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Recycling of WEEEs: An economic assessment ~~Of~~of present and future e-waste streams

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Abstract

Waste from Electric and Electronic Equipments (WEEEs) is currently considered to be one of the fastest growing waste streams in the world, with an estimated growth rate going from 3% up to 5% per year. The recycling of Electric or electronic waste (E-waste) products could allow the diminishing use of virgin resources in manufacturing and, consequently, it could contribute in reducing the environmental pollution. Given that EU is trying, since the last two decades, to develop a circular economy based on the exploitation of resources recovered by wastes, a comprehensive framework supporting the decision-making process of multi-WEEE recycling centres will be analysed in this paper. An economic assessment will define the potential revenues coming from the recovery of ~~fourteen~~14 e-products (e.g. LCD notebooks, LED notebooks, CRT TVs, LCD TVs, LED TVs, CRT monitors, LCD monitors, LED monitors, cell phones, smart phones, PV panels, HDDs, SSDs and tablets) on the base of current and future disposed volumes in Europe. Moreover, a sensitivity analysis will be used to test the impact of some critical variables (e.g. price of recovered materials, input materials composition, degree of purity obtained by the recycling process, volumes generated, and percentage of collected waste) on specific economic indexes. A discussion of the economic assessment results shows the main challenges in the recycling sector and streamlines some concrete solutions.

Abbreviations: Au, ~~Gold~~gold; CRT, ~~Cathode Ray Tube~~cathode ray tube; CV, ~~Collected~~collected volumes; EEE, ~~Electric~~electric and ~~Electronic Equipments~~electronic equipments; EoL, ~~End~~end of ~~Life~~life; E-waste, ~~Electric~~electric or electronic waste; EU, ~~European Union~~european union; GV, ~~Generated~~generated volumes; HDD, ~~Hard Disk Drive~~hard disk drive; LCD, ~~Liquid Crystal Display~~liquid crystal display; LED, ~~Light Emitting Diode~~light emitting diode; PCB, ~~Printed Circuit Board~~printed circuit board; PV, ~~Photovoltaic~~photovoltaic; RoHS, ~~Restriction~~restriction of ~~Hazardous Substances~~hazardous substances; RP, ~~Reduction~~reduction of purity; SSD, ~~Solid State Disk~~solid state disk; TV, ~~Television~~television; WEEE, ~~Waste~~waste from ~~Electric~~electric and ~~Electronic Equipments~~electronic equipments

Keywords: Recycling; WEEE; Economic assessment; E-waste streams

1 Introduction

The international scientific community agrees that an ~~optimized~~optimised management of wastes can allow to achieve economic, environmental and social benefits [1]. The European Union (EU), since the last two decades, tried to put the bases for the development of a circular economy, where wastes should be considered as resources and, so, used in an efficient and sustainable way [2]. To approach the target, renewable energy ~~utilization~~utilisation in a sustainable way has already been developed and performed in various areas [3–10]. To this aim, different directives were activated during the years. The WEEE Directive (Directive 2012/19/EU) on the End of Life (EoL) management of wastes from electric and electronic equipments and the RoHS Directive (Directive 2011/65/EU) on the restriction of the use of certain hazardous substances in electrical and electronic equipments are the most relevant examples. Among all the different waste streams the attention of the European Commission was specially focused on the treatment of WEEEs because of a series of explicit warnings.

First of all, WEEEs represent the widest source of wastes with the highest growth rate per year. Globally, about ~~30 to 50~~ 30–50 million tons of WEEEs are disposed each year, with an estimated annual growth rate of 3–5% [11]. Within these wastes there are different substances (both critical, valuable and hazardous ones) requiring a dedicated recycling process to avoid, from one hand, environmental and health problems and, from the other hand, environmental burdens associated with the extraction and refining of primary new materials. It is re-known by the experts that these activities could offer the chance to reduce Greenhouse gas emissions [12]. Furthermore, the recycling market can be considered as one of the key industries able to close the materials loop. However, there is a large proportion of precious and special metals present in WEEEs that is still lost in the recycling process [13]. The production of modern Electric and Electronic Equipments (EEE) requires the use of scarce and expensive resources and so the recovery of these materials represent a significant economic opportunity [14].

The management of WEEEs is a required challenge to sustainability [15] and literature analysis highlighted that there is a lack of operational indexes to measure and monitor the impacts related to the use of resources [16–19]. A comprehensive framework aiming to support the decision-making process of multi-WEEE recycling centres is analysed in this paper. An economic assessment of the potential revenues coming from the recycling of ~~fourteen~~14 WEEE categories (LCD notebooks, LED notebooks, CRT TVs, LCD TVs, LED TVs, CRT monitors, LCD monitors, LED monitors, cell phones, smart phones, PV panels, HDDs, SSDs and tablets) is proposed and evaluated within several scenarios.

The paper is organised as follows. Section 2 presents a literature review about the different new waste streams that should be managed into the near future by the recycling chain. The high volatility of the price of recovered materials, the variability in the input material compositions and the estimation of waste generated are proposed in Section 3 for each EEE analysed in this paper. Section 4 shows an overview of the main results. Firstly, two unitary indexes (e.g. €/product unit and €/kg of product) are proposed with the aim to evaluate the potential revenues coming from the recycling of single WEEEs. Secondly, a global index (e.g. the overall potential revenue) is calculated basing on EoL volumes in AS IS and TO BE scenarios. Additionally, a sensitivity analysis on critical variables (e.g. price of recovered materials, input material composition, degree of purity obtained by the recycling process, volumes generated, and percentages of waste collected) is conducted. Section 5 proposes an overall discussion of the main issues related to the current state of the recycling sector and streamlines some concrete solutions. Section 6 presents some concluding remarks.

2 State of the art of different WEEE streams

The study of a multi-WEEE recycling plant asks for a wide analysis of all the waste streams (current or future ones) that could be potentially managed within the same centre. To do that, this section will briefly describe the current state of a set of selected waste streams that, because of their volumes or embedded value, could represent an important source of secondary raw materials in the next future.

2.1 PV panels

Photovoltaic (PV) panels represent the most significant waste stream in terms of what it can happen if there is not a correct and preventive definition about how to manage future e-wastes. PV panels are a well-known product that, especially nowadays, is reaching a wide diffusion in private and industrial markets [20]. However, some of them installed at the beginning of the ´90s are currently reaching their ~~End-of-Life.~~ end of life. Hence, there are serious problems among recyclers to decide how to treat these new wastes, if their specific recycling is economically feasible or it is better to throw them into landfills because of a scarcity in embedded valuable materials.

In fact, given their composition, PV panels (especially the silicon-based ones, representing almost the 90% of the market) are not interesting from a recycler´s point of view and, usually, end into landfills [21,22]. Only the remaining 10% of PV panels is really recycled (because of the, even limited, content in key metals like cadmium, tellurium, indium or gallium), but their recycling cost usually goes over the recoverable value coming from the selling of materials [23,24]. Nowadays, this case is not considered as a source of relevant environmental damages because of the even very low volumes. However, some studies and researches demonstrate that in the next decades there could be a massive collection of EoL PV panels, represented by the great amount of products installed during the last years all around the world that will reach their end of life within ~~twenty-thirty~~20–30 years. The same studies show that, even by considering these future trends, the economic advantage coming from the recycling of these products is never obtained, at current material prices [23]. This situation led the experts to consider different recycling technologies, plant dimensions or reverse supply chains to cope with the imminent problem [25].

2.2 CRT, LCD and LED displays and monitors

The displays and monitors market is a good expression of how a change in the productive technology can influence volumes collected by recyclers. In this specific context, Liquid Crystal Displays (LCDs) gradually substituted Cathode Ray Tubes (CRTs) displays and monitors in many application fields. This way, CRTs became (and continues to be) one of the most important (in volumes) waste stream to be managed by recyclers. Fortunately, their recycling process is well-known, economically sustainable and it does not seems to create particular problems to the environment [26]. However, given the great amount of LCD screens sold in the last years (and it will predictably continue in the near future basing on some estimations [27]), it should be of outmost importance also to think about specific recycling processes (currently, only in a development phase) for this new kind of products [28].

The most important material that can be extracted (even if in limited amounts) by LCD screens is, without doubts, indium [17]. However, many studies show that also in Printed Circuit Boards (PCBs) coming from LCD monitors and displays there are interesting contents in other valuable materials (e.g. copper, gold and silver). In addition, the great content of high-tech plastics used for their production (and, nowadays, almost without value) could play a relevant role in recycling [29], if specific recovery processes and alternative application fields will be developed. Light Emitting Diode (LED) screens are the natural evolution of LCD screens and it is expected by the experts a similar trend in their adoption like what previously described for CRTs and LCDs [30].

These new types of screens add to materials embedded into LCDs also gallium, germanium and other rare materials, present in high concentrations into small LED components [31].

2.3 Notebooks and tablets

Notebooks and tablets, together with desktops and servers, are the most valuable WEEE category, given their extremely high content of key metals in some of their main sub-systems [17]. Even if structurally and functionally different, notebooks seem to gradually lose market shares in favour of tablets. In fact, tablets match the features of a screen with the ones of a notebook. From the recycler׳s point of view, this trend could be both positive and negative. From the positive side tablets have a higher content in valuable materials than notebooks (for a given weight), coming both from the screen (equal to little LED displays) and the embedded PCB, because of a more compact design. However, the negative side is that their compactness is also one of the hardest problems to solve when they have to be recycled [31].

To this aim there will be the need to modify recycling processes to enable the recovery of this type of products. To demonstrate the value embedded into these products, two subsections are dedicated to their main components (Printed Circuit Boards – PCBs and Hard Disk Drives – HDDs). LCD and LED screens have been already described before. However, it is important to explain that PCBs are also embedded into other WEEEs (e.g. washing machines, CRT, LCD and LED screens, videogames, etc.), but with lower percentages of key materials and, so, lower market value [17,32].

2.3.1 PCBs

In general terms, PCBs constitute from 3% to 6% [33,34] of the WEEE mass. However, they contain a significant portion of the value embedded into e-wastes. The current recycling of PCBs is challenging (still now, more than 40% end into landfills), because of their complex material composition and physical structure. In fact, a typical PCB consists of more than twenty different types of metals, including precious (e.g. gold, silver and platinum), base (e.g. copper, aluminium and steel) and toxic (e.g. antimony, arsenic, mercury and lead) ones, as well as ceramic compounds and plastics [35,36]. The materials recovery priority varies with PCBs composition, selected ranking metric, and weighting factors within metrics [37]. From the technological point of view, current PCBs recycling approaches are high energy-demanding and environmentally dangerous processes, able only to recover about 30–35% of the metals present in PCBs, with variable purity levels going between 85% and 95% depending on the element [17,38]. The remaining materials (including some key metals or rare earths) cannot yet be economically recycled and recovered, together with the whole non-metal fraction (e.g. plastics and ceramic compounds) [17,39,40].

2.3.2 HDDs and SSDs

The Hard Disk Drives (HDDs) market presents similar trends to what shown by CRT and LCD screens. Even if not yet expressed in a strong way, also in this context a productive technology change has influenced volumes collected by recyclers. In fact, obsolete HDDs are now being substituted by Solid State Disks (SSDs). This substitution is slower than what happened for CRTs and LCDs, as new SSDs are more expensive and less capacious than the old ones, so customers are, in general terms, even reluctant to consider to buy them. However, in the near future it is expected a gradual improvement of SSDs adoption and, so, a related improvement of HDDs that will reach their end of life [31]. Unfortunately, HDDs present some difficulties in their recycling because of their constructive philosophy, having lots of little parts matched together. Among these parts there are some (e.g. magnets) presenting high amounts of critical materials (e.g. rare earths) that could offer interesting revenues to recyclers if rightly recovered and some (the great part) with low value [41]. Paradoxically, SSDs are less interesting than HDDs in recycling terms, given their constructive technology that do not consider the use of magnetic components [31].

2.4 Cell phones and smart phones

The cell phones market is seeing (already since many years) the same trend described for CRT and LCD screens. Smart phones are quickly substituting traditional mobile phones with more attractive and valuable products. However, given their little dimensions, there is still the tendency by customers to maintain old headsets (both cell and smart phones) in their desk drawers instead of adequately dispose them. This led to a lack of potentially reusable resources embedded in these equipment. From the material׳s content view, they can be compared to tablets, even if with an even higher percentage (for a given weight) of valuable resources [31,42]. Because of this lack of volumes, recyclers are not interested in treating these products and specific processes are not yet available at industrial level. Great importance could be associated also to the recycling of the great amount of lithium-ion batteries powering almost the whole mobile phones market [31].

3 Methodology

The economic convenience coming from the reuse of materials embedded into wastes, with the aim to make new products with secondary raw materials, represents nowadays one of the most important sustainability challenges [43]. The recycling process of a product can be generally divided into three main steps, each of which requires an appropriate management method with the aim to optimise the economic result [44]:

- Collection;
- ~~Pre-treatment;~~pre-treatment;
- ~~Recovery~~recovery of valuable materials and disposal of non-recyclable ones.

The recovery of materials embedded into products is a needed condition for the WEEE recycling profitability, but not a sufficient one. In fact, products are, generally, not homogenous and only some of them embed critical and/or valuable materials [45]. The technological evolution of a product implies even the change of the material׳s mix and, so, it is opportune to extend the economic assessment to all the product typologies. The objective of the work is to propose a methodology able to select the WEEE category with the highest recovery economic potential (recovery value). To this aim, the methodological structure is the following:

1. Product׳s selection based on a previous literature analysis (Section 3.1~~);~~).
2. Material׳s ~~characterization~~characterisation for each of the selected products (Section 3.2~~);~~).
3. Generated WEEE volume׳s quantification, both in the AS IS and TO BE scenarios for each of the selected products (Section 3.3~~);~~).
4. Recovery economic potential evaluation for each of the selected products (Section 4.1~~);~~).
5. Overall recovery economic potential evaluation for expected WEEE volumes to be generated (Section 4.2~~);~~).
6. Results consolidation, obtained through a sensitivity analysis conducted on critical variables (Section 4.3).

3.1 Selected WEEEs

The WEEE set considered in this paper is composed by ~~fourteen~~14 different products: LCD notebooks, LED notebooks, CRT TVs, LCD TVs, LED TVs, CRT monitors, LCD monitors, LED monitors, cell phones, smart phones, PV panels, HDDs, SSDs and tablets. As already explained in Section 2, being PCBs a common component for all the previous WEEE categories, they were not analysed as an independent product during the economic assessment. However, their relevance from a recycling point of view is clearly evidenced within the paper. Furthermore, a good classification of different PCBs in economic terms is already available in the literature [17,46], distinguishing among: high grade PCBs (e.g. embedded in mainframes and smart phones), medium grade PCBs (e.g. embedded in PCs, laptops and handheld computers) and low grade PCBs (e.g. embedded in TVs, monitors printers and cordless phones).

3.2 Materials composition

Table 1 presents the materials concentration (in grams) in each product unit. From a first view, it is possible to evidence the presence (or not) of critical materials (e.g. antimony, beryllium, cerium, cobalt, dysprosium, europium, gadolinium, gallium, indium, lanthanum, neodymium, palladium, platinum, praseodymium, terbium and yttrium); the same activity can be done for precious metals (e.g. gold, palladium, platinum and silver) [17,23,40,41,47].

Table 1 Materials composition.

Products	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
~~Materials~~The content of cells is correct but:Insert a line under the two cells of "Materials" and "Increase of potential revenues"	g/unit													
Aluminium			67			242	130	130	12	2.9	1370	441	441	
Antimony	0.77	0.77	14	0.71	0.71					0.084				0.154
Arsenic	0.01	0.01												0.002
Barium	2.5	2.5				1								0.49
Beryllium										0.003				
Cadmium			0.2								0.407			
Cerium	<0.001	<0.001		0.005	<0.001		<0.001	<0.001						<0.001
Chromium	0.07	0.07	0.03											0.014
Cobalt	0.065	0.065							3.8	6.3				0.013
Copper	135	135	656	824	824	952			26	14	78	15	15	27
Dysprosium	0.06	0.06										0.06		0.012
Europium	<0.001	<0.001		0.008	<0.001		0.001	<0.001						<0.001

Ferrite						483								
Gadolinium	<0.001	<0.001		<0.001	0.002		<0.001	0.002						<0.001
Gallium		0.0016			0.005		0.003	0.003			0.119			
Glass			15760	162	216	6845	590	590		10.6	6915			
Gold	0.22	0.22		0.11	0.11	0.31	0.2	0.2	0.024	0.038		0.005	0.005	0.044
Indium	0.04	0.04		0.003	0.003		0.079	0.082			0.119			0.008
Lanthanum	<0.001			0.007			<0.001							<0.001
Lead	5.3	5.3	1319			464	16		1	0.6				1.1
Mercury	<0.001	<0.001					<0.001	0.004	1					<0.001
Molybdenum	0.04	0.04					0.633	0.633			0.295			0.008
Neodymium	2.1	2.1								0.05		1		0.427
Nickel	3.6	3.6				199			1	1.5				0.722
Palladium	0.04	0.04		0.044	0.044		0.04	0.04	0.009	0.015		0.003	0.003	0.008
Plastics			8755	612	573	2481	1780	1780	63	60	1172	44	44	
Platinum	0.004	0.004								0.004				
Praseodymium	0.274	0.274		<0.001			<0.001			0.01		0.145		0.055
Selenium											0.119			
Silicon									5		226			
Silver	0.25	0.25		0.45	0.45	1.25	0.52	0.52	1	0.244		0.031	0.031	0.05
Steel/Iron			2088			3322	2530	2530	11	8		62	62	
Tantalum	1.7	1.7												
Tellurium											0.406			
Terbium	<0.001			0.002			<0.001							<0.001
Tin			32	18	18	20	24	24	1	1	0.116			
Titanium							0.633	0.633						
Tungsten							0.633	0.633						
Vanadium						1								
Yttrium	0.002	0.002		0.11	0.005	1	0.016	<0.001						<0.001
Zinc	0.004	0.004	8.6						4	1	0.4			<0.001
# of critical raw materials	14	13	1	10	8	1	10	7	2	8	2	4	1	14
# of precious metals	4	4	0	3	3	2	3	3	3	4	0	3	3	3

I=LCD Notebooks; II=LED Notebooks; III=CRT TVs; IV=LCD TVs; V=LED TVs; VI=CRT Monitors; VII=LCD Monitors; VIII=LED Monitors; IX=Cell Phones; ~~X=Smartphones;~~ X=Smart phones; XI=PV Panels; XII=HDDs; XIII=SSDs; ~~XIV=Tablets~~XIV=Tablets.

From the data analysis it is possible to say that:

- The maximum number of critical materials embedded into some products (e.g. LCD notebooks and tablets) is equal to 14, while it is equal to 1 in other ones (e.g. CRT TVs, CRT monitors and SSDs);SSDs).
- The maximum number of precious metals embedded into some products (e.g. LCD notebooks, LED notebooks and smart phones) is equal to 4, while there are no precious metals in others (e.g. CRT TVs and PV panels).

The recovered materials evaluation occurs in function of related market prices [48], that are characterised by a high volatility [49]. To this aim, it is not possible to consider a static value, but it is needed to evaluate the historical trend of prices in a defined period of time. In this work, taking as reference the 2014 March-AugustMarch–August period, weekly values were gathered from the most relevant websites dedicated on the diffusion of raw materials prices (e.g. Infomine.com; London metal exchange.com; Metalprices.com). Table 2 reports average values and standard deviations for each one of the embedded materials. The highest average value is related to three precious metals (platinum, gold and palladium). Curiously, other critical raw materials (e.g. beryllium, europium, terbium and indium) present a higher average value than another precious metal like silver.

Table 2 Materials market price (€/kg).

Materials	€/kg		Materials	€/kg		Materials	€/kg	
	σ	μ		σ	μ		σ	μ
Aluminium	1.5	0.2	Gallium	180	12	Selenium	42	17
Antimony	7.6	0.4	Glass	0.05	0.01	Silicon	1.7	0.3
Arsenic	1.4	0.4	Gold	34,070	4665	Silver	514	58
Barium	550	95	Indium	550	84	Steel/Iron	0.12	0.02
Beryllium	864	201	Lanthanum	7.8	0.5	Tantalum	156	27
Cadmium	1.5	0.2	Lead	1.7	0.3	Tellurium	90	15
Cerium	8.6	2.9	Mercury	90	8.5	Terbium	641	29
Chromium	1.7	0.2	Molybdenum	21	3	Tin	17	2.3
Cobalt	25	0.2	Neodymium	72	4.8	Titanium	11	2.9
Copper	5.2	1.3	Nickel	14	1.3	Tungsten	71	29
Dysprosium	266	147	Palladium	23,214	4806	Vanadium	20	3.4
Europium	781	237	Plastics	1.2	0.08	Yttrium	47	5.6
Ferrite	0.12	0.02	Platinum	37,607	4343	Zinc	1.7	0.1
Gadolinium	104	5.4	Praseodymium	117	19			

σ=average value; μ=standard deviation.

3.3 EoL volumes identification and estimation

Estimates about generated wastes are frequently non-homogeneous because of the high variability given by different reference information sources. Furthermore, this variability is increased by two inefficiencies of the recycling chain:

1. The first one is related to the fact that, in general terms, generated WEEE volumes do not correspond to collected WEEE volumes.
2. Secondly, the management of collected WEEE volumes can, awfully, follow non environmental-friendly processes.

The demonstration of economic advantages related to the recycling of these products can, without considering the regulation´s structure, align WEEE gathered data with the ones generated and allow their treatment in recovery centres. Table 3 tries to quantify these values, by considering both literature works [23,26,29,30,41,42,50–52] and market reports (IDC – Analyse the Future, IMS Research, Statista – The Statistics Portal, Value Market Research), by considering two different scenarios related to the

European market:

- AS IS scenario, related to WEEEs generated volumes in ~~2014;~~2014.
- TO BE scenario, related to estimated WEEEs generated volumes in 2020.

Table 3 WEEE volumes.

Products	Weight (kg)	AS IS (kt)	TO BE (kt)	Δ change
LCD notebooks	3.5	80	97	21%
LED notebooks	3.5	22	45	105%
CRT TVs	25	85	67	−21%
LCD TVs	10	35	399	1040%
LED TVs	10	10	504	4940%
CRT monitors	16	340	133	−61%
LCD monitors	5	155	194	25%
LED monitors	5	43	244	467%
Cell phones	0.08	11.5	5.2	−55%
Smart phones	0.12	19	39	105%
PV panels	80	8.3	10	20%
HDDs	0.58	32	52	63%
SSDs	0.4	0.4	6	1400%
Tablets	0.5	4.9	10	104%

Data related to the AS IS scenario underline that smart phones and cell phones are the waste streams with the highest generation rate (in volumes), equal to almost 158 and 144 million units respectively. The situation changes if WEEE volumes are analysed in terms of mass. In fact, smart phones and cell phones have an exiguous weight. With this perspective, the highest quantity of wastes are related to the CRT technology (TVs and monitors). The TO BE scenario sees, from one hand, a quantity of generated smart phones equal to almost 325 million units; from an opposite hand, WEEEs related to LCD and LED technologies seems to be the most interesting in terms of mass, with a total weight of almost 1.2 million tons.

4 Results

The previous sections provided a picture of the current situation about the WEEE management from both a regulatory and technological point of view, by offering a series of important economic data. Being the main aim of this paper the selection of a set of WEEEs able to guarantee a certain level of profitability, it is of outmost importance the evaluation of the potential revenues of these products. Different results that will be obtained during the work have to be considered as part of a wider research project dedicate to the evaluation of the economic sustainability of multi-WEEE recycling plants. By following this optic, this section will define the recovery potential related to each single product and, subsequently, the overall recovery potential related to the entire amount of the same type of WEEEs in current and future periods of time. At the base of the results obtained in this section there is a common hypothesis, or that all the recovered materials have the maximum purity level required by the market. This way, market prices are not influenced by unpredictable reductions. This choice is justified by the fact that, in this section, the aim is to define the economic potential of different wastes, or the maximum recoverable value that could be obtained by recyclers. Sensitivity analyses conducted in the next subsection 4.3 will contribute on the evaluation of what could happen in alternative contexts, where recovered materials present some impurities.

4.1 Potential ~~Revenues~~revenues – ~~Base Scenario~~base scenario

The recovery economic potential is defined as the product between the WEEE´s material composition (g/unit product ~~–~~– Table 1) and the related market prices (€/kg ~~–~~– Table 2). Fig. 1 compares the previous index (€/product unit) with another index (€/kg of product), obtained as the ratio between the previous index and the weight of each single product (Table 3). By ~~analyzing~~analysing these values it is evident that:

- CRT monitors and CRT TVs value 25 €/product unit and 18 €/product unit, ~~respectively;~~respectively.
- Cell phones and smart phones value 25 €/kg of product and 19 €/kg of product, respectively.

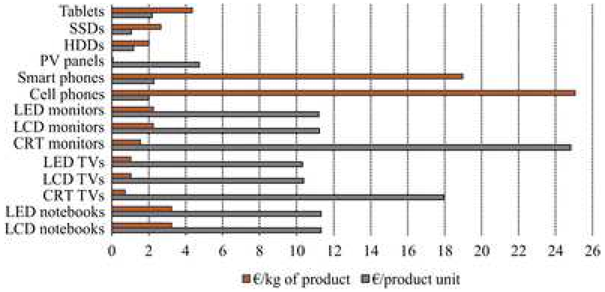

Fig. 1 Potential ~~Revenues~~revenues – ~~Base Scenario.~~base scenario.

The comparison among products in this phase is determined by the weight of each material. In fact, if the €/product unit is considered as the reference index, better results are obtained by the CRT technology, given that the related products are the heaviest ones. This happens despite the reduced content in critical and precious metals related to these products. Instead, if the €/kg of product is considered as the reference index, results are completely different. In this last case, better results are obtained by lighter products, or by different types of phones. This distinction disappear, when the overall potential revenues are analysed. This value can be calculated both as the product between €/product unit and the number of related produced units or as the product between €/kg of product and the volume expressed in weights unit. The economic analysis of some e-waste (CRT monitors, LCD monitors, fluorescent lamps) highlighted as waste PCBs are the most interesting component [53], as evidenced in Section 2.3.1. The potential revenues coming from the recycling of waste PCBs are defined fixing it equal to 21,200 $/t [37]. The incidence of gold on potential revenues is equal to 72%, by considering a value of about 15,200 $/t, but ranging from a minimum level of ~~2,500~~ 2500 $/t up to a maximum level of 40,000 $/t.

4.2 Overall ~~Potential Revenues~~potential revenues – ~~Base Scenario~~base scenario

The choice about what is the most convenient waste to recycle depends not only by the intrinsic recoverable value ~~characterizing~~characterising a single product, but also by the number of generated units. To this aim, two different market scenarios are reported, a current and future ones (Table 4). In this phase the main hypothesis implies that the generated volumes of WEEEs correspond to the collected ones and the recovered ones. This hypothesis has value, if the objective is the estimation of the potential value. The subsequent sensitivity analysis will evaluate different scenarios.

Table 4 Overall ~~Potential Revenues~~potential revenues – ~~Base Scenario.~~base scenario.

Products	AS IS (M€)	Ranking	TO BE (M€)	Ranking
CRT monitors	528	1	206	7
Smart phones	363	2	746	1
LCD monitors	348	3	435	4
Cell phones	288	4	130	9
LCD notebooks	259	5	314	6
LED monitors	96	6	546	2
LED notebooks	71	7	146	8
HDDs	64	8	105	10
CRT TVs	61	9	48	11

LCD TVs	36	10	413	5
Tablets	21	11	44	12
LED TVs	10	12	519	3
SSDs	1.06	13	16	13
PV panels	0.49	14	0.59	14

The technological evolution determines a deep change in the previous WEEE ranking. As it can be easily noted in Table 4, the comparison between TO BE and AS IS scenarios sees an increase of about 71% of the potential revenue. This data depends by higher waste volumes estimated in the TO BE scenario. The first place of the ranking sees smart phones as the most promising product to be recovered. However, there are also significant values related to different types of monitors and TVs, both in LED and LCD version. Speaking about smart phones, 56% of revenues comes from the recovery of the gold content. Other interesting contributions comes from: palladium (15%), platinum and cobalt (7%), silver (5%), plastics and copper (3%). From the monitor′s point of view (both in LED and LCD version) the main contribution is given by gold (61%) followed by: plastics (19%), palladium (8%), tin (4%), steel (3%) and silver (2%). Finally, from the TV′s point of view (both in LED and LCD version) copper (42%) is the most valuable material, followed by gold (36%), palladium (10%), plastics (7%), tin (3%) and silver (2%). However, from an overall point of view, gold is the material determining half of the potential revenues by considering all the WEEEs categories selected in this work. Table 5 resumes all these interesting data.

Table 5 Top-ten materials.

Materials	% Revenues
Gold	50.4
Copper	13.9
Palladium	9.5
Plastics	9.2
Silver	3.6
Aluminium	2.5
Tin	2.0
Barium	1.8
Platinum	1.7
Cobalt	1.6

This ranking does not have the intention to divide WEEEs into two groups, depending on their embedded recovery potential. Instead, these results want to be a support material for the definition of new and sustainable recycling business models based on flexible plants able to manage different WEEE categories, trying to change the common vision from mono-core to multi-cores recycling. Furthermore, a literature review focused on waste PCBs recycling economic impacts evidenced as the existing models are very few and specialized on a particular part of the recycling process [54]. Future addresses of research are geared to assess all phases of recycling process (dismantling, ~~pretreatment~~pre-treatment and refining) in order to define their costs.

4.3 Sensitivity analysis

The sensitivity analysis is an instrument allowing to evaluate how a final index is influenced by variations of some input variables. In particular, the analysed parameters refer to:

1. Material′s market ~~price;~~price.
2. ~~Material′s~~Material's weight within a ~~product;~~product.
3. ~~Material′s~~Material's purity level obtained by the recycling ~~process;~~process.
4. Volumes of generated ~~wastes;~~wastes.

5. Percentage of collected versus generated wastes.

Generally, the overall number of materials embedded in the selected WEEEs is 41. Trying to evaluate what are the most influencing materials on the economic results, the market price of each of them is modified in a range equal to their standard deviation and the recovery potential´s percentage of variation is calculated for each product unit (Table 6).

Table 6 Sensitivity analysis – market prices.

Products: I=LCD notebooks; II=LED notebooks; III=CRT TVs; IV=LCD TVs; V=LED TVs; VI=CRT monitors; VII=LCD monitors; VIII=LED monitors; IX=Cell phones; X=Smart phones; XI=PV panels; XII=HDDs; XIII=SSDs; XIV=Tablets														
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
~~Materials~~The content of cells is correct but:Insert a line under the two cells of "Materials" and "Increase of potential revenues"	~~Increase of potential revenues~~This cells is related to all the cells from I to XIV, please expand the cells													
Aluminium											6%	8%	8%	
Barium	2%	2%												2%
Copper	2%	2%	5%	10%	10%	5%			2%	1%	2%	2%	2%	1%
Gold	9%	9%		5%	5%	6%	8%	8%	6%	8%		2%	2%	9%
Lead			2%			1%								
Palladium	2%	2%	2%	2%	2%	1%	2%	2%	2%	3%		1%	1%	2%
Plastics			4%			1%	1%	1%			2%			
Platinum										1%				
Silver									3%					

Table 6 reports only the list of materials causing the most significant variations and emerges the presence of the four precious metals (gold, palladium, platinum and silver) present in many WEEEs analysed in this work. Instead, there is not the presence of the previously mentioned critical materials having a market price higher than silver. This is caused by their limited content in all the examined WEEEs as: beryllium in smart phones, europium in LCD technologies, indium in LCD and LED monitors and in PV panels (thin film versions) and terbium in LCD TVs. For what regards the materials price, it is possible to define the material causing the highest gap:

- Aluminium for PV panels, HDDs and ~~SSDs;~~SSDs.
- Copper for LCD and LED ~~TVs;~~TVs.
- Gold for cell phones, smart phones, tablets, notebooks and ~~monitors;~~monitors.
- Plastics for CRT TVs.

By focusing the analysis on these last four materials (aluminium, copper, gold and plastics), their composition were increased by 5% in different WEEEs [43] and Table 7 shows the related recovery economic potential variations. What emerges is that these results are in line with the previous ones and, for example, LCD and LED TVs see the variation related to copper (2.1%) higher than the one related to gold (1.8%).

Table 7 Sensitivity analysis – materials composition.

Products: I=LCD notebooks; II=LED notebooks; III=CRT TVs; IV=LCD TVs; V=LED TVs; VI=CRT monitors; VII=LCD monitors; VIII=LED monitors; IX=Cell phones; X=Smart phones; XI=PV panels; XII=HDDs; XIII=SSDs; XIV=Tablets														
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
~~Materials~~The content of cells is correct but:Insert a line under the two cells of "Materials" and "Increase of potential revenues"	~~Increase of potential revenues~~This cells is related to all the cells from I to XIV, please expand the cells													

Aluminium											2%	3%	3%	
Copper			1%	2%	2%	1%								
Gold	3%	3%		2%	2%	2%	3%	3%	2%	3%		1%	1%	3%
Plastics			3%			1%	1%	1%			1%			

Values reported in Table 6 and Table 7 evidenced that gold is the most influencing factor on final results. By considering the materials purity level, the literature explains that this is function of the specific recycling technology taken into consideration. If, after the recycling process, the material is not completely pure, a reduction of the market price will be applied. In the current state, it is not possible to track within the literature homogeneous data for all the selected materials and products present in this work. This way, two different scenarios are estimated:

- RP_{all} is the scenario where the purity level reduction involve all the materials;
- RP_{cmpm} is the scenario where the purity level reduction involves only critical and precious materials.

In both these cases, market prices are reduced of a value equal to their standard deviation (Table 8). The data analysis evidences that variations influence for a great part the recovery of smart phones and tablets. Instead, by varying market prices related to all the other materials, WEEEs presenting different economic recovery are LCD and LED TVs.

Table 8 Sensitivity analysis – ~~Purity~~purity levels.

Products: I=LCD notebooks; II=LED notebooks; III=CRT TVs; IV=LCD TVs; V=LED TVs; VI=CRT monitors; VII=LCD monitors; VIII=LED monitors; IX=Cell phones; X=Smart phones; XI=PV panels; XII=HDDs; XIII=SSDs; XIV=Tablets.														
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
	~~Reduction of potential revenues~~This cells is related to all the cells from I to XIV, please expand the cells													
RP_{all}	15%	15%	12%	19%	19%	15%	13%	13%	13%	14%	13%	15%	14%	15%
RP_{cmpm}	11%	11%	1%	7%	7%	6%	10%	10%	11%	12%	2%	5%	4%	12%

A further critical parameter to consider is represented by the WEEEs generated volumes, given that what previously presented represents an estimation and, hence, is subjected to variations. To this aim a GV_{avg} scenario is proposed where WEEEs generated volumes are equal to the average value between the current and future scenarios. The value of potential revenues increase for three waste streams (CRT TVs, CRT monitors and cell phones), given that they are the ones with a future scenario presenting a decrease of volumes, if compared to the current one, and consequently the average value determines a lower reduction of volumes. Finally, the last variable to consider is the percentage of collected wastes respect to generated ones. Without real values to take into reference for all the products, two scenarios are presented: $CV_{75\%}$ and $CV_{50\%}$ where collected volumes are equal to the 75% and 50% of the generated ones. The absence of a controlled waste management chain allowed to illegally dispose a great amount of WEEEs and the low level of collected wastes, as evidenced in Section 2, represented a brake to the development of the recycling sector. Only through Directives and national governments decisions was possible to make producers responsible for their own products, by determining a great gear shift, to which it must be added the awareness that wastes are now seen as a resource and no more as issues [55–58]. Trying to ~~summarize~~summarise the results obtained by the sensitivity analysis, Table 9 propose many different scenarios:

- Au_{opt} Price and Au_{pes} Price coupled with the increase and decrease of the gold market price for a sum equal to its standard deviation ~~respectively;~~respectively.
- Au_{opt} Weight and Au_{pes} Weight coupled with the increase and decrease of the gold content in different products for a sum equal to 5% of the base ~~scenario;~~scenario.
- RP_{all} and RP_{cmpm} related to the reduction of the materials purity ~~levels;~~levels.
- GV_{avg} coupled with a different estimation of generated ~~volumes;~~volumes.
- $CV_{75\%}$ and $CV_{50\%}$ coupled with the percentage estimation of collected wastes respect to generated ones.

Table 9 Sensitivity analysis – Overall Potential Revenues (M€).

Products	Base	Au_{opt} Price	Au_{pes} Price	Au_{opt} Weight	Au_{pes} Weight	RP_{all}	RP_{cmpm}	GW_{avg}	$CV_{75\%}$	$CV_{50\%}$

LCD notebooks	314	342	286	324	324	266	279	286	235	157
LED notebooks	146	159	132	150	150	123	129	108	109	73
CRT TVs	48	48	48	48	48	42	48	55	36	24
LCD TVs	413	434	393	421	421	337	383	225	310	207
LED TVs	519	545	493	529	529	423	481	265	389	260
CRT monitors	206	218	194	211	211	176	193	367	155	103
LCD monitors	435	472	399	449	449	378	390	392	327	218
LED monitors	546	592	501	563	563	475	489	321	410	273
Cell phones	130	138	123	133	133	113	116	209	98	65
Smart phones	746	804	688	767	767	645	654	555	560	373
PV panels	0.59	0.59	0.59	0.59	0.59	0.51	0.58	0.54	0.44	0.30
HDDs	105	107	103	105	105	89	100	85	78	52
SSDs	16	16	16	16	16	14	15	8	12	8
Tablets	44	48	39	45	42	37	39	32	33	22

Environmental themes pushed many companies to revise their business models, in even more competitive markets. The technological evolution of products, the WEEE generation increase and the higher waste collection rates evidence a significant market also in Europe. Within this continent it will be important to evaluate the distribution of materials fluxes, given that revenues seems to be strictly related to the presence or not of precious metals (gold and palladium in particular), but even more by volumes. The quantification of possible revenues allows companies to decide to operate or not in that business. In fact, given their own costs, they are able to deduce if there is profit margin and if this margin respects their benchmarking indexes.

From one side, mono-core recycling centres can exploit economies of scale and a high ~~specialization.~~specialisation. Furthermore, they can integrate in their manufacturing processes even other EoL strategies, like the remanufacturing one. From an opposite side, these companies need to be located near the place where products are manufactured because, if not, logistic costs could rapidly increase. If this event would occur in parallel of a reduction of collected volumes, the risk could be a non-saturation of the plant´s capability. To this aim, in addition to the multiplicity of products available in the market, multi-core recycling centres are being developed. These centres points on flexibility as their strength. To this aim, technical evaluations assume an important role to allow, from one side, the maximum materials recovery rate with the highest purity level as possible; from another side, they allow to avoid too long setup phases causing unwanted costs.

This paper offers numerical data of different nature (mainly economic ones) and wants, from one hand, to support in the definition of recycling centres profitability and, from another hand, to select the most interesting waste mix to treat. Smart phones, TVs and monitors (both in LED and LCD versions) seems to be the most valuable wastes in a TO BE scenario. Precious metals have a significant impact on recycling activities, but it has not to be neglected also the recovery of less valuable materials that, with their high volumes, could offer the chance to reach interesting economic results.

5 Discussion

Sustainability is a concept that is reaching even more importance in our life. For that reason, almost all the national governments in the world are facing with the management of resources both extracted from their own mines and acquired from other nations. The waste management seems to be the correct way to follow for, at least, reduce the exploitation of natural and non-renewable resources [58].

Nowadays, WEEEs represent the greatest waste stream (from 20 to 50 million tons are globally generated each year) with the highest growth rate (from 3% up to 5%) per year. However, this rate is destined to increase in the next future, even more than expectations, because of a series of facts:

- A great amount (almost 50%) of current WEEEs yearly generated by developed countries continues to be illegally transferred in developing countries under the form of humanitarian aids or used products. The precise amount of these illegal volumes remains, even nowadays, ~~unknown.~~unknown.
- New products were recently included among WEEEs by the last update of the related EU (European Union) Directive (e.g. PV ~~panels);~~panels).

- New electric and electronic products will substitute soon the current ones, influencing both collected volumes, type of recovered materials and recycling processes in an unpredictable way (e.g. CRT versus ~~LCD);~~LCD).
- Innovative materials composing WEEEs (e.g. high-tech plastics and compounds or rare earths), that are currently not correctly managed during their ~~End-of-Life~~ end of life (ending into landfills), could become a valuable source of materials into the next future, asking for additional recycling capacity.

In addition, there are also some issues related to the recycling process that have not yet been completely solved:

- Some electronic parts in WEEEs (e.g. PCBs and HDDs) are not again correctly disassembled or recovered, leaving too early the recycling process or entering into different (and wrong) ~~ones;~~ones.
- Wastes from manufacturing activities (defective products and subassemblies) are not again sustainably reused for the production of new elements, with an evident loss in terms of key materials.

All these trends open the way to impressive volumes of e-wastes that in the next future should be managed by treatment centres and recyclers. From one side, these volumes could offer the potential to increase companies' competitiveness by recycling valuable materials from complex wastes and by reusing, when possible, products and components. This would allow maximum exploitation of the value added embedded into products during the manufacturing phase and guarantee the availability of critical and valuable raw materials, or to lower their acquisition costs. From the opposite side, the current recycling technologies and business models adopted by recyclers and treatment centres ~~don't~~ do not permit to reach an economic advantage for all of the valuable materials coming from these wastes, especially if recycling plants are focused on a particular waste stream or product. This way, the recovery rates remain extremely low. A clear example of that is represented by PV panels recycling [55,59]. These two points underline the importance of the definition of new business models for the recycling sector and the need of more flexible plants, able to treat a mix of different cores. The aim of this paper was, hence, is to assess the potential value added by a multi-WEEE recycling centre able to treat different waste streams together, trying to measure its performances through a series of common economic indexes. The hope was double. Firstly, there was the intent to make profitable also the recycling of products that, because of their composition, variability, reuse potential or uncertainty in volumes end into landfills, causing enormous economic and environmental damages to Europe and the entire world. Secondly, there was the intention to offer an innovative, and concrete, solution to all the actors involved in this supply chain [58,60].

6 Conclusions

The sustainable management of wastes is a well-stressed topic in the scientific literature, with the aim to develop a low-carbon intensive economy able to decouple economic growth and greenhouse gas emissions. It is possible to highlight that:

- The collection, recovery and dismantling of WEEEs were disciplined by the European Commission, with the aim to limit more or less controlled flows of these wastes through other non-EU countries requiring raw materials at low prices.
- The technological development of products and a WEEE collection demand destined to increase push the need to develop new business models where, from one side, it is needed more collaboration between EEEs manufacturers and recovery centres; from another side, it is needed the development of more flexible plants able to intercept different mixes of EoL products.
- In the AS IS case CRT monitors, Smart phones, LCD TVs, Cell phones and LCD notebooks are the potentially most promising wastes, while in the TO BE case Smart phones, LED monitors, LED TVs, LCD monitors, LCD TVs are the potentially most promising wastes.
- Overall Potential Revenues coming from the recycling of e-waste are equal to 2.15 billion euro and 3.67 billion euro in AS IS and TO BE scenario related to the European market, respectively.
- The recovery of critical materials and precious metals is seen as propaedeutic to the development of a recycling economy and data proposed in this work evidence that the gold contribution is so high that it influences the half of the economic recovery potential. Results evidence that, even in presence of materials with low economic value, they can offer relevant contributions if available in high quantities.
- The purity level of recovered materials is a requirement needed to obtain a market price as near as possible to the one of a pure material, but it is necessary to evaluate even the related costs.

All these considerations, together with economies of scale, production processes ~~optimization~~optimisation and supply chain configurations focus on a future research target that will be oriented to evaluate the profitability of multi-WEEEs recycling centres. Economic indexes are proposed in different scenarios with the aim to offer a better solidity to the proposed values and the quantitative analysis distinguished by multiple products wants to be a support to the decision-making process.

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Please confirm that given names and surnames have been identified correctly and are presented in the desired order.

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