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ANALYSIS TOOLS FOR SUSTAINABLE MANAGEMENT OF CELL PHONE WASTE FOR METALS RECOVERY

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ABSTRACT

A modern cell phone contains over 60 metals, combined physically or chemically and in some cases covered with various types of plastics, ceramics, etc. For recycling, each metal from the device needs to be analyzed individually. Some of these metals (copper, gold, silver, platinum, tin, yttrium, etc.) are valuable and their recovery is effective from the point of view of the economic benefits. Others (lead, cadmium, arsenic, mercury, etc.) are toxic and environmentally important. Certain metals are valuable but also toxic at the same time. In this study were identified and discussed a series of analysis tools specific to sustainable management of WEEE. Those applicable to recycling of mobile phones waste, operation which has as main objective the recovery of valuable metals, are the following: quantitative evaluation; potential income from the sale of recovered metals; eco-efficiency of recycling; recovery yield of metal; impact on the environment.

KEYWORDS: cell phone waste, recycling, metals, recovering

1. Introduction

Metals account for approximately 30% of the mass of a mobile phone. Most of them are in printed circuit board, the most important component of the mobile phone. A modern cell phone contains over 60 metals, combined physically or chemically and in some cases covered with various types of plastics, ceramics, etc. (Figure 1).

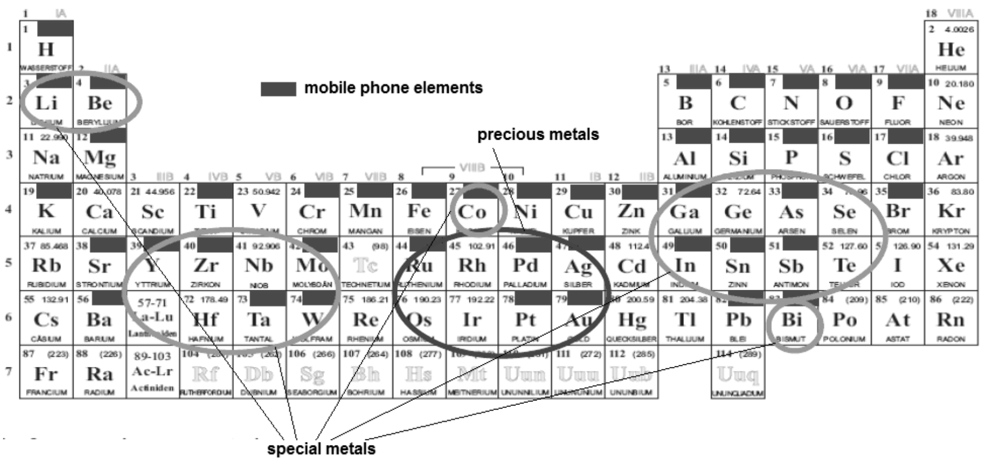


***Fig. 1.** Elements in mobile phone (source Nokia)* [1]

In general, the battery and accessories of a typical mobile phone contain: 43% plastic, 14% glass, 13% copper, 7% iron, 5% aluminum, 3% magnesium, 0.35% silver. Nickel, tin and lead are together about 1%, gold is less than 0.04% (276-446 ppm [2]), 0.1% antimony, < 0.02% palladium, < 0.01% beryllium and < 0.01% platinum (Figure 2).

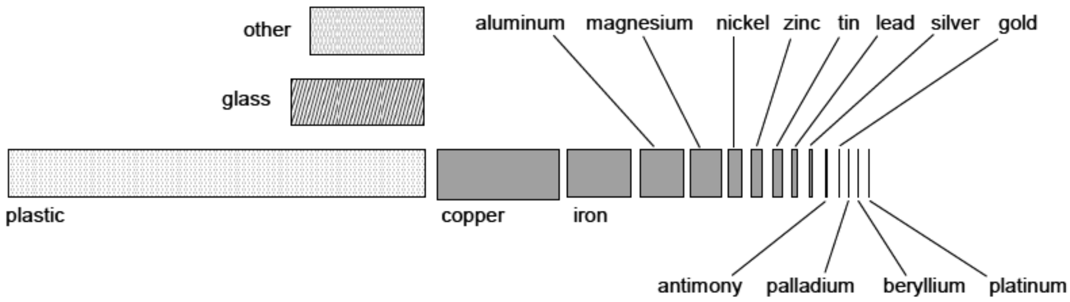


Fig. 2. *Share of materials in the mobile phone (by weight)* [3]

Recycling end-of-life products is a key to achieving sustainable use of metals based on the number of products available for recycling [4]. Each metal from the electronic device needs to be analyzed individually to establish the opportunity and recycling potential. Some of these metals (copper, gold, silver, platinum, tin, yttrium, etc.) are valuable and their recovery is effective from the point of view of the economic benefits. Others (lead, cadmium, arsenic, mercury etc.) are toxic and environmentally important. Certain metals are valuable but also toxic at the same time.

2. Analysis of the sustainable recovery of metals from cell phones waste

By definition, sustainable materials management is an integrated approach toward managing material life cycles to achieve both economic efficiency and environmental viability [5]. The correct selection of metals for which recovery efforts and best recycling practices are justified can be done through management methodologies that are specific to sustainable management: substance flow analysis, product life cycle assessment, eco-efficiency, social integration [6].

The analysis of recycling opportunity focused on metals recovery must consider more indicators. Some are economic and others are related to environmental protection. Particularly for mobile phones waste, it is considered necessary to discuss about: quantitative evaluation; potential revenue from the sale of recovered metals; eco-efficiency of recycling; metal recovery efficiency; impact on the environment.

- Quantitative assessment of metals

This is a simplistic evaluation indicator of cell phone waste recycling process. This can lead to incorrect decisions regarding the metals present in small quantities. Most of them have significant economic and environmental potential [7].

Aluminum, iron, copper, cobalt, zinc, nickel, tin, chromium and lead are the main metals found in the mobile phone. The physical parameter, namely quantity, recommends the recovery of copper especially from the wiring and printed circuit board of the mobile phone.

- Potential revenue from the sale of recovered metals

Even if the quantitative physical parameter recommends the copper recovery from mobile phone waste, the value of precious metals (gold, silver and platinum metals) is the primary goal for recycling WEEE. The most famous precious metals are gold and silver. Also, in this group are included platinum metals: ruthenium, rhodium, palladium, osmium, iridium and platinum. In various contexts, plutonium and uranium are also considered precious metals.

The metal price represents a strong support for creating profitable recycling streams of WEEE (Table 1).

Table 1. *Potential revenues from the sale of metals recovered from mobile phones waste* [8]

Metal	Metal recycled, [g/device]		Price of metal, [USD/g]		Value recovered, [USD/device]	
	with low yield	with high yield	2003	2006	with high yield at the price of metal from 2003	with low yield at the price of metal from 2006
Copper	8.84	14.85	0.0018	0.068	0.03	0.06
Silver	0.30	0.31	0.16	0.36	0.05	0.11
Gold	0.028	0.037	12.87	21.53	0.47	0.61
Palladium	0.012	0.019	6.53	10.61	0.13	0.13
Total	9.2	15.2			0.68	0.90

The benefit of metals recovery from cell phone is evaluated by intrinsic value (Table 2). This is given by multiplying the unit price by the metal concentration in the device [9].

It is noticeable that precious metals account for more than 80% of the total intrinsic value of metals recovered from a printed circuit board extracted from a piece of electronic waste although it represents only 1% (by weight) of the device mass.

Table 2. *Estimation of metals value from EEE used (for 2011)* [10]

Metal	World mine production, [t/a]	EEE demand, [t/a]	EEE demand/mine production, [%]	Metal price, [USD/kg]	Value of metals from EEE used, [billion USD]
Ag	22,200	7,554	34	649	4.90
Au	2,500	327	13	39,443	12.90
Pd	229	44	19	16,948	0.74
Pt	188	7	4	51,811	0.37
Ru	29	21	72	5,069	0.11
Cu	16,200,000	7,174,000	44	8	54.08
Sn	261,000	129,708	50	20	2.65
Sb	135,000	67,500	50	9	0.61
Co	88,000	16,470	19	45	0.75
Bi	7,600	1,216	16	20	0.02
Se	2,260	185	8	82	0.02
In	574	717	125	566	0.41
				Total	77.56

The electronic waste is considered valuable material (high grade material) compared to ores in terms of content in metals (Table 3). The value of electronic waste is given by the gold content. There are three classes of e-scrap: low value with < 100 ppm Au; medium value with 100-400 ppm Au; high value with > 400 ppm Au. The gold content of mobile phone wastes typically ranges from 100 to 400 ppm (in some cases it may exceed 400 ppm). In other types of electronic waste (TV-circuit boards and monitors, computers, etc.) the gold content can decrease below 100 ppm [12, 13].

Table 3. *Average content of metals in ores, in high-grade material and low-grade material* [11]

Content		Ores	High-grade material	Low-grade material
Fe	[%]	30-55	4.5-20	23-62
Cu		0.5-1.0	7-20	3.4-21
Al		25-30	1-4	1-10
Pb		0.5-15	0.3-6	0.2-1
Sn		<1	2.9-4.9	0.72-1.4
Au	[ppm]	5-7	16-566	10-20
Ag		5-7	18-1380	115-280
Pd		3-5	3-210	4-10

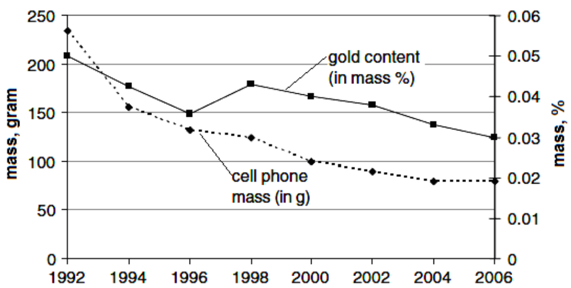


Fig. 3. *Evolution of gold content per mobile phone in relation to the average mass of the device between 1992 and 2006* [14]

Over time, as a result of the constructive evolution of mobile phones, the gold content per unit of product was reduced. For this reason, economic benefits given by proceeds from the sale of gold were decreased (Figure 3). Even so, the recycling of these pieces of equipment is still profitable.

The decreasing of the gold content was offset by the expansion of other metals recovery. In addition to gold, metallurgical refining technologies make it possible to recover palladium, silver, copper and a wide range of special metals such as In, Se, Te, Bi, Sb, etc. By recovering more metals, the gap created by gold is covered. Adding the values of silver, copper and palladium to gold value, over 95% from total revenues are obtained from cell phone recycling

(Table 4). In addition to silver, gold, copper and palladium from printed circuit boards, the cobalt recovering from Li-ion batteries is economically beneficial. The recovery of aluminum or magnesium alloys from the cases of cell phones is economically justified, too.

Table 4. *Value of recoverable metals from cell phones* [14]

Metal	Mass, [g]		Metal price in 2006, [cents/g]	Value of recoverable metals, [cents]	
	High	Low		High	Low
Ag	0.90	0.11	36.01	32.41	4.03
Al	7.20	1.52	0.27	1.94	0.41
Au	0.033	0.026	2151.71	70.15	56.12
Cr	0.72	0.20	0.82	0.59	0.16
Cu	20.68	9.30	0.68	14.09	6.33
Fe	6.62	2.70	0.10	0.66	0.27
Ni	2.74	0.70	2.43	6.64	1.70
Pb	0.80	0.28	0.17	0.14	0.05
Pd	0.09	0.00	1060.97	93.37	0.00
Sn	0.80	0.43	0.92	0.74	0.39
Zn	0.92	0.27	0.35	0.32	0.10
Total	41.57	15.56		221.03	69.56

- Eco- efficiency

This is another analytical tool characteristic of sustainable metals management. This has been launched by World Business Council for Sustainable Development in 1992. Eco-efficiency results from the combination of economic and environmental aspects and has the following objectives:

- the utilization of natural resources in the most efficient way;
- finding ways to reduce natural raw materials;
- identifying alternatives to replace the finite resources with renewable energy sources;
- reducing the negative impact on environment by using recycling solutions.

Maximizing the eco-efficiency of recycling is ensured by optimizing the environmental and economic balances.

This requires:

- maximizing metal recycling, minimizing environmental damage, taking into account the environmental footprint of the metal based on the quantities of saved natural resource, electronics waste not released in environment, CO_2 emissions;
- maximizing revenues from recycling materials, minimizing total recycling costs.

The total efficiency of recycling or the so-called recyclability of end-of-life products is determined by the weakest link of the recycling chain. For this reason, for EEE waste, the analysis should take into account the interdependencies between the stages of the recycling flow. This is the expression of the "concentration dilemma" or of the "degree of recovery" [15].

For the value generated by WEEE recycling but also for the toxicity control of process the following aspects are crucial: dismantling and pretreatment as well as the operations of final stage of waste processing, namely the metals recovery from fractions resulted from the mechanic processing (Figure 4).

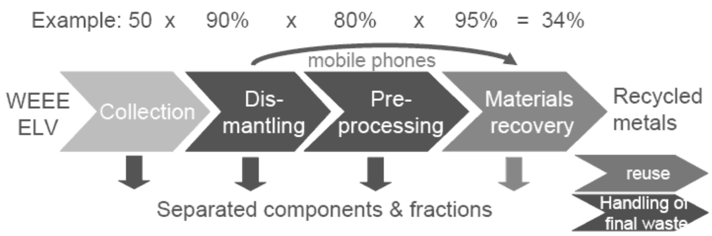


Fig. 4. *Efficiency of metal recovery rate (for Au, Cu, etc.) depending on the performance of the operations in the WEEE recycling flow* [16]

The eco-efficiency of WEEE recycling is directly related to an indicator named ″recovery efficiency of metals″. This reflects the impact of operations in the loop material recycling from the life cycle of product and represents the cumulative impact of several factors. The efficiency of the recycling process varies from metal to metal, depending on the material processed and the optimization degree of the process. Due to physical, chemical, thermodynamic and other limitations, the metal recovery rate will never reach 100%. As a complex function, the recovery efficiency of metals from WEEE depends mainly on two factors: the "collection rate" as a measure of the efficiency of the collection infrastructure; the "extraction yield of metal" as a measure of the efficiency of the metallurgical process focused on obtaining the desired quality of the metal.

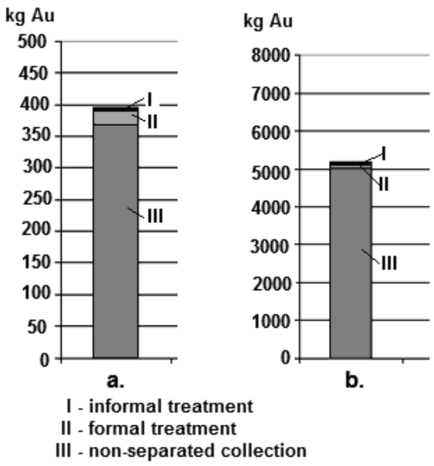


Fig. 5. *Quantity of the gold discarded and the source of the losses: Germany (a) and USA (b) in 2007* [17]

In many countries, the main step in the WEEE recycling stream in which precious metals are lost is the collection. The situation is particularly critical for mobile phone waste. Most of the metals are lost due to defective management, other losses being attributed to non-performing recycling treatments. For example, in Germany in 2007, the mobile waste collection rate was about 18% (not counting the hibernation equipment for the owners), and in the USA it was even lower, collecting only 11% of the equipment out of service, the others being eliminated most likely in the environment (Figure 5).

In practice, the metal recovery from mobile phone wastes ranges between 48 and 64% if the reporting is based on the total amount of metals contained in the equipment or between 12 and 19%, if the total mass of the equipment (including the battery) is taken into account. Unlike other categories of waste (automobiles, equipment and machinery from industrial applications, etc.), the recovery yield of valuable metals from electronic waste is still quite low: Ru 0-5%; Rh 5-10%; Pd 5-10%; Ag 10-15%; Ir 0%; Pt 0-5%; Ru 0-5%; Rh 5-10%; Pd 5-10%; Ag 10-15%; Ir 0%; Pt 0-5%; Au 10-15% [10].

Table 5. *Classification of elements based on the expression mode of the recycling rate (in accordance with Figure 6)* [10]

Interval	Element
Recycling rate expressed by percentage of metal in the end-of-life products that return to the manufacturing process of the new product: $EOL-RR=\frac{g}{d}x100$	
>50%	Al, Ti, Cr, Mn, Fe, Co, Ni, Cu, Zn, Nb, Rh, Pd, Ag, Sn, Re, Pt, Au, Pb
25-50%	Mg, Mo, Ir
10-25%	Ru, Cd, W,
1-10%	Sb, Hg
>1%	Li, Be, B, Sc, V, Ga, Ge, As, Se, Sr, Y, Zr, In, Te, Ba, Hf, Ta, Os, Tl, Bi, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu
Recycling rate expressed by the average content of the recycled metal (RC is the fraction of secondary metal in the total metal input of the production process $RC=\frac{(j+m)}{(a+j+m)}x100$)	
>50%	Nb, Ru, Pb
25-50%	Mg, Al, Mn, Fe, Co, Ni, Ge, Mo, Rh, Pd, Ag, In, W, Pt, Au, Hg
10-25%	Be, Ti, Cr, Cu, Zn, Ga, Cd, Sn, Sb, Ta, Re, Ir
1-10%	Se, Zr, La, Ce, Pr, Nd, Gd, Dy
>1%	As, Y, Ba, Os, Tl, Sm, Eu, Tb, Ho, Er, Tm, Yb, Lu
Share of post-consumer waste in the total waste recycled: post-consumer waste + manufacturing waste resulted from the recycling stream ($OSR=\frac{g}{(g+h)}x100$).	
>50%	Cr, Fe, Ni, Rh, Pd, Ag, Cd, W, Ir, Pt, Au, Hg, Pb
25-50%	Mg, Al, Mn, Co, Cu, Zn, Nb, Mo, Sn, Re
10-25%	Be, Ti
1-10%	Ru, Sb, Ta
>1%	Li, Ga, Ge, As, Y, In, Ba, Os, Ti, Bi

The comparative analyses for different metals or categories of waste should take into account the calculation method used to assess the recycling efficiency. Different values can be obtained because reporting can focus on the recovering of material, energy, or both material and energy, on resulting waste, etc. The results of the analysis performed on 60 metals confirm this hypothesis [10]. The calculating method of recycling rate changes the positioning of the metals in the five groups established: > 50%, 25-50%, 10-25%, 1-10%, <1% (Table 5).

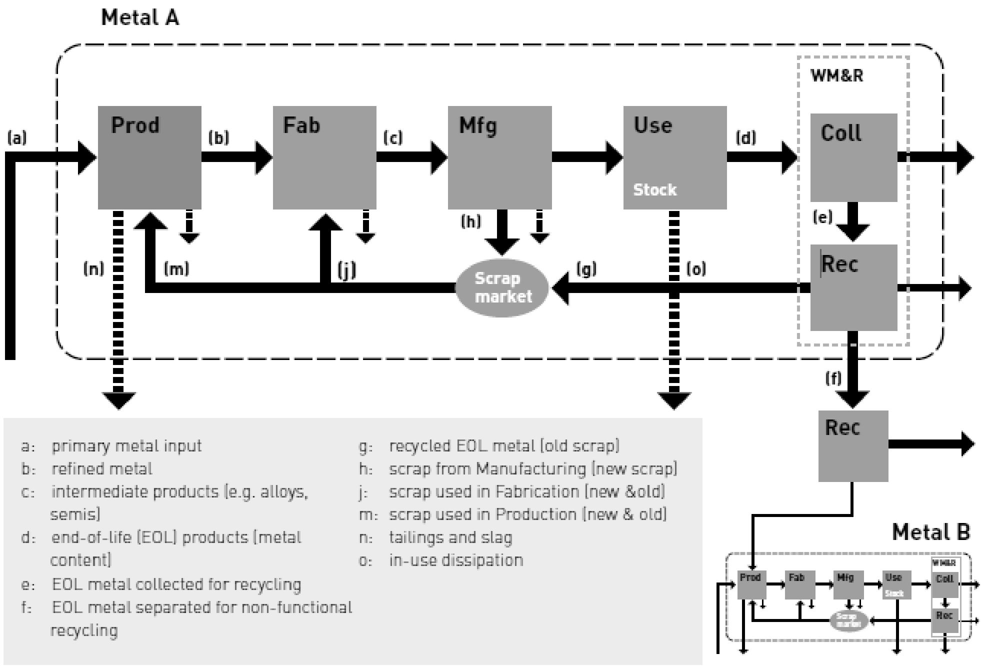


Fig. 6. *Stages of the life cycle of metals in EEE used to calculate recycling yields (Table 5)* [10]

It is noted that for many of the critical metals, especially rare earths, but also for other metals (such as tantalum, gallium and indium), the quantity returned from waste in the manufacturing process of new products is less than 1%. The status of precious metals (platinum, palladium, gold, silver) and cobalt is significantly better, reaching more than 50%. The situation is justified by the existence of efficient recycling technologies and by performant working of the collection systems for the recovered equipment.

- Environmental impact

WEEE recycling reduces the volume of waste damped, attenuates and prevents the pollution of soil, groundwater and air due to the release of hazardous compounds. The treatment of WEEE for metal recovery is mainly important for reducing the ″emissions of greenhouse gas″. Together with the ″material footprint″, the ″carbon footprint″ is one of the most important environmental targets for the recovery of metals from electronic waste.

The energy consumption (electricity, fossil fuels, non-conventional energy) is the indicator that characterizes the eco-efficiency which has influence on the amount of greenhouse gases of a process. Although energy consumption has an important share in the cost of recycling, the recycling processes are less energy intensive than primary metal production (Table 6). The energy consumed for extracting precious metals (gold, silver and palladium) is higher than the energy used for the production of basic metals (Cu, Al, Ni, Sn, Zn, Fe) (Figure 7).

Table 6. *Economic benefits of recycling some metals from the printed circuit boards, expressed by energy consumption* [19]

Material	**Energy savings over virgin materials (%)**
Aluminum	95
Copper	85
Iron and steel	74
Lead	65
Zinc	60

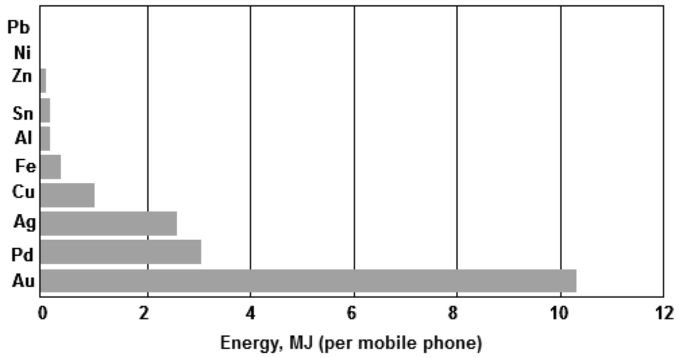


Fig. 7. *Energy consumed for extracting metals necessary for mobile phone manufacturing* [20]

The energy requirements for mining and extraction of raw materials are approx. 7% of the total global energy consumption. The large amount of energy required for the production of primary metals from ores is due to the high level of CO_2 emissions. The energy required for the mining production (extraction and the preparation of ores) is most often obtained from the coal burning. As a result, the environmental impact over the entire life cycle of metals is high. The impact of the production of metals from platinum group is shown in Figure 8.

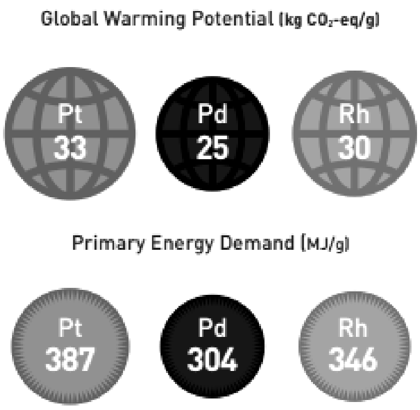


Fig. 8. *Summary result of the life cycle impact assessment for the average production of 1 gram of metals from platinum group* [21]

The extent to which mining and extraction activity affects the environmental factors differs from one metal to another. The metal-induced problems related to eco-toxicity are in close interdependence with the energy required to obtain the metals from ores (Figure 9). Depending on the magnitude of environmental effects, the rare metals are positioned at the top of the ranking.

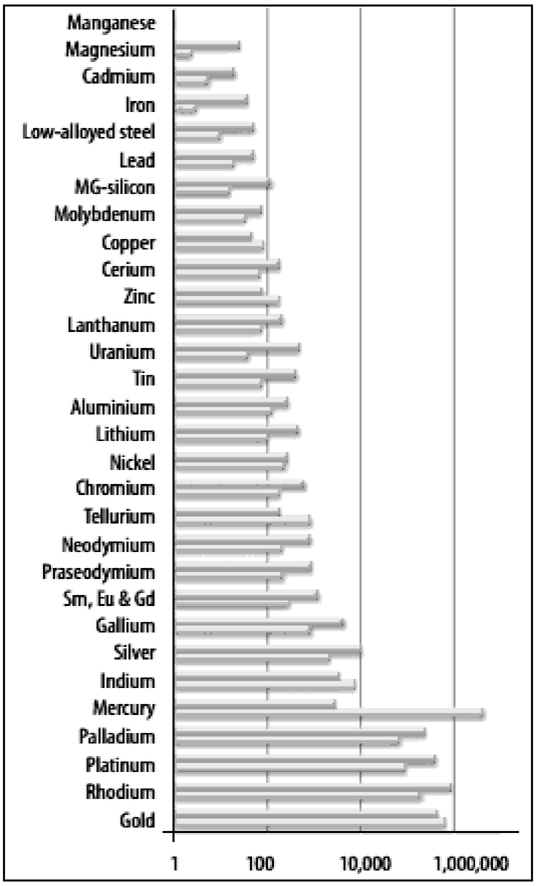


Fig. 9. *Contribution of metals to terrestrial ecotoxicity assessed by greenhouse gases and global warming for 1 kg of primary metal (for each metal the upper value is the greenhouse gases quantity and the lower is the terrestrial toxicity)* [22]

The literature data confirms that the production of primary metals from ores is an important source of CO_2 emissions. In this regard, even metals found in smaller amounts in EEE have a great impact on the environment (Figure 10).

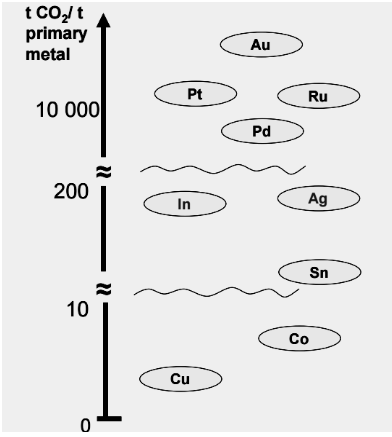
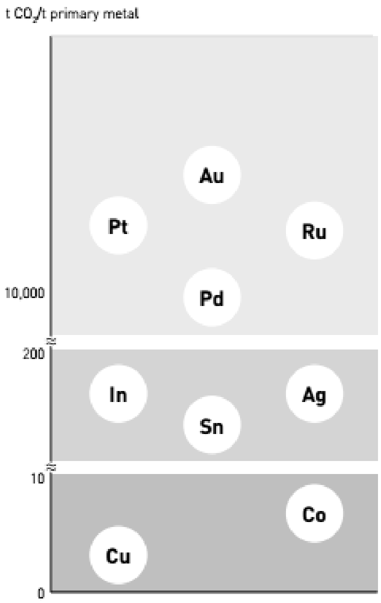


Fig. 10. *CO_2 emitted by 1 t of primary metals production* [1]

For 1 kg of primary copper, nearly 4 kg of CO_2 is emitted [23]. When comparing emissions per unit of metal produced, the typical CO_2 footprint for 1 ton of gold is 5,000 times higher than for 1 ton of copper. But obviously, with more copper being produced, the copper industry annually releases about 1.3 times CO_2 compared to gold production.

The recycling of metals requires far less energy than primary production, often this is consumed only for re-melting. As a result, CO_2 emissions from recycling are substantially lower than those from mining and extraction of primary metal. For example, besides the huge reduction of energy consumption, the aluminum recycling generates only 5% of the amount of CO_2 than those emitted from bauxite ores production (if electrolysis is also taken into account). For 1 kg of recycled aluminum, only 1/10 of the energy required for primary production is consumed. Thus, the generation of red sludge (~1.3 kg) and the emission of CO_2 (~2 kg) can be prevented. The situation is the same for platinum metals and other metals recovered from WEEE (Figure 11) [10, 23].



Metals used in EEE	Primary production intensity t CO_2/t metal	Demand for EEE t/a	CO_2 emissions Mt/a
Au – Gold	16,991	327	5.56
Pt – Platinum	13,954	8	0.11
Ru – Ruthenium	13,954	16	0.22
Pd – Palladium	9,380	30	0.28
Au – Silver	144	4,917	0.71
In – Indium	142	717	0.10
Sn – Tin	16	129,708	2.09
Co – Cobalt	8	16,470	0.13
Cu – Copper	3	7,174,000	24.39
		CO_2 total [Mt/a]	**33.58**

Fig. 11. *Primary carbon footprint for some WEEE elements* [10]

The recycled gold has a smaller carbon footprint than the primary gold from ores. Although there are small amounts of gold in WEEE, this element has the largest footprint, i.e. is about 50 times larger than for copper and about 5000 times larger for aluminum [22].

3. Conclusions

The opportunity and recycling potential resulted from the analysis of each metal from cell phones waste. The indicators considered for sustainable recovery of metals are: quantitative evaluation; potential revenue obtained from recovered metals sale; eco-efficiency of recycling; metal recovery efficiency; impact on the environment. The quantitative evaluation of metals is an incorrect tool to develop sustainable materials management in case of mobile phones waste. The potential revenue obtained from the sale of recovered metals is the most important drive force for sustaining profitable WEEE recycling industry. In terms of metals value, the electronic waste is classified as ″high grade material″. The values of gold, silver, copper and palladium represent over 95% from the total revenues obtained by recycling cell phones waste. Another analytical tool characteristic of sustainable metals management is eco-efficiency. This is expressed by the extraction metal yield from waste. The low recovery yield of valuable metals (Ru 0-5%; Rh 5-10%; Pd 5-10%; Ag 10-15%; Ir 0%; Pt 0-5%; Ru 0-5%; Rh 5-10%; Pd 5-10%; Ag 10-15%; Ir 0%; Pt 0-5%; Au 10-15%) is characteristic of the electronic scrap. The quantity returned from waste in the manufacturing process of new products is less than 1% for many of the critical metals, especially rare earths, but also for other metals (such as tantalum, gallium and indium). The status of precious metals (platinum, palladium, gold, silver) and cobalt is significantly better, reaching more than 50%.

In terms of environmental impact, the eco-efficiency is quantified by greenhouse gases emission, material footprint or carbon footprint. Among metals in WEEE, gold and platinum metals are the most important source of CO_2 emission. The typical CO_2 footprint for 1 ton of gold is 5,000 times higher than for 1 ton of copper.

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