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FINANCIAL AND TECHNOLOGICAL POTENTIAL OF ECO-EFFICIENT RECYCLING OF WASTE ELECTRONIC EQUIPMENT

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ABSTRACT – The paper presents the financial potential of recycling waste electronic equipment (WEE) in the form of printed circuit boards, hard drives, and lithium-ion batteries. The metal contents in selected types of WEE were presented, as well as their price and importance from an environmental, economic, and political perspective using the indicators of relative supply risk and abiotic depletion potential (ADP). The potential benefits that recycling can bring to the company and the environment were presented. Furthermore, the mass balance and value of recovered metals were estimated for southern Poland and potential possibilities for the management of the remaining separation products were presented. Finally, verified methods for physical recycling of the presented WEE were described.

Keywords: Recycling Of Waste Electronic Equipment (WEE), Metal Recovery, Financial and Technological Aspects.

INTRODUCTION

Waste electronic equipment (WEE) is a group of waste whose quantity is growing dynamically from year to year and, due to the presence of metals, often critical, and plastics, constitutes a global environmental, economic, and even political problem. Such a rapid rise in end-of-life electrical and electronic equipment poses a challenge to both companies seeking to recover valuable raw materials and authorities striving to reduce the environmental impact of this waste stream.

This article focusses on the financial and technological potential of eco-efficient WEE recycling. The subsequent sections present the following:

– the content and price of metals in selected types of WEE, along with an overview of indicators that evaluate their importance from environmental, economic, and political perspectives, particularly relative supply risk and abiotic depletion potential (ADP). In this context, three examples of waste categories are discussed in detail: printed

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circuit boards (WPCBs), computer hard disk drives (WHDs), and lithium-ion batteries (WLIBs),

– the mass balance and estimated value of recoverable metals in WEE collected in southern Poland, illustrating the economic and environmental potential of recycling,

– a review of research on the recycling of the analysed WEE, including physical methods as a preliminary step in recycling. It has been shown that physical techniques such as shredding, cryognic grinding, electrostatic separation, flotation, gravity, and optical separation often provide a simpler and more environmentally friendly route to metal recovery, especially at the initial processing stage.

CONTENT AND PRICE OF METALS IN WEE AND THEIR SIGNIFICANCE INDICATORS

In this study, two indicators were considered to assess the importance of metals present in the WEE: the relative supply risk and the potential for abiotic depletion potential (ADP). The second parameter is used to assess the impact of resource depletion. It focusses specifically on abiotic resources, which are non-living materials such as minerals and metals. ADP describes the ratio of the annual production of a resource to its ultimate reserves (based on the crustal content). It allows an assessment of the extent to which the use of a particular material contributes to the depletion of its resources. The higher the ADP value for a particular resource, the greater the potential for the resource to deplete [1]. Just as the global warming potential (GWP) of various pollutants is converted to CO_2 equivalents, ADP values are commonly calculated to antimony equivalents (Sb eq.).

Another parameter is the relative supply risk developed by the Royal Society of Chemistry, which assesses future raw material availability issues. The index is based on factors such as crustal abundance, distribution and quantity of reserves, production concentration, substitutability, recycling rates, and political stability (Royal Society of Chemistry Periodic). The relative supply risk ranges from 1 (very low risk) to 10 (very high risk).

Waste Printed Circuit Boards (WPCB)

One of the most common types of WEEs is waste printed circuit boards (WPCBs), which are made of a composite material with embedded metal tracks as the base. The most commonly used PCBs are of type FR-4, whose composite is made of glass fibre in an epoxy resin matrix with flame retardant additives. As can be seen in Table 1, the WPCB consists of metals with medium (Cu, Al, Zn, Au), increased (Pb, Ni, Sn, Ag) and high (Pd, Pt) relative supply risk, while the ADP is very high for Au, Pd, Pt, medium for Ag, and low or very low for Cu, Al, Pb, Zn, Ni, Sn, which means that the resources of some metals such as Au, Pd, Pt are very limited and the risk of Pd and Pt availability due to production concentration, substitutability, recycling rates, and political stability is high. Both indices show that the key metals from an economic, environmental, and political perspective are Pd, Pt, Au, and Ag. This affects the price of metals. Therefore, the most valuable metals in WPCB, considering their content, are gold, silver, palladium, and due to their high content, also copper (Table 1), and the recovery of these metals can provide significant economic benefits to the recycling company [2]. The estimated value of the metals contained in a ton of WPCB is almost 92 thousand USD, of which a significant part is the value of gold. Metals that have financial value are treated as concentrates, whereas plastics are treated as products for which use is sought.

Table 1 Estimated metal contents of FR-4 type WPCB and related indicators of: relative supply risk and abiotic depletion potential [3–5] and estimated price of metals in WPCB [6,7]

Metal	Average metal content in WPCB, %	Relative supply risk	ADP, kg Sb eq/kg	Estimated price of metal in 1 Mg, $
Cu	20	4.3	2.1E−02	1 821.6
Al	2	4.8	2.5E−08	49.5
Pb	2	6.2	1.9E−02	39.3
Zn	1	4.8	2.8E−03	32.2
Ni	2	6.2	8.1E−04	303.6
Sn	4	6.7	8.1E−02	1 194.1
Ag	0.20	6.2	8.6E+00	1 928.4
Au	0.10	5.7	1.4E+03	84 556.5
Pd	0.0050	7.6	9.7E+02	1 532.0
Pt	0.0015	7.6	9.7E+02	454.3
Sum	31.31	-	-	91 910.9

Waste hard drive (WHD)

Another type of WEE is the waste hard drives (WHDs), which have an average weight of 509.8 g and consist of several elements [8]. These include aluminium, steel, plastic, as well as printed circuit boards and neodymium magnets. Most of the mass share belongs to the HDD casing, which consists of two parts: the main part and its cover. Typically, this casing is made of an Al-Si alloy. The HDD also consists of a disk stack assembly, which includes platters with a spacer and a spindle cover. The platters are made of an Al core with a thin layer of metal alloy providing magnetic properties. This alloy contains Co, Ni, Fe, and Zn [9]. The HDD also contains a PCB that is mounted on the bottom of the case. The HDD also consists of a Voice Coil Assembly (VCA), which is made up of neodymium magnets, ferrous metal holders, and other mechanical parts. VCA contains metals such as Fe, Nd, Pr, Dy, Co [10]. An HDD is composed of about 83% (by weight) metals and about 17% non-metallic assemblies such as PCBs and plastic parts. The Al content is the highest because the HDD casing is made of this metal.

HDD consists of metals with medium (Al, Fe, Cu, Ti, Zn, Au), increased (Ni, Sn, Ta, Ag), high (Co, Pd, Pd, Pt) and extremely high (Nd, Ce, Pr, Dy, Sb) relative supply risk (Table 2), while ADP is very high for Au, Pd, medium for Ag, Sb, low for Cu, Ni, Sn, Zn, Pr, and very low for Ce, Nd, Dy Co, Al, Si, Fe, Ti, Ta (Table 2), meaning that the resources of metals used in HDD production, apart from those from which PCBs are made, are large, but the availability risk, especially of Nd, Pr, Dy, Ce and Sb due to production concentration, substitutability, recycling rates, and political stability, is extremely high. The most important metals from an economic, environmental, and political perspective that drive the need for WHD recycling are Nd, Pr, Ce, and Dy that make up neodymium magnets and Pd, Au, and Ag that are found in the PCBs that control HDD.

The most valuable metals in WHD, based on their content, are gold, cerium, copper, neodymium, palladium, dysprosium, silver and praseodymium, which are contained in neodymium magnets and PCBs (Table 2). Aluminium and quartz are also of great value due to their high content in HDD. The HDD casing is made of aluminium with a steel cover. The estimated value of metals contained in a ton of WHD is around USD 9 908, with the highest value metals found in neodymium magnets, PCBs, and HDD casing. Therefore, they are treated as concentrates in the recycling process.

Table 2 Estimated metal content in WHD and related indicators of: relative supply risk and abiotic depletion potential and estimated price of metals in WHD [1,3,9,11]

Part of WHD	Metal	Average metal content in WHD, %	Relative supply risk, -	ADP, kg Sb eq/kg	Estimated price of metal in 1 Mg, $
HDD casing	Al	64.0	4.8	2.5E−08	1 583.4
	Si	8.9	-	1.4E−11	124.3
	Fe	3.2	5.2	5.24E−08	10.1
PCBs	Cu	5.4	4.3	2.1E−02	491.6
	Ni	0.18	6.2	8.1E−04	27.3
	Sn	0.17	6.7	8.1E−02	50.7
	Ti	0.04	4.8	2.79E−08	2.6
	Zn	0.03	4.8	2.8E−03	1.0
	Ce	0.04	9.5	1.5E−05	1.2
Neodymium magnets	Nd	0.73	9.5	3.1E−05	438.5
	Pr	0.11	9.5	1.4E−04	72.4
	Dy	0.08	9.5	7.0E−05	195.5
	Co	0.07	7.6	1.57E−05	17.0
PCBs	Sb	0.01	9.0	1.0	1.7
	Ta	0.06	7.1	4.06E−5	202.2
	Ag	0.0234	6.2	8.6E+00	225.6
	Au	0.0071	5.7	1.4E+03	6 003.5
	Pd	0.0015	7.6	9.7E+02	459.6
	Sum	83.0	-	-	9 908.3

Waste lithium-ion batteries (WLIB)

The last WEE presented is waste lithium-ion batteries (WLIBs). LIBs are now the dominant portable power source in smartphones, laptops, cameras, hand-held devices, and other high-tech devices. The structure of LIBs is not homogeneous and multimetallic compounds can be found in them. Lithium cobalt oxide (LCO) and lithium nickel manganese cobalt oxide (NMC) are examples of the types of active cathode materials (CAMs) used in these batteries [12]. They typically contain approximately 21.31% Mn, 16.54% Co, 2.56% Ni, 2.22% Li, 5.93-14% Cu, 4.7-9.12% Al, 0.04-25% Fe and approximately 15% organic materials and 7% plastics [13,14]. Organics include electrolytes, binders, and separators [12,14].

LIB consists of metals with medium (Mn, Cu, Al, Fe), elevated (Ni, Li), and high (Co) relative supply risk, while ADP is low or very low for Cu, Ni and Mn, Co, Li, Al, Fe (Table 3), respectively, which means that the resources of metals used for battery production are large, but the availability risk, especially of Co, Li, Ni due to production concentration, substitutability, recycling rates, and political stability is quite high.

WLIB recycling can also provide significant financial benefits to the recycler. Considering the current metal prices on the exchanges and the average metal content in WLIB, it is estimated that in one tonne of WLIB the value of the metals contained is over USD 6 350. Note that cobalt is the key metal determining the profitability of WLIB recycling, although copper, nickel, lithium, and manganese are also high-value metals.

Table 3 Estimated metal contents in WLIB and related indicators of: relative supply risk and abiotic depletion potential [1,3,9] and estimated price of metals in WPCB [6,7]

Metal	Average metal content in WPCB. %	Relative supply risk	ADP. kg Sb eq/kg	Estimated price of metal in 1 Mg, $
Mn	21.31	5.7	3.3E−05	441.1
Co	16.54	7.6	1.57E−05	4 019.2
Ni	2.56	6.2	8.1E−04	388.6
Li	2.22	6.7	5.2E−05	383.5
Cu	5.93-14	4.3	2.1E−02	907.6
Al	4.7-9.12	4.8	2.5E−08	171.0
Fe	0.04-25	5.2	5.24E-08	39.7
Total	53.3-90.75	-	-	6 350.7

MASS BALANCE AND ESTIMATED VALUE OF METALS IN WEE FOR SOUTHERN POLAND

Eco-efficient WEE recycling provides significant economic benefits. It is estimated that in southern Poland the annual mass of collected WPCBs, WHDs and WLIBs per 1 million inhabitants is approximately 27.2, 13.6 and 45.3 Mg, respectively, and the estimated value of metals in them is approximately 2 499, 135 and 288 thousand USD/year, respectively. For example, in Poland, with a population of 38.4 million, approximately 1,045 Mg of WPCB, 522 Mg of WHD and 1,742 Mg of WLID are collected annually, while the value of the metals for these WEE can be estimated at USD 96 million, USD 5.1 million, and USD 11 million. Therefore, this is a huge opportunity for local companies dealing with WEE recycling.

Table 4 Mass balance and estimated value of metals in WEE (WPCBs, WHDs and WLIBs) for southern Poland in 2024 (average values based on data from three companies located in the Silesian Voivodeship dealing with the collection of WEE)

Description	Unit	Value for		
		WPCBs	WHDs	WLIBs
Mass of WEE collected per 1 million inhabitants of southern Poland	Mg/year	27.2	13.6	45.3
Mass of non-metallic product generated during WEE recycling per 1 million inhabitants of southern Poland	Mg/year	19.3	2.3	3.17 (plastics) 6.79 (organic materials)
Estimated value of metals in WEE per 1 million inhabitants of southern Poland	USD/year	2 499 669	134 737	287 863
Estimated value of metals in WEE collected in Poland	USD/year	96 080 394	5 178 930	11 064 661

RESEARCH ON RECYCLING OF WEE

The following section presents an overview of the research conducted by the authors of the paper in the field of WPCB, WHD and WLIB recycling.

In WPCB recycling, one of the most effective physical methods is electrostatic separation [15,16]. To do this properly, disintegration and grinding are required, preferably using a shredder and a knife mill at cryogenic temperatures [17]. Separation occurs as a result of differences in the surface charge accumulation capacity of the grains and is carried out without the use of process water. Separation results in a mixture of metals and separately ground composite parts. Due to the high purity of the products, the valuable metal mixture can be sold to local metal smelters, while the product consisting of non-metallic parts can be used as a filler in the production of composite materials [18].

In the investigated WHD recycling technology, both the initial mechanical shredding and the subsequent selective separation processes play a key role [19,20]. These steps enable the recovery of several material fractions with different compositions and industrial applications, namely neodymium magnets (NdFeB), aluminium, steel, printed circuit boards (PCB) and plastics. The metal recovery process of hard drives begins with mechanical shredding, allowing the disintegration of components and the release of embedded metals [19]. Then, as a result of granulometric classification and magnetic, gravitational, optical, and electrostatic separation, the following materials with grain sizes are separated [20]: a) neodymium magnets (3.150 mm), b) particles of aluminium, plastics, and printed circuit boards (25-3,15 mm), c) steel (>25 mm).

The pre-treatment process, which can be categorized into various steps such as discharge, dismantling, comminution, classification, separation, dissolution, and thermal treatment, is of essential importance, particularly in the cases of hydrometallurgical extraction and direct recycling of spent LIBs. The pre-treatment process has been shown to improve recovery efficiency and reduce energy consumption in subsequent recycling processes similar to mineral processing for extractive metallurgy [21,22]. The primary objective of the pre-treatment is to separate the various components, such as separators, current collectors, etc., from the black mass of the LIBs in a safe and effective manner [23]. After the pre-treatment process, further recycling of the black mass is carried out using the hydrometallurgical method.

CONCLUSIONS

The growing stream of WEE, driven by global demand for critical metals and concurrent digital and energy transitions, highlights both the urgency and the potential of eco-efficient recycling solutions. As demonstrated in this study, WEE such as printed circuit boards (WPCB), hard disk drives (WHD), and lithium-ion batteries (WLIB) contain valuable metals ranging from copper and precious metals (Au, Ag, Pd) to critical elements (Co, Nd, Li) that can be recovered with substantial economic and environmental gains. Metals with the highest relative supply risk and ADP are: Au, Pd, Pt for WPCB, Nd, Pr, Ce, Dy, Pd, Au for WHD, and Co, Li, Ni for WLIB. It should be noted that the estimated value of metals in 1 Mg of WPCB could be almost USD 92 thousand, while 1 Mg of WHD could give recoverable metals worth approximately USD 9,908, and 1 Mg of WLIB could give a potential metals value exceeding USD 6,351. To assess the profitability of recycling, investment and process costs must also be considered.

The annual mass of WPCB, WHD and WLIB collected per 1 million inhabitants of southern Poland is approximately 27.2, 13.6 and 45.3 Mg, respectively, and the estimated value of metals in them is approximately 2,499, 135 and 28 thousand USD/year, respectively, indicating a large financial potential for companies involved in WEE recycling.

Physical recycling methods such as shredding, grinding, electrostatic, magnetic, optical, and gravity separation complemented in the next step by hydrometallurgical or pyrometallurgical processes enable the recovery of high-value metals at low process costs, lower energy consumption, and limited environmental emissions, with the possibility of using plastics for the production of consumer goods.

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