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**Article:**

Cucchiella, F., D'Adamo, I., Lenny Koh, S.C. et al. (1 more author) (2016) A profitability assessment of European recycling processes treating printed circuit boards from waste electrical and electronic equipments. Renewable and Sustainable Energy Reviews, 64. pp. 749-760. ISSN 1364-0321

https://doi.org/10.1016/j.rser.2016.06.057

Acepted by Renewable and Sustainable Energy Review (published in 2016, vol 64, pp. 749-760)

# A profitability assessment of European recycling processes treating printed circuit boards from waste electrical and electronic equipments

## Abstract

The management of Waste from Electric and Electronic Equipments (WEEEs) is a well-stressed topic in scientific literature. However, both (i) amounts of cash flows potentially reachable, (ii) future profitability trends, and (iii) reference mix of treated volumes for profitability optimization are not so clear, and related data are hardly recoverable. The purpose of the paper is trying to fill in this gap by identify the presence of profitability within the recovery process of Waste Printed Circuit Boards (WPCBs) embedded into WEEEs. Net Present Value (NPV) and Discounted Payback Time (DPBT) will be used as reference indexes for the evaluation of investments. In addition, a sensitivity analysis on critical variables (plant saturation, materials content, materials market prices, materials final purity level, PCBs purchasing and opportunity costs) will demonstrate the robustness of results. Finally, the calculation of NPVs for each of the EU-28 nations (in function of both WPCB mix and generated volumes) and the matching of predicted European WPCBs volumes (within the 2015-2030 period) and NPVs will quantify the potential advantages coming from these End of Life practices.

**Keywords:** Economic Analysis; Recycling; Waste from Electric and Electronic Equipments; Waste Printed Circuit Boards

**Nomenclature**

| | | | |
|---|---|---|---|
| Au: | gold | inf: | rate of inflation |
| $C_a$: | acquisition cost of WPCBs | $lm_{pp}$: | lost materials in pretreatment process |
| $C_a^u$: | unitary acquisition cost of WPCB | $lm_{rp}$: | lost materials in refinement process |

| | | | |
|---|---|---|---|
| $C_{cm}$: | conferred material cost | n: | lifetime of investment |
| $C_{cm}^{u}$: | unitary conferred material cost | $n_d$: | number of days |
| $C_d$: | disposal cost | $n_{debt}$: | period of loan |
| $C_d^u$: | unitary disposal cost | $n_h$: | number of hours |
| $C_e$: | electric power cost | $n_{op}$ | number of operators |
| $C_e^u$: | unitary electric power cost | $n_{hrm}$: | number of hazardous recycled metals |
| $C_i$: | insurance cost | $n_{rm}$: | number of recycled metals |
| $C_{inv}^{u}$: | unitary investment cost | $n_{nrm}$: | number of non recycled metals |
| $C_l$: | labour cost | NPV: | net present value |
| $C_l^u$: | unitary labour cost | $O_t$: | discounted cash outflows |
| $C_{lcs}$: | loan capital share cost | PCBs: | printed circuit boards |
| $C_{lis}$: | loan interest share cost | $p_e$: | % of envelope |
| $C_m$: | maintenance cost | $p_{ed}$: | % of “dangerous” envelope |
| $C_{rem}$: | reactant materials cost | $p_h$: | hourly productivity |
| $C_{rem}^{u}$: | unitary reactant materials cost | $p_i$: | % of insurance cost |
| $C_{tax}$: | taxes | $p_m$: | % of maintenance cost |
| $C_{tax}^{u}$: | unitary taxes | $p_{rm,j}$: | % of metal j in 1 kg of WPCB |
| $C_{tr}$: | transportation cost of the plant | Pd: | palladium |
| $C_{tr}^{u}$: | unitary transportation cost of the plant | $pl_{rm}$: | purity level of recycled metal |
| Cat: | category | $pr_{rm}$: | price of recycled metal |
| Cu: | copper | $Q_{P\text{-}srm,j}$: | quantity of powders (selling recycled metal j) |
| $d_{tf}$: | distances of transportation of the plant | $Q_W$: | quantity of WPCBs |
| DCF: | discounted cash flow | r: | opportunity cost |
| DPBT: | discounted payback time | $r_d$: | interest rate on loan |
| EEEs: | electrical and electronic equipments | t: | time of the cash flow |
| EU: | european union | WEEEs: | waste from electric and electronic equipments |
| $e_u$ : | energy power | | |

| | | | |
|---|---|---|---|
| $I_t$: | discounted cash inflows | WPCBs: | waste printed circuit boards |

## 1. Introduction

The mass electronics sector is one of the most important sources of wastes, both in volumes [1, 2] and in materials content terms [3, 4], with dangerous effects on the environment. In fact, even if great improvements in the e-waste recovery (with relevant increases from the sustainability point of view) were done in comparison with decades ago, current performances are yet too low for counteracting the annual increase of generated wastes, especially if we consider WPCBs, or the most complex, hazardous, and valuable component of e-wastes [5-8]. In addition, also from a supply chain point of view, improvements of collaboration between different actors were limited [9, 10]. To this aim, an important objective is the creation of a more efficient, lower cost and sustainable closed loop system [11, 12]. Basic guidelines for the reuse, recovery and recycling of WEEEs were established all over the world in the last decades, and lots of authors analysed and compared different WEEEs directives and national recovery systems [13-15]. However, all these analyses were either rarely or superficially assessed [16, 17]. In particular:

- WEEEs volumes are clearly increasing and their economic potentials was already assessed by the experts. However, they considered entire e-wastes, and not Printed Circuit Boards (PCBs) [18];
- Interesting economic models were already tested in different industrial contexts (e.g. the automotive sector), but not in the mass electronic industry [19].

Given that, the first aim of this paper is assessing the potential profitability characterizing all the phases of a typical PCBs recovery process focused on WEEEs, in different plants configurations. Secondly, potential profits will be exploited for both the comparison of different mixes of WPCBs treated by multi core plants and the definition of future profitability trends in Europe. These data could assist governmental and industrial actors during the definition of corrective measures on current directives.

The paper is organized as follows: Section 2 presents the research framework and a description of the economic model considered within this work. Main results are presented in Section 3. Additionally, a sensitivity analysis on the main critical variables (Section 4) and an overall discussion of results (Section 5) are conducted. Section 6 presents concluding remarks and future perspectives.

## 2. Research framework

PCBs are the most valuable component embedded into Electric and Electronic Equipments (EEEs). The current amount of electronic systems is impressive. Only by considering that, on average, a PCB accounts for almost 3% of the overall weight of a WEEE, the expected volumes of PCBs are enormous and accountable in several million tons [20]. However, current WEEE directives (based on weighting principles) seems to do not adequately take into account their management [6, 21].

### 2.1 European WEEEs volumes

The entire work presented within this paper starts from the overall amount of WEEEs generated in EU28 in 2012 [22]. It was selected as reference year because 2012 is the last year with data referred to all EU28 nations. These date were, then, divided into categories (Cat), by following the WEEE classification guideline defined in the WEEE Directive. Among them, only four were selected because of their relevance (about 93.1%) on the overall amount of WEEE volumes. By following this classification (Cat1, Cat2, Cat3 and Cat4): Cat1 WEEEs represent big household appliances (e.g. fridges, washing machines, air conditioners, etc.); Cat2 WEEEs are small household appliances (e.g. microwave ovens, vacuum cleaners, etc.); Cat3 WEEEs represent IT and telecommunication devices (e.g. PCs, tablets, notebooks, smartphones, etc.) and Cat4 WEEEs are mass electronic products (e.g. TVs, monitors, stereos, cameras, etc.). Given these WEEE categories, it was possible to classify the type of PCBs embedded into these products [23]. In fact, Cat1 and

Cat2 WEEEs are re-known to embed low grade PCBs. Instead, Cat3 and Cat4 WEEEs embeds high grade PCBs. Table 1 reports data about WEEE annual generated volumes in EU28.

Table 1

EU28 WEEE collected volumes in in 2012

| | Cat1 | Cat2 | Cat3 | Cat4 | Total | ∑/Total* |
|---|---|---|---|---|---|---|
| Belgium | 50,711 | 11,792 | 19,290 | 26,322 | 116,458 | 93% |
| Bulgaria | 28,043 | 2423 | 3158 | 2014 | 38,431 | 93% |
| Czech Republic | 24,303 | 2994 | 10,047 | 13,877 | 53,685 | 95% |
| Germany | 235,666 | 77,149 | 160,125 | 171,354 | 690,711 | 93% |
| Estonia | 1797 | 346 | 1463 | 1608 | 5465 | 95% |
| Ireland | 22,348 | 2204 | 6809 | 7868 | 41,177 | 95% |
| Greece | 20,018 | 2638 | 5047 | 7577 | 37,235 | 95% |
| Spain | 90,594 | 7050 | 20,679 | 23,876 | 157,994 | 90% |
| France | 256,560 | 27,021 | 66,229 | 104,342 | 470,556 | 97% |
| Croatia | 6620 | 373 | 2929 | 5223 | 16,187 | 94% |
| Italy | 117,004 | 117,000** | 143,400** | 74,000** | 497,378 | 91% |
| Cyprus | 1403 | 132 | 529 | 344 | 2514 | 96% |
| Latvia | 2150 | 356 | 502 | 610 | 4694 | 77% |
| Lithuania | 7927 | 880 | 1844 | 1687 | 14,259 | 87% |
| Luxembourg | 2073 | 456 | 762 | 1299 | 5010 | 92% |
| Hungary | 23,688 | 4357 | 8961 | 4965 | 44,262 | 95% |
| Malta | 859 | 6 | 332 | 273 | 1506 | 98% |
| Netherlands | 59,590 | 7067 | 17,625 | 29,869 | 123,684 | 92% |
| Austria | 31,326 | 7431 | 17,632 | 16,160 | 77,402 | 94% |
| Poland | 82,246 | 16,946 | 27,154 | 25,746 | 175,295 | 87% |
| Portugal | 25,268 | 4355 | 7062 | 5425 | 43,695 | 96% |

| | | | | | | |
|---|---|---|---|---|---|---|
| Romania | 11,399 | 864 | 4976 | 3514 | 23,083 | 90% |
| Slovenia | 4097 | 1016 | 1782 | 1513 | 9430 | 89% |
| Slovakia | 11,372 | 2071 | 2835 | 3222 | 22,671 | 86% |
| Finland | 26,803 | 1912 | 7640 | 14,214 | 52,972 | 95% |
| United Kingdom | 240,887 | 32,432 | 173,720 | 32,161 | 503,611 | 95% |
| Iceland*** | 747 | 68 | 455 | 244 | 1589 | 95% |
| Liechtenstein | 17 | 39 | 43 | 40 | 140 | 99% |
| EU 28 | 1,385,516 | 343,378 | 723,630 | 584,347 | 3,231,094 | 94% |

* = ∑ (Cat1 + Cat2 + Cat3 + Cat4) / Total; ** = Estimated ; *** = Referred to 2010

Source: [22]

### 2.2 PCBs recycling processes

The recycling process can be seen as the sum of three main phases that, starting from PCBs, are able to obtain, as final output, a set of (almost pure) raw materials. These phases can be distinguished in: disassembly, pretreatment and refining [20]. During disassembly, hazardous components (e.g. condensers or batteries) are disassembled from the main board and destined to specific treatments. During pretreatment, PCBs are crushed into micro pieces up to become a uniform powder, through the use of several technologies (e.g. shredders and grinders). Then, powders are separated in metal and non-metal ones by exploiting different physical principles (e.g. density, magnetism, weight, etc.). Finally, metal powders are refined through the available technologies (e.g. pyrometallurgy, hydrometallurgy, or a mix of them), up to obtain almost pure secondary resources [16, 24].

### 2.3 Recycling plants sizing

After having defined the typical phases constituting a PCBs recycling process, the plant sizing phase was done by following the available literature data [17, 25]. This way, the hourly productivity was set in 0.125 t/h and 0.3 t/h (for mobile and field plants, respectively). Furthermore, by considering a working period of 240 days and 8 working hours per day, these are the overall resulting values:

- 240 t powders/year (mobile plant);
- 576 t powders/year (field plant).

These two configurations of a plant are proposed together because, within the EU-28, there are very different distributions of e-wastes from one country to another and within the same country, as evidenced in the previous subsection 2.1.

## 2.4 Economic model

The main features (see Section 1) characterizing almost all of the current economic models focused on e-waste recycling processes can be listed in three points: (i) the focus on a particular phase of the process [17], (ii) the absence of standards in material composition of PCBs taken into account [16], and (iii) the limited set of application fields [26]. In practice, the previous three lacks generated a particular kind of papers, focused on either operational costs comparison or theoretical economic models assessment A recent work covered this literature gap and, basing on the Discounted Cash Flow method (DCF), an economic model able to assess the profitability of a complete PCBs recycling process was proposed [19]. Reference indexes were selected to be Net Present Value (NPV) and Discounted Payback Time (DPBT). A summary of the main formulas constituting the original model are reported below:

$$\mathrm{NPV} = \sum_{t=0}^{n} (I_t - O_t)/(1+r)^t \qquad (1)$$

$$\sum_{t=0}^{\mathrm{DPBT}} (I_t - O_t)/(1+r)^t = 0 \qquad (2)$$

$$I_t = \sum_{j=1}^{n_{rm}} Q_{P-srm,j} * pl_{rm} * pr_{rm,j,t} \qquad \forall t = 1 \dots n \qquad (3)$$

$$0_t = C_{lcs,t}^{2^\circ s} + C_{lis,t}^{2^\circ s} + C_{lcs,t}^{3^\circ s} + C_{lcs,t}^{3^\circ s} + C_{a,t}^{1^\circ s} + C_{d,t}^{2^\circ s} + C_{l,t}^{1^\circ s} + C_{cm,t}^{2^\circ s} + C_{e,t}^{2^\circ s} + C_{i,t}^{2^\circ s} + C_{l,t}^{2^\circ s} + C_{m,t}^{2^\circ s} +$$

$$C_{d,t}^{3^\circ s} + C_{e,t}^{3^\circ s} + C_{i,t}^{3^\circ s} + C_{l,t}^{3^\circ s} + C_{m,t}^{3^\circ s} + C_{rem,t}^{3^\circ s} + C_{tr,t} + C_{tax,t} \qquad \forall t = 1 \dots n \qquad (4)$$

In the previous formulas 1°s means “disassembly” step, 2°s means “pretreatment” step and 3°s means “refinement” step. The profitability of a recycling plant is influenced by two main variables, or materials embedded into WPCBs (identifiable from the primary WEEE category) and plant capacity. For this reason the set of selected scenarios evaluated in this paper are eight, or a combination of four WPCBs groups (Cat1, Cat2, Cat3 and Cat4 WPCBs), as defined in Section 2.1, and two plant sizes (240 t/y and 576 t/y), as defined in Section 2.3.

### 2.5 Economic and technical inputs

Table 2 reports data about economic and technical inputs of the model. Results say that a mobile plant investment cost is evaluated in 639 k€, while the one for a fixed plant is assumed to be 1533 k€ [17, 25, 27, 28]. Economies of scale are the main cause of this difference, quantified in about 29%. The recovered materials evaluation occurs in function of market prices historical trend, within a defined period of time. By taking as reference the March 2014-March 2015 period, monthly observations were gathered from the most relevant websites dedicated on raw materials exchanges [29-31]. Initial assumptions about materials concentrations were taken directly from scientific literature [23]. However, in order to better explain the effects of relevant variables changes, a sensitivity analysis is proposed in the next Section 4.

Table 2

Economic and technical inputs

| Input | | Ref. | Input | | Ref. | Input | | Ref. |
|---|---|---|---|---|---|---|---|---|
| $C_a^u$: | 1195 €/t | [17] | $e_u^{3°s}$: | 3900 kWh/t$^{i}$; | [27] | $n_{hrm}$: | Table 3 | [23] |
| $C_{cm}^u$: | 90 €/t | [32] | | 9500 kWh/t$^{ii}$ | | $n_{rnm}$: | Table 3 | [23] |
| $C_d^u$: | 325 €/t | [17] | $d_{tf}$: | 200 km$^{i}$; 0 km$^{ii}$ | [27] | $p_e$: | 70% | [19] |
| $C_e^u$: | 0.11 €/kWh | [17] | inf: | 2 % | [32] | $p_{ed}$: | 5% | [19] |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $C_{inv}^{u,2°s}$: | 913 €/t$^{i}$; | [17, 25] | $lm_{pp}$: | 20% | [23] | $p_h$: | 0.125 t/h$^{i}$; 0.3 t/h$^{ii}$ | [17, 25] |
| | 646 €/t$^{ii}$ | | lmrp: | 5% | [23] | $p_i$: | 2% | [32] |
| $C_{inv}^{u,3°s}$: | 3860 €/t$^{i}$; | [27, 28] | n: | 5y$^{i}$; 10 y$^{ii}$ | [25] | $p_m^{2°s}$: | 25% | [33] |
| | 2740 €/t$^{ii}$ | | $n_d$: | 240 d | [25] | $p_m^{3°s}$: | 5% | [28] |
| $C_l^u$: | 150 €/d | [34] | $n_{debt}$: | 5 y | [32] | $p_{rnm}$: | Table 3 | [23] |
| $C_{rem}^u$: | 830 €/t | [27] | $n_h$: | 8 h | [25] | $p_{rm}$: | Table 3 | [23] |
| $C_{tax}^u$: | 36% | [27] | $n_{op}^{1°s}$: | 1$^{i}$ ; 2$^{ii}$ | [35] | $pl_{rm}$: | 95% | [23] |
| $C_{tr}^u$: | 0.34 €/(km*t) | [36] | $n_{op}^{2°s}$: | 2$^{i}$ ; 3$^{ii}$ | [17] | $pr_{rm}$: | Table 3 | [29-31] |
| $e_u^{2°s}$: | 50 kW$^{i}$; | [17] | $n_{op}^{3°s}$: | 2$^{i}$ ; 3$^{ii}$ | [17] | r: | 5% | [32] |
| | 141 kW$^{ii}$ | | $n_{rm}$: | Table 3 | [23] | $r_d$: | 4% | [32] |

i = mobile plant ; ii = field plant

Table 3

Characterization of materials embedded into PCBs

| Materials | Cat1 WPCBs | Cat2 WPCBs | Cat3 WPCBs | Cat4 WPCBs | |
|---|---|---|---|---|---|
| | $p_{rm}$ (%) | $p_{rm}$ (%) | $p_{rm}$ (%) | $p_{rm}$ (%) | $pr_{rm}$ (€/kg) |
| Selling materials | | | | | |
| Iron (Fe) | 15.45 | 12.00 | 14.10 | 6.93 | 0.05 |
| Copper (Cu) | 13.00 | 11.00 | 20.00 | 17.25 | 5.13 |
| Silver (Ag) | 0.01 | 0.02 | 0.17 | 0.08 | 480 |
| Gold (Au) (*) | 0.003 | 0.002 | 0.04 | 0.01 | 32,500 |
| Palladium (Pd) | 0.003 | 0.001 | 0.01 | 0.002 | 29,000 |
| Aluminium (Al) | 7.65 | 8.60 | 3.38 | 10.05 | 1.5 |
| Beryllium (Be) | 0 | 0 | 0.002 | 0 | 8.6 |
| Bismuth (Bi) | 0 | 0 | 0.02 | 0.03 | 19.5 |
| Chromium (Cr) | 0.02 | 0.02 | 0.54 | 0.02 | 1.75 |

| | | | | | |
|---|---|---|---|---|---|
| Tin (Sn) | 1.49 | 2.70 | 0.69 | 0.73 | 16 |
| Zinc (Zn) | 1.94 | 1.40 | 1.35 | 1.17 | 1.6 |
| Hazardous materials | | | | | |
| Antimony (Sb) | 0.08 | 0.06 | 0.13 | 0.16 | |
| Arsenic (As) | 0 | 0 | 0.0005 | 0 | |
| Bromine (Br) | 0.16 | 0.01 | 0.82 | 0.39 | |
| Cadmium (Cd) | 0 | 0 | 0.000001 | 0 | |
| Chlorine (Cl) | 0.20 | 0.43 | 0.01 | 0.31 | |
| Lead (Pb) | 1.25 | 3.00 | 0.79 | 1.09 | |
| Nickel (Ni) | 0.07 | 0.11 | 1.13 | 0.26 | |
| Conferred materials | | | | | |
| Plastics | 41.50 | 46.00 | 30.20 | 25.00 | |
| Epoxy | 8.50 | 16.00 | 0.92 | 14.75 | |
| Ceramics | 7.00 | 0 | 15.02 | 13.60 | |
| Glass | 0 | 0 | 2.00 | 0 | |
| Others | 2.20 | 0 | 8.38 | 8.50 | |
| Liquid crystals | 0 | 0 | 0.16 | 0 | |

(*) 0.003% of Au means 30 ppm of Au or 30 grams of Au in 1 ton of PCBs

Source: [23, 29-31]

After having defined the economic model structure (and related input values), all the financial indexes useful for the assessment of the investment will be estimated in Section 3.

## 3. Results

Waste recycling processes represent not only an environmental protection action, but also an economic opportunity. As already presented in Section 2, eight scenarios were analysed in this work, and is clear that the financial feasibility is verified only for two categories of WPCBs (Table 4).

Table 4

Economic indexes – Baseline scenario

| Index | Cat1 WPCBs | Cat2 WPCBs | Cat3 WPCBs | Cat4 WPCBs |
|---|---|---|---|---|
| | | Mobile plant (240 tons of powders/year) | | |
| DPBT (y) | >5 | >5 | 1 | >5 |
| NPV (k€) | -1311 | -1457 | 6605 | -153 |
| $NPV/Q_W$ (€/t) | -5463 | -6071 | 27,521 | -638 |
| | | Field plant (576 tons of powders/year) | | |
| DPBT (y) | >10 | >10 | 1 | 2 |
| NPV (k€) | -3918 | -4539 | 29,963 | 1045 |
| $NPV/Q_W$ (€/t) | -6802 | -7880 | 52,019 | 1814 |

More in detail, positive results are coming from Cat3 WPCBs in both the two plants configurations (NPV is equal to 29,963 k€ and 6605 k€ in fixed and mobile plants respectively), and from Cat4 WPCBs only for field plants (NPV is equal to 1045 k€). DPBT results follows NPV values, and are equal to 1 year for Cat3 WPCBs and 2 years for Cat4 WPCBs. This means that cash flows allow the re-entering from the investment already during the first period of activity. Field plants presents a longer lifecycle than mobile plants (10 years out of 5 years). This aspect, starting from equal gross profits, explains the reaching of greater NPVs (both in positive and negative terms). However, as explained in other papers [17, 37] mobile facilities applications can represent an ideal solution for small countries or cities, where volumes are limited.

The results obtained within this work confirm what described by [19], where NPVs varies in the range 96,626 – 495,726 €/t in a field plant and in the range 12,599 – 66,304 €/t in a mobile plant and DPBTs are equal to one year. The Au percentage in automotive WPCBs is very high (900 – 4200 ppm) and this determines greater profits of their recycling process. Other works that considered a lower Au content (5 ppm) evidenced as, in these cases, the focus must be pointed to other materials (Cu in particular), but this does not guarantee a complete profitability: -83 $/t and 14 $/t in a field and mobile plant respectively with a capacity of 0.125 t/h [17] and 256 $/t in a field plant with a capacity of 0.3 t/h [25]. These last two works do not consider the entire recycling cycle and the same lack is common to [28] setting DPBT to one year for a plant treating WPCBs with 1000 ppm of Au.

For what concerns the Au relevance among revenue items, data showed in Fig. 1 are significant (equal for both the plants configurations): in Cat3 WPCBs are estimated 415 ppm of Au (max value, accounting for 72% of revenues), and in Cat2 are estimated 20 ppm of Au (min value, accounting for 30% of revenues), and they represent the main profitability item. Among other materials, significant is the influence of Pd (with a high market price), and Cu (present in a high percentage).

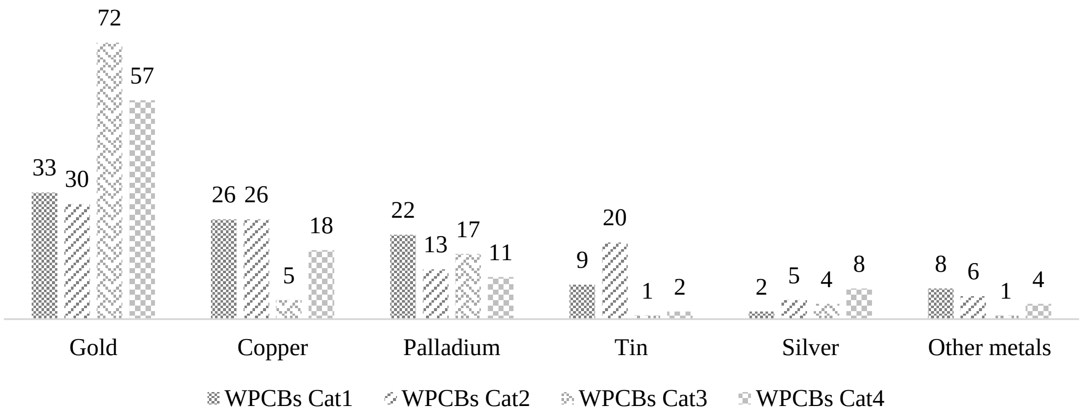

Fig. 1. Plant’s revenues distribution (in percentages)

The costs distribution analysis shows as the operational costs are equal to 94% for a field plant and 87% for a mobile plant (Fig. 2). These results are coherent with respect of what proposed by other works [19, 28]. The most relevant item is represented by WPCBs purchasing both for field and mobile plants (42% and 34%, respectively). This value is followed by labour costs (18% and 21%, respectively). Finally, transport costs are equal to 6.5% in the mobile plant.

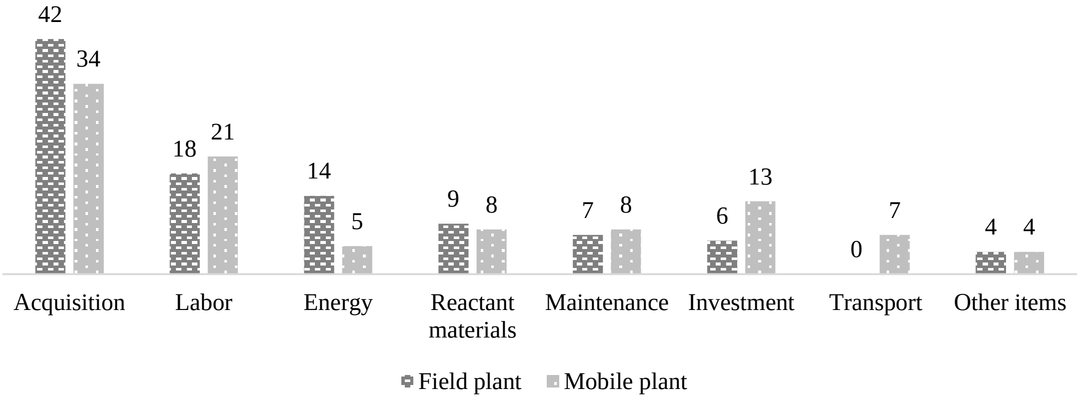

Fig. 2. Plant’s costs distribution (in percentages) – average values

In order to strengthen the obtained results, a sensitivity analysis oriented to alternative scenarios (if compared to what presented before) is implemented in the next section.

## 4. Sensitivity analysis

The obtained results are related to hypotheses on input variables. Hence, a strong variance of the expected economic profitability results could occur. This limit can be overtaken by implementing a sensitivity analysis on critical variables [19]:

- The materials content as percentage of a WPCB total weight for all the four categories. The materials content was already analysed, in fact four categories of WPCBs were evaluated in this paper;
- The materials market price is evaluated for three materials that, more than others, impact on revenues – see Fig. 1 – or Au, Pd and Cu. Pessimistic and optimistic scenarios were analysed where the price was increased or decreased by its standard deviation (28,000-37,000 €/kg for Au, 18,000-28,000 €/kg for Pd and 3.5-6.8 €/kg for Cu respectively);

- The final purity level, applied only to Au because of its high relevance on revenues. Four pessimistic scenarios were analysed, with purity levels reduced within the range 60%-90% in comparison to the initial value of 95% ;
- WPCBs purchasing cost, representing the main cost item. Pessimistic and optimistic scenarios were assessed, with costs variations between 1000 €/t up to 1400 €/t (or an offset of about 200 €/t from the baseline scenario);
- Plant saturation, in which a lower amount of WPCBs in input represents a lower hourly productivity. To this aim, five pessimistic scenarios were assessed, with saturation levels going from 50% up to 90%. For example, considering the mobile plant, 90% of 240 t/h is equal to 216 t/h. Instead, by considering the field plant, 90% of 576 t/h is equal to 518 t/h;
- Opportunity cost, able to evaluate the money value in different periods. Even in this case, an optimistic and pessimistic scenarios are assessed, with values varying from 4% up to 6%;

Table 5.

NPV (k€) in mono-core plants - Sensitivity analysis

| | | Cat1 WPCBs | | Cat2 WPCBs | | Cat3 WPCBs | | Cat4 WPCBs | |
|---|---|---|---|---|---|---|---|---|---|
| | | Field | Mobile | Field | Mobile | Field | Mobile | Field | Mobile |
| Variable | Value | NPV (k€) | | | | | | | |
| $pr_{Au}$ | 37,000 | -3679 | -1255 | -4359 | -1415 | 33,890 | 7522 | 1835 | 36 |
| (€/kg) | 28,000 | -4158 | -1367 | -4720 | -1499 | 26,037 | 5688 | 256 | -343 |
| $pr_{Pd}$ | 28,000 | -3673 | -1254 | -4421 | -1430 | 31,346 | 6928 | 1272 | -99 |
| (€/kg) | 18,000 | -4174 | -1371 | -4662 | -1486 | 28,524 | 6269 | 810 | -210 |
| $pr_{Cu}$ | 6.8 | -3474 | -1207 | -4171 | -1371 | 30,665 | 6769 | 1643 | -10 |
| (€/kg) | 3.5 | -4352 | -1413 | -4899 | -1541 | 29,278 | 6445 | 461 | -285 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $pl_{Au}$ | 90 | -4009 | -1375 | -4608 | -1511 | 28,471 | 6123 | 745 | -275 |
| (%) | 80 | -4191 | -1501 | -4745 | -1619 | 25,485 | 5160 | 145 | -520 |
| | 70 | -4374 | -1628 | -4883 | -1726 | 22,500 | 4196 | -455 | -765 |
| | 60 | -4556 | -1754 | -5020 | -1834 | 19,515 | 3232 | -1056 | -1011 |
| $C_a^u$ | 1400 | -3303 | -1456 | -5186 | -1602 | 29,317 | 6461 | 399 | -302 |
| (€/t) | 1000 | -4565 | -1174 | -3924 | -1320 | 30,578 | 6743 | 1660 | -12 |
| $Q_W$ | 518-216 | -3211 | -1266 | -4323 | -1397 | 26,705 | 5859 | 699 | -226 |
| (t) | 461-192 | -3121 | -1221 | -4110 | -1337 | 23,504 | 5112 | 360 | -299 |
| | 403-168 | -3029 | -1175 | -3894 | -1277 | 20,246 | 4366 | 14 | -371 |
| | 346-144 | -2938 | -1130 | -3681 | -1218 | 17,045 | 3620 | -326 | -444 |
| | 288-120 | -2846 | -1085 | -3464 | -1158 | 13,787 | 2874 | -672 | -517 |
| r | 4 | -4107 | -1344 | -4761 | -1495 | 31,482 | 6796 | 1105 | -153 |
| (%) | 6 | -3743 | -1279 | -4334 | -1421 | 28,551 | 6423 | 989 | -152 |

The obtained results from this section confirm that profitability is not always verified. In particular, in comparison to what presented in Table 4, the plants treating Cat4 WPCBs can have a change in the sign of their NPVs. By considering field plants, NPVs becomes negative when the Au purity level falls to 70% or when the saturation level is 60%. Instead, by considering mobile plants, NPVs become positive when the Au market price is equal to 37,000 €/kg. More in general:

- NPVs are always negative with mobile and field plants treating Cat1 and Cat2 WPCBs;
- NPVs are always positive with mobile and field plants treating Cat3 WPCBs;
- NPVs are almost always negative with mobile plants treating Cat4 WPCBs (18 scenarios out of 19) and almost positive with field plants (15 scenarios out of 19);

In comparison to what proposed in [19], all the proposed critical variables in Table 5 produce significant variations. The cause must be retrieved in the lower Au content characterizing these PCBs. Higher values of NPVs are present in both the plant configurations when the saturation level reaches the 50% for WPCBs pertaining to Cat1 and Cat2 groups (-1085 k€ and -1158 k€

respectively for the mobile plant, -2846 k€ and -3464 k€ respectively for the field plant) and when the Au market price reaches 37,000 €/kg for WPCBs pertaining to Cat3 and Cat4 groups (7522 k€ and 36 k€ respectively for mobile plants, 33,890 k€ and 1835 k€ respectively for field plants). Lower values of NPVs are present in mobile plants when the Au purity level reaches 60% for WPCBs pertaining to Cat1, Cat2 and Cat4 groups (-1741 k€, -1834 k€ and -1011 k€ respectively), and with a saturation level of 50% for WPCBs pertaining to Cat3 (2874 k€). Instead, lower values of NPVs are present in field plants when the WPCBs purchasing cost reaches 1400 €/t for Cat1 and Cat2 WPCBs (-4565 k€ and -5186 k€ respectively), with a saturation level of 50% for Cat3 WPCBs (13,787 k€) and Au purity level of about 60% for Cat4 WPCBs (-1056 k€). However, it is important to evidence as a low saturation level penalizes profitable plants, and offers better results when the plant works in non-profitable conditions (in fact, by augmenting treated WPCBs the costs increase is higher than revenues increases). The limit given by the sensitivity analysis is the absence of an occurrence probability related to each phenomena. However, it is possible to observe as all the scenarios can have positive chances to verify, in fact: (i) the opportunity cost of capital can change because of either the effect of macro-economic conditions related to the specific nation or the nature of investors (private/public capital); (ii) the WPCBs purchasing cost can differ because of the different material composition of WPCBs; (iii) the secondary materials market price can be subjected to great oscillations - the standard deviation is a proxy of their amplitude – reaching their maximum level for precious metals (e.g. Au and Pd); (iv) the Au purity level could fall because of the selection of low performing technologies; (v) the plant’s saturation level is strictly linked to the initial choice in terms of productive capacity and actual working hours. Future research streams could be the risk assessment of these choices. However, it is important to observe as the results proposed in this section can offer a more complete overview on the profitability coming from these mono-core plants. The subsequent section, from one side, will evaluate multi-core plants and, from the other side, will offer an assessment on the economic impact related to the recovery of these wastes in the European market.

## 5. Discussion

The aim of this section is double. From one side, the optimal mix of the four WPCBs categories will be estimated for both the two types of plants. From another side, the quantification of potential revenues coming from the correct management of e-wastes, and the analysis of their expected trends in the next 15 years, will be executed for the four WPCBs categories.

### 5.1 Optimal mix quantification

The first exploitation of data gathered from the Eurostat database about WEEEs generated volumes was the identification of profitability coming from a mix optimization of the four WPCBs categories presented in the previous sections. These economic values derives from the sum of the percentage of WPCBs of a certain category multiplied by the expected amount of materials embedded into them, and results are reported in the following Table 6. However, two considerations have to be done. First of all, no productive setup are considered during the recycling process for the treatment of different WPCBs categories. Second point, waste WPCBs in input are considered to be recovered from specialized suppliers, and no evaluation of generic suppliers is done within this work. These two points could become interesting research objectives for future works.

The economic profitability characterizing only some WPCBs can be a strong obstacle to the development of the recycling sector, also in presence of favourable regulations and proved environmental advantages in n terms of reduced $CO_2$ emissions. The PCBs mix can be a factor able to modify this situation. In this section, the quantification of NPVs related to 28 fractional mixes (equal to 28 European countries assessed and presented in section 2.1) will be presented both for mobile and field plants (Table 6). The main hypotheses taken into account are the following:

- Starting from WEEE volumes presented in Table 1, WPCB volumes were calculated. To this aim, the fractional weight of WPCBs (out of the overall WEEE weight) was defined.

Estimated values are 0.4%, 0.5%, 13% and 11% for Cat1, Cat2, Cat3 and Cat4 WPCBs, respectively [23];

- A multi core-core (and no more a mono-core) recycling plant requires both a dedicated interface with stakeholders from whom PCBs are collected and adequate change in operational phases of the recycling process. Given the lack of information on these aspects, the level of costs is considered to be constant. Instead, from the revenues side, WPCBs are considered as a function of their materials composition, or the fractional mix previously defined. For example, WPCBs recovered from Belgium (4%, 1%, 45% and 50% respectively for categories 1, 2, 3 and 4) present typically 230 ppm of Au, 70 ppm of Pd and 182,600 ppm of Cu.

Table 6

NPV (k€) of multi-core plants in EU-28

| Rkg | Country | Field plant | Mobile plant | Rkg | Country | Field plant | Mobile plant |
|---|---|---|---|---|---|---|---|
| 1° | United Kingdom | 24,825 | 5404 | 15° | Germany | 15,655 | 3261 |
| 2° | Italy | 20,274 | 4341 | 16° | Estonia | 15,653 | 3261 |
| 3° | Iceland | 20,080 | 4296 | 17° | Ireland | 14,678 | 3033 |
| 4° | Hungary | 19,202 | 4090 | 18° | Slovakia | 14,428 | 2975 |
| 5° | Cyprus | 18,447 | 3914 | 19° | Spain | 14,371 | 2962 |
| 6° | Romania | 18,156 | 3846 | 20° | Latvia | 13,960 | 2866 |
| 7° | Malta | 17,183 | 3619 | 21° | Czech Republic | 13,769 | 2821 |
| 8° | Portugal | 16,927 | 3559 | 22° | Belgium | 13,693 | 2803 |
| 9° | Slovenia | 16,823 | 3535 | 23° | Greece | 12,808 | 2596 |
| 10° | Liechtenstein | 16,764 | 3521 | 24° | France | 12,564 | 2539 |
| 11° | Austria | 16,596 | 3482 | 25° | Luxembourg | 12,260 | 2468 |
| 12° | Bulgaria | 15,898 | 3319 | 26° | Netherlands | 12,216 | 2458 |
| 13° | Poland | 15,867 | 3311 | 27° | Croatia | 12,190 | 2452 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 14° | Lithuania | 15,730 | 3279 | 28° | Finland | 11,652 | 2326 |

What is clearly evidenced by results is that profitability is verified in all scenarios and this derives from the presence of Cat3 WPCBs (57.3% in EU-28) and from the quasi-absence of Cat1 and Cat2 WPCBs within the related fractional mix (3.4% and 1% in EU-28, respectively). NPVs are higher in nations where the fractional mix sees a presence of Cat3 WPCBs higher than the European mean value (United Kingdom 83%, Italy 68%, Iceland 67%, Hungary 64%, Cyprus 61% and Romania 60%). The worst result is related to Finland, presenting a fractional data of Cat3 WPCBs equal to 38%. In the subsequent part of the section the analysis of pessimistic scenarios (where the percentage of Cat3 WPCBs will fall to 30%, 20% and 10%) will be implemented. Furthermore, Cat4 WPCBs (presenting a positive NPV in field plants – see Table 4) are hypothesised to have the same weight of Cat3 WPCBs and the remaining part of the mix is equally distributed between the remaining two categories. This way, the assessed scenarios are the following (the numbers represent the percentages related to each WPCB category within the mix of treated WPCBs):

- 20%-20%-30%-30% scenario;
- 30%-30%-20%-20% scenario;
- 40%-40%-10%-10% scenario.

NPVs related to these scenarios are proposed in the following Figure 3.

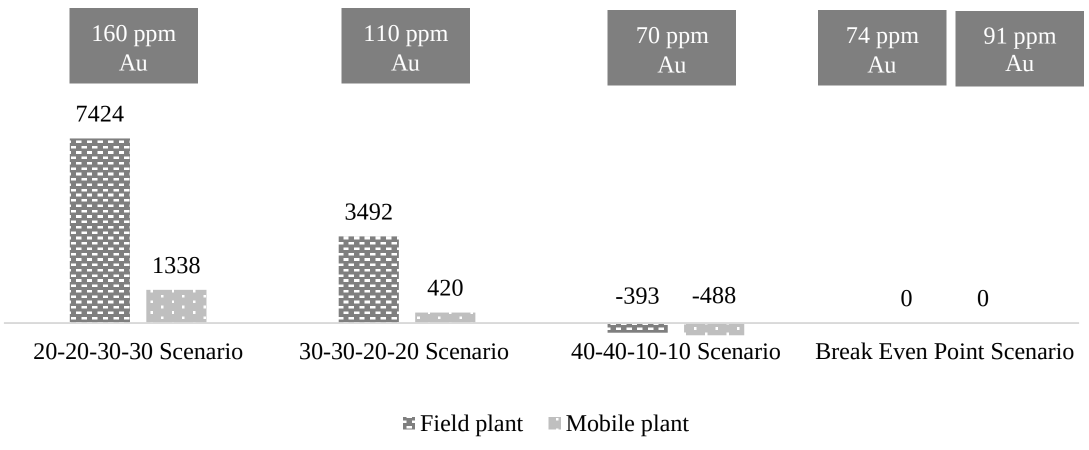

Figure 3. NPV (k€) in multi-core plants – Sensitivity analysis

Results demonstrate that profitability is not always verified. Previously, it was already defined as the content of gold has a great impact on economic results. Here, its effect is evident. For example, by considering an average PCB containing 110 ppm of Au, NPVs are equal to 3492 k€ and 420 k€ for a field and mobile plant, respectively. By decreasing the Au content to 70 ppm, NPVs becomes negative, and both the plants become non-profitable. Hence, it is possible to calculate the specific Break Even Point able to set NPVs to zero by only acting on the Au content. This value was calculated to be equal to:

- 74 ppm of Au for field plants;
- 91 ppm of Au for mobile plants.

Finally, in order to identify the European economic potential coming from the recovery of WPCBs embedded into WEEEs, it is needed to multiply the economic value proposed in Table 6 with the related volumes estimated in 2012 (Table 7).

Table 7

Total NPV (k€) of multi-core plants in EU-28

| Rkg | Country | Field plant | Mobile plant | Rkg | Country | Field plant | Mobile plant |
|---|---|---|---|---|---|---|---|
| 1° | United Kingdom | 1,170,160 | 611,340 | 15° | Greece | 34,691 | 16,875 |
| 2° | Germany | 1,100,186 | 550,016 | 16° | Romania | 33,815 | 17,192 |
| 3° | Italy | 971,921 | 499,450 | 17° | Bulgaria | 20,709 | 10,376 |
| 4° | France | 456,660 | 221,482 | 18° | Croatia | 20,485 | 9889 |
| 5° | Poland | 184,524 | 92,412 | 19° | Slovakia | 19,266 | 9534 |
| 6° | Spain | 140,732 | 69,615 | 20° | Lithuania | 12,462 | 6235 |
| 7° | Belgium | 132,793 | 65,239 | 21° | Slovenia | 12,121 | 6113 |
| 8° | Netherlands | 122,180 | 59,002 | 22° | Estonia | 10,087 | 5043 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9° | Austria | 120,544 | 60,699 | 23° | Luxembourg | 5292 | 2557 |
| 10° | Czech Republic | 69,398 | 34,124 | 24° | Cyprus | 3582 | 1824 |
| 11° | Hungary | 60,430 | 30,892 | 25° | Latvia | 3415 | 1683 |
| 12° | Finland | 53,220 | 25,498 | 26° | Iceland | 3088 | 1586 |
| 13° | Portugal | 47,648 | 24,044 | 27° | Malta | 2262 | 1144 |
| 14° | Ireland | 46,568 | 23,095 | 28° | Liechtenstein | 295 | 149 |

The economic potential related to the recovery of WPCBs embedded into WEEEs is estimated in about 4859 M€ in a scenario with only field plants and 2457 M€ in a scenario with only mobile plants. In comparison to what previously exposed, the role of the fractional mix seems to be less relevant. By assessing the first positions of the ranking presented in Table 7 (by seeing the economic value related to field plants), together with United Kingdom and Italy, there are even Germany and France. These four nations represent almost the 76% of the overall European NPV. This way, the current context delineate a clear picture where the implementation of PCBs recycling plants could improve both environmental and economic performances of the European industrial system.

### 5.2 Future profits quantification

Second aim of this section was the identification of future economic opportunities trend. To do that, the first data required was the overall amount of expected WEEEs generated from 2015 up to 2030. These data, together with related trends, were directly gathered both from Eurostat (regarding 2012 collected volumes in EU28) and literature (regarding the expected growth rate, fixed in about 3% per year even if some author speaks about a 5% rate) [19]. After that, it was possible to predict (with logical approximations) the expected profit (in a min – max range) coming from the correct management of these amounts of WPCBs. The following Table 8 reports all these data. However, it is important to underline the two main hypotheses taken into account, or:

- The growth rate related to each of the four WPCBs categories was considered to be the same;
- Min and max values of NPVs are associated to mobile plants and field plants, respectively.

Table 8

Estimates of generated WPCBs volumes and profits in EU-28 from WEEEs

| | 2012 | 2015 | 2020 | 2030 |
|---|---|---|---|---|
| EU WEEEs expected annual generation (Mtons) | 3.23 | 3.63 | 4.21 | 5.65 |
| EU total PCBs expected annual generation (Ktons) | 161.9 | 167.03 | 193.63 | 260.23 |
| EU total PCBs expected NPVs – min values (M€) | 2457 | 2536 | 2939 | 3950 |
| EU total PCBs expected NPVs – max values (M€) | 4859 | 5013 | 5811 | 7810 |

Sources: [38, 39], self-made analysis

Table 8 reports the potential dimension of the WEEE’s PCBs recycling market. Values are impressive, going from 2.46 billion € up to 3.95 billion € as minimum values, and refer to the baseline scenario presented in Table 6. Maximum levels are even more interesting, going from 4.86 billion € up to 7.81 billion €. However, it is important to underline that minimum and maximum values were calculated on the fractional mix. These numbers, even if theoretical, demonstrate the utmost importance of WEEE’s PCBs management and the amount of profits that could be potentially achieved. Without any doubt, this research will play a critical role in improving society and the world in terms of reducing waste, improving recycling, reducing reliance on natural, rare earth and precious materials, and improving resource efficiency and circular economy in key manufacturing processes where we rely on these materials. Interesting improvements of this work could be the assessment of environmental impacts of the recycling process, the analysis of different business models for the End of Life management of complex products, the proposition of corrective actions to current directives, and the assessment of recycling issues related to future waste streams.

## 6. Conclusions

Waste from Electric and Electronic Equipments are one of the most important sources of secondary raw materials. However, studies demonstrating their economic potentials are quite rare. The paper went in this direction. A quantification of the amounts of materials (and related economic values) potentially recoverable from different types of WPCBs was implemented. Again, the expected profitability coming from WPCBs recycling processes was compared on two different types of plants (mobile and field ones) and into different scenarios, with an increased severity of the context. Furthermore, an assessment of different mixes of WPCBs was implemented for both the identification of the minimum level of Au content guaranteeing the profitability of recycling processes and the identification of the most relevant nations in terms of WEEE generated volumes. Finally, basing on both NPV values and predictions about future WEEE volumes, a quantification of the potential dimension of the recycling market was described for the 2015-2030 period. However, it is important to underline that the obtained economic values are so high, and different from common values available in literature, because of the joined selection of four WEEE streams instead of only one.

## References

[1] Wakolbinger T, Toyasaki F, Nowak T, Nagurney A. When and for whom would e-waste be a treasure trove? Insights from a network equilibrium model of e-waste flows. International Journal of Production Economics. 2014;154:263-73.

[2] Pérez-Belis V, Bovea M, Ibáñez-Forés V. An in-depth literature review of the waste electrical and electronic equipment context: Trends and evolution. Waste Management & Research. 2015;33:3-29.

[3] Rahman S, Subramanian N. Factors for implementing end-of-life computer recycling operations in reverse supply chains. International Journal of Production Economics. 2012;140:239-48.

[4] Lu C, Zhang L, Zhong Y, Ren W, Tobias M, Mu Z, et al. An overview of e-waste management in China. J Mater Cycles Waste Manag. 2015;17:1-12.

[5] Koh SCL, Gunasekaran A, Tseng CS. Cross-tier ripple and indirect effects of directives WEEE and RoHS on greening a supply chain. International Journal of Production Economics. 2012;140:305-17.

[6] Cucchiella F, D'Adamo I, Rosa P, Terzi S. Scrap automotive electronics: A mini-review of current management practicess. accepted by Waste Management & Research. 2015.

[7] Chen M, Zhang S, Huang J, Chen H. Lead during the leaching process of copper from waste printed circuit boards by five typical ionic liquid acids. Journal of Cleaner Production. 2015;95:142-7.

[8] Babar Z, Shareefdeen Z. Management and control of air emissions from electronic industries. Clean Technologies and Environmental Policy. 2014;16:69-77.

[9] Bogataj D, Bogataj M. The role of free economic zones in global supply chains—a case of reverselogistics. International Journal of Production Economics. 2011;131:365-71.

[10] Fahimnia B, Sarkis J, Choudhary A, Eshragh A. Tactical supply chain planning under a carbon tax policy scheme: A case study. International Journal of Production Economics. 2015;164:206-15.

[11] Andriolo A, Battini D, Persona A, Sgarbossa F. Haulage sharing approach to achieve sustainability in material purchasing: New method and numerical applications. International Journal of Production Economics. 2015;164:308-18.

[12] Battini D, Persona A, Sgarbossa F. A sustainable EOQ model: Theoretical formulation and applications. International Journal of Production Economics. 2014;149:145-53.

[13] Sakai S-i, Yoshida H, Hiratsuka J, Vandecasteele C, Kohlmeyer R, Rotter V, et al. An international comparative study of end-of-life vehicle (ELV) recycling systems. J Mater Cycles Waste Manag. 2014;16:1-20.

[14] Kilic HS, Cebeci U, Ayhan MB. Reverse logistics system design for the waste of electrical and electronic equipment (WEEE) in Turkey. Resources, Conservation and Recycling. 2015;95:120-32.

[15] Wang J, Chen M. Management status of end-of-life vehicles and development strategies of used automotive electronic control components recycling industry in China. Waste Management & Research. 2012;30:1198-207.

[16] Ghosh B, Ghosh MK, Parhi P, Mukherjee PS, Mishra BK. Waste Printed Circuit Boards recycling: an extensive assessment of current status. Journal of Cleaner Production. 2015;94:5-19.

[17] Zeng X, Song Q, Li J, Yuan W, Duan H, Liu L. Solving e-waste problem using an integrated mobile recycling plant. Journal of Cleaner Production. 2015;90:55-9.

[18] Cucchiella F, D’Adamo I, Lenny Koh SC, Rosa P. Recycling of WEEEs: An economic assessment of present and future e-waste streams. Renewable and Sustainable Energy Reviews. 2015;51:263-72.

[19] Cucchiella F, D′Adamo I, Rosa P, Terzi S. Automotive Printed Circuit Boards Recycling: an Economic Analysis. Journal of Cleaner Production. 2015.

[20] Hadi P, Xu M, Lin CSK, Hui C-W, McKay G. Waste printed circuit board recycling techniques and product utilization. Journal of Hazardous Materials. 2015;283:234-43.

[21] Nelen D, Manshoven S, Peeters JR, Vanegas P, D'Haese N, Vrancken K. A multidimensional indicator set to assess the benefits of WEEE material recycling. Journal of Cleaner Production. 2014;83:305-16.

[22] Eurostat. Environmental Data Centre on Waste. 2015.

[23] UNEP. Metal recycling: opportunities, limits, infrastructure. 2013.

[24] Ferella F, De Michelis I, Scocchera A, Pelino M, Vegliò F. Extraction of metals from automotive shredder residue: Preliminary results of different leaching systems. Chinese Journal of Chemical Engineering. 2015;23:417-24.

[25] Li J, Xu Z. Environmental Friendly Automatic Line for Recovering Metal from Waste Printed Circuit Boards. Environmental Science & Technology. 2010;44:1418-23.

[26] Wang X, Gaustad G. Prioritizing material recovery for end-of-life printed circuit boards. Waste Management. 2012;32:1903-13.

[27] Cucchiella F, D'Adamo I, Gastaldi M, Koh SCL. Implementation of a real option in a sustainable supply chain: An empirical study of alkaline battery recycling. International Journal of Systems Science. 2014;45:1268-82.

[28] Kamberovic ZJ. Hydrometallurgical process for extraction of metals from electronic waste-part ii: development of the processes for the recovery of copper from Printed Circuit Boards (PCB). Association of Metallurgical Engineers of Serbia. 2011;17:139-49.

[29] London metal exchange. https://www.lme.com/. 2014.

[30] Metalprices. http://www.metalprices.com/. 2014.

[31] InfoMine. http://www.infomine.com/. 2014.

[32] Cucchiella F, D'Adamo I, Rosa P. End-of-Life of used photovoltaic modules: A financial analysis. Renewable and Sustainable Energy Reviews. 2015;47:552-61.

[33] Copani G, Rosa P. Demat: sustainability assessment of new flexibility oriented business models in the machine tools industry. International Journal of Computer Integrated Manufacturing. 2014.

[34] Ardente F, Mathieux F, Recchioni M. Recycling of electronic displays: Analysis of pre-processing and potential ecodesign improvements. Resources, Conservation and Recycling. 2014;92:158-71.

[35] Zeng X, Li J, Xie H, Liu L. A novel dismantling process of waste printed circuit boards using water-soluble ionic liquid. Chemosphere. 2013;93:1288-94.

[36] Zhao W, Ren H, Rotter VS. A system dynamics model for evaluating the alternative of type in construction and demolition waste recycling center – The case of Chongqing, China. Resources, Conservation and Recycling. 2011;55:933-44.

[37] Song Q, Zeng X, Li J, Duan H, Yuan W. Environmental risk assessment of CRT and PCB workshops in a mobile e-waste recycling plant. Environmental Science and Pollution Research. 2015;22:12366-73.

[38] Eurostat. End-of-Life Vehicles statistics. European Commission2014.

[39] Møller Andersen F, Larsen HV, Skovgaard M. Projection of end-of-life vehicles. Development of a projection model and estimates of ELVs for 2005-2030. European Topic Centre on Resource and Waste Management; 2008.