding the long-term extraction and use of REE (with a 2030 horizon) will bring substantial long-term financial benefits.

**Keywords:** state security, energy security, critical raw materials, rare earth elements, outer space

### INTRODUCTION

Numerous states ensure their energy security through mining and extracting maximum amounts of the available critical raw materials. The term itself refers to the non-fuel chemicals that ensure the proper functioning of the state economy. Rare Earth Elements (REE), also referred to as Rare Earth Metals (REM) are relatively new additions to the group of critical raw materials. According to the definition proposed by the International Union of Pure and Applied Chemistry (IUPAC), which is a body concerned with the standardisation of weights, measures, names and symbols used by chemists, rare earth elements are a set of 17 chemical elements: cerium, dysprosium, erbium, europium, gadolinium, holmium, lanthanum,

lutetium, neodymium, praseodymium, promethium, samarium, scandium, terbium, thulium, ytterbium and yttrium (Zepf, 2013, s. 11). Contrary to their name, rare earth elements – with the exception of the radioactive promethium – are relatively common in the Earth's crust, constituting a seventh of all the elements present in nature; many of them are as abundant as generic metals.

This paper reports on a review study aimed at presenting rare earth metals as a raw material the importance of which for energy security of states is gradually increasing. The proposed work is financed through the funds for scientific activity as part of the research task: Militarisation of Outer Space, and Threats to State Security (task number: II.1.6.0).

## Developments in the global REE mining – the domination of China

In the 1950s, the most extensive mining of rare earth ore deposits was carried out in Brazil and India. Subsequently, it was South Africa that pushed its way to the forefront of the REE mining industry but was soon overtaken by the mines in the United States of America, more precisely in the state of California. The American dominance was not broken until the 1980s. The major terrestrial sources of rare earth metals are found in the mineral deposits of bastnaesite and monazite. The bastnaesite deposits in the United States and China are the largest concentrations of REE, while the monazite deposits in Australia, South Africa, China, Brazil, Malaysia and India constitute the second largest concentration of this resource. Bastnaesite occurs as a primary mineral, while monazite is more commonly found as an accessory mineral in other ores and is typically obtained as a by-product.

In 1993, China was responsible for 38% of the world REE production, the United States – 33%, Australia – 12%, while Malaysia and India – 5%. The remaining rare earth metal producers were Brazil, Canada, South Africa, Sri Lanka and Thailand. By 2011, the Chinese REE mining industry accounted for nearly 95–97% of the global REE production (Pui-Kwan, 2011, s. 1, Sutherland, Gregory, Carnes, & Worman, 2013, s. 1), thus effectively dominating other global markets. However, since 2011, stabilisation in the demand and consumption of rare earth metals has been observed (Figure 1).

At present, with 97% share in mining and 53% share in consumption, the Republic of China remains the REE mining tycoon. Apart from China, the only countries involved in the rare earth metal extraction are Germany (7%), France (4%), as well as Malaysia and Brazil, which account for less than 1% of the total market (the grey part of the graph). With respect to the demand for consumption, the presented data indicate that Japan is currently consuming 17% of the REE resources<sup>1</sup>, USA (10%) and India 2% (the dashed part of the graph).

Beginning with 1990, increasing problems have occurred with rare earth metal procurement due to the Chinese government's imposition of limits on the amount of REE available on the market. That controversial practice was

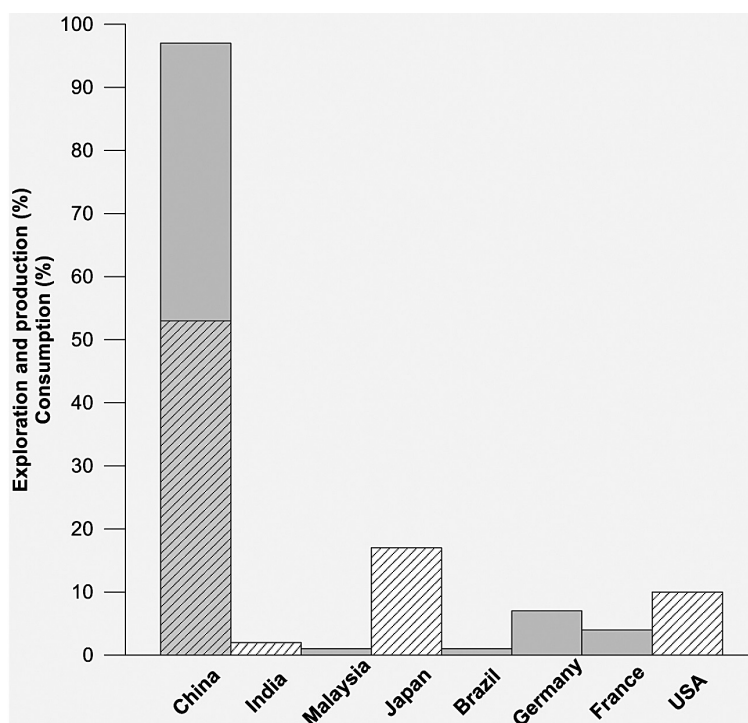
implemented with the intention of monopolising the market and exerting price control. Moreover, the Chinese government began curbing the number of Chinese and Chinese-foreign equity joint ventures that were permitted to export the natural resources from China. This effectively forced a further limitation on the supply of numerous valuable and crucial raw materials.

Notably, China holds 50% of the global REE deposits (55 million metric tons out of the total 110 million tons), whereas, according to the recent estimates of the United States Geological Survey, the United States is in possession of 13% (*Mineral Commodity Summaries*, 2019). Nevertheless, South Africa and Canada are expected to have a considerable potential for the occurrence of rare earth metals. In addition, the REE deposits are also found in Australia, Brazil, India, Russia, South Africa, Malaysia and Malawi. Some geologists propose that careful consideration should be given to the possibility of mining and processing of rare earth metals as a by-product of phosphorus, titanium and niobium deposits in Brazil and other parts of the world. What is more, several Canada, China and the US-based companies have recently assessed various rare earth deposits with respect to the development of primary minerals such as gold, iron ore and mineral sands.

Considering the world rare earth element supply chain, China holds the leading position at each of its links, beginning with their extraction, through the separation, and subsequently refinement, alloying, to processing into the ready-made components.

While striving in its efforts to search for new solutions and applications for rare earth metals, the Chinese government is placing increased emphasis on developing well-educated teams of engineers and scientists, which is imperative for the functioning of the REE companies. Consequently, the most talented Chinese citizens are awarded educational grants and are sent to study at the Ames Laboratory, the United States Department of Energy national laboratory ([https://www.ameslab.gov/about/factsheets/students\\_statistics](https://www.ameslab.gov/about/factsheets/students_statistics)). At present, half of the students of that prestigious institution are Chinese citizens. Simultaneously, there are two key state research centres for rare metals that have been operating in China for many years. The institutions in question are the National Laboratory of Rare Earth Material Chemistry and Application affiliated with the Peking University in Beijing, and the other one is

<sup>1</sup> Most likely due to extensive production of electronics.



**Figure 1.** Extraction, production and consumption of rare earth metals by individual countries [Based on “Rare Earths, exceptional metals with growing geopolitical issues” 2012]

the State Key Laboratory of Rare Earth Resource Utilization affiliated with Changchun Institute of Applied Chemistry.

Presently, the most extensive rare earth metals extraction centres are located in China; the leading mine is Bayan Obo, located in the Inner Mongolia province; however, other key deposits are also located in China, predominantly in its southern region. The Bayan Obo mine specialises in iron ore mining, whereas rare earth metals are the by-products. It is, nevertheless, estimated that the Inner Mongolia’s REE deposits amount to nearly 48 million tonnes, which is approximately 48% of the global resources („Rare Earth in Bayan Obo”, 2006).

Effective REE resource management, controlling the market and preserving the monopoly proved to be complicated and demanded implementing strong measures. A prominent example of such a course of events could be observed in 2009, the Chinese government imposed limitations on the REE export in an attempt to strengthen its monopolist position in the market (Mancheri, 2015). Other actions include the attempts to consolidate the internal Chinese market and to establish the state control over REE mining, while simultaneously striving to curb the rare earth smuggling. Under the pretext of environmental protection, the Chinese authorities are constantly

introducing successive restrictions, as a result of which several private mining companies have been already closed down. In addition, these restrictive actions are perceived by other states as a method of forcing entrepreneurs to invest directly in China.

The excessive regulations on the part of the Chinese government regarding the amount of exported raw material have triggered strong reactions of numerous states, culminated in filing a consolidated class action complaint to the World Trade Organization. The European Union, the USA and Mexico were the first to take action, submitting the complaint in 2009. The lead plaintiff argued that the said actions constituted unfair favouring of the domestic – Chinese – industry (Chuin-Wei, 2015). The subsequent complaint was filed in 2012 by the USA, the European Union and Japan, and followed similar argumentation. The official verdict of the World Trade Organization has confirmed the validity of the argumentation and concurred with the claim that restricting the export of rare earth metals is illegal. The Chinese party, however, maintains that their decisions are dictated by the ecological concerns and the protection of the natural environment. It should, therefore, appear that their primary motivation is to increase the price of the raw materials in question and to exert an economic and political

pressure. Nevertheless, experts point out that the undertaken tactic may produce an opposite effect to the originally intended. It is believed that the artificial inflation of the global REE deficit, combined with the accumulation of substantial reserves may necessitate and eventually lead to the tightening of the trilateral cooperation in the field between the European Union, the USA and Japan, and the formulation of a common policy by the three actors (Brickley, 2017).

Eventually, China respected the decision of the World Trade Organization and partially gave in when announcing the decision to double the rare-earth raw materials export quota for the second half of 2011 (Miles & Hughes, 2014). The released amounts were nonetheless insufficient to fulfil the demand of the countries concerned. From the Chinese standpoint, it allowed them to maintain the satisfyingly low export levels; however, the European Union considered the decision as “extremely disappointing” given that the list of Chinese products covered by additional export restrictions was extended further. As a result, this would lead to a 7–20% decrease in the amount of rare earth metals available for export (World Trade Organization, 2016).

### Applications of rare earth elements

The range of applications for rare earth metals is quite extensive, as they are widely used in the advanced electronic and information technologies. REEs are found in the components of over 200 particularly advanced products, such as: mobile phones, hard drives, camera lenses, electric and hybrid vehicles, wind turbines, all kinds of modern batteries, flat-screen monitors. Their multiple applications include such technologies as electronic displays (LED, LCD technology), guidance systems, or laser, radar and sonar systems, which are implemented in the medical, automotive and aircraft industries, notwithstanding the defence and the space industry (“What are rare earth elements, and why are they important?”, 2019).

The aerospace industry is an important recipient of the REE-based technologies, which are e.g. used in the construction of engine systems to increase their thermal properties. Rare earth metals are applied in thermal barrier coatings on the rotor blades. The coatings are prepared with the addition of yttria-stabilised zirconia and deposited

by means of plasma spraying or physical vapour deposition (Sims et al., 2016).

Moreover, REEs are typically found in the renewable energy sector applications. Over the past 5 years, there has been a consistent upward trend towards the use of solar energy, which has experienced a global increase in popularity as a source of renewable energy for private and industrial purposes. The marked popularity of photovoltaics, i.e. the conversion of sunlight into electricity, may be attributed to their low environmental impact (production of energy without noise and pollution) and low costs, as well as the easily adaptable output power settings. At present, the solar cells satisfy mere 1% of the US domestic energy consumption from all renewable energy sources – while the renewable energy sources alone account for 6% of all energy sources. However, based on the specific levels of national and state investment, experts predict that over the next few decades, we will observe a substantial rise in the popularity of solar systems as a source of electricity (Hart, 2018). The photovoltaic cells are produced with the use of cadmium telluride (CdTe) or copper indium gallium selenide (CIGS: Cu (In, Ga) Se<sub>2</sub>), while the more energy-efficient cells require gallium arsenide (GaAs) and rare earth metals (“Projected rare earth production for China and the rest of world from 2013 to 2018 (in metric tons REO)”, 2018).

### Strategic importance of rare earth metals

#### *Strategic importance of rare earth metals for the USA*

The analysis shows that the USA consumes 10% of the global rare earth metal production, and is completely dependent on other global suppliers, mainly China. REEs are found in the components of US military weapon systems, cell phones, solar panels, lithium-ion batteries, and other high-tech products. There are several sources of this dependence; however, these are the political factors rather than the geological obstacles that play a decisive role in this respect. Vast stretches of the US public land have not been sufficiently explored, and it takes 7–10 years to obtain a mining permit in the United States. By way of comparison, this procedure takes 2–3 years in Australia and Canada, which is why, the present state of affairs is unacceptable for the current state authorities.



On 20<sup>th</sup> December 2017, a Presidential Executive Order on a Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals was issued. Its primary objective is to lead to the development of the strategies reducing the US dependence on the foreign key mineral resources, such as rare earth metals. Furthermore, it plans to promote the policies aimed at fostering the development of critical mineral resource extraction in the USA (America, 2019). The strategy involves providing the access to the federal lands and streamlining the licensing process so that the rare earth metal could be mined in the American land, thus ensuring that the USA becomes a resource-independent state. A secondary motivation is to boost the US economy by providing an additional annual influx of 50 billion USD (Moore&Mamula,2018).

Following the President Trump’s directive, Secretary of the Interior, Ryan Zinke, issued Secretarial Order, “Critical Mineral Independence and Security.”The purpose of the document was to identify four lines of action for the US independence from other REE suppliers, which are as follows:

- identifying the critical minerals and new sources – predominantly US-based;
- extending the list of minerals of critical importance to the state security;
- improving advanced topographic, geologic, and geophysical mapping data and ensuring the access to the data in order to promote the

research on critical minerals in the private sector;

- streamlining leasing and permitting processes to expedite exploration,

According to Secretary Zinke:”The fact that previous administrations allowed the United States to become reliant on foreign nations, including our competitors and adversaries, for minerals that are so strategically important to our security and economy is deeply troubling,” he said. “As both a former military commander and geologist, I know the very real national security risk of relying on foreign nations for what the military needs to keep our soldiers and our homeland safe”(Lasley, 2018).

As part of further works of the American government towards gaining the independence from other suppliers of critical raw materials, a three-layer American Resource Risk Pyramid was presented (Figure 2) (American Resources Policy Network Report, 2012, s. 15). The tip of the pyramid contains: aluminium, beryllium, chromium, cobalt, manganese, niobium, platinum, tantalum, tin, titanium, tungsten, yttrium and zinc. The middle section of the chart is composed of such raw materials as: bauxite, bismuth, copper, europium, iridium, lanthanum, molybdenum, neodymium, nickel, samarium and silicon. The pyramid base holds: antimony, beryllium, cadmium, cerium, chromite, dysprosium, gadolinium, gallium, germanium, indium, lead, lutetium, mercury, palladium, praeosodymium, rhenium, rhodium, rubber, scandium, silver, terbium and vanadium.



Figure 2. American Resource Risk Pyramid [American Resources Policy Network Report, 2012, p. 15]

palladium, praseodymium, rhenium, rhodium, scandium, silver, terbium and vanadium.

In conclusion, the USA, driven by the need to fulfil the demand for REE expressed in the pyramid presented above, should begin exploring its domestic resources. In this way their reliance on the foreign state actors, such as China, Russia or Kazakhstan, could be limited or eliminated.

#### *Strategic importance of rare earth metals for China*

The current problem of the Republic of China is to maintain its dominant position in the REE market. With this end in view, one of its practices is to force the foreign producers to transfer their business activities to China, thus maintaining low prices and high supply. Secondly, there is a common practice to merge large companies and liquidate dispersed small enterprises. Moreover, at the beginning of August 2018, the Chinese Ministry of Industry and Information Technology (MIIT) established the minimum turnover thresholds for domestic companies, preventing the smallest REE producers from profitable extraction. Thirdly, the Chinese companies have resolved to protect their monopoly by dominating the potential international rivals, as exemplified by the case of an Australian-based Lynas Corp., after it had announced the plans to open a new rare earth elements mine. As a result, in May 2009, a Chinese state-owned company made an offer of 366 million USD, which concluded in the acquisition of the controlling block of shares in the Australian company.

China has often demonstrated its monopoly and readiness to utilise it as a political lever. The evidence for the confirmation of this thesis may be found *e.g.* in China's response to the 2010 dispute with Japan over the Senkaku Islands, which culminated in issuing an embargo on the REE export to Japan. Bearing in mind the heavy involvement of the Japanese industry in the production of high-tech electronics, it is completely dependent on China. In fact, the United States is dependent to a similar degree. The American production companies implement rare earth metals in wind turbines, electric cars and other similar products, as well as weapon and defence systems. Americans express concern over the threat of a potential interruption of the REE supply from China, which has prompted the publication of a report "Rare Earth Elements in National Defence," that

emphasises the high priority of reliable supplies of the raw materials in question.

The United States and Japan have been undertaking continuous efforts to counter the China's monopolistic practices. An example of their actions is the intensive lobbying in the REE trade dispute. In July 2011, the World Trade Organization ordered China to abolish the export duties and quotas for nine industrial raw materials. In addition, the USA has also implemented its national policies. In March 2012, President Obama signed an act aiming to provide the assistance to enterprises and trade unions in filing anti-subsidy cases against the imports from China and other non-market economies.

According to China Industry Nonferrous Metals Industry Association, China plans to accumulate a strategic reserve of rare earth elements. The Inner Mongolia province, which contains 75% of the Chinese REE deposits, has been made responsible by the Chinese government to build the said strategic reserve. The ten warehouses that are being constructed will boast the capacity exceeding 39,813 tonnes, which corresponds to an annual export quota allocated by the Chinese (Aredy, 2011). The building works are managed and controlled by the world's largest producer of rare earths, Baotou Steel Rare-Earth Hi-Tech Company. The Chinese state media reports indicate that the emergency stock could eventually reach the level of 100,000 metric tons ("Rare Earth Quotas: Big Bark, Less Bite", 2011).

The results from the security analysis of China's critical minerals have led to the formulation of valuable solutions, proposed to improve the China's raw material security (Pei, 2005). The first important conclusion was the observation that availability is the most fundamental indicator determining the state's raw material security. Furthermore, it is crucial to account for the fact that the mineral resources are non-renewable by nature, and that the demand for raw materials is growing. Therefore, experts have suggested the following solutions. Firstly, sustained effort should go into the geological exploration, mapping and exploration of the available raw materials. Secondly, it is recommended that greater importance should be given to the recycling of raw materials listed as critical, with particular emphasis on metals and rare earth metals, given that modern technological solutions are extremely effective and profitable. Nevertheless, the recycling of critical raw materials appears to exhibit

considerable potential as an alternative source of deficient materials. In recent years, the European countries have imported large shipments of steel scrap from Russia, thus significantly reducing the demand for this raw material. China has employed a similar tactic by importing scrap metal from Japan and South Korea, which has successfully reduced the demand for metal by almost 30% per year (Yueming, 2018). With respect to recycling, it becomes evident that the inclination of the developed countries to recycle raw materials, metals in particular, is beginning to assume a key role in satisfying the market demand for critical raw materials. In the United States, the recycled aluminium scrap satisfies over 70% of the market demand for aluminium. Similar results are observed in Japan, where this indicator remained at approximately 44%, while in Germany it amounted to nearly 30% (Long, Tu, Ge, Li, & Liu, 2016).

#### *Strategic importance of rare earth metals for the European Union*

Critical minerals are crucial for the stability and development of the European economy. They constitute a strong industrial basis, being implemented in a wide range of goods and applications for everyday life and in cutting-edge technologies. Ensuring reliable and unlimited access to certain critical raw materials is becoming a pressing issue in the EU and globally. Faced with the challenge, the European Commission created the Critical Raw Materials list (CRM), which is being regularly reviewed and updated. The list comprises the elements of fundamental importance for the EU economy as well as those that are at high risk of procurement deficiency (Commission, 2011).

The European Commission carries out a criticality assessment at the EU level on a wide range of non-energy and non-agricultural raw materials. The 2017 criticality assessment concerned 61 materials, of which 58 were individual materials and 3 – material groups. The current, third CRM list contains 27 critical raw materials, categorised into 3 groups: HREEs (heavy rare earth elements), LREEs (light rare earth elements), and PGMs (platinum group metals) (European Commission, 2017).

The primary problem lying ahead of the European Union is to ensure the continuous import of rare earth materials. It is estimated that 90% of the demand is met through import, and China remains the key supplier for Europe. In anticipation

of the increase in the REE demand, the EU has undertaken to improve the access to these raw materials, reduce their consumption and improve the mining conditions in Europe. To this end, the European Rare Earths Competency Network (ERECON) was established. The ERECON experts are divided into 3 working groups, whose activities focus on: roadblocks for REE supply in Europe, European REE resource efficiency and recycling and finally European end-user industries with respect to the REE supply trends and challenges.

Another EU initiative that is expected to guarantee the access to valuable raw materials and, therefore, prevent disruption to the economy, is an integrated strategy that sets out to channel the EU efforts and measures towards securing and improving the access to raw materials for the EU. One of the priority activities of this concept was to create the said CRM list. It is, moreover, essential from the point of view of the REE supplies provision to cultivate dialogue and cordial diplomatic relations with the USA and Japan, such as through organisation of conferences as the one held on 12<sup>th</sup> October 2017 in Pittsburgh. The primary focus of the conference was given to the technological innovations using REE, e.g. smartphones, solar panels, wind turbines and electric cars. The participants pointed at the considerable importance of these technologies in view of the projected climate change, indicating their positive influence on improving the quality of the environment by 20% by 2030 (Vidal-Legaz i in., 2018).

The development of proper legislation is another point on the list of activities of the European Union towards the protection of the undisrupted REE supply chain. On 2<sup>nd</sup> December 2015, the European Commission adopted an action plan aimed at helping to achieve a circular economy (European Commission, 2015), which also included the communications to other EU institutions and proposals for waste legislation amendments<sup>2</sup>. The communication in question advocated for *the transition to a more circular economy, where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised, is an essential contribution to the EU's efforts to develop a sustainable, low carbon, resource efficient and competitive economy*. The planned activities

<sup>2</sup> As follows from the legislative package containing acts: COM(2015) 593, COM(2015) 594, COM(2015) 595, COM(2015) 596.

are designed to support the circular economy at every stage of the supply chain – from production to consumption. The purpose of changes is to establish an appropriate regulatory framework for the development of a circular economy in the single market and to give clear signals to economic operators and the general public for the future, with an indication of the long-term waste targets. The guidelines determine a set of activities to be carried out by 2020. The actions at the EU level are planned to drive investments and create a level playing field, remove the obstacles resulting from the European legislation or inadequate law enforcement, deepen the single market as well as foster innovation and involvement of all stakeholders.

The discourse on REE as a critical raw material for the EU should encompass the question of the defence industry. The European defence industry heavily depends on a number of rare earth metals, which are fundamental to the development of its key defence capabilities. As a result, 39 minerals were labelled as critical, whereas 215 as essential for the production of the defence-related components and subsystems. Unfortunately, precise information regarding the type, composition and quantity of materials used in the European defence applications is classified.

In response to the developments, on 30<sup>th</sup> November 2016, the European Commission proposed the European Defence Action Plan. The proposals described in the document, and listed below, are aimed at promoting strong and innovative European defence industry and priorities for the EU defence capabilities agreed on by the EU Member States and consist in:

- launching the European Defence Fund to provide funding for joint research projects and development of defence capabilities expected of the EU countries in priority areas;
- helping small and medium-sized enterprises by supporting the investment in the defence and security supply chains;
- overcoming the fragmentation of the European defence market, and boosting its competitiveness.

The procurement security is considered the cornerstone of a truly single EU defence market. Hence, the Commission strives to identify the bottlenecks and assess the supply risks that involve the materials critical for the development of key strategic capabilities.

Therefore, in the near future, with the view of developing high defence capabilities, the following measures are set to be introduced:

- collecting the information on the supply chains of the materials for semi-finished defence products and determining, from particular assessments, whether the European defence industry is exposed to a supply risk,
- providing the financial support for the defence research focused on mitigating the raw supply chain deficiency risks of the materials that are critical to the development of key defence capabilities by the European defence industry
- exploring the solutions to improve the resource efficiency, recycling and replacement of critical raw materials.

### **“Space mining” and rare earth metals**

The available data on the global volume of REE deposits juxtaposed with the rising consumption of rare earth metals in the developed and developing countries indicate that these minerals of critical importance to numerous modern industries, energy and production are likely to be depleted in 50 to 60 years (Cohen,2007). This perceived inevitability necessitates the seeking alternative solutions for the accommodation of the global demand for critical raw materials. The deficiency of terrestrial reserves forces the recipients of REE to turn to the outer space in search for them. The raw materials that have been found to exist in space can be categorised into 4 groups:

1. raw materials that could be potentially transported to Earth (iridium, osmium, palladium, platinum, rhenium, rhodium, ruthenium, tungsten, etc),
2. raw materials of use in the development of the space infrastructure (e.g., titanium, iron, cobalt, manganese, molybdenum, nickel),
3. substances necessary for the life support systems (water and oxygen),
4. potential rocket fuel (hydrogen, oxygen, ammonia) (Boyle,2017).

It is considered that asteroids are objects in space that may contain critical raw materials. On the basis of the existing space research, three methods have been developed to extract raw materials. The first is to transport the space raw material to Earth for further processing. The second is the transport of the excavated minerals that would most likely include the fuel components



extracted during the primary excavation, which would be used by a spacecraft on the return flight. The third way should consist in transporting the asteroid from the outer space to the safe orbit of the Moon, the Earth, or a specialised space station, which could, in theory, enable safer extraction and reduction of the mineral loss during the extraction process (Lee, b.d.).

Several concepts regarding the exploration of the outer space in search of rare earth metals have been developed. An asteroid mining company, Planetary Resources, for instance, plans to set up a network of orbital satellites to detect the nearby asteroids and determine their geological and chemical composition. If the presence of deposits of valuable raw materials is confirmed, the entire mining procedure will be launched. The technology developed by Planetary Resources to locate and collect these asteroids requires constructing three different types of satellites. The first type, the Arkyd Series 100 (Leo Space telescope), will be a cost-effective solution for the discovery, analysis and exploration of resources on nearby asteroids. The second one, the Arkyd Series 200 (Interceptor), would land on an asteroid to obtain a more accurate geological analysis of available resources. The third one, Arkyd Series 300 (Rendezvous Prospector), would perform research and resource exploration in deep space (Shaw, 2012).

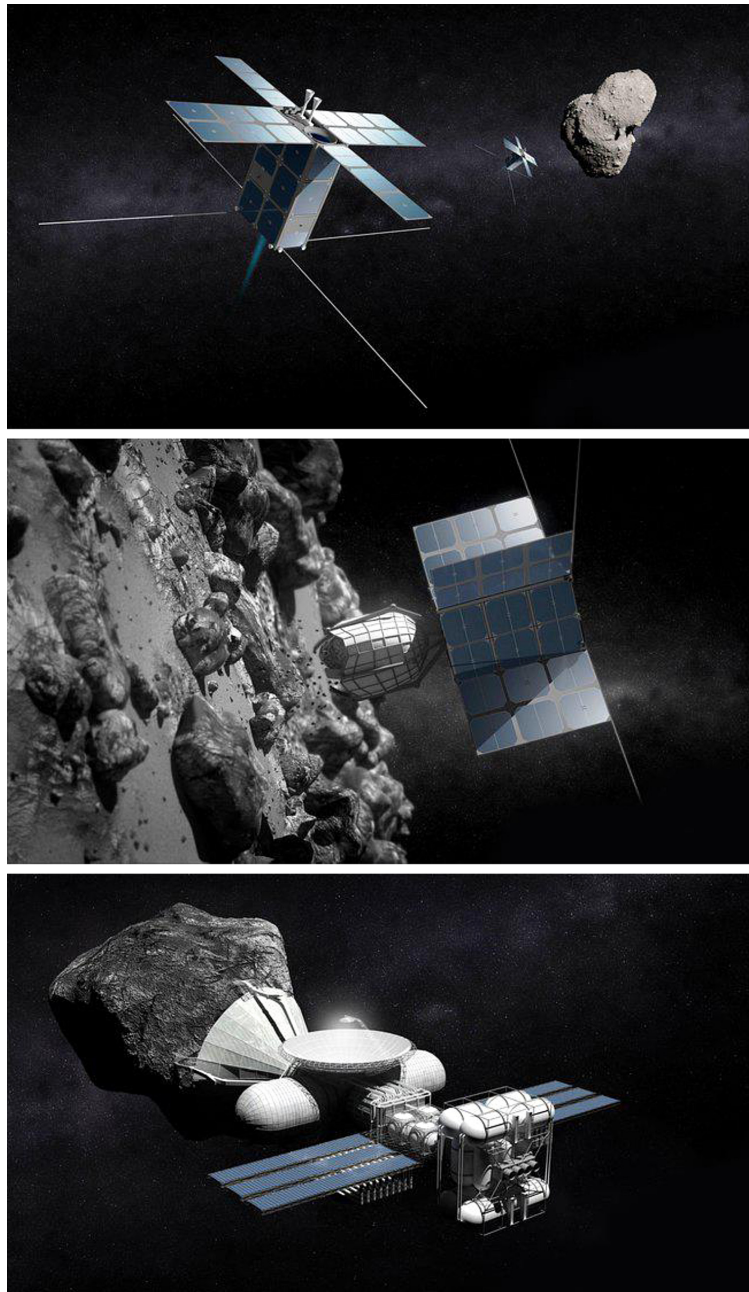
Another company from the private sector, Bradford Space (formerly known as Deep Space Industries), plans to place specialised space stations/factories in the orbit that will process the raw materials extracted in space so that the final refined resources are sent to the Earth. Bradford Space has developed a technology for researching, sampling and collecting asteroids executed by three families of spacecraft. The first model, *Fire Flies* (Figure 3a), is a team of spacecraft “triplets,” launched towards various asteroids. Their objective is to land on an asteroid and sample the research material from its surface. The second type of spacecraft is *Dragon Flies* (Figure 3b). Similarly to the former system, *Dragon Flies* work in groups. They are expected to land on an asteroid with an objective of collecting 5–10 kg of samples, upon which they return to base in order to carry out further analyses of the collected material. The third model is *Harvester* class spacecraft (Figure 3c), designed to collect large quantities of material (up to 20 t). It will then return to a specialised space station/factory parked in safe orbit to further process the

collected ores into a finished product, eventually transported to the Earth (“Deep Space Industries, Inc.”, 2019).

The economic feasibility of space mining investments seems to be confirmed by the recent developments in the field. Planetary Resources has recently applied to the US government to obtain a 700-thousand dollar subsidy from NASA for the construction of the first of the designed devices (*Fire Flies*).

The development of the mining techniques for the REE extraction from the surface of celestial bodies is currently the subject of research debates and works. Surface mining is one of the recurring mining concepts. It involves “scraping” the material off the surface of an asteroid with shovels or augers, or in the case of larger pieces, with a tool resembling a crane gripper. An alternative solution considered by scientists is shaft mining. In this method, the material is extracted through a shaft drilled in an asteroid. However, this would require accurate knowledge regarding the geological structure and dimensions of the celestial body where the mine would be located, given that a suitable mineral transporting system would have to be installed in the shaft to transfer the ores to the processing plant (Hartmann, 2000). Another concept taken into account is the magnetic rake. It would employ highly powerful electromagnets, able to attract the loose metal particles from the surface of asteroids (L. Kuck, 1995).

With respect to asteroids such as carbonaceous chondrites, the hydrated minerals, water and other volatile components can be extracted by heat treatment. In the laboratory water extraction test, carried out by Honeybee Robotics in 2016, the employed asteroid model, developed by Deep Space Industries and University of Central Florida, reflected the mass mineralogy of a particular carbonaceous meteorite. Although the model fluid was physically dry, *i.e.* no water molecules were adsorbed in the rock material, it was shown to release substantial amounts of water steam with molecular structures of layered silicates and sulphur compounds upon heating it to a temperature of approx. 510°C. As the vapour was going through condensation to form a liquid state, it filled the hoppers. That test proved the theory that water and mineral extraction from certain physically dry asteroids is possible. In the case of the volatile materials in the extinct comets, heat can be reused to melt and extract mineral compounds by evaporation (Zacny et al., 2016).



**Figure3.** Arkyd Series satellites for sampling celestial body resources  
[Deep Space Industries (BryanVersteeg)]

Another analysed method for space mining of rare earth elements is nickel extraction by means of the Mond process. This technique consists in passing carbon monoxide heated to a temperature between 50–60°C through the asteroid, as a result of which the nickel tetracarbonyl gas and iron pentacarbonyl are obtained. The REE extraction by means of extraction from the produced gases would only occur at elevated temperatures (Jenniskens et al., 2015).

Another essential step towards space mining, in addition to the development and selection of

suitable REE extraction techniques, is the establishment of cost-effective space infrastructure<sup>3</sup>. A regular transportation platform would bring substantial benefits. Apart from the long-term savings, reduced fuel consumption would be the vital advantage of this solution. Water is believed to exhibit the necessary potential to substitute regular fuel successfully. It could be obtained from

<sup>3</sup> In this case, the critical infrastructure is understood as a system of devices necessary for proper extraction, processing and transporting mineral resources extracted from celestial bodies back to Earth.

celestial bodies (in particular from asteroids) and split into hydrogen. In addition, the solar energy could be used for fission, leading to a further cost reduction.

A dwarf planet, Ceres, which is the largest celestial body in the asteroid belt, is considered as a potential location for the space base and transportation hub for the future mining infrastructure. It could be an intermediate station, enabling the transport of mineral resources to Mars, the Moon and the Earth. There are several advantageous factors that could provide the decisive argument for the selection of Ceres for that purpose. The primary reason is that the spacecraft would need to develop a relatively low escape velocity to counter the gravitational pull of Ceres. Moreover, due to large deposits of water ice on the planet, it could provide a source of water, fuel and oxygen for the ships passing through the asteroid belt and beyond. Finally, it is estimated that transporting payloads from Mars or the Moon to Ceres would be more energy efficient than in the case of the Earth-Moon connection (Zubrin, 2018). The preliminary analyses of the asteroid surface composition indicate that they may become a source of not only rare earth metals and water, but also of such precious metals as: nickel, cobalt, gold, platinum, which are found there at higher concentrations than their terrestrial counterparts. For instance, one of the discoveries has shown that an asteroid with a diameter of approximately 1 km is estimated to contain up to 7.5 tons of platinum, worth 100 billion USD (Lewis, 2013).

An interesting fact is that space mining is also endorsed by the largest investment bank in the world – Goldman Sachs. The bank representatives are apparently convinced that the space mining of precious metals and rare earth elements is, in fact, a promising business opportunity, particularly given that the financial and technical obstacles are relatively easy to overcome. However, the space mining industry will have to resolve the mental blocks. Another concern is an economic slump that space mining could heavily contribute to. There is a great risk that the terrestrial mining could suffer a serious blow on account of a sharp drop in the prices of raw materials, including CRMs. This, in turn, could exert a detrimental effect on the energy security of states.

Besides the issues concerned with the technological nature of space exploration, another problem that has to be solved is the human factor of space mining. The personnel working in

an extremely hostile environment will have to operate in vacuum, struggling with extremely high and low temperatures (extreme day/night temperature amplitudes amounting to hundreds centigrade), radiation, as well as rock and interstellar dust. The severity of the environment necessitates greater process automation along with self-repair and self-maintenance of machines and their components. Although this practice would significantly increase costs at the initial phases, it would prove profitable in the long-term horizon. It appears that a fleet of reusable spacecraft could prove to be a suitable solution to the automation of space infrastructure and equipment. Apart from maintenance and operation, the platform would perform its primary mission –transporting the mined resources to Earth. This concept is in the centre of attention of the Japan Aerospace Exploration Agency, JAXA, which has signed a Memorandum of Understanding with ISpace Technologies, a company specialising in robotic space exploration. The main objective of the consortium is to develop a map of safe space routes for the future mining robots. Both parties agreed to contribute their knowledge, experience, connections and capabilities to develop the entire framework for the space mining industry. Three lines of action are drawn in the document:

1. A comprehensive plan for the space resource industry including the necessary technologies and industrial value chains involving lunar resource mapping (including positions, compositions, characteristics), mining, storage, delivery, sales and utilization in space.
2. Division of tasks between public and private sectors for the R&D activities and building a national and international framework needed for the new industry to set off.
3. All other necessary actions, including the development of relevant consortia and sub-consortia.

The Japanese initiative includes the activities under the Japanese space mining industry expansion programme, which was included in the Japanese New Space Development Strategy for the next 20 years. Already in 2016, the Japanese parliament and subsequently the government declared its wholehearted support for this modern industry. As Takeshi Hakamada, the CEO of ISpace, points out, *it is important to actively participate in the rule-making and commercialization while being technologically competitive*



*globally with for future lunar mining.* The long-term vision of ISpace Technologies involves the plans to construct and initiate a regular, reliable transportation system between the Earth and the Moon, as well as to develop the technology and methods for large-scale water extraction from the surface of celestial bodies (Japan Aerospace Exploration Agency,2019).

## Rare earth metals and environmental hazards

### *Radioactive products*

Rare earth deposits typically occur along with other minerals. This fragmentation requires supplementing an additional step in the REE extraction chain – the separation process. In addition, the extraction of radioactive elements, such as thorium, radium and uranium is inherent in REE mining. Therefore, there is a certain paradox associated with the extraction of rare earth elements. On the one hand, they are indispensable in the production of ecological and environmentally friendly technologies; on the other hand, the current extraction technology has a dramatic effect on the environment („Rare earth mining in China: the bleak social and environmental costs”, 2014). The key issue with regards to environmental protection is the emergence of “rare earth lakes,” as they have come to be referred to. These reservoirs of toxic and radioactive waste hold the residues from the separation of the high-priced minerals. Since they need to be neutralised, this raises the overall mining costs.

### *Toxic chemicals*

The extraction of rare earths is performed with the application of large amounts of acid. The acid is pumped into the holes where the raw material is deposited. Thus extracted minerals are subsequently processed with the use of even more harmful chemicals—high-concentration acids at elevated temperatures. In China, these by-products are released into artificial ponds with earth dams, which are susceptible to seepage: chemicals leak killing crops and animals, and also bring a direct threat to the human health. In the city of Baotou in Mongolia, 7 million tonnes of rare earth waste is discarded into a 5-mile wide lake. Consequently, the neighbouring arable fields cease to operate while thousands of people fall ill due to the leaks. At one point, the degeneration

processes seriously threatened one of the key waterways in China. The official studies conducted 5 years ago indicated a high percentage of cancers, osteoporosis, skin and respiratory diseases in the local population. Since then, the toxicity and radiation assessments in this area have been kept secret (Blanchard,2010).

### *Waste*

In order to curb the negative effects of the excessive REE mining, different alternative approaches for obtaining the precious minerals are employed. Several countries, including the USA, have attempted to reuse the mining waste and other waste products from the current or previous mining operations. Nevertheless, this solution causes certain political and technical problems. Numerous experts are convinced that the recycling of waste can help alleviate the global rare earth resources shortages without the need for opening new mines, or exploration of new sources of the raw materials in question (Szamałek, Konopka, Zglinicki, & Marciniak-Maliszewska, 2013).

In the context of the mining waste disposal, the scientists from the United States Geological Survey, an American research agency, re-analyse rocks, minerals and other mining samples to assess the content of rare earth metals. The process employs modern induction technology – laser ablation. It consists in the removal of material from a solid to a gaseous or plasma state omitting the liquid phase. The process is applicable in the determination of the REE content in mining waste and recycling.

### *REE Substitutes*

Bearing in mind the Chinese monopoly and high prices of rare earth metals, coupled with high demand for these raw materials, substitutes and methods of obtaining them are being actively sought. With respect to the current situation on the REE market, the US Department of Energy, for instance, actively promotes the search for substitutes by providing funding to numerous projects aimed at searching for the REE substitutes or the development of the REE-free devices. The US DOE has granted a subsidy to Ames Lab of USD 120 million to develop alternative solutions for the production of turbines and electric vehicles that would eliminate rare earth materials from the design. In turn, the Japanese car



manufacturer Toyota is developing future hybrid vehicles, equipped with induction motors, the design of which does not require the use of rare earths. The Department of Energy has joined the project, proposing to provide financial support and conducting works on the use of double-stator induction in an electric motor (Bakker,2018).

Another subsidised solution was presented in 2012 by Northeastern University in Boston, the researchers of which had developed a magnetic material free of rare earth compounds. Currently, this research centre is conducting a project worth 3.3 million USD (also co-financed by the Department of Energy) developing an REE-free permanent supermagnet, which could successfully replace the former solutions in e.g. wind turbines. The primary practical outcome of the implementation of hybrid drives will be the reduction of demand for neodymium (Courtice, 2012). The energy sector is actively involved in the development of environmentally friendly solutions, one of which is the substitution of fluorescent bulbs and LEDs (which represent the group of luminophores such as terbium, europium and yttrium, hence, rare earth elements) with organic cells. Organic light-emitting diodes (OLEDs) and halogen bulbs are REE-free ("Researchers Propose New Technology without Rare Earth Metals for LED Lighting", 2015).

### Recycling

Recycling is one of the methods of environmental protection. In the field of REE, the term encompasses the extraction of rare earth elements from the discarded, worn or damaged devices in which rare earth metals were incorporated. At present, the lack of efficient processes is the key problem concerning the REE/REM recycling. The rate of REM recycling from various devices in recent years amounts to 1% ("Rare Earth Recycling for Europe (REE4EU)", 2019).

Honda has been able to break the spell of recycling inefficiency. The company has patented a novelty technique for extracting the rare earth elements from the batteries installed in its hybrid vehicles. Honda recovers rare earth oxide from used nickel metal hydride batteries in the process of electrolysis of molten salt. This rare earth oxide can be recycled and used as a negative electrode in the nickel-metal hydride cells. The process produces astonishing results considering the purity of the material, estimated at 99%. The Honda's concept and practices enable

the extraction of over 80% of rare earths from the spent battery cells (Els,2013).

The Japanese company Dowa Holdings, operating in environmental management and recycling, also has rare earth metal recycling in its portfolio. The company has built recycling facilities that extract precious metals and rare earths from a variety of old electronic components. The process takes place in a 60-metre-tall furnace heated to the temperatures amounting to 1400°C where *E-Scrap Recycling* is conducted. The soldering technology of spent electronic circuits is capable of handling 300 tonnes of recycled material per day. Given that 150 grams of REE are recovered from each tonne, the daily raw material recycling capacity is 45 kg of pure raw material (Tabuchi,2010).

A Dutch study has shown that in the short term, recycling may, and is partly expected to, fail to affect the rare earths market to a great extent or to be economically viable. However, in the long term (up to 2030), the role of recycling is highly likely to become increasingly important, due to the fact that by then the devices constructed with the use of REE will have been pulled from service (Peake, 2017).

## CONCLUSIONS

Over the past decade, the rare earth elements mining market has undergone dramatic changes. Currently, it is dominated by China, which has successfully monopolised the supply of these raw materials. The major problem of the Chinese today is to maintain this *status quo* for as long as possible. To this end, the Chinese government makes substantial investments in the education of future engineers, and has resorted to imposing a set of political and economic barriers. Under the false pretence of protecting the environment, it imposes the restrictions or embargoes on the suppliers for whom these minerals are essential for the proper functioning of their country's economy. In addition, these limitations force entrepreneurs to invest in China.

Rare earth metals are found predominantly in the information technology and electronic devices applications, as well as in the defence industry. They are indispensable components of such elements as: guidance systems, laser technology as well as radar and sonar systems. However, the most promising field of application are the technologies

contributing to environmental protection, such as photovoltaic systems and electric motors.

This paper has shown that rare earths are of strategic importance to a number of countries and organisations. A perfect example is found in the American market: the USA consumes 10% of the world's mining volume and is completely dependent on foreign providers—mainly China. The present state of affairs forces the US decision-makers to seek changes in the legal framework that would allow the state and private entities to explore the range of opportunities within their country. Apart from the declarations, the US authorities have gone to lengths to give the national businesses the edge in the highly competitive market. Their actions included issuing official documents—executive orders—or the evaluation of critical elements in the form of the American Resource Risk Pyramid. The steps undertaken by the Republic of China, on the other hand, are implemented to maintain their dominance on the market of critical raw materials and rare earth metals by controlling the monopoly. The currently followed objective of the Chinese authorities is to create a strategic reserve of these raw materials, by maintaining the extraction sites, on the one hand, and by implementing new extracting techniques for the recovery of REE from scrap, on the other. While analysing the strategic importance of rare earths, it was found that they hold the key to the stability and development of the European economy. A worrying EU problem is the lack of access to own resources and dependence on the Chinese monopoly. The EU has approached the problem from different angles, and the first step taken was to draft a list of critical raw materials crucial to the EU economy. It emerged that rare earth elements constituted a large share of the list. The CRM list divides the minerals into 3 groups: heavy REE, light REE and platinum metals. The EU has recognised the importance of diplomacy and has worked towards a reasonable tightening of the trilateral relations with the USA and Japan. Other implemented practices included developing a legal framework and capabilities for REE recycling and, finally, securing the interests of the EU defence industry, in recognition of its high priority and the fact that it makes use of the REE components. Rare earth metals are fundamental to ensuring high defence capabilities in Europe. The lack of proper regulations in the field was, therefore, resolved by the development of European Defence Action Plan.

The growing demand for rare earth elements has caused the stakeholders to turn to space exploration. The preliminary studies indicate that space asteroids could provide a source of rare earth metals. The problem to crack is how to extract these raw materials so that the process is safe and economically viable. The theoretical concepts that have been proposed include the development of a system of orbital satellites to detect and extract raw materials from asteroids. The possibilities of establishing a permanent space infrastructure are also being discussed. Such an expensive investment would be rational in the long term, with the additional possibility of splitting water into hydrogen using the solar energy, which could then be used as fuel. Such concepts have already been subsidised by the government institutions and private investments by large enterprises, such as Goldman Sachs.

The presented study shows the negative environmental impact of the REE mining and processing. Rare earths are usually found in mineral deposits with radioactive elements such as thorium, radium and uranium. These substances are highly hazardous and their separation additionally increases the production costs. Critical raw materials are often extracted with the use of toxic acid (often at high temperatures), which is released into the deposits. This treatment has been proven to contribute to the rising rates of crop, animal and human diseases in mining areas. A solution that is tested as an alternative to mining is the recycling of mine waste and other waste products from the current or former mining operations, using state-of-the-art methods. The search for REE substitutes is yet another initiative that may prove beneficial from multiple standpoints. The sectors leading in the REE substitution is the automotive industry (induction motors without rare earths) and the energy industry, which, in turn, focuses on replacing the traditional light sources with *e.g.* organic light-emitting diodes – OLED. The low rare earths recycling rate (at 1%) is another burning issue and a serious environmental problem, which has, however, only recently been recognised and began to be addressed with a view to increasing the said factor. The trend is best observed in the automotive industry. It is estimated that the REE recovery rate from battery cells is likely to amount to 80%. However, the analyses show that recycling of devices built with the use of REE pulled from service must be approached from a long-time perspective, as it is not expected to bring noticeable benefits before 2030.

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