Renewable and Sustainable Energy Reviews 64 (2016) 749–760

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

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

Federica Cucchiella [a], Idiano D'Adamo [a], S.C. Lenny Koh [b], Paolo Rosa [c,*]

[a] Department of Industrial and Information Engineering and Economics, University of L'Aquila, Via G. Gronchi 18, 67100 L'Aquila, Italy
[b] Advanced Resource Efficiency Centre (AREC), The University of Sheffield, Conduit Road, Sheffield S10 1 FL, United Kingdom
[c] Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

ARTICLE INFO

Article history:
Received 21 December 2015
Received in revised form
10 June 2016
Accepted 26 June 2016

Keywords:
Economic analysis
Recycling
Waste electrical and electronic equipments
Waste printed circuit boards
Resource assessment

ABSTRACT

The management of waste electrical and electronic equipment (WEEE) is a well-stressed topic in the scientific literature. However, (i) the amount of cash flows potentially reachable, (ii) the future profitability trends and (iii) the reference mix of treated volumes guaranteeing a certain profitability level are not so clear, and related data are unrecoverable. The purpose of the paper is to fill in this gap by identifying the presence of profitability within the recovery process of waste printed circuit boards (WPCBs) embedded in WEEE. Net present value (NPV) and discounted payback time (DPBT) are used as reference indexes for the evaluation of investments. In addition, a sensitivity analysis of critical variables (plant saturation level, materials content, materials market prices, materials final purity level and WPCBs purchasing and opportunity costs) demonstrates the robustness of the results. Furthermore, the calculation of the national NPV for each of the twenty-eight European nations (in function of both WPCB mix and generated volumes) and the matching of predicted WPCB volumes (within the 2015–2030 period) and NPV quantify potential advantages. The break even point of gold allowing some profits from selected recovery plants goes from 73 to 93 ppm per WPCB ton, for mobile and field plants, respectively. Finally, the overall European values go from 2404 million € (mobile plant) to 4795 million € (field plant) in 2013, with Germany and United Kingdom as reference nations.

Contents

* Corresponding author.
E-mail addresses: federica.cucchiella@univaq.it (F. Cucchiella), idiano.dadamo@univaq.it (I. D'Adamo), S.C.L.Koh@sheffield.ac.uk (S.C. Lenny Koh), paolo1.rosa@polimi.it (P. Rosa).

http://dx.doi.org/10.1016/j.rser.2016.06.057
1364-0321/

1. Introduction

The mass electronics sector is one of the most important sources of waste, both in terms of volume [1] and materials content [2], with dangerous effects on the environment [3,4]. 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, both current recovery performance and recyclability measurement procedures [5] are yet inadequate to counteract the annual increase of generated waste, especially considering WPCBs, or the most complex, hazardous, and valuable component of e-waste [6–8]. Shortfalls also emerge from the point of view of optimization techniques that, even if well explained in the literature and applied in several fields [9,10], are not so common within the EoL context. Consequently, the definition of the goal function [11], the integration of several control parameters [12], the implementation of dedicated simulation models [13] and the application of sensitivity analyses [14] for the definition of future trends [15] are relevant topics scarcely debated by the experts, with a negative impact on the definition of innovative – and more sustainable – end-of-life (EoL) strategies [16–18]. In contrast, basic guidelines for the reuse, recovery and recycling of WEEE were established all over the world in the last decades, and many authors analysed and compared different WEEE directives and national recovery systems [19–23]. However, all these analyses were rarely implemented [24,25]. In particular:

- WEEE volumes are clearly increasing and the experts already assessed their economic potential. However, they considered entire e-waste, and not only printed circuit boards (PCBs) [26];
- Interesting economic models were already tested in different industrial contexts (e.g. the automotive sector), but not in the mass electronics industry [27].

Addressing these gaps, the aim of this paper is multi-fold. First, the potential profitability characterizing all the phases of a typical PCB recovery process focused on four WEEE categories (big household appliances, small household appliances, IT and telecommunication equipments and consumer equipments) and different plant configurations (field and mobile ones) are assessed. Second, the economic profitability is defined for nine products (refrigerators, washing machines, air conditioners, desktop PCs, notebook PCs, mobile phones, CRT TVs, stereo systems, digital cameras) pertaining to three of the previous four categories (given the lack of literature data, small household appliances are not considered). Third, the break even point is set on the gold content of WPCBs, for both field and mobile plants. Fourth, potential profits are compared with different mixes of WPCBs treated by multi-core plants. Fifth, the overall profit of WPCB recycling plants is estimated for each European nation. Finally, future profitability trends are defined for Europe as a whole. These results could assist governmental and industrial actors in defining 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;
- Section 3 describes the results coming from its application within the European WEEE market;
- Section 4 presents a sensitivity analysis on a set of critical variables;
- Section 5 conduces an overall discussion of the results and an estimation of future trends;
- Section 6 presents some concluding remarks and future perspectives.

2. Research framework

PCBs are the most valuable component embedded into Electrical and Electronic Equipments (EEEs). The current amount of electronic systems is impressive. Only considering that, on average, a PCB accounts almost from 3% to 5% of the overall weight of a WEEE, the expected volumes of WPCBs are enormous and accountable in several million tons [28,29]. However, current WEEE directives (applying weigh-based principles) seem to do not adequately take into account their management [8,30].

2.1. European WEEE volumes

The entire work starts from the overall amount of WEEE collected in the EU-28 during 2013 [31]. This year is selected as reference because the most recent data referring to all of the EU-28 nations pertain to 2013. These data are divided into categories (Cat) following the WEEE classification guideline defined within the European WEEE Directive. Among them, only four are selected because of their relevance (about 94%) on the overall amount of WEEE volumes. Following this classification (Cat1, Cat2, Cat3 and Cat4): Cat1 WEEE represents big household appliances (e.g. fridges, washing machines, air conditioners, etc.); Cat2 WEEE represents small household appliances (e.g. vacuum cleaners, toasters, fryers, etc.); Cat3 WEEE represents IT and telecommunication equipments (e.g. PCs, tablets, notebooks, smartphones, etc.) and Cat4 WEEE represents consumer equipments (e.g. TVs, stereo systems, digital cameras, etc.). Given these WEEE categories, it is possible to classify the type of PCB embedded into these products [32]. In fact, Cat1 and Cat2 WEEE are known to embed low grade PCBs. In contrast, Cat3 and Cat4 WEEE generally embed medium-high grade PCBs. Table 1 reports data about WEEE annual collected volumes in EU-28 for each of the four selected categories.

2.2. PCB recycling processes

A generic PCB 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, treatment and refining [28]. During disassembly, hazardous components (e.g. condensers or batteries) and valuable ones (e.g. memories and microprocessors) are disassembled from the main board and destined to specific treatment processes. During treatment, PCBs are crushed into micro pieces up to become a uniform powder, through the use of several technologies (e.g. shredders and grinders). Subsequently, these powders are separated between metal and non-metal ones by exploiting their different physical principles (e.g. density, magnetism or weight). 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 [24,33]. Considering this paper, the refining process taken into account is the hydrometallurgical methodology. However, the

Nomenclature

Au: Gold
C_a^u: Unitary acquisition cost of WPCB
Cat: Category
Cu: Copper
DCF: Discounted cash flow
DPBT: Discounted payback time
EEEs: Electrical and electronic equipments
EoL: End of life
EU: European Union
NPV: Net present value
NPV/Size: Ratio between NPV and size
PCBs: Printed circuit boards
Pd: Palladium
pl_{Au}: Purity level of recycled metal (gold)
pr_{rm}: Price of recycled metal
Q_W: Quantity of WPCBs
r: Opportunity cost
WEEE: Waste electrical and electronic equipment
WPCBs: Waste printed circuit boards

same economic principles could be used to assess also other refining methods, without twisting the overall value of the work. Given both its high sustainability level in comparison to other metal refining methods (e.g. pyrometallurgy and pyrolysis) and the flexibility level of related plants, hydrometallurgy is the optimal choice to implement field and mobile plants [34,35].

A list of materials embedded into generic PCBs pertaining to one of the four categories are presented in Table 3. The metal part of a PCB represents only about 30% of its overall mass and the remaining part is constituted by non-metal elements (plastics, resins and organic materials).

Two kinds of plant (based on the same constructive philosophy) are taken into account, a mobile and a field one. The mobile structure presents a limited capacity, but it can be transferred easily from one site to another. In contrast, the field one presents a greater capacity and can be used to manage higher volumes [25,36].

2.3. Economic model

The main features (see Section 1) characterizing almost all of the current economic models focused on e-waste recycling processes can be summarized in three points: (i) focus on a particular phase of the process [25], (ii) absence of standard materials composition of PCBs taken into account [24], and (iii) limited set of application fields [37]. In general, the previous three lacks implicitly enabled a particular kind of studies, focused on either operational costs comparison or theoretical economic models assessment. A recent work covered this literature gap and, based on the discounted cash flow (DCF) method, an economic model able to assess the profitability of a whole PCB recycling process is proposed [27]. Coherently with this approach, NPV, DPBT and NPV/plant size (NPV/size) are selected as reference indexes. The same model is adopted also in this paper and the main formulas constituting it are reported below:

$$Q_W = p_h * n_h * n_d \quad (1)$$

Table 1
EU-28 WEEE collected volumes in 2013.
Source: [31]

	Cat1	Cat2	Cat3	Cat4	Total	∑/Total*
Belgium	52,112	15,576	18,482	24,961	120,365	92%
Bulgaria	26,341	1677	2851	2224	35,162	94%
Czech Republic	25,925	4112	8753	12,308	54,215	94%
Denmark	32,342	5053	12,797	19,250	72,080	96%
Germany	274,093	91,677	157,357	147,818	727,998	92%
Estonia	1584	321	1138	1397	4658	95%
Ireland	19,463	1883	7197	8954	42,629	88%
Greece	21,172	2961	4641	7305	38,268	96%
Spain	127,972	9636	23,510	37,486	209,505	95%
France	264,468	29,682	64,151	98,673	479,694	95%
Croatia	6228	267	2650	5187	15,025	95%
Italy	222,347**	37,885**	85,664**	82,452**	437,090	98%**
Cyprus	1124	279	477	326	2283	97%
Latvia	2364	448	466	504	4827	78%
Lithuania	8119	1318	3317	1461	16,154	88%
Luxembourg	2364	466	754	1239	5176	93%
Hungary	26,004	5691	9606	6635	49,778	96%
Malta	1005	27	419	230	1704	99%
The Netherlands	58,517	7362	14,437	27,547	117,499	92%
Austria	31,400	7679	17,503	15,223	76,835	93%
Poland	76,518	16,614	30,781	27,736	171,728	88%
Portugal	30,851	5938	7151	4868	50,051	98%
Romania	11,399	864	4976	3514	23,083	90%
Slovenia	4124	515	1497	1775	8539	93%
Slovakia	11,299	2000	3629	2665	22,584	87%
Finland	28,862	3453	8230	14,329	57,919	95%
Sweden	84,744	5484	30,895	46,371	176,567	95%
United Kingdom	262,186	33,423	137,595	33,435	492,490	95%
EU-28	1,715,477	292,291	660,924	636,145	3,513,906	94%

* = ∑ (Cat1 + Cat2 + Cat3 + Cat4) / Total;
** = Estimated on EU-27 average;

Table 2
Economic and technical inputs.

Input		Ref.	Input		Ref.	Input		Ref.
C_a^u:	1195 €/t	[25]	$e_u^{3°s}$:	3900 kW h/t[i];	[39]	n_{hrm}:	Table 3	[32]
C_{cm}^u:	90 €/t	[44]		9500 kW h/t[ii]		n_{rnm}:	Table 3	[32]
C_d^u:	325 €/t	[25]	d_{tr}:	200 km[i]; 0 km[ii]	[39]	p_e:	70%	[27]
C_e^u:	0.11 €/kWh	[25]	inf:	2%	[44]	p_{ed}:	5%	[27]
$C_{inv}^{u,2°s}$:	913 €/t[i];	[25,38]	lm_{pp}:	20%	[32]	p_h:	0.125 t/h[i]; 0.3 t/h[ii]	[25,38]
	646 €/t[ii]		lm_{rp}:	5%	[32]	p_i:	2%	[44]
$C_{inv}^{u,3°s}$:	3860 €/t[i];	[39,40]	n:	5y[i]; 10 y[ii]	[38]	$p_m^{2°s}$:	25%	[45]
	2740 €/t[ii]		n_d:	240 d	[38]	$p_m^{3°s}$:	5%	[40]
C_l^u:	150 €/d	[46]	n_{debt}:	5 y	[44]	p_{rnm}:	Table 3	[32]
C_{rem}^u:	830 €/t	[39]	n_h:	8 h	[38]	p_{rm}:	Table 3	[32]
C_{tax}^u:	36%	[39]	$n_{op}^{1°s}$:	1[i] ; 2[ii]	[47]	pl_{rm}:	95%	[32]
C_{tr}^u :	0.34 €/(km*t)	[48]	$n_{op}^{2°s}$:	2[i] ; 3[ii]	[25]	pr_{rm}:	Table 3	[41–43]
$e_u^{2°s}$:	50 kW[i];	[25]	$n_{op}^{3°s}$:	2[i] ; 3[ii]	[25]	r:	5%	[44]
	141 kW[ii]		n_{rm}:	Table 3	[32]	r_d:	4%	[44]

i=mobile plant ; ii=field plant

Table 3
Characterization of materials embedded into generic WPCBs.
Source: [32,41–43]

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	850
Bismuth (Bi)	0	0	0.02	0.03	11.4
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 g of Au in 1 ton of PCBs

$$Q_e = Q_W * p_e / (1 - p_e) \quad (2)$$

$$Q_{hwd} = Q_e * p_{ed} \quad (3)$$

$$Q_{end} = Q_e - Q_{hwd} - Q_W \quad (4)$$

$$Q_{lmpp} = (1 - lm_{pp}) * Q_W \quad (5)$$

$$Q_{P-rmat} = Q_W - Q_{lmpp} \quad (6)$$

$$Q_{P-rnm} = Q_{P-rmat} * p_{rnm} \quad (7)$$

$$Q_{P-rmbr} = Q_{P-rmat} - Q_{P-rnm} \quad (8)$$

$$Q_{lmrp} = (1 - lm_{rp}) * Q_{P-rmbr} \quad (9)$$

$$Q_{P-rm} = Q_{P-rmbr} - Q_{lmrp} \quad (10)$$

$$Q_{hwr} = Q_{P-rmbr} * q_{hwr} \quad (11)$$

$$Q_{P-rm,j} = Q_{P-rm} * p_{rm,j} * m_u * \left(1 / \sum_{j=1}^{n_{rm}} p_{rm,j} * m_u\right) \quad \forall j = 1..\, n_{rm} \quad (12)$$

$$NPV = \sum_{t=0}^{n} (I_t - O_t)/(1 + r)^t \quad (13)$$

$$\sum_{t=0}^{DPBT} (I_t - O_t)/(1 + r)^t = 0 \quad (14)$$

$$NPV/Size = NPV/QW \quad (15)$$

$$I_t = \sum_{j=1}^{n_{rm}} Q_{P-srm,j} * pl_{rm} * pr_{rm,j,t} \quad \forall t = 1..\, n. \quad (16)$$

$$C_{inv}^{2°s} = C_{inv}^{u,2°s} * Q_W \quad (17)$$

$$C_{lcs,t}^{2°s} = C_{inv}^{2°s} / n_{debt} \quad \forall t = 0..\, n_{debt} - 1. \quad (18)$$

$$C_{lis,t}^{2°s} = \left(C_{inv}^{2°s} - C_{lcs,t}^{2°s}\right) * r_d \quad \forall t = 0 \ldots n_{debt} - 1. \quad (19)$$

$$C_{inv}^{3°s} = C_{inv}^{u,3°s} * Q_{P-rmbr} \quad (20)$$

$$C_{lcs,t}^{3°s} = C_{inv}^{3°s} / n_{debt} \quad \forall t = 0..\, n_{debt} - 1 \quad (21)$$

$$C_{lis,t}^{3°s} = \left(C_{inv}^{3°s} - C_{lcs,t}^{3s}\right) * r_d \quad \forall t = 0..\, n_{debt} - 1 \quad (22)$$

$$O_t = C_{lcs,t}^{2°s} + C_{lis,t}^{2°s} + C_{lis,t}^{3°s} + C_{lcs,t}^{3°s} + C_a^u * Q_W + C_l^u * n_d * n_{op}^{1°s} + C_d^u * Q_{hwd} + \quad \forall t = 1..\, n. \quad (23)$$

$$C_{cm}^{u} * Q_{P-rnm} + C_{e}^{u} * (e_{u}^{2^\circ s}/p_{h}) * Q_{W} + p_{i} * C_{inv}^{2^\circ s} + C_{l}^{u} * n_{d} * n_{op}^{2^\circ s} + p_{m}^{2^\circ s} * C_{inv}^{2^\circ s} + C_{cm,t}^{3^\circ s} * Q_{P-hrm} + C_{e}^{u} * e_{u}^{3^\circ s} * Q_{P-rmbr} + p_{i} * C_{inv}^{3^\circ s} + C_{l}^{u} * n_{d} * n_{op}^{3^\circ s} + p_{m}^{3^\circ s} * C_{inv}^{3^\circ s} + C_{rem,t}^{3^\circ s} * (1 + inf) + C_{tr}^{u} * (Q_{W} + Q_{e}) * d_{tf} + ebt_{t} * C_{tax}^{u}$$

$$C_{t+1} = C_{t} * (1 + inf) \quad \forall\, t = 1..\, n \tag{24}$$

Technical-Economic nomenclature

C_a:	Acquisition cost of WPCBs	n_{op}:	Number of operators
C_a^u:	Unitary acquisition cost of WPCB	n_{rm}:	Number of recycled metals
C_{cm}^u:	Unitary conferred material cost	n_{nrm}:	Number of non-recycled metals
C_d^u:	Unitary disposal cost	NPV:	Net present value
C_e^u:	Unitary electric power cost	NPV/ Size:	Ratio between NPV and size
C_{inv}:	Investment cost	O_t:	Discounted cash outflows
C_{inv}^u:	Unitary investment cost	p_e:	% of envelope
C_l^u:	Unitary labour cost	p_{ed}:	% of “dangerous” envelope
C_{lcs}:	Loan capital share cost	p_h:	Hourly productivity
C_{lis}:	Loan interest share cost	p_i:	% of insurance cost
C_{rem}^u:	Unitary reactant materials cost	p_m:	% of maintenance cost
C_t:	Cost in period t	$p_{rm,j}$:	% of metal j in 1 kg of WPCB
C_{tax}^u:	Unitary taxes	p_{rnm}:	% of non-metals in recycled materials
C_{tr}^u:	Unitary transportation cost of the plant	pl_{rm}:	Purity level of recycled metal
d_{tf}:	Transportation distance of the plant	pr_{rm}:	Price of recycled metal
		Q_e:	Quantity of envelope
DPBT:	Discounted payback time	Q_{P-hrm}:	Quantity of hazardous recycled metal
ebt:	Earnings before taxes	Q_{hwd}:	Quantity of hazardous waste
e_u:	Energy power	$Q_{P\text{-}rmbr}$:	Quantity of powders (before refinement)
I_t:	Discounted cash inflows		
inf:	Inflation rate	$Q_{P\text{-}rnm}$:	Quantity of powders (recycled non-metals)
lm_{pp}:	Lost materials during the treatment process	$Q_{P\text{-}srm,j}$:	Quantity of powders (selling recycled metal j)
lm_{rp}:	Lost materials during the refinement process		
n:	Lifetime of investment	Q_W:	Quantity of WPCBs
n_d:	Number of days	r:	Opportunity cost
n_{debt}:	Period of loan	r_d:	Interest rate on loan
n_h:	Number of hours	t:	Time of the cash flow

In the previous formulas 1°s means “disassembly” step, 2°s means “treatment” step and 3°s means “refinement” step. In general, the profitability of a recycling plant is influenced by two main variables, or the set of materials embedded into WPCBs (identifiable from the primary WEEE category) and the plant's capacity. Another source of profits is the material recovered by cases embedding PCBs. However, potential revenues coming from these flows (Q_{end}) are not considered within this paper.

2.4. Economic and technical inputs

The plant sizing phase is done by following the available literature data [25,38]. Field and mobile plants are proposed together because, within the EU-28, there are very different distributions of e-waste from one country to another and within the same country, as evidenced in the previous subsection 2.1. This way, the hourly productivity is set in 0.125 tons/h and 0.3 tons/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 of capacity:

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

Table 2 reports data about economic and technical inputs of the model. The results show that a mobile plant investment cost is assumed to be 639 k€, while the one for a field plant is assumed to be 1533 k€ [25,38–40]. Economy of scale is 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. By taking as reference the March 2014–March 2015 period, monthly observations are gathered from the most relevant websites dedicated on raw materials exchanges [41–43]. Initial assumptions about materials concentration are taken directly from scientific literature [32]. However, in order to better explain the effects of relevant variables changes, a sensitivity analysis is proposed in the next Section 4.

Table 4 reports the nine products considered within the paper. The selection of these nine products derives from the literature. In general, the authors [49,50] analyse WEEE by selecting specific categories (Cat 1, Cat 3 and Cat 4, in particular). Given these three categories, only three products are extensively assessed by the experts – and within this paper – representing the most cited ones [32]. This is due to a lack of data in the literature about the characterization of Cat2 WEEE [51,52]. This way, the calculation and comparison of profits is possible only for three WEEE categories. Cat1 is represented by refrigerators, washing machines and air conditioners. Cat3 is represented by desktop PCs, notebook PCs and mobile phones. Finally, Cat4 is represented by CRT TVs, stereo systems and digital cameras.

Table 4
Characterization of metals embedded in specific WPCBs (p_{rm} in percentage). Source: [49,50]

	I	II	III	IV	V	VI	VII	VIII	IX
Iron (Fe)	2.1	9.5	2.0	1.3	3.7	1.8	3.4	1.2	3.0
Copper (Cu)	17.0	7.0	7.5	20.0	19.0	33.0	7.2	15.0	27.0
Silver (Ag)	0.0	0.0	0.0	0.1	0.1	0.4	0.0	0.0	0.3
Gold (Au)	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.0	0.1
Aluminium (Al)	1.6	0.1	0.7	1.8	1.8	1.5	6.2	2.9	2.4
Barium (Ba)	0.0	0.0	0.0	0.2	0.6	1.9	0.2	0.1	1.6
Chromium (Cr)	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.3
Lead (Pb)	2.1	0.2	0.6	2.3	1.0	1.3	1.4	1.9	1.7
Antimony (Sb)	0.3	0.0	0.0	0.2	0.1	0.1	0.3	0.0	0.2
Tin (Sn)	8.3	0.9	1.9	1.8	1.6	3.5	1.8	2.2	3.9
Zinc (Zn)	1.7	0.2	0.5	0.3	1.6	0.5	5.3	1.4	0.9

I = Refrigerator; II = Washing machine; III = Air conditioner; IV = Desktop PC; V = Notebook PC; VI = Mobile phone; VII = CRT TV; VIII = Stereo system; IX = Digital camera

However, it is important to point out that metal values reported in Table 4 are taken from the same source, in order to favour homogeneity. In contrast, non-metal values are not proposed and their values are chosen in function of the average percentage for each category. This is the same principle followed by other experts during their studies [53,54].

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

3. Results

Waste recycling processes represent not only an environmental protection action, but also an economic opportunity. This way, this section evaluates the potential profitability characterizing all the phases of a typical PCB recovery process focused on four WEEE categories and two plant configurations. For this reason, the assessed scenarios are eight, as a combination of four WPCB groups (Cat1, Cat2, Cat3 and Cat4 WPCBs) and two plant sizes (240 tons/year and 576 tons/year). In addition, cost and revenue distributions are assessed within this section. Subsequently, the economic profitability are restricted to nine products pertaining to three of the previous four categories.

3.1. Profitability of WPCBs

As aforementioned, eight scenarios are analysed in this research. The results clearly indicate that the financial feasibility is not always verified (Table 5).

Positive results come from Cat3 WPCBs in both the two plant configurations (NPV is equal to 29,966 k€ and 6606 k€ in field and mobile plants, respectively), and from Cat4 WPCBs only for field plants (NPV is equal to 1050 k€). DPBT results follow 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 initial investment already during the first period of the activity. Field plants present a longer lifecycle than mobile plants (10 years out of 5 years). This aspect, starting from equal gross profits, explains the greater NPVs (both in positive and negative terms). However, as explained in other papers [25,36] mobile facilities application can represent an ideal solution for small countries or cities, where WEEE volumes are limited.

The obtained results confirm the studies by [27] and are summarized in the following Table 6. NPVs vary within the range 96,626–495,726 €/ton in a field plant and within the range 52, 495–276,267 €/ton in a mobile plant, with DPBTs equal to one year. The gold percentage in WEEE PCBs varies a lot (30–400 ppm) and this value strongly influences the overall profit of recycling processes [32]. Other works consider a lower gold content (5 ppm) and their focus is on other materials (copper in particular). However, it does not guarantees a complete profitability in similar field and mobile plants [25,38]. These last two works do not consider the entire recycling process and the same shortfall is common to [40] setting DPBT to one year for a plant treating WPCBs with 1000 ppm of gold.

Table 5
Financial 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	6606	–152
NPV/Q_W (€/t)	–5463	–6071	27,525	–633
	Field plant (576 tons of powders/year)			
DPBT (y)	> 10	> 10	1	2
NPV (k€)	–3918	–4539	29,966	1050
NPV/Q_W (€/t)	–6802	–7880	52,024	1823

Table 6
A summary of current economic values from the literature.

Index	Value	Reference
Gross profit	129–256 $/t	[38]
Gross profit	(–83)-14 $/t	[25]
Net profit	600–1300 RMB	[55]
Net present value	52,495–495,726 €/t	[27]
Discounted payback time	1 y	[27]
Payback time	2.5 y	[56]
Internal rate of return	43%	[56]
Potential revenues	3800–52,700 $/t	[37]
Total revenues	62,000–339,000 $/y	[40]
Payback time	Not feasible-3 y	[40]

Given the structure of the presented economic model (see Section 2.3), it is easily possible to change any parameter and extend the analysis to other case studies. For the evaluation of profits coming from recycling plants, costs and revenues are evaluated in the following subsection and the effect given by a variation of some critical variables on the overall results is assessed.

3.2. Discounted cash flows distribution

Within this subsection, an assessment of potential costs and revenues related to hypothetical field and mobile recycling processes are described into detail. About the gold relevance among revenue items, the results shown in Fig. 1 are significant (equal for both the two plant configurations): for Cat3 WPCBs are estimated as 415 ppm of gold (maximum value, accounting for 72% of revenues), and for Cat2 are estimated as 20 ppm of gold (minimum value, accounting for 30% of revenues), and they represent the main profitability item. Among other materials, significant is the influence of palladium (with a high market price) and copper (present in a high percentage).

The cost 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 other researches [27,40]. The most relevant item is represented by WPCB purchasing costs for both field and mobile plants (42% and 34%, respectively). This value is followed by labour costs (18% and 21%, respectively). Finally, transportation costs are equal to 6.5% for mobile plants.

However, the plant's cost distribution could differ, depending on a number of reasons. The choice of a recycling process is connected to multiple parameters and technological solutions [57,58]. WPCB purchasing costs can differ because of their different materials composition. Unfortunately, this issue is not well analysed in the literature [24,59]. In particular, this cost can be influenced by several aspects, including the supply chain dimension, the type of PCB (low, medium or high grade) and the related volumes.

3.3. Profitability of specific WPCBs

The characterization of materials embedded into specific WPCBs has a great influence on the financial results (see Table 4). The profitability related to the nine selected products is evaluated within this subsection.

Considering the results reported in Table 7, it is clear that NPVs are positive only for Cat3 products and for digital cameras, whatever the plant's configuration. Other products, given their productive features, do not guarantee positive cash flows. The same finding

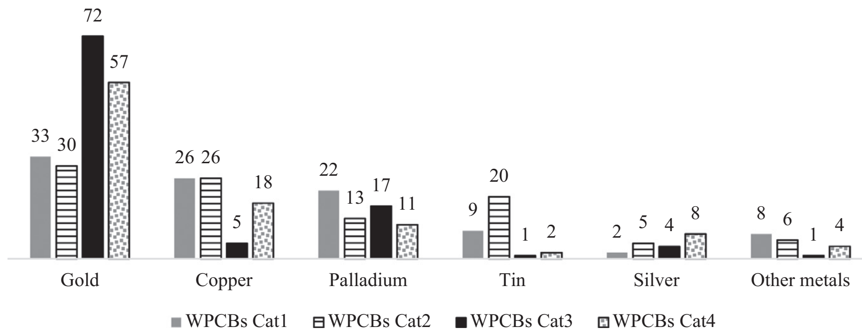

Fig. 1. Plant's revenue distribution (in percentages).

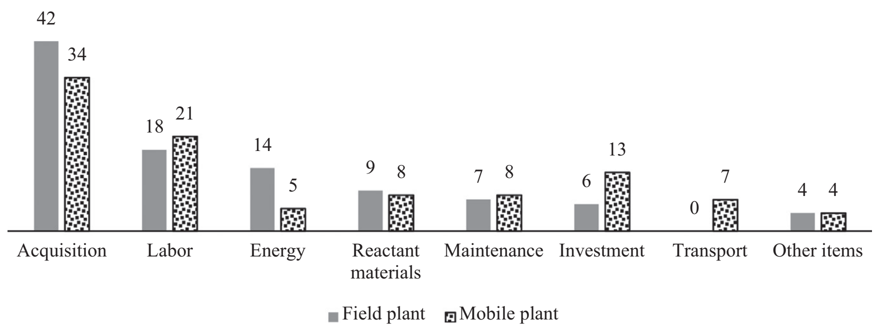

Fig. 2. Plant's cost distribution (in percentages) – average values.

is demonstrated by DPBTs. It is opportune to highlight that a specific product of Cat 4 (Digital Camera) has a DPBT equal to 1 year, while it is equal to 2 years in generic products pertaining to Cat 4 (see Table 5). Furthermore, it shows that the characterization of materials is relevant and some products have a value greater than the average one for each category. However, also the opposite situation can occur. In order to strengthen the obtained results, a sensitivity analysis of alternative scenarios (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 can occur. This limitation can be avoided by implementing a sensitivity analysis on the following critical variables [27]:

- The materials content, as a percentage of a WPCB total weight for all the four categories. The materials content has been already analysed and four categories of WPCBs are evaluated within this paper;
- The materials market price is evaluated for three materials that, more than others, affect revenues – see Fig. 1 – or gold, palladium and copper. Pessimistic and optimistic scenarios are analysed where the price is increased or decreased by its standard deviation (28,000–37,000 €/kg for gold, 18,000–28,000 €/kg for palladium and 3.5–6.8 €/kg for copper, respectively);
- The final purity level, applied only to gold because of its high relevance on revenues. Four pessimistic scenarios are analysed, with purity levels decreased within the range 60–90% in comparison to the initial value of 95%;
- WPCB purchasing costs, representing the main cost item. Pessimistic and optimistic scenarios are assessed, with costs variation between 1000 €/ton up to 1400 €/ton (or an offset of about 200 €/ton from the baseline scenario);
- Plant saturation, in which a lower amount of WPCBs in input represents a lower hourly productivity. Therefore, five pessimistic scenarios are assessed, with saturation levels going from 50% up to 90%. For example, by considering a mobile plant, 90% of 240 tons/h is equal to 216 tons/h. Instead, by considering a field plant, 90% of 576 tons/h is equal to 518 tons/h;
- Opportunity cost, able to quantify the value of money in different periods. Even in this case, an optimistic and pessimistic scenarios are assessed, with values varying from 4% up to 6%.

Table 7
Profitability of specific WPCBs.

	Field plant			Mobile plant		
	NPV (k€)	DPBT (y)	NPV/Size (€/t)	NPV (k€)	DPBT (y)	NPV/Size (€/t)
Refrigerator	–1022	> 10	–1774	–637	> 5	–2654
Washing machine	–5484	> 10	–9521	–1685	> 5	–7021
Air conditioner	–4937	> 10	–8571	–1559	> 5	–6496
Desktop PC	18146	1	31,503	3839	1	15,996
Notebook PC	46,938	1	81,490	10,566	1	44,025
Mobile phone	113,620	1	197,257	26,149	1	108,954
CRT TV	–5074	> 10	–8809	–1586	> 5	–6608
Stereo system	–5243	> 10	–9102	–1626	> 5	–6775
Digital camera	59,903	1	103,998	13,599	1	56,663

The obtained results from this section confirm that profitability is not always verified. In particular, in comparison to Table 5, plants treating Cat4 WPCBs can present a change in the sign of their NPVs. By considering field plants, NPVs become negative when the gold purity level falls to 70% or when the saturation level is 60%. Instead, by considering mobile plants, NPVs become positive when the gold market price is equal to 37,000 €/kg. 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 (16 scenarios out of 19);

In comparison to what has been described in [27], all the proposed critical variables in Tables 8 and 9 produce significant variations. The cause must be retrieved in the lower gold content characterizing these types of PCBs.

Higher values of NPVs are present in both the plant configurations, when the saturation level reaches 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 gold market price reaches 37,000 €/kg for WPCBs pertaining to Cat3 and Cat4 groups (7523 k€ and 33 k€ respectively for mobile plants, 33,893 k€ and 1839 k€ respectively for field plants).

Lower values of NPVs are present in mobile plants when the gold 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 €/ton for Cat1 and Cat2 WPCBs (−4565 k€ and −5186 k€ respectively), with a saturation level of 50% for Cat3 WPCBs (13,787 k€) and a gold 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 (by augmenting the number of treated WPCBs costs increase more than revenues). The plant saturation level is strictly linked to the initial choice in terms of productive capacity and actual working hours. However, a key-role is played by the differences between generated and collected volumes [60]. They depend upon four aspects: (i) illegal flows, (ii) inaccuracy of citizens towards environmental problems; (iii) absence of regulations and (iv) inadequate location of collection centres.

Table 8
NPV (k€) in mono-core field plants - sensitivity analysis.

Variable	Value	Cat1 WPCBs	Cat2 WPCBs	Cat3 WPCBs	Cat4 WPCBs
pr_{Au} (€/kg)	37,000	–3679	–4359	33,893	1839
	28,000	–4158	–4720	26,040	260
pr_{Pd} (€/kg)	28,000	–3673	–4421	31,349	1276
	18,000	–4174	–4662	28,527	814
pr_{Cu} (€/kg)	6.8	–3474	–4171	30,668	1648
	3.5	–4352	–4899	29,281	466
pl_{Au} (%)	90	–4009	–4608	28,474	750
	80	–4191	–4745	25,489	149
	70	–4374	–4883	22,503	–451
	60	–4556	–5020	19,518	–1051
C_a^u (€/t)	1000	–4565	–5186	29,320	403
	1400	–3303	–3924	30,581	1665
Q_W (t)	518	–3211	–4323	26,790	785
	461	–3121	–4110	23,669	525
	403	–3029	–3894	20,492	261
	346	–2938	–3681	17,371	1
	288	–2846	–3464	14,195	–264
r (%)	4	–4107	–4761	31,486	1110
	6	–3743	–4334	28,555	993

Table 9
NPV (k€) in mono-core mobile plants - sensitivity analysis.

Variable	Value	Cat1 WPCBs	Cat2 WPCBs	Cat3 WPCBs	Cat4 WPCBs
pr_{Au} (€/kg)	37,000	–1255	–1415	7523	33
	28,000	–1367	–1499	5689	–336
pr_{Pd} (€/kg)	28,000	–1254	–1430	6929	–99
	18,000	–1371	–1486	6270	–207
pr_{Cu} (€/kg)	6.8	–1207	–1371	6770	–12
	3.5	–1413	–1541	6446	–288
pl_{Au} (%)	90	–1375	–1511	6124	–274
	80	–1501	–1619	5160	–519
	70	–1628	–1726	4196	–765
	60	–1754	–1834	3233	–1010
C_a^u (€/t)	1000	–1456	–1602	6461	–296
	1400	–1174	–1320	6743	–14
Q_W (t)	216	–1266	–1397	5892	–189
	192	–1221	–1337	5179	–227
	168	–1175	–1277	4466	–265
	144	–1130	–1218	3752	–302
	120	–1085	–1158	3039	–340
r (%)	4	–1344	–1495	6797	–152
	6	–1279	–1421	6423	–151

The sensitivity analysis shows the absence of an occurrence probability related to each phenomena. However, it is possible to observe that all the scenarios can have positive chances to verify: (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 WPCB purchasing cost can differ because of the different materials composition of WPCBs; (iii) the secondary materials market price can be subjected to great fluctuations – the standard deviation is a proxy value of their amplitude – reaching their maximum level for precious metals (e.g. gold and palladium); (iv) the gold purity level could fall because of the selection of low performing technologies; (v) the plant saturation level is strictly linked to the initial choice in terms of productive capacity and actual working hours.

Future research streams could be focused on 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, evaluates multi-core plants and, from the other side, offers an assessment on the economic impact related to the recovery of these wastes in the whole European market.

5. Discussion

The aim of this section is multi-fold. First, the mix of the four WPCB categories is estimated for both the two types of plants. Second, the break even point on the minimum gold content in WPCBs is assessed. Third, the quantification of the overall potential profits coming from the correct management of e-waste in each of the EU-28 nations is quantified. Finally, the analysis of expected future trends in the next 15 years is executed for each of the four WPCB categories.

5.1. Profitability of multi-core plants

The first exploitation of data gathered from the Eurostat database about WEEE collected volumes is the identification of profitability coming from a mix of the four WPCB categories presented in the previous sections. These economic values derive from the sum of the percentage of WPCBs of a certain category multiplied by the expected amount of materials embedded into them. The results are reported in the following Table 10. However, two hypotheses have to be made. First, no productive setups are considered during the recycling process for the treatment of different WPCB categories. Second, WPCBs in input are 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 WEEE recycling chains, also in the presence of favourable regulations and proved environmental advantages in terms of reduced CO_2 emissions. The PCB mix can be a factor able to modify this situation. In this subsection, the quantification of NPVs related to 28 fractional mixes (equal to 28 European countries assessed and presented in Section 2.1) are demonstrated both for mobile and field plants (see Table 10). The main hypotheses taken into account are the following:

- Starting from WEEE volumes presented in Table 1, WPCB volumes are calculated. To this aim, the fractional weight of WPCBs (out of the overall WEEE weight) is defined. Estimated values are 0.4%, 0.5%, 13% and 11% for Cat1, Cat2, Cat3 and Cat4 WPCBs, respectively [32];
- A multi-core (and no more a mono-core) recycling plant requires both a dedicated interface with stakeholders supplying WPCBs and adequate changes in operational phases of the recycling process have to be considered. Given the lack of information on these aspects, the level of costs is considered to be constant. In contrast, 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 gold, 70 ppm of palladium and 182,270 ppm of copper.

Table 10
NPV (k€) of multi-core plants in EU-28.

Ranking	Country	Field plant	Mobile plant
1°	United Kingdom	23,506	5096
2°	Lithuania	20,537	4403
3°	Malta	19,634	4191
4°	Romania	18,159	3847
5°	Cyprus	18,102	3833
6°	Hungary	17,892	3784
7°	Slovakia	17,398	3669
8°	Portugal	17,211	3625
9°	Austria	16,922	3558
10°	Poland	16,405	3437
11°	Germany	16,379	3431
12°	Italy	15,998	3342
13°	Estonia	14,838	3071
14°	Slovenia	14,659	3029
15°	Bulgaria	14,402	2969
16°	Ireland	14,392	2966
17°	Latvia	14,346	2956
18°	Belgium	13,639	2791
19°	Czech Republic	13,469	2751
20°	Sweden	13,192	2686
21°	Denmark	13,161	2679
22°	France	12,647	2559
23°	Luxembourg	12,404	2502
24°	Spain	12,170	2447
25°	Greece	12,123	2436
26°	Finland	12,023	2413
27°	Croatia	11,586	2311
28°	The Netherlands	11,343	2254

What is clearly evidenced by the results is that profitability is verified in all the alternative scenarios. This effect derives from the presence of Cat3 WPCBs (52.9% in EU-28) and from the quasi-absence of Cat1 and Cat2 WPCBs within the related fractional mixes (4.2% and 0.9% 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 79%, Lithuania 69% and Malta 65%, followed by a group of nations - Hungary, Cyprus and Romania – sharing a 60%). The worst results are related to Croatia and The Netherlands, presenting a fractional data of Cat3 WPCBs equal to 37%.

5.2. Break Even point analysis

The second aim of this subsection is the assessment of the break even point. This is needed to define the minimum gold content that WPCBs must present to guarantee some profits from their recovery. This way, the subsequent part of the work is the analysis of a set of pessimistic scenarios (where the percentage of Cat3 WPCBs will fall to 30%, 20% and 10%). Cat4 WPCBs (presenting a positive NPV in field plants – see Table 5) 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. The assessed scenarios are the following (numbers represent the percentage 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 shown in Fig. 3.

Results demonstrate that the 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, considering an average PCB containing 114 ppm of gold, NPV is equal to 3494 k€ and 420 k€ for a field and mobile plant, respectively. By decreasing the gold content to 68 ppm, NPV becomes negative, and both the plants become non-profitable. Hence, it is possible to calculate the specific Break Even Point able to set NPV to zero by only acting on the gold content. This value is equal to:

- 73 ppm of gold for field plants;
- 93 ppm of gold for mobile plants.

5.3. Overall profitability of WPCBs in Europe

In order to identify the European economic potential coming from the recovery of WPCBs embedded into WEEE (reported in Table 11) the procedure is to multiply the economic value proposed in Table 5 with the related volumes estimated in Table 1 (concerning only the four categories previously described).

The economic potential related to the recovery of WPCBs embedded into WEEE in 2013 is estimated in about 4509 M€ in a scenario with only field plants and 2261 M€ in a scenario with only mobile plants. In comparison to what has been previously exposed, it is important to point out that the overall results of each

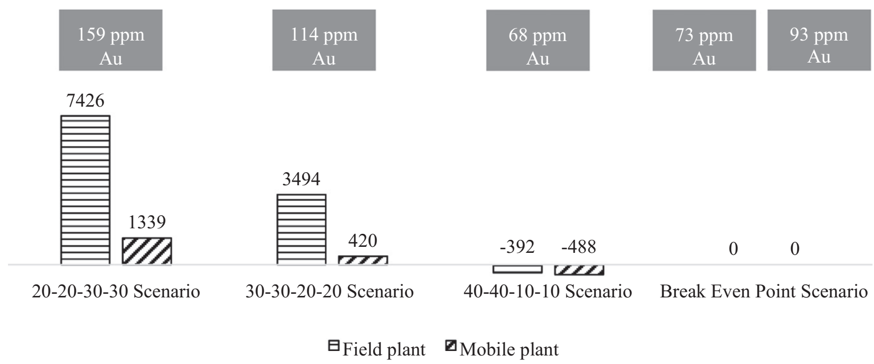

Fig. 3. NPV (k€) in multi-core plants – Break even point.

nation depend on both their volumes and fractional mixes. France and Italy offer an explicable example. Even if France presents higher volumes than Italy, its fractional mix has lower amounts of valuable WPCBs. This way France occupies a lower position than Italy within the overall ranking.

By assessing the first positions of the ranking presented in Table 11 (by seeing the economic value related to field plants) Germany and United Kingdom occupy the first positions in terms of both field and mobile plants. However, Germany has greater WEEE volumes and United Kingdom has WEEE volumes characterized by medium-high grade PCBs. This way, the current context delineates a clear picture where the implementation of PCB recycling plants could improve both environmental and economic performances of the European industrial system. A useful tool is represented by per capita indexes [61]. Consequently, also within this work the total NPV of WPCB recycling plants per capita is proposed.

Considering Table 12 results, it is possible to see as two northern Europe (Sweden and Denmark) countries present the most relevant total NPV per capita, followed by United Kingdom. It is opportune to highlight the relationship of this index with WEEE collected volume per capita [31]. The first is related to the four categories (equal to 94% of WEEE volumes). The second covers all the ten WEEE categories. Also for this index, Sweden (18.4 kg per capita) and Denmark (12.8 kg per capita) occupy the first positions. Together with other ten countries (Belgium, Finland, Luxembourg, Ireland, Austria, Germany, United Kingdom, France, Italy and The Netherlands) they have a value greater than the European average (equal to 7.0 kg per capita, obtained by dividing 3,513,906 tons (Table 1) and 505,127,210 inhabitants). Considering the index proposed in Table 12, ten of these twelve countries have a value greater than the European average (equal to 8.9 € per capita for field plants). France and The Netherlands are the exceptions. However, their value (equal to 7.3 kg per capita and 7.0 kg per capita, respectively) is similar to the EU-28 average. Once again, this ranking demonstrates the role of the recycling chain efficiency on the national overall result. This can be explained by the fact that, especially in northern Europe countries, the gap between generated and collected WEEE volumes is lower than the European average.

5.4. *Future profits quantification*

The last aim of this section is the identification of future economic opportunities trend. To do that, the first data required is the overall amount of expected WEEE generated from 2015 up to 2030. These data, together with related trends, are directly gathered both from Eurostat (regarding 2013 collected volumes in EU-28) and the literature (regarding the expected growth rate, equal to 3% per year – even if some authors speak about a 5% rate) [27].

Table 11
Total NPV (k€) of EU-28 WPCB recycling plants in 2013.

Ranking	Country	Field plant	Mobile plant
1°	Germany	1,075,659	540,778
2°	United Kingdom	925,580	481,588
3°	Italy	584,303	292,948
4°	France	441,414	214,358
5°	Sweden	214,014	104,580^{-1}
6°	Poland	209,575	105,379^{+1}
7°	Spain	161,155	77,767
8°	Belgium	126,914	62,330
9°	Austria	119,519	60,312
10°	The Netherlands	100,339	47,853
11°	Denmark	88,608	43,288
12°	Hungary	64,958	32,971
13°	Czech Republic	60,309	29,563
14°	Finland	57,105	27,506
15°	Ireland	49,496	24,481
16°	Portugal	47,916	24,221
17°	Romania	33,821	17,196
18°	Greece	31,902	15,835
19°	Slovakia	24,530	12,415
20°	Lithuania	22,341	11,496
21°	Bulgaria	18,768	9333
22°	Croatia	18,621	8914
23°	Slovenia	10,272	5094
24°	Estonia	7866	3907
25°	Luxembourg	5220	2527
26°	Cyprus	3230	1642
27°	Latvia	3143	1554
28°	Malta	2837	1453

After that, it is possible to predict (with logical approximations) the expected profits (in a min – max range) coming from the correct management of these amounts of WPCBs. Table 13 reports all these results. However, it is important to highlight the two main hypotheses taken into account:

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

The expected annual collected volumes were obtained by considering a PCB mass estimated in 5% of the overall WEEE mass - see [27]. Consequently, given that the amount of WEEE is equal to 3,304,837 tons in the EU-28 (see Table 1) regarding the only Cat1, Cat2, Cat3 and Cat4 categories, it is possible to define the quantities of related WPCBs equal to 165,242 tons. By considering the European average mix, mobile and field plants values become equal to 13,682 € per ton (obtained dividing 2,260,841 k€ for

Table 12
Total NPV (€) per capita of EU-28 WPCB recycling plants in 2013.
Sources: [62,63], original analysis

Ranking	Country	Field plant	Mobile plant
1°	Sweden	22.4	10.9
2°	Denmark	15.8	7.7
3°	United Kingdom	14.5	7.5
4°	Austria	14.1	7.1
5°	Germany	13.4	6.7
6°	Belgium	11.4	5.6
7°	Ireland	10.8	5.3
8°	Finland	10.5	5.1
9°	Italy	9.8	4.9
10°	Luxembourg	9.7	4.7
	EU-28	8.9	4.5
11°	Lithuania	7.5	3.9
12°	Malta	6.7	3.4
13°	France	6.7	3.3
14°	Hungary	6.6	3.3
15°	The Netherlands	6.0	2.9^{-1}
16°	Estonia	6.0	3.0^{+1}
17°	Czech Republic	5.7	2.8
18°	Poland	5.5	2.8
19°	Slovenia	5.0	2.5
20°	Portugal	4.6	2.3
21°	Slovakia	4.5	2.3
22°	Croatia	4.4	2.1
23°	Cyprus	3.7	1.9
24°	Spain	3.4	1.7
25°	Greece	2.9	1.4
26°	Bulgaria	2.6	1.3
27°	Romania	1.7	0.9
28°	Latvia	1.6	0.8

Table 13
Estimates of collected WPCBs volumes and profits in EU-28 from WEEEs.
Sources: [62,63], original analysis

	2013	2015	2020	2030
EU WEEE expected annual collection (ktons)	3514	3728	4322	5808
EU total WPCB expected annual collection (ktons)	176	186	216	290
EU total WPCB expected NPV – min values (M€)	2404	2550	2956	3973
EU total WPCB expected NPV – max values (M€)	4795	5087	5897	7925

165,242 tons) and 27,290 € per ton (obtained dividing 4,509,415 k€ for 165,242 tons). These values are referred to 2013. Consequently, total WPCBs expected NPV is equal to 5087 million € in 2015 for field plants (obtained by multiplying 27,290 € per ton and 186 ktons). Furthermore, it is important to clarify that Table 11 values are referred to the first four WEEE categories (out of ten). Instead, Table 13 refers to overall volumes coming from all the ten WEEE categories together, and considering the percentage mix of EU-28.

In addition, Table 13 reports the potential dimension of the WEEE PCB recycling market. Values are impressive, going from 2.40 billion € up to 4.79 billion € as minimum values in 2013, and refer to the baseline scenario presented in Table 5. Future trends define 3.97 billion € as minimum value and 7.92 billion € as maximum value in 2030. This difference depends by the development of field and/or mobile plants. However, it is important to emphasise that minimum and maximum values are calculated on the European fractional mix. Another important point related to these results is the presence of already established sites in some European nation that are focused on the recovery of materials, generally owned by multinational companies, like Aurubis, Umicore, SIMS and Boliden. Given their dimensions, these plants, generally field ones, are able to take into account relevant quantities of WEEE. This could represent an issue for the implementation of new plants. However, the economic impact given by these already existing plants is not measurable, given the absence of data in the literature about their physical and economic characteristics.

These numbers (even if theoretical) demonstrate the utmost importance of the WEEE PCB management and the amount of profits potentially achievable. Without any doubt, this research will play a critical role in improving the global sustainability level in terms of waste reduction, recycling improvement, raw materials dependency reduction, resource efficiency improvement and circular economy diffusion in key manufacturing processes. Interesting improvements of this work could be the assessment of environmental impacts of current recycling processes, the analysis of different business models for the EoL management of complex products, the proposition of corrective actions to current WEEE directives and the assessment of recycling issues related to future waste streams.

6. Conclusions

Waste Electrical and Electronic Equipment is one of the most important sources of secondary raw materials. However, studies demonstrating its economic potentials are quite rare. The paper follows this direction. A quantification of the amounts of materials (and related economic values) potentially recoverable from different types of WPCBs is undertaken. The expected profitability coming from WPCB recycling processes is compared into two different types of plant (mobile and field ones) and into different scenarios with an increased severity of the context. The results demonstrate how the profitability is not always verified. Considering the baseline scenario, NPV is positive for WPCBs coming from IT and telecommunication equipments (equal to 29,966 k€ and 6606 k€ in field and mobile plants, respectively) and from consumer equipments (equal to 1050 k€ in field plants). DPBT varies from 1 to 2 years with interesting influences on returns from investments. Furthermore, the analysis of specific products confirms the wide range of results. From one side, notebook PCs and mobile phones, unlike desktop PCs, present a NPV greater than the average value of their category. From the other side, CRT TVs and stereo systems are unprofitable, while digital cameras present a value greater than the average value of their category. Subsequently, an assessment of different mixes of WPCBs is implemented for the identification of the minimum level of gold content guaranteeing the profitability of recycling processes. From this view, the break even point analysis quantifies this value in 73 ppm of gold for field plants and 93 ppm of gold for mobile ones. Finally, potential total profits in the EU-28 are calculated in function of both WEEE collected volumes and WPCB mixes. This value is equal to 2404 million € and 4795 million € in 2013, by considering mobile and field plants, respectively. A key role is played by Germany (24%) and United Kingdom (21%), followed by Italy (13%) and France (10%) and hypothesizing that all the collected WEEE volumes are recycled. Based on both NPV values and predictions of future WEEE volumes, a quantification of the potential dimension of the recycling market is described for the 2015–2030 period. An ambitious value of profits equal to 7925 million € could be reached in 2030. However, it is important to stress that the obtained economic values are so high and different from common values available in the literature because of the joined selection of four WEEE streams instead of only one.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] 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 Manag Res 2015;33:3–29.
[2] 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.
[3] Sulaiman N, Hannan MA, Mohamed A, Majlan EH, Wan Daud WR. A review on energy management system for fuel cell hybrid electric vehicle: issues and challenges. Renew Sustain Energy Rev 2015;52:802–14.
[4] Luglietti R, Rosa P, Terzi S, Taisch M. Life cycle assessment tool in product development: environmental requirements in decision making process. Procedia CIRP 2016;40:202–8.
[5] Zeng X, Li J. Measuring the recyclability of e-waste: an innovative method and its implications. J Clean Prod 2016;131:156–62.
[6] 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. J Clean Prod 2015;95:142–7.
[7] Babar Z, Shareefdeen Z. Management and control of air emissions from electronic industries. Clean Technol Environ Policy 2014;16:69–77.
[8] Cucchiella F, D'Adamo I, Rosa P, Terzi S. Scrap automotive electronics: a mini-review of current management practices. Waste Manag Res 2016;34:3–10.
[9] Mahdizadeh Khasraghi M, Gholami Sefidkouhi MA, Valipour M. Simulation of open- and closed-end border irrigation systems using SIRMOD. Arch Agron Soil Sci 2015;61:929–41.
[10] Anbuudayasankar SP, Ganesh K, Lenny Koh SC, Ducq Y. Modified savings heuristics and genetic algorithm for bi-objective vehicle routing problem with forced backhauls. Expert Syst Appl 2012;39:2296–305.
[11] Valipour M, Montazar AA. Sensitive analysis of optimized infiltration parameters in SWDC model. Adv Environ Biol 2012:2574–82.
[12] Valipour M. Sprinkle and trickle irrigation system design using tapered pipes for pressure loss adjusting. J Agric Sci 2012;4:125.
[13] Valipour M, Sefidkouhi MAG, Eslamian S. Surface irrigation simulation models: a review. Int J Hydrol Sci Technol 2015;5:51–70.
[14] Valipour M. Optimization of neural networks for precipitation analysis in a humid region to detect drought and wet year alarms. Meteorol Appl 2016;23:91–100.
[15] D'Adamo I, Rosa P. Current state of renewable energies performances in the European Union: a new reference framework. Energy Convers Manag 2016;121:84–92.
[16] D'Adamo I, Rosa P. Remanufacturing in industry: advices from the field. Int J Adv Manuf Technol 2016. http://dx.doi.org/10.1007/s00170-016-8346-5.
[17] Ruan J, Xu Z. Constructing environment-friendly return road of metals from e-waste: combination of physical separation technologies. Renew Sustain Energy Rev 2016;54:745–60.
[18] Genovese A, Acquaye AA, Figueroa A, Koh SCL. Sustainable supply chain management and the transition towards a circular economy: evidence and some applications. Omega 2015. http://dx.doi.org/10.1016/j.omega.2015.05.015.
[19] 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.
[20] Kilic HS, Cebeci U, Ayhan MB. Reverse logistics system design for the waste of electrical and electronic equipment (WEEE) in Turkey. Resour Conserv Recycl 2015;95:120–32.
[21] 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 Manag Res 2012;30:1198–207.
[22] Garlapati VK. E-waste in India and developed countries: management, recycling, business and biotechnological initiatives. Renew Sustain Energy Rev 2016;54:874–81.
[23] Zeng X, Li J, Liu L. Solving spent lithium-ion battery problems in China: opportunities and challenges. Renew Sustain Energy Rev 2015;52:1759–67.
[24] Ghosh B, Ghosh MK, Parhi P, Mukherjee PS, Mishra BK. Waste Printed Circuit Boards recycling: an extensive assessment of current status. J Clean Prod 2015;94:5–19.
[25] Zeng X, Song Q, Li J, Yuan W, Duan H, Liu L. Solving e-waste problem using an integrated mobile recycling plant. J Clean Prod 2015;90:55–9.
[26] Cucchiella F, D'Adamo I, Lenny Koh SC, Rosa P. Recycling of WEEEs: an economic assessment of present and future e-waste streams. Renew Sustain Energy Rev 2015;51:263–72.
[27] Cucchiella F, D'Adamo I, Rosa P, Terzi S. Automotive printed circuit boards recycling: an economic analysis. J Clean Prod 2016;121:130–41.
[28] Hadi P, Xu M, Lin CSK, Hui C-W, McKay G. Waste printed circuit board recycling techniques and product utilization. J Hazard Mater 2015;283:234–43.
[29] Kalmykova Y, Patrício J, Rosado L, Berg PE. Out with the old, out with the new – the effect of transitions in TVs and monitors technology on consumption and WEEE generation in Sweden 1996–2014. Waste Manag 2015;46:511–22.
[30] 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. J Clean Prod 2014;83:305–16.
[31] Eurostat. Statistics database. Eurostat Luxembourg; 2016.
[32] UNEP. Metal recycling: opportunities, limits, infrastructure. 2013.
[33] Ferella F, De Michelis I, Scocchera A, Pelino M, Vegliò F. Extraction of metals from automotive shredder residue: preliminary results of different leaching systems. Chin J Chem Eng 2015;23:417–24.
[34] Innocenzi V, De Michelis I, Kopacek B, Vegliò F. Yttrium recovery from primary and secondary sources: a review of main hydrometallurgical processes. Waste Manag 2014;34:1237–50.
[35] Rocchetti L, Vegliò F, Kopacek B, Beolchini F. Environmental impact assessment of hydrometallurgical processes for metal recovery from WEEE residues using a portable prototype plant. Environ Sci Technol 2013;47:1581–8.
[36] 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. Environ Sci Pollut Res 2015;22:12366–73.
[37] Wang X, Gaustad G. Prioritizing material recovery for end-of-life printed circuit boards. Waste Manag 2012;32:1903–13.
[38] Li J, Xu Z. Environmental friendly automatic line for recovering metal from waste printed circuit boards. Environ Sci Technol 2010;44:1418–23.
[39] 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. Int J Syst Sci 2014;45:1268–82.
[40] 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). Assoc Metall Eng Serbia 2011;17:139–49.
[41] London metal exchange. ⟨https://www.lme.com/⟩; 2014.
[42] Metalprices. ⟨http://www.metalprices.com/⟩; 2016.
[43] InfoMine. ⟨http://www.infomine.com/⟩; 2016.
[44] Cucchiella F, D'Adamo I, Rosa P. End-of-Life of used photovoltaic modules: a financial analysis. Renew Sustain Energy Rev 2015;47:552–61.
[45] Copani G, Rosa P. Demat: sustainability assessment of new flexibility oriented business models in the machine tools industry. Int J Comput Integr Manuf 2014.
[46] Ardente F, Mathieux F, Recchioni M. Recycling of electronic displays: analysis of pre-processing and potential ecodesign improvements. Resour Conserv Recycl 2014;92:158–71.
[47] 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.
[48] 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. Resour Conserv Recycl 2011;55:933–44.
[49] Oguchi M, Sakanakura H, Terazono A. Toxic metals in WEEE: characterization and substance flow analysis in waste treatment processes. Sci Total Environ 2013;463–464:1124–32.
[50] Oguchi M, Murakami S, Sakanakura H, Kida A, Kameya T. A preliminary categorization of end-of-life electrical and electronic equipment as secondary metal resources. Waste Manag 2011;31:2150–60.
[51] Bovea MD, Pérez-Belis V, Ibáñez-Forés V, Quemades-Beltrán P. Disassembly properties and material characterisation of household small waste electric and electronic equipment. Waste Manag 2016;53:225–36.
[52] Bovea MD, Ibáñez-Forés V, Pérez-Belis V, Quemades-Beltrán P. Potential reuse of small household waste electrical and electronic equipment: methodology and case study. Waste Manag 2016;53:204–13.
[53] Xu Y, Liu J. Recent developments and perspective of the spent waste printed circuit boards. Waste Manag Res 2015;33:392–400.
[54] Wang C, Zhao W, Wang J, Chen L, Luo C-j. An innovative approach to predict technology evolution for the desoldering of printed circuit boards: a perspective from China and America. Waste Manag Res 2016.
[55] Niu Q, Liu X, Shi C, Xiang D, Duan G. The Recycle Model of Printed Circuit Board and Its Economy Evaluation. In: Proceedings of the 2007 IEEE International Symposium on Electronics & the Environment: IEEE; 2007. p. 106–11.
[56] Xue M, Li J, Xu Z. Management strategies on the industrialization road of state-of- the-art technologies for e-waste recycling: the case study of electrostatic separation—a review. Waste Manag Res 2013;31:130–40.
[57] Li J, Lu H, Guo J, Xu Z, Zhou Y. Recycle technology for recovering resources and products from Waste Printed Circuit Boards. Environ Sci Technol 2007;41:1995–2000.
[58] Kasper AC, Carrillo Abad J, García Gabaldón M, Veit HM, Pérez Herranz V. Determination of the potential gold electrowinning from an ammoniacal thiosulphate solution applied to recycling of printed circuit board scraps. Waste Manag Res 2015.
[59] Liu J, Yang C, Wu H, Lin Z, Zhang Z, Wang R, et al. Future paper based printed circuit boards for green electronics: fabrication and life cycle assessment. Energy Environ Sci 2014;7:3674–82.
[60] Sthiannopkao S, Wong MH. Handling e-waste in developed and developing countries: initiatives, practices, and consequences. Sci Total Environ 2013;463–464:1147–53.
[61] Colling AV, Oliveira LB, Reis MM, da Cruz NT, Hunt JD. Brazilian recycling potential: energy consumption and Green House Gases reduction. Renew Sustain Energy Rev 2016;59:544–9.
[62] Eurostat. End-of-Life Vehicles statistics. Eur Comm 2014.
[63] 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. Eur Top Centre Resour Waste Manag 2008.