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e-WASTE: Everything an ICT Scientist and Developer Should Know

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ABSTRACT Every dazzling announcement of a new smart phone or trendy digital device is the prelude to more tons of electronic waste (e-waste) being produced. This e-waste, or electronic scrap, is often improperly added to common garbage, rather than being separated into suitable containers that facilitate the recovery of toxic materials and valuable metals. We are beginning to become aware of the problems that e-waste can generate to our health and the environment. However, most of us are still not motivated enough to take an active part in reversing the situation. The aim of this article is to contribute to increase this motivation by pointing out the significant problem that e-waste represents and its social and environmental implications. We have chosen this forum in which multidisciplinary researchers in ICT from all countries access on regularly to explain the serious problems we are exposed to when we do not make a responsible and correct use of technology. In this paper, we also survey the composition of contemporary electronic devices and the possibilities and difficulties of recycling the elements they contain. As researchers, our contributions in science enable us to find solutions to current problems and to design more and more powerful intelligent devices. But responsible researchers must be aware of the negative effects that this industry causes us and, consequently, assume their commitment with more sustainable designs and developments. Therefore, the knowledge of e-waste issues is crucial also in the scientific world. Researchers should consider this problem and contribute to minimize it or find new solutions to manage it. These must be the additional challenges in our projects.

INDEX TERMS Consumer electronics, electronic waste, health and safety, pollution, recycling, sustainable development, waste management.

I. INTRODUCTION AND MOTIVATION

Electronic waste or e-waste is the term applied to all that electrical and electronic equipment (EEE) that has reached the end of its useful life and is discarded or becomes obsolete. This includes household electrical appliances, air conditioning units, television sets, computers, and all types of electronic devices for example, smartphones, tablets, printers, memory cards, and game consoles.

Basel Convention [1] assesses as hazardous residues, among others, the waste containing polychlorinated and polybrominated flame retardants; heavy metals such as hexavalent chromium, cadmium, lead, mercury, or copper; toxics derived from incineration for example, dibenzofurans and dibenzoparadioxins (all typical of electronic waste); and even considers hazardous garbage any electrical and electronic assemblies including electrical cables. So, all electronic garbage contains and generates toxic waste sings and must be handled as such: as a dangerous waste.

Due to the increase in consumption of electronic and intelligent devices for personal and domestic use, (often known as consumer electronics, CE), the frequency with which they are discarded, and the large number of damaging and toxic elements they contain, this article mainly focuses on this type of e-waste. The global issue of e-waste is a not yet enough well known effect of the social and environmental implications of technology.

A study carried out by the United Nations University (UNU) in 2017 [2] and supported with data provided by the International Telecommunications Union, forecast that around 50 million tons of e-waste will be generated during 2018. Although there is still no official global data to confirm this forecast, a World Economic Forum report from January 2019 [3] anticipates a sum of 48.5 million tons of

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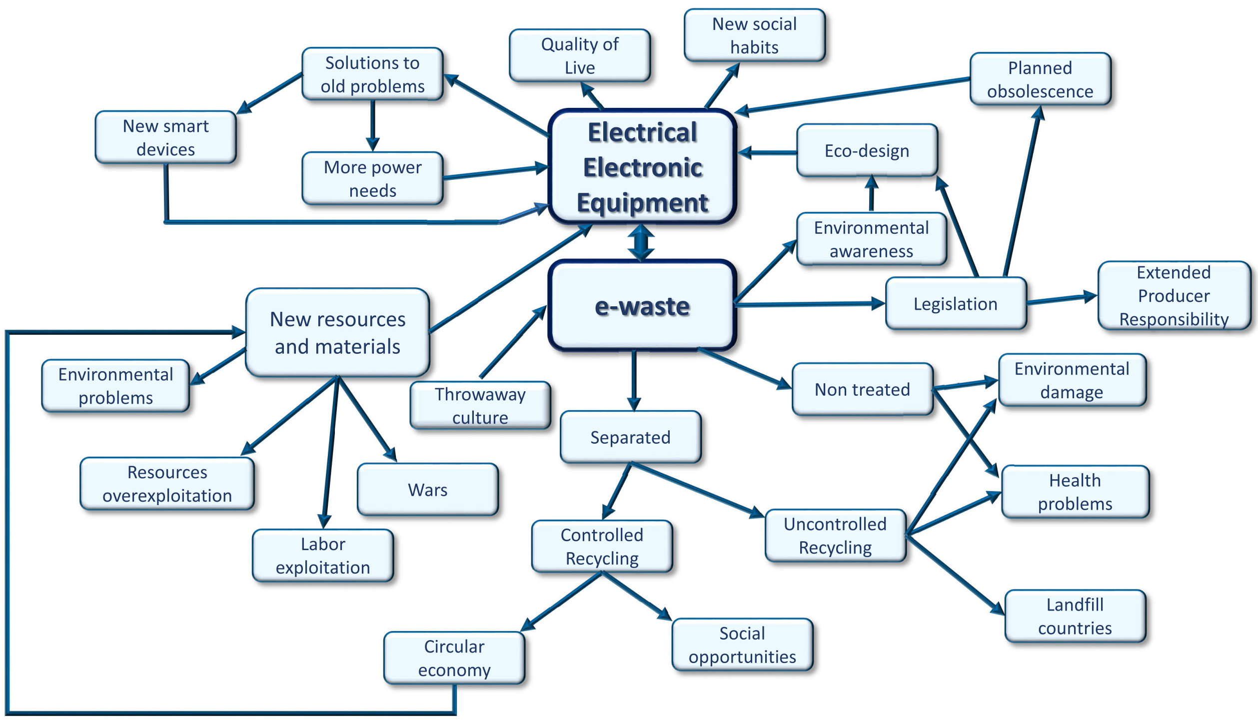

FIGURE 1. Key issues related to e-waste.

e-waste produced in 2018. As a particular example, just in Spain 113,131 tons of e-waste were managed during 2018, which is 10 percent more than the previous year, according to the information provided by the Ecolec Foundation,[1] a non-profit organization that focuses its activity on the recycling of EE devices.

For those who like comparisons, the UNU report also explains that the e-waste produced during 2016 was equivalent to almost ten Giza Pyramids, or 5,000 Eiffel Towers. The United States, followed by China, Japan, Germany, and India, produce the most electronic waste. America and China together produce a third of all e-waste. Nevertheless, the problem is not only the production of this scrap, but the use and treatment it is given. Only 35% of this waste is recycled, while the remaining 65% is exported, illegally recycled, or simply thrown into common landfills. Electronic waste is already the fastest growing waste (up 20% every year) and the least controlled. Despite the fact that this report has not been updated until now, it provides very interesting data, numbers and statistics about the main e-waste related issues.

Many consumers remain unsure about how to safely dispose of old computers, smartphones, and other electronic devices and, their opportunities for recycling may depend on where they live. When electronic waste is not selectively disposed of in a controlled way, toxic metals and elements present in the device damage the environment, pollute the air we breathe, as well as the land we grow, and the water we drink. Health experts point out the problems for our body caused by the harmful substances contained in e-waste. On the positive side, proper management of this e-waste could generate new jobs and contribute to development.

Fortunately, thanks to the dissemination of information about this problem by the media, the contamination caused by the toxicity of e-waste has become a problem for all sectors of the community and a major concern for national and international organizations such as governments, NGOs and universities, who have begun to establish a serious commitment to intervene on this issue. Many are the causes of the huge amounts of e-waste around the world and many are their consequences and direct effects. An entire book could be written to address all of them. Fig. 1 shows the most important related issues as a mind map. Our article, less ambitious, focuses on those aspects directly related with the harmful effects of certain elements and materials, their possibility of recycling and the potential for the development of the new circular economy more sustainable with the environment and human progress.

In addition, our work includes information related to regulations and laws for the management and manipulation of these e-waste and other related issues for example, planned obsolescence and throwaway culture. This is not a typical research article where new contributions to the field are shown. Conversely, it is an article addressed to researchers of any field related to new technologies and their applications with the aim of pointing out the enormous problem

[1]https://www.ecolec.es/

that our progress and development generates, poisoning our future if we do not assume our share of the responsibility. The article is organized as follows, Section II explains the chemical composition of the main parts of consumer electronics; in Section III the main health problems related with the hazardous components of e-waste are described; Section IV provides insides on different recycling techniques; Section V presents an overview about the current legislation in different world regions; some indications about what we should do to reduce e-waste are provided in Section VI; finally Section VII summarizes the main conclusions of this work.

II. CHEMICAL COMPOSITION OF CONSUMER ELECTRONICS

Currently, consumer electronics (CE) are the most common form of electronic, computing and communication devices. Among others this term usually includes articles such as: computers, laptops and tablets, mobile phones, smart appliances for example, washing machines or refrigerators (some of them connected to the Internet), smart televisions, or even the new wearable products. These devices are the main responsible of the electronic garbage that we generate. Every device includes printed circuit boards (PCB) such as motherboards or memory/graphic/sound/network cards. Peripheral elements such as storage systems, CRT monitors or LCD screens, keyboards or power supplies are also present in many CE. Specific elements as for instance antennas, loudspeakers and microphones can be found not only in mobile phones but also in many smart gadgets. Rechargeable batteries and plastic cases are present in multiple devices. A complex mixture of metals, plastics, and other chemical substances is the base of all these components. They may contain up to a total of 60 elements of the periodic table, including base metals (for example Cu, Pb, Sn, Al, Fe), precious metals (such as Au, Ag, Pd, Pt), rare metals (Ta, Ge, some rare earths), and hazardous elements (for instance Hg, Cd, Pb, Be, Br, Cr, Zn, Ni, Ba, halogens) [4], [5]. In what follows, we analyze the composition of the different parts commonly present in many CE. In this article the names of the elements or their chemical symbols are used interchangeably. The latter are used mostly in the figures or lists. For those readers who would like to refresh the symbols of the elements of the periodic table, the Royal Society of Chemistry website[2] provides useful information in an interactive way.

A. PRINTED CIRCUIT BOARDS (PCBs)

PCBs, always present in any smart device, contribute to 30% of total e-waste. They are the components that more elements contain. These elements can be classified into three groups: metals, non-metal (ceramics and fiber glasses), and organic substances (resins) [4], [6]. Each group represents approximately 1/3 of the PCB weight [7], [8]. These elements are present in the different parts and components of the PCBs, i.e.: i) the insulating non-metallic polymer substrate; ii) the metal foil laminated layer on the surface or inside of the substrate and; iii) the Electrical and Electronic (EE) components (integrated circuits, transistors, diodes, resistors, capacitors, coils or transformers) mounted on the substrate, together with sockets, contacts and solders [9].

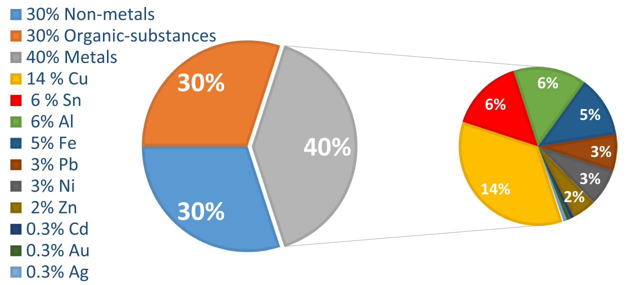

FIGURE 2. Component distribution in PCBs.

Fig. 2, shows the approximate distribution of components in the PCB weight, and the percentage of different type of metals [10]. These values vary according to the purpose of the PCB and manufacturers. In particular, different works [5], [7], [11] show that concentrations (percent by PCB weight) of precious metals such as gold, silver, and palladium in mobile phones boards are significantly higher than in personal computers (PC) motherboards.

A summary of the main elements present in a PCB and their distribution among the different components and parts is shown in Fig. 3. In general, we can distinguish:

- **Integrated circuits (IC).** Pure silicon is the basis for most IC and other electronic components such as transistors and diodes [12]. Fig. 3 shows the elements used as dopant on typical n and p-type semiconductors in IC and those present in the internal connections [13]. In particular, CPU and RAM chips contain a higher concentration of precious metals than other PCB components [14].
- **Ceramic capacitors**. They consist of two or more ceramic layers and a metal layer acting as electrode. Ceramic layers are commonly based on barium titanate with different additives as can be observed in Fig. 3 according to [15] and [16]. For the metal layer, precious metals (such as platinum, silver, palladium) are commonly used, but also nickel, copper or iron can be employed [17].
- **Electrolytic capacitors**. They are polarized capacitors whose anode is made of a metal covered by an oxide layer of the same metal that acts as dielectric, which is as well covered by an electrolyte material serving as cathode. This kind of capacitors provides higher capacity than ceramic ones. Depending on the metal used in the anode, electrolytic capacitors can be classified as aluminum, tantalum, and niobium electrolytic capacitors [18]. Tantalum capacitors have typical tantalum concentrations between 24.4% and 42.6% and a mean value of 36.7% regarding the capacitors weight.
- **Resistors**. They may contain different metals such as nickel, zinc, iron, silver, copper, and lead covered by an

[2] http://www.rsc.org/periodic-table

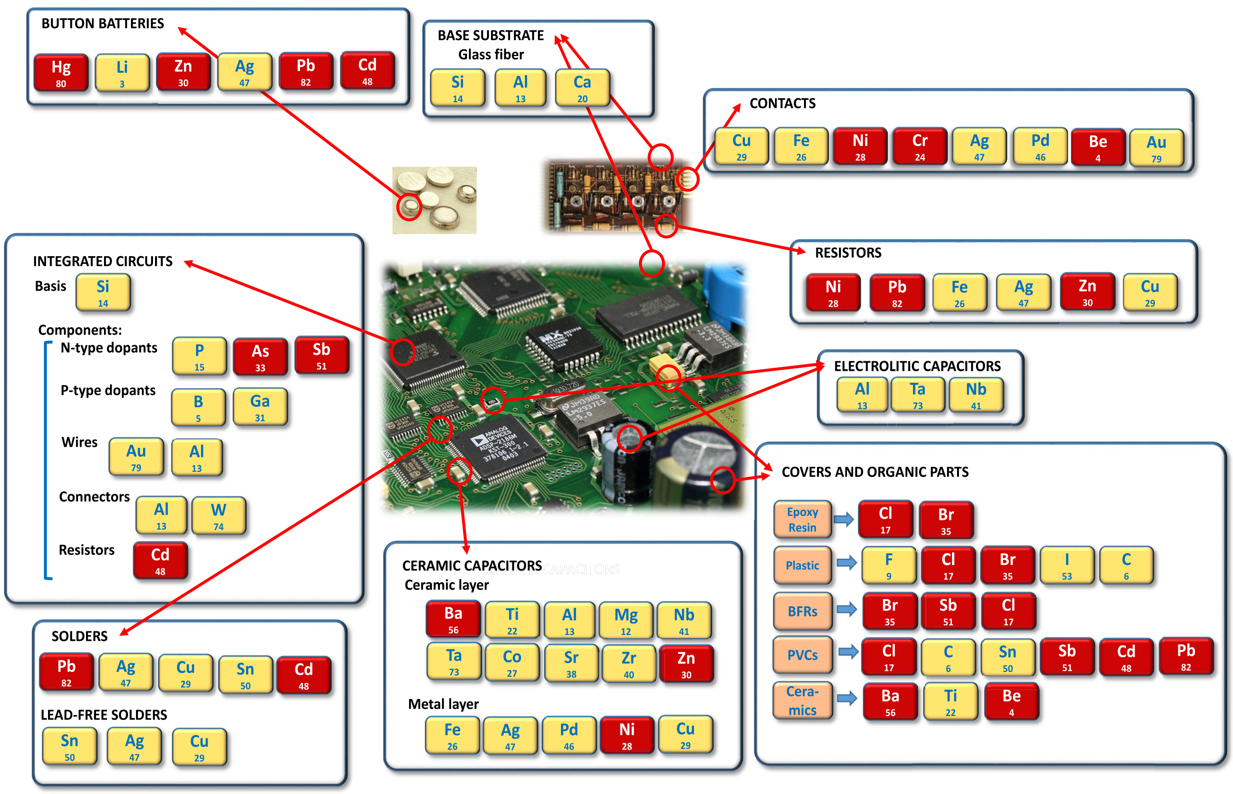

FIGURE 3. Elements and composition of a PCB. Red colour means hazardous elements.

insulating ceramic substrate [19]. Cadmium is included in chip resistors [20].

- **Contacts**. The contacts on the PCBs are commonly built using metals such us copper, iron, nickel, chromium or silver, usually including gold or palladium as coating element [7]. Also, copper-beryllium alloys can be used in contacts, connectors and sockets.
- **Solders**. They are mainly composed of tin combined with other metals such us lead, silver, and copper. Cadmium can also be used [4]. Because of its danger, the lead content in solders has been decreasing in the last years. Current lead-free solders are composed, for example, of Sn (95,5%)-Ag (3,8%)-Cu (0,7%) alloys [21].

Some PCBs, especially those used in computers, include button batteries, referred to as CMOS batteries. They are responsible for powering the system clock and keeping important system parameter values. Old button cell batteries that used mercury-oxide as anode material are no longer manufactured. The current alkaline, lithium, zinc-air and silver oxide button cell batteries may also contain mercury but in small quantities not exceeding the limits imposed by legislation. Other heavy metals such as lead and cadmium may also be present in these batteries [22].

The non-metal group of elements present in PCBs corresponds to: glass fibers (mainly oxides of silicon, aluminum, and calcium); ceramic packages of electric and electronic devices; ceramic insulator of electronic components such as resistors and capacitors [7]; and thermosetting resins, for example epoxy, cyanate esters and acrylic/phenolic resins [6], [23], [24]. The base substrate of the PCBs is a thermoset fiberglass-reinforced polymer of composite material [14], [25]. Ceramics are primarily silica and alumina. Other ceramic materials include alkaline earth oxides, mica, beryllium oxide and barium titanate [4].

The organic part of a PCB is mainly epoxy resin or thermoplastics with contents of flame-retardants and paper, which are used as insulating substrate for PCBs and encapsulation of electronic components [7], [25], [26]. Plastics are mainly C-H-O and halogenated polymers. However, nonhalogenated epoxy resins can be used for green PCBs production. Nylon and polyurethane are also used sometimes in smaller amounts [4]. These plastics usually contain organobromine compounds denominated brominated flame retardants (BFRs) such as the brominated bisphenols, especially tetrabromobisphenol-A (TBBPA), or the polybrominated diphenyl ethers (PBDEs), which are used to prevent combustion and/or retard the spread of flames in plastics and other materials [11], [27]. The bromine content of PCBs may reach 20% [28]. Also chlorinated compounds for example the polychlorinated biphenyl and the poly-chlorinated dioxins, may be present in flame retardant substances [11]. Another halogenated compound is the polyvinyl chloride (PVC), which is a chlorinated thermoplastic largely used as insulating coating for computer cables and wires. Often, PVC contains heat stabilizers such as those based on organotins (organic compounds of carbon and tin), lead and cadmium. Also, flexible PVC includes plasticising additives like phthalate esters. All of them are classified as hazardous substances according to the Agency for Toxic Substances and Disease Registry (ATSDR),[3] a federal public health agency of the U.S. Department of Health and Human Services.

B. MONITORS

Monitors and displays constitute an important component of PCs and mobile phones and they are one of the parts that more hazardous elements contain.

1) CATHODE RAY TUBE (CRT) MONITORS

Massively used in old computers, they contain hazardous elements such as lead, barium, and strontium. In these monitors three types of glass can be distinguished, each one with a different chemical composition: the glass of the neck (5%), the glass of the funnel (30%) and the glass of the panel (65%). Lead is contained in the funnel and the neck glasses. Also, lead is highly concentrated in the frit solder joining the funnel glass with the panel glass. The panel glass mainly contains barium and strontium, in addition to phosphorous. Also, lead, cadmium, and zinc are present in low quantities in the panel glass [29].

2) FLAT SCREENS

Liquid-Crystal
Display (LCD), Thin-Film Transistor-LCD (TFT-LCD), and Organic Light-Emitting Diode (OLED) monitors are currently used in both PCs and mobile phones. In a common way, all this technologies use indium in the form of indium tin oxide (ITO) as internal coating (electrode material) [30].

- **LCD displays** require background illumination. The older LCD monitors use cold cathode tubes (CCFL) as backlight. They contain much less lead than CRTs but their content of other toxic substances such as mercury is much higher. Fortunately, manufacturers are transforming the new monitor models towards mercury-free products based on LED backlighting. However, it is still possible to find that cheap LED monitors contain mercury. In LCD displays uthat use white LED background illumination, indium is also used as a component of the LED semiconductor chip, which is largely composed of indium gallium nitride (InGaN) [30]. White LEDs also make use of a luminescent substance, which converts the short-wave light produced by the LED semiconductor chip (blue/ultraviolet LED) into the visible spectrum. The support matrix (luminescent substance carrier medium) is usually made from yttrium aluminum garnet (YAG) with substantial admixtures of gadolinium. The doping consists of few percentages of cerium and sometimes europium [30]. Alternatively, LCD displays can use RGB LED background illumination, which combines three LEDs (red, green, blue) to provide the white light required for the backlight. Each LED requires a different semiconductor chip: gallium arsenide phosphide (GaAsP) for red LED; aluminum gallium phosphide (AlGaP) for green LED; and InGaN or silicon carbide for blue LED.
- **LCD-TFT screens** contain transistors made by depositing thin films of semiconductor material over a glass substrate. In addition, plastic elements (constituted of different polymers), steel and aluminum sheets, together with organic components (liquid crystals, polarization filters, resins) are contained in all flat screens [30].
- **OLED monitors** are replacing LCD ones due to their self-emitting property, high contrast, slimness, and flexibility. They consist mostly of organic substances, thus reducing the consumption of rare-earth metals. However, an OLED display can contain more metal-based components than LCD (for instance, a pixel circuit in OLED needs two thin-film transistors (TFTs), while in LCD only one is needed), due mainly to the high concentrations of gold, selenium, silver, palladium, and tin. Even more, they exhibit higher toxicity potentials due primarily to the high concentrations of arsenic, cadmium, chromium, and antimony [31].

C. STORAGE DISK DRIVES

Other relevant component in computers is the storage system, such as hard and optical disk drives. The substrate material used in hard disk drive platters is generally based on either glass or aluminum. Whereas aluminum-based platters are usually used in a 3.5 inch format, 2.5 inch hard disk drives (commonly used in notebooks) are primarily equipped with two or three glass-based platters. Hard disk drive platters also contain a certain amount of precious metals such as silver, gold, platinum, palladium, rhodium, and ruthenium. These are mostly located on the surface of the storage medium. These metals have increased the area density (number of stored bits per unit of surface area) seen to date, which determines the storage capacity of hard disks [32].

Hard disk drives contain other mechanical components such as the spindle motor (also present in optical drives) which is responsible for spinning the platters, and the voice coil accelerator, which is in charge of positioning the read/write head on the platters. These components require permanent magnets, which are commonly based upon neodymium-iron-boron (NdFeB) alloys. They may contain small admixtures of praseodymium, gadolinium, terbium, and especially dysprosium, as well as other elements such as cobalt, vanadium, titanium, zirconium, molybdenum or niobium [33]. In particular, neodymium, praseodymium, and dysprosium represent globally about 30% of the magnet weight [30].

D. RECHARGEABLE BATTERIES

Rechargeable batteries are one of the most relevant components in laptops and mobile phones. Li-ion, Ni-metalhydride

[3]https://www.atsdr.cdc.gov

(NiMH), and Li-polymer batteries are the most common. Li-ion batteries mainly use lithium cobalt oxide as cathode material, although other lithium oxides may be used (for example, those with nickel or manganese) [34]. The NiMH batteries, besides nickel and cobalt, also contain a mixture of rare earth elements such as lanthanum, cerium, praseodymium, and neodymium. The average content of cobalt in batteries ranges between 65 gr. for laptops and 3,8 gr. for standard mobile phones [35]. In addition, batteries contain other elements such as copper, iron, aluminum, and graphite, together with plastic substances [5]. These batteries are replacing the old Ni-Cd rechargeable ones, which present high contents of nickel and cadmium.

E. OTHER COMPONENTS

Keyboards and power supplies are constituted by a PCB together with plastic or metallic elements (for example keys, casings, cables, transformers, heat-sinks and, fans). The most common heat-sink materials are aluminium alloys. Fans are made of plastic or some kind of resin. Transformers are constituted by a pair of iron cores, around which copper wires of different lengths are wrapped. Mobile phones also contain small loudspeakers with neodymium iron boron magnets and small admixtures of praseodymium [30]. Nickel has been traditionally used in the microphone [36], while the vibration unit of the phone uses neodymium, terbium, and dysprosium [37]. Finally, the elements present in the laptop or phone casing depend on whether the case is metal, plastic, or a mix of the two of them. Metal casings can be made of magnesium alloys, while plastic casings are of course, carbon based. The casing also contains flame retardant compounds; brominated flame retardants are still often used, but efforts are being made to minimize their use, and so, other organic compounds that do not contain bromine are now more frequently employed. BFRs like TBBPA are also used on plastic cases of PCs and mobile phones.

III. E-WASTE AND HUMAN HEALTH

We often think that the risks of electronic waste only affect the people who come directly in contact with it and are mainly a consequence of inappropriate handling. Obviously, this is right and there are several studies that evidence the risks resulting from direct contact with toxic materials such as lead, cadmium or chromium [38]–[41]. These studies also alert about how other elements, for example brominated flame retardants or polychlorinated biphenyls, generate toxic fumes; others such as mercury, zinc, nickel, etc. accumulate in the soil, reach river waters or sea and finally, end up being part of the food chain, affecting wide areas. Therefore, not only the health of those who come into direct contact with electronic waste is affected, the risk extends to all the people.

Certainly, the risk increases for the entire population because of uncontrolled waste, illegal transportation of discarded electronics and, dismantling and handling electronic components without appropriate security [42], [43]. But it is also true that the toxicity of the elements is such that they also affect negatively (although are less significant) the health of workers in regulated recycling plants [44].

Moreover, children are especially vulnerable to the health risks that may result from e-waste exposure and, therefore, need more specific protection. The picture of children from developing countries playing or working in electronic dumps is sadly becoming familiar to us. The chemical absorption of hazardous substances in children is greater than in adults. This is because their bodies' functional systems, such as the central nervous, reproductive, immune and digestive systems are still developing, thus the exposure to toxic substances may cause irreversible damages [45]–[49].

Here we present a brief description of the potential adverse health effect, according to the Agency for Toxic Substances and Disease Registry (ATSDR), of exposure to the main elements and hazardous substances present in electronic devices. A summary of the effects is presented in Fig. 4.

- **Lead:** It is distributed throughout the body to the brain, liver, kidneys and bones and is deposited in teeth and bones where it accumulates over time. Exposure to lead can cause neurological problems, anemia, hypertension, renal dysfunction, immunotoxicity and reproductive toxicity. If the degree of exposure is high, it attacks the brain and central nervous system, causing coma, seizures and even death. It is believed that the neurological and behavioral effects associated with lead are irreversible. This effect is particularly serious in children. Children who survive severe lead intoxication can suffer various sequelae, such as mental retardation or behavioral disorders.
- **Mercury:** Elemental mercury and methylmercury are toxic to the central and peripheral nervous systems. The inhalation of mercury vapor can be harmful to the nervous and immune systems, the digestive system and the lungs and kidneys, with sometimes fatal consequences. Inorganic mercury salts are corrosive to the skin, eyes and intestinal tract and, when ingested, can be toxic to the kidneys. After inhalation or ingestion of different mercury compounds or after skin exposure to them, neurological and behavioral disorders can be observed, with symptoms such as tremors, insomnia, memory loss, neuromuscular effects, headache or cognitive and motor dysfunctions.
- **Cadmium:** It has toxic effects on the kidneys and on the bone and respiratory systems. In addition, it is classified as carcinogen for humans. Cadmium expands rapidly from the emission source through the air. It accumulates rapidly in many organisms, mainly mollusks and crustaceans. Concentrations, although lower, can also be found in vegetables, cereals and tubers rich in starch.
- **Chromium:** The most common health problem that occurs in workers exposed to chromium involves the respiratory tract. These effects include irritation of the lining inside of the nose, runny nose, trouble breathing (asthma, cough, shortness of breath, wheezing) and, lung cancer. Workers have also developed allergies to

Pb 82	Convulsions Coma		Deposits		Anemia Hyper-tension	Neurological disorders			Renal disorders	Inmuno-toxicity	Reproducti-ve toxicity	Deposits
Hg 80	Tremors Insomnia Memory loss			Digestive disorders		Neuro-muscular harms	Lung harms	Corrosive	Renal disorders	Inmuno-depression		
Cd 48							Cancer		Cancer			Cancer
Cr 24			Liver disorders				Respiratory disorders Lung cancer	Allergy	Renal disorders		Genetic ateration	
As 33				Digestive disorders			Cancer	Cancer				
Zn 30				Digestive disorders	Blood cells alteration					Inmuno-depression		
Ni 28		Heart diseases					Asthma Bronchitics Cancer	Allergy			Prostate cáncer Birth defects	
Sb 51				Digestive disorders Cancer								
Li 3		Cardiac alterations		Digestive disorders		Neurological disorders						
Ba 56	Brain inflammation	Heart diseases	Liver inflammation	Stomach pain	Hyper-tension	Neurological disorders	Respiratory disorders		Renal disorders			
Be 4		Heart diseases					Lung harms Pneumonia	Allergy	Berylliosis			

FIGURE 4. Summary of health effects due to exposure of hazardous substances present in e-waste.

chromium compounds, which can cause breathing problems and skin rash. Chromium can also cause liver and kidney damage, as well as alteration of genetic material.

- **Arsenic:** Prolonged exposure to inorganic arsenic, mainly through contact or consumption of contaminated water or food can cause chronic intoxication. The immediate symptoms of acute arsenic poisoning include vomit, abdominal pain and diarrhea. Then, other effects appear, such as numbness of limbs, muscle cramps and, in extreme cases, death. The continuous exposure to arsenic produces, in addition to skin cancer, bladder and lung cancer.
- **Zinc:** Although zinc is an essential nutrient for the human body related to the growth and proper functioning of the immune system, the ingestion and inhalation of excessive doses of zinc can cause, among others, diarrhea, cramps, sickness, vomit, loss of appetite, depressed immune system function, altered formation of red blood cells, and reduced levels of HDL cholesterol.
- **Antimony:** The inhalation of antimony for long periods of time causes, among others, stomach pain, vomit, diarrhea and stomach. It has been classified as carcinogenic.
- **Nickel:** The most common adverse effect of exposure to nickel in humans is an allergic reaction. Furthermore, people poisoned by nickel can develop multitude of problems such as: asthma and chronic bronchitis; nose, larynx, lung and prostate (in men) cancer; lung embolism; respiratory failure; birth defects and, heart diseases.
- **Lithium:** Neurological disorders, which can be accompanied by cardiac and gastrointestinal alterations, is the predominant clinical manifestation in lithium poisoning. Severe cases can present fatal cardiovascular complications.
- **Barium:** Barium can cause difficulty in breathing, increased blood pressure, arrhythmia, stomach pain, muscle weakness, changes in nervous reflexes, inflammation of the brain and liver and, kidneys and heart damage.
- **Berylium:** Beryllium is one of the most toxic metals known. It can be very harmful when it is breathed in by humans, because it can damage the lungs and cause pneumonia. The most commonly known effect of beryllium is called berylliosis, a dangerous and persistent disease of the lungs that can even damage other organs, including the heart. It also causes allergic reactions in people who are hypersensitive to chemicals. These reactions can be very acute. Other symptoms of beryllium poisoning are weakness and fatigue.

The natural presence of these metals in a given place is generally very low. However, the amount of them that can be found in the soil of any hazardous landfill as a result of human activity can be very high (sometimes hundreds of thousands of times the natural levels).

Almost all of these elements are released into the environment by factory chimneys or garbage incinerators (for instance, lead, nickel, mercury, cadmium, ...). The mineral dust particles remain in the air for a while and can move long distances before landing in the soil. Others, like chromium, do not remain in the atmosphere, but are deposited in the soil and water. Drains from industries that manufacture or handle products containing zinc, lead, or other metals can discharge particles of these elements into water streams.

Although there is no official data on fires in recycling plants or landfills, it is suspected that lithium ion batteries are one of the main causes. These fires not only release lithium into the atmosphere but also other harmful elements present in garbage. Certain environmental conditions and soil characteristics facilitate their filtration into groundwater and after this they can become part of the food chain. Cadmium, for example, adheres strongly to organic matter and can be incorporated by plants, thus entering the food chain.

To the previous list of metals and elements of high toxicity other very dangerous compounds according to the World Health Organization (WHO, https://www.who.int) must be added, such as brominated flame retardants (BFRs), polychlorinated biphenyls (PCBs), polyvinyl chloride (PVC) or chlorofluorocarbons (CFCs). All of them are known as persistent organic pollutants (POPs), meaning they are chemical substances characterized by:

- *Being persistent*: they have a high permanence in the environment being resistant to degradation. Most POPs are organochlorine compounds (with a molecular structure based on carbon and chlorine). The carbon-chlorine bond is difficult to break, so the presence of chlorine also decreases the reactivity of other bonds in organic molecules.
- *Being bioaccumulable*: as they are soluble in fats they incorporate into the tissues of living beings being able to increase their concentration through the trophic chain.
- *Being highly toxic and causing serious effects on human health and the environment*: chlorine chemistry produces more than 11,000 organochlorine compounds, most of them are harmful to people, animals and the environment in general.
- *Being transported over long distances*: they are able to reach regions where they have never been produced nor used.

Below we can see a brief summary of their main characteristics and harmful effects:

- **Brominated flame retardants (BFRs)**. This group includes polybrominated biphenyls (PBBs), polybrominated diphenyl ethers (PBDEs) and tetrabromobisphenol (TBBPA). As mentioned, those substances are used to reduce flammability in printed circuit boards and plastic housings, keyboards and cable insulation. These substances are highly toxic to the fetus, produce hormonal changes and are carcinogenic.
- **Polychlorinated biphenyls (PCBs)**. Although the production of these substances has been banned or restricted for many years in numerous countries they are still present in old electronic equipment and, even today, they are widely spread throughout the environment. In these compounds, the degree of toxicity increases as the chlorine content increases. The common symptoms of chronic intoxication are: nausea, vomit, weight loss, edema and lower abdominal pain.
- **Polyvinyl chloride (PVC)**. Basically, it can be considered an environmental poison, since it forms organ chlorinated substances when it is burned, emitting dioxins that end up in the environment. Perhaps the main problem with PVCs is their massive use throughout the world. Although it is considered a recyclable plastic it is not biodegradable, therefore, it is of great environmental toxicity. According to the World Health Organization PVCs can be responsible for many types of cancer and birth defects. In addition, heavy metals and carcinogens are used to manufacture them.
- **Chlorofluorocarbons (CFCs)**. Although their use has noticeably dropped thanks to the Montreal Protocol [50], in recent years there has been a surprising increase in emissions of chlorofluorocarbons (CFCs), particularly CFC-11 [51], suggesting that they may still be manufactured clandestinely. The effect of CFCs is well known; they degrade the ozone layer favoring the penetration of harmful ultraviolet rays. Exposure to stronger ultraviolet rays can cause skin cancer, cataracts and weak immune system. Direct exposure to some types of CFCs can cause loss of consciousness, shortness of breath and irregular heartbeat. It can also cause confusion, dizziness, cough, sore throat, shortness of breath and redness and eye pain. Direct contact with the skin with some types of CFCs can cause burns from cold or dry skin.

As a summary, Fig. 5 shows the main hazardous elements present in the most common components of electronic devices, their source of exposure and their main via of absorption by humans.

IV. RECYCLING AND CIRCULAR ECONOMY

As shown in Section II, the large amount of EEE in use represents a huge metal resource that could be recycled once the equipment reaches its End-of-life. Precious metals are recycled for their economic value despite the fact that they represent a small percentage of the electrical and electronic scrap weight. For example, in a mobile phone they represent less than 0,5% of the weight for over 80% of the value, while copper represents 5-15% of the value with 10-20% of the weight. Indeed, the recycling of less valuable elements for example lead, tin, indium and ruthenium is economically feasible because other valuable elements such as gold, silver, palladium, and copper are present [5].

Several metals used in EEE, specially rare earths (for example, Nb, Ta, In, Co, Ga) are critical raw materials for the EU [52], [53] because of their high supply risk, mainly due to their scarcity and production concentration in a few countries, some of them located in conflicted geographical areas [54]. Often, the concentrations of many metals in EEE range from several dozens up to one hundred times higher than in natural metal ores [19]. Also, recycling can save resources such as energy and water (for example, aluminum recycling uses only 1/20 of the energy required for primary

ELEMENTS	Present in					Exposure source						Absorption via			
	PCB´s & Electronics	Batteries	Hard Disks	Monitors	Cases and others	Air	Dust	Water	Soil	Fishes	Food	Ingestion	Inhalation	Skin contact	Transplacental
Pb 82	●	●		●		●	●	●	●			●	●	●	
Hg 80		●		●		●	●	●	●	●		●	●	●	
Cd 48	●	●		●		●	●	●	●		●	●	●		
Cr 24	●					●	●	●	●			●	●		
As 33	●			●		●	●	●	●			●	●		
Zn 30	●			●		●		●	●			●	●		
Ni 28	●	●			●	●		●	●		●	●	●	●	●
Sb 51	●			●		●		●	●			●	●		
Li 3		●				●		●	●		●	●	●	●	
Ba 56	●			●		●		●	●		●	●	●	●	
Be 4	●					●		●			●	●	●		●
BFRs	●	●	●		●	●	●	●	●			●	●		●
PCBs	●	●	●		●	●	●	●	●	●		●	●		
PVC	●	●	●		●	●	●	●	●			●	●		
CFCs					●	●							●	●	

FIGURE 5. Summary of dangerous elements present in components of electronic devices, source of exposure and absorption via.

production) [55]. In addition, for special and precious metals the environmental footprint of recycling is much smaller than for primary production [35]. Moreover, the environmental impacts per kg for the production of precious metals is higher than for base metals [56].

Finally, recycling is mandatory taking into account that, on average, the reproduction of consumer electronics needs about 10 times the final weight on raw resources [57]. Furthermore, all this makes the "urban mining" an important source of metal resources economically and environmentally beneficial [9]. However, while some metals, like precious metals, have recycling rates that are higher that 50%, others, such as tantalum, indium, gallium, lithium and lanthanides, present poor recycling rates, lower than 1% [30]. Currently, however, most e-waste continues to be usually disposed of in sanitary landfills [10].

Recycling is one of the existing End-of-life options for e-waste, together with upgrade, reuse, re-manufactoring, resale and energy recovering. All of them contribute to the objectives of the circular economy [57] and the Sustainable Development Goals.[4] E-waste collection is of crucial importance to determine the amount of material available for recovery before entering the recycling chain. The collection rates are largely influenced by the awareness of consumers and by the availability of collection infrastructures [55], as well as by the type of device. For example, only 15% of the obsolete small mobile phones are collected while the rest is kept 'hidden in a drawer" [19].

Commonly, the process of recycling involves three stages: pretreatment, physical recycling and chemical recycling [58]. The total recycling efficiency will depend on the recovery rate at each stage, including the initial collection phase [54], [59]. Also, for the sake of the recycling effectiveness, the number of infrastructures dedicated to each of the recycling stages should resemble an inverted pyramid, with tens of thousands of collection points, thousands of dismantling plants, hundreds of preprocessing plants and only several metallurgical plants [59]. Fig. 6 shows a detailed diagram of the phases

[4]https://www.un.org/sustainabledevelopment/

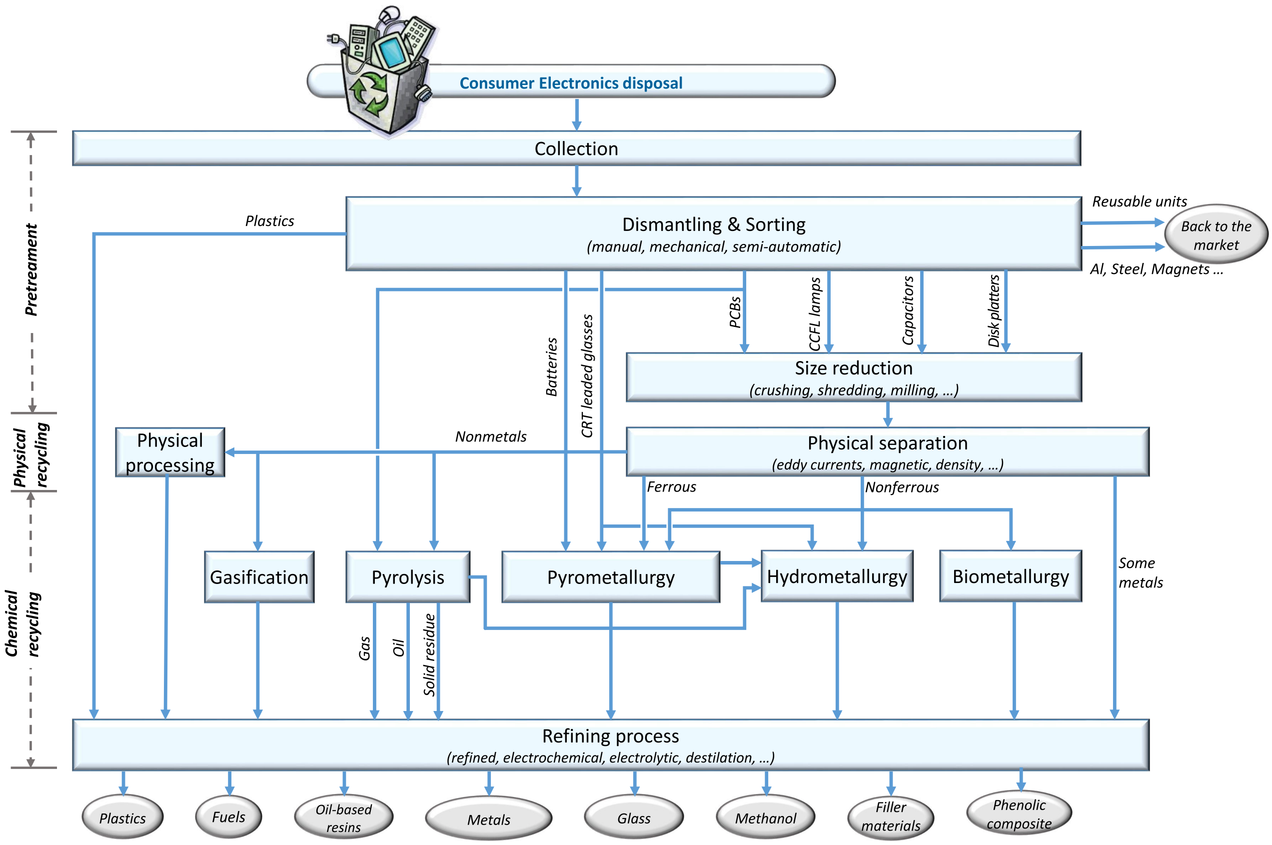

FIGURE 6. Phases and processes involved in the recycling of MFS & NMFS on e-waste.

and processes involved in the recycling of the Metallic Fractions (MFS) and Non-Metallic Fractions (NMFs) present on the waste of EE components.

A. PRETREATMENT

The pretreatment stage is crucial to guarantee the efficiency of the subsequent recycling stages [55]. Pretreatment is started by a dismantling process intended to perform a first classification of the materials. Initially, some components such as PCBs (mother boards, sound cards, graphic cards, etc.), plugs/contacts, HD/CD/DVD/floppy drives and power supplies are separated, extracting the PCBs of the last two. Also, magnets are extracted from HD drives and speakers. Hazardous/toxic components for example plastics, CRT monitors, CCFL lamps, batteries and capacitors are identified to be separately handled through the subsequent processing phases. Material streams, for instance aluminum and steel, and components such as transformers, fans, spindle motors, magnets, etc., can be directly shipped back to the market to be reused.

Manual dismantling, aided by simple mechanical or electrical tools, is the most common procedure. Although it is quite flexible and precise, it is not economically viable, being preferable an automatic o semiautomatic disassembly process [57], [60]–[62]. Components can be removed (de-soldered) from the PCB by hot air, selective infrared or laser heating. Laser technique causes minimal thermal stress for the components, resulting in an extended life-time for the re-usable components [57]. Next, disassembled components may be automatically identified and classified (for instance, Cu-, Fe-, Al-, precious metals-containing components, magnets, disk platters, . . .) [60].

Regardless of the dismantling method applied, complete liberation of all materials is not feasible in complex components like PCBs, due to the intricate linkage between materials. This may lead to an incorrect classification and the consequent loss of material, which may penalize the recycling rate of each one [55].

Also, the pre-treatment may include an incineration process [4] with the aim of removing organic materials and part of the NMFs present in the PCBs, such as plastic and paper. The lower plastic content can improve the refining capacity during the subsequent recycling stage, but, it has a negative impact on the environment due to the release in the air of dioxins and the emission of mercury and cadmium. Alternatively, pyrolysis can be used, because it reduces great part of dioxin emissions and has a lower impact than incineration, while increasing the efficiency of subsequent metal recovery stage [14].

Dismantling is commonly followed by a size reduction stage, which consists in a mechanical process of granulating and shredding, in order to convert PCBs, capacitors, CCFL lamps and disk platters into small pieces or fine particles. The process comprises a coarse grinding stage followed by a fine pulverization stage, using a cutting machine and a hammer mill [63]. However, as shown in Fig. 6, other components, such as CRT glasses and batteries are prevented from being crushed in order to be processed in subsequent stages. Some material may be lost through the dust generated during the shredding or crushing process. In some cases (for example, gold and palladium recovery), omitting granulation step may significantly increase the recovery rate [55]. The milling process involves a level of energy consumption that should be properly evaluated. [10].

Given the heterogeneous composition of different PCBs, chemical and analytical methods, such as atomic absorption spectroscopy (AAS), inductively coupled plasma/atomic emission spectroscopy (ICP/AES) and Energy-dispersive-X-ray-fluorescence-analysis (EDRFA/EDXRF), may be used during the pretreatment stage in order to obtain information regarding material composition to later apply the optimal recycling process. Other methods, for example derivative thermogravimetry (DTG), differential thermal analysis (DTA), and Fourier transform infrared spectroscopy (FTIR), may be applied to analyze plastic and additives (such as flame-retardants) [60].

B. PHYSICAL RECYCLING

In this stage, granular materials are separated by using different physical methods, such as electrostatic, magnetic, eddy current, size, density and gravity separation. They allow the partial concentration and recycling of some metals, for example Cu, Al, Fe, Pb and Sn [11], once they are separated from NMFs. Those methods are relatively simple, require low energy consumption and are in general environmentally friendly. Electrostatic methods [64] and eddy currents [65] allow the separation of metallic fractions from the non-metallic ones, while magnetic methods are widely used for the recovery of ferromagnetic metals [66]. These methods can be combined with others that carry out the separation of particles depending on their behavior when they are subjected to a viscous liquid (for example, water or air) according to their size, density and gravity features [8], [67], [68]. Although this stage allows the direct recovery of some metals, it is commonly followed by a chemical stage and refining process in order to achieve complete recovery of most metals. NMFs recovery requires either chemical treatment or some kind of physical processing, as shown in Fig. 6. In what follows, we analyze separately the recycling of MFs and NMFs.

C. RECYCLING OF METALLIC FRACTIONS

Metals recovery is one of the most important processes in EEE recycling. Most of the metals suitable for recycling are concentrated in PCBs, so following we will focus on the processes that are carried out for the recovery of metals in these components. However, as it will be seen, some of these processes are also suitable for recovering metals from other devices, such as batteries, CRT monitors, CCFL lamps or disk platters. Most of the metals can be recovered using chemical methods.

Chemical methods, both thermal and non-thermal ones, modify the chemical composition of the processed material. They often constitute a refining stage performed at the end of the recycling process in order to recover materials that have not been able to be recovered along the previous stages. Most chemical processes are aimed at metal recovery, such as hydrometallurgical, pyrometallurgical, biometallurgical and pyrolysis processing.

1) HYDROMETALLURGICAL PROCESSING

MFs are dissolved into leaching solutions such as strong acids (sulfuric, nitric, aqua regia) and alkalis (for example a cyanide solution) depending on the substrate material. In case of non-metallic substrate (for instance ceramic, glass, polymer, ...), metals are recovered from the substrates by the process of leaching in the resulting solution. Metals can be recovered using techniques such as solvent extraction, precipitation or filtration [6]. In case of metallic substrate, pure metals can be recovered by applying electrochemical (for example idiode electrolysis) or crystallization processing without any further treatment [4]. For example, selective dissolution of lead and tin present in solder alloys can be recovered from the copper substrate [69]. The main drawback of this recycling method is the corrosive and poisonous nature of the liquid being used and the high quantity of totally dissolved solids generated [11]. Also, mechanical pretreatment of e-waste is required [6]. Recently, hydrometallurgical leaching, after suitable pretreatment, has been used for lead recovery from CRT funnel glasses [70]. Also, lithium could be recovered from the cathode of the Li-ion and Li-polymer batteries by leaching, using formic acid and reaching a recovery efficiency of up to 99,3% [71].

2) PYROMETALLURGICAL PROCESSING

Incineration followed by melting at high temperature in blast or arc plasma furnaces has been a conventional process to recover non-ferrous and precious metals from the EEE [6], [72]. Also, a top blowing process, where melting with oxidizing/reducing is carried out, can be used [73]. By rapidly heating up to high temperatures (>1250 °C), followed by a rapid cooling of gases, organic material (for instance brominated organic compounds) is speedy decomposed avoiding dioxins and generation of pollutants [9], [74]. Moreover, lower emissions can be achieved in bath smelter furnaces by using oxyfuel burner (pure oxygen or oxygen-enriched air) as oxidising agent [73]. Integrated smelters technologies improve the efficiency of the metal recovery process, while providing extensive off gas emission installations (for example, absorption by activated carbon) to safeguard the environment [5], [75].

The energy released from the incineration of organic compounds present in PCBs contributes to the energy saving during the smelting process [6]. The metal oxides in the incineration residues can be recycled by physical or chemical processes, such as the hydrometallurgical and electrochemical treatments commonly required to obtain pure metals [6], [9], as shown in Fig. 6. Thermal reduction process, using iron powder as reduction agent, can be used for lead recovery from the CRT funnel glass [70]. Moreover, mercury present in CCFL lamps can be recovered by thermal desorption methods. The obtained mercury is distilled, followed by an acid treatment for impurities removal through the refining stage [76]. Smelting is also used to recycle Li-ion, Li-polymer and Ni-metalhydride batteries with high efficiency rates. After being extracted in the smelter and refined through a hydrometallurgical process, metals such as nickel and cobalt can be used to obtain the electrodes of new batteries. The remaining metals such as copper, iron and manganese are extracted during the smelting process, while lithium is collected in the slag (used for cement or steel industry) and organic compounds are appropriately treated [5]. Most of the battery materials can be converted into useful products (such as concrete, cement and steel industry), including new batteries.

3) PYROLYSIS

Pyrolysis is a particular case of thermal treatment under moderate temperature in inert atmosphere (without oxygen) which allows the potential recycling of all the materials, both organic and inorganic ones, contained in PCBs while still being economically attractive (reducing energy consumption and cost) and potentially environmentally friendly. Also, the absence of oxygen prevents dioxins from being easily generated and metals from being oxidized, making then easier their subsequent recovery. Removing organic material from PCBs facilitates the subsequent extraction of the metallic fractions. Polymers are decomposed into gases and oils, while metals, glass fiber and carbon form the solid pyrolisis residue. The metallic compounds contained in the pyrolisis residue are mainly copper, iron, calcium, nickel, zinc and aluminum, as well as low concentrations of valuable metals such as gold, silver, gallium and bismuth [9]. Further treatments may be required to separate and recover the different metals, for example leaching and electrochemical processes, as shown in Fig. 6. Vacuum pyrolysis combined with centrifugal separation constitutes a clean and non-polluting technology for the combined recovery of solder and organic material from PCBs [77]. Also, a U-shaped pyrolysis vessel, that uses a continuous fluid of inert stable molten salt for heat transferring, can be applied to separate the metal products in either liquid (solder material, zinc, tin, lead, etc.) or solid (copper, gold, steel, palladium, etc.) form [78].

4) BIOMETALLURGICAL PROCESSING

Metal extraction and recovery is also possible through bio-metallurgical processes. Some microorganisms, for instance algae, bacteria, yeasts and fungi are able to actively accumulate heavy and precious metals when they come in contact with the metal ions present in a solution. Furthermore, some microorganisms possess the ability to convert solid metals into soluble and recoverable elements (bioleaching) through subsequent electro-refining process [4]. For example, metals such as zinc, cadmium, lead and copper are recovered by bioleaching using the aspergillus niger fungi [79].

D. RECYCLING OF NON-METALLIC FRACTIONS

Among the non-metallic fractions (NMFs) we can distinguish those identified during the dismantling stages constituted basically of plastics, from those obtained after being powdered during the granulating and shredding phase. Then, the later ones, which are constituted of plastics, glass fibers and traces of heavy metals, are separated from the MFs. Traditional treatment of this non-metallic powder includes incineration, landfill or dumping in open scrap yards, which represents a serious threat to the environment [6]. Alternatively, NMFs could be recycled. However, their diverse and complex composition, along with their toxicity, makes difficult their efficient and safe recycling. Unlike MFs recycling, where mature technologies exist, the research on NMFs recycling is just beginning. The current methods of recycling NMFs can be classified as physical and chemical methods [63], as shown in Fig. 6.

1) PHYSICAL RECYCLING METHODS

These recycling methods are relatively simple, practical and low cost. In some cases, they basically require the application of heat and compression. Non-metallic powder could be used as filler material in a wide variety of applications [11], [63], such as the production of composite boards (furniture, automotive, decoration, ...); phenolic molding composites (radios, kitchen appliances, ...); reinforcing for thermoplastic resins (packaging, automotive, textiles, ...); building materials (cement mortar, lightweight concrete, ...); modeling materials (ornaments, decorative objects, ...); and modifier for viscoelastic materials like asphalt-modified bitumen [80]. The use of non-metallic powder as filler material, replacing traditional fillers such as, silica, talc, calcium carbonate or wood flour, contributes to improve the performance and to reduce the cost of the final product, thus achieving environmental and economic benefits.

2) CHEMICAL RECYCLING METHODS

Unlike physical recycling, chemical recycling of NMFs decomposes synthetic polymers, including polymers mixed with glass fibers, through chemical reactions, converting them into chemical feed stocks or raw material for fuels. They have the advantage of removing hazardous substances such as brominated flame retardants (BFRs) and heavy metal traces present in NMFs, thus eliminating pollution caused from hazardous substances. Pyrolysis and gasification are the current main chemical recycling methods of NMFs.

- **Pyrolysis:** Among the previously analyzed recycling methods for MFs, pyrolysis is the only one able to recover NMFs of the PCBs and do it, to a certain extent, being environmentally friendly. Pyrolisis removes the hazardous BFRs used in PCBs, avoiding the emission of gas and liquid pollutant and, enabling the safe disposal of the recovered materials [71]. Also, the absence of oxygen prevents dioxins from being easily generated. However, toxic substances continue to be present in both pyrolysis oil and gas. Non-condensable pyrolysis gases could be used as fuels after heat recovery [9] or they could be emitted once they have been appropriately scrubbed [4]. Pyrolisis oils could be used as a source of energy (fuel oils). However, pyrolisis oil concentrates a large number of toxic materials, so its direct use as energy could release them to the environment [71]. The addition of specific additives can reduce the presence of bromine in pyrolisis oil [25], [81]–[83]. Moreover, due to its high content of phenol and phenol derivatives generated by the decomposition of epoxy resins, pyrolisis oil can be also used as raw material to synthesize oil-based resins like phenolic resins, which can be used as polymer composites and coating materials [71], [84]. Glass fibers present in the residue can be recovered unaltered by means of controlled combustion. They can be either employed as raw material for different glass applications or re-compounded into molding compound structures as a filler replacement [84].

- **Gasification:** Alternatively, gasification processes can be used to convert plastic waste into carbon monoxide and hydrogen, which can be used as raw material for the synthesis of methanol. Gasification has the advantage of avoiding the generation of brominated dioxins by heating plastics at a high temperature followed by a rapid shock cooling under a controlled environment with oxygen and/or steam [85], [86].

Other recycling techniques for example depolymerization in supercritical fluids and hydrogenolytic degradation could be also applied to the processing of resins present in NMFs [63].

E. CIRCULAR ECONOMY

The correct, safe and efficient recycling (meaning economically viable) of the EE components is the key element for the development of a circular economy model, sustainable and respectful with the environment. It is known that the current and prevailing linear economy model (Fig. 7), based on ''extract-produce-use-dump'', has been defined for many years as aggressive with the environment and unsustainable [87], because it will exhaust natural sources of supply, both material and energy. This type of economy is strongly dependent on raw materials which supposes a risk associated with their supply and prices. Also, it means a significant reduction of natural capital and consequently economic losses.

On the opposite side, circular economy (Fig.7) tries to maximize the available resources [88], both material and energy, in order to maintain them as long as possible in the productive cycle. Circular economy aims to reduce to its maximum the generation of waste and when this generation cannot be avoided, make them the most. This applies to both biological and technological cycles. Thus, from the waste generated, materials and substances are recovered and subsequently reincorporated, in a safe way for human health and the environment, back into the production process.

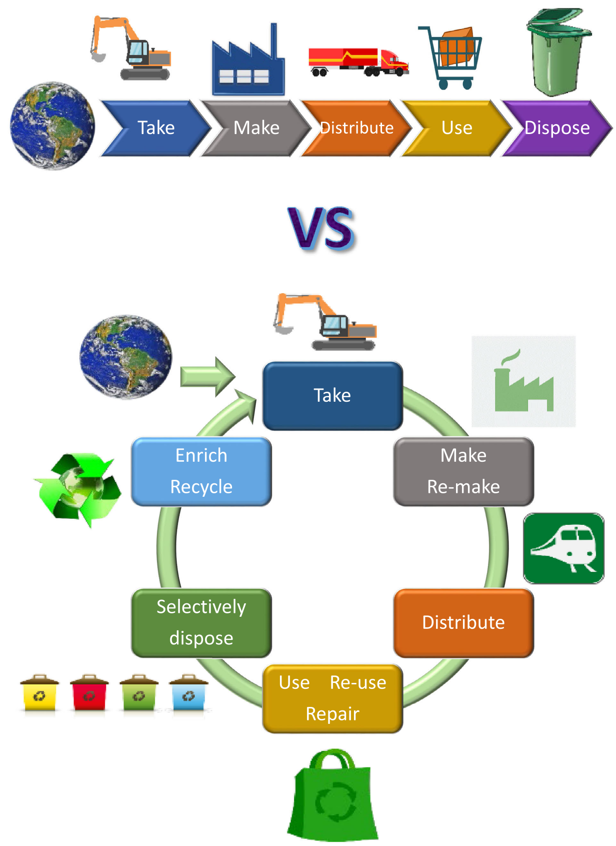

FIGURE 7. Linear economy model versus circular economy model.

In a similar way to the cyclic model of nature, circular economy is presented as a system of resource exploitation where the reduction of the elements is the key: minimizing production, making good use of the product and, when its useful life ends, reusing the elements that, because of their properties, cannot return to the environment and, recycling those that can still be useful.

This model also defends the use of biodegradable materials in the manufacture of consumer goods so that they can return to nature without causing any environmental damage when their useful life finishes. So, circular economy includes everything from the design and manufacture of environmentally friendly products (eco-design) to the selective disposal of waste for its subsequent recycling or enrichment to put them back into the production chain. In summary, it's about decoupling economic growth from the consumption of finite resources.

This new economy paradigm is not possible without the awareness and involvement of all actors. In Section VI some key aspects in relation to the circular economy and sustainable development will be discussed.

Circular economy is currently being promoted by the EU, by several national governments including China, Japan, UK, France, Canada, The Netherlands, Sweden and Finland as well as by several businesses around the world. But, it is necessary to start a transition path to move from the linear economy to the circular economy.

V. RULES AND LEGISLATION

Despite the fact that the common objectives of any regulation about e-waste are the protection of human health and the environment, their scope and the actors involved are very different. On one hand, it is necessary to regulate the selective disposal of e-waste; on the other, it is required to take into account the management, dismantling, logistics and transport of this garbage and, finally, the aspects related to recycling and recovering the materials and elements should be also considered.

In the development of laws and rules that cover all these aspects, local, territorial, national and, also international administrations are involved; each one with a different role and responsibility. The competency and the distributed commitment of the involved administrations allow to act at different levels of the problem, thus guaranteeing a greater coverage of the laws. But, it is also true that entities responsible for coordinating the specific actions and maintaining a general control to guarantee the application and compliance of the norms are needed.

However, in order to help e-waste policies and legislation to work properly, they must be based on the existence of a viable, fair and sustainable economy and financial model; thus, the formulation of these models is a co-requisite for a successful legislation.

In addition, if society is not aware of the problems arising from e-waste, it will be difficult to guarantee that all the involved parties will accomplish their obligations. So, information and awareness campaigns are as important or even more than legislation.

The circle must be closed by involving producers for accepting responsibility throughout all stages of a product's life cycle, including End-of-life management. Fig. 8 gives an idea of the main participants involved in this plot.

In this section, we analyze the main legal aspects directly related to electronic waste. We will not go into detail in general regulations on the handling of toxic and polluting products, although, obviously, these are also applicable to some of these residues.

A. E-WASTE DISPOSAL AND HANDLING

Currently, most of the large cities in developed countries and also in some developing countries (especially those that are big producers of e-waste such as India or China) have local regulations for the selective disposal of waste. But many times these regulations are not accompanied either by the necessary infrastructures to facilitate citizens the disposal of this garbage nor by the necessary awareness programs to become conscious about of the importance of a safe disposal. Many consumers remain unsure about how to safely dispose of old computers, smartphones, and other electronic devices and, their opportunities for recycling may depend on where they live. The lack of treatment and recovery facilities that meet international standards and also the lack of collection infrastructure that safely directs e-waste to these recovery plants are the main problems that the consumers face.

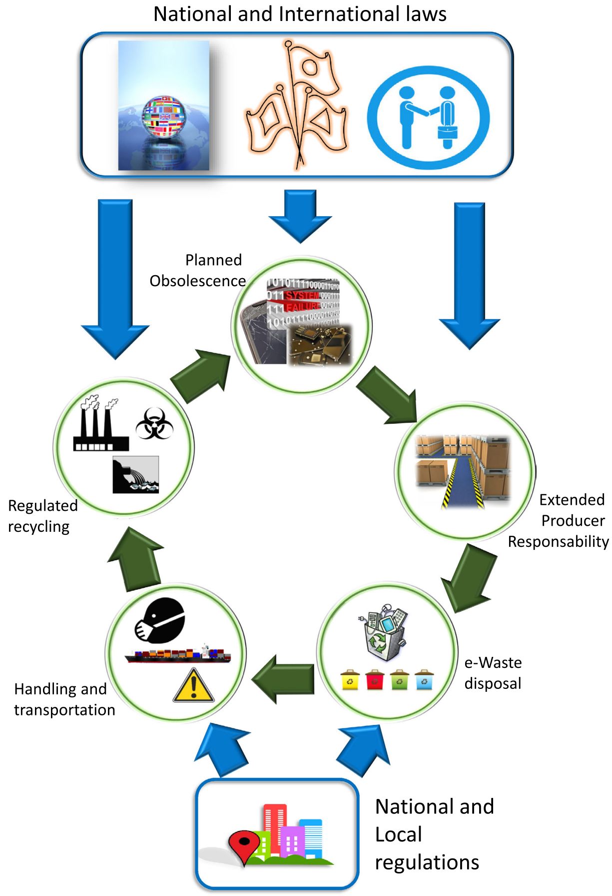

FIGURE 8. **Rules and legislation related to e-waste.**

One of the main issues of existing regulations is to define what is understood by electronic waste and this fact complicates international coordination. In this sense, European rules [89] on separation of waste and subsequent recycling are much wider than, for example, those of the USA.[5] Moreover, the number of products and elements cataloged as e-waste in Europe are also much greater. In the case of the USA, there is no federal law on the recycling of electronic products, but many states (25 currently) have approved their own regulations for this. However, as the number of product catalogued as hazardous waste in the USA is too short, the rules do not apply to many of them. Nevertheless, because of federal exemptions, the USA can legally export almost all electronic

[5]https://www.epa.gov/laws-regulations

waste to developing countries, if these countries explicitly express their consent. Also, rules do not apply when the purpose of the exportation is recycling.

E-waste collection and recycling also have regulations in other countries of North and South America, East Asia and South Asia. On the other side, national legislation on e-waste is completely absent, in many countries of Africa, the Caribbean, Central Asia, East Asia and Melanesia, Polynesia and Micronesia.

B. TRANSPORTATION

Many developed countries find an easy solution to the problem of e-waste by sending the garbage to developing countries to be ''theoretically'' recycled there with a much lower cost than at its place of origin (due to the practically inexistence of regulations and cheap salaries). However, this practice, far away from generating an economic opportunity for these countries, turns them into great dumps of the obsolete technology of rich countries, generating serious environmental and health problems for their citizens.

The Basel Convention [1] is an international environmental treaty signed initially in 1989 by 170 countries (181 parties as at 18 July 2014) within the UN system agreed, to protect the environment and human health from the harmful effects caused by generation, management, transboundary movements and disposal of hazardous waste. This global environmental document strictly regulates the transboundary movement of hazardous wastes and their disposal, defining obligations for the involved parties to ensure environmentally sound management of them. Particularly, their final disposition applies the procedure of ''prior informed consent'' meaning that the shipments made without consent are considered unlawful, unless there is a special agreement.

Basel Convention also obliges country members to treat and dispose waste as close as possible to the place where it is generated, and to prevent or minimize the generation of waste at origin. This Convention also presents an exemption on equipment intended for reuse. This exemption should be fully compatible with the main environmental objective of the agreement since reusing extends the life cycle of equipment and, therefore, minimizes the generation of hazardous waste. However, the distinction of whether something is a waste or not, and therefore is intended for reuse, is still an open question of Basel Convention and, a final agreement has not yet been reached. The exemptions open a back door to illegal trafficking of hazardous waste.

Beyond the well-known reports and campaigns of Greenpeace [90], [91], there are several authors who have documented the illegal traffic of these dangerous goods from Europe to Ghana [92] or from the USA to China [93].

C. EXTENDED PRODUCER RESPONSIBILITY

An interesting proposal for regulations aimed at reducing pollution and the waste generation are the Extended Producer Responsibility (EPR) models [94], [95]. These models try to transfer to the manufacturers the responsibility on any type of products that they put out on the market. To this end, the regulations propose that producers have to assume the management of the waste they generate. It is a way of involving the productive chain in the social and environmental impacts caused by the products leaving the factories.

Manufacturers are required to accept responsibility for all stages of a product's life cycle, including End-of-life management. In short, the idea is to carry out the principle that ''polluter pays''. The proposals look out to minimize the costs and the impact of disposable or short life products, or the presence of residues of difficult treatment, transferring the responsibility to those that have the capacity to prevent them: the producers. The EPR model has three main objectives:

- Encourage companies to improve the design of their products considering the reuse, recyclability, and material reduction.
- Raise consumer awareness by labeling products to inform about their mode and cost of recycling.
- Promote innovation in recycling and recovering technologies.

The producer's responsibility can be individual or collective. In the first case, the involvement of the manufacturer may be greater but the legislation can be very complex, this is why regulations usually refer to collective rather than individual responsibility.

The implementation of the EPR varies a lot from one country to another and, the lack of adequate facilities for the treatment is, in general, the most important obstacle for manufacturers to obey the regulations. Therefore, it is necessary that the recycling of materials becomes part of the economy model and that policy makers develop strategies that support and encourage this.

D. OBSOLESCENCE AND PLANNED OBSOLESCENCE

The term obsolescence for any product refers to the process of becoming discarded or obsolete. EEE becomes obsolete mainly because the technology evolves towards more powerful, versatile or less polluting devices. This means that old ones are no longer appropriate for new uses and applications or simply they do not adapt to regulations and rules. One of the most striking cases, for being one of the largest components of e-waste and one of the most polluting, is the case of the CRTs monitors.

With the advent of new LCD and LED technologies, computer monitors based on cathode ray tubes have quickly become obsolete and they do not respect neither the EU Directive on the Restriction of Hazardous Substances (RoHS) [96] nor the Total Threshold Limit Concentrations (TTLC) used by the California Department of Toxic Substances Control (DTSC) [97], which characterizes this type of garbage as hazardous.

Despite this, around 120 million units of CRTs were produced in China between 2013 and 2016. Today, all these units can be considered as scrap [98], and a large number of these devices have been transported ''to be processed'' to developing countries where labor is cheap, such as Ghana, India or Pakistan [99].

Products obsolescence is not unusual but, the problem starts when, in order to increase sales and profits, producers are interested in speeding up this process. Planned obsolescence occurs when products are deliberately designed to fail after a certain time [100].

Manufacturers commonly use relatively unreliable parts in a product, so that it fails within a predictable period, or after a programmed number of operations, for example USB memories, ink cartridges, LED lamps, or batteries. But failures can occur in many different and subtle ways. For instance, new versions of gadgets are frequently introduced and producers find ways to convince us to replace our old ones, even if they are still fully or mostly functional. We often feel the pressure to buy a new product even when its usefulness is unclear.

New apps for our smartphones or tablets appear every day. Phones that worked perfectly well suddenly become slow when a new app is installed. Another example, one day the memory on your tablet is unexpectedly full, and you are unable to download any upgrade or application. Sometimes, inexplicably, there is no more support for your mobile operating system, it cannot support new applications, or begins acting strangely.

Repairing an electronic device is sometimes an impossible mission. In addition to difficulties in finding replacements for the damaged element, the repair cost is often more expensive than buying a new device.

Design plays also an important role in planned obsolescence. How many devices are discarded because they are uncool despite working perfectly?

We will not go into this article to analyze the effects on the economy of the planned obsolescence, its pros as a driving force of the economy and technological development and its cons in relation to ethics and possible violation of consumer rights. The points of view on these aspects are multiple and different. For those who wish to know more about this effects, Kamila Pope's book [101] is a good and current reference. What we want to point out here is the direct relationship of this practice and the current throwaway culture with the generation of e-waste.

Despite the controversy, the European Parliament started a debate on this in 2017 and unanimously stated that consumers should know approximately how long their products will work and how they can be repaired. Brussels recognizes that most European citizens demand a more sustainable production model and less compulsive consumption, but not all policy makers agree to legislate against the planned obsolescence. The measures that are currently being considered only include:

- Tax incentives for products that bet on quality, durability and that are easy to repair.
- Allow users to choose an independent repairer (for example in the case of mobile phones).
- Labeling of the products showing their durability and reparability.

France has long been at the forefront in the fight against planned obsolescence globally, making it a criminal offence in the 2015 law on energy transition. Spain has developed the mark ISSOP awarded by the Foundation for Energy and Sustainable Innovation Without Planned Obsolescence (FENISS) to certify those companies producing environmentally-respectful goods and services, without planned obsolescence, preferably by fair trade, contributing to emissions reduction and correct waste management.

VI. THE MANTRA OF THE 3R's + 3 more R's

The rule of the three R's, also known as the three R's of ecology or simply 3R (reduce, reuse, recycle), is a proposal with the purpose of developing responsible consumption habits to preserve the environment by reducing the volume of waste generated. This rule was originally proposed by Greenpeace and defended by Japan during the G8 Summit in 2004, with the aim of building a recycling oriented society. This proposal is now widely spread and even is a part of early childhood education in many countries. Obviously, this general rule is applicable too to the case of e-waste as a particular case of residue. Below, we present some suggestions on how we can apply the rule to minimize the effect of e-waste:

A. REDUCE

As a general principle, we can reduce our electronic waste by buying only what we really need, making careful use of our devices, and maintaining them. In addition, we can reduce the power consumption of our devices. In fact, currently the production of energy also produces hazardous wastes (nuclear waste, carbon dioxide ...). More specifically, waste can be reduced from its origin through the development of "clean" manufacturing technologies that promote the saving of raw materials, the use of waste generated and the reduction of waste production. Also, information about the energy consumption of any device is very convenient in order to be able to choose between the most efficient and respectful with the environment models. Finally, we should also take into account the type of packaging used, avoiding, if possible, those products using single-use packaging and valuing more those easy to recycle.

There are numerous initiatives throughout different countries aimed to minimize the generation of e-waste. Most of these initiatives are included in the Sustainable Development Goals (SDGs)[6] promoted by the United Nations General Assembly in 2015. Among the objectives proposed by the SDGs, the Target 12.5 encourages to substantially reduce waste generation through prevention, reduction, repair, recycling and reuse, by 2030 [102].The accomplishment of this target mainly depends on how EE products are designed. In this sense, the Okala Eco-design Strategy Wheel [103] is a useful tool, developed by the Industrial Designers Society of America, to help designers steer their work towards more ecologically responsible designs. The environmentally

[6]https://www.un.org/sustainabledevelopment/

sustainable design practices amongst the world's largest consumer electronics manufacturers has been analyzed in [104]. This work shows that electronics producers do adopt a wide range of sustainable design strategies, while promoting their leadership in environmental innovation and corporate social responsibility. For example, regarding the saving of raw materials and resources, Apple has reduced plastic use in its packaging by 48% in three years, while reducing the average energy use for each product by 70% in 10 years and the carbon emissions by 64% since 2011 [105]. Dell aims to reduce average energy intensity of its entire product portfolio by 80% in the period 2011-2020 and reach zero waste generation by ensuring that every part of its products can be reused or recycled. Dell claims that more than 90% of the parts of their laptops are recyclable [106]. The total amount of material used by HP to develop personal computers has decreased by 14% since 2016, while the energy consumption has dropped by 44% on average since 2010 [107]. Finally, small companies like Fairphone [108] are also contributing to reduce e-waste by designing longer-lasting products that are easier to repair.

B. REUSE

To reuse electronic devices is to give them a new opportunity to be useful. This task is usually the one that receives the least attention and is one of the most important. Functioning devices can be reused by donating or selling them to someone who can give them a second useful life. A device not valid for us can be used by another person that does not need desperately to be up to date. The donation of computers, mobile phones and other gadgets is normally a simple and satisfactory practice. Probably, all users in developed countries have close entities or NGOs that can collect our devices for a second use in developing countries or in places where useful electronic equipment is needed. Our old computers can also achieve a second life used in another way, for example as a multimedia center, as computer for children, HotSpot or as a VoIP phone. The Linux Terminal Server Project (LTSP)[7] proposes to use old computers connected as clients to a higher performance server to run simple tasks for example browse the web, send e-mails, create documents, and run light desktop applications. Another example of an initiative devoted to the reuse of electronic equipment is the international platform eReuse.org.[8] This platform was born in Catalunya in 2015 and their members and partners provide skills, training and open technologies to ensure the reuse of quality second-hand electronics. They also promote the reutilization of devices and ensure their circular consumption. Finally, they track devices to ensure their correct final recycling.

Reusing electronic devices often depends on the opportunity to repair them, which is sometimes an impossible mission. In addition to the difficulties in finding replacements for the damaged element, the repair cost is often more expensive than buying a new device. However, the increasing pressure of users who demand the right to repair their devices has allowed the successful emergence of companies from all around the world that are making good business providing this service. A special case is iFixt,[9] a California-based company that is increasing its presence in more countries. The task of iFixit is not only to repair electronic devices but also to provide replacement parts for the most popular gadgets, to supply tools for any repair and, most importantly, to teach how to repair.

In particular, reusing:

- prevents goods and materials from entering the waste chain, thus reducing the volume of garbage;
- reduces the pressure on valuable resources, such as minerals, fuels, forests and water;
- helps to preserve wild ecosystems;
- pollutes less air and water than making new things or recycling them;
- helps you save money;
- avoids costs of acquisition of new goods (transportation, distribution, advertising, etc.);
- increases creativity.

C. RECYCLE

Those products that cannot be repaired must be correctly recycled in order to obtain new ones, preserve potentially useful materials and, avoid the environmental damage and health risks caused by the elimination of their hazardous substances (gases and other toxic elements as seen in Section IV). To do this properly and cheaply, we have to look for green points where our old gadgets can be deposited and safely recycled. As mentioned in Section IV, classification of the waste at origin and its disposal in the specific containers facilitates the later recycling, which achieves the saving of energy and raw materials. This requires the existence of adequate infrastructures in all municipalities and the collaboration of citizens.

Sweden is a well-known example of a community that is involved at all levels in the garbage recycling process and, in particular, in e-waste. The Swedish system tracks and monitors the amounts of e-waste generated and processed, the composition of the waste and, controls the efficiency of collection and recycling methods. The collection system which, as previously mentioned, is the previous step and guarantees the success of the entire recycling process, is well-distributed, easily accessible and keeps improving over time. Information is easily available for citizens using multiple channels According to the Avfall Sverige[10] (Swedish Waste Management and Recycling Association), Sweden has currently 580 staffed recycling centers where consumers can drop off their e-waste. In addition, there are also more than 10,000 battery containers available not only in recycling stations but also in stores, malls, apartment buildings and

[7] http://www.ltsp.org/

[8] https://www.ereuse.org/

[9] https://www.ifixit.com/

[10] https://https://www.avfallsverige.se/in-english/

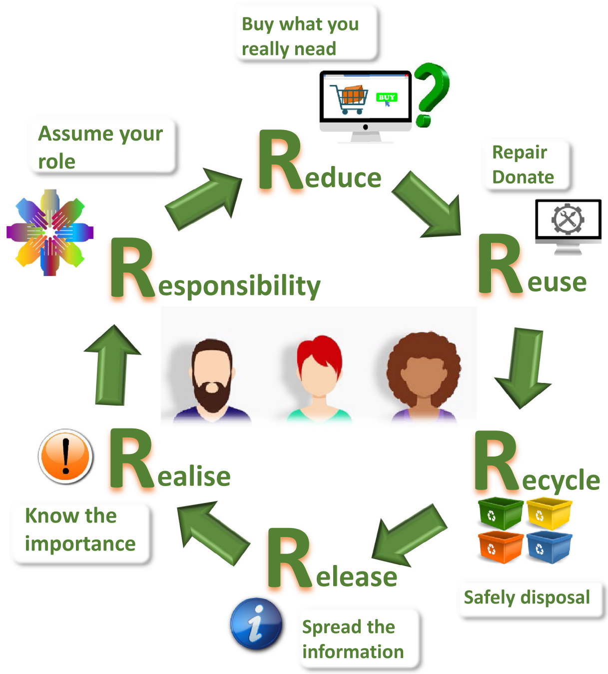

FIGURE 9. The 3 R's rule plus 3 more R's.

public places. Several attempts have been made to export the Swedish model to other countries, such as Singapore and India, with different levels of success.

Japan is another country that has the best infrastructure for the recycling of electronic devices [109]. In fact, Japan, South Korea and Taiwan are the countries leading this challenge in Asia because they have been tackling e-waste management since around 2000.

All cited countries have included the Extended Producer Responsibility (EPR) in their legislation and the success of their policies is not just a result of environmental consciousness but also the result of economic profits.

A curious example of recycling in which all the members of society are involved to achieve a common goal is the "Tokyo 2020 Medal Project"[11] promoted by the Tokyo Organizing Committee of the Olympic and Paralympic Games (Tokyo 2020). This project encourages the collection of small electronic devices, such as used mobile phones, from all over Japan to produce the Olympic and Paralympic medals. In the two years between April 2017 and March 2019, with the effort and contribution of people from all over Japan, 100 per cent of the metals required to manufacture the approximately 5,000 gold, silver and bronze medals had been obtained from small electronic devices.

D. ADDING R's

In the mantra of the three Rs: reduce, reuse, and recycle, we should add almost three extra R's: release, realise and responsibility, as seen in Fig. 9

- **Release**. Information about the problems of e-waste for humans and the environment needs to be released and spread.
- **Realise**. Be aware of the importance of every individual's role in the e-waste global issue.
- **Responsibility**. For a more conscious consumption and correct management of this scrap.

As university professors, scientists, developers of new technologies, we have the duty to spread among our students and collaborators the dangers and risks of electronic waste. In our academic environment we are usually surrounded by open minded people, socially and environmentally aware. Involving them in the fight against e-waste should not be a difficult task. They can disseminate these ideas in other environments, as family and friends. As researchers and designers of new techniques and technologies we should include the eco-design in our projects, improving the design of the components in EE devices in order to make them easier to collect, reuse and recycle. As responsible persons for the acquisition of new equipment in universities, research centers, institutions or companies we should look at the eco-design of the devices and packages. Our concern should gradually force manufacturers to include the eco-footprint in their products. As designers and developers of new products, we should also include this eco-footprint whenever possible. This label should inform consumers about the effect of the components on the environment and health, about the energy consumption (advising too how it can be reduced), how the device can be repaired when necessary and, how to proceed finally to facilitate recycling and reuse when it ceases being useful. This information would not only allow greater control of this type of waste, but also recover many of them as useful resources.

The rule of Rs is still open. We can continue adding Rs. Each one of us can have their own rules according to their convictions, ideology and concerns.

VII. CONCLUSION

E-waste is one of the most growing scraps every year. The current technological development of the digital society, where the use of electronic devices is continuously increasing and the time between manufacture and obsolescence is increasingly shorten, suggests that this kind of scrap will continue expanding in the future. This situation is alarming because some of the components of this waste are toxic to humans and the environment. When e-waste is not selectively disposed in a controlled way, the toxic metals and other elements that compose it are polluting the environment, damaging the air we breathe, poisoning the land and the water we drink.

Consequently, e-waste management is an urgent issue for everyone. The responsibility in the control of the management of this type of waste must be shared alike between manufacturers, policy makers, and consumers. Therefore, it is necessary the cooperation of all the parts to control their production.

[11] https://https://tokyo2020.org/en/games/medals/project/

But, with electronic scrap people are inadvertently throwing away also precious metals such as gold, silver and platinum, which are used in the manufacture of microchips, motherboards and other EE devices. In fact, e-waste is a rich source of raw materials. Re-extracting those materials means an opportunity to generate economic, social and environmental benefits. Consequently, more and more companies are involved in the recycling and material recovery because of the actual business opportunity.

Due to the increasingly severe environmental and health regulations, in recent years the industry has made significant efforts to reduce the toxic elements in many components and electronic devices. But, the design and manufacture of more sustainable and environmentally friendly equipment is still a great challenge which involves many sectors of science and technology.

However, despite the regulations that limit or prohibit the traffic of electronic waste, excuses such as reusing equipment and reducing the digital gap, are still being used in order to transport to developing countries a large number of devices, most of them in the limit of obsolescence. In most of these developing countries the necessary facilities to recycle them properly do not exit and they tend to accumulate in immense landfills.

Current recycling technologies are able to recycle most of the elements that are part of e-waste, however, research on this topic must be continued and pushed forward in order to find more efficient, economically attractive and environmentally friendly recycling processes that, consequently, can be applied in an extensive manner. But, without a widespread awareness among society and the existence of suitable infrastructure to collect e-waste, all improvements in recycling techniques are useless. Currently, only a few developed countries have the appropriate technology to start up safe and efficient recycling plants. The investment in developing countries to guarantee that they can carry out a competent and productive recycling industry is mandatory.

The aim of this article has been the dissemination of the main aspects related to e-waste from a rigorous perspective so that scientists and ICT professionals can know the associated problems, their scope and possible solutions and, above all, participate and get more and more involved in the sustainable design of new technologies and their responsible use.

Any initiative intended to raise awareness of the serious harmful effects of e-waste, or advising and providing solutions for a more responsible consumption, must be welcomed.

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