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ON TRENDS RELATED TO RECOVERY OF RARE EARTH METALS FROM THE WASTE OF ELECTRONIC DEVICES

Individual Project Work

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Examiner(s): Professor Harri Eskelinen, D. Sc. (Tech.)

ABSTRACT

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

t	Metric Tons
lbs	Pounds
kg	Kilograms
mln	Million
ppm	Parts per Million

Abbreviations

AUKUS	Trilateral security partnership between Australia, United Kingdom and United States
CRM	Critical Raw Materials
CSTO	Collective Security Treaty Organization
EEE	Electrical and Electronic Equipment
EoL	End-of-Life
EROI	Energy Return on Investment
EU	European Union
HREE	Heavy Rare Earth Elements
IR4.0	Industrial Revolution 4.0
LCA	Life Cycle Assessment
LREE	Light Rare Earth Elements (from La to Gd)
NATO	North Atlantic Treaty Organization
n/a	not available
PEST	Political, Economic, Social, Technologic dimension
RoHS	Restriction on Hazardous Substances
StEP	Solving the E-Waste Problem
STEPS	Stated Policies Scenario
WEEE	Waste Electrical and Electronic Equipment
WEF	World Economic Forum

1 INTRODUCTION

The introduction section presents the problem in its complexity following this structure. First, we introduce the background for the study, motivation to conduct the study, research problem and the related research questions, objective of the study and the framework used for that.

1.1 Background of the study

It seems that the Schwab's Industrial Revolution 4.0 (IR4.0) advanced by the World Economic Forum (WEF) platform becomes the predominant vision for the post-industrial development of the western civilization. For the lack of alternatives, this vision is accepted, supported and advanced by the wide range of followers among which are global elites, governments, businesses, educational institutions, mass media, and further projected down to the masses. This vision relies on high levels of digitalization, interconnectivity and smart automation (see more Schwab, 2016). In practical terms, this means more electronic devices are going to enter the market and daily lives as well as more devices will become obsolete and replaced. If we further develop this observation, the devices become more complex, faster and smaller in size requiring specific materials to facilitate such mix of performance. The category of materials that support performance requirements is becoming strategic in its value given the pursued vision of development. In fact, the European Commission refers to them as *critical raw materials* (Blengini et al., 2020; Bobba et al., 2018). These strategic elements can be divided in five categories: rear earth elements, fusion elements, platinum group elements, rare metals and metalloids, phosphorus (MIT, 2016). Primarily, only 3 categories of these elements are used in electronics – rear earth elements, platinum group elements and rear metals and metalloids. These elements are "rare" in a sense that the mineral containing ore stocks are rarely concentrated in amounts economically feasible for mining deposits. On the other hand, the scrap of electronic devices already contains those same materials although their content rarely exceeds 1-5% of the total weight of the product. Nevertheless, provided the elements are efficiently recovered, e-scrap has a potential of becoming an additional source for diversification of supply of strategic elements.

Coupled with the “green agenda” (in particular, the promotion of the Circular Economy perspective), the IR4.0 vision is challenged by certain levels of contextual limitations. Among them are 1) political resistance of major suppliers of the raw materials to the idea of becoming a prey and follow the enforced agenda, 2) absence of the image of the future with the functional economic system capable of supporting the economic change towards the new normal accepted by all stakeholders and 3) the justified technological innovations to support all of the IR4.0 hopes (see discussion on energy return on investment (EROI) (Weißbach et al., 2013; Ferroni and Hopkirk, 2016; IEA, 2020; Conca, 2015)). Noticeable is that the viability of the agenda directly relates to the existence and smooth functioning of the globalization and cross-border institutions facilitating the smooth technology, knowledge and resource cross-border flow. In other words, smooth supply chain functioning, low inflation rates, accessible credit, abundant natural resources immediately available for the on-demand accessibility to fuel and support the transition. Given the recent geopolitical developments, we notice that the globalization is still working, but it is on the edge of collapse jeopardizing the hopes and dreams of the new world order promulgated by the WEF.

The availability of the resources to fuel the IR4.0 transit in such scenario either precondition the advancement or predetermine the delay and decline. Although the common sense reasoning requires the limitation of the scope of the research to those trends related mainly to the technological side with hope of finding a probable solution, the issues of geopolitics, economics and sustainability **cannot** be left outside of the perspective without a risk of oversimplification of the actual state of affairs and groundless optimism about the future prognosis. When we talk about the resources, we not only mean the REEs, but also such widely available materials as non-ferrous metals (e.g. aluminum and copper), demand for which is on the rise and is far from normalizing in the one-digit demand growth rate following the demand for the semiconductors.

Considering the fact that any Industrial Revolution requires intensive engineering involvement, there is also an increasing demand in understanding the underlying processes in whose favor the change happens. In recent publications on sustainability and industrial design, the engineers were assigned with the burden of responsibility for the progress. Industrial designers are required to use sustainable materials and product design, and carry the moral responsibility in case they are not (Rammler, 2015; Melles, 2015; Kretschmer, 2014; Katzenstein, 2013; Stahel, 2019), but the reason why is argued vaguely. Besides the common clichés about saving the planet for thankful future generations while making sustainable profit, there is a vacuum of undeniable teleologic reasoning why that is important for each individual and corporate decision maker besides the altruistic feelings reserving to the legal enforcement of the agenda. The main reason for surficial justification relates to the nature of the answers which are outside the limitations of the typical technology-oriented engineering discussion. The topic of sustainable design is stirred and mingled with topics related to the sociology, economy and to political economy in particular (see Rammler, 2015; Melles, 2015; Kretschmer, 2014; Katzenstein, 2013; Stahel, 2019). Obviously, that such mix is nonrandom. If the engineers are made responsible and are demanded to act in a certain way, the engineers are entitled and obligated to have also the understanding in what interests and for what function the changes happen. In such case, it is irresponsible to focus only on the technologic side without acquiring the bigger system-level perspective on the REE related issues. This brings us to the motivation of the research.

1.2 Motivation

The primary motivation of the study is to identify the major trends and tendencies related to REEs and their recovery from e-waste as an alternative to mining, but also to place that discussion into a broader perspective. We aim at identifying the stakeholders suitable for cooperation on the identified trends. The expected outcome of the project is the proposition of a matrix containing the Circular-Economy-related actions connected and attributed with stakeholders in the political, economic, social and technological areas to be consolidated for action on the observed trends.

1.3 Research problem

To define the research problem, it is important to recognize that the problem with REEs lays only partly within the rare elements themself and rather bigger issues lay within the external environment around them. REEs is a well-researched clear topic – the elements are important, useful and demanded, but why and what can be done to secure their availability is uncertain. Answering the “why” and “what” questions requires turning to the external environment, which very distantly relates to the elements and technology intrinsically. When talking about the external environment, we refer to such recognized in social studies categories as the political, economic, social (in particular, the environmental dimension) and technologic aspects (PEST), which independently and collectively significantly shape the discussion around the topic. As there are various groups in a society, there are also various interests often contradicting each other. These contradicting interests find their reflection in the topic of REEs. That is why recognizing such trends and seeing through them is an important step to developing a viable acceptable solution. As for design engineers, trends help allocate the opportunities and get beyond the arguably hardest part of the design – identification of the need for design. Thus, trends help with setting in motion what otherwise would remain static.

Some of the contradicting trends are explicit and easily observed, some are tacit. Below are just a few contradicting trends:

- The scale of IR4.0 and transit to the implementation of the agenda requires a lot of various materials among which the REEs take a special place. That same agenda promotes the “green economy” one of the postulates of which is reduction of the negative effect on the environment, which is a contradiction in itself with the material sourcing especially given that the REE mining and extracting is a polluting, energy and natural resource demanding process.
- The agenda of IR4.0 requires abundance of other non-critical materials (e.g. Al, Cu, Fe), but an increase in their availability goes in contradiction with the scale of financing, regulation and implementation of the green agenda (4Rs) for their responsible supply.
- The user of an electronic device, for example a smartphone, enjoys the pleasure of a touch screen requiring REEs for its functionality, the engineers recognize the advantages of space and weight reduction or enhanced electronic properties for better performance associated with the use of REEs, while the policymakers recognize the need in reducing the dependence on the suppliers of those critical elements as well as reducing the threat to the environment;
- More devices enter the daily usage and more leave. How they are treated after their end-of-life attracts a lot of attention from various institutions, state and the public. A good example is smartphones. Some devices are resold, when they get old, some end up on shelves in an “old devices” box, some are returned to the collection points and

> are processed for recycling, the others get trashed and landfilled. The wasted materials affect the entire society and can significantly impact the environment as some elements are dangerous/radioactive. Especially when landfilled, the elements can reach the potable waters. The contradiction is, thus, the convenience of smartphone utility on the one hand and the waste generation on the other.

The task of defining the problem around the REEs would be easier if we can limit the **context** of the environment to a certain country or a region and REEs related issues in certain application. Unfortunately, the REEs have strategic importance for any developed and rapidly developing economy. In their significance, they become equal to such resources as gas or oil, and require consideration of their impact on the cross-regional/global scale. When necessary though, we limit the discussion only to the context of the EU especially when we turn to the topic of the waste treatment. Accepting a more limited context defies the purpose of seeing the major trends and limiting the potential of developing a better solution. Contrarily, acquiring a more holistic perspective sets the ground for development of the better political, economic, environmental and engineering practices. This means that we need to step up and out of purely technical discussion about the REEs and their applications, and explore the trends beyond the accessible technical discussion context.

The research problem can be defined in the following statement: what trends surround the REEs and e-waste treatment. In other words, we see the importance of the REEs for the present, but what can we expect of the future and more importantly what actions can be taken to be ready for the arising trends in various domains.

To have an acceptable discussion, it is also important to define and limit the perspective to the context of a region when needed.

At the same time, the **perspective** from which the discussion is laid down can and should be limited. Perspective as the point of view significantly affects what one sees and how one perceives the object in perspective. In other words, the REE related issues and conclusions will differ significantly when considered from perspective of China as the biggest supplier of REEs than from perspective of the EU as one of the major consumers. That is why we look at the issues of REEs, PEST aspects and sustainability from the perspective of the EU although when possible we target at maintaining a rather country/region-neutral discussion as some trends are global.

1.4 Research questions

Given the background of the study, the motivation and the problem definition, the research questions for this study are formed as following:

- What are REEs and what trends surround them?
- What are the e-waste-related trends in the context of REEs' discussion?
- Are there reasonable alternatives to REEs?
- How REEs recovery from e-waste relate to Circular Economy perspective?
- What contextual trends relate the REEs and the REE recovery from e-waste?

1.5 Objective of the study

The aim of the study is to acquire a system-level perspective (PEST) and explore the REM-related trends in regards to their role in the Circular Economy (4Rs and e-waste). The expected outcome of the study is the proposition of a matrix with complex set of measurements that include political, economic, social and technological measures meeting the Circular Economy objectives.

The goal:

- Trends in related to REE and their impact on industrial design engineering
- Recognize the trends in the area of technology development in relation to REE and identifying the directions of the further development
- Life-Cycle-Assessment of REEs and/or e-waste
- Exploring the state of affairs in respect to waste electric and electronic equipment (WEEE or e-waste) management and REE recovery.
- Consider the existing sustainability strategies of e-waste management with respect to REEs.
- Explore the REEs and e-waste trends related to the political, economic, social and technical domains.

1.6 Framework

As a framework for the study, we take two models. One relates to the Circular Economy – the 4Rs action strategy. The other one is the PEST tool for strategic analysis. The associated context is the recovery of the REE from WEEE provide the subject for which the solution is proposed.

1.7 Structure of the study

To answer the research questions, the study follows this structure. We start with the literature review. It focuses on the definition of the REEs and their role in global economy, the WEEE as side effect of rapid digitalization, discussion about the Circular Economy and REE recovery from WEEE, followed with observations from the observations from the PEST environmental dimensions. The conduction of expert interview is adopted as a research method. The observed trends and topics from both literature review and expert interviews are used to develop an action matrix in response to observed trends.

2 LITERATURE REVIEW

The literature review section explores four major categories and their relations in search for trends. We start with the topic of rare earth elements, followed by e-waste, 4Rs of Circular economy and PEST analysis of REE recovery from WEEE.

2.1 Rare earth elements

Rare earth elements (REEs) are the seventeen chemical elements from the periodic table two of which are transition elements (^{21}Sc and ^{39}Y) and fifteen belong to the lanthanides group from ^{57}La to ^{71}Lu. These elements are Figure 1 presents the location of the elements in the Mendeleev's periodic table of elements along with their atomic weight. The other names commonly used for these elements are the rare earth metals (REM) and rare earths (RE).

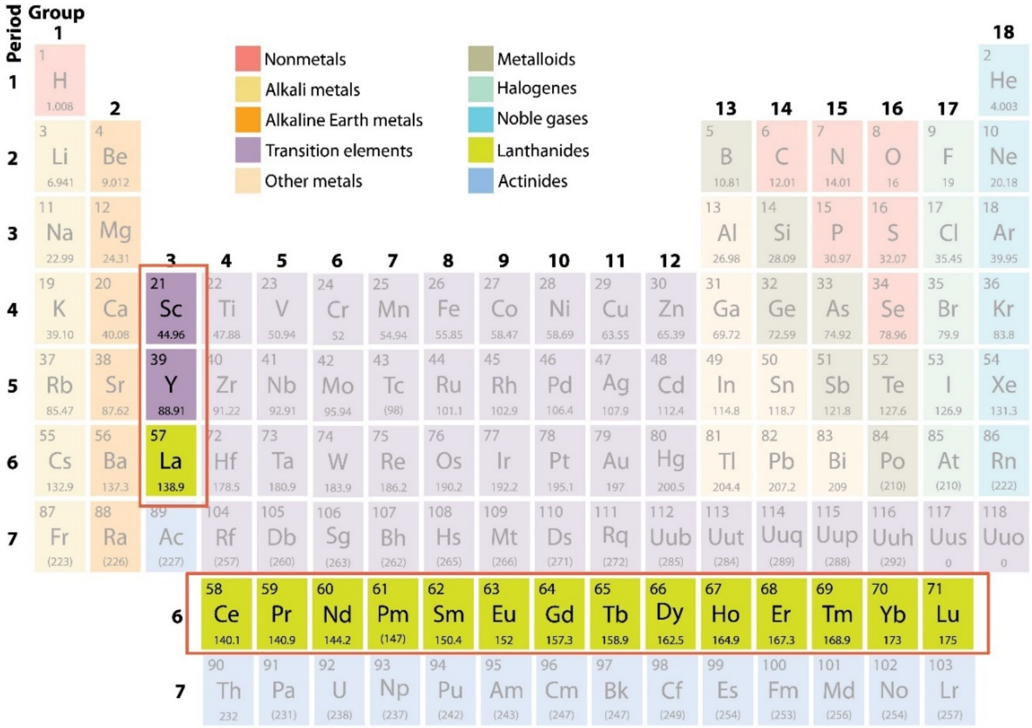


Figure 1. Periodic table: lanthanoids (Rare Element Resources, 2016).

Calling REs "rare" is only partly accurate. These elements are quite abundant in the Earth's crust, but seldom in the significant concentrations to support the economic extraction focused only on these elements. Figure 2 illustrates this by showing the abundance of the

REEs. Noticeable is that yttrium, cerium or lanthanum is as plentiful as copper. (Deboer and Lammertsma, 2013). This is an important observation to which we will return as a part of minerology and global supply discussion (2.1.3).

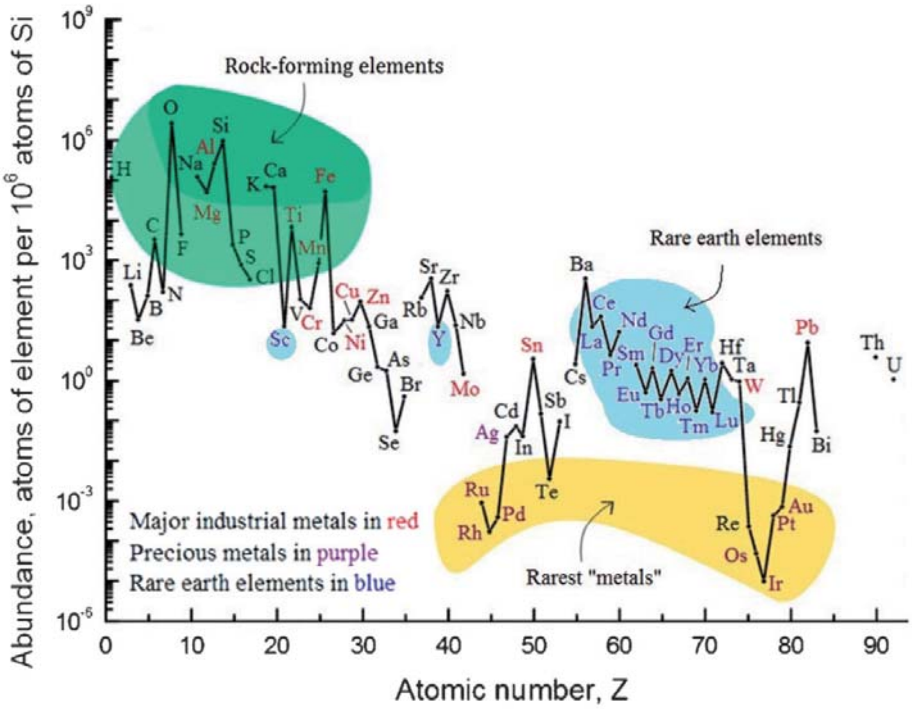


Figure 2. Relative importance of REEs in blue (Deboer and Lammertsma, 2013)

Although the REE were discovered at the dawn of the 18th century by Finnish chemist Johan Gadolin, the first useful applications were found only a century later. The gas mantle was the first reported commercial product which used the lanthanum oxide in Vienna in the 1890s. From this time, the REEs gain their significance in the industrial, energy and military applications. (Dushyantha et al., 2020; Voncken, 2016; Gupta and Krishnamurthy, 2005).

Figure 3 presents the time scale along with the years and the name of the discoverers of each REE, which reveal important lessons about the elements. The history presents an exciting scientific adventure, with which one can get familiarized in the works of Voncken, 2016; Generalic, 2022; Gupta and Krishnamurthy, 2005; Dushyantha et al., 2020 among others. Yet, the history is also weighty in understanding the major issues with the REE recovery. First of all, the story shows that there is a complex composition of two starting minerals – cerite and ytterbite (gadolinite), from which the discovery of the other REEs started. Second, the pattern of elements' discovery followed the logic of a Russian nesting doll, matryoshka: when sourcing one element in its pure state leads to discovery of the other elements. Third, the REEs occur in the same deposits with exception of Sc and this is quite significant also from the perspective of their extraction/recovery. The elements are quickly reacting with other REEs from the same branch forming compounds making them harder to extract. In fact, all of these aspects shed the understanding about the degree of complexity related to extraction of the REE, which also hint towards the reasons why the elements are recovered at the present scale.

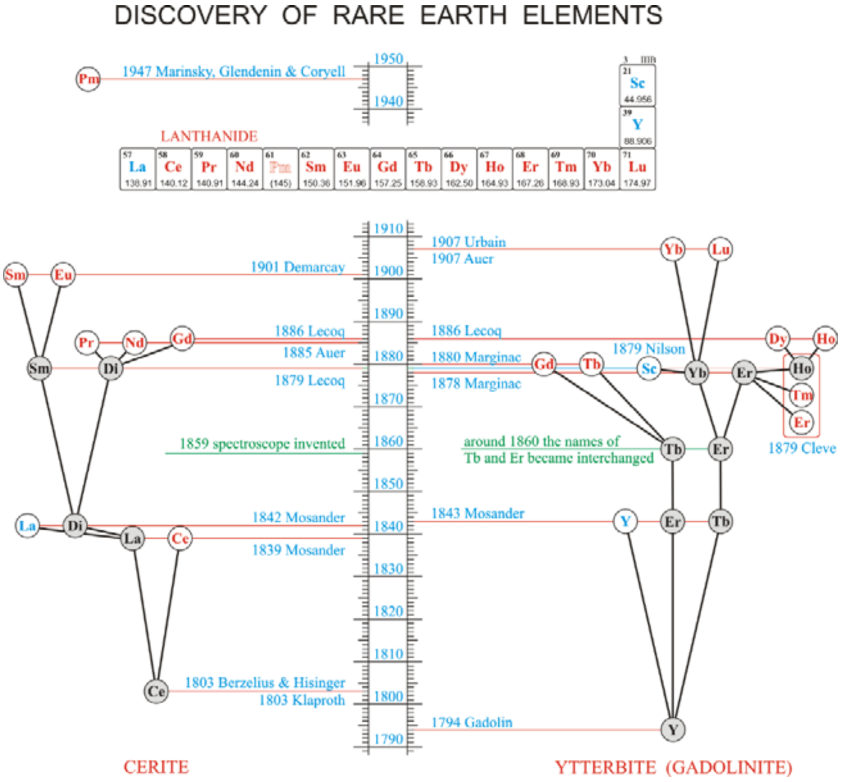


Figure 3. History of REE discovery. Clean chemical elements are shown in color, transition compounds - in grey (Generalic, 2022)

2.1.1 What makes REEs special? *4f*-electrons

The main differentiation points allowing outstanding magnetic, electric and optical properties of the rear earths are the *4f*-electrons and the way they interact with each other and with other elements when they are mixed together (Strange et al., 1999). A good illustration is the neodymium-iron-boron magnets ($Nd_2Fe_{14}B$), which have the best magnetic properties. As we see from the atomic formula of the compound, neodymium is not the primary element, yet it is only because of what neodymium brings into a compound make the magnets have their property (Schwartz, 2020). The lanthanides are distinguished by the *4f*-electrons and ionic radii for the R3+ ion. According to Gschneidner and Pecharsky (2019), the *4f*-electrons have lower energies and radially lie inside the outer three valence electrons, and thus they do not directly participate in the bonding with other elements when a compound is formed. Because of that, the lanthanides are chemically similar and difficult to separate when and why they occur together in various minerals. (Gschneidner and Pecharsky, 2019). Table 1 briefly summarizes the chemical properties of the REEs. A more detailed description of elements which includes besides atomic properties, mechanical, thermal, electrical, magnetic properties are summarized by Gupta and Krishnamurthy (2005) in Table 1.2 of their work. The variations between the properties of the elements are caused by the lanthanide contraction and hybridization of the *4f*-electrons with the valence electrons (Gschneidner and Pecharsky, 2019). The implication of these differences affects the performance of the materials.

Table 1. REE properties (Humphries, 2013; Gschneidner and Pecharsky, 2019)

Name	**Code** (atomic nr)	**Valence**	**Atomic mass**	**Density (g/cm⁹ at 20ºC)***	**Ionic radius (Å)**	**Melting/boiling points (ºC)**	**Molar heat capacity (J mol⁻¹ K⁻¹)**	**Electric resistivity (nΩ·m)**	**Price ($/kg)****
Scandium	^{21}Sc	$3d^1 4s^2$	44.956	2.985	0.745	1539/2836	25.52	562	14 000
Yttrium	^{39}Y	$4d^1 5s^2$	88.906	4.472	0.900	1526/2930	26.53	596	2 200
Lanthanum	^{57}La	$4f^0 5d^1 6s^2$	138.905	6.162	1.045	920/3464	27.11	615	640
Cerium	^{58}Ce	$4f^1 5d^0 6s^2$	140.116	6.77	1.01	798/3457	26.94	828	570
Praseodymium	^{59}Pr	$4f^3 5d^0 6s^2$	140.908	6.77	0.997	931/3130	27.20	700	1 700
Neodymium	^{60}Nd	$4f^4 5d^0 6s^2$	144.243	7.01	0.983	1016/3074	27.45	643	1 100
Promethium	^{61}Pm	$4f^5 5d^0 6s^2$	144.913	7.26	0.97	1042/3000	27.6	750	N/A
Samarium	^{62}Sm	$4f^6 5d^0 6s^2$	150.360	7.52	0.958	1074/1900	29.54	940	1 300
Europium	^{63}Eu	$4f^7 5d^0 6s^2$	151.964	5.264	0.947	822/1529	27.66	900	36 000
Gadolinium	^{64}Gd	$4f^7 5d^0 6s^2$	157.250	7.90	0.938	1313/3000	37.03	1310	1 910
Terbium	^{65}Tb	$4f^9 5d^0 6s^2$	158.925	8.23	0.923	1365/3123	28.91	1150	18 000
Dysprosium	^{66}Dy	$4f^{10} 5d^0 6s^2$	162.500	8.54	0.912	1412/2567	27.7	926	2 100
Holmium	^{67}Ho	$4f^{11} 5d^0 6s^2$	164.930	8.79	0.901	1474/2600	27.15	814	7 400
Erbium	^{68}Er	$4f^{12} 5d^0 6s^2$	167.259	9.066	0.890	1529/2868	28.12	860	2 700
Thulium	^{69}Tm	$4f^{13} 5d^0 6s^2$	168.934	9.32	0.880	1545/1950	27.03	676	70 000
Ytterbium	^{70}Yb	$4f^{14} 5d^0 6s^2$	173.055	6.90	0.868	819/1916	26.74	250	5 300
Lutetium	^{71}Lu	$4f^{14} 5d^1 6s^2$	174.967	9.841	0.861	1663/3402	26.86	582	69 000
🟧	- Light Rare Earth Elements (LREE) group (Voncken, 2016; Gupta and Krishnamurthy, 2005)								
🟦	- Heavy Rare Earth Elements (HREE) group (Voncken, 2016; Gupta and Krishnamurthy, 2005)								
**	- source: (Material Properties contributors, 2022b)								
*	- density source: (Chemical Study contributors, 2020; Material Properties contributors, 2022a)								

2.1.2 Common applications

The REEs have **various applications,** which are summarized in Table 2 by an element. Among these applications, there are four major one driving the market demand for the materials. These applications concern the metallurgies, catalysts, polishing powder and magnets accounting for three out of four uses of the rare earths. The other common uses relate to pigmentation in glasses, ceramics and phosphors. (Cardoso et al., 2019; Gupta and Krishnamurthy, 2005).

Table 2. Applications of rare earths (Gupta and Krishnamurthy, 2005; Voncken, 2016; Sastri et al., 2003; Cardoso et al., 2019)

Element name	**Application**
Scandium (Sc)	Radioactive tracking agent in oil refineries, aerospace framework and components, high-intensity street lamps, additive in metal-halide lamps and mercury vapor lamps, ceramics, electronics
Yttrium (Y)	High-temperature alloys, enhances strength of alloys in metallurgy, red phosphor, high temperature superconductors, optical glasses, ceramics, gas mantles, catalysts, lasers, filters in microwave devices, TV sets, cancer treatment drugs, energy efficient light bulbs, spark plugs
Lanthanum (La)	Night-vision goggles, camera lenses, high-reflection low-dispersion glasses, fluid catalysts for oil refineries misch-metal*, arc light carbons, petroleum cracking catalysts, battery-electrodes, hydrogen storage
Cerium (Ce)	Polishing powders, opacifier for porcelain coatings, glass decolorizer, colored glass, glass melting accelerator, photographic materials, textiles, chemical oxidizing agent, arc lamps, steel production, ferrous and non-ferrous alloys including high-temperature Mg-alloys, automotive catalytic converters, misch-metal, catalytic converters,
Praseodymium (Pr)	Alloys, magnets, didymium glass (for protective goggles), welding goggles, yellow ceramic pigments, cryogenic refrigerant, misch-metal, lasers
Neodymium (Nd)	Laser range-finders, permanent magnets, guidance systems, communications electronics, microphones, steel manufacture, glazes and colored glass (including didymium glass), lasers, petroleum cracking catalysts, misch-metal, electric motors of hybrid automobiles
Promethium (Pm)	Miniature nuclear batteries for harsh environments. Pm has few applications due to all isotopes being radioactive and synthetically prepared.
Samarium (Sm)	Stable at high temperatures permanent magnets, nuclear reactor control rods, precision-guided weapons, “white noise" production in stealth technology, reactor control and neutron shielding, magnets, luminescent and infra-red absorbing glasses, X-ray lasers, catalysts, ceramics, electronic devices, magnetostrictive alloys, misch-metal, cancer treatment, masers
Europium (Eu)	Fluorescents and phosphors in lamps and monitors, phosphor activator, electronic materials, neutron absorber, color TV screens, genetic screening tests
Gadolinium (Gd)	Electronic materials, high-temperature refractories, increases durability of alloys, cryogenic refrigerant, thermal neutron absorber, superconductor, magnetic materials, bubble memory substrates, shielding in nuclear reactors, nuclear marine propulsion
Terbium (Tb)	Lasers, electronic materials, TV sets, erasable optical memory substrate, magnetostrictive alloys fuel cells, sonar systems, florescence lamps
Dysprosium (Dy)	Catalysts, transducers, electronic materials, hard disk devices, phosphor activators, magnetic refrigeration, magnetostrictive alloys, commercial lighting
Holmium (Ho)	Electronic devices, catalysts, glass coloring, refractories, magnetic materials, high-strength magnets, magnetostrictive alloys lasers
Erbium (Er)	Amplifiers in fiber-optic data transmission, infrared-absorbing glasses, glass colorant, phosphor activator signal amplification for fiber optic cables, metallurgical uses
Thulium (Tm)	High efficiency lasers, Portable X-ray machine units, high temperature superconductor
Ytterbium (Yb)	Research applications, improves stainless steel, lasers, ground monitoring devices
Lutetium (Lu)	Research applications, refining petroleum, LED light bulbs, integrated circuit manufacturing
*Misch-metal is an alloy of about 50% cerium, 25% lanthanum, 15% neodymium and 10% other rare earth metals. Uses include manufacture of a pyrophoric alloy with iron and deoxidizer in metallurgical applications, getter for removal of oxygen from vacuum tubes, high strength magnesium alloys. (Sastri et al., 2003).	

The presented in the Table 2 summary of the REEs' uses describes the major applications which are often hard to trace down to each individual use. For instance, nickel metal hydrate batteries (NiMH) are familiar by the main elements though contain La and Ce ions as well. These batteries are convenient for use in portable electronics and hybrid/electric vehicles though the frequency of use is decreasing ceasing to more efficient Li-ion batteries. $Nd_2Fe_{14}B$ magnets also contain Pr, Dy, and Sm ions. The major application of these permanent magnets are hard-disc drives, industrial motors, hybrid/electric vehicles and wind turbines. Light REEs (elements from La to Pm) are used in metallurgy to improve the mechanical properties of the alloyed steels, for desulphurization purposes, to bind trace elements in stainless steel, in MgAl alloys. (Cardoso et al., 2019).

The various applications reveal another trend towards the increasing importance of the elements for the contemporary and the new economy. The importance of the REEs can be illustrated with an example of widely known products from two radically different categories – an iPhone and the F-35 combat aircraft. By observing the use of REEs in these products, we can better comprehend the dry statistic numbers.

Since the focus of our study on the electric devices, we can see the scale of importance of REEs and demand for them on the example of one common electric device. An iPhone uses eight REEs in phone circuitry, speakers, touchscreen functionality. Rare earths is just a fraction of phone weight, but their contribution is essential and the number of phones sold yearly is impressive (Nogrady, 2016; Rare Element Resources, 2016). Considering that the average amount of smartphone users globally reaches 2 billion units and the upgrade rate to a new phone is currently at about 11 months (Nogrady, 2016), this creates not only an environmental challenge in recycling of the old equipment but also in supply of the necessary materials for the new phones. For instance, by December 2021, Apple sold 100 mln new iPhone 13 units (Li, 2021) and the total of all active iPhone units in 2021 globally is 1 231 mln units (Curry, 2022). If we assume that each iPhone contains a total of 1 gram of REEs, this amounts to 100 metric tons per year of the REEs necessary for production of **one** product category in **one** selected company. The number of the iPhone in use also means that this is an abundant source of REEs and other precious materials which can be recovered when processed or wasted if the phones are landfilled or stacked at the end of their life on a shelf or in a box.

Another good example of the reliance scale on the REE is the use in military applications. It is not a secret that the contemporary military systems are a complex integration of the advanced electronics with “primitive” mechanics. Consider the latest iteration of the F-35 airplane. Each F-35 combat aircraft contains about 417 kg (920 lbs) of REE (Kenlan, 2020), which are mainly used to enhance the operational functionality of the machines without bearing the costs in weight gains inevitable when the REEs are not used. Yearly, Lockheed Martin and F-35 Joint Program Office have agreed to peak the production of the planes at 153 in the 2022 year and top 156 in 2023 (Tirpak, 2021). This amounts to almost 64 metric tons of elements per year.

After considering an individual application, we can turn to the REEs global distribution by application. Figure 4 presents the global distribution and the US market distribution by application as one of the leading consumers of the REEs. Here, we also see the distribution spread of elements by application in a given economy. For instance, we see that the global frequency of REE application in catalysts is 15.5%. Meanwhile, the US uses 43% of REEs in catalysts. Among the catalyst applications, they go into petroleum refining, catalytic converters, fuel additives, chemical processing and air pollution control. This figure gives a perspective to the numbers, which affects the prospects of replacing the elements by resources with a better availability for the same application. The scale at which the elements are used in the green economy and various advanced applications show the bitter truth – the REEs cannot yet be replaced or avoided without significant implications in performance when considered in the light of present needs and increasing demand for materials for the transit to the green economy driven by IR4.0.

The possibility of REE substitution by other materials was studied by Öko Institute in 2011 (Schüler et al., 2011). The final conclusion of the study is that lanthanides have unique properties, which are hard to march by other alternatives. There are quite rare cases of successful substitution of REEs in a product but such cases come at significant cost. Such changes require complete redesign of the product, which defies the entire idea of substitution (Schüler et al., 2011).

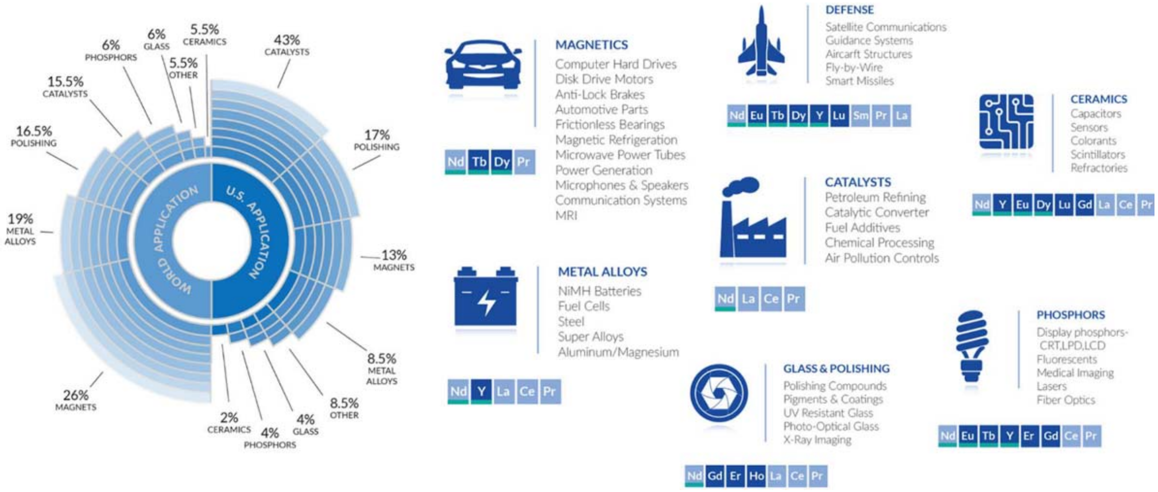


Figure 4. Global and the US REEs distribution by application (Tracy, 2020)

2.1.3 Minerology and global supply (production)

As mentioned before, the rarity of the REEs is a common misconception. The consideration of their availability in perspective of availability of other elements helps seeing the point and for this we need to turn to minerology.

The abundance or shortage of an element is conveyed by its average concentration in the Earth's crust. From this point of view, the REEs are moderately abundant in the Earth's crust. The total abundance of the REs is 220 ppm. It is higher than that of carbon (200 ppm) and of many other better-known metals. Surely, the relative abundance varies significantly among the REEs. Those elements that have an even atomic number are move abundant that their odd neighbors in the periodic table. Figure 2 above expresses that in a chainsaw pattern especially among the HREEs. Figure 5 presents the abundance of REEs in comparison to some common elements in the Earth's crust. The LREEs are more concentrated in the continental crust than HREEs. Hence, lanthanum, cerium, praseodymium, and neodymium are the most abundant REEs. Among all REEs, cerium is the most abundant and thulium is the least. Cerium is in fact more abundant than copper; neodymium, yttrium, and lanthanum are more plentiful than lead and cobalt. Such commonly used in electronics material as tin is less plentiful than praseodymium, samarium, gadolinium, dysprosium, and erbium. Such least abundant of the rare earths as ytterbium and thulium are each more plentiful than mercury or silver. (Gupta and Krishnamurthy, 2005).

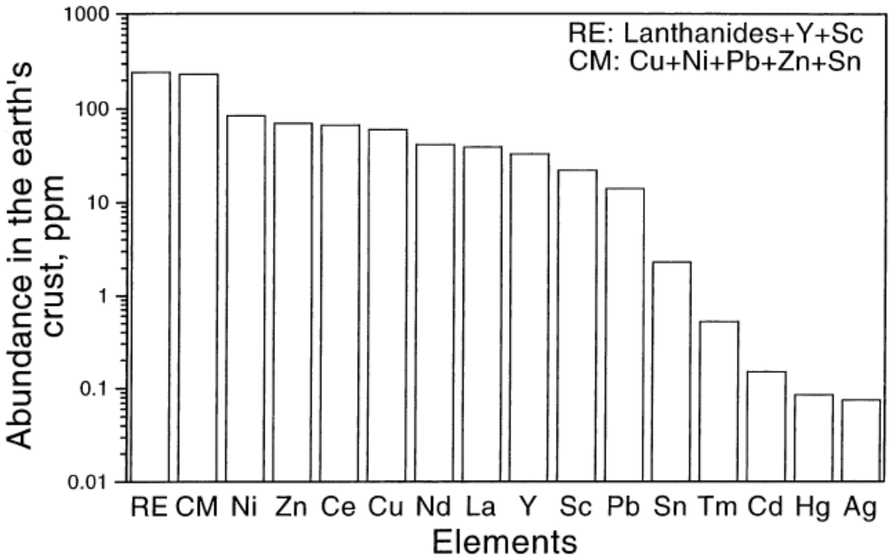


Figure 5. Abundance of REEs in comparison to some common elements in the Earth's crust (Gupta and Krishnamurthy, 2005)

What makes the rare earths then "rare"? Considering the crustal abundance, the REEs are not rare. The less abundant elements as copper and lead are not considered rare because they form fairly concentrated deposits. REEs, in contrast, are widely distributed in the crust with low concentration. The other aspect which justifies their rarity is the complexity of the extraction. (Gupta and Krishnamurthy, 2005). To these two categories, the concentration and extraction, we turn our attention next by identifying the minerals in which the elements are deposited, the biggest mining sites, and the extraction and separation methods.

Minerals. In nature, REEs do not occur in their elemental state nor as individual compounds. They are scattered in basalts, granites, gneisses, shales and silicate rock formations. Their concentrations range from 10 to 300 ppm (Govindarajan and Gupta, 2000; Voncken, 2016). Because of their strong propensity to react with oxygen, the REEs are mostly found as oxidic compounds. REEs occur in over 160 discrete minerals among which the most important are aeschynite, bastnaesite, euxenite, fergusonite, gadolinite, loparites, monazite, orthite, parasite, priorite, samarskite, thorite, xenotime, yttrocite. Even though the RE minerals are so many in number, about 95% of all REEs resources occur in three minerals – bastnaesite, monazite and xenotime (Gupta and Krishnamurthy, 2005). Most of the minerals are rare, but the rare earth oxides (REO) can reach up to 60% as a fraction of total weight of a deposit. As a rule, which has its explicit visualization in the history of the REE discovery (Figure 2), **any** rare earth mineral usually contains **all** the REEs in different proportion with some at higher and other at lower concentration. (Gupta and Krishnamurthy, 2005; Voncken, 2016).

Major mining sites. Table 3 provides a summary of the biggest deposit sites and their location. Here is also mentioned the main REEs and the REE minerals. Initially, the biggest sourcing location for REEs was in the Mountain Pass. Later, China has discovered abundant deposits in the Inner Mongolia and until these days REE supply from that destination determines global market.

Table 3. The biggest REE deposit sites (Voncken, 2016)

Deposit	**Location**	**Main REE**	**REE-minerals**
Bayan Obo	Inner Mongolia, China	LREE	Bastnaesite, parasite, monazite
Mountain Pass	California, USA	La, Ce, Nd	Bastnaesite
Mount Weld	SW- Australia	LREE	Apatite, monazite, synchysite, churchite, plumbogummite-group minerals
Ilimaussaq (*Kvanefleld, Kringlerne, Motzfeldt Sø*)	Greenland, Denmark	La, Ce, Nd, HREE	Eudialyte, steenstrupine
Steenkampskraal	South Africa	La, Ce, Nd	Monazite, apatite
Pilanesberg	South Africa	La, Ce	Eudialyte
Hoidas Lake	Canada	La, Ce, Pr, Nd	Apatite, allanite
Thor Lake	Canada	La, Ce, Pr, Nd, HREE	Bastnaesite
Strange Lake and Misery Lake	Canada	La, Ce, Nd, HREE	Gadolinite, bastnaesite
Nolans Bore	Australia	La, Ce, Nd	Apatite, allanite
Norra Kärr	Sweden	La, Ce, Nd, HREE	Eudialyte
Khibina and Lovozero	Kola Peninsula, Russia	LREE+Y, minor HREE	Eudialyte, apatite
Nkwombwa Hill	Zambia	LREE	Monazite, bastnaesite
Kagankunde	Malawi	LREE	Monazite-Ce, bastnaesite-Ce
Tundulu	Malawi	LREE	Synchesite, parasite, bastnaesite
Songwe	Malawi	LREE, especially Nd	Synchysite, apatite
Chinese ion adsorption deposits	South China	La, Nd, HREE	Clay minerals
Maoniuping	Sichuan, China	LREE	Bastnaesite
Dong Pao	Vietnam	LREE	Bastnaesite, parasite

Since we mentioned the rare earth minerals, a brief mentioning of the global production and rare earths' reserves is appropriate. The estimated total global mine production in 2020 was around 240 000 metric tons being absolutely dominated by the minerals from China. Table 4 presents the summary of the leading global REEs suppliers by country and their deposit reserves. The information is based on the United States Geological Survey.

Table 4. World REE mine production and reserves (King, 2020)

Country	Production (t)	Reserves (t)
China	140 000	44 000 000
United States	38 000	1 500 000
Burma	30 000	n/a
Australia	17 000	4 100 000
Madagascar	8 000	n/a
India	3 000	6 900 000
Russia	2 700	12 000 000
Thailand	2 000	n/a
Vietnam	1 000	22 000 000
Brasil	1 000	21 000 000
Burundi	500	n/a
Greenland	--	1 500 000
Tanzania	--	890 000
Canada	--	830 000
South Africa	--	790 000
Other countries	100	310 000
World total (rounded)	**240 000**	**120 000 000**

The static information presented in the Table 4 when set in historic perspective in Figure 6 allows for a number of insightful observations. In particular, it is obvious that there is a positive trend towards the increasing supply of the REEs. Another observation is that China is a market leading supplier of the REEs. The global trend towards reduction of REE production outside China starts with 1985. The abundant availability and relatively lower prices charged by Chinese companies drove the competitors out of business. As long as such state of affairs did not pose strategic threats for supply of raw materials it was acceptable by major consumers, especially the US. Another trend is evident starting with the year 2010. After this year, China has limited its production while other countries have increased it. The reasons for such trends are not related directly to the REEs as raw materials and are discussed as a part of the political impacts of REEs in the environmental analysis.

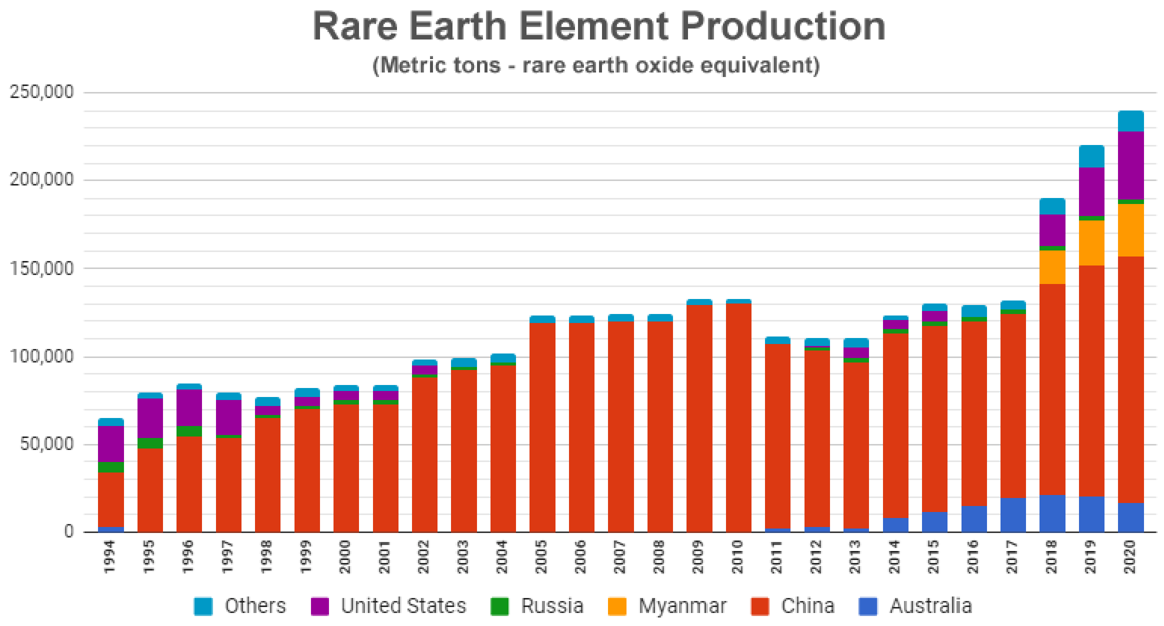


Figure 6. REE production (supply) between 1994-2020 by country (King, 2020)

Major REEs sources. Often the mining is discussed as if it is the only source of REEs (see for example Gupta and Krishnamurthy, 2005; Voncken, 2016; Atwood, 2012). Besides the commercial ore concentration mining, there are other major sources of REEs. Dutta and colleagues identify at least four more major sources (Dutta et al., 2016), among which are:

- **Ion-adsorption clays** – the source requires fairly simple process of chemical weathering and dissolution of granite and granite porphyry, where REEs interact with clay surface and get adsorbed in the clay forming the ion-adsorption clay (Dutta et al., 2016);
- **Sedimentary marine phosphate deposits** (phosphorites) contain high HREE concentration (500-2000mg Kg^{-1}) to be considered a major source. The extraction of REEs is similar to phosphate fertilizer production with 100% rate of dissolving of the REEs in the phosphate deposits. The process is equally easy where the phosphate rock is dissolved in dilute sulfuric acid to produce phosphoric acid used in chemicals, fertilizers and animal feed (Dutta et al., 2016);
- **Coal and coal by-products** – a source of REE with 71-89% recovery rate from ash-containing by-products of coal mining. The recovery of REEs involves the ammonium sulfate, leaching 89% of REEs into the filtered solution. Followed by

the use of ionic liquid and deep eutectic solvent as lixiviants, this results in 80% and 71% respective recovery rate of the REEs (Dutta et al., 2016; Perämäki et al., 2019);

- **Fly ash from fossil fuel and other wastes** – though not related to the mining process directly, this can be considered as a source of secondary source of REEs discussed more in subsection 2.2.4 as urban mining. The municipal solid waste incineration and coal combustion are a valid source of REE in extractable amounts (Dutta et al., 2016; Perämäki et al., 2019).

Process of REE extraction. Before we turn to the element separation and purification, it is important to mention the basic processing steps the element rich ore goes through. Ore usually contains just a few percent of valuable material although some rich deposits can contain from 5-15% of ore mass (Voncken, 2016). Separation techniques involve separation of the REEs from a worthless bulk, "gangue". Figure 7 shows a basic material flow through the ore processing.

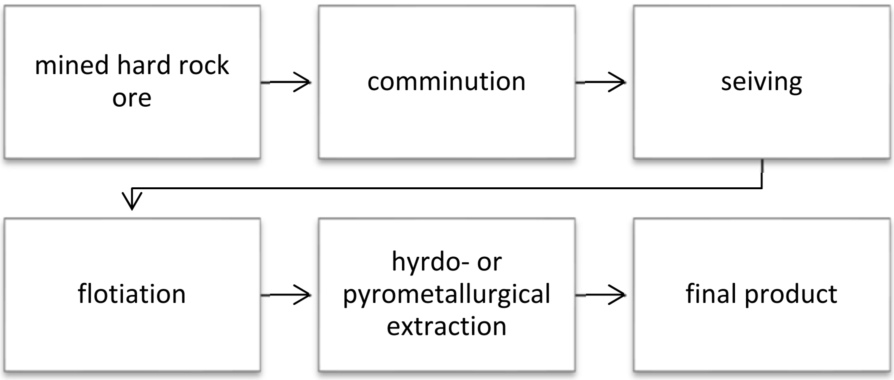


Figure 7. Basic flowchart of REE ore processing (Voncken, 2016)

The process has roughly six major steps. First, the hard rock ore is **mined** and transported to the processing facility. Next, it undertakes **comminution**, which is a process of crushing the ore to such size that yields relatively clean particles of either mineral or gangue. This is usually the most expensive stage of processing adding up to 50% of the total production cost. After that, the **sieving** stage, where the separation of large and poorly grinded particles from smaller particles takes place. The large particles accordingly return to the comminution stage. The particles of the acceptable smaller size move to the next processing step. At the **flotation** stage, a gravity separation technique is applied since the REEs are hardly magnetic and such process does not work. The elements are hydrophobic though. For separation is used a container full of liquid with a rotational agitator mechanism and the air flow supply to the bottom of the container. When the air flow passed through the liquid, the hydrophobic elements adhere and raise to the surface forming a foam layer where they are collected. The gangue is tailing on the bottom. The flotation stage is usually performed in a several sub-steps with rather self-explanatory names – rougher, scavenger and cleaner. The next step is **hydrometallurgical or pyrometallurgical extraction**. At this stage, the purification of the elements happens by means of hydrometallurgical processing, involving chemical solutions, or by pyrometallurgical processing, which involves heat treatment in air or controlled atmospheric environment. (Voncken, 2016). Gupta and Krishnamurthy (2005) provide more detailed overview of the separation (ch. 3.5), reduction (ch. 4) and REE refining (ch. 5) processes. As the outcome, there is the RE concentrate ready for further purification.

Separation. As we remember the lesson from the history of REE discovery, the elements are often found along with other rare earths requiring separation of the individual elements from the naturally occurring mixtures. For that, the small difference in basicity resulting in decrease in ionic radius from La to Lu are utilized. The basicity differences influence the solubility of salts, the hydrolysis of ions and the formation of complex molecules (Gupta and Krishnamurthy, 2005).

Gupta and Krishnamurthy (2005) identifies a number of common separation methods of REEs among which 1) selective oxidation, 2) selective reduction, 3) fractional crystallization, 4) fractional precipitation, 5) ion exchange, 6) solvent extraction. **Selective oxidation** is used to separate the Ce early in the separation sequence by heating the basnaesite to 650ºC in air or when drying rare earth hydroxides in air at 120-130ºC. **Selective reduction** is applied to separate Sm, Eu and Y from trivalent mixture of REE by reducing to a divalent state. **Fractional crystallization** utilizes a change in temperature or evaporation of a saturated solution when a part of the salt in solution is precipitated. This method gains high level of purity. As such, double ammonium nitrates are used for separation of La, Pr, Nd; double magnesium nitrates for separation of Sm, Eu and Gd. For separation of Er, Tm, Lu and Y is used rare earth hexa-antipyrine iodide salt. Fractional crystallization of Gd, Tb, Dy, and Y is achieved by using the Ethylenediaminetetraacetic acid disodium salt. **Fractional precipitation** method removes a part of rare earths from solution by addition of a chemical reagent to form a new, less soluble compound. The remaining in the solution REEs are recovered either by precipitation as the same compound of by complete precipitation as the oxalate, hydroxide or other compound. By double sulfate precipitation, the La-Dy range of elements can be separated. By basic precipitation, the Eu-Lu are removed. Thus, such method can effectively separate the entire range of REEs. In **ion exchange** method, an ion exchange raisin takes place of an ionic salt in which one of the ions is attached to an insoluble organic matrix. When the ion exchange happens, resin comes into contact with a salt solution, the mobile ion in the resin matrix can be displaced. As a result, an ion of higher charge displaces an ion of lower charge; between similarly charged ions, the one with a larger radius displaces the one with smaller radius, and finally displacement happens according to the law of mass action. This is the oldest method and has passed through the number of updates, but still returns a good quality refined material in the end for practically all REEs. In **solvent extraction** method, the separation of REEs depends on the preferential distribution of individual REs between two immiscible liquid phases that are in contact with each other: one of liquid phase is an aqueous solution and the other is in non-aqueous phase in the organic phase. This is a very advantageous method as rare earth loading in a solvent can be as high as 180g of REO per liter so an aqueous solution with concentration of 100-140g of REO per liter can be used. Thus, the equipment for processing the materials can be very compact. (The presented above methods are a summary of ch. 3.5 from Gupta and Krishnamurthy, 2005).

Reduction and refinement. Thus far, the extraction and separation concerned the REOs as the final outcome of ore processing operations, but these are the intermediary steps before getting the actual pure RE metals. REOs are natural starting materials before the conversion to metals by the reduction process. The reduction of REOs is resource demanding process because the oxides are extremely stable, the REs' melting point and their conversion requires special atmospheric conditions (Voncken, 2016). There are three methods of metal reduction: reduction of a halide, fluoride, chloride. On the example halide conversion, we will illustrate the challenges of RE metals' processing. The liberation of the metal from its compound happens by following reaction (Gupta and Krishnamurthy, 2005):

$$MX_n + iR = M + iRX_{n/i}$$

Here, **M** is the obtained metal; **X** is either oxygen, fluorine or chlorine; R is the reducing element, which may be hydrogen, carbon, or other metals which in most cases are lithium, magnesium, aluminum, sodium, calcium or potassium (Gupta and Krishnamurthy, 2005). The major problem is that formation of a halide prior to the reduction happens at rather high temperatures. Figure 8 shows the temperatures that are required for the reaction to take place. The metallurgical thermodynamics requires that at a chosen reaction temperature the difference between the free energies of formation of a starting compound and the corresponding compound of the reductant element is negative (Gupta and Krishnamurthy, 2005).

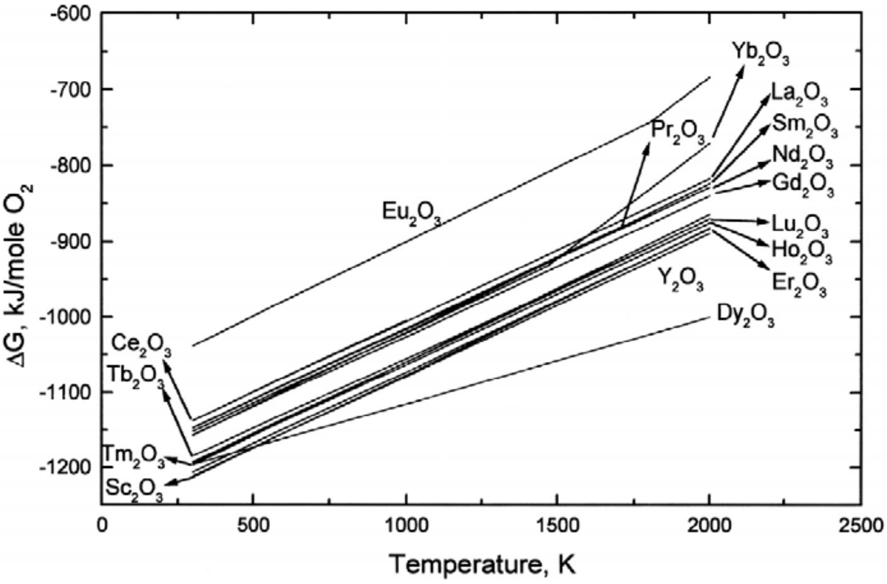


Figure 8. Standard free energy formation of REOs as a function of temperature (Gupta and Krishnamurthy, 2005)

The temperatures at which the reaction happens is rather resource demanding, which leaves the serious mark on the argumentation favoring the green transit.

The final purity of the metals is high, but often requires more refinement. Usually, the reduced REEs are 98-99% pure. Further reduction of impurities to about 0.5% can happen by careful selection of pure raw materials and processing in a controlled environment. Additional gain in purity is either technically impossible or requires significant increase in costs especially in a scaled operation. The REE purity suitable for major purposes is usually obtainable at sensible prices. The grade of ultrapure materials is seldom uniform. Thus, a grade that is suitable for one operation fails at another. Therefore a certain degree of customization and adaptation is required, which in turn converts in a higher costs. (Gupta and Krishnamurthy, 2005).

2.1.4 Global demand

In the estimation of the global demand for the REEs, we rely either on relatively dated information, on the assumption of the industry consultants or on hints from adjacent materials used in similar technologies. Nevertheless, since our main goal is to identify the trends, this information is sufficient and acceptable for the purpose. Figure 9 summarizes the estimates for the demand between 2016-2020. The estimated market demand was projected at 170 000 tons with 6% yearly growth rate (Rollat et al., 2016). The supply was estimated to reach 200 000 tons per year. The actual supply of REEs already mentioned in Figure 6 shows the increased in supply to 240 000 tons. Such increase in supply originates from the increasing demand, which in turn is an evidence of the growing interest in the REs on the market.

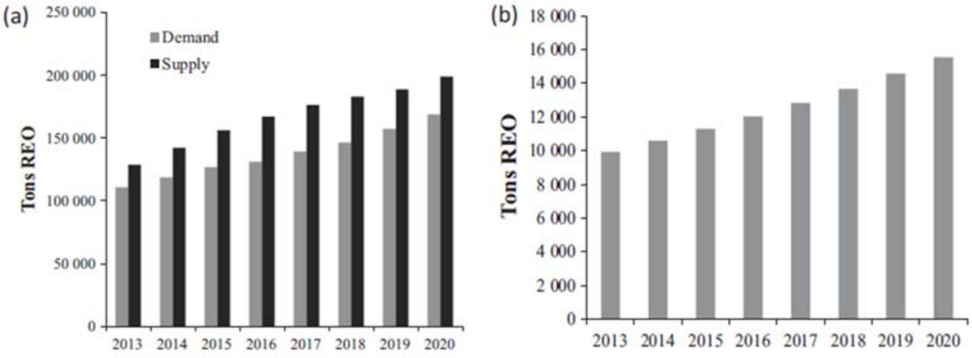


Figure 9. Anticipated evolution of global RE demand and supply from 2016 to 2020 (a), anticipated RE demand in Europe (b) (Rollat et al., 2016)

The projected demand growth for the REEs in the 2020-2040 time horizon is estimated to exceed +10% annual growth rate even in most conservative scenario. Considering the increasing interest to the clean energy transition (IEA, 2021) and corresponding transit to the new structure of the world economy accidentally and absolutely unintentionally synchronized with the COVID-19 crisis, stock market bubble, collapse of the supply chains, economic slowdown and the raising inflation around the world, we can safely estimate a double digit increase in the global demand for the REEs. In fact, the International Energy Agency has conducted research and made estimates based on two scenarios for the demand growth of the critical materials for the clean energy transitions (IEA, 2021). Under the first, the looser scenario, which is based on the currently implemented sustainability measures and future plans around the world, the Stated Policies Scenario (STEPS), the projected demand for REEs is expected to triple (+300%) by 2040. Under the more stringent scenario called to meet in full the net-zero emission targets set out in the Paris Agreement goals by 2050 called the Sustainable Development Scenario (SDS), the demand for REEs is expected to increase seven times (700%) by 2040 to suffice the needs. In either case, there is enough evidence to state that the general demand is trending towards the increase.

The 10% yearly demand increase is a significant environmental issue. If we take the current demand as the base (240 000 t) add the yearly increase (+24 000 t) and multiply all by the percentage of ore from the total mineral mass (5%), we see that the total mass of ground needed to be processed to extract those minerals equals to 5 280 000 t per year. This number is impressive and it concerns only the initial part of the processing. The amount of energy and other resources required to process the REE containing ore into a 99% pure material is shocking. What shocks more is that process behind the dry extraction statistics and estimates are repeated year after year compounding the previous result.

2.1.5 REEs deposits in Europe

In Europe, there are regions rich in REEs and other resources critical for the development of the local and global economy. Those major regions located within the borders of such states as Finland, Sweden, Denmark (Greenland), Portugal, UK, Balkan countries, Turkey (Goodenough et al., 2016; Dutta et al., 2016; Deboer and Lammertsma, 2013; Perämäki et al., 2019). Figure 10 is showing the overview map of Europe showing the approximate extent of the key REE metallogenetic belts. Though the deposits are present in abundance and sufficient for the growing demand, they are not as rich as those from China, Vietnam or Brasil.

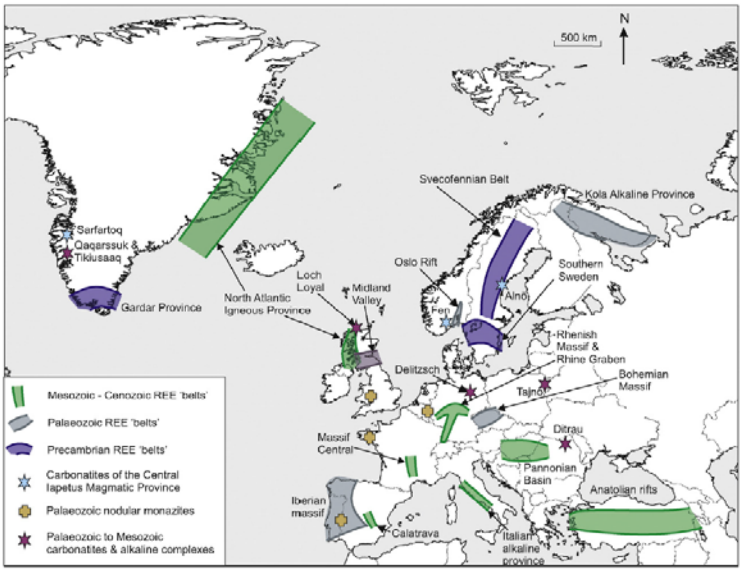


Figure 10. Overview map of Europe showing the approximate extent of the key REE metallogenetic belts (Goodenough et al., 2016)

Figure 11 shows the simplified geotectonic map of Europe and Greenland with the discovered REE occurrences. Coupled with the Figure 10, geotectonic map helps identify the area for further exploration. The value of the map for the study relates primarily to the identification of the state borders within which the deposits can be sourced.

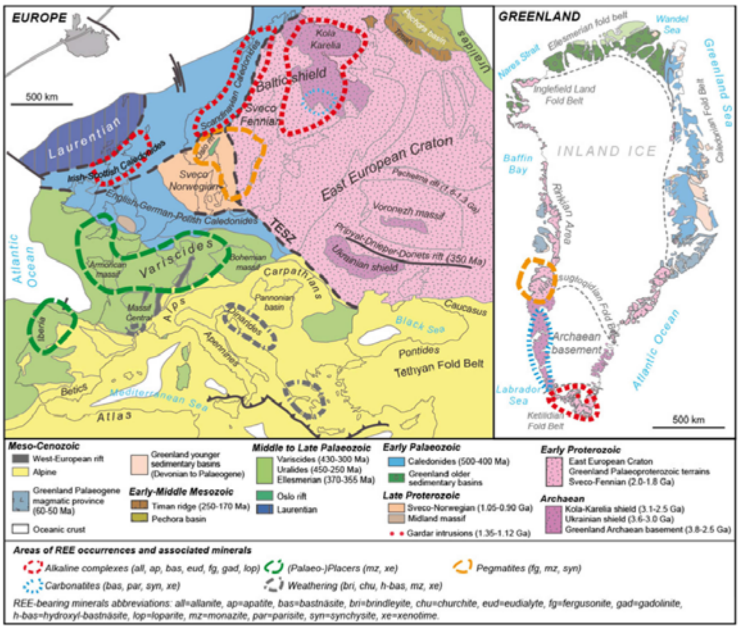


Figure 11. Simplified geotectonic map of Europe and Greenland (Charles et al., 2013)

Figure 12 shows the grade and tonnage comparison between the EU REE deposits to the similar worldwide resources. Current REE production comes from high-grade carbonatites from Bayan Obo and Mountain Pass. In comparison to such carbonatites, the European carbonatites are lower grade (Goodenough et al., 2016).

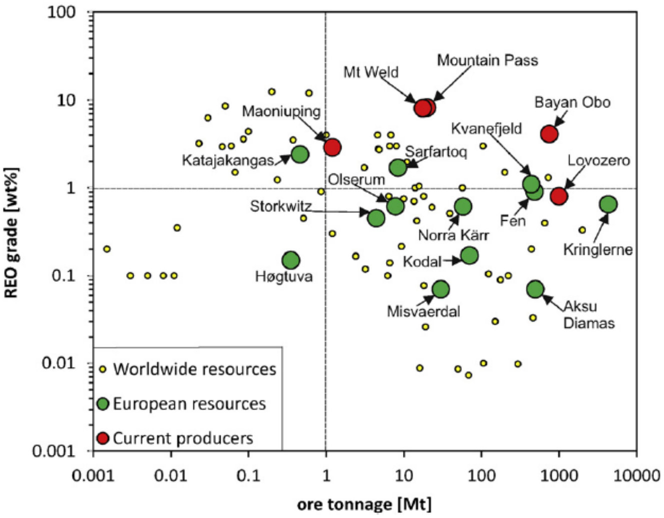


Figure 12. Grade and tonnage plot comparing EU REE deposits and the worldwide resources (Goodenough et al., 2016)

Figure 13 shows the bauxite deposits in the Mediterranean area. As mentioned above, the majority of REEs deposits sourced these days comes among others from bauxite minerals. These deposits are distributed along the Mediterranean costal area.

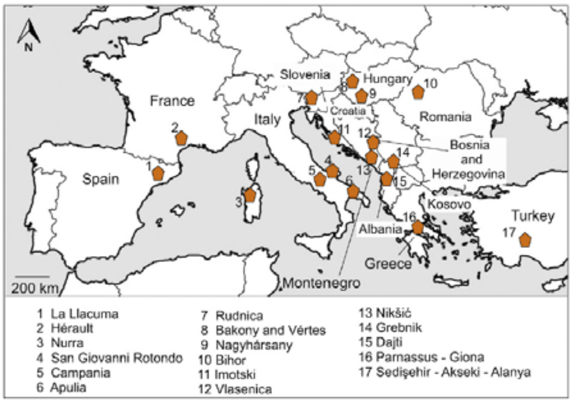


Figure 13. Bauxite deposits in the Mediterranean area (Deady et al., 2014; Goodenough et al., 2016)

The section presents the REEs deposits in Europe omitting one major issue. The mining and processing of REEs within the EU is at the zero level (Wyns and Khandekar, 2020). It might take significant financial and time resources to arrange the mining and processing of the resources to the economically scalable state. As the demand is expected to grow, the continuous supply is under a threat, and the local infrastructure is underdeveloped, the obvious response to secure the local supply is a matter that has to raise high on the policymakers' agenda.

2.1.6 EU supply and demand of REEs

The dimensions of the supply and demand for REE in the EU are derived from the underlying economic activities. The economy of the European Union is heavily depending on the imports of the REE and other critical for the economy raw materials. As mentioned above, the EU does not engage in mining and production of the REEs (Wyns and Khandekar, 2020; European Commission, 2020). The existing deposits are conserved at the moment. On the other hand, Figure 14 shows the estimated shares of the REE demand by element and the use of the materials in the economy. The categories with advanced outputs require the supply of raw materials abroad. So, the internal supply is absent and the stability of the external supply is threatened by various factors including the supply chain disruptions. There is an option of recycling and sourcing the REE from existing e-waste. According to the European Commission (2020, p.665) study on the EU's list of critical raw materials, the REE recycling is under 1% because of lack of efficient collecting system and prohibitive costs of building REE recycling capacities.

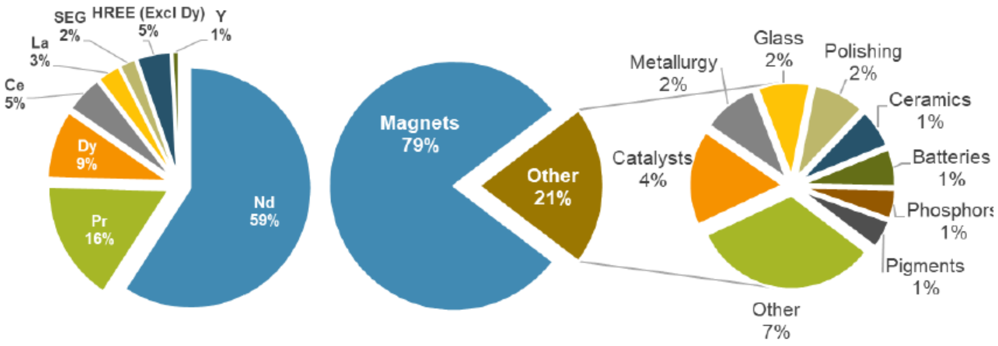


Figure 14. Estimated shares of RE value by element (left) and end-use (right) in 2019 (European Commission, 2020)

The rate of dependence on Chinese resources presented in the Figure 15 is vividly observed, when we turn to the manufacturing value chain of one product where the magnets play the fundamental role. The wind power turbines rely heavily on the permanent magnets. Though REE material sourcing is rather diversified, the processing of the REEs are concentrated in China. The EU also engages in some processing activities, but its contribution is only about 1%. Further, the not so important assembling activities of the wind turbines are again diversified. This shows strategic dependence of the EU on China in the industrial processing activities, which are resource intensive and costly to build in case of the interruption from the main source.

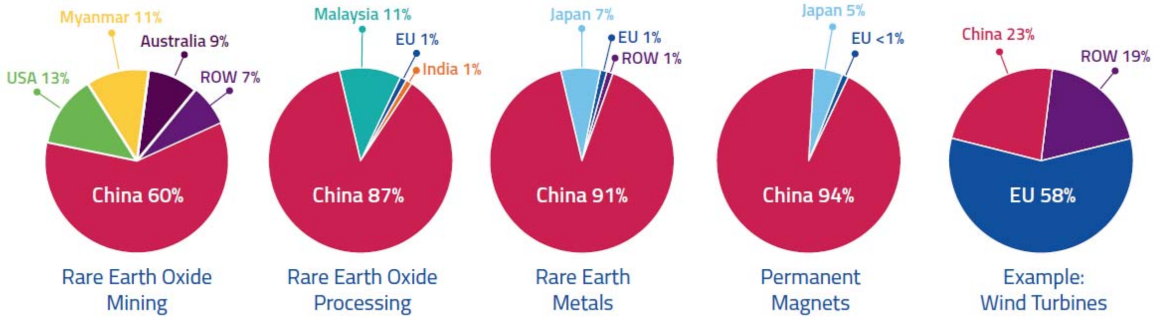


Figure 15. Estimated market shares in the wind turbine manufacturing value chain in 2019 (Roland et al., 2021)

When considering the largest suppliers of the critical for the EU economy raw materials, it is hard to avoid the heavy dependence on one predominant source. The Figure 16 shows the largest suppliers of critical raw materials (CRMs) to Europe (Blengini et al., 2019; European Commission, 2020). Noticeable is the practically full dependence on China for supply of the REEs; 99% of LREE and 98% of HREE come to the EU from one source. In recent years, we can observe the trend towards diversification of the REE supplies; only 85% of LREE and 84% of HREE come from China (European Commission, 2020). Nevertheless, the heavy reliance on the external supply has forced the EU to develop diversification strategies and transform them to action.

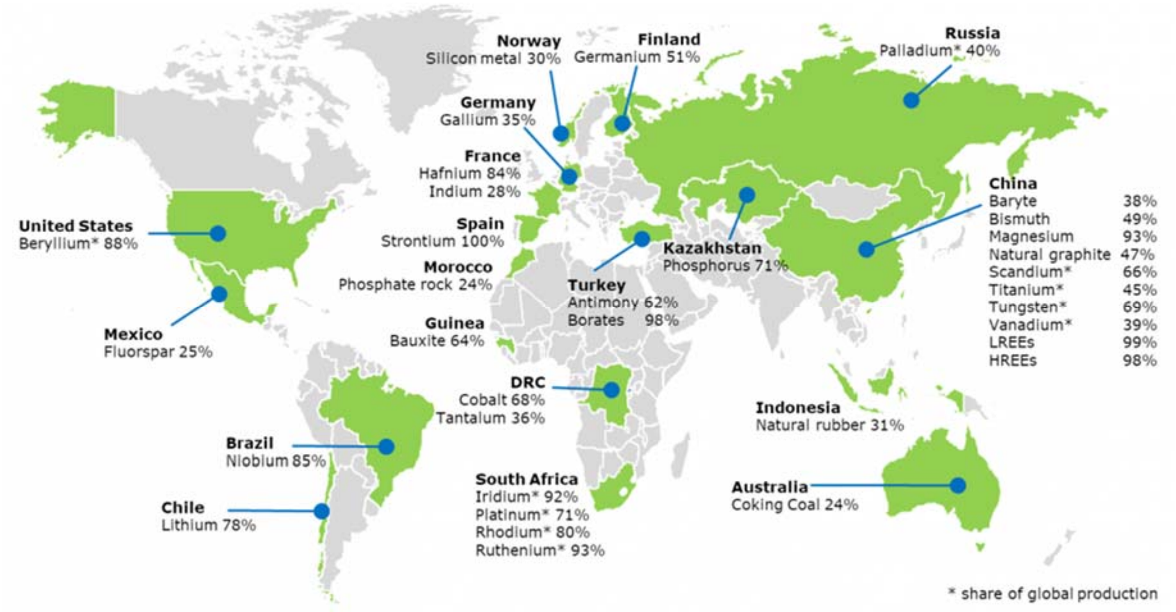


Figure 16. Largest suppliers of CRM to Europe (Blengini et al., 2019)

2.1.7 REEs as critical raw materials for EU

A modern economy requires a consistent supply of metals, minerals and other natural materials supply. Limited availability or threat of supply disruption makes these elements a bottleneck for economic growth raising their status to the critical level. EU publishes the list of critical materials for the Member States' economy every three years starting with 2011. The latest report is from 2020 (Blengini et al., 2020). The list evaluates 83 individual raw material positions for their criticality. The latest report has identified 30 positions as critical. Table 5 below shows those positions among which there are also the HREEs and LREEs.

Table 5. 2020 EU Critical Raw Materials (Blengini et al., 2020)

2020 EU Critical Raw Materials List			
Antimony	Fluorspar	Magnesium	Silicon Metal
Baryte	Gallium	Natural Graphite	Tantalum
Bauxite	Germanium	Natural Rubber	Titanium
Beryllium	Hafnium	Niobium	Vanadium
Bismuth	**HREEs**	PGMs	Tungsten
Borates	Indium	Phosphate rock	Strontium
Cobalt	Lithium	Phosphorus	Scandium
Coking Coal	**LREEs**		

Figure 17 below shows the results of critical material assessment for 2020. The results were distributed along the economic importance on the X-axis and the supply risk on the Y-axis.

The placement on the plot shows the estimated importance of the raw materials. Although the relative economic importance of the REEs is quite high on par with such materials as lead or silicon metal, the high risk of supply disruption is what attracts significant attention to these elements. When compared to the 2017 ranking (Beatriz et al., 2018; Bobba et al., 2018), the economic importance of the REEs have changed along with the supply risks.

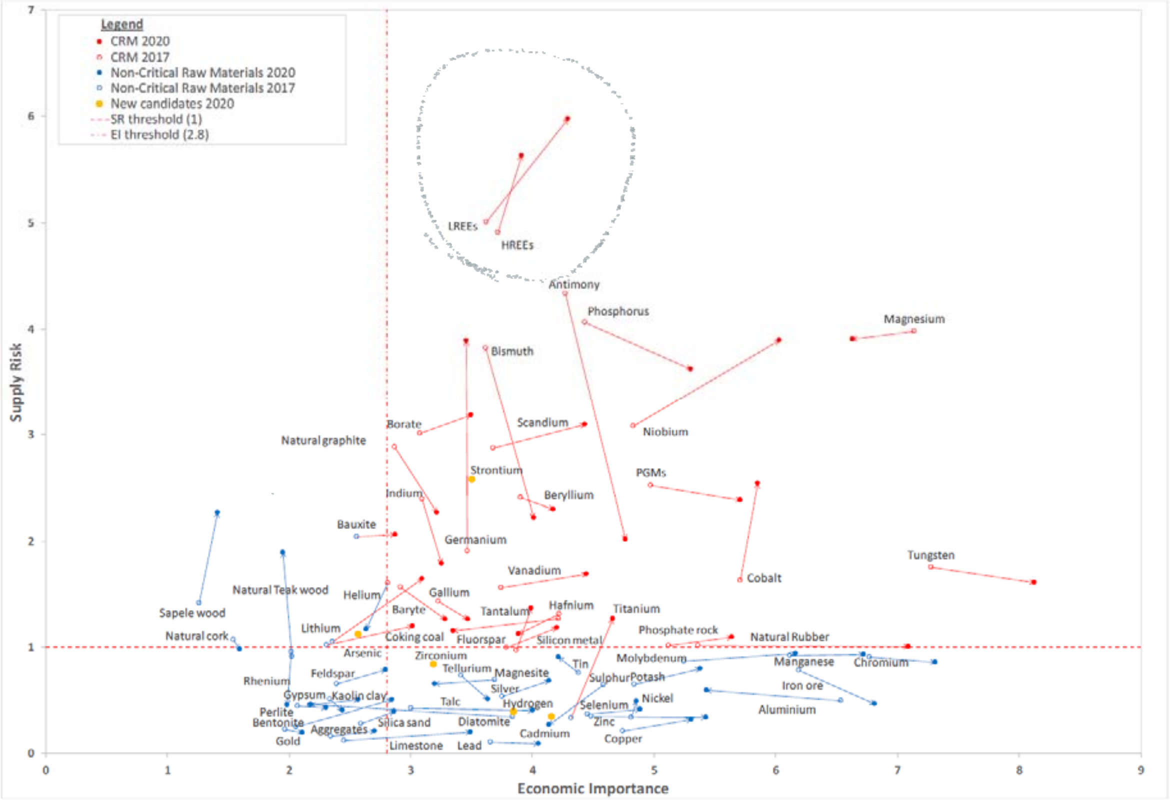


Figure 17. Critical material assessment results 2020 compared to 2017 ranking (Beatriz et al., 2018; Blengini et al., 2019)

As mentioned, the REEs are seldom used as stand-alone elements. Often, they are a part in a compound, which are used in a range of devices, especially in electric devices. According to World Bank report, the clean energy transition drives demand for REE, but also for the other minerals such as Al, Cu, Fe, Zn, Li, Ti, etc. (Hund et al., 2020; see also Wyns and Khandekar, 2020) and the table with critical materials shows that this stands true for EU as well. The bauxite rock high in aluminum, copper, lead, zink, – to name the few – have changed their relative position towards increasing economic importance.

2.1.8 Summary of observed trends

The major observed trends in this section are summarized below:

- REEs critical for the new economy which relies heavily on digitalization
- Substitution of the REE in modern applications is often impossible or requires product redesign
- Matryoshka effect – RE elements form bonds with other elements during recovery components making the pure elements harder to recover from e-waste too
- China has the biggest discovered deposits, biggest deposit sites and biggest volume of element processing for sale
- Supply and demand for REE is expected to grow 10% annually for the coming 20 years
- REE processing methods require high temperatures, high energy consumption or has chemical waste as by-product – an argument against the circularity and green economy
- The mining and mineral processing in the EU is practically equal to zero
- Arrangement of the mining operation requires time and resources prior to reaching scalability
- REE recycling in the EU is <1% due to lack of efficient collecting systems and prohibitive costs of building the REE recycling capacities
- EU is dependent on China REO mining, processing, supply and manufacturing.
- Clean energy transition drives the REE along with other critical raw materials

The observed trends get bet better expression when considered from the perspective of e-waste and REE recovery.

2.2 REE recovery from e-waste and EU regulations

Scope. When we turn to the e-waste discussion, we also need to reduce the focus from the global trends to the issues primarily related to the EU countries. Such change in scope is natural as it helps focus attention on certain context. This subsection presents the definition of e-waste, the rate of recovery, existing EU regulations, urban mining as alternative source of source REE, life cycle assessment of REEs.

2.2.1 Definition

Prior to discussing the issue of waste, it is important to establish the definitions of such terms as “electrical and electronic equipment (EEE)”, “waste electrical and electronic equipment (WEEE)” also used interchangeably as “e-waste.” If we consider EU WEEE Directive 2012/19/EU, Basel Action Network and StEP definitions, we notice that there is no strict standard definition, which leaves room for interpretations (Kaya, 2019). The accepted definition for this work is presented in the Directive 2012/19/EU (The European Parliament, 2012) as quoted:

- ***‘Electrical and electronic equipment’*** *or ‘EEE’ means equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation, transfer and measurement of such currents and fields and designed for use with a voltage rating not exceeding 1 000 volts for alternating current and 1 500 volts for direct current (article 3 (1a))*
- *Categories of EEE (ANNEX I):*
    - *Large household appliances*
    - *Small household appliances*
    - *IT and telecommunications equipment*
    - *Consumer equipment and photovoltaic panels*
    - *Lighting equipment*
    - *Electrical and electronic tools (with the exception of large-scale stationary industrial tools)*
    - *Toys, leisure and sports equipment*
    - *Medical devices (with the exception of all implanted and infected products)*
    - *Monitoring and control instruments*
    - *Automatic dispensers*
- *‘**Waste electrical and electronic equipment**’ or ‘WEEE’ means electrical or electronic equipment which is waste within the meaning of Article 3(1) of Directive 2008/98/EC, including all components, sub-assemblies and consumables which are part of the product at the time of discarding*

This definition sets apart the smaller sized e-waste from large stationary industrial tools, large-scale fixed installations and non-road mobile machinery. In practical terms, this means the EEE refers to such products as smartphones, fridges, PC and servers, not the wind turbines, massive electric power generators or industrial heavy machinery. Figure 18 shows the type of WEEE and the potential critical elements that can be recovered from each component in this waste category.

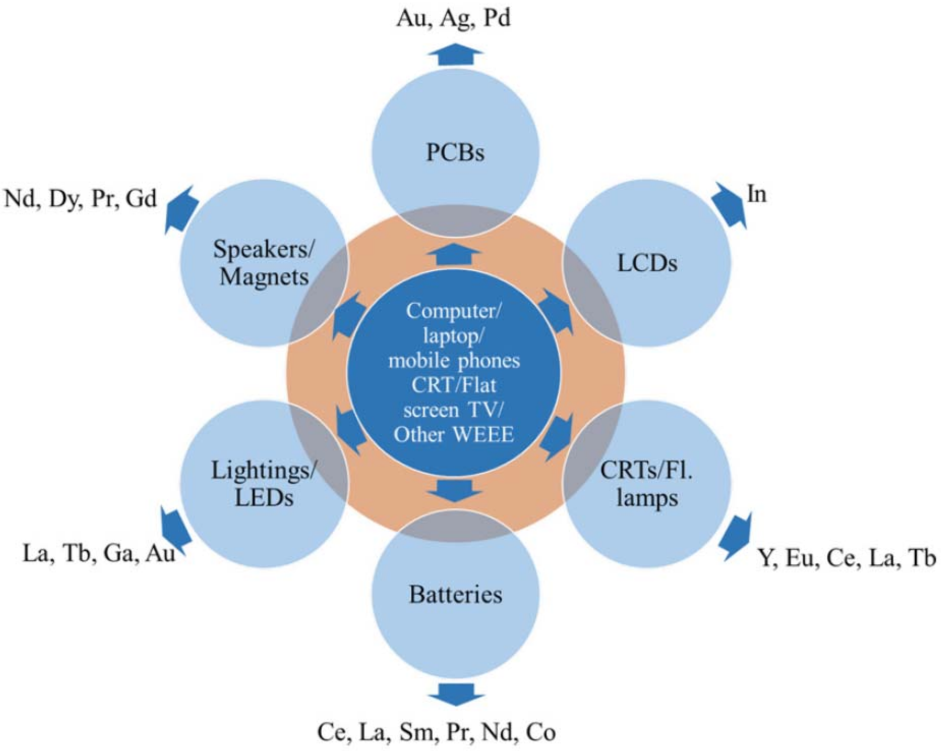


Figure 18. WEEE and the major critical raw materials (Sethurajan et al., 2019)

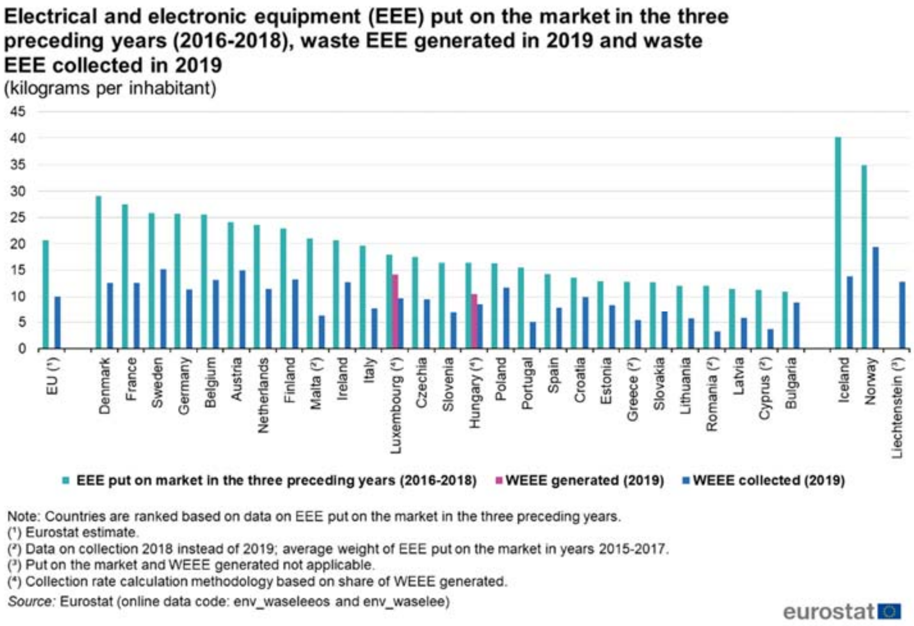
2.2.2 Current rate of REE recovery from WEEE

The numerous benefits of digitalization and availability of the various electr(on)ic solutions entering yearly the lives of inhabitants of the planet are counter balanced with the negative impact associated with the e-waste that yearly reaches the end-of-life. According to the recent studies (Forti et al., 2020), the global WEEE generation has increased at stunning pace from 44.4 Mt in 2014 to 53.6 Mt in 2019 and is expected to grow to 74.7 Mt by 2030. European region (the EU states and entire Russian Federation) takes the leading position in WEEE documentation and the highest recycling rate (42.5%), but also the leading position in waste generation per citizen. Table 6 summarizes global e-waste by region, which gives interesting insight into the issue. Europe leads in recycling high comparing to the closest follower, Asia (11.7%). At the same time, these values present a distorted perspective unless we consider the total population of each region and e-waste generated per capita. The European region is doing good in terms of waste documentation and treatment, but the consumption and pollution rate of its inhabitants requires significant attention and conscious redirection towards sustainability. When considering the total population of each region, Asia and Africa produces less waste per capita than the developed western economies.

Table 6. Global e-waste by region (summary of Forti et al., 2020, p.25)

Region	**WEEE (Mt)**	**E-waste per capita (kg)**	**Documented and recycled (Mt)**	**Recycled of total e-waste (%)**
Europe	12	16.2	5.1	42.5
Asia	24.9	5.6	2.9	11.7
Americas	13.1	13.3	1.2	9.4
Oceania	0.7	16.1	0.06	8.8
Africa	2.9	2.5	0.03	0.9

When we consider the amount of e-waste generated within the EU only, the urgency of the WEEE problem becomes even more evident. According to the Eurostat report, the average per capita collection rate of the generated e-waste is to 10.0 kg with average put on the market being equal to 20.7 kg per capita (Figure 19). The wide spread of waste collected between countries indicates the differences in the consumption patterns and existing e-waste collection schemes. Taking into account that roughly 50% of the e-waste is collected for treatment in the EU, which is indirectly indicated by the values from Luxemburg and Hungary (in purple), we can estimate that actual values lie between the green and blue bars.



Electrical and electronic equipment (EEE) put on the market in the three preceding years (2016-2018), waste EEE generated in 2019 and waste EEE collected in 2019

(kilograms per inhabitant)

Note: Countries are ranked based on data on EEE put on the market in the three preceding years.
(1) Eurostat estimate.
(2) Data on collection 2018 instead of 2019; average weight of EEE put on the market in years 2015-2017.
(3) Put on the market and WEEE generated not applicable.
(4) Collection rate calculation methodology based on share of WEEE generated.
Source: Eurostat (online data code: env_waseleeos and env_waselee)

Figure 19. EEE put on the market in the three preceding years (2016-2019), waste EEE generated in 2019 and waste EEE collected in 2019 (Eurostat, 2022)

In more details, Figure 20 below presents the breakdown of the e-waste generated in the EU countries in 2014. The figure shows the trend that can also be observed on the global scale. The developed countries produce also the biggest quantity of e-waste. The leading e-waste generators are also the biggest economies – Germany, France and the UK. The comparison of the biggest e-waste generators between the Figure 19 and Figure 20 shows that the conclusion that the developed countries produce more e-waste because they can afford to change and the less developed countries can be equally wasteful if the existing infrastructure and learned behaviors do not encourage recycling.

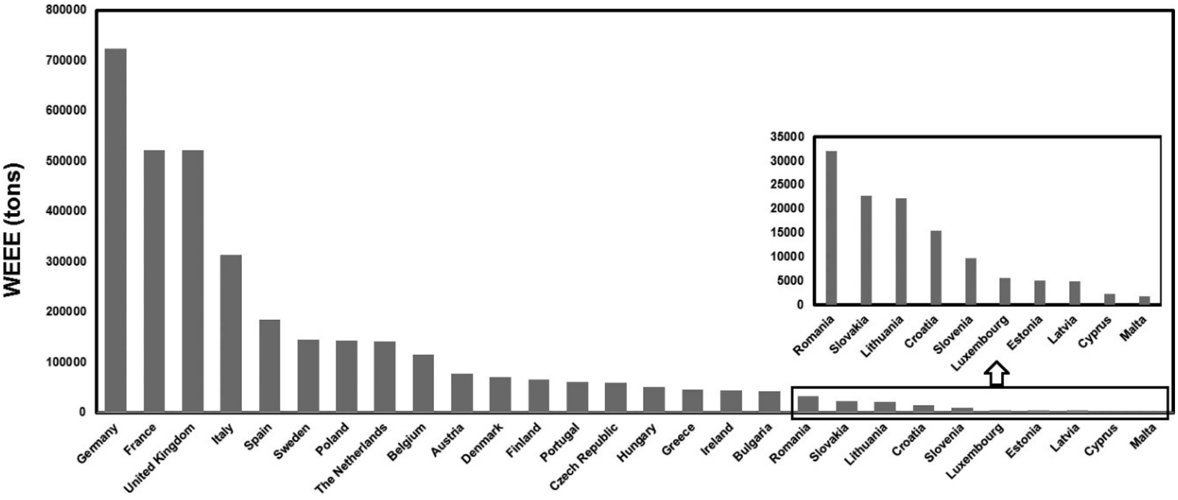
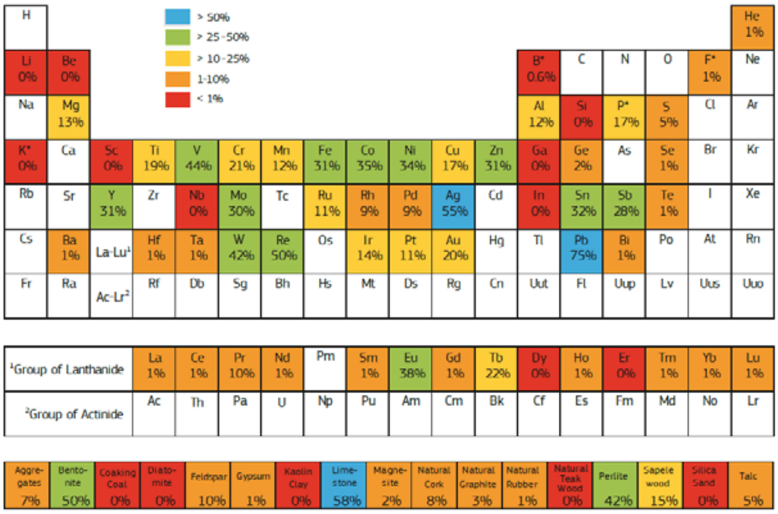


Figure 20. Amount of WEEE generated in EU countries in 2014 (Sethurajan et al., 2019)

Now, that the amount of e-waste generated in Europe is relatively evident, it is interesting to find out how much of the waste attributed to the CRM is extracted. The European Commission CRM datasheet (European Commission, 2020, p.665) summarizes the end-of-life recycling values as seen in the Figure 21. It presents the rate at which the material used in various production systems returns to production after being recycled from the old scrap. The elements in white have no data. The predominant trend of that the lanthanide recycling is towards very low rate of recovery and reuse. European Commission has estimated that the REEs' recovery rate is under 1% (European Commission, 2020). Only Y, Pr, Eu and Tb get recycled at rate higher than 10% from total waste. Even if the recycling rate is 31-38%, there are still a lot of hidden potential to be captured provided the opportunity is identified and pursued. The main challenge to improved recapturing of the CRMs among which are the REEs identified is the lack of efficient collecting system, prohibitive costs of building REE recycling capacities and comparatively low market prices discouraging investments in capital while there is an easier solution (European Commission, 2020). REEs in particular are delicate materials which can be lost if automated processing, such as crushing is applied. For instance, automated shredding for all magnetic material leads to a recovery rate below <10%, which is low by all means (Sprecher et al., 2014; Tsamis and Coyne, 2015). The need to have manual disassembly increases in labor costs adding up negative arguments against REEs' processing within the EU where labor cost is comparatively high (Sethurajan et al., 2019; Sprecher et al., 2014; Goodship and Stevels, 2012). Yet, there is evidence that along with better rates of elements' recovery, the manual disassembly uses 58% less energy and 81% less toxic for humans, which are undeniably significant (Sprecher et al., 2014; Sastri et al., 2003, pp.159–161, 884).

The e-waste contains only a small fraction of REEs along other common materials. The more common materials (Cu, Al, Au, etc.) form the main mass of the most electric and electronic devices (Sethurajan et al., 2019; Wyns and Khandekar, 2020; Goodship and Stevels, 2012). That is why focusing only on the issue of the REEs' recovery from WEEE is an unacceptable oversimplification. The recycling process must account for the various materials and have a more complex systemic solution addressing extraction of the entire spectrum of elements. Such complexity negatively affects the associated investment costs.



* F = Fluorspar; P = Phosphate rock; K = Potash, Si = Silicon metal, B = Borates.

Figure 21. End-of-life recycling input rate (%) to contribute to the EU demand of CRMs (Beatriz et al., 2018; Blengini et al., 2019)

Combining the fact that the REE production in Europe equals to zero and the recycling of the CRMs is rather rudimental then multiplying this by the economic importance of the materials and the supply risks, we see that there is enough reasons to focus on developing operational capacities for both mining and recycling within the Circular Economy paradigm (WEF, 2019) to secure that the future needs are met. On the other hand, the amount of e-waste to treat also opens the opportunities to capture through WEEE processing.

2.2.3 WEEE EU regulation

The EU has a long list of international and internal legislation and initiative programs targeting the e-waste problem. The EU legislative directories settle the stringent regulatory body. Besides joining the international agreements such as Basel Convention limiting the transboundary shipping of hazardous waste or the Solving the E-Waste Problem (StEP), the EU has implemented a set of own legislative initiatives and ran a number of projects targeted at better e-waste treatment among which are (Kaya, 2019; Bobba et al., 2018; Goodship and Stevels, 2012):

- A comprehensive approach for the recycling of electronics CARE "Vision 2000" (1994)
- Directive 2000/53/EU (ELV Directive) – regulates vehicle end-of-life with stringent targets for reuse, recovery and recycling
- Directive 2002/96/EC (2002) – on WEEE in the EU revised in 2006 and 2009
- RoHS (Restriction of Hazardous Substances) (2003) – directive limits the use of six hazardous substances (Pb, Hg, Cd, Cr^{6+}, polybrominated biphenyls, polybrominated diphenyl ethers) and entrance of new products with these elements to the EU market; regulates lead-free solder use
- Directive 2002/96/EC – regulates reuse/recycling of electronic parts: manufacturers internalize take-back/recycling cost; expected recycling rate 25-40%
- Directive 2005/64/EC – regulates type approval of motor vehicles regarding their reusability, recyclability and recoverability
- Directive 2006/21/EC – the Extractive Waste Directive provides regulations for measurement, procedures and guidance to prevent or minimize negative effects of the extractive waste from mining activities

- Directive 2006/66/EC – the Batteries Directive regulates the Member States obligations to maximize the collection, proper treatment and recycling of waste batteries and accumulators
- HydroWEEE-231962 (2009) – regulation of hydrometallurgical processes to recover metals from WEEE including lamps, CRTs, PCBs, and batteries
- Directives 2008/98/EC on waste and 2018/850 on landfill waste regulating the waste treatment and rules for landfill operation
- Raw Materials Initiative (2008) – complements national policies on raw materials
- Directive 2009/125/EC – the EcoDesign Directive regulates the potential negative impact from the energy-related products on the environment.
- Directive 2010/30/EU – Energy Labeling regulation instructing the customers about the energy efficient products through clear energy labeling
- Directive 2012/19/EU (2012) – improvement to regulations of WEEE generation and disposal. Directive encourages the reuse and recycling of metals and resins
- RECLAIM project – research for regulation of Galium, Indium, and REE reclamation from photovoltaics, solid-state lighting, e-waste
- SCARE project – strategic comprehensive approach for electronics recycling and re-use
- TV Target project – focus on eco-efficient treatment of TV sets and monitors
- CONCEERN project – CONex Central European electric and electronic recycling network
- ReLCD – project about the LCD re-use and recycling
- MobileRec project – collection, disassembly, and recycling of mobile telecommunication equipment
- Demonstration plant for the economic disassembly of PCBs
- AREP project – advanced recycling, recovery and reuse project
- EIP – European innovation partnership on raw materials

As we see, the field is regulated, but it is not overregulated at the same time. The order never was a problem. The problem lays outside – perhaps, the issue is that the rest of the world has less stringent rules on controlling the waste. Thus, it is easier to transfer the costs of recycling either to our ancestors in a form of a landfill or to foreigners as precious waste for recycling.

The Directive 2012/19/EU (article 10 (1, 2)) provides regulations for the process of exporting the e-waste for treatment and they are far from being stringent.

2.2.4 Urban mining from WEEE

Besides mentioned before mining as the REE source, there is another source. The primary source and undeniably the major one is from mining activities. The major sources in this category were already mentioned in subsection 2.1.3. The secondary source is from the urban mining. Urban mining is the process of reclaiming the valuable elements from by-products of human activity such as e-waste or landfill. Under this definition, we consider the fly ash from fossil fuel and other wastes such as the municipal solid waste incineration and coal combustion as valid source of REEs (Dutta et al., 2016). The WEEE is another source suitable for the urban mining (Chen et al., 2018; Dutta et al., 2016).

There are a number of technologies at different stage of maturity for WEEE treatment and REE recovery. Researchers and businesses around the world develop and improve the recycling technologies aiming at a more efficient recovery rate of the e-waste (Reuter et al., 2013; Oakdene Hollins Ltd, 2011; Schüler et al., 2011; Tsamis and Coyne, 2015; Klinger, 2018; Walton et al., 2015; Binnemans et al., 2013; Lixandru et al., 2017; Kamimoto et al., 2018; Wang et al., 2017). Figure 22 summarizes the major steps for recovery of the REE from the WEEE. Despite of the technology, the pretreatment stage is common for all of the recovery methods. This stage brings numerous challenges related to disassembly of hazardous or otherwise environmentally relevant component regulation in Directive 2012/19/EC.

At the dismantling stage, there is a risk of losing the valuable materials. This stage is what differentiates the mining of the REEs from urban and natural mining. Dismantling is labor intensive stage and automation is not always a solution given the small amount of REEs in the e-waste posing the risk of losing the elements for instance in the pretreatment dust. A fine tuning of the automated recycling process is possible yet there is a higher risk of REEs lost (Sethurajan et al., 2019). Automation requires more standardized input of materials for a standardized output. The inconsistent nature of the e-waste makes the challenge rather complex. The proverbial “throwing the baby out with the bath water” is applicable to REEs if the careful consideration is not taken.

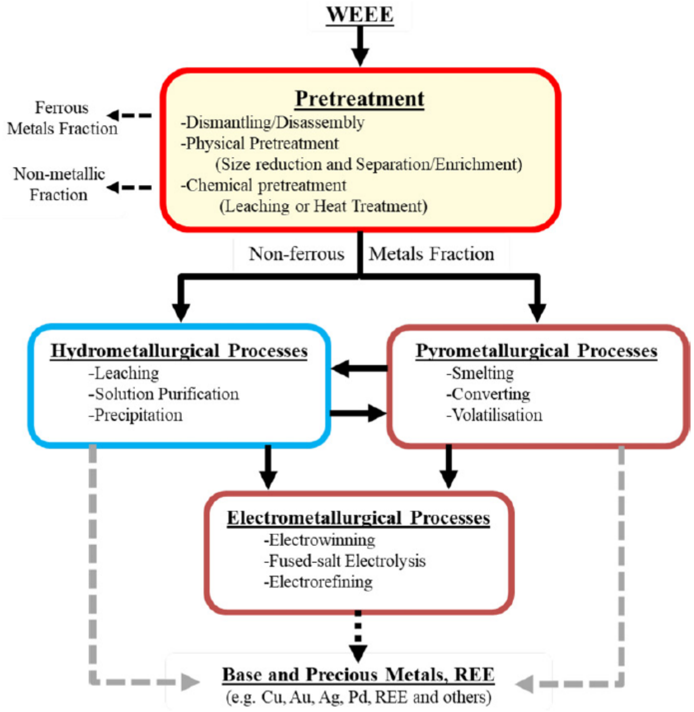


Figure 22. Major steps in processing the WEEE for recovery of contained valuable materials (Sethurajan et al., 2019)

2.2.5 Life Cycle Assessment of REEs

Life Cycle Assessment (LCA) is a tool used for understanding and quantification of the environmental and human health impact of a product, service, or a system over its entire life cycle from manufacturing to disposal. Since this work is conceptual, there are no quantifications to do, but rather identify the main stages of LCA. major actors, observe the patterns. In relation to the WEEE with regards to REE, the stages of LCA start with material extraction and processing from both ore and waste, manufacturing using the REEs, packaging and distribution of the product, usage stage, EoL of EEE (see Figure 23). The main challenge of LCA in relation to REEs is how to optimize the life cycle of the entire EEE product instead of focusing on the valued materials and their extraction.

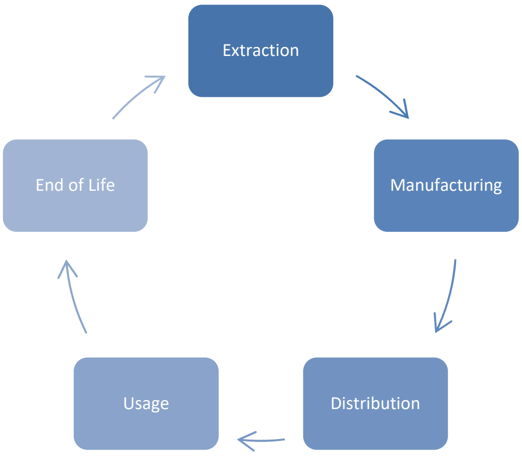


Figure 23. Stages of LCA of WEEE (Hauschild et al., 2017; Kaya, 2019)

Figure 24 shows the lifecycle of the EEE from production to disposal. It is easy to observe each actor and his role. The Figure shows main actors yet not all, which is a common omission (Bressanelli et al., 2020). It is also easy to follow through the entire cycle.

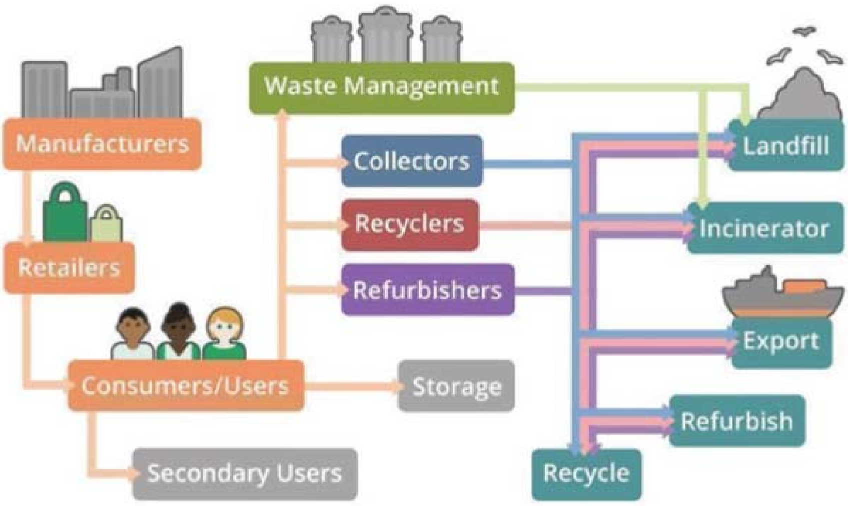
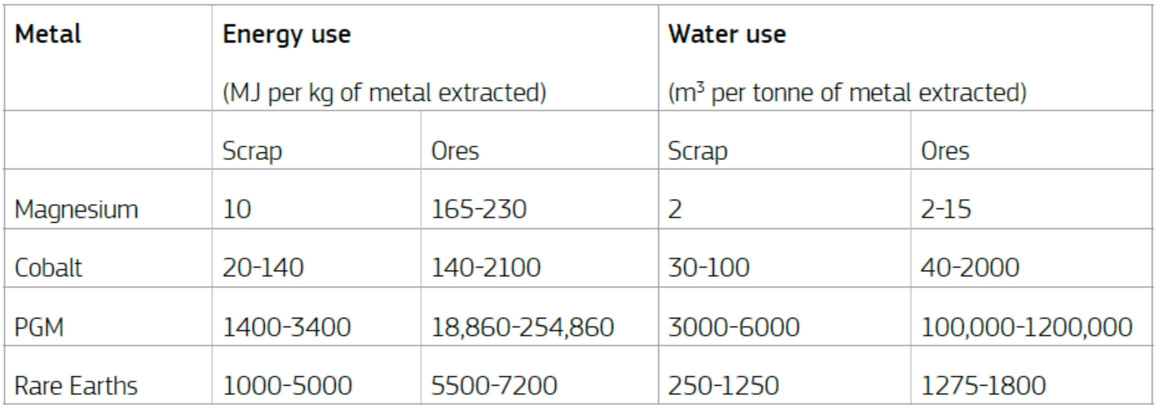


Figure 24. Lifecycle of WEEE from production to disposal (Kaya, 2019, p.21)

The systematic literature review conducted by Bressanelli and the colleagues (2020) identifies three major groups of actors commonly considered in the research related to the WEEE recycling: the users, the manufacturers and the end-of-life (EoL) actors. Authors noticed that these categories do not account for retailers and service providers. Only 2 articles of 115 evaluated have taken into consideration all five categories of actors (i.e. manufacturers, retailers, users, service providers and EoL actors). The major attention is given to the users as the main drivers for the effective WEEE management and little to the retailers or local service providers. End of use is the most addressed life cycle stage, which in turn includes the application of such strategies as reuse, remanufacture, recycle or disposal. The WEEE can be recovered on both the component and material level, which is a benefit, but on the other hand brings complexity to estimation models. The second most popular topic for research is the usage stage. Little attention in literature is given to the manufacturing and especially design stage, which is a major issue since the design determines not only the user experience and product performance, but also the ease of product/materials recycling. Another significant issue identified is that only 11 out of 115 reviewed articles consider users during the design stage. Given the primary importance of the users for the success of the WEEE recycling, this is a significant omission and a clear research gap (Bressanelli et al., 2020).

The effective WEEE treatment has significant impact on environment by allowing significant savings. If we take the mining stage as the example, Figure 26 presents the comparison of energy and water consumption in production of metals from scrap and ores. The recovery of REEs from scrap is times less resource intensive and wasteful in comparison with the processing of ores (Bobba et al., 2018; Roland et al., 2021). Another argument in favor of material sourcing from scrap is that the average elemental concentration of materials is also higher (Rajahalme et al., 2021; Lahtinen et al., 2018; Lahtinen et al., 2017).



Metal	**Energy use** (MJ per kg of metal extracted)		**Water use** (m^3 per tonne of metal extracted)	
	Scrap	Ores	Scrap	Ores
Magnesium	10	165-230	2	2-15
Cobalt	20-140	140-2100	30-100	40-2000
PGM	1400-3400	18,860-254,860	3000-6000	100,000-1200,000
Rare Earths	1000-5000	5500-7200	250-1250	1275-1800

Figure 25. Energy and water consumption in production of metals from scrap and ores (Bobba et al., 2018)

The recycling nevertheless does not fully eliminate the environmental footprints. Pyrometallurgical recycling methods for REEs and other CRM still require high levels of energy usage (Bobba et al., 2018). The hydrometallurgical methods require consumption of large amounts of chemicals. Elements extraction and refinement requires generation of waste chemicals and waste water. The overall environmental impact of certain recycling processes leaves room for improvement yet the current state of developed processes show significant benefits of WEEE recycling against the mining and processing of ores. (Tsamis and Coyne, 2015; Bobba et al., 2018).

There is abundance of scientific and academic sources about the WEEE treatment and CRM recovery with detailed description of processes, which is not the part of the study. They are significant on their own and command attention for further studies (Kaya, 2019; Hashmi, 2019; Veit and Bernardes, 2015; Goodship and Stevels, 2012; Chagnes et al., 2016).

2.2.6 Summary of WEEE related trends

The list below summarizes the observe trends and key observations:

- The European region is the leading WEEE generator
- European region is also the best recycler
- The most developed countries are the highest consumers of EEE and also the highest polluters
- With exceptions, the REEs are recovered at rates below 10%
- The lack of efficient collecting systems and prohibitive costs of building the REE recycling capacities, low price alternatives available on the market
- Better rates of REE recovery require manual disassembly
- REE recovery requires systemic solution integrated with recovery of other critical elements
- REEs have high economic importance and high supply risk
- REE mining and recycling is either absent or too low.
- Technical difficulty: high energy intensity of processing, generation of waste chemicals, waste
- EU provides good set of regulations to arrange the elements’ recovery

- The developing and underdeveloped countries are not that well-regulated, which allows a loophole for the EU companies to dump the WEEE abroad, thus, draining the potential of developing the REE&WEEE recycling inside the Union.
- Urban mining is an alternative source of REEs
- WEEE major actors: EEE manufacturers, retailers, consumers, service providers (repair, refurbishing), EoL actors.
- Service providers and retailers need more engagement in the circularity of the e-waste
- Product design stage can benefit from implementation of LCA as early as possible
- Despite of challenges, REE/CRM recovery has high environmental promise because of elemental concentration and energy/water use

2.3 4R strategies of Circular Economy

Circular Economy is an economic model targeting at sustainable sourcing, manufacturing, consumption and disposal in such way that it reduces the negative impact on the environment. This model supports system-focused approach that is restorative and regenerative in its core. Common themes discussed in this model is circularity and sustainability. Its proponents believe that it is possible to achieve the high levels of profitability without reduction of available products and services while achieving high levels of sustainability. (Lovins et al., 2018; McDonough and Braungart, 2002; Stahel, 2019; Weetman, 2016).

The Circular Economy is often juxtaposed to the linear economy. The underlying argument of the Circular Economy is that linear economic approach summarized by “take-make-dispose” model is irresponsible and unsustainable in the long-run. In contrast, the conceptual message of Circular Economy model is careful use of resources by reduction of wasteful activities through effective design and implementation of product and processes for improved efficiency (Jawahir and Bradley, 2016; McDonough and Braungart, 2002). The underlying mechanism of circular material flow is described with the 4Rs actions: Reduce, Reuse, Recycle, Recover (Stahel, 2019; Weetman, 2016; Bressanelli et al., 2020). Figure 27 illustrates the model and fundamental vision how it should work. It shows the materials entering the system, being designed, processed, distributed for consumption, consumed, collected and returned to the cycle by effective treatment with as little residual waste as possible (Bobba et al., 2018). Recently, there appeared the development of the strategies by adding recover, redesign and remanufacture actions (Spaltini et al., 2021; Jawahir and Bradley, 2016). These dimensions add more clarity and increase the precision in tracking the related actions. For the scope of the study though, we use the 4R strategies.

Next, we turn to the definition of the 4R actions. **Reduce** actions concern with using less material while retaining the functionality of the final solution. In practical terms, it means that the measures can be taken already on the design and manufacturing stage to lower the generation of waste and consider the solutions that encourage the resource conservation. **Reuse** actions involve steps for a solution to be used again in its current form and function. **Recover (remanufacture)** actions involve using the recovered components from discarded WEEE to return them to operational conditions and extend their lifecycle. **Recycle** actions consider using the recovered from the waste resources to make other new products. (Bressanelli et al., 2020; Kaya, 2019).

The actions have different level of desirability as well as the impact on waste. The hierarchy of preferred actions follow this pattern: Reduce > Reuse > Recover > Recycle > Energy Recovery/Disposal. Evidently, that the most desirable course of actions is actually the prevention of any material usage if a functionality of a product is not affected. Reduce action helps preventing the waste generation. The other actions can only help manage the created waste. Still, having a plan is better than no plan. (Kaya, 2019).

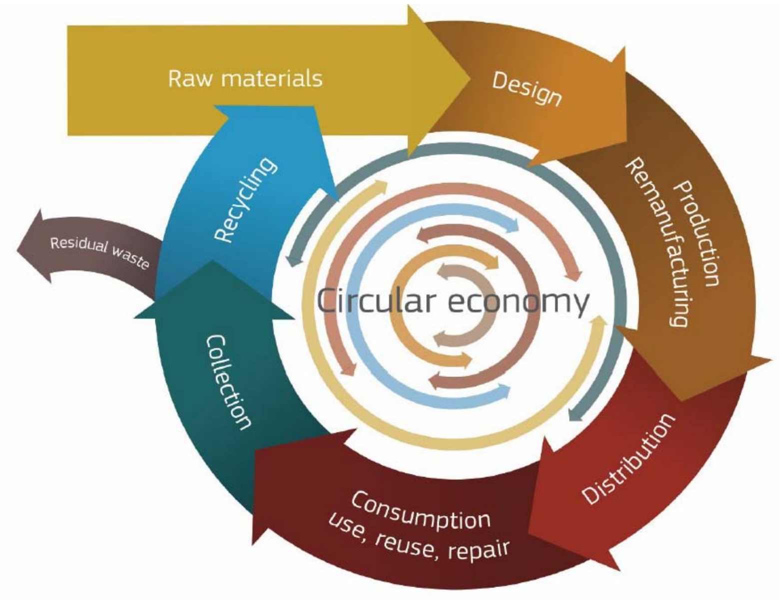


Figure 26. Simplified diagram illustrating the Circular Economy model (Bobba et al., 2018)

The systematic literature review conducted by Bressanelli and colleaugues (2020) has observed a pattern relative to the 4Rs strategies. The majority of the articles focus on Reduce (69) and Recycle (63) strategies in an attempt. The Circular Economy in WEEE industry has been approached as a way to provide economic savings to the users through the Reduce narrative and the potential economic advantages through the supply chain optimization as a Recycle message. The Reuse and Remanufacture strategies gain less attention (35 and 339 respectively) though these can hide a higher impact potential to bring transformation in the way a customer/user thinks about the product usage, but more importantly how the manufacturers design their products and policymakers approach the issue of consumption regulation favoring the extension of products' lifecycle. The cascading hierarchy among the 4R action strategies as well as holistic approach to the Circular Economy using 4R scheme has not been considered by the literature. (Bressanelli et al., 2020).

In practical terms, the 4Rs action can transform into strategies and action plans that have a high potential of transforming the otherwise wasteful activities in a gain through social transformation. In Table 7, we summarize the potential strategies and actions that can be taken to improve the sustainability aspect of EEE manufacturing and its circularity.

Table 7. Planning based on 4Rs Circular Economy (Hua et al., 2021; Tsamis and Coyne, 2015; Bressanelli et al., 2020; Kaya, 2019; Atwood, 2012; Spaltini et al., 2021; Roland et al., 2021; Schüler et al., 2011)

Reduce	Methods to reduce: use less of the material **Reduce strategies** applied in the (W)EEE industry to achieve Circular Economy gains: - Developing energy efficient EEE products' design - Implementation of the design for recovery approach - Extending the life span of the EEE: product design and material selection, suitability for repair and maintenance - Resource efficient design of EEE with potential of upgrading - Replace REE/CRM materials when possible with more available alternatives - Sharing of a pool of product/components among several users reducing the product stock - Use EEE in a more sustainable way - Digital and automated solutions employed to improve efficiency during product manufacturing - Reduce toxic and environmental consequences during product use by rethinking the function of the product and material choice - Advance the message of smart buying behavior: buying durable, buying consciously, buying used and in some cases not buying at all
Reuse	Methods to reuse: when designed for recyclability, a solution can be used again in its current form retaining its form and function. Example: some permanent magnets can be reused without any physical changes for other purposes. **Reuse strategies**: - Extend the product life-span by second hand market encouragement: ex. using the old corporate PCs that are not suitable for a firm's needs to sell to the private users at a discount. - Reduces the need in new EEE by maintenance and upgrades: checking, cleaning, repairing, refurbishing or upgrading
Recover	Methods to recover: using the recovered components from discarded EEE Not a strategy, but rather **Recover steps**: - Disassembly > Cleaning > Inspection > Sorting > Reconditioning and reassembly - Increase recovery of the WEEE through a buy-back programs similar to plastic bottle collection deposits - Require the manufacturers to provide the BOMs for certifications - BOM database is used to assess the EoL valuation of the EEE before sending the product to the recycling stage
Recycle	Methods to recycle: to reuse equivalent amount which otherwise needs to be produced from the virgin resources **Recycle strategy:** - Collection > Disassembly > Shredding > Separation of residuals for further processing - Arrange a database of products and BOMs for more efficient recycling - Develop and enforce design for recovery into legislation and standards

Although the disposal is not a part of the 4R Circular Economy approach, it still requires mentioning. The existing methods for the e-waste treatment involve energy recovery prior to disposal. Among the methods are the incineration, pyrolysis and gasification for fuel, heat or power. These methods allow the maximization of the energy recovery and reduction of the loss in otherwise energy rich resource as well as minimal land use for landfilling. (Kaya, 2019).

Noticeable is that the Circular Economy rhetoric is a mix of economic, political, social and technological (PEST) dimensions. Since this is an economic model first, the inevitable reference to the operational environment on the system level is natural. Seldom it retains a one-dimensional perspective without switching to the discussion about others. For example, an economic discussion quickly transforms into a social program. Technological advancement requires political volition and regulation. (see Lovins et al., 2018; McDonough and Braungart, 2002; Stahel, 2019; Weetman, 2016). Such discussion makes natural transit to the consideration of the REEs from the system-level perspective.

2.4 PEST of REEs

To understand the trends related to the REE and the urge of acquiring them, sourcing them or substituting them all together, we need to draw the macroeconomic context around this issue. Since REE play such significant role in the undergoing Great Reset transformation, it as well becomes a strategic asset access to which requires consideration of the political, economic, social and technologic (PEST) dimensions. PEST analysis is a business analytics tool employed to scan the macro-economic operational environment for strategic business planning (Nitank and Treivdi, 2016). Consideration of these factors are immanent and unavoidable in making sense of the scattered and seemingly disconnected details presented in the discussion above.

As our goal is to identify the trends and patterns related to REEs, this section aims at building a more complex picture surrounding the environment around the scarce elements. In order to see that, we need to turn to the dimensions of PEST. Since the political, economic and technologic dimensions are used in their most recognized sense and social dimension is rather loaded notion requiring elaboration.

The initial PEST model included only the mentioned four dimensions. Currently, the PEST analysis was extended to PESTLE by adding the legal and environmental dimensions as separate categories (Nitank and Treivdi, 2016). Such expansion does not deem the PEST model functionality. The social dimension in this discourse concerns less with the social interactions and cultural aspects, but rather the overall to the natural environment which affects wellbeing of a human within such society. The environmental costs are seldom attributed to politics, economy or technology, but are transferred to the society, the relation of the political, economic and technologic aspects of REE and WEEE treatment with respect to nature preservation and sustainable living is valid. At the same time, our goal is to keep in the focus the potential of using the information for better technologic designs and product solutions.

History of REE crisis. From 1960s until 1985, the US was the world's largest producer of the REEs yet not for long. Starting with the mid-1980s, China began mining and extraction of REEs as well. The Chinese mining was cheaper and had no direct environmental costs unpopular in the West. Within twenty years, China became the largest supplier of the REEs on the market and one of the main EEE manufacturer as well. By 2010, nearly 85% of the world supply of REEs and 95% of processed REEs were originating from China. (Tracy, 2020). Besides being a supplier, China has also taken the time learn how to process and use the elements. The government encourages the export of minerals as part of the semi-finished products (Kiggins, 2015, pp.28–29; Chen and Zheng, 2019).

In 2010, People Republic of China (PRC) imposed export quotas, which lasted until 2015, resulting in significant price increases (Chen and Zheng, 2019; Klinger, 2018). The export restrictions have risen the geopolitical concerns on availability of the resources and served as a trigger for the reanimation of the mining in the USA and Australia (Deboer and Lammertsma, 2013; Chen and Zheng, 2019). The threat of another ban or restriction since then is a part of any REE conversation. The joke saying "God made a man – everything else is made in China" does not sound that funny anymore. REEs come from China. EEE come from China. Numerous positions in the supply chain come also from China. This creates an uncomfortable background for the further discussion environmental context summarized in the PEST.

This section is supposed to be the first before we present the REEs and WEEE policies, but it can make sense only now, when the smaller elements of the "play" are set on the "stage." The expected outcome of the project is the proposition of a matrix with complex set of measurements that include political, economic, social and technological measures meeting the Circular Economy objectives. Since the context of the study is technology-related, the political and economic aspects are mentioned briefly in as much as it is necessary to facilitate the solution.

2.4.1 Political

The political aspect in the PEST analysis is usually concerned with the government policy, regulations and actions that affect an economy. When considering the aspect of REEs and its safe supply, we have established that the strategic importance of these elements requires a switch in perspective from the politics of a state or agglomeration to the level of geopolitics, where multiple states engage in political games to secure the resources, to guarantee the survival and prosperity.

Chen and Zheng (2019) provide fairly detailed overview of the impact of the 2010 REE crisis. Besides the recognition of threat of REE interruption with associated economic and technologic paralysis, the crisis led to revision of the existing reserves. Figure 27 shows the deplorable facts about the security of the resource availability for the development. It is apparent that the reserve estimates in both USA and Australia are overrated, when reserves in China, Brasil, Malaysia are underrated. This creates tension to secure more resources if possible. Especially, this applies to the US, which gradually loses its leading economic and politic position, but still retains access to the most powerful instrument – the money printing press of the global reserve currency. The urgency and nervousness shared over the Atlantics is recognized in Europe, but Europe, lacking the political volition and strategic foresight, shadows the Great Reset agenda (Schwab, 2016; Xu et al., 2018; Weetman, 2016; Kumar et al., 2019; Lovins et al., 2018) expressed among others in the Circular Economy model often at its own expense.

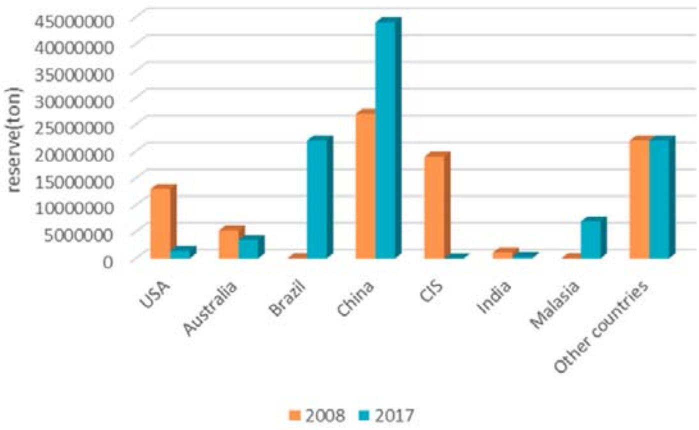
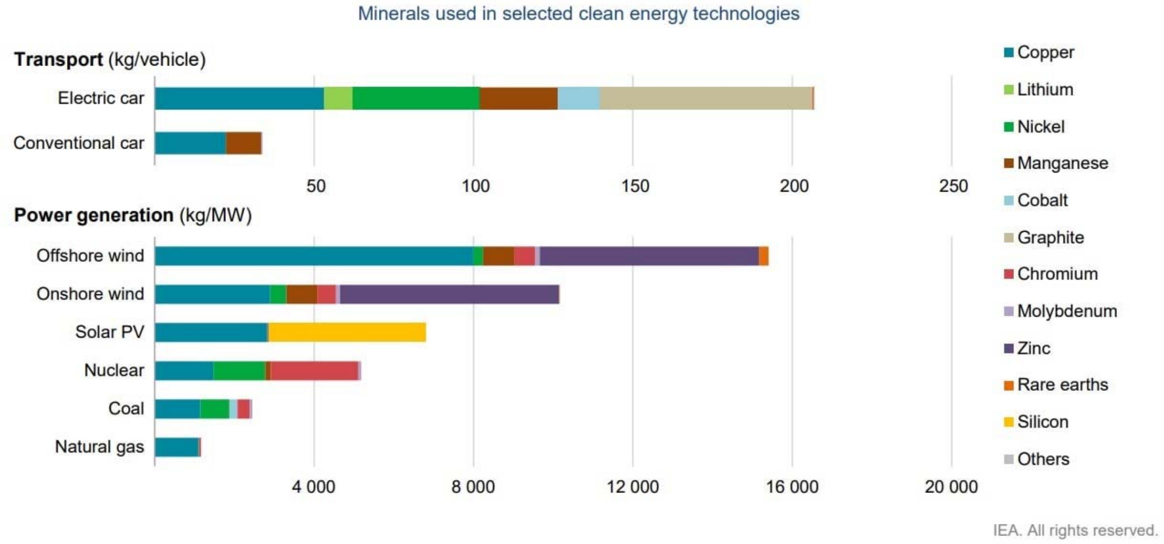


Figure 27. Main reserves of REE in different countries according to the U.S. Geological Survey (Chen and Zheng, 2019)

The disadvantage of following the Circular Economy agenda is evident by following the common trend towards favoring the green transport and power generation technologies along the minerals required to facilitate the change. Figure 28 shows the effect on the rapid change towards the clean energy and demand for CRM materials to meet the requirements. It is evident that the fossil fuel driven transportation and power generation requires significantly less CRMs than the clean energy. It inevitably makes the green economy and the underlying technology expensive for the masses having inverse immediate economic and social impact.

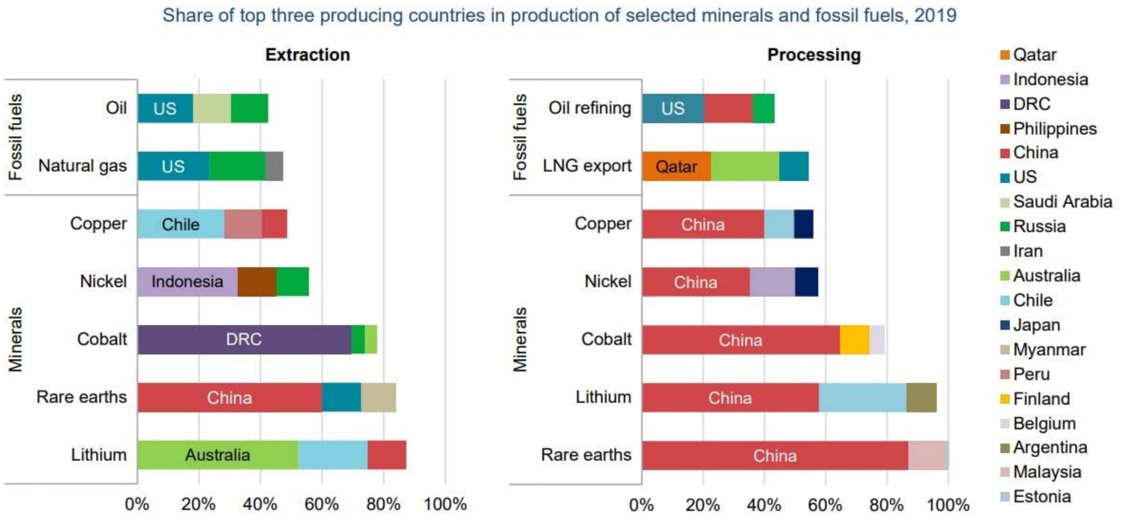

Minerals used in selected clean energy technologies

IEA. All rights reserved.

Notes: kg = kilogramme; MW = megawatt. Steel and aluminium not included. See Chapter 1 and Annex for details on the assumptions and methodologies.

Figure 28. Relation between the rapid deployment of green technology and the demand for CRM raw materials (IEA, 2021)

Besides the economic and social consequences, there is a significant political threat too. Figure 29 shows the extent of the problem. The media in the Europe talks about the critical reliance on the oil and gas coming from Russia. The common message is that combustible natural resources give Russia instruments for political manipulation and control. When we consider the actual state of affairs, the plots presented on the Figure 29 show that EU has broader diversification when it comes to supply of fossil fuels than minerals. By rapidly navigating away from the fossil fuel typically associated also with the linear economy, the EU is falling in even more significant dependence on single supplier. The prevalent dominance of China in REE supply and leading position in processing the key elements seems significantly more dangerous than diversified fossil fuel market. This observation leads to another conclusion, that the green transit pursues other goals than steady evolutionary development and rapid technologic progress unless there is belief that the resources can be acquired in necessary volumes by either trade or war.



IEA. All rights reserved.

Figure 29. Concentration of the transit minerals in comparison to the oil and gas (IEA, 2021)

The situation with China leading the markets in critical domains increases the risk of open confrontation. Demand for REEs goes along the increasing demand for other metals (Arrobas et al., 2017; Wyns and Khandekar, 2020), which only increases the complexity of the situation because China is one of the leading suppliers in those categories as well. Gaining control over the resources might require confrontation if any political decision is taken to restrict the resource availability.

The big geopolitical Game is seldom played in one obvious direct step. If we set the chessboard with major players around the table, we notice that those are the US, China and Russia. Economically, China is as big as the US but militarily weaker. Russia is militarily stronger than the US, but weaker economically. In recent years, the strategic convergence of China and Russia was actively forced by the impulsive politics of the US. Since China is a strategic target, Russia is the tactical. In other words, gaining control over China and its resources is possible only after Russia is weakened or destroyed. This explains many confrontations happening around the Russian borders. The political environment surrounding the REEs is undeniably volatile, which requires from European governments a clear raw material strategy that includes the following objectives and principles:

- Free cross-border trade,
- Diversification of supply,
- Search for substitution alternatives,
- Research & Development investments,
- Transparency & good governance,
- Bilateral raw material partnerships,
- Efficiency in material usage,
- Recycling for material recovery,
- Integration of member states' and European policies (Kiggins, 2015, p.71).

There are other political and legal action that have a potential to improve the availability of the REEs from the WEEE sources. One of them are tax incentives for the supply and consumption of domestic REE (Tracy, 2020). The other one is to require companies to provide the bill of materials during certification before entering the market. It helps planning and estimating the recovery. Create such privileged database to be used by those companies that recycle the materials. Cooperation with equipment manufacturers for acquisition of the BOM for arranging of the recovery. In case, there is a resistance, enforce the cooperation on legislative level on terms of exchange of access to market for access to information or internalization of EoL-related costs. Develop a set of standards and normative acts to require manufacturers to design in such way that allows an easier EoL processing.

2.4.2 Economic

The economic aspects are closely interconnected with politics. The common cliché says that economy is the extension of the politics yet from the other side. This section discusses the factors that determine the economic performance, actions to tackle inflation, investments, structure of the economy. The underlying processes, the tectonic changes and transformations in the global economy is often attributed to the environmental issues beyond the human control, when there are more fundamental issues embedded in the capitalist economic system itself.

End of capitalism. The capitalist economic system has reached its logical end (Rasmussen et al., 2018). There is a need in an alternative system and the alternative is absent. What happens in the economic environment of the present is clear evidence of the claim. The booming inflation that is not monetary in its nature but related to the transaction cost economies and structural imbalances in the US economy, which is exported around the globe since the US dollar is the global currency and accepted measure of value. We witness the demolition of the foundations of the capitalism – the property rights (Schwab, 2016) – and its replacement is unclear. The West which usually played a role of change visionary does not have an alternative to the liberalist/global capitalism model, where the power belongs to the capitals/the banks. That is why the actions that contemporary elites are taking favor saving the existing model while transiting to the new order of digital integration and control. Such order is going to be forced by the totalitarian in its essence Great Reset agenda, where the individual is dehumanized, stripped of its rights and property, and turned into a mere binary digit in the digitalized economies, where only those that bring value are considered as one, the rest are the unnecessary zeros. This claim finds its evidence in the taken actions by the Western elites and the local governments in fighting the COVID-19 virus spread against its own nations and economies.

Despite of its plausibility, the Circular Economy is not possible within the existing economic paradigm. Capitalism is built on the egoistic drive; circular economy is more altruistic in its concepts, but remains capitalistic in its implementation. Capitalism requires continuous expansion to sustain itself. This was explained by K. Marx in his works and the history of the 20th century is the vivid illustration to the claim. That is why on the rise of capitalism it expanded by conquering the new territories and exploiting the resources. Nowadays, the territories are conquered and further expansion without significant costs are impossible. When expansion is impossible, the capital starts devouring oneself. That is why the rate of hostile acquisitions of smaller companies by full of capital gigantic corporations increased, supply chain disruptions (Kiggins, 2015, pp.85–105), starvations and wars, and increasing pressure on the middle class and the poorer strata of societies not only in underdeveloped countries, but also among the developed countries. The capital needs to grow to sustain its existence.

Significant change towards the Circular Economy requires the economic model change, which in turn requires the change of the mindset of the entire humanity. Unfortunately, the collective West does not have neither the model of future nor alternative economic perspective capable of bringing the civilization to that illusory bright future. The Circular Economy argumentation is trending as long as it serves its purpose and there is the funds' inflow in the institutions preoccupied with spreading the ideas. The agitation around the topic of sustainable development and circular economy is projected from the elites in a top down pattern instead of being driven from the bottom up, from the public demand to the elites. The media and academia create the required information flow to the public demand for the illusion to create the sense of progress. The paradigm change enforced from the top down is nothing but dictatorship and eventually can evolve into a protest. Judge for yourself, how long a person is ready to think about the preservation of the trees when a family is freezing in cold. The public interest to the sustainable economy correlates with the standard of living and the situation with calling the nuclear power and natural gas a green energy source (as discussed in 2.4.5) is an indirect evidence to the claim. The raising inflation in the developed economies coupled with the decreasing standard of living of the population creates a cognitive dissonance with the illusions of the plentiful future.

The major economic trends reveal the tendency towards lasting economic crisis rather than the potential for economic revolution (Rasmussen et al., 2018). The industrial productivity is decreasing; the internet-economy did not get going; the EROI index show low rates of return per investment in the energy sector questioning the green economy viability (Weißbach et al., 2013; Conca, 2015; Carbajales-Dale et al., 2014); the decreasing demographics of the white color population in developed countries overlapped with growing number of immigrants from Africa and Asia, which reach critical numbers to threaten the comfortable livelihood and cultural fabrics of the developed countries; climate change leads to increasing areas of land not suitable for sustainability of living in turn driving the flow of immigrants to the global North and West. The mentioned trends should they be even distantly valid indicate the systemic crisis and overall direction towards the economic collapse, not the revolution. This is rather grim and gloomy forecast. Nevertheless, it is better to see the trends, prepare for the worst and turn wrong in estimations rather than retain the positive attitude in the face of a tsunami, being unprepared and get swiped away by the natural forces.

REE economics. The economic background has direct relation to the demand for REEs and the need of supplying its availability. The increasing digitalization requires increasing levels of REE supply. As discussed above, the rapid transit of the EU towards the green economy leads not only to the political dependence on a single supplier, but also reduces the space for bargaining maneuver in case of the price change or other emergency.

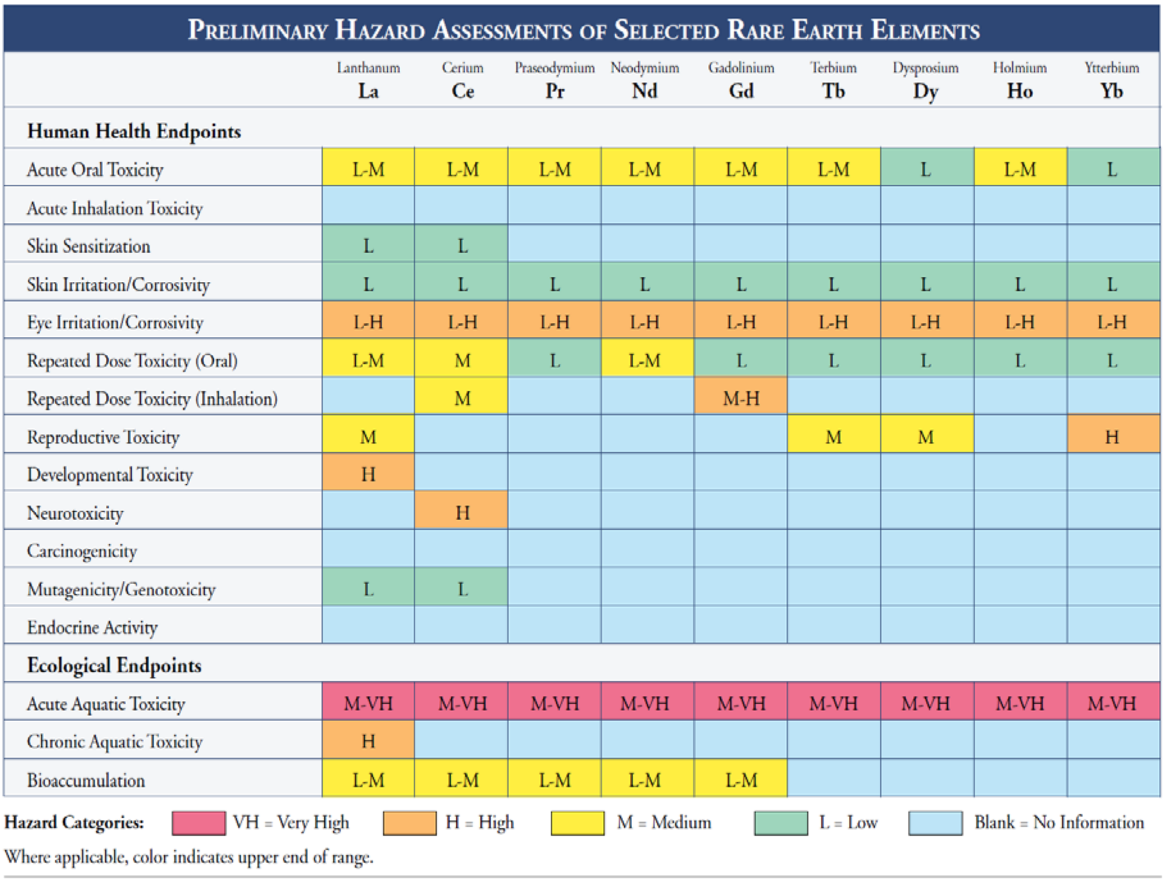
Recycling along mining is available source of REE. Neither option is immediately available for scaled operation in the EU. Since our focus is on REE and WEEE, these economic challenges the EU needs to tackle:

- Availability of the affordable supply of REEs on the market makes investments in the EoL processing of WEEE for REE recovery unattractive despite of the promising benefits (Corder et al., 2015).
- Therefore, REEs’ recovery from WEEE requires systemic solution with integrated response from politicians, economic agents, technology leaders and consolidation of the population. Access to such scale of response can provide the state involvement.
- In practical terms, the REE recycling from WEE requires building effective e-waste collection and recovery systems, with differentiated responsibilities for producers, resellers and users/consumers. Besides the REE recovery, adoption of a systemic approach leads to the recovery and reclamation of other valuable and critical materials with considerable economic promise. (Zeng and Li, 2016; Klinger, 2018; Shuva et al., 2016; Corder et al., 2015; Wyns and Khandekar, 2020; Arrobas et al., 2017; Hund et al., 2020).

- The problem with REEs' recovery is primarily related to the economic challenges expressed in scalability. Numerous sources stress the considerable economic promises of recycling (see for example Corder et al., 2015). At the same time, the actual implementation by Solvay of the recycling project in 2011 has been discontinued in early 2016 facing challenges with the scalability of the processing (Delamarche, 2016).
- To organize reasonable in economic terms scale of recovery. recycling of both precious materials from WEEE, a careful consideration of the auxiliary waste treatment is needed to gain the economic justification (Spaltini et al., 2021).

2.4.3 Social

The social aspect of the REE and WEEE is expressed in terms of environmental impact. The REEs have numerous positive contributions, but they all come at a cost which is either adsorbed in present or passed to the future generations in a landfill. The scale of mining necessary to support the growing demand for REE discussed above has significant impacts on the environment not only of the areas where the elements were mined, but also in distant unrelated locations where the product is consumed and disposed. When the WEEE is improperly treated, this creates threats of radiation, environmental threats to water and soil, which returns back to people in the potable water, the safety and health impacts. (Voncken, 2016; Gupta and Krishnamurthy, 2005; Ali, 2014; European Commission, 2020, p.676; Sastri et al., 2003; Chen and Zheng, 2019). Figure 30 shows a number of health hazards from a set of selected REE. The significance of these health effects seems distant, but can have its impact even in the developed countries if the WEEE is processed poorly.



Preliminary Hazard Assessments of Selected Rare Earth Elements

	Lanthanum La	Cerium Ce	Praseodymium Pr	Neodymium Nd	Gadolinium Gd	Terbium Tb	Dysprosium Dy	Holmium Ho	Ytterbium Yb
Human Health Endpoints									
Acute Oral Toxicity	L-M	L-M	L-M	L-M	L-M	L-M	L	L-M	L
Acute Inhalation Toxicity									
Skin Sensitization	L	L							
Skin Irritation/Corrosivity	L	L	L	L	L	L	L	L	L
Eye Irritation/Corrosivity	L-H	L-H	L-H	L-H	L-H	L-H	L-H	L-H	L-H
Repeated Dose Toxicity (Oral)	L-M	M	L	L-M	L	L	L	L	L
Repeated Dose Toxicity (Inhalation)		M			M-H				
Reproductive Toxicity	M					M	M		H
Developmental Toxicity	H								
Neurotoxicity		H							
Carcinogenicity									
Mutagenicity/Genotoxicity	L	L							
Endocrine Activity									
Ecological Endpoints									
Acute Aquatic Toxicity	M-VH	M-VH	M-VH	M-VH	M-VH	M-VH	M-VH	M-VH	M-VH
Chronic Aquatic Toxicity	H								
Bioaccumulation	L-M	L-M	L-M	L-M	L-M				

Hazard Categories: 🟥 VH = Very High 🟧 H = High 🟨 M = Medium 🟩 L = Low 🟦 Blank = No Information

Where applicable, color indicates upper end of range.

Figure 30. Health hazards of selected REE (Mayfield, 2012)

The both positive and negative social impacts of REEs require careful approach to the issue. Balancing the interests of all the stakeholders becomes a challenge considering that each stage of EEE production, distribution, consumption and reclamation involves different actors pursuing different goals. Overregulation can suffocate the economic activity. The reliance on the invisible hand of the market for self-regulation usually leads to selection of the individual goals over the social benefits by the players resulting into a disaster and the adsorption of the environmental costs by all.

Dutta and colleagues has proposed a number of solutions that can have a positive effect, when responsibility is adapted by all stakeholders to reduce the REE impact (Dutta et al., 2016) among which are:

- establishing stringent industrial standards and laws for the REE industry and WEEE processing to set the rules for a sustainable recovery of valuable resources,

- reducing unnecessary bureaucracy to promote faster system response to the rising challenges along with implementation of the stimulating financial programs for e-waste processing,
- centralizing management of REE resources by eliminating illegal mining,
- developing integrated REE market pricing and distribution systems,
- encouraging investment in environmental programs to combat the environmental consequences associated with the REE industry,
- encouraging transnational dialog and participatory actions from nations with high annual consumption of REEs worldwide and e-waste generators,
- encouraging REE recycling from enriched waste materials, EoL products, and other under-utilized resources.

These steps resonate with Circular Economy ideals. The steps have significant promise of environmental impact when effectively implemented in a society as well as publicly discussed the urgency of their implementation.

2.4.4 Technologic

Technologic factors include the availability of the necessary methods to process the REEs from WEEE, the attractiveness of this source of resources for extraction, the research and development, and prospects of innovation. As it was discussed, the REEs are essential for contemporary technologic solutions and technology of the future. There are attempts to substitute the elements with less critical materials, but such attempts face the trade-off challenges related to unique properties of the REE (Schüler et al., 2011). The availability of technology is date labeled as of yesterday with time constraints to develop the technology, financing constraints, human resource constraints and infrastructure that needs to be built to meet the demand.

The discussion about the technology for mining of REEs, recovery of REEs from WEEE was discussed above. These topics attract abundance of attention. A separate attention requires the design and distribution issues in the context of technology discussion.

As established, one of the sources to tackle the scarcity of the resources is by substitution, but there is more to that. Adaption of the design for recycling principles on the EEE design stage is an effective tool to promote the circularity. (Norgren et al., 2020) propose the following set of principles and actions to advance such approach:

- Set the functionality, longevity, reliability and cost as product requirements from the first steps of design;
- Take care of the material choice for functionality, but also for the extraction at the EoL of a product;
- Minimization of the hazardous materials or making materials recoverable;
- Minimize non-reversable adhesives over the entire surface or dissimilar materials to facilitate disassembly and material liberation;
- Apply design for recyclability that promotes modular product structure for better disassembly, repair/replacement of components, choice of fasteners and joining methods;
- Using BOM labels to identify recyclable and non-recyclable materials;
- Design products that are recycling friendly. (Norgren et al., 2020).

As mentioned, the disassembly is the stage when REEs can be lost (Sprecher et al., 2014; Tsamis and Coyne, 2015). The poorly designed products are more expensive to refurbish and extend the operational life. A good design, which includes consideration for EoL and recycling, cannot be forced on each individual designer even when a standard is developed without the political will and economic interests/resources to back the decision. This does not excuse the need to raise awareness for the issue in the academic environment though.

The other issue that can impact the WEEE recycling attractiveness is the engagement of the equipment distributors in the collection process as well. One of the tools is e-waste collection points at the sales points. This is not a novel idea and in many EU countries this is actually a norm. What we propose is an introduction of the EEE deposit collection at the time of purchase, which can be returned at the EoL of the equipment. It can be nominal – 5-10% of the value of the purchased equipment. The distributors can collect extra cash for its operation for the time when a customer uses the product. When the deposit is called back and the product is returned to the seller for the return of the charged deposit, the collected WEEE can be sold to the collecting agency for a fraction of cost. Thus, businesses get a credit for their operation at no interest rate and still can turn the e-waste into profit.

2.4.5 Seeing REEs in PEST perspective

So far, we have focused on the individual aspects and issues, which create maze of meanings and solutions. Here, we step back and put the information into a perspective. This requires rolling back to the level of geopolitics. At this level, the economies and states add up as a layer. Seemingly unnecessary, this deflection provides valuable insights into the scale of the problem with the REEs and the urgency of finding either alternative sources or replacement technologies built on more available element base.

In recent publications on sustainability and industrial design, the engineers were forced to bury the burden of using sustainable materials and design, and carry the moral responsibility in case they are not (Rammler, 2015; Melles, 2015; Kretschmer, 2014; Katzenstein, 2013; Stahel, 2019), but the reason why is argued vaguely. The main reason for that relates to the nature of the answers which are outside the limitations of the typical engineering discussion. The topic of sustainable design is stirred and mingled with topics related to the sociology, economy and to political economy in particular (see Rammler, 2015; Melles, 2015; Kretschmer, 2014; Katzenstein, 2013; Stahel, 2019). Such mix is nonrandom. If the engineers are made responsible and are demanded to act in a certain way, we are entitled and obligated to have also the understanding in what interests and for what function the changes happen. In such case, it is irresponsible to focus only on the technologic side without acquiring the bigger system-level perspective on the REE related issues.

Despite of the great intentions, the sustainability agenda is valid for as long as it does not cross certain economic interests (see how the nuclear and natural gas energy became “green energy” despite the opposition (BBC, 2022)) and as long as it “sells (see Chen and Zheng, 2019, where the main interest to REEs comes from the sustainability field with focus on economic research).” The question is in whose best interests this agenda is advanced. In political domain, it sells to the voters as the better bright/green future with numerous benefits and business opportunities; in marketing domain, it sells to the trustful conscious buyers as “feel good as you save the world”.

On the surface, it seems fairly evident from the marketing messages that the beneficiary of the green economy is the public. It is natural to strive for future generations to live in a beautiful and comfortable world and this intrinsic desire natural to every human is utilized to advance the green agenda. At the same time, neither media, academia nor state has managed to present yet the convincing underlying bigger picture, the ideology and the image of the future that supports long-term sustainable development. In other words, the change towards the sustainability and green economy is built on an appeal towards the animal instincts rather than rationally argued vision and strategic planning. There is no convincing answer to the question: in a capitalist economic paradigm, what is the motivation to be sustainable other than altruism. Why be sustainable, when other national individuals, businesses, economies are not, for what better good (the Prisoner's dilemma from the Game theory)?

Contrary, there is an explicit hypocrisy and double standards when it concerns the sustainability. The sustainability agenda is forced top down, by implementation of the stringent regulations and policies (e.g. Paris climate agreement). The good in its nature intrinsic human motivation to do good for the better world is used by the world decision-makers organized under the WEF and alike organization to lead towards the Great Reset. "You will own nothing and be happy" by Klaus Schwab does not sound that positive and public oriented as it is portrayed to appear. The society is expected to maintain the same attitudes, behavioral patterns and levels of consumption while doing it in less dangerous/sustainable ways. Instead of focusing on developing an economic system and changing toxic consumption patterns and wealth accumulation model, we change the materials in consumed products calling it sustainability (see for instance the discussion in Rammler, 2015).

As any coin has two sides, this section presents the other side of the sustainability coin, which in capital letters reads "RARE EARTH ELEMENTS." We believe REEs are the key to understanding many patterns that touch global political, economic, social and technologic domains. In IR4.0 enabled economies, REEs become analogous in its importance to crude oil and natural gas and their by-products for the linear economy (Chen and Zheng, 2019). This is an important statement which is worth mentioning again: in the IR4.0 enabled economy, the REEs is the foundation on which the new economy is expected to be built just as the old economy was built on crude oil and natural gas. If the EU plans to replace the dependence on the oil and gas with the hydrogen and other sources of green energy, there is a need to consider the alternatives for the technologic development in the light of the scarce availability of REEs.

Starting with 2020, we are at rather critical transitional point in the global history related to the change in the economic model on the global scale in a forced rapid pace. If the other three revolutions were synonymous to evolution with the change horizon taking up to 100 years, the horizon for the Great Reset transit is in decade(s) with the 2050 horizon. This point’s significance is determined by the attempt of the global elites to destroy the old capitalist economy built on the fundamental values of property rights and on the ashes of the old to build the new one, where the masses own nothing and are happy. The problem is that resources for the rapid change are locked in the old economy and they are needed in the new one as of now.

Thus, it is evident that there are two economies which compete for the same scarce resources. There is a **new economy,** the circular one. It is presented under the image of sustainable green economy powered by wind and solar panels, operated by automated processes, digitalization and robotized solutions, the world that is interconnected in an internet of things and tempted by the prospects of gaining access to depths of artificial intelligence and machine learning which one day can be shared with humans. There is that **old economy** driven by the rigid conservative values, dirty fossil fuel and nuclear energy, grounded in the industrial physical output, property rights, human rights and privacy. The old economy is the one we gradually grow disgusted under continuous bombardment and criticism from the media, public opinion and academia. Old economy requires resources, markets and control. The same requires the new economy. Unfortunately, the resources are scarce. In order to liberate resources from one economy for the needs of the other a catastrophe is required. This justifies the appearance of the COVID-19, which has played its role in disrupting the economies, practically shutting down entire industries globally and breaking the established supply chains.

Transit to the new economy has to be rapid otherwise it will fail by raising the cost of the transit and hoax can become evident to the masses resulting in public unrest and protests. That is why the attention of the masses is distracted by any means from the Johnny Depp’s divorce to war in Ukraine. The tedious work required for the transit is done publicly yet with lower publicity and under the boring façade of the routine work. The pattern resembles with the famous German propaganda, where the masses are scared by the external threats (e.g. COVID-19 or Ukraine), overloaded with the mass flow of worthless information, entertained and distracted by the booming entertainment industry, and casually informed about the changes in the regulations to maintain the appearance of the public discussion. The articulation of the scale of change is downgraded in the media to keep the public protest movements at a controllable level.

Another challenge is that the transit has to be accepted by all major states without an exception. In such case, Russia's and China's disagreement with the role of the vassals and the conflict in Ukraine along with threats of war over Taiwan destroys the possibility of successful establishment of the new economy along with the new government. Resources for the old economy are in abundance available in Russia, while the resources for the new economy, REEs, are in China so they are ready to capitalize on the change. In either case scenario, the indirect and immediate beneficiaries of the green transit or the fossil fuel suspense are not in the West which intended to be the sole beneficiary of the transit.

The collective West, primarily the US, tries to secure the necessary resources to prepare for the inevitable economic jump in the arms of the green future. The evidence for such arrangement can be observed through two trends. On the one hand, the US "tries" to cope with the energy crisis by releasing/getting rid of its oil reserves and encouraging the oil economies to increase the supply coping with the high fuel prices. On the other, disrupting the established state of affairs around its strategic challengers, Russia and China, in its favor. For this reason, there is formed Trilateral security partnership between Australia, United Kingdom and United States (AUKUS), military alliance. For the same reasons, Finland and Sweden are forcefully pulled into North Atlantic Treaty Organization (NATO). The connection between these arguments and the topic of our study becomes evident after opening the mineral map of global deposits in Figure 18 (see also Figure 10, Table 4 above). The combined deposits of the US, Australia, the EU are smaller than those of China or Russia, or Vietnam, or Brasil, or India. If our assumption about the strategic importance of REEs for the new economy correct, the available to the US deposits are not enough in the long-run.

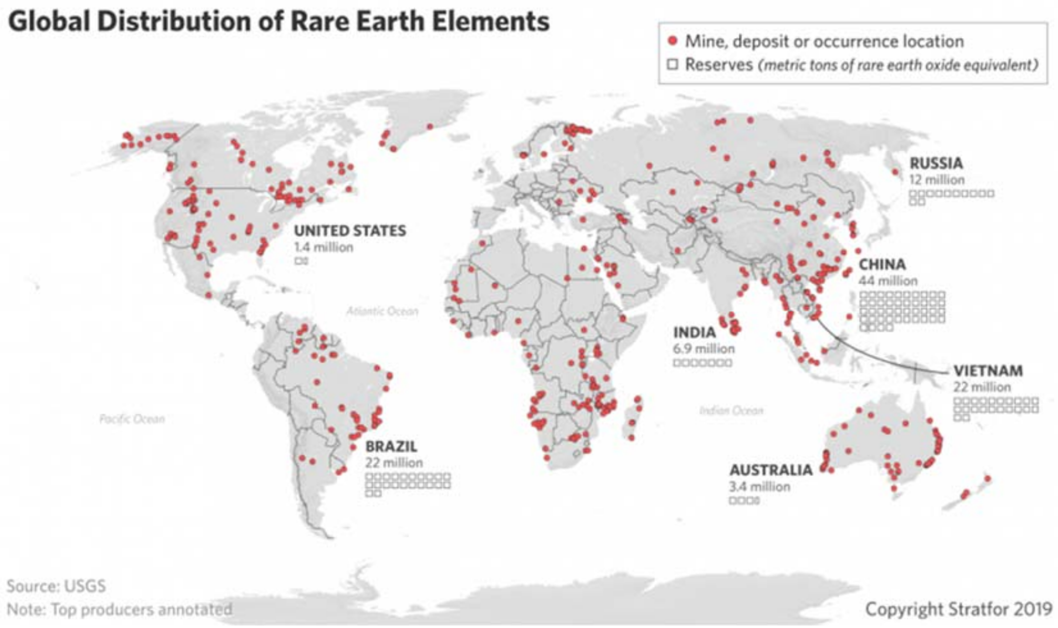


Figure 31. Global distribution of REEs (Stratfor, 2019)

Therefore, the available REE resources require protection and the new resources must be acquired. The recently formed AUKUS and the NATO serve the purpose. The AUKUS is intended to protect Australia from ceasing its REE resources to Chinese control. Interesting is the part of the UK in the AUKUS alignment as it has minor deposits of REEs, which can be turned into production (British Geological Survey, 2020), but contributes in a far more prosaic role in this alliance as an access control to the REE deposits in Eurasia (Finland, Sweden, Denmark, Ukraine, Turkey, Kazakhstan, Kyrgyzstan, Afghanistan) using its distributed network of influencers. The NATO as a rudiment is intended to protect the European deposits from Russian threats.

The new resources must be acquired as well. From the beginning of 2022 we were the witnesses of the failed unrest in Kazakhstan and the war/special operation in Ukraine. Both former Soviet countries along Russia have rich REEs and critical resource deposits. Both were on the hotbed of political intrigues by the UK. Kazakh elites have close ties with Britain; they have British education and network, but the Kazakh state remains the part of the Russian dominated Collective Security Treaty Organization (CSTO), which is an unacceptable duality. The protests were intended to change the regime and its participation in the CSTO with the formation of an alliance with Turkey – something that we still see happening as the rudiments of the initial plan in the media. The war in Ukraine was orchestrated by UK as well through the rumors about nuclear weapon development on the nuclear power plants and public claims by Ukrainian state leadership to have a right on nuclear weapon. Such rumors and claims, Russia has taken very seriously and sent the elite troops at all costs to take over the Chernobyl and Zaporozhe power plants during the first days of operation. Evidently, the rumors were just rumoring which explains the retraction of the Russian forces from the occupied territories and focus on the operation in the east of Ukraine.

As a part of the same scenario to which the events in Ukraine and Kazakhstan relate, the lightning rapid decision by Finland and Sweden to give up its convenient more than half a century old state of neutrality in favor of the arguable raise in security threat from the East in favor of the NATO. The fact that UK has signed the security pact with Finland and Sweden days before they submitted the NATO application vividly points in the direction of the one who orchestrated the acceptance of the decision.

How these seemingly random points connect? The US is arguably the biggest economy and it still prints the currency used in the global transactions. What happens with the US has direct impact on the other countries globally. When the oil reserves in the US will dry out and the price for the fuel at the gas pumps will raise to the levels unbearable for the majority, the US government can explain to its internal public and global public that they tried hard to preserve the old economy and status quo, but this is impossible. The state has done its best to secure the availability of the fossil fuel, but situation is now out of control. The sole source of the problem, Biden, will leave the office. The newly established administration will come up with a better answer. The only possible solution is the transit to the green economy and, by the way, the state with its faithful allies have secured the access to the necessary resources. Here, the US has access to own stock of REE and critical materials, there are Australian mines, Finnish and Swedish mines, Danish mines in Greenland, Turkish mines and other resources available on the global market so the public and investors should stay calm as the leadership has a clear image of the future.

In such complex and often conflicting environment, the engineers are expected act responsibly while making the design decisions following the nonsense motivation. Being blindfolded, the engineers bury alone the responsibility that the entire structure of the society must carry. On the other hand, when the same engineers are equipped with the knowledge and understanding of the external environment, when the actors and interested stakeholders are clear, when the goals are set, those same decisions make a better sense and acquire far more strategic role than that assigned to it.

Given this discussion, we can turn to the research methods and observed results. The complexity of the discussed issues, though arguably being far from the purely technical discussions, adds more value to the observed individual patterns and trends in forming a model for the better sustainable decision making.

3 RESEARCH METHOD

The selected primary research method for the study is the qualitative method in a form of semi-structure interview. An expert interview allows access to the specialized knowledge, which otherwise is rather challenging to get and the relative freedom to ask additional questions offers relatively high level of validity.

3.1 Qualitative research method

The nature of the study predetermined the choice of the research method. The ability to conceptualize the trends into an overall structured matrix with actionable suggestions required confirmation of the observed conclusions and observations from an expert. As an expert in the field, we have reached out to professor of Sustainability Science in LUT Dr. Risto Soukka (Diduc, 2022). Dr. Soukka has a long academic track record with primary areas of expertise related to the sustainable development, environmental footprint, Life Cycle Modeling and strong connections to the industry to provide his informed opinion as a valid source for confirmation of the information obtained from other source.

The research has taken a form of a semi-structure interview. The qualitative study was conducted in the beginning of the research after the identification of the major topic in the field through preliminary literature review and online information search. A set of themes were shared in advance as a starting point for a conversation:

- REE and sustainability aspects in general;
- The entire LCA dimension of REE usage as materials for electronics especially with the sustainable future in mind;
- As the part of LCA, the energy consumption/efficiency in REE production and recovery;
- Politics and economics: conflict materials and the EU regulations. Although the REEs are not the part of conflict minerals yet, given the fact that China is the major player on the REM market, if Chinese government restricts the exports, REEs might quickly become the conflict minerals. What are the options in case a major supplier denies the delivery?
- EU directives for electronic devices (WEEE and RoHS) and REEs.

It was followed with the interview meeting over the Teams application.

3.2 Findings

The interview has given valuable perspectives and has given the impulse for the further exploration of the researched topics. The major topics and emerging from discussion are summarized below in a thesis form:

- REEs are rare, hard to mine, expensive to process – only 1% is recovered, which is both a threat and an opportunity
- LCA of REEs: they have negative environmental impact as pollutants, some are radioactive. There no methodology developed to assess the impact in e-waste. One of the possible reasons is the challenge of separating the elements' impact from the overall environmental impact of a product.
- The biggest challenge with REEs is that China owns 95% of those and that can cause issues for the EU. (Noticeable is that the discussion about REEs immediately starts with geopolitics – tension between EU and China in case of supply disruption)
- Conflict minerals – sourcing of the minerals in countries that either solely dominate the market or mining happens in the inhumane conditions. A careful consideration is required in assessment of the benefits from REE exploitation and the environmental impact on society even if it is something that happens thousands of kilometers away.
- Complexity of products and used for their production materials makes recycling challenging – this also applies to REEs. The challenge is amplified by the small amount of the RE elements as the mix of the entire product.
- Recycling methods need more development if the elements are to be recovered.
- The small quantity is a significant issue. The recycling in the West is quite expensive. It is easier to dump the e-waste in the ground or export to those countries that want to take care of the e-waste.
- The concentration of REEs in China poses significant threat to the European manufacturers. The alternatives to the single supplier dependence is a threat, which also becomes a risk especially in the light of the historical export restrictions by China in 2010. China can raise the price of neodymium and dysprosium for the foreign markets. Since these elements are used in the wind turbines, such move can significantly affect the competitiveness of the other manufacturers if the Chinese

manufacturers would have access to cheap elements. That is why the interest towards circular economy is growing.

- The increasing demand for the REEs creates a lot of environmental hazard in terms of the scale of production. This resonates with the findings from the literature review.
- Circular economy is intended to mitigate the risks of the supply disruptions. The interest to such economic system is growing and it is developing in the EU comparing to the other parts of the world at much faster pace.
- The challenge of replacement: “if the replacement of the REEs would be possible, it would be done by now.” That is why it is critically important to improve the recycling methods especially since the materials are available without the expensive mining and crushing of the minerals.
- When we talking about the energy consumption for pyrometallurgic processing, it is significantly higher that with other materials. That is why it is important to improve the existing processing methods and search for better solutions
- Calculating the energy efficiency is important for REEs. The recycling against mining shows significantly lower cost of recycling. In case of aluminum, recycling of the material saves up to 95% in energy consumption, 60% saving in case of steel recycling comparing to mining the iron ore, 70% in case of plastics, 40% for the paper and 30% of glass recycling. The improvement in costs in other industries can suggest that there is a possibility to save also in the REEs and other WEEE related material costs.
- The REE concentrations are low and processing is resource demanding, the recycling of the existing materials makes better sense. Finding the actual energy consumption for mining and recycling from the literature can help with the decision about the economic potential of the recycling process.
- LCA and end-of-life: it is challenging because it is rather hard to model the study. The question comes from the methodological point of view is what kind of method should be used to model the recycling option. Different kind of instructions for different methods: substitution, product category rules and they are sector specific. Product category rules related to product declaration. It causes problems when we think about the LCA of a wind turbine, for example. How to assess the value of recycling? It is a challenging methodologic issue.

- Assessing the recycling and end of life issues already on the design stage would be a good solution. The major problem is how and where from do we get the data to model at the design stage. Some of the wind turbines entered the production 5, 10 or 20 years ago. Are the recycling of the materials or the reuse of the technology suitable for the contemporary environment? Can they be used to predict the future performance? These are challenging questions to answer.
- If a designer intends to consider the material choices on the design stage, the good source of information is the literature review. If someone has skills in dynamic models for recycling process, useful data comes from Gabi LCA database in Solidworks.

Without exaggeration, the collected data provides additional insights to support the confirmation bias with an exception that it does not given the sequence of data collection. The interview was conducted on the initial stage of the research when the author has had rather surficial understanding of the actual extension and depth of the issue. The literature was considered in sufficient details though not to the degree to settle the agenda in such way that it affects the validity of the study. Data collected from the conducted interview has found its confirmation numerous times also in the literature review from various perspectives. The issue of REE recovery from the WEEE is a complex technological, political, economic and social issue. It requires careful multilateral consideration from the decision-makers on different levels from politicians (e.g. the theme of China as a major source of REEs) to product designers (the theme of LCA prior to designing a product) and scientists (theme of LCA, energy efficiency, modeling challenge).

3.3 Reliability, validity, sensitivity aspects of the selected method and project

The reliability, validity and sensitivity aspects are addressed through application of triangulation principle, transparent explanation of the way the data is gathered, the nature of the data and its interpretation. The triangulation is met by conduction of the literature review from peer-reviewed academic sources, open sources from governmental and non-governmental institutions specializing in the field as well as expert interview. The semi-structured interview as a research method provides relatively high level of validity yet allows collection of the reach data focused on certain theme and delimited topics. At the same time, we recognize that the increase in the number of conducted interviews with experts in the field of e-waste treatment, politicians, economists and engineers has higher potential of improving the quality of the observed trends and can open the dimensions that are not fully explored in the literature review and analytic observations.

4 RESULTS

As a result of the study, we have observed a set of trends from REE, WEEE discussion, have arranged in a matrix with possible 4R action strategies. In addition, we have outlined the overall external environment and potential risks, threats and opportunities. The conducted expert interview has led to a number of observations that has found its confirmation in the literature review reflection and reinforcement of the observed trends. Overall, we can assess that the study has reached the set goals and answered the set upfront questions.

4.1 Scientific contribution

The observed trends and tendencies reveal the multi-level complex nature of the REEs-related issues especially in the light of the recovery of them from e-waste sustainably. Table 8 summarizes consolidation of the observed trends, potential action strategy and the involved stakeholders as dimensions. For the illustration purpose, we have chosen some of the dominant trends related to the REEs and their recovery from WEEE. Another column allows assignment of the possible 4R response. Different responses require different actions on the PEST stakeholders' side. Some actions are beyond the limits of the matrix and require awareness being marked with an exclamation mark (!).

The study has identified numerous trends but their entire analysis seems unnecessary. For the purpose of the study, we have sampled some trends among those mentioned above and apply the analysis matrix. This helps illustrate the principle of how to use the model and its potential application. More importantly, such framework allows to structure the discussion, find and assign players to a task, see resources required to tackle the issue and delegate responsibility.

The primary value of this action matrix is that it is easier to decide on the nature of the trend and easy to assign the direction of action. As such, engineers can identify the possible trends requiring the technological response and can identify the 4R action, expand the perspective to consider other interested in a solution parties and commit to a focused work together. Not all trends have immediate actions assigned yet being aware of them allows foreseeing threat or identification of opportunity.

Table 8. Trends related to REEs and its recovery from WEE: a decision matrix of 4R actions with regards to PEST

Trend	**4R**	**P**	**E**	**S**	**T**	**(!)**
Systematic approach to recuperation of the REEs from the WEEE	R1	•	•	•	•	
	R2		•	•		
	R3	•	•		•	
	R4	•	•	•	•	
Involvement of all major actor in circularity effort (all)	R1-4	•	•	•	•	•
Manufacturers	R1	•	•	•	•	
	R3				•	
	R4		•	•	•	
Retailers	R3	•	•	•		
	R4		•	•		
Consumers	R1		•	•		
	R2		•	•		
	R3		•	•		
	R4	•	•	•		
Service providers	R2		•	•	•	
	R3	•	•	•	•	
EoL actors	R4	•	•	•	•	
Normative acts to Design for Recovery	R1-4	•			•	
Design for extend life-span	R1-4	•		•	•	
BOM database for certification	R4	•			•	
R&D in recovery of REEs from WEEE	R1	•	•		•	
REE supply risks for businesses	R1	•	•		•	•
	R3		•		•	•
Dependence on one major source of REE supply (China)	R1,4	•	•		•	•
Search for alternative materials	R1		•	•	•	
Refundable e-deposits	R4	•	•			

4Rs – 4Rs response to tackle the challenge
R1 – reduce
R2 – reuse
R3 – recover
R4 – recycle
P – political
E – economic
S – social
T – technological
(!) – awareness

4.2 Practical applications

The practical application of the study is the ability to set the observed sustainability related trends into actions with identification of possible interested parties as it was successfully demonstrated on the example of the REEs and their recovery from the WEEE. This tool is expected to help the upper level decision-makers in technology-oriented tasks but also entrepreneurs and senior managers, which aim at finding the practical business connection to the observed abstract trends.

4.3 Generalized results

The results of the study and the 4R/PEST matrix in particular can have a practical application in the areas unrelated to technology yet which relate or have significant impact on the environment. For instance, the model can be applied to critical raw materials recovery related trends. There are different areas related to sustainability and building a more environment-friendly solutions, where this model can help identify the potential actions and potential stakeholders. Evidently, the currently presented scale from which the stakeholders are perceived does not allow for the detailed consideration of each individual player, but at the least, it can serve as the starting point in a search for a sustainable solution with an actionable strategy.

5 DISCUSSION

This section is dedicated to the discussion of the results of the study. It sets the results into perspective by comparing and connecting with the former research, by considering the objectivity, reliability and validity, highlighting the key findings, stressing the novelty value and proposing the topics for future research.

5.1 Comparison and connection with former research

This study is built on top of the existing studies in material management, sustainable development and strategic management. From the perspective of material management, we consider the REEs and related trends extending the discussion into the practical domain of REEs' recovery from the e-waste. The sustainability aspect is presented with the help of the 4Rs actions of Circular Economy. Addition of this dimension provides the necessary dynamism to the model, which is so often absent in scientific works. It become useful by showing the trend, attaching the stakeholders and showing what can be done. This is particularly useful for designers and product developers as finding the idea often is the most demanding part of the creative process. With this tool, the identification of the trends and the opportunities becomes a routine task. The strategic management dimension expressed through the use of PEST tool helps sorting out the significant trend categories and possibility to act on those trends swiftly.

To the best of our knowledge, the proposed model is a novel approach to strategic decision-making with focus on sustainable development. It has a potential of the wide range applications that is not limited to the technology or design related categories. The value of this model comes from the context of its application that shows that the tools is useful not only in strategic decision-making but also as an instrument for strategizing the technologic development.

5.2 Objectivity

The objectivity of the study is assured through the triangulation approach of the study. Conduction of the expert interview along with the literature review, helps assuring that the issue is free from subjectivity and a hidden agenda.

5.3 Reliability and validity

The reliability and validity aspects are addressed through application of triangulation principle, transparent explanation of the way the data is gathered, the nature of the data and its interpretation. The triangulation is met by conduction of the literature review from peer-reviewed academic sources, open sources from governmental and non-governmental institutions specializing in the field as well as expert interview. The semi-structured interview as a research method provides relatively high level of validity yet allows collection of the reach data focused on certain theme and delimited topics. At the same time, we recognize that the increase in the number of conducted interviews with experts in the field of e-waste treatment, politicians, economists and engineers has higher potential of improving the quality of the observed trends, and can open the dimensions that are not fully explored in the literature review and analytic observations, and assess the potential of the use of the model in practice.

5.4 Key findings

The key findings of this research can be conditionally divided in two categories. One of the key findings concern the observation of the trends related findings. The other concerns with the tool-related findings discussed next.

Trends-related findings: They are the essence of the new economy and demand for them is going to keep growing. REEs are here to stay because of the unique properties used especially in the context of growing digitalization and IR4.0. There are few applications allowing replacement of the material. For the rest, the reduction or the REEs' removal correlates with lower performance or the significantly higher costs for product redesign. The REE resources are scarce and there is an intense geopolitical competition to secure their availability. Mining of the REEs in the EU is practically inexistent, while the level of EEE consumption is quite high. This opens numerous opportunities for e-waste management. Iv fact, it becomes a viable and underutilized source of the scarce elements.

Tool-related findings: the 4Rs action of Circular Economy along with the PEST analysis provide a viable framework for actionable decision-making. The reduce, reuse, recover and recycle actions serve as a scenario for addressing the REE scarcity by considering the e-waste as alternative source. On the PEST level, the ghost of another export restriction of the REEs by China dominates the fears and actions of the major stakeholders in the West. One of the triggering events can be the growing tension between the West-backed Taiwan and China, which eventually can turn into an open conflict. Being able to foresee and prepare for the growing uncertainties in a changing world is a luxurious convenience that the proposed in this study model helps dealing with.

5.5 Novelty value of the results

This novelty of the research gives the answer to “so, what to do with the this?” question in a form of the actionable model. The study is cross-disciplinary taking into account both social science (political, economic and social perspective) and practical with the focus on technologic/technic application.

Additionally, it mixes the sustainability strategies and contextual dimensions (PEST) thus giving the observed trends not only informative or recreational value, but also allows setting the trend into motion while finding the suitable stakeholders in various stratum of the society. This allows to actually set the clearly defined steps to address the environmental challenges and attract supporting the cause stakeholders. Thus, engineers can act according to the endowed responsibilities and lead the sustainable transformation. The engineers can act as the gluing element consolidating the society towards the change. With the help of the model, engineers can step out of the comfort zone of the purely technologic discussion.

5.6 Topics for future research

Every research has its limitations and opens opportunities for further development. This study is not an exception. There are a few potential areas for improvement and development of the study. We recognize that the proposed model and selected trends are sufficient for the illustration of the working principle of the model, but consideration of the wider range of trends have the promising potential. Additionally, the observed trends can benefit from drawing more relations between them.

Another area of improvement and future study relates to the conduction of bigger number of interviews as well as verification of the findings with the use of quantitative methods. A broader range of experts and influential stakeholders can add value to the discussion and open the areas which otherwise can be missed.

The trends seldom happen in a moment and are better observed in a longitudinal study context. The selected trends in this study can be better organized and their choice needs more detailed argumentation, which was outside the scope of the study. Once the important trend categories are identified, the longitudinal study of the trends can help with better decision-making on various levels from selection of materials, design of products, to personal patterns of consumption change, implementation of supportive regulations and better economic choices.

This study has taken a rather lose approach to the focus solely on the technologic side of the issue, but it is related to the nature of the problem, which is not purely technologic. The higher scale is necessary to set the ground also for the future research and development. More detailed approach and closer attention to the methods of REEs recovery from e-waste can be paid in the light of the observed tendencies. Building on the observed trends, the availability of options for a better selection of sustainable solution becomes better organized.

6 CONCLUSION

The application of this study has direct application for the decision-makers taking the leading positions and requiring a tool for observing trends and crafting a sustainable response. The results of the study show that the tool is valid and has wide practical application. Besides exploring trends with relation to the REEs, REE recovery from WEEE, 4R actions of circularity and placing it in a context of the bigger picture of the PEST aspects, we propose an instrument to make sense in the maze of numerous indicators/trends, which can be quite overwhelming to account for in decision-making. This instrument can be used to apply the 4R strategies for circularity with regards to the global and local trend related to PEST as we see it in the context of REE recovery from the e-waste.

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