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ANALYSIS OF FACTORS WITH CONSIDERABLE ACTION ON RECYCLING WEEE FOCUSED ON METALS RECOVERY

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ABSTRACT

From an economic point of view, the driving force of rapid technological development of WEEE recycling solutions is the recovery of valuable metals, until not long ago just on copper and gold. Nowadays many other metals have become the target of WEEE recycling. From this point of view, the importance of WEEE recycling results from the analysis of factors with considerable action on this process. This paper highlights the necessity of WEEE recycling by analyzing the following key issues regarding the recovery of valuable metals. The study was mainly focused on the following aspects: electronic waste is a significant source of base and precious metals, and also of scarce metals; many of the metals which are essential in the manufacture of EEE; the availability of metals necessary in the production of EEE constantly decreases; supply shortages for many elements obtained from natural resources; worldwide ore reserves are limited and unequally distributed; in the world, the production of essential metals in the construction of a mobile phone is dominated by a few companies; the extraction of many metals in a ore deposit is co-dependent on other factors.

KEYWORDS: WEEE, recycling, valuable metals, recovery, economic factors

1. Introduction

The rapid progress of electronics and telecommunications industry over the past few years has focused on meeting the increasingly demanding requirements of consumers across the world for performing and multifunctional devices. The electronic industry has been steadily developing and growing both in market size, as well as in models and suppliers of devices. The smartphone can be given as example (Figure 1) [1].

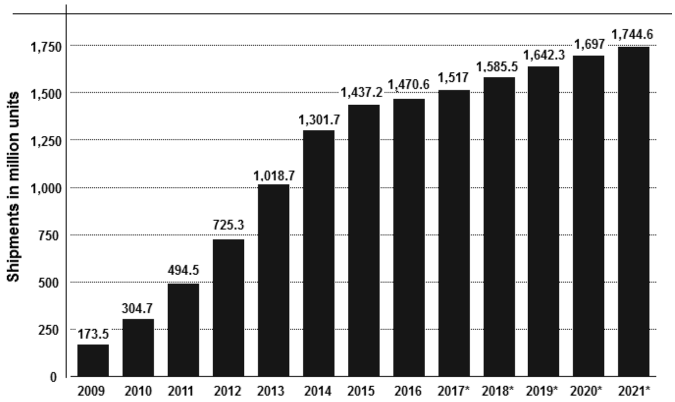

Fig. 1. *Global smartphone shipments, forecasted from 2010 to 2021 (in million units). Observation: The statistic depicts the forecast total unit shipments of smartphones worldwide from 2009 to 2016 with data forecasted for 2017 to 2021* [1]

This evolution has led to a very high growth in both the number of metals needed to produce increasingly complex devices and the number of devices that meet market requirements (Figure 2 and Figure 3).

Technological innovation and intensive marketing forced the acceleration of the EEE replacement process. These aspects, correlated with the quantity of EEE on the market and the evolution of equipment life, have led to a huge increase in the amount of generated waste (Table 1).

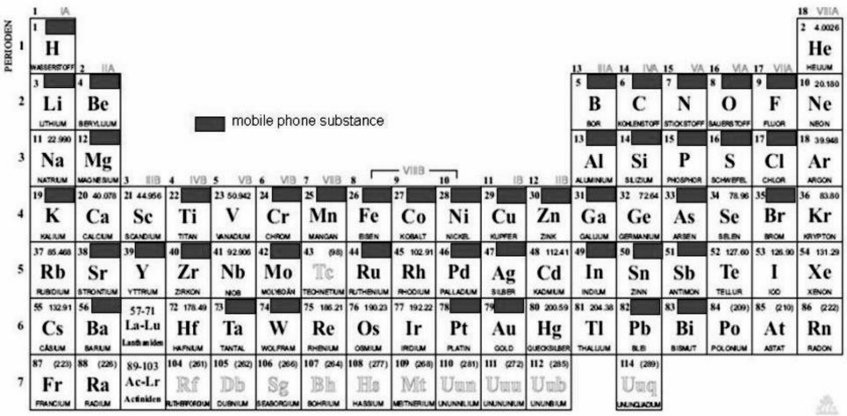

***Fig. 2.** Elements used at mobile phone fabrication* [2]

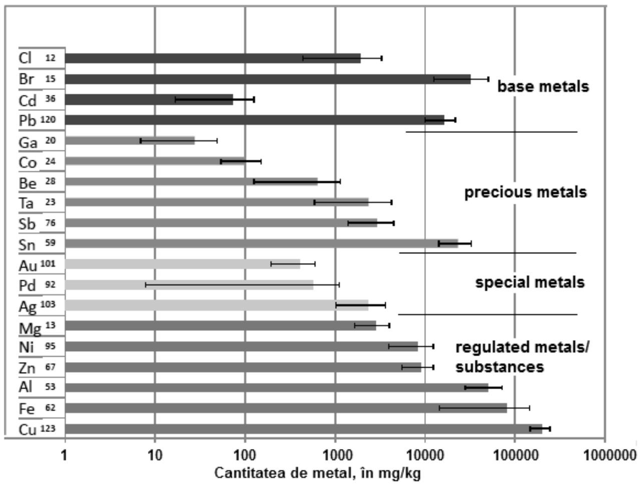

***Fig. 3.** Evaluation of datasets on the content of printed circuit boards 1995-2013* [3]

***Table 1.** Total quantity of generated electronic waste* [4]

Year	E-waste generated (Mt)	Population (billion)
2010	33.8	6.8
2011	35.8	6.9
2012	37.8	6.9
2013	39.8	7.0
2014	41.8	7.1
2015	43.8	7.2
2016	45.7	7.3
2017	47.8	7.4
2018	49.8	7.4

The electronic waste becomes a valuable resource of metals, especially for those that are precious and scarce [5-7].

WEEE are an excellent resource for metals because they contain many rare and very valuable elements from the periodic table. As a result, these are considered as "urban mining deposits". The literature notes that WEEE have valuable metals in higher concentration than ores, even though over the years, manufacturers have gradually reduced the content of these metals to reduce the cost of the equipment. So, the gold content in WEEE is greater than 4 to 80 times and also, the copper content is 30 to 40 times higher in relation to their concentration in natural resources. As example the gold: content in ores is ~5 g/t Au; content in WEEE is 200-250g/t Au in PC circuit boards, 300-350 g/t Au in cell phones and respectively 2000 g/t PGM in automotive catalysts [2].

2. Highlight and discussion of factors important for WEEE recycling

The recycling of end-of-life devices must be analyzed from an economic and environmental perspective. The disposal of WEEE in landfills essentially impedes to reintroduce the metals from their composition in the production cycle of new products. Lost metals must be replaced by those extracted from ores, and thus natural resources in the earth's crust would be quickly exhausted. Moreover, the operations specific to primary mining and extractive metallurgy are accompanied by significant consumption of material and energy resources and by damage to the environment [7]. Consequently, at end-of-life the EEEs need to be collected and introduced into environmentally sound recycling streams where technologies with maximal recovery efficiency are applied.

The importance of recycling WEEE for metal recovery is highlighted by the analysis of factors with significant action on the process. The key factors of WEEE recycling related to metal recovery are the following:

- importance of metals for electronic industry;
- availability and security of the metal supply;
- existence and availability of substitutes for the considered metal;
- consequences of deficit for certain metals;
- strategic importance of the application in which metal is used;
- impact of recycling on the environment;
- benefits of DEEE recycling.

For electronic industry, the increasing demand for metals can be assessed as high or moderate. The supply risks must be evaluated in relation to the regional concentration of mining operations. Moreover, the deficit must be assessed by comparing data on resource, production and demand. The restrictions for recycling are assessed by the nature of requests. The metals are necessary in many devices but in low quantity. As a result, the metals are dissipated in more types of devices. There are physical or chemical limitations on recycling. Many countries do not have adequate technologies and/or recycling infrastructure because they do not have financial incentives for these operations.

Electronic wastes, in particular printed circuit boards, are significant source of base and precious metals, and also of scarce metals. In agreement, United Nations Environment Program - UNEP, U.S. Congress, U.S. Department of Defense, Resource Efficiency Knowledge Transfer Network of the United Kingdom, German Environmental Agency have named many of the important elements for EEE manufacture as *strategic*, *rare*, *special or critical metals* [8]. This characterization is based on the economic, social and political importance of metals and the applications in which they are used. Furthermore, according to these criteria, metals from EEE can be arranged in a series in relation to themselves. This allows for the prioritization of metals that must be recovered from electronic waste. In agreement with UNEP’s strategy regarding resource efficiency / sustainable consumption and production, the list of critical metals in EEE includes: indium (In), germanium (Ge), tantalum (Ta), magnesium (Mg), niobium (Nb) and tungsten; PGM or platinum group metals, such as ruthenium (Ru), platinum (Pt) and palladium (Pd)], tellurium (Te), cobalt (Co), lithium (Li), gallium (Ga) and RE (rare earths) [9]. In the case of mobile phones, antimony, beryllium, palladium, indium and platinum especially must be considered [6].

In high-performance electronic equipments, the metals named critical perform essential functions. For these metals, there are few replacement materials or these have not been found yet to meet the requirements. For example, palladium or platinum have no substitution alternatives and their huge dispersion in various products makes recovery much expensive and difficult. The possibility of supplying these metals can sometimes be limited. This leads to significantly higher prices and also to difficulties to ensure the amount necessary for current production, with negative economic and social consequences [10]. By common agreement, the countries members EU, Japan and USA have considered that the supply of some of these metals would be endangered in the very near future [8]. A study made by the Öko-Institut for UNEP about the situation of critical metals used in the EEE industry pointed out that tellurium, indium and gallium are the most problematic elements in the short term (the prospect for the next five years); on a medium-term perspective, rare earth elements, lithium, tantalum, palladium, platinum and ruthenium are crucial; on long term, by 2050, germanium and cobalt will come to be critical (Figure 4) [8, 9].

The majority of important reserves of ores (with sufficient concentration of the element of interest from which are produced the metals necessary for the EEE industry) have been intensively exploited and as a result their availability in nature is constantly decreasing (Table 2). As example, in Figure 5 is shown the situation of gold from primary mining. The depletion of mineral resources requires the extraction of metals from poor ores. In this situation, even with performing technologies, the energy consumption is higher and the pollutants are emitted in larger quantities.

The quantity of metals that can be ensured from natural resources is limited. Electronics industry has a significant impact on metal demand. The total amount of metals with important role in the construction of new equipment used in emerging technologies has a relatively large proportion (Table 3).

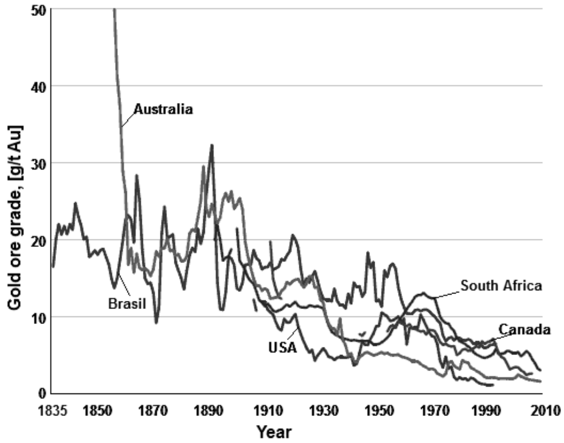

Fig. 5. *Evolution of gold ores in the period 1830 - 2010* [8]

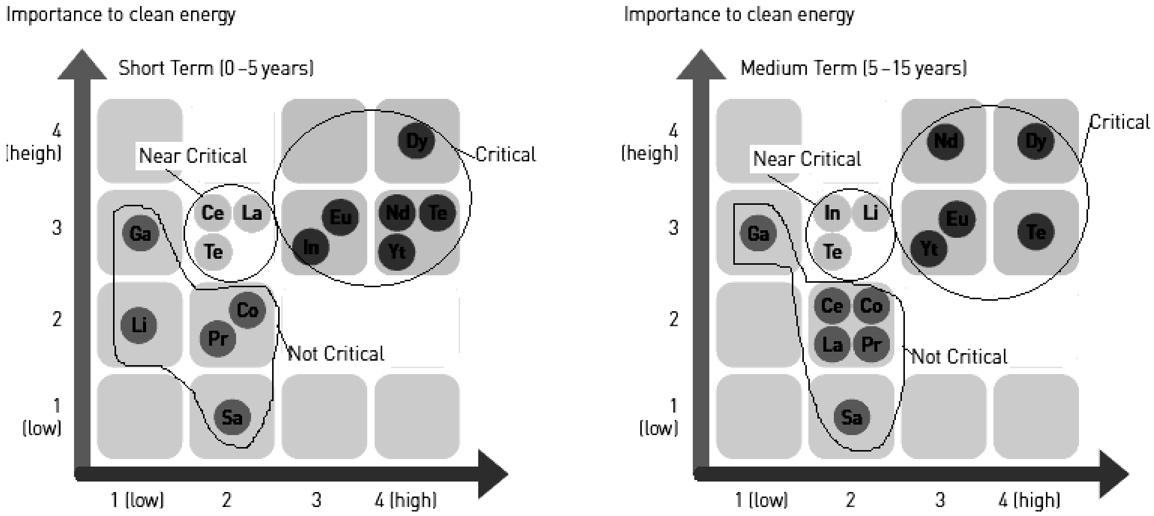

Fig. 4. *Critical levels of some elements, according to U.S. Department of Energy for 2010* [8]

Table 2. *Availability of rare and expensive metals from natural resources (if the consumption and the production of critical metals is maintained at current rate)* [11]

Number of years left	Elements
100-1000	Cr, Al, P, Se, Pt, Ta, earth metals (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Yb, Lu)
50-100	Ni, Cu, Cd, Tl, U
5-50	Zn, Ge, Ga, As, Rh, Ag, In, Sn, Sb, Hf, Au

Table 3. *Global demand for metals used for manufacturing EEE and the quantity produced* [12]

Element	World mine production*, [tons/year]	Demand for EEE*, [tons/year]	Demand related to mine production, [%]
Ag	20,000	6,000	30
Au	2,500	250	10
Pd	215	32	15
Pt	220	13	6
Ru	30	6	20
Cu	16,000,000	4,500,000	28
Sn	275,000	90,000	33
Sb	130,000	65,000	50
Co	58,000	11,000	19
Bi	5,600	900	16
Se	1,400	240	17
In	480	380	79
*rounded quantities. Source: USGS Mineral commodity summaries 2007			

The depletion of raw material reserves coupled with the increased demand of technological metals makes predictable the supply deficit for many elements (Table 4) [12]. For example, by estimation, the abundance of indium in the Earth's crust is evaluated only at 0.24 ppm. For this vital element for LCD screens, solar cells and semiconductors, the natural resources can be estimated to disappear in about 13 years [8].

Over the years, the worsening of the deficit in accordance with the accelerated growth of metals demand has reflected indirectly on their price (Figure 6).

On the other hand, the availability of critical metals is influenced by how ores deposits are geographically distributed. In the world, the regions where ore resources are concentrated are non-uniformly distributed (Figure 7). For four metals, important in electronic industry, the situation is as follows: 89% of antimony production is located in China; 89% of beryllium production is located in the United States; 44% of palladium production is established in Russia; 75% of platinum is produced in South Africa along with a significant supply of palladium [13].

Table 4. *Estimates of the demand for various scarce and valuable technological metals and their compounds used in emerging (sustainable) technologies* [12]

Element	**Production[1)], [t]**	**ETRD*, [t]**		**Indicator****	
		2006	**2030**	**2006**	**2030**
Gallium	152[5)]	28	603	0.18[1)]	3.97[1)]
Indium	581	234	1,911	0.40[1)]	3.29[1)]
Germanium	100	28	220	0.28[1)]	2.20[1)]
Neodymium[6)]	16,800	4,000	27,900	0.23[1)]	1.66[1)]
Platinum[7)]	255	Very little	345	0	1.35
Tantalum	1,384	551	1,410	0.40[1)]	1.02[1)]
Silver	19,051	5,342	15,823	0.28[1)]	0.83[1)]
Cobalt	62,279	12,820	26,860	0.21[1)]	0.43[1)]
Palladium[7)]	267	23	77	0.09[1)]	0.29[1)]
Titanium	7,211,000[3)]	15,397	58,148	0.08	0.29
Copper	15,093.00	1,410,000	3,696,070	0.09	0.24
Ruthenium	29[4)]	0	1	0	0.03
Niobium	44,531	288	1,410	0.01	0.03
Antimony	172,223	28	71	<0.01	<0.01
Chromium	19,825,713[2)]	11,250	41,900	<0.01	<0.01

*ETRD = Emerging Technologies Raw Material Demand;
**Example of calculation for Ga: Indicator 2006 = 28/152 = 0.18; Indicator 2030 = 603/152 = 3.97.
[1)]Data updated by the BGR based on new information [2)]chromite; [3)]concentrate from ore; [4)]consumption; [5)]estimates of global production in China and Russia; [6)]rare earth elements; [7)]platinum group metals

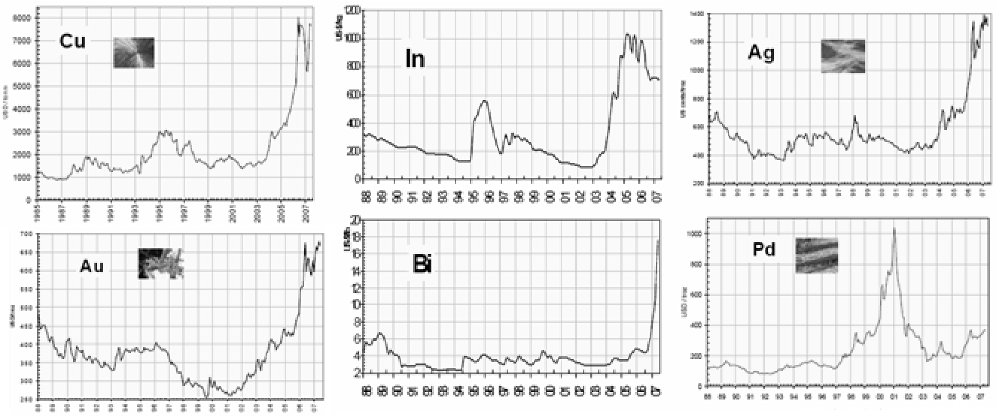

Fig. 6. *Variation of price for some metals over the years* [12]

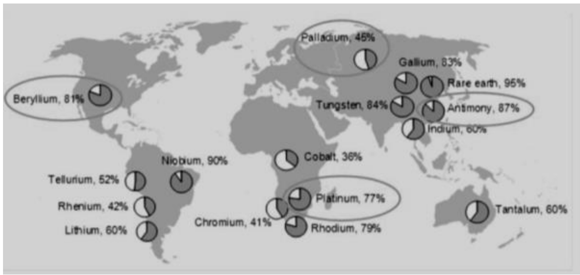

Fig. 7. *Regions with dominant production of primary metals used in mobile phones manufacturing* [14]

The mineral reserves are dynamic, being strongly influenced by technical, economic and political realities. The global resources for some metals and the countries with dominant reserves are given in Table 5.

In addition, with the concentration of natural reserves in certain geographic regions, the availability and security of some metal supplies are conditioned also by an essential aspect. In the world the production of metal is dominated by a few companies (Table 6). Consequently, both supply and price may, in certain circumstances, depend on their behavior.

Table 5. *World reserves of antimony, beryllium, palladium and platinum* [15]

Critical metal	Global reserves in the world, [ktons]	Country with dominant reserves	
		Number 1	Number 2
Antimony	2,100	China (87%)	Bolivia (3%)
Beryllium	80	USA (81%)	China (11%)
Palladium*	100	Russia (45%)	South Africa (39%)
Platinum*	-	South Africa (77%)	Russia (11%)

*World reserves of Pt and Pd combined with rare earth metals

Table 6. *Companies controlling the production of some metals important for electronic industry* [15]

Metals in mobile phones	Share of world production	Country	Mining company, (mine)
Critical metals			
Antimony	82-87%	China	Hsikwangshan Twinkling Star (Hsikwangshan)
Beryllium	81-90%	USA	Brush Wellman (Delta)
Palladium	45-65%	Russia	Norilsk (Norilsk)
Platinum	77-80%	South Africa	Amplants-Implats-Lonnin (Bushveld)
Other metals			
Lithium	60-80%	Chile	Sociedad Quimica y Minera de Chile SA-Soquimich (Salar d'Atacama)
Niobium	90%	Brazil	Companhia Brasileira de Metallurgia e mineraçao CBMM (Araxa)
Rare earth metals	85-95%	China	Baotou Iron and Steel Company (Bayan Obo)
Tantalum	60-70%	Australia	Sons of Gwalia (Woogina)
Tungsten	75-84%	China	Jianxi Tungsten (Minnetals)

Many of the metals, indispensable to the production of EEE, are usually required in very small quantities in an electronic device. But, overall, the huge number of EEE products requires high quantity of these metals. Approximately 80% (or even more) of the cumulative primary production of several technological metals (Ru, Rh, Pd, Os, Ir, Pt, Ga, In or rare earth elements) has been requested in a relatively recent period, being extracted intensively after 1980 [2, 16]. This must be correlated with a period of great progress in electronic industry (Figure 8).

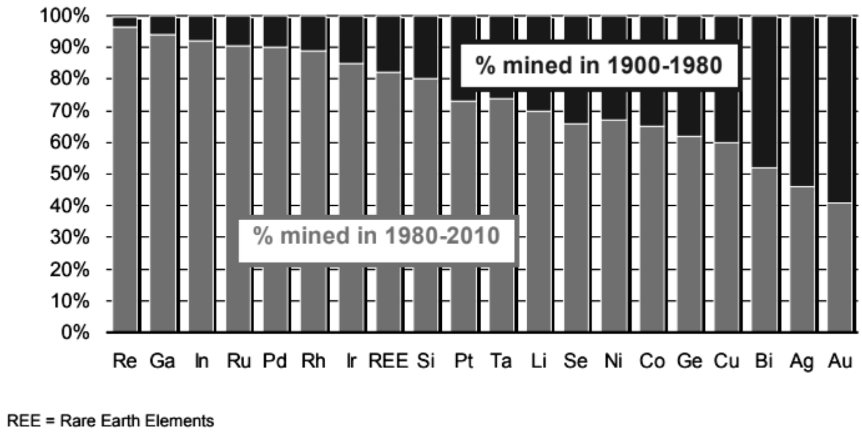

Fig. 8. *Mine production of technological metals: comparison between periods 1900-1980 and 1980-2010* [17]

From the metallurgical point of view, the extraction of many metals in a deposit is often co-dependent on others that are economically viable for exploitation [14]. For a polymetallic ore, the interdependence between minor metals with base metals that coexist in the same ore is explained by the tool called "Metal Wheel". This is a graph which illustrates the complex interactions between metals and when it is possible to recover some critical metals from an economic and thermodynamic point of view from other ores [15]. For example, the production of zinc and lead is associated with obtaining gold and silver. Moreover, other metals important for electronics industry, like indium, cobalt or germanium, result from secondary streams of the metallurgical process for obtaining base metals. Antimony can be obtained directly from its minerals, but also as a secondary metal at the extraction of copper, lead or silver. Platinum and palladium are rarely extracted from native ores that predominantly contain platinum group elements. These are generally together in some ores and are often associated in ores with copper, silver or nickel and obtained as secondary metals in nonferrous metals industry.

These co-dependencies make the production of minor metals sensitive to the factors that have influence on the base metals. The non-intended decisions referred to the production of common metals may have consequences on minor metals. This situation is specific to critical metals used in electronic industry. For example, the EU legislation restricts the use of hazardous substances in electrical and electronic equipment (RoHS Directive 2002/95/EC). For compliance with legislation, the lead alloys have been substituted by safer alternatives. The diminishing of lead production by mining has negative effects on the supply of other metals necessary in electronics industry [15].

3. Conclusion

The electronic devices contain a complex of metals: precious metals (Ag, Au, Pd), base metals and special metals (Cu, Ni, Co, Sn, Al, Fe, Ti, Ta, Bi), metals of concern (Be, Pb, Cd, As, Sb, Cr, In etc.). Recycling is a significant source for the supply of many of the metals and provides numerous benefits such as: resource conservation, energy savings, reduced volumes of waste, reduced emissions associated with primary materials production. In the past years, the WEEE recycling industry had a simple objective: recovery of copper and gold. Today the sustainable recycling is focused on recovering rare or special metals for electronic industry. A comprehensive analysis of the metals from EEE devices made possible the identification of factors with considerable action on recycling WEEE focused on valuable metals recovering. Using data collected from literature, were identified the opportunities and barriers regarding the importance of metals from electronic products. The result of the analyses highlights the metals which should be recovered from WEEE by recycling based on the following indicators: availability and security of the metal resources; existence of substitutes for the considered metal; consequences of deficit for certain metals; geographical distribution of resources and of important companies for their production.

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