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Synergizing industrialized and developing countries to improve resource recovery for e-waste: case study Belgium - Kenya

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Abstract

Due to high labor costs, e-waste recycling companies in industrialized countries increasingly adopt destructive mechanical pre-processing based treatments. These processes perform poorly for precious metals and plastics due to material incompatibility and increased entropy, resulting in low effective recycling efficiencies for these material categories. In developing countries most e-waste treatments consist of manual dismantling, followed by primitive refining techniques, which is not only inefficient, but also poses a serious threat to the environment. This article assesses, from an economic and environmental perspective, a cooperation scenario between Belgium and Kenya in which manual dismantling and state of the art metal refining techniques for recycling computers are combined. Findings show that international cooperation could offer a more sustainable solution, yet measures must be taken to avoid the "cherry picking" of valuable components and environmentally unsound disposal of the remaining parts.

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Keywords: E-Waste;WEEE; Recycling; Disassembly.

1. Introduction

Waste prevention and recycling play a primordial role in the European flagship initiative towards a more resource efficient future [1]. In Europe only about 40% of the 2.7 billion tonnes of waste disposed each year is reused or recycled [1]. One of the fastest growing waste streams is the Waste of Electrical and Electronic Equipment (WEEE), which is expected to increase by roughly 11% between 2008 and 2014 in Europe [1]. It is estimated that worldwide 20 to 50 million tonnes of WEEE are annually discarded [2], of which approximately 10 million tonnes are generated in Europe [3].

WEEE treatment represents a technical challenge due to the presence of a complex mix of materials [4]. According to Widmer et al. WEEE contains more than 1000 different substances, of which many are hazardous and others have considerable market value [5, 6]. On average WEEE contains 60% metals, 15% plastics, 12% Cathode Ray Tube (CRT) and Liquid-Crystal Display (LCD) screens, 5% metal-plastic mixture, 2% cables, 2% Printed Wiring Boards (PWB), 3 % pollutants, and 1 % other materials [2].

In industrialized countries, due to boundary conditions, WEEE treatment is mainly based on mechanical size reduction (shredding) followed by automated separation at pre-processing, and high-tech refining processes for the recovery of metals at end-processing [7]. This high throughput scheme yields high recycling rates for ferrous metals, but performs poorly for plastics and Precious Metals (PM). The main reason for this poor performance are the technical limitations of mechanical shredding and automated sorting, which lead to imperfect liberation and separation, resulting in impure fractions and the inevitable loss of materials [8]. Chancerel et al. state that only 38% of the original PMs content in PWBs can be recovered after mechanical shredding [9]. This low recovery efficiency of mechanical pre-processing contrasts with the recovery rate of over 95% of refining processes available in industrialized countries [8, 10]. In this regard Wang et al. conclude that the best End of Life (EoL) treatment

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for PM-rich fractions is to combine manual dismantling with state of the art refining processes [11]. Regarding plastic recycling from WEEE, Peeters et al. demonstrate that by applying disassembly based processes, closed loop recycling of post-consumer engineering plastics with flame retardant is technically feasible and financially viable, whereas shredding based treatment still requires major improvements to become applicable [12].

A significant number of used electronic devices are exported to developing countries, mainly driven by the demand for second-hand products [13]. This helps to bridge the digital divide for developing countries; moreover, refurbishment of Electrical and Electronic Equipment (EEE) offers an income-generating activity for local people. In addition to this influx of used equipment, consumption of new EEE is rapidly growing in developing countries [14]. As a consequence, a dramatic increase of WEEE is expected over the next ten years; Schluep et al. estimate that, compared with 2007, the number of discarded computers will be five times higher in India and two to four times higher in China and South Africa by 2020 [10]. WEEE treatment in emerging economies is characterized by informal activities: manual dismantling, open burning of PWBs and cables to recover metals, and open dumping of residues are common practice in most countries [15]. These informal activities not only have a huge impact on the environment and health [6], but are also extremely inefficient: for example, Schluep et al. estimate an efficiency of only 25 % for gold recovery [15].

It can be concluded from the previous paragraphs that commonly applied recycling practices in industrialized countries and developing countries differ substantially and both have specific strengths and weaknesses. The international cooperation scheme where the strengths of both treatments are combined has been summarized as the Best of 2 Worlds (Bo2W) by the StEP Initiative. Bo2W aims to achieve a sustainable solution for WEEE in developing countries by combining local pre-processing (manual dismantling) and state of the art end-processing in industrialized countries [11]. The objective of this article is to provide insights in the environmental benefits and the financial viability of the Bo2W approach. To do so this paper analyzes a cooperation scheme between Belgium, where a first-level recycling plant and a high-tech metal refinery is located, and the pilot recycling plant “WEEE Centre” in Kenya. This case study focuses on Kenya, since this country is identified to have the potential for Bo2W by Wan et al.[11]. The cooperation scheme is sponsored by the international non-profit organization WorldLoop. This NGO strives to extend the positive impact of ICT projects in developing countries by offsetting the environmental impact of its hardware through facilitating the creation of sustainable WEEE recycling solutions [16].

2. Materials and Treatment Methods

2.1. Product Composition

The selected products are two main components of a desktop computer: the Central Processing Unit (CU) and CRT monitor. The material composition of the CU as well as the PM content of its PWBs is based on Gmünder’s analysis [17] and summarized in the first two columns of Table 1. The assumption that Hard Disk Drive (HDD) magnets are made of Neodymium is included. Moreover, the material composition of the CRT is based on a 14” display characterized by Lee and His [18]. The CRT unit is mainly composed of different kinds of glass: panel glass, made of strontium/barium oxides in front of the monitor; funnel glass, leaded glass that covers the CRT unit; neck glass, highly leaded glass that covers the electron gun; and frit glass, highly leaded glass that results from welding the funnel glass to the panel glass. Aside from the glass, the CRT unit contains a ferrous shadow mask and an electron gun. A summary of the CRT materials is presented in the first two columns of Table 2. The PM content of the PWBs is based on the estimation made by Hageluken [19] and the phosphor content on Resende and Morais [20].

2.2. Current Treatment Processes in Industrialized Countries

The analyzed treatment scenario for CUs in industrialized countries consists of a combination of manual and automated processes:
Smashing: The products are smashed for initial opening and dismantling while limiting the crushing of components.
Manual sorting: The material obtained by the smashing process is fed onto conveyors for manual picking of valuable materials such as PWBs and wires. At this point three assumptions are included: 1) 80% of the motherboards are manually sorted after smashing, 2) no PM losses occur in the smashing, 3) the remaining 20% is shredded and sorted by means of automated equipment.
Size reduction: The remaining material is shredded to small particles.
Automated sorting: The shredded material is sorted based on physical properties. The efficiencies of the pre-processing separation and the automated sorting shown in Table 1 are based on the estimations made by Chancerel et al. [9].

In the proposed scenario, PM-rich material and PWBs are sent to an integrated smelter refinery with a recovery efficiency of 95% for gold, silver and palladium [8, 10]. The separated aluminium, ferrous and non-ferrous fractions are sent to metal smelters where no material losses are assumed. Since plastic housings of CRT monitors and CUs may contain a high concentration of banned substances, such as Brominated Flame Retardants (BFR): Penta-BDEs, Octa-BDEs and Deca-BDEs [21], it is assumed that in industrialized countries all plastic housings are incinerated with energy recovery along with the rest fraction. Incineration is conducted in facilities with proper flue gas treatment systems.

For the economic analysis presented in Table 1, the recycling efficiency and the prices of secondary materials are used to calculate the material revenue. The commercial prices of secondary materials are based on data from literature; the processing costs are based on the study of Cryan et al. [22], who estimate the processing costs and investment required for mechanical treatment of WEEE in the UK. Both operating costs and overhead costs are included in the estimation. The treatment cost for the extraction of PMs in a metal refinery is estimated to be 1.2 €/kg of PWBs, regardless of the PM concentration [23] .

The environmental performance of mechanical treatment, which is summarized in Figure 1, is calculated utilizing the Life Cycle Assessment database Ecoinvent v2.2, and the ReCiPE H/A method, through the software SimaPro 7.3. The avoided environmental impact thanks to metal recycling was modeled as the subtraction of the impact of production of "secondary material at refinery" from the impact of the avoided natural resource extraction. The data record of plastic disposal of consumer electronics in municipal incineration was used to model the impact of plastic incineration.

For the treatment of CRT monitors in industrialized countries, a combination of manual dismantling followed by mechanical treatment is adopted as the most common procedure. The analyzed process consists of:

Dismantling: Monitors are dismantled to separate the CRT unit, PWBs, cables, plastic shell, yoke and metals. 5 minutes of manual labor and 100 % separation efficiency are assumed, based on observations, for this manual dismantling step.

Automated size reduction: The CRT unit is shredded to small particles.

Automated sorting: The ferrous metals of the shadow mask are sorted by a magnetic separator. The phosphor is washed from the glass and the leaded glass is separated from the panel glass by means of density separators with an efficiency of 95 % [24].

In this scenario, PWBs are sent to an integrated metal refinery after separating the aluminium capacitors. The plastic shell is incinerated with energy recovery and cables are treated in a copper smelter with an appropriate flue gas system. The separated panel glass is assumed to be landfilled, whereas the leaded glass is utilized as a fluxing agent by metal smelters, such as Metallo-Chimique [24, 25]. Similarly to the economic analysis for CUs, the material revenue shown in Table 2 is calculated accounting for material recovery efficiency and the price of recyclates. The processing cost of 0,22 €/kg is based on the estimation by Zumbuehl for a Swiss plant [25]. The environmental assessment for recycling metals and plastics is performed in the same fashion as for CUs. In addition, the impact of lead recycling and landfilling of glass is included.

2.3. Current Recycling Processes in Developing Countries

The analyzed scenario for EoL treatment of CUs in developing countries is entirely based on manual dismantling; 100% separation efficiency is assumed. Informal recyclers dismantle the CU and its valuable components: HDD, Compact Disk Drive (CDD), Floppy Disk Drive (FDD), and Power Supply (PS). As no PM refinery is available in Kenya, PWBs are commonly sold to Chinese traders, who presumably use cyanide leaching to recover gold, as hydrometallurgical refining processes are operational in China [26, 27]. Assessing the gold recovery efficiency for PWBs, Keller estimates that cyanide leaching extracts only 10% of the gold present [28]. Ferrous metals and aluminium are sold on local markets and treated by smelters. Open burning of wires for copper recovery is assumed to have a recovery rate of 92%. Furthermore, plastics are modeled as being disposed in an urban landfill.

The performed economic assessment of recycling in developing countries focuses on material revenue: no labor or process costs are included, thus the presented values in Table 1 and 2 represent the upper revenue limit for this scenario. The prices of recyclates in Kenya differ only slightly from the prices in Belgium [29], so the same price was used for the economic evaluation. The environmental evaluation of the cyanide leaching was modeled in SimaPro utilizing the inputs and outputs described by Keller [28]. The emissions from the waste solution to the drain are modelled as emissions to surface water. The emissions of open air burning of cables and PWBs are based on the research of Gullett et al. [30]. The emissions to air are modeled as emissions in highly populated areas to resemble the direct exposure of informal recyclers, whereas the residual ash is modeled as emissions to soil in urban areas. Aluminium, copper and steel end up at regional smelters, which typically have no flue gas treatment, so paints and organic material cause undesired emissions [10]. However, due to lack of data the environmental impact of aluminium, steel and copper recycling is assumed to be similar to the processes operated in industrialized countries. The landfilling of plastics is modelled as disposal in sanitary landfill. It is worth noting that this process does not fully account for the leaching of hazardous substances such as specific BFRs.

The modeled treatment for CRT monitors by informal recyclers is as follows: PWBs, cables and yoke, copper components, and aluminium and ferrous metals are manually extracted. PWBs are sold to Chinese recyclers, cables and yoke are burned in open air to remove plastics and then melted to recover copper. The CRT unit is smashed to recover the electron gun and the ferrous mask. The non-valuable fractions, such as plastics and most of the CRT unit, are modelled as being landfilled in an uncontrolled manner, which involves a high risk for leaching lead and phosphors.

The economic analysis for CRT monitors shown in Table 2 is similar to the aforementioned analysis performed for CUs. The environmental impact of dumping leaded glass is of great concern as Musson et al. indicate in their study [31]. However, this impact is not considered because of the lack of data on the leaching of lead and phosphors and possible long term effects in Kenya.

2.4. International Cooperation

WorldLoop has set up an international cooperation, in which CUs are manually disassembled in a pilot plant in Nairobi and multiple fractions that cannot be treated in South-East Africa are shipped to Belgium. In the analyzed scenario, PWBs and cables are manually disassembled from CUs and shipped to Belgium to be treated in an integrated copper smelter. Aluminium, copper and ferrous fractions are locally treated by smelters in Kenya.

Table 1. Economic Comparison of Current Recycling Processes with International Cooperation for the Treatment of EoL CUs.

		Industrialized Countries				**Developing Countries: Informal Sector**				**International Cooperation**			
Fractions /Materials	Mass (g)	Recovery Rate Pre-processing (%)	Recovery Rate Precious Metals (%)	Material Value (€/ kg)	Material Revenue (€)	Recovery Rate Pre-processing (%)	Recovery Rate Precious Metals (%)	Material Value (€/ kg)	Material Revenue (€)	Recovery Rate Pre-processing (%)	Recovery Rate Precious Metals (%)	Material Value (€/ kg)	Material Revenue (€)
Ferrous	6544	91		0.27 [18]	1.58	100		0.27 (c)	1.77	100		0.27 (c)	1.77
Plastics	930	100		-0.12 [19]	-0.11	0		-	0.00	100		0,095 [29]	0.09
Non-Ferrous (Al)	404	67		0.94 [20]	0.25	100		0.94 (c)	0.38	100		0.94 (c)	0.38
PWB (Motherboard)	906	82.8	95	6 [29]	4.50	100	10.2	1.75 (b)	1.58	100	95	6 [29]	5.43
PWB PS	167	14	95	0.6 (a)	0.01	100	10.2	0.48 (b)	0.08	100	95	0.6 (a)	0.10
PWB (Other)	289	14	95		0.41	100	10.2		0.50	100	95		2.70
PWB CDD	98	14	95	10.95 (a)	0.15	100	10.2	1.42 (b)	0.14	100	95	10.95 (a)	1.08
PWB FDD	44	14	95	8.74 (a)	0.05	100	10.2	0.88 (b)	0.04	100	95	8.74 (a)	0.38
PWB HDD	41	14	95	7,15 [29]	0.04	100	10.2	2.67 (b)	0.11	100	95	7,15 [29]	0.30
Other PWB	105	14	95	0.77-1.79 (a)	0.16	100	10.2	0.35-1.04 (b)	0.21	100	95	0.77-1.79(a)	0.94
Cables	235	100		1.6 [21]	0.38	100		1.6 (c)	0.38	100		1.6 (c)	0.38
Copper	140	67		3.35 [22]	0.31	100		3.35 (c)	0.47	100		3.35 (c)	0.47
Neodymium magnet	21	0		21.46 [23]	0.00	0		21.46 (c)	0	100		21.46 [23]	0.45
Total	**9637**				*7.32*				*5.08*				*11.77*
Transport + Processing costs (€)					*1.14*				*0*				*1.85*
Profit (€)					**6.18**				**5.08**				**9.92**

(a) Calculated based on PM content by Gmünder [17] and recovery efficiencies in integrated metal refinery; (b) Calculated based on PM content by Gmünder [17] and recovery efficiencies in the informal sector; (c) Assumed to be similar to the price in industrialized countries

Table 2. Economic Comparison of Base Lines and Scenario with International Cooperation for CRT monitor.

		Industrialized countries				**Developing Countries: Informal Sector**				**International Cooperation**			
Fractions /Materials	Mass (g)	Recovery rate Pre-processing (%)	Recovery Rate Precious Metals (%)	Material Value (€/ kg)	Material Revenue (€)	Recovery rate Pre-processing (%)	Recovery Rate Precious Metals (%)	Material Value (€/ kg)	Material Revenue (€)	Recovery rate Pre-processing (%)	Recovery Rate Precious Metals (%)	Material Value (€/ kg)	Material Revenue (€)
Plastics	2030	100		-0.12 [19]	-0.24	0		-	0.00	100		0.095 [29]	0.19
Leaded glass	1731	100		-0.11 [24]	-0.19	0			0.00	100		-0.11 [24]	-0.19
Ferrous	1375	95		0.27 [18]	0.35	62		0.27 (c)	0.23	100		0.27 [18]	0.37
Cables	660	100		1.6 [21]	1.06	100		1.6 (c)	1.06	100		1.6 [21]	1.06
Copper	400	67		3.35 [22]	0.90	100		3.35 (c)	1.34	100		3.35 [22]	1.34
Phosphor dust	3	100		-0.12 [24]	-0.0004	0			0	100		-0.12 [24]	-0.0004
PWB	1350	100	95	1.39 (a)	1.88	100	10.2	0.93 (b)	1.26	100	95	1.39 (a)	1.88
Aluminum	250	100		0.94 [20]	0.24	100		0.94 (c)	0.24	100		0.94 [20]	0.24
Barium /Strontium glass	3156	95		-0.06 [19]	-0.18	0			0.00	100		-0.06 [19]	-0.19
Total	**10955**				*3.81*				*4.11*				*4.70*
Transport + Processing costs					*3.22*				*0*				*2.58*
Profit					**0.59**				**4.11**				**2.12**

(a) Calculated based on PM content by Hagelüken [19] and recovery efficiencies in integrated metal refinery ; (b) Calculated based on PM content by Hagelüken [19] and recovery efficiencies in the informal sector ;(c) Assumed to be similar to the price in industrialized countries

Plastics are recycled to make fences and planks by a local company in Nairobi which aims to prevent the felling of hardwood by recycling plastics. It should be noted that currently there is no regulation in place on hazardous substances for plastic recycling in Kenya. The operational costs are estimated with a wage of € 0.85 per hour in Kenya and the costs of infrastructure and overhead are allocated to both CUs and monitors on the basis of the time required for disassembling these products. By measuring the time involved, it was determined that complete disassembly of a CU takes 42 minutes in the Kenyan setting. Shipping costs are estimated to be € 0.3 /kg for PWBs and € 0.1 /kg for shredded plastics. This estimation is based on prices for transport by truck from Nairobi to Mombasa and by ship from Mombasa to Antwerp and either the weight or volume limitation of different sizes of containers. The environmental model for the extra transport accounts for 11800 km by ship and 500 km by truck; the entries 'transoceanic freight ship' and 'lorry 20-28 t fleet average' are used from Ecoinvent. The recycled plastics are modeled to avoid the harvesting of timber. Due to lack of data, the assessment does not include the effects of emissions from the recycling process and leaching of hazardous substances possibly present in plastics.

The scenario for CRT monitors consists of complete manual disassembly; furthermore heat sinks and cables are removed from PWBs prior to being shipped to Belgium, whereas manually cleaned steel, aluminium and copper fractions are sold to local smelters in Kenya. Plastics are locally recycled to make fences and planks. Dismantling of the CRT unit is performed with hot wire techniques to separate the funnel and the panel glass, and phosphor is removed by suction cleaning. Subsequently the ferrous shadow mask is extracted. The leaded glass is sent for proper treatment in facilities in industrialized countries [24, 25]. The strontium glass is locally landfilled and the phosphor is shipped to Belgium for storage. The economic assessment is similar to the one for CUs; the measured disassembly time for a monitor is 22 minutes. Processing costs include estimates for infrastructure and administration in Kenya. The transport cost of the leaded glass is estimated to be 0.1 €/kg. For the environmental assessment, the impacts of transport and plastics recycling are included as previously explained for CUs.

3. Discussion

As shown in Tables 1 and 2, a 60 % higher profit can be achieved by implementing a scenario with international cooperation for the treatment of EoL CUs compared to the analyzed recycling processes in industrialized countries. This difference is mainly due to the low recovery efficiency of PMs when PWBs are shredded. Due to the higher profit, almost double of the material revenue obtained by informal recyclers, this scenario allows cooperation with the informal recycling sector as well as components trade with the latter. With respect to CRT monitors, the material revenue obtained is 24% and 14 % higher than the scenarios in industrialized and developing countries respectively. PWBs and copper contribute most to the recovered material value, but as the main PWBs are manually dismantled, the extra material revenue compared to the mechanical treatment comes mainly from copper and from the recycled plastics. As for the treatment in developing countries, the techniques applied by the informal sector for copper recycling achieve high recovery rates. The additional material revenue comes mainly from PM and recycled plastics. Since manual labour is required in industrialized countries for dismantling monitors, most of the material revenue is absorbed by the high processing costs, resulting in almost four times less profit. It is worth noting that in industrialized countries environmentally sound treatment of hazardous fractions represents a cost, whereas the informal sector in developing countries avoids these costs by non-controlled disposal of problematic fractions.

The results of the environmental assessment for the treatment of CUs are shown in Figure 1. The scenario of international cooperation (Int. C) performs better; the differences between scenarios are almost completely due to the increased PMs recovery. This clearly illustrates the key role of pre-processing in resource efficiency. The environmental performance of the informal sector in developing countries is rather poor, which is mainly due to the limited recovery of PMs and the impact related to open air burning and uncontrolled disposal of residues. It is also interesting to highlight that the environmental impact of the extra transport of dismantled components from Kenya to Belgium is almost negligible compared to the environmental impact of the recycling process. With respect to CRT monitors, the environmental evaluation shows that international cooperation performs better, but the differences are not as noticeable as for CUs. The main contributor is the higher copper recovery from the deflection coil by disassembly in developing countries compared to the copper recovery efficiency of post-shredder separation processes in industrialized countries.

It can be concluded that for components with a high concentration of PMs international cooperation offers clear opportunities due to cheaper labour costs, which makes manually disassembling WEEE more economically attractive. In this scheme the additional material revenue can pay for the environmentally sound treatment of problematic fractions such as leaded glass.

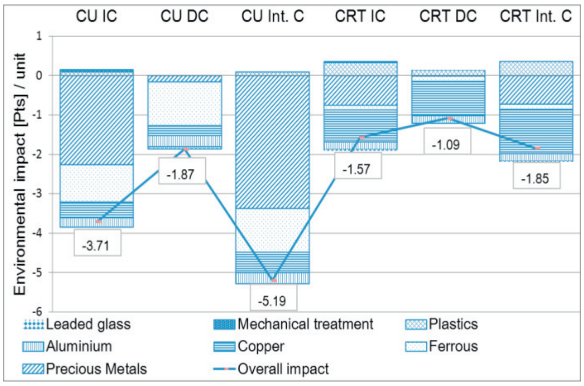

Figure. 1. Environmental evaluation for scenarios of CUs and CRTs

4. Conclusions

By combining manual disassembly and sorting with state of the art end-processing, international cooperation for WEEE treatment offers great opportunities to significantly improve the recovery of resources in a sustainable manner. These cooperative arrangements enable developing countries to access high-tech processes for the environmentally sound treatment of hazardous substances. Furthermore, international recycling cooperation is expected to have a positive social impact through the creation of jobs in emerging economies. However, measures must be taken in order to set up minimum standards for treatment of WEEE in developing countries that safeguard social conditions and environmentally sound processes, and prevent the “cherry picking” of valuable components and uncontrolled disposal of other fractions.

In the analyzed scenarios, about 80% of the material revenue comes from PMs, especially from gold. Therefore, the PM content and more specifically gold content and price play a crucial role. Special attention is required for the evolving material composition of PWBs and fluctuation of PM prices at the moment of setting up long term international cooperation schemes. Therefore, integrated information channels among producers, recyclers and researchers are essential to tune recycling cooperation schemes accordingly.

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