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Material Flow Analysis of Waste Electrical and Electronic Equipment in Ukraine

Lilia Hlavatska[1], Vitalii Ishchenko[1], Volodymyr Pohrebennyk[2*], Ivan Salamon[3]

[1] Department of Ecology and Environmental Safety, Vinnytsia National Technical University, Khmelnytske shose 95, Vinnytsia, 21021, Ukraine

[2] Department of Ecological Safety and Nature Protection Activity, Viacheslav Chornovil Institute of Sustainable Development, Lviv Polytechnic National University, Lviv, 12 Bandera St, 79013, Ukraine

[3] Department of Ecology, Faculty of Humanities and Natural Sciences, University of Presov, 17, Novembra 1 St., Prešov, 081 16, Slovakia

* Corresponding author's e-mail: vpohreb@gmail.com

ABSTRACT

The composition of widespread electronic devices (mobile phone, computer mouse, keyboard, web-camera, monitor) was studied by manual dismantling. The material flow analysis was conducted for e-waste components. For the case study of Ukraine, five devices under investigation contain over 4 thousand tons / year resources. Most of them (first of all, plastic and metal) can be easily recovered. The content of chemical elements in the components of the electronic devices was determined by X-ray fluorescence analysis. Taking into account the mass of electronic waste generated in Ukraine, the resource potential of metals was estimated. Most of metals are concentrated in mobile phones and monitors (about 2000 tons/year). Apart from common metals, silver, molybdenum, vanadium, rubidium, zirconium, antimony, yttrium, rhodium, bismuth, and gallium were also found.

Keywords: resource potential, electronic device, waste electrical and electronic equipment, material flow analysis, metals.

INTRODUCTION

Today, the issue of resource depletion is very crucial. At the same time, large amounts of resources are lost in waste [OECD 2013, Ishchenko et al. 2019, Bejanidze et al. 2019, Ishchenko et al. 2017, Pohrebennyk et al. 2016, Ishchenko et al. 2016]. The total amount of waste in the world reaches almost 800 billion tons, of which more than 300 billion tons corresponds to solid waste. Therefore, not only environmental pollution by waste is important [Mitryasova and Pohrebennyk 2017, Zaporozhets et al. 2020, Mitryasova and Pohrebennyk 2020, Karpinski et al. 2018, Mitryasova et al. 2017, Bobylev et al. 2014, Przydatek and Kanownik 2021], but also recovery of valuable components from waste. Regarding the resource value, waste electrical and electronic equipment (WEEE) is important. This is the most intensively growing fraction of household waste. The large number and variety of electronic and electrical devices results in constant increasing of the resources lost due to landfilling or burning. These resources include many precious and rare elements. Thus, this is relevant for most countries since usually WEEE is not collected separately. In Ukraine, only a small part of some old equipment is returned as resources (parts of computers, mobile phones, or some large equipment). The remaining WEEE is landfilled together with mixed household waste. This creates serious obstacles to the implementation of the circular economy principles.

Technological progress causes regular changes of equipment and WEEE composition. The Ukrainian market of electrical equipment is quite large, so the WEEE amount is significant. In order to assess the resource potential of WEEE, a material flow analysis is necessary. Although many studies of WEEE composition are known [Chancerel et al. 2009, Dimitrakakis et al. 2009a, Ishchenko 2019, Morf et al. 2007, Musson et al. 2006], covering different countries and different types of WEEE, no studies have been conducted in Ukraine. Many researchers [Bigum et al. 2013, Dimitrakakis et al. 2009b, Ernst et al. 2000, Lincoln et al. 2007, Nnorom and Osibanjo 2009, Oguchi et al. 2013, Pohrebennyk et al. 2016, Salhofer and Tesar 2011] have analyzed the content of hazardous substances and found lead, cadmium, mercury, brominated flame retardants (BFRs), polyvinyl chloride and other toxic compounds in WEEE.

Other studies on the material flow analysis of WEEE show their significant resource potential. For example, the copper content in WEEE is estimated at 2.5–5% [Duan et al. 2016, Holgersson et al. 2018], and over 40 g/kg in cables [Charles et al. 2017]. Other metals include chromium (average content in magnetic data tapes is 9.9 g/kg), lead (average content in screens, batteries, printed circuit boards is 2.9 g/kg), nickel (average content in batteries and cathode ray tubes is over 10 g/kg), tin (average content in solders and liquid crystal screens is 2.5 g/kg), zinc (average content in cathode ray tubes is over 5 g/kg) [Ghosh et al. 2020]. Precious metals like Au, Ag, Pt, and Pd are also worth noting. In WEEE, silver is more common. For example, the Ag content exceeds 1 g/kg in mobile phones [Cesaro et al. 2018]. Many studies show the WEEE composition changes over a time. For example, the content of some metals (aluminium, steel) in liquid crystal monitors decreased by an average of 30% in recent years. At the same time, the share of difficult-to-recover components has increased [Hong and Choi 2018]. Many metals are lost due to their low recovery efficiency. The importance of metal recycling is evidenced e.g. by the fact that 47% of aluminium in the EU is obtained by recovering from waste [Goodship et al. 2019].

The purpose of this paper is to assess the resource potential of WEEE in Ukraine through a material flow analysis.

METHODS AND MATERIALS

Five used electronic devices were selected for the study: a mobile phone, a computer mouse, a keyboard, a web-camera, and a monitor. Old models of devices currently being disposed as waste were studied. These devices were dismantled into components (according to functional purposes) and weighed. Besides, the components were grouped by materials for each device: plastic, metal, glass, printed circuit boards, cables. The chemical composition of each component was measured using the “Expert-3L” X-ray fluorescence analyzer (INAM, Ukraine). The resource potential of metals in the selected WEEE was estimated by multiplying the metal content in the device by the total weight of device in the waste in selected year.

RESULTS AND DISCUSSIONS

WEEE components

The weight of components of the electronic devices analyzed is included in the Tables 1-5.

Table 1. Components of the mobile phone

Component	Weight, g
cable	0.95
toggle switch	3.7
capacitor	4.2
winding №1	0.04
winding №2	0.04
screen backing	0.23
membrane	0.55
plastic case	15.45
screen sensor (inn.)	8.69
screen sensor (out.)	5.37
metal part of the case	12.25
PCB	15.09
battery	22.46
other	20.86
Total	109.88

Table 2. Components of the computer mouse

Component	Weight, g
plastic case	40.43
PCB	11.15
cables	22.45
screws	0.26
other	4.12
Total	78.41

Table 3. Components of the keyboard

Component	Weight, g
keycaps	102.44
case	392
cable	28.99
PCB	5.77
backplate with traces	21.85
backplate under keycaps	20.43
screws	7.77
other	1.56
Total	580.81

On the basis of Tables 1-5, the following groups of materials were calculated for each device: plastic, metal, glass, rubber, PCB, and cables (see Table 6).

Plastic, metal and rubber are WEEE components that can be easily recovered. Thus, one can consider them as resources. The largest weight fraction of plastic was measured in the keyboard (85%), while the highest absolute weight of plastic was found in the monitor. The highest metal parts and glass content (1 kg or 29% and 1 kg or 27%, respectively) was found in the monitor due to its size. Most of the valuable elements are usually concentrated in the printed circuit boards of electronic devices. The largest weight of PCBs was measured in the monitor (over 250 g per 1 monitor), and the highest relative content was found in the mobile phone and computer mouse (14% each).

In order to estimate the total weight of resources available in the WEEE analyzed, the data on the WEEE number (weight) are necessary and can be obtained from the UN Comtrade database (UN Comtrade). Since the electronic devices studied in this paper are not produced in Ukraine, it is sufficient to assess the difference between their import and export. It can be simplified to consider the WEEE amount equal to the number of equipment on the market (import minus export) with a delay of 2-5 years, depending on the type of device. Accordingly, the weight of waste electronic devices was estimated (see Table 7). On the basis of on these data, resource flows were estimated for the devices studied (Figs. 1–5).

Therefore, up to 4100 tons of resources per 1 year can be easily recovered from the WEEE analyzed, including almost 2000 t/y of plastic, about 1200 t/y of metal, almost 900 t/y of glass, 80 t/y of rubber. At the same time, more than 600 t/y of resources can be recovered after the application of special processing methods (from PCB and cables). Almost half of this amount is available in mobile phones.

Table 4. Components of the web-camera

Component	Weight, g
rubber base	20
case	45.8
cable	32.67
PCB	2.84
flexible connector	36.3
objective	1.63
Total	139.24

Table 5. Components of the monitor

Component	Weight, g
frame	395.9
case	600
binding	271.59
back cover	179.09
screen films	488.57
screen glass	925
cable	28.4
fluorescent lamps	5.35
tissue insulation	10
PCBs	262.38
інше	8.46
Total	3174.74

Metals in WEEE

An important task is to estimate the amount of different metals, which are contained in WEEE in one form or another and can be potentially considered as valuable resources. Below are the

Table 7. Average WEEE weight in Ukraine for last 5 years

WEEE	Weight, t/y
Mobile phones	1802
Computer mice	121
Keyboards	1244
Web-cameras	231
Monitors	2200

Table 6. Groups of materials in WEEE

WEEE	Weight, g					
	plastic	metal	glass	rubber	PCB	cables
Mobile phone	15.45	33.11	14.06	–	15.09	–
Computer mouse	42.69	0.26	–	1.86	11.15	22.45
Keyboard	494.44	9.33	–	20.43	5.77	28.99
Web-camera	45.8	36.3	–	20	2.84	32.67
Monitor	699.84	846.58	925	–	262.38	27.79

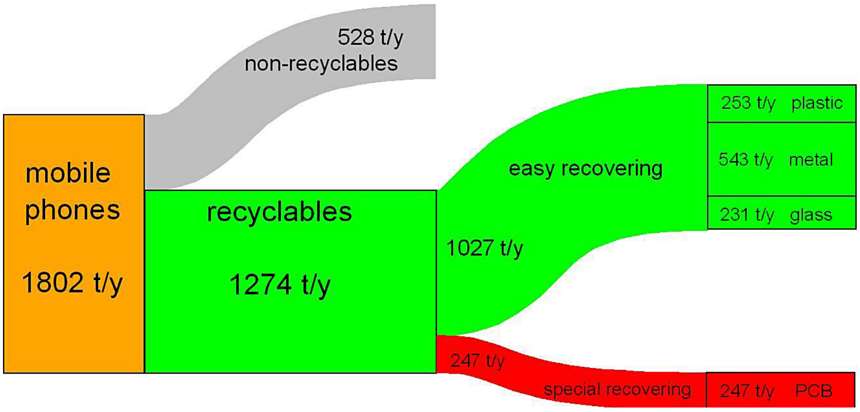

Figure 1. Resource flows for the mobile phone

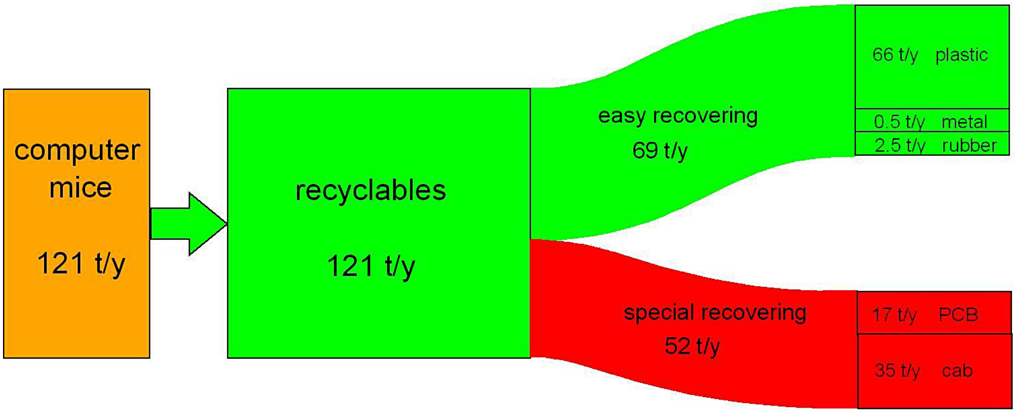

Figure 2. Resource flows for the computer mouse

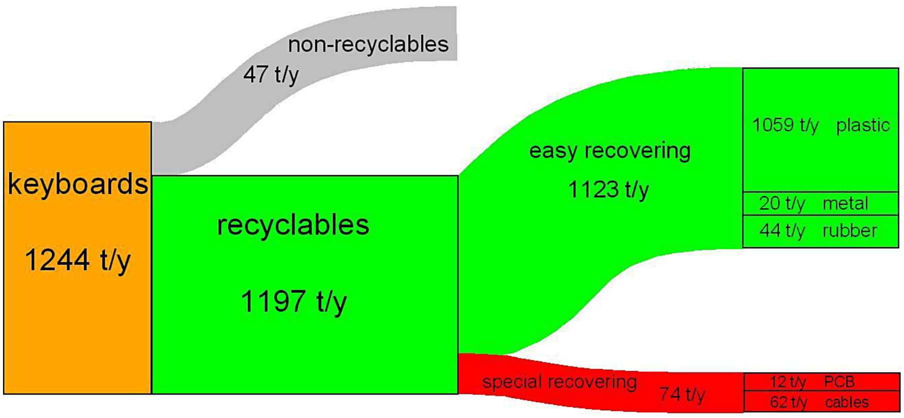

Figure 3. Resource flows for the keyboard

results of X-ray fluorescence measuring of metals (and some other elements) in the electronic devices analyzed. In order to assess the total weight of elements in the device, their weights in the device components (see Tables 1-5) were added.

Mobile phone

In the mobile phone (weight 109.88 g), the following metals were found (Fig. 6): iron – 24.76 g, strontium – 14.21 g, copper – 13.4 g, titanium – 10.16 g, chromium – 6.15 g, nickel – 5.49 g, calcium – 4.55 g, zinc – 2.92 g, other chemical elements weigh below 1 g. The data do not include the metals of the phone battery, as it is recycled separately.

99% of iron and chromium are found in the metal part of the phone. Almost all strontium is found in the screen sensor. Copper is present in almost all components of the phone, while

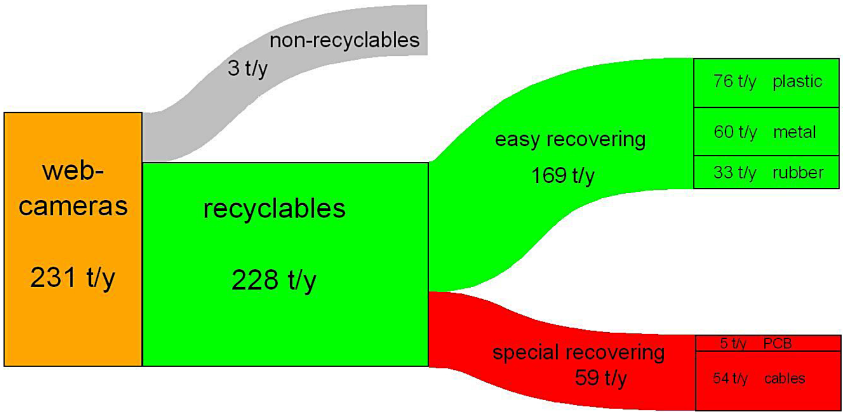

Figure 4. Resource flows for the web-camera

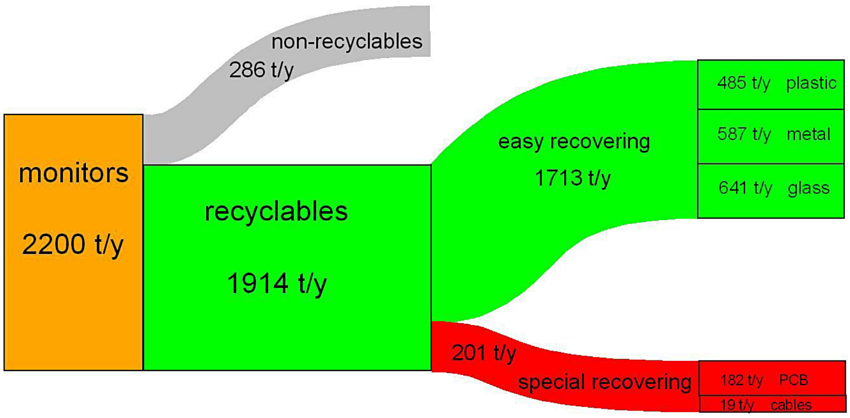

Figure 5. Resource flows for the monitor

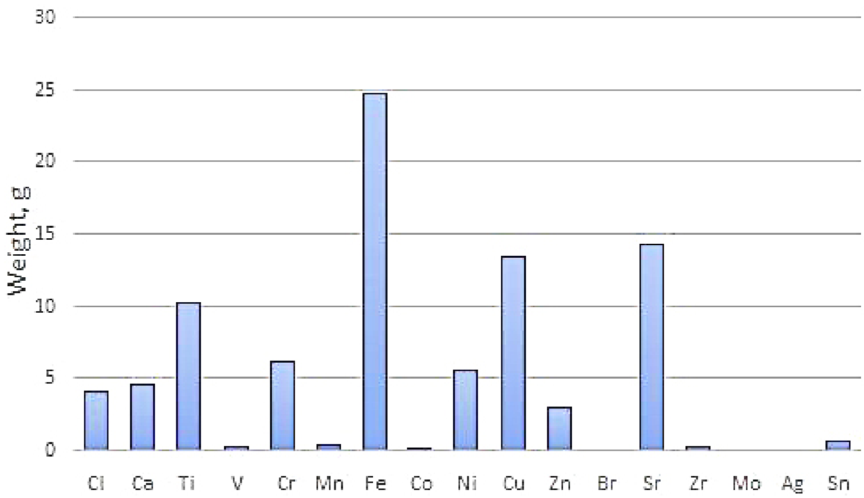

Figure 6. Chemical elements in the mobile phone

its largest part is in the PCB (over 9 g). Almost the total weight of zinc was also found in the PCB. All titanium is concentrated in the plastic case. Nickel is evenly distributed between the metal part of the case and PCB. Among the rare and precious metals, zirconium was found (mostly in the sensor).

Obviously, the great variety of mobile phones does not allow unifying their composition. Moreover, it changes very quickly. For example, in the study [Cucchiella et al. 2015] of 2014 year, approximately the same amount of copper was found in a mobile phone, but the contents of iron, nickel, zinc, and titanium were much lower.

Computer mouse

The computer mouse is not rich in valuable metals: the total weight of copper is a little more than 4.5 g, zinc – almost 2.5 g, tin – about 3 g (Fig. 7). Most of the weight is formed by calcium (in the form of calcium carbonate used as a filler in polymers) and titanium (titanium dioxide is used as an additive to polymers to provide white colour and some physical properties).

The content of iron, in contrast to a mobile phone, is minimal – only few milligrams. Antimony, strontium and rubidium were also found in trace amounts.

Keyboard

The distribution of elements in the keyboard is similar to that found in the computer mouse: most of the weight is composed by titanium and calcium (Fig. 8). Regarding the valuable metals, one should note relatively large weight of silver (2.19 g) and zinc (25.77 g, zinc oxide is used in plastics as a filler and pigment). Almost all Ag is found in the electrical traces of the keyboard backplate. Moreover, a significant weight of iron was measured (over 15 g). Other valuable metals are found in PCB, but their content is low: tin – 2.94 g, zirconium – 1.09 g, rhodium – 0.87 g, copper – 0.47 g, nickel – 0.27 g. Besides, some toxic metals were found: mercury and lead –in PCB (0.09 g) and cables (1.36 g).

Web-camera

Apart from calcium and titanium in the plastic, the web-camera contains over 2 g of copper (more in PCB, less in the cable) and a bit over 1 g of iron (Fig. 9). Other metals are found in small quantities: zinc – 0.49 g, rubidium – 0.22 g, strontium – 0.19 g (all these metals are found mainly in the web-camera case), nickel and vanadium – 0.06 g and 0.04 g, respectively (PCB).

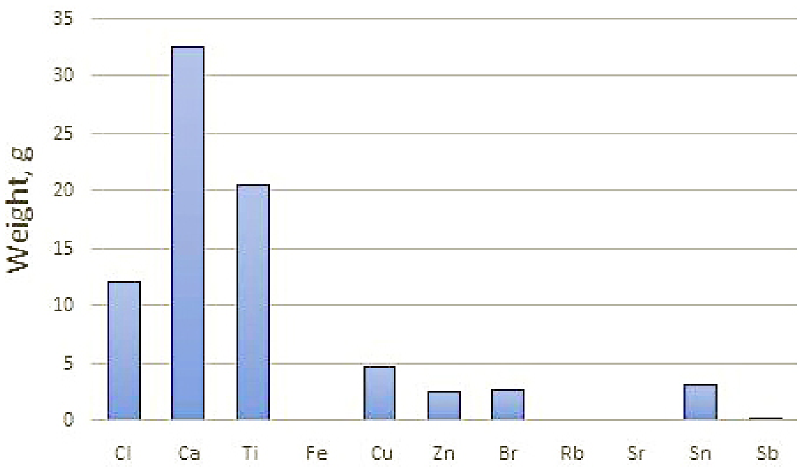

Figure 7. Chemical elements in the computer mouse

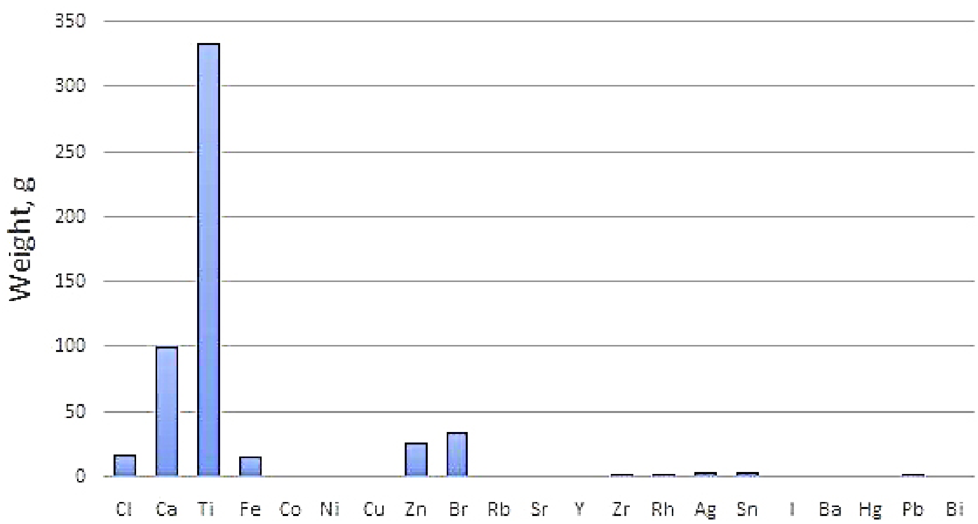

Figure 8. Chemical elements in the keyboard

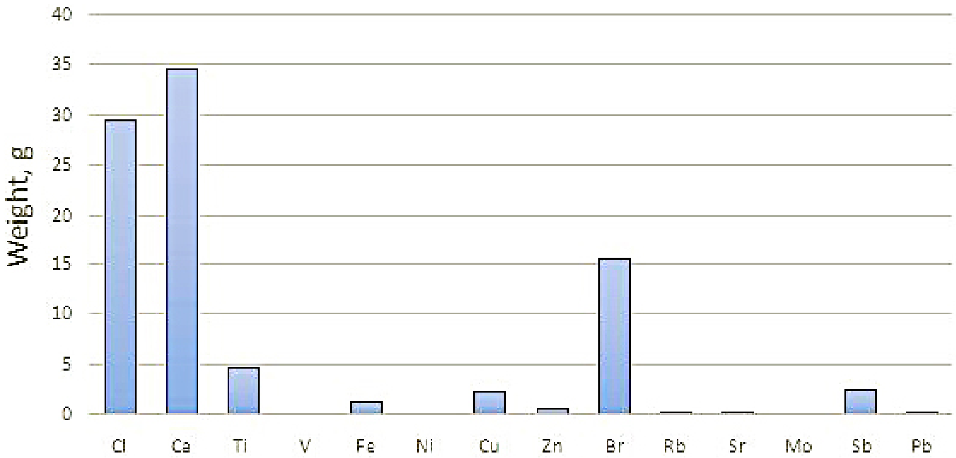

Figure 9. Chemical elements in the web-camera

Regarding the hazardous substances, it is worth noting a significant weight of bromine (over 15 g, in brominated flame retardants of plastic) and antimony (about 2.5 g, antimony oxide is used in some types of plastic as a filler), as well as 0.23 g of lead found in rubber base.

Monitor

Due to its size, the monitor can be a great source of resources (Fig. 10). Excluding the plastic components, iron (440 g, metal parts of the case), strontium (326 g, screen glass), copper (147 g, PCBs), tin (85 g, PCBs), zinc (48 g, larger part – in metal parts of the case, smaller part – in screen glass) predominate among the metals. Zirconium and molybdenum (6.9 g and 0.23 g, respectively, screen layers), silver (4.24 g, PCBs), rubidium (0.67 g, PCBs and screen layers) have a higher weight in comparison to other devices. Besides, trace amounts of gallium and yttrium (as part of PCB elements) were detected.

Among the toxic metals, the following were found: arsenic (16.87 g, mostly in screen layers) and lead (1.71 g, PCBs), as well as small amount of chromium (0.01 g, PCB elements).

The results for the monitor, as well as for the mobile phone, are slightly different comparing to other studies. For example, [Cucciella et al. 2015] found much less tin and silver, as well as much more lead. The amounts of molybdenum, gallium and yttrium are commensurate.

Taking into account the weight of devices (Table 7), the weight of metals available for recovering from WEEE can be estimated (Table 8). One can see that mobile phones and monitors have the greatest resource potential (in terms of valuable metals), while web-cameras and

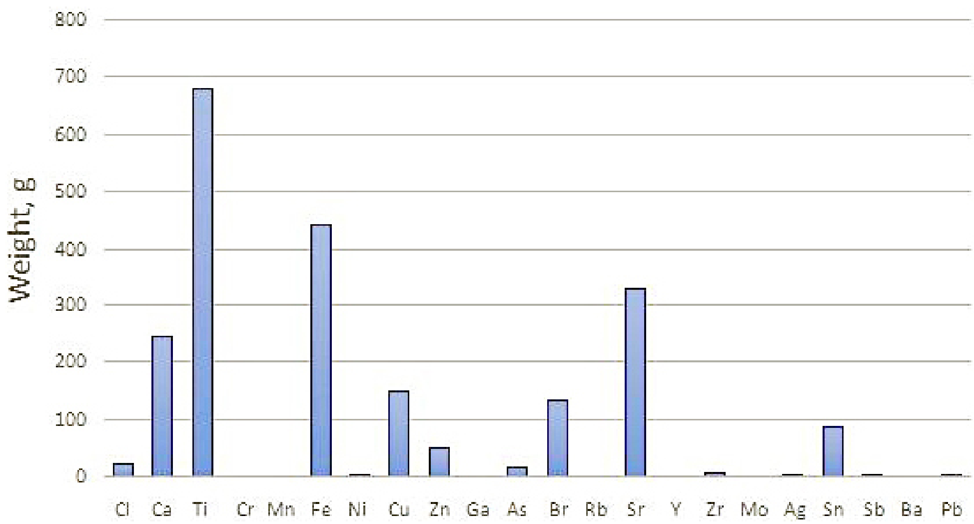

Figure 10. Chemical elements in the monitor

Table 8. Weight of metals in WEEE

Metal	Weight, t/y					
	Mobile phones	Computer mice	Keyboards	Web-cameras	Monitors	Total
Mn	6.293				0.386	6.679
Fe	406.103	0.036	32.615	1.84	305.342	745.936
Ni	90.081		0.578	0.096	1.811	92.566
Co	1.987		0.064			2.051
Cr	100.842				0.009	100.851
Hg			0.19			0.19
Pb			2.917	0.382	1.185	4.484
As					11.691	11.691
Sn	9.943	4.745	6.29		59.138	80.116
Zn	47.931	3.702	55.204	0.82	33.443	141.100
Cu	219.757	7.226	1.006	3.713	102.142	333.844
Zr	5.031		2.34		4.786	12.157
Mo	0.999			0.008	0.156	1.163
Ag	0.016		4.711		2.938	7.665
V	3.111			0.066		3.177
Sr	233.013	0.01	0.13	0.324	226.053	459.530
Rb		0.044	0.0002	0.372	0.462	0.878
Sb		0.272		3.906	2.251	6.429
Y			0.088		0.0003	0.088
Rh			1.858			1.858
Bi			0.0004			0.0004
Ga					0.0007	0.0007
Ba					0.436	0.436
Total	1125.107	16.035	107.9916	11.527	752.23	2012.891

computer mice have the least. The metals with greatest weight in WEEE analyzed are as follows: iron, strontium, and copper. Most weight of these 3 metals is measured in mobile phones and monitors. Zinc (mostly in keyboards, mobile phones, and monitors) and chromium (mostly in mobile phones) also have a fairly high resource potential. Regarding the precious metals, silver is mainly found in keyboards, and slightly less in monitors. Regarding the rare metals, the largest resources of molybdenum, vanadium and zirconium are present in mobile phones, while antimony – in web-cameras, rubidium – in monitors, yttrium and rhodium – in keyboards.

CONCLUSIONS

The results of the study confirm e-waste having a significant resource potential. Up to 4100 tons of resources per 1 year can be easily recovered from the WEEE analyzed, including almost 2000 t/y of plastic, about 1200 t/y of metals, almost 900 t/y of glass, 80 t/y of rubber. Over 600 t/y of resources can be recovered after application of special processing methods. Of course, most of the weight is made up of plastic and ferrous metals. In the devices analyzed, most of them are found in monitors (due to the size). However, many valuable metals are also available. Most of them are usually concentrated in the printed circuit boards of electronic devices. Among the precious and rare metals, silver, molybdenum, vanadium, rubidium, zirconium, antimony, yttrium, rhodium, bismuth, and gallium were found. It is worth noting a fairly large weight of strontium – in the glass of screens. Mobile phones and monitors are considered to be the devices with the greatest resource potential. Taking into account the weight of electronic waste in Ukraine, mobile phones and monitors contain almost 2000 t/y of valuable metals. However, some rare metals (yttrium, rhodium) are present mainly in other WEEE like keyboards.

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