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Hanna Spasowska-Czarny

Maria Curie-Skłodowska University in Lublin, Poland

ORCID: 0000-0003-4000-5837

hanna.spasowska@poczta.umcs.lublin.pl

Environmental and Legal Conditions of Rare Earth Elements

Środowiskowe i prawne uwarunkowania pozyskiwania pierwiastków ziem rzadkich

SUMMARY

To run an efficient and well developed economy, it is necessary to procure materials and elements belonging to four main groups, that is energy resources, organic resources, water and mineral resources. Non-energy resources, including critical raw materials, have limited resource base, significant dispersal of minerals and very limited possible substitution. Those resources include rare earth elements, which set directions for contemporary dynamic development of many industries. With the development of innovative technologies, the demand for essential components has grown. The use of rare earth elements to develop energy-efficient technologies is very promising, especially in wind generators and hybrid cars.

Keywords: rare earth elements (REEs); critical raw materials; recovery; recycling; low-carbon economy; energy-efficient technology

INTRODUCTION

Raw materials of four main groups are necessary for the efficient functioning and development of each economy. These are energy raw materials, organic raw materials, water and mineral raw materials[1]. How much raw materials in each of these groups the economy consumes is determined by three main factors: the application of the raw material, the size of the population and the standard of living which decides about the amount of individual consumption. It is, therefore, clear

1 S. Zieliński, *Surowce mineralne*, „Chemik" 2014, nr 5, p. 429.

that population growth and rising living standards are the main drivers of increased demand for raw materials. This increase in demand has become a problem the world economy faces today.

The control over resources of raw materials increases the impact on the global economy and brings huge profits. With the development of modern technologies, the demand for components necessary for their development and manufacture has increased. This regards primarily a particular group of elements referred to as rare earth metals, which have become strategically important mineral resources[2]. They have unique chemical and physical properties (due to the similar structure of their external electron shells and ionic radii), are resistant to high temperatures, have specific magnetic and phosphorescence properties; and, in combination with other elements, form compounds which have properties that cannot be obtained otherwise[3]. Ensuring access to rare earth metals is a fundamental issue for increasing and maintaining a competitive advantage internationally.

THE NOTION AND IMPORTANCE OF RARE EARTH ELEMENTS

Rare earth elements are a group of 15 lanthanides (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium) as well as scandium and yttrium. Since their discovery by C.A. Arrhenius in 1787 in the Ytterby quarry on one of the Stockholm Archipelago islands, scientists and researchers have been very interested in looking for further methods of their application for both commercial and military purposes[4].

[2] A special working group was set up at the initiative of the European Commission to identify raw materials of critical importance to the EU. The report published in 2010 listed the following materials: antimony, beryllium, cobalt, fluorite, germanium, graphite, indium, magnesium, niobium, platinum, rare earth metals, tantalum and tungsten. See *Report of the Ad-hoc Working Group on defining critical raw materials*, European Commission, Brussels, July 2010, p. 36. The Hague Center of Strategic Studies (HCSS and TNO) has also considered rare earth elements critical for the EU economy. See J. Kooroshy, R. Korteweg, M. de Ridder, *Rare earth elements and strategic mineral policy*, Report No. 2010/02, The Hague 2010. However, the term "critical raw materials" is challenged by E. Sermet and J. Auguścik (*Krytycznie o pojęciu surowców krytycznych i nie tylko*, „Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią Polskiej Akademii Nauk" 2015, nr 91, pp. 171–177), they propose the term "deficit raw materials".

[3] The non-substitutability of rare earth elements is addressed, i.a., by Professor Tadeusz Łukasiewicz from the Institute of Electronic Materials Technology (*Instytut Technologii Materiałów Elektronicznych*) in Warsaw. See K. Kapiszewski, *Lantanowce niczym ropa*, „Przegląd" 2011, nr 2, www.tygodnikprzeglad.pl/lantanowce-niczym-ropa [access: 20.03.2019].

[4] R. Tomański, *Bez lantanowców nie ma nowoczesnej technologii*, www.komputerswiat.pl/aktualnosci/bez-lantanowcow-nie-ma-nowoczesnej-technologii/vplecne [access: 20.03.2019]. More on the topic in M. Burchard-Dziubińska, *Strategiczna rola metali ziem rzadkich w gospodarce opar-*

The applications for these elements were found more than a hundred years after their identification. Despite the relatively low volume of demand (135–140 thousand tonnes per year, compared to 13–14 million tonnes for zinc and copper), they are indispensable for the manufacture of high-tech products for the energy, defence, automotive or telecommunications sectors[5]. Their use has allowed the development of technologies for the production of display screens, TVs, smartphones, microwave ovens, ovens with self-cleaning coating, lasers, UV filters, fuel cells or hybrid cars; they are also used in aerospace technology. Yttrium, erbium, terbium and ytterbium are used, respectively, in spark plugs, photo filters and microwave ovens, energy-efficient light bulbs and radiography, and in stainless steel production. Thanks to europium, it became possible to strengthen the red colour in TV sets, scandium is used in flash units, lutetium in computer tomography, lanthanum for the production of X-ray films, dysprosium can be found in hard digital drives, while dysprosium and neodymium in hybrid cars. Moreover, neodymium has very strong magnetic properties, therefore, it is used to manufacture wind turbines for wind power plants[6]. Gadolinium, samarium, erbium and holmium are used to build various elements of nuclear reactors and nuclear fuel rod controllers, while promethium in the structure of nuclear batteries. In military applications, these elements are used, for example, in the production of night vision devices, cruise missiles and weaponry parts[7]. Not only do the appropriate magnetic, luminescent and electrochemical properties of these metals reduce the weight of the equipment or their components, but also these properties increase their performance, durability, speed and thermal stability.

The commonly accepted and used term is quite misleading, as rare earth metals are in fact not rare. When in low concentrations, they can be found almost everywhere, in almost every larger rock formation, but it is their dispersion which poses a considerable problem. They usually form part of oxides and carbonates (mainly silicates and phosphates), so their presence in nature remained unnoticed for such a long time. Some are as common as basic metals (e.g. nickel) or precious metals

tej na wiedzy, „Gospodarka w Praktyce i Teorii" 2014, nr 1(34), p. 22; A. Paulo, M. Krzak, *Metale rzadkie*, Kraków 2015, p. 186 ff.

[5] B. Wiśniewski, *Rosnące znaczenie metali ziem rzadkich*, „Biuletyn PISM" 2013, nr 46, p. 1.

[6] As an example, the battery in the Toyota Prius contains over 10 kg of lanthanum, and a magnet in a large wind turbine is built of at least 260 kg of neodymium. See *Ukryte (chińskie) składniki (niemal) wszystkiego*, www.national-geographic.pl/ludzie/ukryte-chinskie-skladniki-niemal-wszystkiego [access: 20.03.2019]. For more on the topic of the use of rare earth metals, see e.g. K. Podbiera-Matysik, K. Gorazda, Z. Wzorek, *Kierunki zastosowania i pozyskiwania metali ziem rzadkich*, „Chemia. Czasopismo techniczne" 2012, z. 16, pp. 147–156.

[7] For example, see A. Jarosiński, L. Madejska, *Wybrane zagadnienia otrzymywania miszmetalu i innych metali ziem rzadkich*, „Inżynieria Mineralna" 2016 (styczeń–czerwiec), pp. 249–250.

(such as gold)[8]. Lanthanum, discovered in 1893, is in more quantities on Earth than silver or lead[9]. The problem is finding deposits concentrated enough to make their mining profitable[10].

From the second half of the 19th century to the 1980s, rare earth metals were predominantly mined in the Mountain Valley in California, USA. Since 1998, more than 80% of rare earth metals production has come from China. Today, it is China, with 23% of the world's resources held, that satisfies 93% of the global demand for these raw materials. The largest deposit of Bayan Obo is located on the territory of Inner Mongolia belonging to China[11].

The main cause behind the imbalance between demand and availability of rare earth elements is the specificity of the deposits. There are few deposits with concentrations high enough to make production profitable[12]. Currently, we do not yet have technologies available for the industrial-scale extraction of dispersed elements, and their extraction is only possible if they occur as minerals, i.e. highly concentrated aggregations of many elements formed by natural geological processes in the highest layers of the planet, in the earth's crust. Only the minerals present in the earth's crust can be explored and extracted mechanically[13]. Rare earth metals occur as combined in ores and are difficult to separate. In addition, the extraction of radioactive elements such as uranium, thorium, radium, etc. is necessary during the mining process, which poses an additional risk[14].

In Poland, rare minerals occur, but their content is small and they are not of an economic significance. They occur in the area of Szklarska Poręba, the average content of these elements is 0.28% of Ln2O3, and the resources are estimated at about 65 thousand Mg[15]. They contain monazite, xenotime, apatite and zirconium. Also, the minerals from the area of Bogatynia have only mineralogical significance.

[8] J. Blas, *Rosną obawy o skąpe zasoby metali przejściowych i metali ziem rzadkich*, http://forsal.pl/artykuly/395923,rosna_obawy_o_skape_zasoby_metali_przejsciowych_i_metali_ziem_rzadkich.html [access: 15.11.2019]. See also W. Brzyska, *Lantanowce i aktynowce*, Warszawa 1996, p. 10.

[9] V. Goldsmith, a Norwegian mineralogist, classified the elements as a separate group of lanthanides in 1925. See R. Tomański, *op. cit*.

[10] A. Klupa, *Cenniejsze niż złoto. Metale ziem rzadkich w światowej strategii gospodarczej*, „Przegląd Strategiczny" 2012, nr 1, DOI: https://doi.org/10.14746/ps.2012.1.15, p. 240. Similarly J. Całus-Moszko, B. Białecka, *Potencjał i zasoby metali ziem rzadkich w świecie oraz w Polsce*, „Prace Naukowe GIG – Górnictwo i Środowisko" 2012, nr 4, p. 61; K. Chyla, *Strategiczny charakter pierwiastków ziem rzadkich*, „Pisma Humanistyczne" 2014, nr 12, p. 276.

[11] J. Całus-Moszko, B. Białecka, *op. cit.*, pp. 62–63.

[12] K. Chyla, *op. cit.*, p. 282.

[13] S. Zieliński, *op. cit.*, p. 430.

[14] K. Chyla, *op. cit.*, p. 282.

[15] J. Kowalczyk, C. Mazanek, *Metale ziem rzadkich i ich związki,* Warszawa 1989; eosdem, *Ziemie rzadkie – problem zaspokojenia potrzeb gospodarki narodowej*, „Fizykochemiczne Problemy Mineralurgii" 1987, nr 19, pp. 233–241.

Geological research confirms that rare earth minerals in Lower Silesia are not of a deposit character and their precise assessment requires further research[16]. In the sands of the Baltic Sea beaches and in the area of Tajno near Białystok, rare earth elements occur in the form of carbonates at considerable depths[17]. They are also found in Polish phosphates, poor in both phosphorus and rare earths. To sum up, it can be concluded that rare earth elements minerals present in Poland are useless, mainly due to their low content, which adversely affects the economic efficiency of the whole process of extracting rare earth concentrates.

Rare earth elements are obtained primarily from bastnaesite (95%) as well as monazite and xerothyme[18]. Their production differs significantly from the extraction of other fossil resources. The extraction process is complex, depending on the chemical composition of the ore, and forms a combination of a variety of different processing methods[19]. The first stage is extraction of the material using standard mining procedures. To extract minerals from the ore, they are ground to gravel, and then crushed several times to obtain fine sand or silt to separate the grains of individual minerals[20]. The elements are then separated in a filtration process in which the metals adhere to the particles of air flowing through the tank in which they are located. As a result, metals can be collected from its surface. Then, using various chemical compounds, individual rare earth metals are obtained, the chem-

[16] J. Kulczycka, B. Radwanek-Bąk, *Bezpieczeństwo podaży surowców nieenergetycznych i ich znaczenie w rozwoju gospodarki Unii Europejskiej i Polski*, [in:] *Czy kryzys światowych zasobów?*, red. B. Galwas, B. Wyżnikowski, Warszawa 2014, pp. 125–136; B. Radwanek-Bąk, *Zasoby kopalin Polski w aspekcie oceny surowców krytycznych Unii Europejskiej*, „Gospodarka Surowcami Mineralnymi" 2011, z. 1, p. 13.

[17] J. Kowalczyk, C. Mazanek, *Ziemie rzadkie…*, p. 235.

[18] A. Jarosiński, *Możliwości pozyskiwania metali ziem rzadkich w Polsce*, „Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią Polskiej Akademii Nauk" 2016, nr 92, p. 75.

[19] As the primary method, Mountain Pass used flotation and leaching with hydrochloric acid, resulting in the 70 percent concentrate. For the processing of monazite and xerothyme ores, gravitational methods are applied, using jigs, spiral concentrators, conical concentrators and concentrating tables. Magnetic electrostatic separation methods and dissolution in hot concentrated acid solutions and extraction with concentrated NaOH are also used. See B. Castor, J.B. Hedrick, *Rare Earth Elements*, [in:] *Industrial Minerals and Rocks-Commodities, Markets and Uses*, eds. J.E. Kogel, N.C. Trivedi, J.M. Barker, S.T. Krukowski, Littleton 2006, pp. 769–792.

[20] The elements are flushed with water into the solution, and other ingredients are precipitated into waste. The separation of lanthanide elements from solutions is the most difficult stage of acquiring rare earth metals. The following methods are used for this purpose: fractionated crystallization method, fractionated precipitation from the solution, ion exchange chromatography and extraction (see J. Całus-Moszko, B. Białecka, *op. cit.*, pp. 62–63). The latter two methods are considered the most efficient, as they allow achieving 99.99 percent concentrates in kilogram amounts. See A. Bielański, *Podstawy chemii nieorganicznej*, Warszawa 2002.

ical process is repeated until the elements are completely pure. They are then in the form of oxides that can be processed into metals and alloys[21].

Traditional methods of metal mining do not allow the extraction of ores located deeper than 1,500 meters below the earth's surface. KGHM Polska Miedź, accompanied by 22 partners from all over Europe, is working on a solution to this problem. The goal of the pioneering BIOMOre project is to devise a demonstration technology that will allow the extraction of metals even from deeper deposits, but without building underground infrastructure. The bioleaching method involves the use of microorganisms (including bacteria and fungi) that produce acids at the end of their metabolism. As a result, the acidity increases and the pH of the environment decreases, the substances becoming soluble; then the metals can be washed off and reclaimed from the material. Bioleaching can be used on an industrial scale, and the project supervised by KGHM will significantly improve the entire process[22].

ENVIRONMENTAL HARMFULNESS OF EXTRACTING RARE EARTH ELEMENTS

A kind of paradox is associated with rare earth metals resources. Many applications of these elements contribute to the reduction of emissions (as they are necessary for the production of so-called "green technologies" of low carbon emissions), but their extraction is highly harmful to the environment[23].

Rare earth mining and processing are very energy-intensive, which means that it is difficult to clearly determine by analysing the entire product life-cycle whether the decrease in emissions due to the use of rare earth metals offsets emissions arising from their acquisition[24]. Like most mining activities, it consumes significant amounts of energy from coal combustion power plants.

In experts' opinions, there is currently no environmentally safe technology for mining these metals. Rare earth element concentrates are obtained as a result of enrichment of enormous amounts of ores that are a carrier of minerals containing rare earth metals, which causes the degradation of large areas.

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[21] A. Klupa, *op. cit.*, p. 241.

[22] M. Wąsowski, *Cicha rewolucja w pozyskiwaniu metali. O metodzie KGHM może być głośno na świecie*, http://businessinsider.com.pl/technologie/nauka/kghm-pracuje-nad-pozyskaniem-metali-bez-koniecznosci-ich-wydobycia/6g172ch [access: 20.03.2019].

[23] The United States Geological Survey reports that within the recent 30 years the use of rare earth elements in environmental protection has grown considerably and it expects that this trend is maintained. Avalon Rare Metals, a mining company listed on the Toronto Stock Exchange, confirms that approx. 25% of new technologies are based on transition metals and rare earth metals. See M. Burchard-Dziubińska, *op. cit.*, p. 27. Similarly J. Blas, *op. cit*.

[24] M. Burchard-Dziubińska, *op. cit.*, p. 26.

Moreover, such chemical compounds as sulphuric acid and hydrofluoric acid are used in the refining process. These compounds can be released into the atmosphere from production waste, and the effects of their release have not yet been studied[25].

The level of radioactivity of materials which usually accompany rare earth metal deposits also raises concern. The problem is the so-called "lakes of rare earth metals" – reservoirs of radioactive and toxic liquids, which are by-products of extraction of desired elements[26].

In China, where most rare earth metals are mined, illegal mining activities have caused serious environmental damage on a local scale. Water, inadequately treated by mining plants, pollutes the environment[27]. Each year, the mines of the Botou area dump 10 million tonnes of highly acidified or radioactive water, which is not treated or neutralised in any way. Due to the contamination, the population of the neighbouring villages was displaced. The ore is transported in open railway cars and part of it goes to the Yellow River and further to the Yellow Sea. No procedures are in place to protect from radioactive radiation and pollution the population employed in the mining industry. The number of people suffering from cancer and lung diseases is increasing[28].

In southern China, it is very difficult to supervise small mines. In the provinces of Jiangxi and Guangdong, mafia groups have set up dozens of mining pits which destroy the natural environment. The official news agency Xinhua reported that as many as 20,000 tonnes of rare earth elements had been illegally smuggled abroad in 2008. This is nearly one third of China's total exports[29].

POSSIBLE PROTECTIVE MEASURES – ALTERNATIVE SOURCES OF RARE EARTH METALS

To reduce the environmental impact of any product throughout its life cycle, one should develop an innovative approach to integrated environmental criteria of the service, good or product. Due to the disastrous environmental impact of the extraction and processing of rare earth elements, their alternative sources are be-

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[25] *Metale ziem rzadkich*, „Infos" 2012, nr 1(115), http://orka.sejm.gov.pl/WydBAS.nsf/0/8306DB-0738B6B1F4C1257981004A4357/$file/Infos_115.pdf [access: 19.11.2019], p. 3. The original text of the study is available at www.parliament.uk/documents/post/postpn368rare_earth_metals.pdf [access: 25.03.2019]. According to data published by the Chinese Society of Rare Earths, there is 8.5 kg of fluoride and 13 kg of dust per each tonne of rare earth metals produced – see C. Hurst, *China's Rare Earth Elements Industry: What Can the West Learn?*, Washington 2010.

[26] K. Chyla, *op. cit.*, p. 282.

[27] C. Hurst, *op. cit*.

[28] A. Klupa, *op. cit.*, p. 249.

[29] M. Burchard-Dziubińska, *op. cit.*, pp. 26–27.

coming more and more important. To ensure the safety of the development of high technologies, the search for materials that could replace or reduce the consumption of rare earth elements is being considered, and product design are being modified in order to reduce their dependence on these elements[30]. Sources of rare earth elements include phosphogypsum, fly ash from hard coal combustion, recyclable materials and waste products, as well as waste electrical and electronic equipment and catalytic converters.

1. Phosphogypsum and hard coal combustion products

Phosphogypsum is a waste product from the extraction of phosphoric acid from phosphoric raw materials (phosphates or apatites). It is estimated that 2.2–2.6 million tonnes of phosphogypsum are produced in Poland annually. Due to the content of phosphates and fluorides of rare earth metals, etc., this material does not meet the requirements for building gypsum. The resources of apatite phosphogypsum stored on the area of the former chemical plant of Zakłady Chemiczne "Wizów" have been estimated at 8.28 thousand tonnes of rare earth metals, including 200 tonnes of yttrium and at least 33 tonnes of europium[31].

An alternative waste material that contains a lot of rare earth metals is ash and slag from the combustion of hard coal[32]. These raw materials contain not only the main slag-making components, i.e. compounds of aluminium, iron, calcium, silicon in various proportions, but also lanthanum, cerium, neodymium and yttrium. The resources of these metals in Polish hard coal deposits are estimated at 1,400 tonnes, and the average total content of rare earth metals is 114 ppm[33]. In the process of combustion, rare earth elements are transferred to ashes or slag in which they are concentrated. The average content of rare earth elements in fly ash is 400 mg per kg of coal. The content of rare earth elements in ashes from Polish coal power plants is 280 ppm, but in some of them it reaches 600 ppm or even higher figures[34].

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[30] Peculiar properties of rare earth elements result in that either replacement raw materials are not available or their application causes a decrease in efficiency. For example, no material has been invented so far, from which a magnet with strength comparable to that of neodymium magnets could be obtained. On the other hand, studies are under way aimed at the development of an electric motor produced without the use of rare earth elements, e.g. Tesla Motors has used inductive motors in its electric cars. See *Metale ziem rzadkich*, p. 4.

[31] A. Jarosiński, *op. cit.*, p. 84.

[32] *Ibidem*, p. 86. Such research was also undertaken in Polish academic centres, e.g. in the Central Mining Institute. These studies are of a preliminary character and are aimed at the development of a chemical concept for the recovery of rare earth elements from fly ashes from hard coal combustion.

[33] J. Całus-Moszko, B. Białecka, *op. cit.*, pp. 67–80.

[34] J. Kierczak, K. Chudy, *Mineralogical, chemical and leaching characteristics of coal combustion bottom ash from power plant located in northern Poland*, „Polish Journal of Environmental Studies" 2014, z. 5, pp. 1627–1635.

2. Recycling of rare earth metals

In the last decade, interest in waste electrical and electronic equipment as a valuable source of various metals, including precious metals and rare earth elements, has increased significantly[35]. It is estimated that about 11 million tonnes of such waste is produced annually in Europe, which accounts for 22% of the total amount of this type of waste generated globally.

As the market expands and innovation cycles become shorter, electronic appliances are being replaced more often, so that EEE (Electrical and Electronic Equipment) is becoming a rapidly growing source of waste. Although Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment[36] has effectively contributed to the reduction of hazardous substances contained in new EEE, hazardous substances such as mercury, cadmium, lead, hexavalent chromium and polychlorinated biphenyls (PCBs), as well as ozone-depleting substances will continue to be present in WEEE (Waste Electrical and Electronic Equipment) for many years.

The provisions of the RoHS (Restriction of use of certain hazardous substances) Directive has been in force in Poland since 1 July 2006. The RoHS Directive was implemented into national law by the regulation of the Minister of Economy and Labour of 6 October 2004 on detailed requirements for the restriction of use in electronic equipment and some substances that may have a negative impact on the environment[37]. The act was closely linked to the so-called waste directive, on waste electronic and electrical equipment, so-called WEEE (Waste from Electrical and Electronic Equipment)[38], which was in force from August 2005. Both were aimed at protecting the natural environment by reducing electrical and energy waste entering the environment and recovery as much of it as possible.

The RoHS Directive was supposed to limit the use of harmful substances in certain types of electrical and electronic equipment intended for the European market. On 3 January 2013, the RoHS I Directive was replaced by RoHS II, which sets out the rules for limiting the use of hazardous substances in electrical and electronic equipment, which is supposed to improve the protection of human health and the environment, with particular emphasis on the recovery and disposal of waste SEE[39].

[35] M. Cholewa, A. Jarosiński, J. Kulczycka, *Możliwości pozyskiwania surowców nieenergetycznych z elektroodpadów w Polsce*, Kraków 2013, pp. 145–159.

[36] OJ L 37 of 13.2.2003, p. 19.

[37] Journal of Laws No. 229, item 2310.

[38] Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (OJ L 197/38).

[39] In accordance with Commission Delegated Directive (EU) 2015/863 of 31 March 2015 amending Annex II to Directive 2011/65/EU of the European Parliament and of the Council as regards

The RoHS II Directive was implemented by the regulation of the Minister of Development and Finance of 21 December 2016 on the essential requirements for limiting the use of certain hazardous substances in electrical and electronic equipment[40]. Compared to the RoHS I Directive, the RoHS II Directive has been extended to include a conformity assessment procedure necessary to assess the compliance of SEE with the requirements for the listed restrictions, as well as issues regarding the preparation of a declaration of compliance and affixing CE marking on SEE.

Since 14 August 2012, the so-called WEEE 2 Directive has been in force[41]. It replaced the previous WEEE Directive and introduced many significant changes, including new levels of minimum collection of electro-waste from 2016 (40% of the mass of equipment placed on the market in the previous three years, POM) and from 2021 (65% of POM). Member States may set collection levels alternatively: either based on the weight of the equipment sold or on the basis of waste equipment, i.e. the estimated mass of electro-waste actually generated. From 2018 there has been a change in the number of product groups – there are 6 of them.

The content of hazardous components in EEE is the main problem in waste management, and WEEE recycling is being implemented to an insufficient extent. Lack of recycling results in the loss of valuable resources.

The proportion of rare earth metals depends on the type of equipment and may range from several hundred ppm to several dozen percent. Rare earth metal recycling is not as easy as for glass or plastic. Many uses of these elements with their low concentration in waste products, thus making recycling difficult and expensive. The recycling capabilities are better in products that contain more of these materials[42]. In general, the rare earth metal extraction processes are preceded by pre-processing, which includes operations such as disassembly, comminution to a given grain size composition, thermal processing, etc. Basic processes include recovery of rare earth elements by thermal or hydrometallurgical processing[43].

the list of restricted substances, the following substances will be restricted as from 22 July 2019: bis (2-ethylhexyl) phthalate labelled DEHP, butyl benzyl phthalate labelled BBP, dibutyl phthalate labelled DBP, diisobutyl phthalate labelled DIBP.

[40] Journal of Laws of 2017, item 7.

[41] Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) (OJ L 197/38).

[42] *Metale ziem rzadkich*, p. 4.

[43] A. Jarosiński, *op. cit.*, p. 85. For example, the process of recovering neodymium from scrap magnets involves the extraction of neodymium with liquid magnesium, the separation of the liquid phase from the solid phase and the evaporation of liquid magnesium. The resulting product contains over 96% of neodymium, and the rate of extraction is usually above 90% (see M. Kucharski, *Recykling metali nieżelaznych*, Kraków 2010). The studies on the recovery of neodymium or samarium from scrapped permanent magnets using hydrometallurgical method are also being conducted in Poland. In Poland, a method of recovery of yttrium and europium from spent phosphor has been developed. See S. Góralczyk, E. Uzunow, *The recovery of yttrium and europium compounds from waste materials*,

In many countries, the recovery of rare metals is a valuable source of recyclable raw materials also known as urban raw materials[44]. About 70% of the world's rare earth metals are recycled and recovered in China. This results from low labour costs, which makes this process economically viable. A similar situation occurs in India. That is why only about 13% of the global amount of waste electrical and electronic equipment is recycled in Europe[45]. The number of such devices in Poland has grown in recent years, and the ratio of 4 kg of collected electrical and electronic equipment per inhabitant has still not been achieved. Since 14 August 2016, the so-called WEEE Directive has required Poland to collect less than 45% but more than 40% of the average weight of equipment placed on the market in the previous three years[46]. This directive supplements the basic Union waste management legislation, such as Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste[47], Directive 2009/125/EC of the European Parliament and of the Council establishing a framework for the setting of ecodesign requirements for energy-related products[48] and the above-mentioned Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment[49].

The WEEE directive extends the deadline for reaching a collection rate of 65% of the average mass of equipment placed on the market in the three preceding years or, alternatively, 85% of the mass of waste equipment produced in that Member State.

"Archives of Environmental Protection" 2013, Vol. 39(3), DOI: https://doi.org/10.2478/aep-2013-0023, pp. 107–114.

[44] So-called "urban mining" involves the recovery of valuable compounds and elements from products, structures and waste. See K. Poznański, *Ekonomiczna efektywność recyklingu metali*, „Recykling" 2013, nr 7 (dodatek specjalny: Cztery strony recyklingu, cz. III: Metale).

[45] In Poland, in 2012 it was 3.88 kg per capita, and in the EU this indicator amounted to, on average, 17 kg per capita. Such data provide M. Cholewa, A. Jarosiński, J. Kulczycka, *op. cit.*, pp. 145–159; *Surowce krytyczne i strategiczne w Polsce*, red. B. Witkowska-Kmita, Warszawa 2015; A. Wojnarowska, J. Baron, S. Kandefer, W. Żukowski, *Charakterystyka procesu spalania odpadów elektronicznych w reaktorze z pęcherzowym złożem fluidalnym*, „Przemysł Chemiczny" 2013, t. 92(6), pp. 997–1005. The highest rate of increase in amounts of waste is recorded in the category of mobile phones and personal computers. These types of waste differ both in terms of their material and chemical composition. See J. Kozłowski, W. Mikłasz, D. Lewandowski, H. Czyżyk, *Nowe technologie oraz nowe konstrukcje maszyn i urządzeń do wzbogacania i metalurgicznego przerobu surowców mineralnych. Analiza jakościowa i ilościowa złomu zespolonego wybranych grup i rodzajów sprzętu elektrycznego i elektronicznego występującego w Polsce*, Gliwice 2013, pp. 115–125, after A. Jarosiński, *op. cit.*, p. 84 ff.

[46] Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) (OJ L 197/38).

[47] OJ L 312 of 22.11.2008, p. 3.

[48] OJ L 285 of 31.10.2009, p. 10.

[49] OJ L 37 of 13.2.2003, p. 19.

These levels should be achieved no later than on 14 August 2021. This means that more and more e-waste needs to be recycled[50].

3. Recovery for the production of nanoparticles

It is estimated that the total amount of waste electrical and electronic equipment in the EU will reach 12.3 million tonnes by 2020[51]. Therefore, it is worth mentioning the EU-funded RECYVAL-NANO project, which aims to recover rare earth metals from electrical and electronic equipment for the production of nanoparticles[52].

In the Commission communication of 4 November 2008 "The raw materials initiative – meeting our critical needs for growth and jobs in Europe"[53] and in the communication of 2 February 2011 "Tackling the challenges in commodity markets and on raw materials"[54], the European Commission has recognized that securing reliable and interference-free access to raw materials is important for EU competitiveness. The communications presented an integrated strategy to address problems related to access to non-energy and non-agricultural raw materials. The raw materials initiative is based on three pillars: 1) ensuring fair and sustainable supply of raw materials from global markets; 2) supporting sustainable supply of raw materials within the EU; and 3) supporting efficient management of resources and promoting recycling[55]. The Council supported this initiative in its conclusions of 10 March 2011 on tackling the challenges on raw materials and in commodity markets, and the European Parliament in its resolution of 13 September 2011. In June 2010, the Commission published an expert opinion establishing a methodology for identifying raw materials defined as critical for the EU[56]. The EC report presented a list of fourteen critical raw materials, including rare earth metals.

As part of the RECYVAL-NANO project, an innovative strategy for the mechanical recycling of flat video displays has been developed in cooperation with

[50] K. Poznański, *op. cit*.

[51] A. Wojnarowska, J. Baron, S. Kandefer, W. Żukowski, *op. cit*.

[52] The RECYVAL-NANO project, registered as number NMP2-SE-2012-310312, was approved by the European Commission and co-financed with the amount of EUR 3,141,676.45 (in total EUR 4,411,639.60 was allocated to the project). The project lasted four years – from December 2012 to November 2016.

[53] COM (2008) 0699 final.

[54] COM (2011) 0025 final.

[55] Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the implementation of the Raw Materials Initiative, COM/2013/0442 final.

[56] The assessment was based on a quantitative methodology using the criteria of economic significance, supply shortage risk and environmental risk for the state. The risk of shortage of supply included such elements as political and economic stability, degree of concentration of production, substitution rate and recycling factor. A total of 41 raw materials were assessed using this methodology.

industrial partners specialised in the processing and recycling of electrical waste[57]. The first step was to optimise mechanical sorting and extraction techniques to increase the amount and purity of the fractions containing metals to be reclaimed; then manual disassembly procedures were improved to better separate valuable materials from waste, and a technique was developed for magnetic separating and concentrating desired metals. Methods were also investigated as regards extracting pure solutions containing the metals to be reclaimed for direct use in the production of nanoparticles. This required the optimisation of hydrometallurgical processes and refining mechanically recovered fractions to concentrate and extract valuable metals. The project allowed the development of both a global recycling process for flat video displays by mechanical separation of valuable materials and hydrometallurgical processes for refining rare earth metals. This contributed to saving natural resources, less environmental pollution by reducing the amount of electronic waste and reducing the dependence of EU member states on countries which are the suppliers of necessary natural resources[58].

CONCLUSIONS

Non-energy raw materials, including critical raw materials are characterised by a limited raw material resource base and a significant dispersion of minerals and very limited possibilities of substitution. These materials include rare earth elements which define directions of modern, dynamic development in various manufacturing sectors[59]. The use of these metals in technologies associated with the development of low-carbon economy is very promising, especially in wind turbines and hybrid cars[60].

Undoubtedly, the importance of rare earth metals will grow. The raw material needs in the current global economy seem to be unlimited and the growing demand, determined by technological progress, forces the search for new sources of them. One of solutions is the accumulation of reserves. The ever more frequent practice is entering into raw material partnerships concluded internationally.

The countries extracting rare earth elements are obliged to ensure global environmental security. The care for the natural environment is one of the most

[57] The international consortium was established by 12 partners (LUREDERRA, COOLREC, TECNAN, ABCRlabs, MOS, MEAB, EPI-LIGHT, TWI, Chalmers University of Technology, Delft University of Technology, PLASMA QUEST LIMITED and EXCAL) based in Spain, Sweden, the UK, Ireland and the Netherlands.

[58] *Nowe metody odzyskiwania, recyklingu i ponownego wykorzystywania metali ziem rzadkich*, http://cordis.europa.eu/result/rcn/159640_pl.html [access: 20.05.2019].

[59] A. Jarosiński, *op. cit.*, p. 76.

[60] M. Burchard-Dziubińska, *op. cit.*, p. 24.

important arguments against mining these metals. It is necessary to use highly advanced technologies to effectively reduce the disastrous effects of their mining. This requires huge capital expenditures, but in the long run it can positively stimulate the spheres of high-tech and innovation.

Is it difficult to predict now whether there will be developed a common international policy for the exploitation of rare earth metals, setting the direction for joint activities, forms of dialogue, institutions in order to develop standards, methods and manners of conduct of entities concerned. Undoubtedly, the necessity of acquiring resources will generate competition that will affect a part of international economic relations[61].

It is in the interest of highly industrialized countries, including Poland with its plans to increase the role of renewable energy in primary energy production and perhaps also the development of nuclear power sector, to seek new sources of supply for rare earth metals, including increasing the investment in research on their recycling and work on fully equivalent substitutes for those elements which are more difficult to acquire. The purpose of the EU legislation is to contribute to sustainable production and consumption by, first and foremost, reducing the amount of WEEE, and also by contributing to the efficient use of resources and reclamation of valuable recyclable raw materials through the re-use, recycling and other forms of recovery of such waste so as to reduce the amount of waste disposed. This includes also attempts towards improving the environmental friendly character of the activities of all entities involved in the life cycle of EEE, i.e. manufacturers, distributors and consumers, including in particular those directly involved in the collection and processing of WEEE.

The manufacturer's liability rules, when variously implemented in individual countries, can lead to significant discrepancies in the financial burden imposed on businesses. Diversified policies on the management of WEEE in the Member States negatively affect the effectiveness of implementing the recycling strategy. For this reason, the most important criteria should be established at the Union level, and also the minimum standards for WEEE processing should be defined.

Is it worth looking for investors, i.e. entities that are holders of advanced technology of extraction and processing of critical elements, guaranteeing high environmental standards, willing to get involved in the exploration and management of Polish and global resources[62].

[61] K. Chyla, *op. cit.*, p. 291.

[62] B. Wiśniewski, *op. cit.*, p. 2.

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STRESZCZENIE

Do wydajnego funkcjonowania i rozwoju każdej gospodarki niezbędne są surowce należące do czterech głównych grup. Są to surowce energetyczne, surowce organiczne, woda i surowce mineralne. Surowce nieenergetyczne (w tym tzw. surowce krytyczne) cechują się ograniczoną bazą surowcową i znacznym rozproszeniem minerałów oraz bardzo ograniczonymi możliwościami substytucji. Do tych surowców zaliczane są pierwiastki ziem rzadkich, które wyznaczają kierunki nowoczesnego, dynamicznego rozwoju różnych gałęzi przemysłu. Wraz z rozwojem nowoczesnych technologii wzrosło zapotrzebowanie na komponenty niezbędne do ich rozwijania i wytwarzania. Bardzo obiecujące jest wykorzystanie metali ziem rzadkich w technologiach związanych z rozwojem gospodarki niskoemisyjnej, zwłaszcza w turbinach wiatrowych i samochodach hybrydowych.

Słowa kluczowe: metale ziem rzadkich; surowce krytyczne; odzysk; recykling; gospodarka niskoemisyjna; technologia energooszczędna