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Rebound Effects in the Use of Rare Earth Metals in ICT

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Abstract

This work looks at the rebound effects associated with digitalization of the use of rare earth metals in terms of environmental sustainability with a focus on the life cycle of REE in its technological applications. There is no doubt that digitization offers numerous advantages for industry and society. These primarily include improving efficiency and performance, as well as optimizing the susceptibility to disruption of production and business processes through automation, the consistent availability of information in connection with rapid knowledge transfer. This also results in lower process costs and short reaction times to problems within the value chain. Employees can be used more flexibly due to mobile work. The most important topics of digitization include artificial intelligence, robotics, the Internet of Things, cloud computing and autonomous driving. However, digitization also has environmental disadvantages. These include, above all, an increasing demand for raw materials and its cost-effective procurement in countries with low environmental and social standards instead of a sustainable circular economy, which is financially and industrially more complex for manufacturers. For this purpose, a model calculation of ICT devices in the consumer sector is carried out within the scope of this work and the resulting electronic waste is determined.

Keywords: Rare earth metals; Digitalization; ICT; Rebound effect; Sustainability

Introduction

Due to their special physical and chemical properties, rare earth metals are one of the most important raw materials to produce electronic applications in various industries and thus play a decisive role in technological progress. The term „rare“ in connection with rare earths is often used misleadingly and does not refer to the real frequency of their occurrence. At the time of their discovery and in the following decades, scientists assumed that these elements occur only in very small quantities in a few places. However, they are not rarer than, for example, copper and more common in nature than lead [1]. Another explanation is also the meaning of „rare“ in the sense of „strange“ or „extraordinary“. The term „earth“ is the term taken from Latin for „oxides“. Even though this term is often assigned to all critical raw materials, „rare earths“ is clearly defined in the terminology of chemistry. Rare earth metals include 17 chemically similar elements – scandium, yttrium, and the group of lanthanides. Except for promethium, a fission product of uranium, these metals occur socialized in nature due to their identical reaction behavior. Therefore, in the past, the biggest challenge was to isolate and analyze them. Only with the technological advancement of analytics such as mass and atomic emission spectrometry was it possible to identify these elements. Due to their special physical properties, they are used in a variety of technical applications. Although they are very similar in their chemical and physical properties, each of the rare earth elements has its own specific disposition. Due to their wide range of applications, REE are also regarded as a driver of innovation. This is evident in the rapid increase in publications, applications, and patents since the beginning of the 21st century.

Figure 1 publications related to REE shown in Figure 1 also results in an ever-increasing demand for rare earth metals. At the same time, economic growth through technological progress also requires a higher demand for resources. A decisive rebound effect can be observed: the more economical a system is, the more purchasing power and innovation potential there is. This in turn increases the consumption of resources. Companies also tend to obtain production factors as cheaply as possible. As a result, raw materials important for technologies are often sourced from countries with low social and environmental standards.

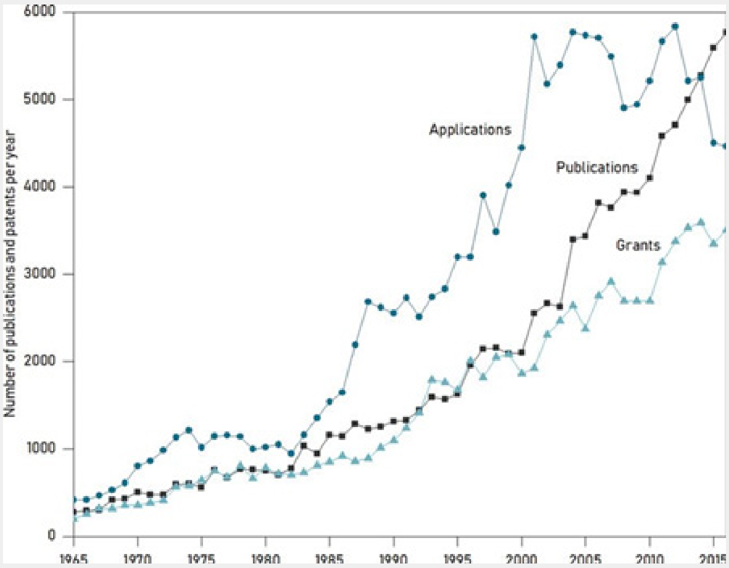

Figure 1: Increase in publications, applications and granted patents related to REE [2].

Rebound Effects

In 1865, the English economist William Stanley Jevons argued in his book „The Coal Question“ that the more economical consumption of coal did not lead to lower consumption, but caused exactly the opposite [3]. This gave rise to the so-called Jevons paradox, which describes the connection between the increase in energy efficiency and the increase in demand [3]. Efficiency gains are thus compensated [4], because efficiency gains also lead to an increase in the production of goods. Khazzoom went a step further in his 1980 article in the „Energy Journal“ and described that an increase in demand due to energy savings still exceeds the demand in its initial value [5]. This theorem is also known as backfire. This is illustrated, for example, by the study by Fouquet and Pearson, which shows that with the increase in more efficient light sources due to new technologies, total lighting consumption in the United Kingdom increased 25,000 times from 1800 to 2000 [6]. Leonard Brookes made similar observations, but made the connection between energy prices, gross domestic product, and energy demand. He found that an increase in energy prices would not lead to lower consumption [7]. This resulted in the Khazzom-Brookes Postulate, which describes a rebound effect of < 100% due to additional demand. Even today, more energy- and resource-efficient production often leads to higher demand. Sorrell defined the rebound effect as unintentional increased consumption because of efficiency gains [8]. In the appraisals prepared by Madlener and Alcott for the Enquete Commission of the German Bundestag, they defined rebound as a theoretical percentage amount of possible savings, starting with a technical increase in efficiency. They further describe that these assumptions are only theoretical, since in the reality the system is expanding. The increase in technical efficiency makes it possible to increase the population, goods, and services. According to Madlener and Alcott, the rebound effect refers to the increased consumption of resource inputs, which (1) ‚follows‘ these efficiency increases and (2) is somehow caused or at least made possible by them [9]. The amount of the rebound effect is the percentage of the savings potential of an efficiency-enhancing measure or technology, which is compensated by the increase in demand [10]. The literature distinguishes between direct, indirect and intersectoral rebound effects [8]. In the case of direct rebound effects, there is an increased demand for the same good or service that is related to the increase in efficiency. Intersectoral rebound effects result in increased demand for an alternative good or service. Macroeconomic rebound effects are difficult to quantify microeconomically. They relate to entire economic sectors or the entire economy. In the field of digitization, the energy requirement for the operation of data centers but also for the development of artificial intelligence applications is particularly crucial. This results from hardware-intensive training and test runs of the algorithms [11]. It can also be assumed that energy consumption will continue to increase in the future due to the increasing use of AI applications [12]. In this work, however, the production-side [3] rebound effect in times of digitization about the use of rare earth metals should be in the foreground.

Rare Earth Elements

Physical/chemical basics of rare earth metals

Rare Earth Elements (REE) include the lanthanides of the 6th group of the periodic system and scandium and yttrium [13] of the 3rd subgroup. A total of 17 elements, which are divided into heavy and light elements depending on their electron configuration, are therefore [14] counted among the rare earth metals (Table 1).

Table 1: Rare earth metals with the ion radius in the 3rd oxidation state [15].

REE	Symbol	Ordinal Number	Ionenradius Ln3+ (pm)
Scandium	Sc	21	88,5
Yttrium	Y	39	104
Lanthanum	La	57	117,2
Cerium	Ce	58	115
Praseodymium	Pr	59	113
Neodymium	Nd	60	112,3
Promethium	Pm	61	111
Samarium	Sm	62	109,8
Europium	Eu	63	108,7
Gadolinium	Gd	64	107,8
Terbium	Tb	65	106,3
Dysprosium	Dy	66	105,2
Holmium	Ho	67	104,1
Erbium	Er	68	103
Thulium	Tm	69	102
Ytterbium	Yb	70	100,8
Lutetium	Lu	71	100,1

Lanthanides have a very similar chemical behavior and occur together in nature. Separating them from each other was almost impossible for many years [13]. Scandium and yttrium have been counted among the rare earth metals by IUPAC due to their strong similarities to the lanthanoids [1] The reason for the similarity is the special structure of the electron configuration. In all REE, the electron shell is equally occupied with 5p6s2. The distinction of the elements is only created by filling the f-orbital. However, the f-orbital has no effect on the chemical reactions [16]. This growing nuclear charge and atomic mass causes a decrease in the ion radii of the lanthanides (lanthanide contraction), [17] which makes efficient extraction of the REE difficult. Due to the lanthanide contraction, the nuclear charge is poorly shielded and causes a stronger attraction of the 5p and 6s ions (Figure 2).

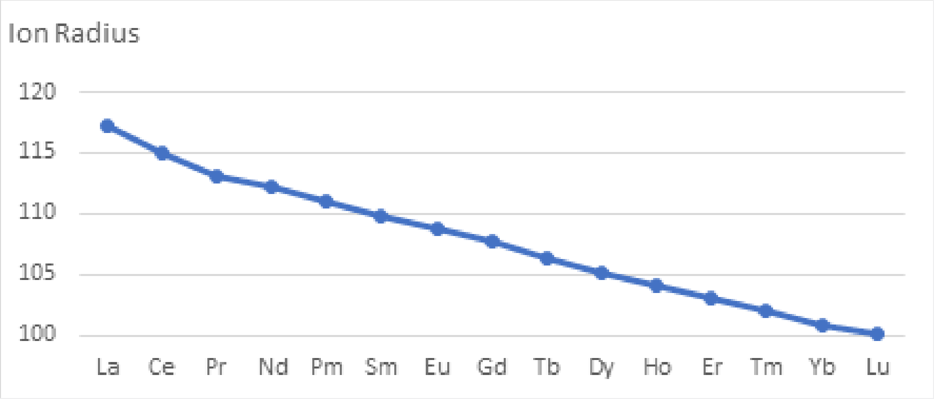

Figure 2: Ion radii of lanthanides [18].

REE form predominantly positively charged ionic bonds, which are very stable and poorly soluble [19]. In connection with lanthanide contraction and ion radii, the differences in basicity are an important property for the separation of REE. Depending on their ion radii, the basicity of lanthanum decreases to lutetium. Due to their paramagnetic properties, REE are particularly suitable for use in permanent magnets and storage media. However, paramagnetic properties also play an important role in

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recycling. Paramagnetism describes elements that do not have a measurable magnetic moment without an external magnetic field. This results from unpaired electrons and the only partially filled f-shell of the electron configuration of the atom, which realign themselves by an external magnetic field. Due to this property, REE can be magnetized very well. REE have line-rich and sharp absorption bands [20]. The width of the frequency interval is in the range of some 100 to about 10GHz. These luminescence properties also result from the lanthanide concentration and the associated poorer shielding of the nuclear charge, resulting in the relationship between frequency and wave number [21]. Luminescence properties are particularly crucial for the area of security documents, in plasma displays, LEDs and lasers. For the detection of rare earth metals, the most common method today is ICP atomic emission spectrometry. Hot plasma is injected into the samples. These ionize and are stimulated [17]. When falling back from the excited to the ground state, the atoms release energy in the form of light in the wavelength typical of each element [22]. However, this process is very costly. Therefore, research is increasingly being carried out on biochemical processes to establish more economical separation processes, especially in the field of recycling.

Occurence

The term „rare“ and „earth“ in connection with these metals is misleading and historical. At the time of its discovery, only the site of Ytterby in Sweden was known [23]. These elements were obtained only as oxides from certain minerals. REE do not occur in nature individually but oxidized and socialized in over 200 known minerals [24]. The main minerals for the extraction of REE are allanite (cerium, lanthanum, neodymium, yttrium), monazite (lanthanum, cerium, samarium, gadolinium, praseodymium, yttrium, thorium), bastnaesite (cerium, lanthanum, neodymium, yttrium), xenotime (yttrium, dysprosium, ytterbium, erbium) [17] and thortveitite (scandium) [25]. Here, too, Harkins‘ rule applies, which states that elements with an even atomic number occur more frequently in nature than those with an odd atomic number [26]. Only the unstable promethium occurs in nature usually only as a product of spontaneous fission with uranium and is therefore produced in the laboratory (Figure 3).

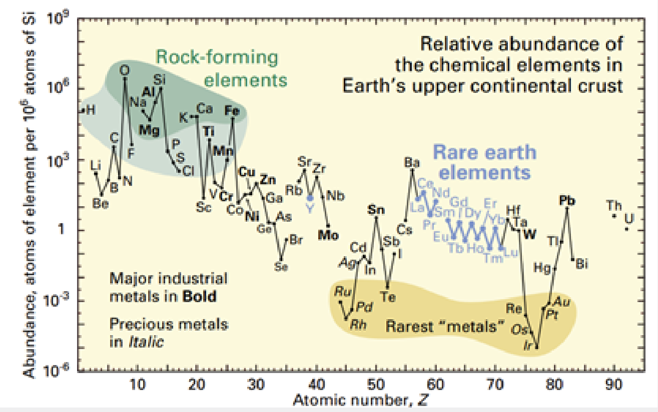

Figure 3: Occurrence of REE in the earth's crust [27].

Until the 40s of the last century, India and Brazil were the main producers of rare earth metals. From the mid-1960s to the early 1990s, the U.S. was the largest producer of REE [23]. Their mining site was mainly located on Mountain Pass in southeastern California. Since the 1980s, REE‘s economically viable deposits have been located primarily in China, Canada, Australia, USA, Brazil, India and Russia. The largest deposits are located in Bayan Obo, Mongolia [28]. Global reserves are estimated at 130 million tons [24] and global resources at 308 million tons [29]. The U.S. Geology Survey estimates the availability of reserves for 1100 years and of resources for 2480 years [29]. The difference between resources and reserves is that reserves are raw material deposits that are reliably detected in the earth‘s crust and can be mined by known technical means, while resources are suspected based on geological conditions and cannot be mined with known technologies [30]. REE resources are reported as rare earth oxides (REO). Thus, REE deposits are measured in relation to the amount of recoverable REO. It can be assumed that with a high REO content of the deposit, more expensive mining technologies often must be used and are therefore not necessarily more economically viable than the low REO-indicated mines (Figure 4).

At over 90%, China has the highest share of world production. The most economically significant deposit is Bayan Obo in Mongolia with an iron ore deposit of more than one billion tons and a REE grade of 3-5.4%. Bayan Obo is followed by of Maoniuping in Siuchan will be followed with reserves of 62.3 million tons of ore and a REE grade of 2.89% [31]. The economic availability of REE is therefore mainly dependent on the world market leader China. In addition to political instruments such as pricing and government-determined export quotas and export restrictions, there is also a lack of sustainability measures. In addition to China, the main suppliers include the USA with the Mountain Pass deposit with 90 million tons of iron ore (REE share 5%) [32] as well as Brazil and Russia (Table 2).

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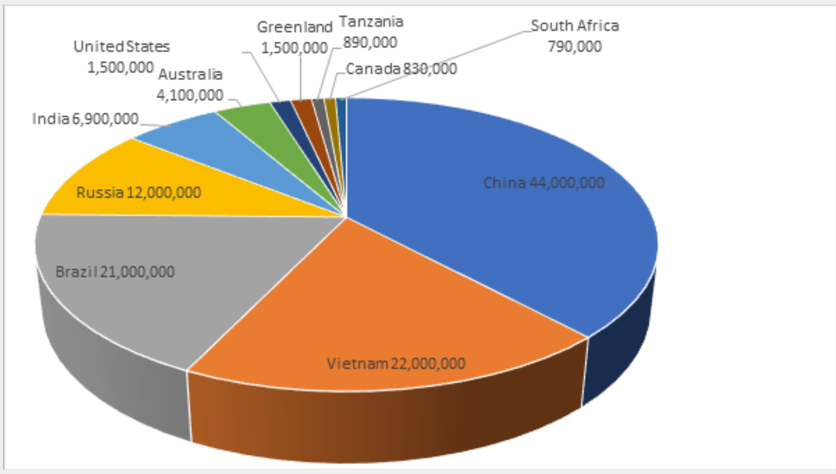

Figure 4: Reserves of REE 2021 [29].

Table 2: Main applications of REE [17,33].

Application	REE
Screens, picture tubes	Y, Ce, Sm, Eu, Gd, Tb, Tm, Lu
Illuminants	Sc, Y, La, Pm, I, Tb, Ho, Lu
Laser technologies	Sc, Nd, Sm, Dy, Ho, Er, Tm, Yb, Lu
Magnets	Pr, Nd, Sm, Dy, Ho, Tb
Magnetic data storage	Sc, Gd, Tb, Dy, Nd, Pr
Doping	Dy, Ce, Eu
Semiconductor	Tb, Lu
Drive technologies	Y, Nd, Sm, Tb, Eu
Nuclear power	Y, Ce, Sm, Eu, Gd, Dy, Ho, Er
Spectrometry	Y
Fuel cells	Y
Medical technologies	Y, Sm, Nd, Pr, Eu, Gd, Dy, Tb, Tm, Yb, Lu
Pharmacology	La, Ce, Eu. Yb
Batteries, rechargeable batteries	La, Pm
Glass industry	La, Ce, Pr, Nd, Sm, Ho, Tm
Condensers	La, Dy
Aerospace	Ce, Pr, Pm
High performance electrodes	Ce
UV-Filter	Ce
Catalysts	Ce, La, Pr, Nd, Yb
Steel and metal processing	Ce, Yb
Material and material testing technology	Ce, Tb, Dy, Tm
Insulators	Ce, Tb
Pyrotechnics	Ce
Clothing industry	Ce
Microwaves	Gd, Tm
Kyro cooler	Er
Fiber optics	Y, Eu, Tb, Er
Bank notes (Lorenz & Bertau, 2019)	Eu, Tb

Main applications

The areas of application of REE are diverse. The following table gives a rough overview of the main applications of the REE.

REE play an important role in the use of ceramics. These are present in almost all technical devices in actuators, sensors, resistors, and insulators. In view of the ever-increasing technologization, increasing demand for REE is to be expected. The field of application with the highest demand are permanent magnets, which are used in numerous electronic devices. A market analysis by Adamas Intelligence [34] came to the conclusion that demand is expected to rise steadily by 9.7% by 2030. Therefore, it can be assumed that as technology progresses, a shortage of raw materials will occur about REE, as these elements are not a renewable resource, and their availability is limited.

Environmental Aspects

Funding and processing

The degradation of REE is associated with considerable environmental and health damages, as energy- and cost-intensive separation processes and intensive chemical post-treatment are necessary [30]. The extraction of REE can be divided into 4 process steps: mining of the ores from the mine, washing of the ores, separation of the REE from the concentrates, as well as the production of metals and alloys [23]. Depending on the deposit, ore mining takes place in open pit mining, underground mining, and leach mining (Table 3).

Table 3: Degradation methods of REE [30].

Experience	Description	Advantage	Disadvantage
Opencast mining	· Mining in open pits with deposits < 100 m below the earth's surface · Conveying with bucket wheel excavators	· No artificial underground tunnels and shafts necessary	· Large amounts of overburden
Underground mining	· Mining by means of underground tunnels and shafts at occurrences > 100 below the earth's surface	· More precise development of the deposits than in opencast mining · Less overburden	· Damage caused by crime and subsidence · Risk of lowering the groundwater level and pollution of water bodies
In-Situ-Mining	· Mineral development in ion-based clay deposits · Drilling and dislocation with chemicals to convert REE into their sulfates	· No movement of large amounts of rock · Also suitable for small deposits · Technically undemanding	· Frequently illegal mining without environmental protection measures · Contamination of rock layers carrying drinking water
Deep-sea mining (no mining technologies available yet)	· Mining from manganese nodules in the deep sea		· Immense environmental damages

In the next step, the ore washing, the ores are separated from the adhering rock by leaching with chemicals or by mechanical digestion (dry processing). They are then crushed, ground, sieved and slurred with water. Then the separation of the ores is carried out by flotation with a variety of chemicals and separated according to density differences or magnetic fields conferring to magnetic properties [23]. The REE must be extracted from the minerals obtained in this way. This is done by various chemical processes, which must be adapted to the respective mineral concentrate. The separation then takes place by means of ion exchange chromatography and solvent extraction [30]. These processes consist of several complex process steps and require a high degree of technical know-how. To produce a metal from the oxide, the extremely energy-intensive process of melt flow electrolysis is used. Melt flow electrolysis uses a salt mixture as an electrolyte and thus increases the solubility of the REE. To eliminate further non-metallic impurities, the REE are then refined or distilled using various processes (Figure 5) [23].

Environmental impact of the extraction process of REE

The entire extraction process is characterized by a high intensity of the use of water and energy. Due to China's dominance in mining and processing, well-founded data is scarce. Even the government-mandated volume targets for exports cannot curb this problem. In addition, China has illegal mines to trade REE on the black market [77]. Due to the mining processes, the creation of overburden leads to increased land consumption. Massive ecological damage results from the strong intervention in the soil structure. The technical machines for conveying the ores generate dust and emissions. Large quantities of hazardous waste and residues such as the release of radioactive elements and heavy metals as well as silicates and leaching chemicals are also generated during in-situ mining. These blind rocks are stored on heaps, which leads to the spread of dusts of toxic substances by wind and debris in wastelands and groundwater. The heaps are surrounded by dams. If these dams break due to weather influences, the toxic chemicals enter the surrounding areas and damage nature and the environment in the long term. It is estimated that in China, the refining of one ton of REE oxide produces 63,000m^3 of sulphuric and hydrofluoric acid residues and 1.4 tons of radioactive waste [36]. Another possibility of mining is seen in the deep sea. Manganese nodules at a depth of about 3000-6000m have cobalt, copper, nickel iron and REE in addition to manganese. These manganese nodules are formed by

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erosion or from hydrothermal vents of volcanically active marine areas [37]. They grow dia- or hydro genetically by attaching metal ions. Since the manganese nodules grow very slowly (10mm/ million years), they can only form where constant environmental conditions prevail over long periods of time [37]. So far, however, there are no proven technologies for the extraction of REE from the deep sea. Mining licenses are also not yet available due to a lack of legal framework conditions. In the mining methods currently under discussion, the seabed surface with its fauna is removed. This damage to the seabed is lasting for many centuries [38].

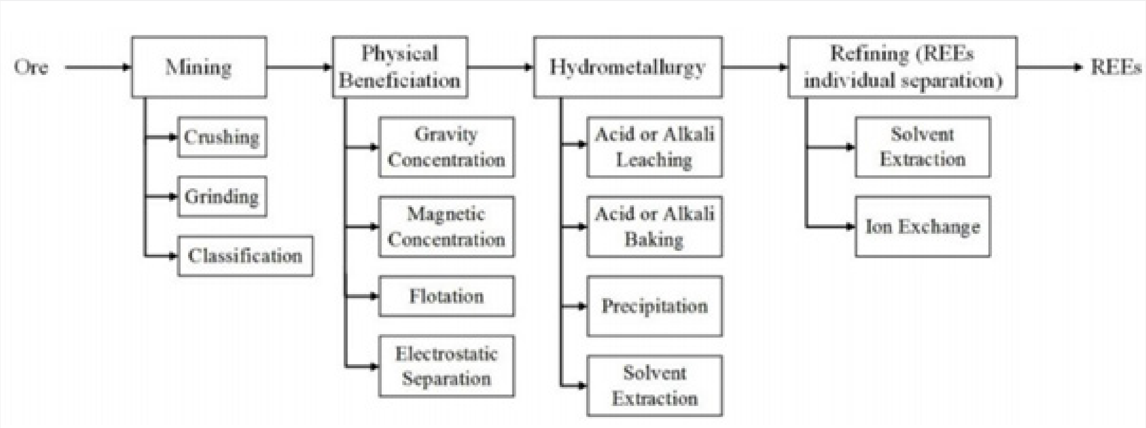

Figure 5: REE Production Process [35].

In the mining areas of the REE, these are also deposited to a particularly high degree in the human body. This applies in particular to the miners but also to the residents in the vicinity of the mine [39], as the occupational safety measures are inadequate in most areas. Little is currently known about the effects of rare earths on bioaccumulation. However, in affected mining areas, an increased number of leukemia cases and birth defects are reported [40]. However, these substances also enter the organism through the penetration of REE into environmental compartments, both during production and disposal. The highest concentrations in the human body are accounted for by the element's cerium, neodymium and lanthanum [41]. At present, there are few studies on the biological effects of REE exposures. This area requires further, detailed research [42].

Recycling and disposal

Table 4: REE flows (in %) for recycling [46,47].

	Pre-Consumer Recycling	Post-Consumer Recycling		
REE	Production residues (magnetic waste, slag, FCC process) (%)	Phosphors (LED, LCD, plasma screens, optical glass) (%)	Neodymium-iron-boron magnets (hard disks, computer peripherals, mobile phones) (%)	Batteries (%)
Scandium	0,0064			
Yttrium	0,015	53,55		0,71
Lanthanum	1,84	40,8		22,58
Cerium	0,2	1,8		8,8
Praseodymium	3,5		22,87	4,69
Neodymium	27		171,31	7,13
Samarium	0,0008		39,2	6,2
Europium	0,0002	3,98		
Gadolinium	0,0008	3,99	0,3	
Terbium	0,14	1	2	
Dysprosium	3,15		46,29	
Erbium	0,0013			
Ytterbium	0,0003			

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Despite the great importance of REE in ICT and industries of other high technologies as well as the relatively high potential for recycling possibilities, only about 1% [43] – 2% [44] are recycled from end products. This is largely due to the low profitability of using expensive and technically demanding recycling processes compared to the moderate raw material prices of the import [30]. Particularly affected by the fall in prices are the elements cerium and yttrium, which have lost more than 90% of their value since 2011 [45]. Furthermore, recycling is difficult due to the very low occurrence of REE in the end products and the high degree of dilution in the components as well as their dissipative distribution. The conventional recycling methods of hydrometallurgical and wet chemical methods are inefficient and uneconomical due to low market prices. In order to achieve the desired product quality, hydrometallurgical processes are usually used [46]. These process steps are carried out by ore washing and the use of large amounts of acid. So far, only the recycling of REE is only commercialized from phosphors, magnets, and batteries [29]. An overview of this is given in Table 4. In the case of recycling processes, a distinction is made between pre- and post-consumer recycling. Pre-consumer recycling refers to the recycling of REE from production residues, while post-consumer recycling refers to the recycling of the end device (Table 4).

For example, in 2015, only an average of 5% of e-waste generated in the EU was recycled. No recycling cycle is known for Scandium [48]. However, a controlled circular economy reduces the serious environmental impact of mining and production. In addition, the important resources of the REE are irretrievably lost without a reappraisal [49]. Furthermore, the dependence on China as the main producer will be weakened. Important know-how in the field of REE processing can also be built up [50]. The processes of recycling REE are mechanical processing, thermal extraction (pyrometallurgy) as well as wet chemical extraction (hydrometallurgy) and reduction of REE alloy. In practice, a combination of the pyro- and hydrometallurgical process is often used [49]. However, in addition to their low economic efficiency, these processes are also energy- and resource-intensive with too low economic efficiency and high processing costs. However, novel and more efficient recycling approaches have recently been developed. In the REEgain project [51], researchers are developing a method based on bioaccumulation with algae on which the REE of the raw material is attached.

As part of the EU project RECUMETAL, a pilot plant for the recovery of indium, yttrium, and other valuable metals from discarded flat screens was designed and developed [52]. A team of researchers from the University of Pennsylvania developed a tripodal nitroxide ligand to separate neodymium and dysprosium from e-waste. This method differs from the usual energy-intensive industrial solvent extraction in that it can be performed at room temperature and with standard laboratory equipment [53]. A fluorescence-based sensor developed by researchers at Penn State University that detects the lanthanide-binding protein Lanmodulin (LanM) in bacteria enables the detection of tiny amounts of REE in samples [54]. This technology is useful for cost-effectively quantifying REE in environmental and industrial samples, because today‘s gold standard for detecting REE is ICP mass spectrometry. Due to the use of special, very sensitive instruments, this process is very cost-intensive [55] and therefore uneconomical for most manufacturers of electronic components. Furthermore, the research showed that the rare earth metals with atomic numbers 57 to 64 enter the cytosol of the cells of the bacterium. The reasons for this high intake selectivity are not yet known. In further research, the extraction of REE by LanM was applied to pre-combustion coal and electronic waste. After only a single purely aqueous step, a quantitative and selective recovery of the REEs from all initially existing non-REEs (Li, Na, Mg, Ca, Sr, Al, Si, Mn, Fe, Co, Ni, Cu, Zn and U) was achieved, which demonstrates the universal selectivity of LanM for REEs against non-REEs and its potential application even for industrial substandard sources that are currently underutilized, demonstrated [56]. The EU project SCALE developed a process to extract scandium from red sludge from bauxite residues of the aluminium industry using various crystallisation techniques. For this purpose, scandium ions are leached with reagents to form a liquid solution, which is then upgraded by an ion exchange technology newly developed in the project. No waste is generated. Iron oxide concentration as a solid by-product can be used for pig raw iron production.. Scandium is extracted from acidic waste from the titanium (IV) oxide pigment industry using a novel nanofiltration technology. Based on the recovery processes, the SCALE project also developed technologies to produce metallic scandium in an environmentally friendly manner [57]. The r4-Lan-Tex project developed a novel technology for the selective separation of the lanthanum ions via fiber-fixed bonds to polyelectrolytes from wastewater from FCC catalyst production [58]. The EU project SepSELSA became a reprocessing and recovery process of REE based on solid chlorination. With the use of diffusion dialysis [59], about 25 tons of production waste could be processed and REE returned to the production cycle as part of the project. The innovation of this process is the isolation of the metals in pure form without the countless separation stages of conventional processing [45]. The BioKollekt team [60] is researching a separation process for the economical recycling of complex material mixtures with a special focus on the finest particles with the help of specially developed peptides that specifically bind particles in solutions. For this purpose, these are firmly anchored to a carrier material with certain chemical and physical properties, so that the target materials are selectively isolated from the complex material mixture. The matching peptides are produced using the phage surface display method [61] developed by chemistry Nobel Laureate George P. Smith. With classic particle separation methods, the chemical collectors stick to the target particles and cannot be recycled. All other collectors, including the residual materials, end up on the stockpiles. Biocollectors, on the other

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hand, are recyclable and can be used again and again in separation processes. The target substances are dissolved by the biocollector, for example, by changing the pH value in the solution. The magnetic carriers, like the peptides, are fully biodegradable [60].

Substitution

Another way to reduce the resource consumption of REE is to use alternative materials and processes. However, the success of material substitution in relation to REE to date is very limited, as many of the main applications of ICT are not currently substitutable. These include above all optical cables, miniaturized permanent magnets, ferrites and components made of laser devices, magneto-optical storage materials, monitors and displays, pn LEDs, compact disks and cooling devices based on the magnetocaloric principle [23]. A study by Yale University's Center for Industrial Ecology found that for 62 different metals, the potential substitutes for their main applications are either inadequate or currently non-existent. In addition, for not one of the 62 metals examined, exemplary substitutes are available for all important applications [62]. Since the REE uses their specific physical properties, the substitution of one REE by another REE is usually required. For example, researchers at Iowa State University's U.S. Department of Energy have developed a method for replacing dysprosium with the commonly occurring cerium in permanent magnets [63]. However, research approaches in the field of magnets show that, for example, with iron, substituted in lithium nitride (Li2 ($\mathrm{Li}_1 - \mathrm{Fe}_x$)N), behaves like a rare earth metal in relation to its magnetic anisotropy [64]. However, since REE are degraded together, the environmentally friendly effect is small. On the other hand, technological substitution, in which manufacturing processes are improved, offers more potential. The Fraunhofer Institute developed the so-called Net-Shape method to produce high-performance permanent magnets, in which post-processing can be dispensed with and thus the consumption of dysprosium and neodymium is reduced by 15% [65]. Siemens developed a process for the production of REE-free permanent magnets based on an iron-cobalt compound with magnetic nanostructures [66]. Other approaches include the development of new rotor structures with increased demagnetization resistance and higher magnetic cooling performance while reducing the dysprosium and terbium content in NdFeB magnets [67]. In the field of hard disks, a functional substitution was achieved by the development of SSD, in which not the magnetic effect, but the atomic spin is used for data storage. Also, the use of OLEDs instead of energy-saving lamps replaces part of the REE with organic light-emitting diodes. The binding layer does not require ANY REE, only Europium is still used in the emitting layer. However, from today's perspective, no disruption from LEDs to OLEDs is to be expected, as they are smaller than conventional light-emitting diodes due to their size and burn time. The main applications for OLEDs are currently small area displays such as smartphones.

Use of ICT in the Consumer Sector

Information and communication technologies are now an indispensable part of society and the economy. In addition to broadband use, smart devices are also becoming increasingly popular. The most common devices are smartphones with a share of 72.5% of Germans [68] followed by headphones (71%) [69], TVs (44%) [70], game consoles (39.7%) [69], radios (35.8%) [71], wearables (33%), [69] smart speakers and e-book readers with 26% each [69], laptops (23.5%) [72], desktop desktop PCs (22.3%), vacuum cleaner, lawn mower or window cleaning robots (18%) [69], augmented reality devices (14%) [69] and tablets with 9.9% [69]. With several households of 41.5 million with a total of 83.2 million household members almost every second German citizen will own [72] at least one TV set in 2020. This results in a total number of ICT devices of approx. 364.8 million in Germany. Smart home applications for energy management, building security, home automation and health were not considered (Figure 6).

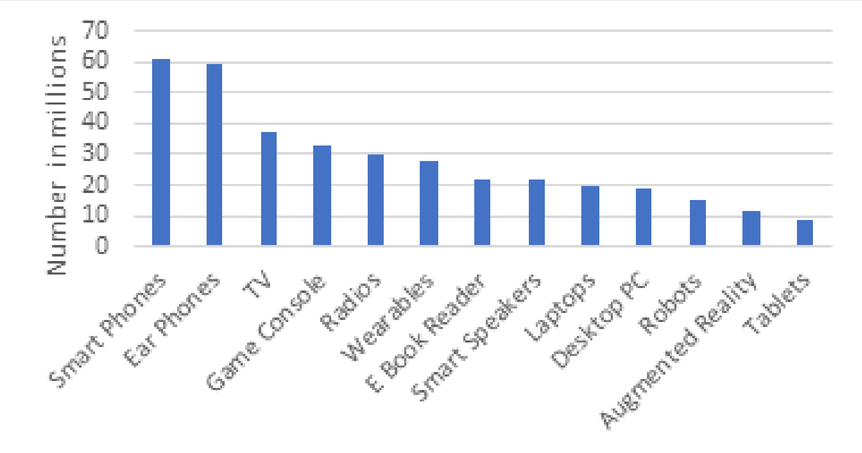

Figure 6: Number of ICT devices in Germany in 2020.

Model Calculation of ICT Devices Worldwide

In the following, these data are extrapolated to the countries with a very high Human Development Index (HDI). The HDI is calculated from life expectancy, school education in combination with the expected total education and gross national income per inhabitant in USD [73]. This results in values between 0 and 1 for the following classification (Table 5 & Figure 7):

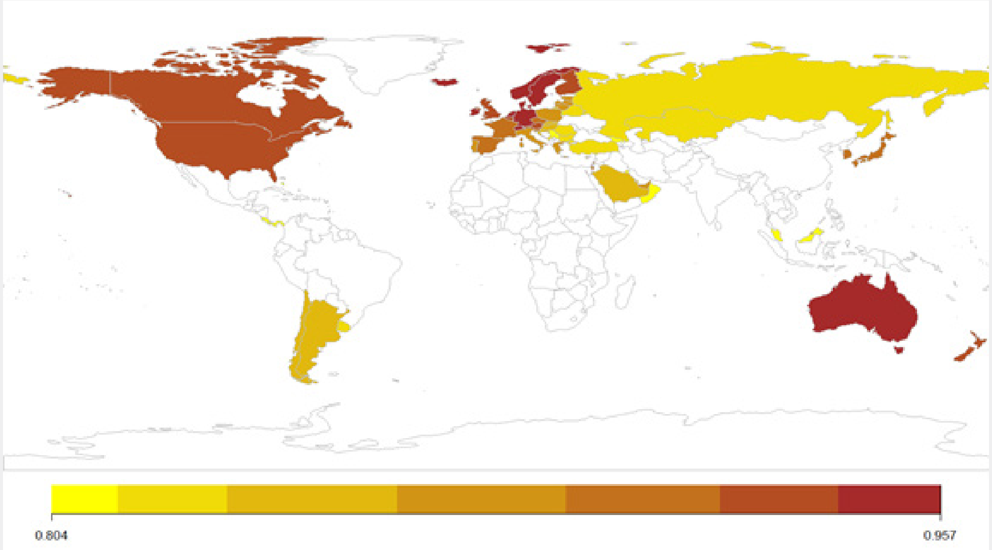

Figure 7: Human Development Index (≥ 0.8).

Table 5: Development categories [73].

HDI-Range	Category
≥ 0,8	Countries with very high levels of development
≥ 0,7	Countries with high human development
≥ 0,55	Countries with medium human development
< 0.549	Countries with low human development

A total of 66 countries were able to achieve an HDI ≥ 0.8 [73]. When calculating the extrapolation, it is assumed that the ICT equipment of citizens in the individual countries is fundamentally similar. These countries have a total population of 1.57 billion people [74]. This results in an assumed number of ICT devices of 7 billion (Figure 8).

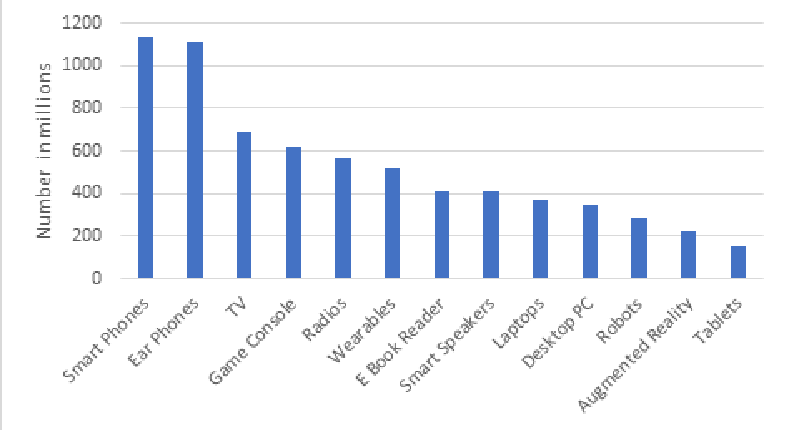

Figure 8: Extrapolated number of ICT devices in the 66 countries with HDI value ≥ 0.8.

Considering the short service life of ICT devices between about 2.5 years for smartphones and 5 years for other digital devices, the amount of electronic waste is immense. After 10 years this amounts to approximately 68 billion ICT devices (Figure 9).

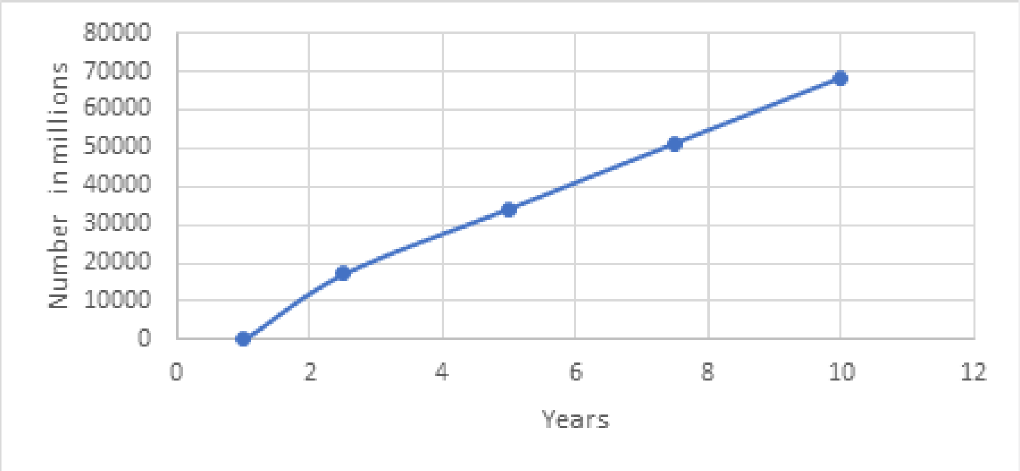

Figure 9: Electronic waste of digital devices.

Assuming a recycling rate of 5% within the EU and 1.5% in other countries [75], the total amount of e-waste is 67 billion unrecycled e-devices (Figure 10).

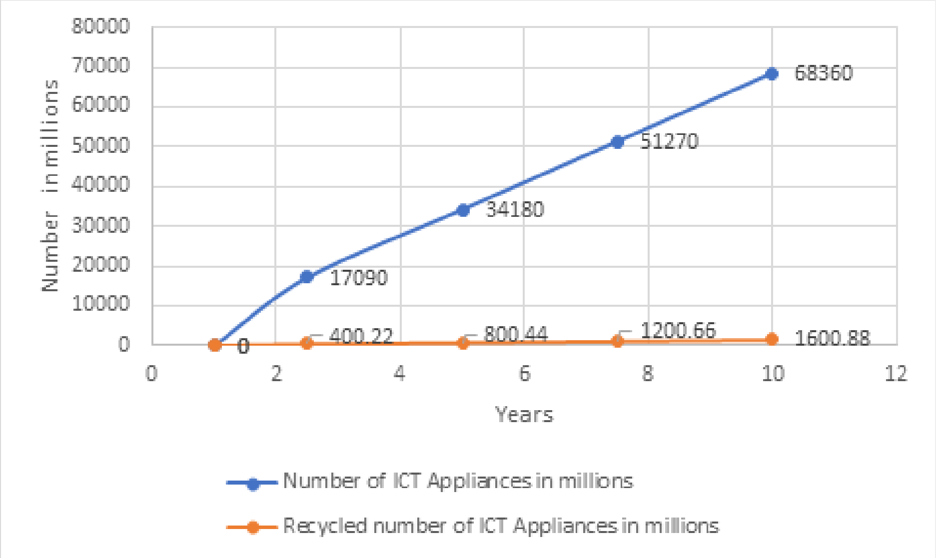

Figure 10: Recycling rate of electronic devices.

Discussion

There is no question that digitization has a decisive influence on sustainability in some areas, but in its entirety leads to ecological problems in other areas. Ecological rebound effects also occur in relation to consumer behavior in online retail. The main drivers for this are personalized advertising and constant availability of products, even if logistics and delivery conditions are more predictable and thus more optimizable using technology. On the other hand, digitization enables simpler and more targeted reuse of products, for example through sharing models, second-hand platforms, and sharing platforms. More and more manufacturing companies are using intelligent software applications to optimize their material and energy flows. Profitable waste recycling in the context of circular economy can be technologically realized in the form of virtual marketplaces for the reuse of waste by other companies across industries and regions. Intelligent circular economy with automized process optimization enables the careful

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use of resources over the entire life cycle. However, these methods only make sense if the use of resource efficiency is also reflected in consumer behavior, and this results in a longer use of end devices. This, in turn, requires a business model oriented towards long-term use by the companies. A combination of the production of high-quality goods with user-friendly services (maintenance, repair) would be conceivable. Furthermore, more investment should be made in the commercialization of mining and recycling processes of rare earth metals. The development of innovative processes for the extraction and recycling of REE during mining, physical processing, refining, pyro- and hydrometallurgical processes require more comprehensive political support. Novel processes offer the potential for commercialization and create a basis for reducing dependence on China's existing market leadership. The material substitution of the REE is more difficult. Rare earth metals are extracted and mined together. About this phase of its life cycle, there are no differences in the environmental impact of substitution by another REE. Elements outside the family of REE offer only inadequate alternatives [62]. More promising at the present time are technological substitutions such as the development of innovative manufacturing processes. High savings potential can also be found in the recovery of rare earths from waste products. For comprehensive recycling, however, there are hardly any processes that are economical for companies in terms of effort and cost recovery. In particular, the low raw material prices make recycling processes unattractive for companies. Recycling possibilities consist in the separation of rare earths from waste magnets and fluorescent tubes by solid chlorination [45]. REE have only been used in technical applications for about 20 years. The effects of REE on living organisms have therefore not yet been fully investigated. The current state of research assumes that there is no toxicity to humans [23]. However, REE with their compounds have only been released into the environment for some time through recycling processes. Long-term studies are not yet available. If a society and its economic system depend on growth, there will also be rebound effects. In combination with an efficient circular economy and conscious consumer behavior, the effects of rebound effects can potentially be reduced. Innovative technologies such as AI, if targeted and used, can make meaningful contributions to greater sustainability. More digitization does not necessarily lead to more efficiency [76]. As a result, it can be said that the existing resources of rare earth metals must be used optimally and sparingly. Investments in research to develop ecological and economic recycling and substitution processes are needed, as are environmentally friendly processes for the degradation and separation of REE.

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