

WEEE management in a circular economy perspective: an overview

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Abstract. The circular economy approach represents a strategy to optimize product lifecycles, thus improving the sustainability of consumption patterns. In the European Union a recent legislative proposal has addressed this concept by promoting waste prevention and re-use as well as extensive recovery of materials. Such approach is particularly interesting for the management of Waste Electrical and Electronic Equipment (WEEE), that is regarded as an urban stock of different metals, and in particular of both precious metals and rare earth elements. The recovery of metals is the main focus of WEEE management strategies and, more recently, it has been receiving a great deal of attention, especially due to the continuously increasing production of this waste stream. However, great room for improvements can still be recognised to ensure the overall sustainability of WEEE management. The present work discusses both the current needs and the main challenges regarding WEEE management in a circular economy perspective. To this end, WEEE generation trend and

composition is provided and the legislative framework for its handling is overviewed, in order to point out future perspectives to develop a more sustainable management approach of this waste.

Keywords: precious metals, rare earth elements, recovery, recycling, sustainability, waste electrical and electronic equipment

1. Introduction

The production of waste has been traditionally regarded as a wealth indicator: the better is the economic condition of a community, the greatest is its tendency to consume and, as a consequence, to generate residues. The recognition of such a relationship addressed the introduction of strategies, aiming at decoupling the economic growth from the increase in waste production, which have been recently brought into the concept of “circular economy”. It is a completely new approach in the field of waste management, which goes beyond prevention and recycling, changing the function of resources in the economy. The actions following the circular economy approach aim at the minimization of waste production through eco-design, the development of new business models as well as the identification of new recycling technologies to return raw materials back to production processes.

In this view, the management of Waste Electrical and Electronic Equipment (WEEE) is particularly challenging.

WEEE is the kind of waste characterized by the highest growth rate per year (Cucchiella et al., 2015; Tuncuk et al., 2012): in 2014 approximately 41.8 million tons of WEEE were estimated to be globally generated (Baldé et al., 2015) and around 65.4 million tons were predicted in 2017 (UNEP, 2013). Moreover, it has a complex composition, including relatively high concentrations of base and precious metals (Lee and Pandey, 2012; Tuncuk et al., 2012) as well as the presence of rare earth elements (REEs) which are classified as critical raw materials with high industrial interest (Cossu and Williams, 2015).

In the transition towards a circular economy approach, the recycling of WEEE is, thus, a relevant opportunity in both environmental and economic terms (Cui and Zhang, 2008). To this end, the development of both innovative recycling technologies and new business models to process complex materials from WEEE stream in more energy efficient and environmental friendly manner is essential (Tesfaye et al., 2017).

This paper aims at overviewing the key points of WEEE management under a circular approach.

As a comprehensive understanding of the characteristics of the material to be processed is essential in order to set a sustainable handling strategy (Chancerel and Rotter, 2009; Cui and Forssberg, 2003), the elemental composition of WEEE is presented with a focus on the contents of both base and strategic metals, as the precious ones and rare earth elements. Moreover, bearing in mind that the management of waste designed for material recovery is addressed by legislation and promoted by clearly identified economic drivers boosting the business, the legislative framework for WEEE management in the European Union as well as in other countries is outlined. The discussion is addressed towards the identification of the current needs and the main challenges for the sustainable management of WEEE in a circular economy perspective.

2. WEEE generation and composition

2.1. Production trends

The quantification of WEEE flows is a fundamental prerequisite to develop effective and sustainable management solutions. However, the global monitoring of such waste streams is challenged by lack of reliable data. The difficulty of mapping WEEE flows is related to several factors, including: (i) the collection outside official take-back systems in developed countries; (ii) the transboundary movement of electronic waste mostly from developed to developing countries; (iii) the informal collection systems in developing countries.

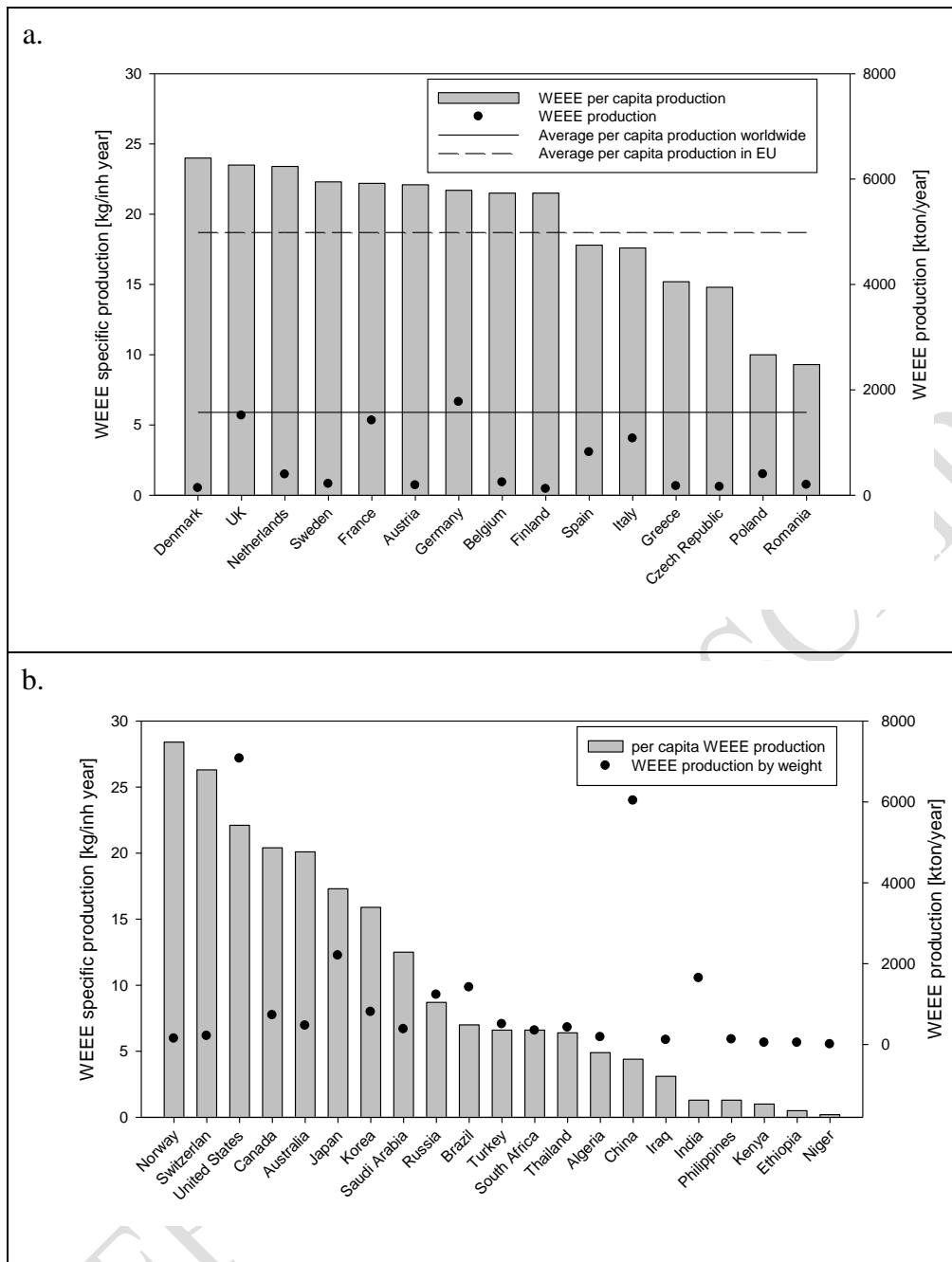


Figure 1 WEEE generated in 2014 in EU (a.) and non EU (b.) countries (www.step-initiative.org)

Moreover, the different lifespan of electronic devices within the several categories and the typical accumulation of obsolete small equipment in households contribute to hinder WEEE quantification (Baldé et al., 2015; Bigum et al., 2012).

Figure 1 displays the amount of domestic WEEE produced in 2014 by European (a.) and non-European countries (b.).

Although the specific production varies considerably among different States, WEEE generation is directly related with the population wealth, so that in Denmark, Sweden, France, Austria, Germany, Belgium, Norway and Switzerland the WEEE pro-capita production reaches values above 20 kg per inhabitant while in countries as India, Philippines and Africa it remains rather low.

When considering the overall production, in 2014 the United States of America (USA) were the major WEEE producer with 7072 kilo tons of electronic waste generated. China follows the top of the ranking, generating 6033 kilo tons of WEEE; Japan and India were just behind with a production of 2200 and 1641 kilo tons, respectively. In the same year, approximately 6 kg of WEEE per capita were globally generated, but only the 15.5% has been reported to be formally treated (Baldé et al., 2015).

2.2. The content of metals

The wide number of electric and electronic appliances, the year of production, the origin as well as the manufacturer make WEEE material composition highly variable and difficult to generalize. However, metals cover the dominant material fraction accounting for approximately 60% by weight (Tuncuk et al., 2012; Widmer et al., 2005).

The metal fraction is composed by a variety of base metals, including aluminium (Al), copper (Cu), iron (Fe), lead (Pb), nickel (Ni), tin (Sn) and zinc (Zn), which are mainly present in printed circuit boards (PCBs). When considering the entire WEEE rather than its components, few information is available.

Morf et al. (2007) detected around 49000 mg/kg of Al, 41000 mg/kg of Cu, 360000 mg/kg of Fe, 10300 mg/kg of Ni, 2900 mg/kg of Pb, 1700 mg/kg of Sb and 5100 mg/kg of Zn in small WEEE, including consumer electronics (audio, video) as well as IT and telecommunication equipment, entering a recycling plant in Switzerland. In roughly agreement with these values, Oguchi et al. (2012) found Fe (480000 mg/kg) as the most prevalent metal in input WEEE at a Japanese municipal waste treatment plant, treating both large and small household appliances, information technology and communications equipment, consumer and lighting equipment. They found a content of Cu and Al

with one order of magnitude lower than iron whereas Pb, Sn and Zn were on the order of 10^3 mg/kg. However, it should be pointed out that different proportions of items in input WEEE determine different metal content.

Moreover, WEEE contains less common metals, as bismuth (Bi), cobalt (Co), gallium (Ga), strontium (Sr) and tantalum (Ta), as well as others defined as toxic metals, including barium (Ba), beryllium (Be), cadmium (Cd), chromium (Cr), lead (Pb) and antimony (Sb), which raise great concern and set the need for an appropriate management of this waste stream (Oguchi et al., 2011, 2013).

Among base metals, copper and zinc are those with the higher economic value (Cui and Zhang, 2008) as well as the more relevant concentrations. Conventional WEEE treatment processes are thus directed to the selection and recovery of this kind of metals. Copper generally makes up around 10-20% of the PCB total weight; 4-6% consists of Pb/Sn solders while the remaining metallic fraction is composed of other metals, including the precious ones (Ghosh et al., 2015).

Gold (Au), silver (Ag) and platinum-group metals (PGMs), including platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir) and osmium (Os), are mainly present in PCBs (Table 1), either connected or mixed with other metals in contacts, cables, solders and hard disk drives or with ceramics in multi-layer capacitors, integrated circuits and hybrid ceramics or, furthermore, with plastics in PCB-tracks, inter-board layers and integrated circuits (Hagelüken, 2006). However PCBs represent only 3-6% of the WEEE mass (Cucchiella et al., 2015).

Differently from base metals, the concentration of the precious ones in WEEE is rather low. However, their economic relevance is very high. Moreover, the concentration of precious metals in PCBs is generally much higher than that in mineral ores and the environmental impacts associated with the production from secondary sources is much lower than their primary production. For instance, Chancerel (2010) reported that approximately 540 tonnes of virgin material have to be used in order to produce just one gram of gold.

WEEE is considered as an interesting “urban mining” target not only for precious metals, but also for REEs. These are a group of 17 metallic elements, including 15 lanthanides, namely lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium

(Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu) plus scandium (Sc) and yttrium (Y).

REEs can be found in cathode ray tube (CRT), fluorescent lamps, magnets, accumulators, electrodes, semi-conductors, capacitors and electric contacts (Menad and van Houwelingen, 2011).

Table 1 Precious metal content in selected WEEE

Equipment type	Precious metal concentrations (mg/kg)				Ref.
	Ag	Au	Pd	Pt	
LCD notebooks	71	63	11	1	Cucchiella et al., 2015
LED Notebooks	71	63	11	1	Cucchiella et al., 2015
LCD TVs	45	11	4	-	Cucchiella et al., 2015
LED TVs	45	11	4	-	Cucchiella et al., 2015
CRT Monitors	78	19	-	-	Cucchiella et al., 2015
LCD Monitors	104	40	8	-	Cucchiella et al., 2015
LED Monitors	104	40	8	-	Cucchiella et al., 2015
Cell Phones	12500	300	113	-	Cucchiella et al., 2015
	1340	350	210	-	Hagelüken, 2006
Smart Phones	2033	317	125	33	Cucchiella et al., 2015
HDDs	53	9	5	-	Cucchiella et al., 2015
SSDs	78	13	8	-	Cucchiella et al., 2015
Tablets	100	88	16	-	Cucchiella et al., 2015
Portable audio	150	10	40	-	Hagelüken, 2006
DVD player	115	15	4	-	Hagelüken, 2006
Calculator	260	50	5	-	Hagelüken, 2006

As some of them have been recently claimed as critical raw materials for the economy of the European Union, the interest towards their recycling has been growing exponentially. However, the research on REE recycling has been mainly focused on three categories of end-of-life products: those containing phosphors which are capable of luminescence; devices containing permanent magnets and batteries due to their REE contents (Tunsu et al., 2015).

A relevant obstacle in proposing recycling technologies for REEs is in the fragmentation of data on their concentrations in WEEE, which is tightly related to trade secrets which cover some devices (Buchert et al., 2012).

A characterization in terms of critical materials of selected WEEE has been provided by Cucchiella et al. (2015): the data reported in Table 2 show that the concentration of REEs in WEEE is very low, especially when compared with base metals. This aspect could further hinder the implementation of proper recovery technology at industrial scale.

Table 2 Content of REEs in selected WEEE (Cucchiella et al., 2015)

Equipment type	REE concentrations (mg/kg)								
	Ce	Dy	Eu	Gd	La	Nd	Pr	Tb	Y
LCD notebooks	<0.3	17	<0.3	<0.3	<0.3	600	78	<0.3	0.6
LED Notebooks	<0.3	17	<0.3	<0.3	-	600	78	-	0.6
LCD TVs	0.5	-	0.8	<0.1	0.7	-	<0.1	0.2	11
LED TVs	<0.1	-	<0.1	0.2	-	-	-	-	0.5
CRT Monitors	-	-	-	-	-	-	-	-	62
LCD Monitors	<0.2	-	0.2	<0.2	<0.2	-	<0.2	<0.2	3.2
LED Monitors	<0.2	-	<0.2	0.4	-	-	-	-	<0.2
Smart Phones	-	-	-	-	-	417	83	-	-

HDDs	-	103	-	-	-	1724	250	-	-
Tablets	<2	24	<2	<2	<2	854	110	<2	<2

3. The legislative framework for WEEE management

In many countries worldwide, WEEE management is formally disciplined by specific Regulations. The strategies enforced by law usually adopt the extended producer responsibility (EPR) as the key aspect for the management of this kind of waste (Tanskanen, 2013).

South Africa, Kenya and Nigeria are the only African countries that have recently implemented the EPR strategy (Li et al., 2013). However, in Africa informal sector still plays a significant role in WEEE processing (Ongondo et al., 2011). Moreover, 88% of African destinations countries involved in the transboundary movements of electronic waste have not yet established regulation on WEEE import (Li et al., 2013).

In Asia, China, Malaysia, India, Hong-Kong, Japan and South Korea have enforced EPR regulations. Although some of these countries banned the import of WEEE, in others the illegal traffic is still prevalent. In Japan the illegal dump of WEEE as well as the intensive end-of-life export as second-hand goods are likely stimulated by the recycling fees (Ongondo et al., 2011).

The illegal WEEE management affects also European countries, where only one-third of this waste is reported to be separately collected and treated (www.ec.europa.eu) in accordance with the WEEE Directive.

3.1. The European WEEE Directive

In the European Union, the management of WEEE is disciplined by the WEEE Directive 2012/19/EU, which entered into force on the 13th of August 2012, being effective since the 14th of February 2014.

The electrical and electronic equipment (EEE) including appliances powered by electric currents or electromagnetic fields as well as equipment for the generation, transfer or measurement of such

currents and fields, which the holder discards or intends or is required to discard fall under the WEEE Directive.

The Directive on the restriction of the use of certain hazardous substances in EEE or RoHS (Restriction of Hazardous Substances) Directive represents a further reference, setting the beginning-of-pipe of EEE lifecycle (Schluep, 2014).

In accordance with the EPR principle, the WEEE Directive put on EEE producers the responsibility, physical and/or economic, for the take back and the recycling of their post-consumer products. Such responsibility aims at promoting the development of sustainable design of electric and electronic products, namely eco-design, in order to simplify reuse or recycle. The implementation of eco-design for EEE would indeed promote recycling and result in the reduction of the waste management costs that are assigned to producers. According to the Directive, producers can address their duties individually or creating producer responsibility organizations (PROs), thus setting up either individual or collective take-back systems.

However, for developing an efficient and sustainable management system, not only producers but all the stakeholders and the operators, from governments to consumers as well as recycling industry, need to be involved (Tanskanen, 2013). In this view, it is worth pointing out that the European WEEE Directive introduced also a responsibility for distributors, namely any natural or legal person who makes an electric or electronic device available on the market. Distributors have to ensure that the obsolete EEE can be returned at least free of charge on a one-to-one basis when a new equal equipment is supplied. The role of consumers has been outlined as well, as they have to actively contribute to the successful collection of WEEE.

This formally identified systems is adopted to ensure environmental prevention, by promoting WEEE separate collection and recovery. To this end, the WEEE Directive fixed collection targets for all WEEE, based on volumes of the corresponding EEE placed on the market: 65% of the average weight of EEE placed on market in the previous three years has to be collected by 2019.

Recovery targets were set as well, in order to ensure that WEEE collected is then properly treated.

4. Needs and challenges for WEEE handling under a circular approach

The globally increasing trend in WEEE production and its heterogeneous composition, which makes this waste both a potential source of secondary materials and a vehicle of hazardous substances if improperly handled, require the implementation of sustainable management strategies (Rubin et al., 2014).

The currently established legislative frameworks, when existing, implement the principle of the Extended Producer Responsibility, with the main aim of reducing adverse health and environmental effects from WEEE unregulated practices. However, such approach is still far away from promoting the management of this waste stream in a circular perspective, so that specific challenges can be identified to fulfill the current needs.

4.1. WEEE characterization

The material composition of WEEE acquire fundamental importance to set up proper management strategies.

This category of waste includes a wide range of electric and electronic appliances, constantly evolving in accordance with the product technological innovation, so that it is difficult to create a harmonized list of end-of-life electric and electronic appliances.

The literature review highlighted that scattered information is available, especially if referred to REEs: the trade secret covering some devices is a relevant obstacle in the collection of reliable data about the concentration of the different materials composing a specific equipment.

Most scientific works report the characterization of WEEE components, mainly in terms of metals. However, the relevance of these data is limited as usually few details (origin, manufacturer, year of production, ...) about the analyzed component are given. Moreover, the lack of standard methods to assess total element concentration in WEEE results in the application of different protocols which, in turn, affects the outcome of the analytical determination as well as the comparability of data from different experimental works.

The creation of an official database including data on WEEE components and their material composition represents a challenging as well as pressing issue, that should be addressed together with the identification of shared and scientifically-based standard analytical procedures to optimize the characterization of methods and to ensure the comparability of results.

4.2. Collection programs and take back and strategies

In order for WEEE to enter the formal handling system, it has to be taken back and this requires both supporting policies and proper infrastructures. In this view, different priorities can be recognized in different global regions.

In countries (e.g. European Member States, USA, India, Canada, ...) where specific legislations are enforced, collection is formally identified and differently implemented in accordance with the EPR principle. In these countries, the improvement of collection rates must be pursued. Corsini et al. (2017) recently pointed out the relevance of a more productive cooperation between the private and public sectors by implementing competitive collection systems. Moreover, in order to implement WEEE management in a circular perspective, collection methods should effectively promote recycling and, in this view, the design of systems ensuring the concentration of critical metals in source selected WEEE streams can be regarded as the main challenge.

Different needs can be recognized in the countries lacking in both specific legislation and WEEE handling capacity, which is expected to develop to a worse scenario due to the increasing WEEE amount. In these regions, the identification of effective policies represents a key challenge to be faced. Filling this gap is not an easy task and, although the existing experience can be addressed, the identification of the most sustainable strategies to intercept WEEE streams must take into account region-specific conditions.

It is worth pointing out that the absence of a legislative framework also contributes to the growth of the informal WEEE management sector. It is mostly fed by illegal e-waste trade, including both imported and domestic stockpiled WEEE, so that it represents a concern of both exporting and importing countries. Both banning WEEE import and improving formal collection rate could limit the

volume of WEEE entering the informal sector and tracking the waste is thus fundamental. However, as spotted initiatives could prove to be ineffective, data from local monitoring systems should convey to a wider, internationally based network.

4.3. Recycling processes

The identification of innovative recycling technologies stands as a backbone of the circular economy approach.

At industrial scale, recycling processes currently include a pre-treatment stage, usually based on mechanical separation techniques, and a refining stage to get target materials. It is well known that pretreatments are designed to select base metals, so that they are responsible for great losses of critical metals, which tend to concentrate in output streams not destined to further recovery. Moreover, only few facilities hold the technical know-how to effectively implement the refining stage (Tansel, 2017). In this context, despite the economic value of the recoverable materials from WEEE, the recycling industry is not well developed, because the profitability does not properly counterbalance both capital and operating costs.

In the last decade, numerous studies have investigated alternative recycling treatments, but great room for improvement can be still identified. The efficiency of the proposed techniques is indeed negatively affected by the complexity of most WEEE components, which would require both expensive and labor-intensive pretreatments. WEEE complexity also accounts for the poor selectivity of refining processes.

WEEE recycling in a circular economy perspective should entail the maximization of resource extraction from waste, while pursuing the reduction of the related environmental impacts (Cesaro et al., 2017a). To this end, both the improvement of EEE recyclability and recycling process upgrade can play a key role and can be regarded as the main challenges in this field.

The utilization of hazardous substances in EEE should be more and more limited, so as to enhance the environmental compatibility of the subsequent recycling process (Guna et al., 2016; Cesaro et al., 2017b).

It is worth pointing out that some potentially hazardous substances have already been replaced in WEEE manufacturing processes, but both heavy metals and organic pollutants are still present (Baldé et al., 2015). As already discussed for the valuable fractions, the scarce information about WEEE characterization in terms of hazardous materials can represent an obstacle in setting up innovative recycling technologies that are intended to be also environmentally-friendly.

More recently, green electronic processes, referring to the pioneer use of bio-based electronic components, have also been proposed (Guna et al., 2016). Although this kind of technology can be regarded as an option to reduce the potential hazard associated to recycling practices, further efforts should be provided to ensure their scale up.

Electric and electronic goods should also be designed and realized in order to make their disassembly easier. Such condition would not only facilitate the pretreatment for recovery, but it would also positively affect the reuse and refurbishing of end-of-life appliances in accordance with the circular economy principle.

The sustainability of recycling processes should entail, together with the environmental compatibility, the profitability. The process has to end up in a material that can be effectively used to replace natural resources, while lowering the environmental burdens. To this end, the pretreatment step should rely on more sophisticated automatic techniques, capable of dealing with WEEE material complexity. The more effectively the disassembly is performed, the higher will be the material recovery yields of the overall process.

As for the refining stage, the need to shift from conventional metal recovery processes based on pyro- and hydro-metallurgical techniques to more environmentally sound treatments has driven the research interest towards bio-metallurgical treatments (Isildar et al., 2017).

Although both bioleaching and biosorption processes have been proven to be promising techniques, the prolonged reaction time as well as the low loading capacity as solid materials to be treated still hinder their scale up.

4.4. Human health and environmental protection

The presence of hazardous substances in WEEE and their possible release into the environment raise great concern about the adverse effects on human health. These effects, which have been largely described in scientific literature (Sepúlveda et al., 2010; Tsydenova and Bengtsson, 2011), are particularly severe when associated to informal waste recycling practices. These uncontrolled processes can determine different contamination scenarios, depending on both the processed kinds of WEEE and the treatment operating conditions.

As long as WEEE management relies on rudimentary, unregulated practices despite the increasing amount to be handled, both workers and population living in the surroundings of the informal working sites will be exposed to potentially hazardous concentration of pollutants in air, soil and water.

Cesaro et al. (2018) has recently proposed a strategy to identify the relative potential harm of different kinds of WEEE by their content in metals, selected as target contaminants. Although the proposed methodology indicated a prioritization criteria for WEEE management, the quantification of the risks associated to the possible contamination scenarios represents one of the main challenges in this area (Grant et al., 2013; Rim et al., 2013).

The comprehensive characterization of both inorganic and organic contaminants that can be generated during WEEE informal treatment as well as the identification of human exposure to complex contaminant mixtures still hinder the assessment of the risk for human health, which could address the definition of either guidelines or best practices.

Dealing with these aspects is a demanding task, especially when considering WEEE characteristics, in terms of material composition. The evolution in technology includes indeed the use of different and innovative substances for EEE production, so that the characterization of what can be released or

generated when the end-of-life EEE undergoes a specific informal treatment practice can vary with the device as well as over time.

Risk based procedures could be also of support for the definition of a specific regulatory framework: a direct transfer of the solutions implemented in developed countries does not seem to be applicable indeed, due to the specific socio-economic conditions of different areas.

In order to take into account local socio-economic dynamics, a legally established integration between formal and informal system has been proposed as a valuable alternative to strict and punitive laws (Ardi and Leisten, 2016). According to this approach, the informal sector should handle both collection and manual dismantling, to separate valuable WEEE components; the formal sector should be in charge of both the metal refining process and the disposal of residues.

This kind of measure could reduce the volume of WEEE generated on site and entering the informal sector. However, such upstream strategy should go hand in hand with policies acting on the illegally imported WEEE.

In this view, the involvement of developed countries is fundamental: the strengthening of WEEE regulations on separate collection and recycling targets, the clear distinction between second-hand appliances and waste as well as the export banning of the latter are possible actions to reduce mislead streams to developing countries, decreasing the share of waste treated within informal systems.

More efforts are needed to address these issues, and more field studies should be carried out to either support or validate the research work.

5. Conclusive remarks and future perspectives

WEEE management has raised as an attractive as well as challenging issue in the last few years.

The presence of valuable metals and critical elements acts as a driver for its recycling, whereas the heterogeneous composition and the content of hazardous substances hinder the sustainability of material recovery. Such conditions are even more complex if WEEE handling is intended to comply with the circular economy principles.

In this context, the role of interdisciplinary research seems fundamental to address the current, pressing issues dealing with WEEE characterization, collection, treatment as well as facing the global WEEE trades and the related impacts, both in terms of human health and environmental protection.

WEEE production minimization and the identification of strategies pursuing the effective extraction of materials to be brought back into production processes requires the comprehensive understanding of the material composition as well as the in-depth study of innovative and material-selective recycling treatments. A trans-national approach is also worth pursuing, in order to overcome the limits set by locally established conditions, so as to support WEEE management in a circular economy approach while protecting both human and environmental health on global scale.

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