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WEEE Management in the EU

TESI DI LAUREA MAGISTRALE IN MANAGEMENT ENGINEERING

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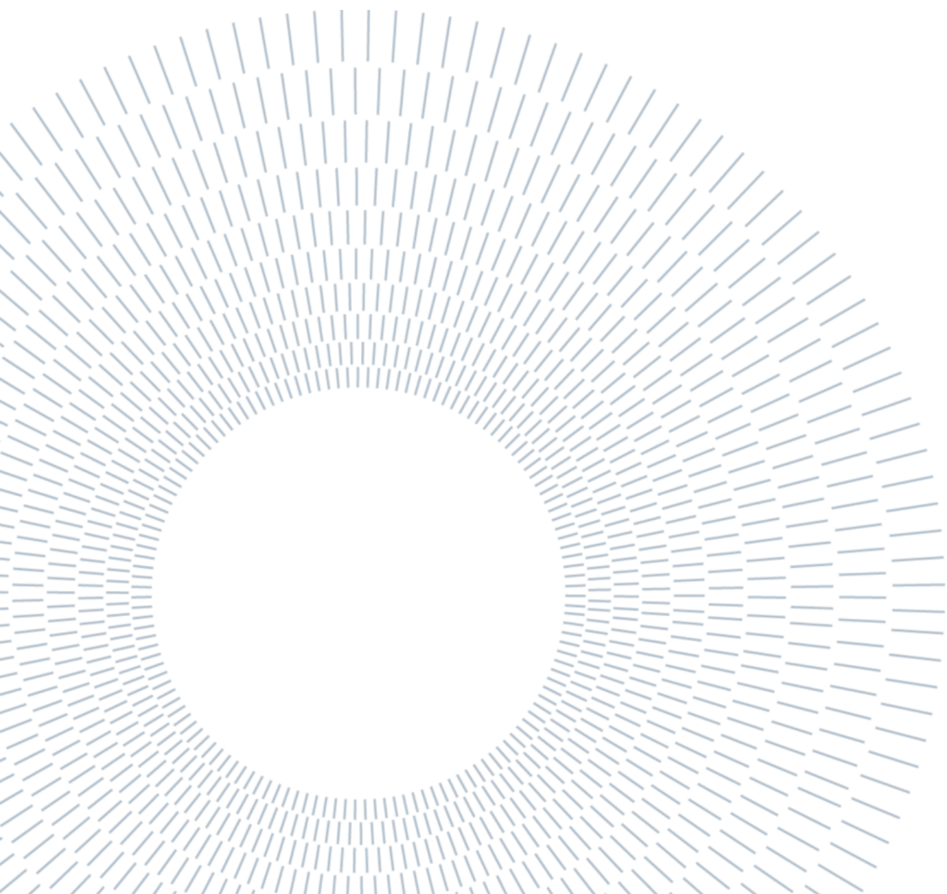

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Abstract

Electrical and electronic equipment (EEE) has become an essential component in the everyday life of individuals. Its widespread availability and use have enabled many of the world's population to enjoy higher living standards. However, the way we generate, consume, and dispose of e-waste is not sustainable. Many countries face significant environmental and human health risks from improperly managed Waste Electrical and Electronic Equipment (WEEE), also known as e-waste. Even countries with formal e-waste management systems face relatively low collection and recycling rates. In 2019, the world produced 53.6 million metric tons (Mt), but only 17.4% of this was properly collected and recycled.

Once this waste stream is not collected and recycled in an environmentally sound manner, it may pose severe risks to the environment and human health. It is because e-waste often contains several hazardous substances like heavy metals and other toxicants. They may leak into the open environment and accumulate in living organisms through food chains causing detrimental health problems. On the other hand, it may provide just as big of an opportunity as the challenge. It is because e-waste has been termed as an 'urban mine' containing several precious and critical materials. The worth of raw materials in the global WEEE produced in 2019 is estimated to be equal to $57 billion USD.

In such circumstances, it becomes essential for the management in companies and young engineers joining the job market to have a basic knowledge and understanding of the topic. This report provides an overarching view of the subject matter of WEEE management, and the environmental and social considerations related to e-waste and its lifecycle. Besides a brief global perspective, this report mainly focuses on European e-waste management systems and their legislative instruments. Different collection, transportation, and recycling approaches practised in the field are explored. Various related aspects such as critical materials, circular economy business models (CEBMs), and consumer trends are also introduced and explained in a popular science manner. In short, the report will work as a WEEE Management handbook for a new reader, who is unfamiliar with the topic, and assist them in better understanding those aspects of WEEE which are relevant to them.

Contents

1. Introduction

In order to better understand the topic of WEEE Management, the first chapter of the Report begins by defining Electrical & Electronic Equipment (EEE) and Waste Electrical & Electronic Equipment (WEEE). The definitions have been explored in a bit of depth such that the reader may get a thorough understanding of the term WEEE. It, furthermore, provides a synopsis of the overall condition of WEEE in the world and particularly in Europe. Various statistics at the global and European levels have been highlighted to give an idea about the magnitude of the topic. Moreover, the problems associated with WEEE are highlighted to show the seriousness of the issue. Lastly, the chapter ends with the objective of writing this report and how it has been structured into the following chapters.

1.1 What is WEEE

In order to understand the term WEEE or e-waste, there is a need to first define the term EEE. According to the Environment Agency of the United Kingdom (UK), EEE has been defined as equipment that depends upon electric currents or electromagnetic fields to function, and it is used for generating, transferring, and measuring those currents and fields. Moreover, it is designed for use with a voltage rating of 1,000 volts or less for alternating current (AC) and 1,500 volts or less for direct current (DC) (*Electrical and Electronic Equipment (EEE) Covered by the WEEE Regulations*, 2021). In other words, any equipment which needs electricity to work, whether battery-operated or plugged-in, and is below a certain voltage limitation, is called EEE. WEEE or e-waste is the waste or End of Life (EoL) of such Electrical & Electronic Equipment (EEE).

While looking into a more precise definition of WEEE or e-waste, numerous definitions exist in policies, decrees, regulations, guidelines, guidance documents, etc. Based on those definitions, the number of types of WEEE or e-waste included in government initiatives differs across the globe. But on the general level, WEEE or e-waste is a term that covers all EoL products with either a battery or cord/circuitry. Hence, it may include mobile phones, computers, TVs, white goods such as washing machines & refrigerators, toys, toasters – almost any household or business items, including even medical devices. Moreover, it may include the Internet of Things (IoT) devices, including sensors, actuators, and other small networking devices, as well as the equipment used for data servers used to provide internet services in the world.

1.2 WEEE Statistics from Around the World

For getting insights into the key global statistics regarding WEEE or e-waste, mainly the latest report of the Global E-waste Monitor has been consulted. The Global E-waste Monitor 2020 is a report prepared by the Global E-waste Statistics Partnership (GESP). This partnership is formed by UN University (UNU), the International Telecommunication Union (ITU), and the International Solid Waste Association (ISWA), in close collaboration with the UN Environment Programme (UNEP).

In order to have a look into the statistics of e-waste, it becomes essential to first look into the numbers of EEE consumption. As it is evident that there is an enormous amount of EEE appearing in the global markets these days, which may be attributed to the higher levels of incomes, growing urbanization, and further industrialization in some parts of the world. Although the consumption of EEE strongly varies from one country to another, but on average, the total weight (excluding photovoltaic panels) of global EEE consumption increases annually by 2.5 million metric tons (Mt) (Forti et al., 2020). After the use, this EEE is disposed of, generating e-waste which may contain both hazardous substances as well as valuable materials.

According to the Global E-waste Monitor 2020, in 2019, the world generated a striking 53.6 Mt of e-waste, an average of 7.3 kg per capita (Forti et al., 2020). That represented a 21% increase of 9.2 Mt in the 5 years period since 2014, which is further projected to grow to 74.7 Mt by 2030 – almost doubling in 16 years. Such striking growth may be attributed to the higher consumption rates of e-products, their short life cycles, and few repair options afterward.

If the statistics from the same report are seen on a regional basis, Asia accounted for the highest quantity of WEEE generated in 2019 at 24.9 Mt. It is followed by Americas at 13.1 Mt and Europe at 12 Mt, while the regions of Africa and Oceania generated 2.9 Mt and 0.7 Mt respectively (Forti et al., 2020). It shows a different picture when looked at in terms of e-waste generation per capita. Europe tops the list with 16.2 kg per capita, followed by Oceania and the Americas at 16.1 and 13.3 kg per capita respectively. While Asia and Africa show substantially low per capita rates compared with the other regions, standing at 5.6 and 2.5 kg per capita respectively (Forti et al., 2020).

When looked at the handling side of e-waste, there may be different ways to deal with it for the collection as well as the treatment. Various such methods and techniques for the e-waste management shall be discussed at length in the following chapters. It is pertinent to mention for now that such management methods can be both formal documented and informal without any sort of records. In 2019, the formal documented collection and recycling was 9.3 Mt, which is only 17.4% of the total e-waste generated. While the fate of the rest 82.6% (44.3Mt) is uncertain, which is likely dumped, traded, or recycled in a non-environmentally sound way.

Although the number of countries in the world that have adopted a national e-waste policy or regulation has increased up to 78, the regulatory advances in many countries are slow, and the enforcement is poor (Forti et al., 2020). Furthermore, due to lack of investment and political motivation, the policy or regulation does not yet stimulate the collection and proper management of e-waste. In addition, the rest of the world countries from a total of 193, leave more than half of all the countries without any proper e-waste policy, legislation, or regulation.

1.3 Problems and Opportunities Associated with WEEE

E-waste often contains several hazardous substances like heavy metals such as mercury (Hg), cadmium (Cd) or lead (Pb) and toxic chemicals such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and brominated flame retardants (BFR). The increasingly alarming levels of e-waste, low collection rates, and often non-environmentally sound treatment of such waste pose major risks to the environment and the human health.

Approximately 71 kt of plastic containing BFR arose from the unaccounted flows of e-waste generated in 2019 (Forti et al., 2020). Basically, BFR are used in appliances containing plastic to reduce the product's flammability. It appears, for example, in the outer casings of computers, printed wiring boards, connectors, relays, wires, and cables (McPherson et al., 2004). The recycling of BFR containing plastics represents a major challenge for e-waste recyclers due to the higher costs related to the separation of plastic containing PBDEs and PBBs from other plastic. Therefore, in most cases, recyclers incinerate such plastic under controlled conditions to avoid the release of dioxins and furans. On the other hand, if such incineration is not carried out in a controlled manner, these substances are likely to pose a danger to the health of the people and the environment. As various studies have shown that they can be responsible for kidney damage, skin disorders, and may affect nervous and immune systems.

Mercury is used in lighting devices in flat screen displays, in compact and normal fluorescent lamps, in measuring & control equipment, and in old switches (Baldé et al., 2018). If such appliances are dumped in the open without being properly recycled, mercury may enter the food chain and accumulate in living organisms. It can cause damage to the brain, kidneys, nervous system, and immune system (McPherson et al., 2004). A total of 50t of mercury could be found in the unaccounted flows of e-waste generated worldwide in 2019 (Forti et al., 2020).

Another one of the most commonly used metals until very recently has been Lead. Lead plays an important role in the overall metal production process and was mainly used for soldering of circuit boards. Although its use has been banned in a lot of applications, but it is still used in several applications where its substitute hasn't been found. So much so that even the lead-free solder elements are co-produced with lead. If not managed well and exposed to the environment, high levels of Lead cause anaemia, kidney and brain damage in humans. Similarly, Cadmium, which was used in rechargeable batteries, and contacts & switches in CRT monitors, once left in the environment, can bioaccumulate and is extremely toxic to humans and may adversely affect human kidneys and bones.

Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs) are found in old generations of cooling and freezing equipment where they are used in in refrigerant circuits and insulating foams of the equipment such as refrigerators, freezers, and air-conditioners. These molecules are known to have a long lifespan in the atmosphere. Once released in the open, they react with O3 molecules of ozone generating O2 molecules of oxygen and damage the ozone layer in the stratosphere causing an ozone hole. The depletion of the ozone layer causes the increment of the Ultraviolet (UV) radiation passing from the stratosphere. Which in turn may cause diseases like skin cancers, eye-related diseases, and weakening of the immune system. Moreover, CFCs and HFCs are known to have high global warming potential (GWP). According to the estimates of the Global E-waste monitor, a total of 98Mt of CO2 equivalents were released from an inappropriate recycling of undocumented fridges and air-conditioners, accounting for 0.3% of global energy-related emissions in 2019 (Forti et al., 2020).

Another thing which further adds to the issue of global warming from e-waste is the fact that if the materials present in e-waste are not extracted through proper recycling techniques, they cannot replace primary raw materials. Such that the extraction and refinement of virgin raw materials would cause a substantial increment in the greenhouse gas emissions. On the other hand, it provides just as big of an opportunity as the challenge. As the E-waste has been termed as an 'urban mine' containing several precious and critical materials. The worth of raw materials in the global WEEE produced in 2019 is estimated to be equal to $57 billion USD (Forti et al., 2020).

In 2011, 2014, 2017, and finally 2020, the EU has been releasing a list of critical materials which are absolutely vital for the society and its welfare. These are defined as critical due to the increasing mismatch between supply and demand, high price volatility or politically induced limitations of supply (Bobba et al., 2020). The most recent list of 2020 contains 30 materials, including rare earth elements (REEs) and platinum group metals (PGMs). Figure 1.1 is taken from a report commissioned by the EU commission into looking at foresights of critical raw materials in the EU and it shows all the materials defined as critical in 2020 in the EU.

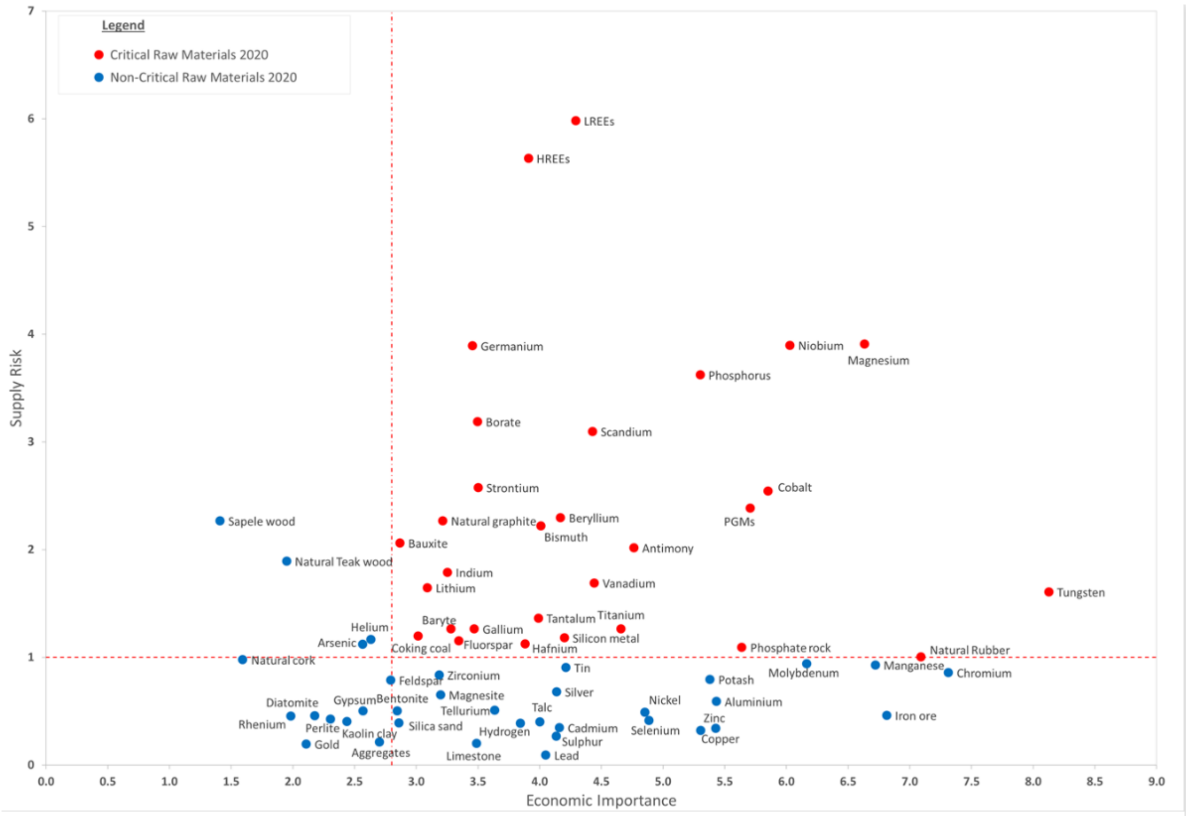

Figure 1.1: *The list of Critical Raw Materials in the EU highlighted in red (source: Bobba et al., 2020*

The report analysed the critical raw materials for strategic technologies and sectors in the EU. It indicated that the critical raw materials are essential for the EU to deliver on its climate ambitions set for 2050 as the technologies used for renewable energy, e-mobility, and aerospace strongly rely on an increasing number of exotic materials (Bobba et al., 2020). In such case, urban mining provides a great opportunity to preserve valuable materials by recycling the waste from electric & electronic products. It, rather, becomes an indispensable factor due to the presence of such precious and scarce materials like gold, platinum, neodymium, indium, ruthenium, cobalt, and palladium in EEE in high quantities.

1.4 Objective

Given the growing importance of the topic of WEEE management due to the rise in the problems associated with it as well as the opportunities it may present, the aim of this research is to better understand different types of WEEE, European Legislation about it, and different ways in which it is managed starting from collection and transportation to treatment methods used for its recycling. It will work as a WEEE Management handbook for a new reader, who is unfamiliar to the topic, and assist them in better understanding those aspects of WEEE which are relevant to them. The main focus will be kept on the circumstances and practices in the EU, but a short synopsis from around the world needs to be taken to give an overall view to the reader about the subject matter.

1.5 Methodology for Research

With the aim of extensive research, information gathering, and analyses on the essential matter of WEEE management, its implications, Regulations, types of WEEE and handling methodologies, the mentioned sources below were consulted due to the convenience of their availability and particularly their reliability.

Literature Sources: Online database of Scopus was extensively used to look for relevant research articles on the subject of interest. Other online sources like reports from international bodies like UN, online articles, and research journals were also explored. Lastly, one of the most important and helpful sources was the online archive of European Commission. It included the statistics from Eurostat, the Legislative Articles around the subject matter of WEEE management, and the reports commissioned by the Commission to various research institutions for conducting a third-party review.

All the information gathered during the research process was carefully read and understood. It is furthermore analysed and presented in a sequential way such that it gives a thorough understanding to the reader about the topic of WEEE management and its practices in the EU.

1.6 Structure of the Report

From the introduction the reader must have got an idea about the subject matter of WEEE and its growing importance in today’s world due to the challenges it presents and the opportunities it may offer. During the next chapter the reader is first taken into the depth of understanding various categories of WEEE and different materials found in it. Further into the report, the chapters are organised in such a way that chapter 3 enlists the legislative framework of the EU about WEEE management and touches upon its historical development. During chapters 4 & 5, the operational activities of waste management systems in the EU are explored. Similarly, during chapter 6 both of these aspects, i.e legislation & waste management systems of other continents, are briefly reviewed. The author’s intention is to provide the reader an overarching picture of WEEE management particularly in Europe but with a short picture from around the world. Lastly, some of the future trends in WEEE management have been looked at in the last chapter, which guide towards the conclusion of the report.

2. Types of WEEE

Before going into the detailed discussion about WEEE management including Legislation about WEEE and technical techniques to manage it, a brief chapter has been dedicated to defining and distinguishing among various categories and types of WEEE. Such that in the following chapters of the report, the reader may conveniently navigate and understand various e-products under discussion.

2.1 Categories of WEEE

As defined in the beginning of the report that WEEE is simply EoL or waste of EEE products, such that the owner has discarded them as waste and does not intend to reuse them. There are many types of EEE products on the market and each product has a different material content, is recycled in different ways, and has different implications for the environment as well as human health. However, for statistical purposes, and to make analyses for management and effective policymaking, EEE has been classified under various criteria such as similar function, comparable material composition, and similar end-of-life characteristics. These criteria may change from country to country, resulting in the same products placed in two different categories in two different countries. However, one of the most used criteria and categories list around the world is that of UN University, and it is commonly known as UNU-KEYS.

The list of UNU-KEYS comprises of 54 different product categories, and it is constructed such that product groups have comparable weights, similar material compositions, relevant EoL characteristics, and related lifespan distributions (C. P. Baldé et al., 2015). In most countries around the globe, the list of UNU-KEYS is used to classify various EEE products into 54 product categories. However, the categories' list used in the EU is different than that. In the EU the products have been categorised into 6 groups, that mainly correspond closely to the waste management characteristics of the products. According to the European WEEE Registers Network (EWRN), those categories have been defined and elaborated below:

1- Temperature Exchange Equipment

It is the type of EEE that has the internal circuits where substances other than water (e.g., oil, gas) or a refrigerant are used for the purpose of cooling and/or heating and/or for heat exchange (EWRN, 2018). Typical examples from this category include refrigerators, freezers, air-conditioning equipment, dehumidifying equipment, and heat pumps etc.

2- Screens and Monitors

It is the type of EEE that is intended to provide images and information on an electronic display, without considering any dimensions (EWRN, 2018). Some of the typical examples from this product group are cathode ray tubes (CRT), LCD displays, LED displays, or other kind of electronic displays like notebooks and tablets.

3- Lamps

Lamps are defined as such EEE that produces light from electricity and are intended to be used in luminaires, and amongst that they can also have other functions like lamps containing camera, perfume dispenser or an insect repellent etc (EWRN, 2018). Typical examples include straight and compact fluorescent lamps, high-intensity discharge lamps, and LED retrofit lamps.

4- Large Equipment

It is such type of EEE that is not allocated to categories 1, 2 or 3 and it has an external dimension of more than 50 cm (EWRN, 2018). Some of the typical examples include washing machines, dish washing machines, electric stoves, knitting and weaving machines, large printing machines, large medical devices, and photovoltaic panels etc.

5- Small Equipment

In the category of small equipment that kind of EEE is considered that is not allocated to any of the categories above as well as the category 6. Furthermore, no external dimension is more than 50 com (EWRN, 2018). Typical equipment included comprises of vacuum cleaners, microwaves, ventilation equipment, irons, toasters, electric kettles, videos cameras, calculators, radios sets, electrical & electronic toys, small monitoring & control instruments, and other small electrical & electronic tools.

6- Small IT and Telecommunication Equipment

According to EWRN information equipment is defined as the equipment that is used for collecting, transmitting, processing, storing and showing information, while telecommunication equipment is considered such equipment that is designed to transmit signals – voice, video, and data – electronically over a certain distance. Furthermore, dimensions are determined in the same way as that of category 5 i.e no external dimension greater than 50 cm (EWRN, 2018). Typical examples from this category include mobile phones, GPS devices and navigation equipment, pocket calculators, routers, printers, and telephones etc.

2.2 Materials Found in WEEE

Many electronic components are used in e-products, which are created from a variety of raw materials. Different materials provide different electro-physical qualities & features ranging from insulation to conductivity. More than 60 elements from the periodic table are known to be found in EEE these days (Balde et al., 2017). Metals and polymers make up the majority of the used materials by weight, although they can be divided into four primary categories.

1. Metals

Electrical and electronic products could contain a wide range of metals. The main ones, however, are steel & iron, which make up nearly 50% of such equipment's weight. In addition, copper and aluminum are also widely utilized materials in EEE because of their excellent conductivity and malleability properties. In resistors, capacitors, and transducers, several additional metals, including nickel, chromium, lead, silver, gold, or tin, are utilized. However, most of these additional metals are used in very tiny quantities.

2. Rare Earth Elements (REEs)

Yttrium, scandium, and other members of the lanthanides series make up the rare earth elements (REEs) (17 elements in total). Although REEs are often employed at extremely small or negligible levels, they are essential for many high-tech applications, including phosphors, batteries, lasers, and permanent magnets, etc.

3. Plastics

Plastics make up about 20% of the weight of e-waste and are the second-largest group of materials utilized in electronic equipment. Plastics are primarily employed in electronics due to their heat-resistant and insulating properties. Around 2.6 Mt of plastics are used annually in the EU for the manufacture of electric and electronic equipment, which equates to 5.6% of the EU's total worldwide plastics demand (Miliute-Plepiene & Youhanan, 2019).

4. Minerals & Non-metallic Materials

Many of the fundamental technological elements of e-products are made possible by the use of certain metalloid (or semimetal) materials, such as silicon. Silicone and its derivatives are the primary substrate materials used in the manufacturing of microchips and semiconductors. Antimony, bismuth, cobalt, garnet, fluorite, magnesium, talc, and bismuth are additional nonmetal or semimetal materials used in EEE. Moreover, ceramics, such as clays, glasses, etc., are often used due to their insulating qualities.

5. Hazardous Substances

Hazardous substances, such as heavy metals like mercury, lead, cadmium, chromium, etc., are found in many e-products (Balde et al., 2017). These have the potential to penetrate human food chains and ecosystems and pose dangers to human health and the environment. Moreover, some other hazardous substances like brominated flame retardants are used in plastics of EEE, and they also have comparable detrimental effects on human health and the environment. Due to their harmful effects, quite a few such hazardous substances have been banned in the EU. Their details will be discussed in the following chapter of the Legislation. For now, a table has been attached below, which shows a list of materials that are used in various electrical & electronic equipment.

Material	**Applications**
Gold	Mobiles, PCBs, computer chips, connectors/fingers
Silver	PCBs, computer chips, capacitors
Platinum	Hard drives, circuit board components
Palladium	Hard drives, circuit board components
Copper	CPU heat sinks, wiring & cables, PCBs, computer chips
Nickel	Circuit board components
Tantalum	Circuit board components
Cobalt	Hard drives
Aluminum	PCBs, computer chips, hard drives, CPU heat sinks
Tin	PCBs, computer chips
Zinc	PCBs
Neodymium	Hard drives
Lead	CRT monitors, PCBs

Mercury	LCDs, fluorescent bulbs
Cadmium	Light sensitive resistors, corrosion resistant alloys
BFRs	Used to reduce flammability of plastics in EEE

Table 2.1: *List of materials' used in EEE.*

3. EU Legislation on WEEE Management

In the EU countries, most of the legislation regarding management of waste, not only of e-waste, flows from the EU. Such legislation is then implemented in each EU member state through domestic laws. In the following sections the author does not look into the legislations of individual member states, rather focuses on the EU legislation with regards to the environmental matters such that the provisions of the relevant waste directives and regulations are explored in a bit of detail.

3.1 The EU and the Environment

The founding treaty of the EU i.e. the treaty of Rome in 1957, did not contain any reference to the environmental policy. A number of amendments had to be made later on to bring forth the environmental legislation. It was in 1973 that the first Environmental Action Programme (EAP) was adopted, and it provided a framework for the development of environmental legislation in the EU. There have been eight such programmes to date and the current programme, EAP 8, expires in 2030. Each programme spans a 5 to 10 years' time frame, and during their course they have become the main driving force behind EUs environmental policy. Although the proposals of the EAPs are not legally binding, they anyhow set out the aspirations of the EU.

The current action plan of EAP8, was adopted this year on 2nd of May and for the first time an EAP was provided with an additional enabling framework. That framework is in the form of the European Green Deal. It is the new growth strategy for the EU economy, and it sets out a plan of action to make the EU's economy sustainable across all areas of policy. Hence, from now on in line with Green Deal's oath of 'no harm', the 8th EAP supports an integrated approach to policy development and implementation across the EU (*Environment Action Programme to 2030*, n.d.). It furthermore forms the EU's basis for achieving United Nations Sustainable Development Goals (SDGs) and its 2030 Agenda.

EAP8 has 13 different environmental policy areas, and it defines the EU action plans in those areas. One such area is that of waste management, treatment, and recycling. The EAP policy in this regard is called the Waste Framework Directive and it provides a legal framework for treating and managing waste in the EU. Moreover, as certain categories of waste require specific approaches, it therefore, provides an overarching legal framework to make separate laws to address different types of waste. Examples of such laws for particular categories of waste include the directive for waste electrical & electronic equipment (WEEE Directive) and the directive on the restriction of the use of certain hazardous substances in electrical & electronic equipment (RoHS Directive). In the following sections of this chapter, a summary of all these directives has been provided.

3.2 The Waste Framework Directive

As stated in the last section, the Waste Framework Directive provides a framework for treating waste in the EU. It has been amended several times since its introduction in 1975 as Directive 75/442 EEC. The current waste directive was adopted in 2008 under the name of Directive 2008/98/EC. Its main effects were to simplify the legislation by repealing the existing waste directive as well as the directives on hazardous waste (Directive 91/689 EEEC) and waste oils (Directive 75/439 EEC). Lastly, in 2018, an amending directive of EU 2018/851 was adopted into the current waste directive and the member states were given until July 2020 to transpose it into their national law.

The waste framework directive sets the basic concepts and definitions related to waste management, including definitions of waste, recycling, and recovery (*Waste Framework Directive*, n.d.). It lays down the basic waste management principles requiring that the waste management must be carried out:

- Without endangering the human health and the environment
- Without any risk to water, air, soil, plants, or animals
- Without causing a nuisance through noise or odours
- Without harming the countryside or places of special interest

The Directive also explains the difference between waste and raw materials as well as between waste and by-products. It furthermore introduces the concept of 'extended producer responsibility' (EPR) and establishes the waste management hierarchy. Both of these principles, EPR and waste hierarchy shall be discussed at length in the following chapters as they provide the foundation for managing the e-waste in the EU.

Some of the other important points from the directive include the special conditions for the management of hazardous waste, waste oils, and bio-waste. Competent national authorities are given the responsibility of establishing waste management and waste prevention plans and programmes. Member states are advised to take necessary measures for achieving the recycling & recovery targets for the years 2025, 2030, and 2035.

3.3 WEEE Directive

The objective of the WEEE Directive (Directive 2012/19/EU) is to protect the environment and human health by preventing the creation of WEEE and promoting various ways of recycling & recovery in line with the waste hierarchy established in the Waste Framework Directive. The current directive recasts and repeals the original WEEE directive (Directive 2002/96/EC) which had been amended several times since its adoption (*Directive 2012/19/EU of the European Parliament and of the C. . . - EUR-Lex*, n.d.). The current directive entered into force in February 2014 and since then a couple of implementing regulations have been adopted into it. In 2017, implementing regulation (EU) 2017/699 was adopted and it sets out the methods to calculate the volume of EEE and WEEE produced in each EU country. In 2019, implementing regulation (EU) 2019/219 was adopted and it sets out the format for registration and reporting of producers of EEE to the register.

The WEEE Directive is set out over 27 articles and some of the main points can be summarised as follows:

- It categorises the e-waste into 6 different types as outlined in the 2nd chapter
- It does not apply to certain types of EEE, notably the equipment used for military & space purposes, implantable medical devices, and means of transport etc.
- It puts the responsibility on member states to minimise the disposal of WEEE into unsorted municipal waste and allow private households to return the e-waste free of charge.
- It puts a minimum annual e-waste collection rate. From 2019, it sets the target at 65% of total weight of EEE placed on the market (POM) in the past three years or 85% of the total WEEE generated (WG) in that year.
- It puts on the member states to establish a register of all companies producing EEE and check that all plants treating e-waste are officially licensed.
- It requires producers to meet minimum treatment targets for different e-waste categories and it bans the disposal of e-waste without such treatment. Moreover, the producers must finance the cost of collection, treatment, recovery, and disposal from all their users apart from private households.
- Lastly, it encourages the cooperation between producers and recyclers to design electrical equipment in line with the eco-design directive (Directive 2009/125/EC). The eco-design directive or in other words energy-related products directive (ErP Directive) provides a framework for minimum eco-design requirements for energy consuming products and it has been briefly described in the following sections of this chapter.

3.4 RoHS Directive

The RoHS Directive aims to prevent the risks posed to the environment and human health by limiting the use of specific hazardous materials in EEE. The current RoHS directive (Directive 2011/65/EU) was adopted by the European Commission in 2011 as a recast to the old RoHS directive (Directive 2002/95/EC). Since then, further amendments were made in 2017 with the directive (EU) 2017/2102, and additional 12 delegated directives regarding exemptions for the use of mercury in lamps were adopted by the EU Commission in December 2021.

The current RoHS directive restricts the use of ten substances in EEE which can cause severe environmental and health problems. These substances include heavy metals, like lead, cadmium, mercury, and hexavalent chromium, and flame retardants or plasticizers like polybrominated biphenyls (PBB), polybrominated diphenyl ethers (PBDE), diisobutyl phthalate (DIBP), butyl benzyl phthalate (BBP), bis (2-ethylhexyl) phthalate (DEHP), and dibutyl phthalate (DBP). The directive makes it obligatory for manufacturers to make sure that any EEE that they place in the EU market is designed and produced in line with the requirements of the legislation. Furthermore, importers of goods as well as distributor of goods must also ensure that the equipment has been certified to meet the required standards.

The ban applies to all EEE and to cables and spare parts with a short list of exclusions, given to certain special cases. That list includes a range of items such as weapons, space equipment, large-scale stationary industrial tools like printing presses, milling, and drilling machines, fixed installations such as electricity generators, and photovoltaic panels. It removed the ban on secondary-market operations such as repair, replacement of spare parts, refurbishment & reuse, and retrofitting of EEE that fell outside of Directive 2002/95/EC but would not comply with Directive 2011/65//EU. Moreover, it provided the clause that the reused spare parts recovered from any type of EEE can also be exempted if reuse takes place in auditable closed-loop B2B return systems.

3.5 ErP Directive

The ErP Directive establishes a framework to set mandatory design requirements for energy-using and energy-related products sold in all member states of the EU. The current directive (Directive 2009//125/EC) came into force in October 2009 and member states were given until November 2010 to transpose it into their national laws. It was amended once afterwards in 2012, with the directive 2012/27/EU and member states had until the June of 2014 for its transposition into their national legislation. The scope of the ErP directive covers more than 40 product groups including several products from EEE, while it does not apply to transport used for carrying people & goods.

The ErP Directive has established an EU-wide legal methodology for the eco-design of energy consuming products such that the environmental aspects are integrated into product design with the aim of improving the environmental performance of the product during its whole life cycle. Some of the key points from this directive can be summarised as follows:

- Eco-design requirements cover all stages of a product's life, taking a cradle to grave principle, from raw materials to manufacturing, packaging, distribution and to maintenance, use & end-of life.
- For each phase, various environmental aspects are assessed by designated bodies of the member states. They verify aspects such as the materials & energy consumed, emissions into the environment, and waste & its possible re-use, recycling, and recovery options.
- It is made compulsory for manufacturers to construct an ecological profile of their products describing the inputs & outputs of a product throughout its life cycle.
- Products satisfying the requirements of this directive bear the CE marking, and they are allowed to be sold in the EU market.

3.6 Transboundary Waste Shipments Laws

In the EU, there exist various rules and regulations regarding the transboundary movement of the waste. The most important of all is the decision 93/98/EEC, approving the Basel Convention by the European Community. The Basel Convention on the Control of transboundary movements of hazardous waste and their disposal was adopted in 1989 in Basel, Switzerland and it entered into force in 1992. The overarching objective of the Basel Convention is to protect human health and the environment by regulating the transboundary movements of hazardous wastes & other wastes and it requires its parties to ensure that they manage and dispose of such wastes in an environmentally safe manner. Till date this multi-lateral treaty has been ratified by 190 parties, and in the EU, it was adopted in 1993 through the decision 93/98/EEC approving the Basel Convention on behalf of the European Economic Community (now the EU). It was later incorporated into the EU law in 2006 by means of regulation (EC) No 1013/2006 on shipments of waste and its subsequent amendments. The Basel Convention proposed a guidance draft in 2011, especially for the trans-boundary shipment of e-waste, and it was adopted by the meeting of the Conference of Parties (COP12) in 2015. This guidance added additional requirements to the transboundary shipment of used equipment in an attempt to limit the flux of illegal waste shipment disguised as used EEE for reuse. If the requirements are not satisfied, the border authorities are advised to consider the shipment as an illegal shipment of waste and carry out legal action.

4. How the WEEE is Managed

In this chapter we talk about how the WEEE or e-waste is managed operationally in the European Union (EU). Although the operational practices strongly vary across different member states, but in this chapter the author has tried to take an overview from a generalised European perspective. The first section begins with exploring in detail the hierarchy of waste management set up by the EU in the Legislation where we get a complete definition of the terms of the hierarchy. The second section focuses on the principle of extended producer responsibility (EPR) as has been entailed in the Waste Framework Directive that the responsibility has been placed on the producer to deal with the EoL of their products. Further into the chapter, the value chain of WEEE has been explained with different actors involved in the chain. Lastly, a generalised cost structure for the division of costs among various actors is sketched along with practical example from Sweden as to how the WEEE is managed.

4.1 The Waste Management Hierarchy

It has been highlighted in the above chapter regarding Legislation that in the EU all the member states have a common principle to decrease the environmental impact of the waste and manage it in a certain preferential manner. This guiding principle is termed as the waste management hierarchy in the EU according to the Legislative Framework of Waste Management. The waste management hierarchy is basically a strategy for the producers, consumers, government organizations, and other actors in the society that guides them on how to prioritize the waste management approaches to decrease its environmental impacts. The waste hierarchy has been depicted in the figure 4.1 and its various stages have been explained in the following paragraphs of this section.

1. Waste Prevention & Reduction

This is the first step of the hierarchy which suggests that waste should be avoided in the first place. In case it cannot be prevented, the maximum effort should be put in place to reduce the amount of waste and its toxicity. This could be achieved for example by producers designing and producing the high-quality products with longer lifespans such that they may be given multiple life cycles. Moreover, the goal minimization of waste generation may be achieved if businesses start offering new value-added offers for their customers, like offering products for rent instead of ownership, and consumers start changing their consumption patterns by sharing products, and substituting products for services etc.

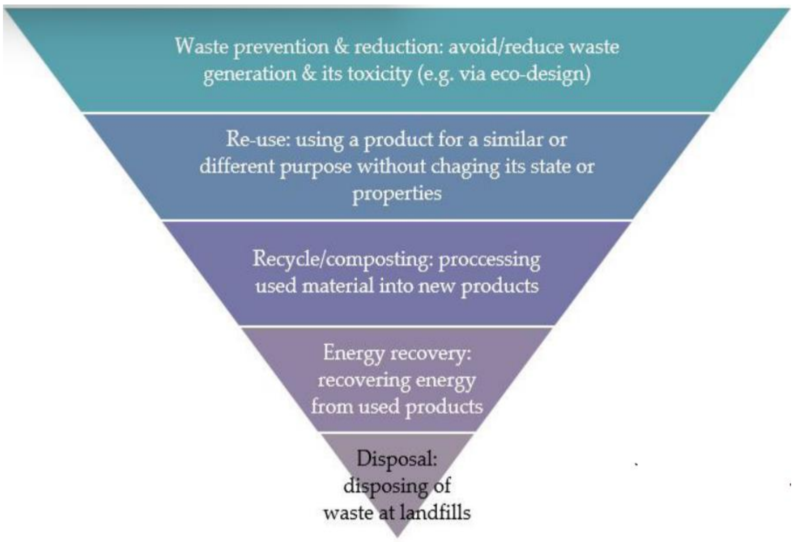

Figure 4.1: Waste management hierarchy (source: *Waste Framework Directive,* n.d.)

2. Re-use of the Product or its Parts

Re-use is considered as the second-best option for waste management. It means to use the product for the same or different purposes without changing its primary properties. Re-use may be categorized into two categories of reuse of the product and reuse of parts of the product. These may further be divided into the following subcategories:

- Reuse of the product
    a. Reuse as complete product
    b. Reuse after servicing
    c. Reuse after remanufacturing

- Reuse of parts of the product
    a. Reuse of subassemblies
    b. Reuse of components

The names indicate quite clearly different of these strategies which may be followed within the reuse option. In any of those cases, i.e., reusing as a product or using parts of the product, the re-thinking at the design stage for longevity, maintainability, and upgradeability becomes essential. Some of the examples of reuse may include buying & selling second-hand products instead of new products, sharing products with others, getting things repaired, and using the parts from one product to be used into another one etc.

3. Recycling the Material

This is the third suggested strategy in the hierarchy when it is no longer possible or feasible to reuse the product or its parts in either of the ways shown above. Recycling basically means that all waste should be material-recycled as much as possible since it often implies much greater environmental efficiency compared with the virgin raw material extraction. Some of the ways in which this strategy is implemented may include:

- Back to original application
- In lower grade applications
- Back to feedstock (in case of plastics)

The recycled material may be eligible to be used in the exact same applications, it often happens for the case of metals like gold and aluminium etc. Moreover, the recycled material may often not be of the same standard as to be used in the same application, in such cases it is used for lower grade application, and it often happens for iron and steel. Lastly, in the case of plastics, recycled plastics are broken down into monomers which can be used as virgin material alternatives for making new polymers.

4. Energy Recovery

This is the fourth preferred strategy in the hierarchy, and it may also be regarded as a low-grade recycling, where instead of the material value, energy content of the product is recycled. According to the waste management hierarchy of European Laws, it should only be applied when the material extraction from the waste is not feasible from a technical or economic point of view, and the best option available is the recovery of its embedded energy content. The place where such energy is often extracted is called an incinerator where the waste products are burnt at very high temperatures in a controlled manner such that the generation of harmful pollutants to the air is minimal. Moreover, the highest environmental benefits are extracted out of this energy in combined heat & power plants producing electricity & heat for district heating and industrial uses.

5. Disposal as Waste

This is the least favourable option according to the waste management hierarchy. It is only suggested for the materials that cannot be re-used, recycled or recovered for its energy from the technical and economic points of view. Disposal of waste at landfills can cause serious environmental and health problems as there are emissions of greenhouse gases into the atmosphere and toxic leachate into the groundwater. As described in the above chapters it may cause serious contagious diseases in the humans as well as other living organisms. Therefore, according to the European law, landfilling should only take place on properly designated sites, where the formation of methane gas is prevented & controlled by flaring and special leachate treatment is applied.

4.2 The Principle of EPR

The principle of extended producer responsibility (EPR) has been enacted in the EU Legislation of Waste Framework Directive to deal with the waste of any products placed on the EU market. As the WEEE directive was formed under this framework, it is therefore made compulsory for waste of electrical & electrical equipment (WEEE) to be dealt with under the same EPR principle. The EPR principle is essentially a policy approach that places an obligation on the producers who place their products on the EU market to take a significant responsibility – both financial and/or physical – for the treatment or disposal of post-consumer products (*Extended Producer Responsibility - OECD*, n.d.). One of the main motivations behind assigning such responsibility to the producers is to provide incentives to prevent waste at the source, by promoting & making use of the design for sustainability (DfS) while taking a whole life-cycle approach as directed under the eco-design directive. Moreover, it is to support the achievement of the public recycling and materials management goals as the governments alone cannot control it.

Within the EPR, the producers are, therefore, obliged to finance and make sure that their products are collected & recycled in an environmentally sound manner once they have become a waste. Everyone placing a product on the EU market, be it a manufacturer or an importer, is considered to be a producer. Besides organising and financing take-back collection schemes, the further obligations of producers include registering on a national register of the member state they operate in, declaring the products sold & placed on the market, and informing the end-user be it a consumer or business client on how to best dispose of the product at the EoL stage. The products must also be labelled with a proper icon to clearly show the end-user that this product mustn't be disposed of in a regular trash bin. Furthermore, the producer is also obliged to make the information available for the recyclers on how to best treat the waste of the product in an environmentally sustainable way by dismantling in a proper manner and recovering the product, or its components or the materials it contains.

Majority of the producers in the EU manage the above-mentioned responsibilities through the use of EPR organisations. These are such organisations that create & manage a common take-back system financed by multiple producers (Magalini et al., 2021). They are made to encounter the administrative and operational burden of the producers exempting them from directly managing their waste. Moreover, such organisations make it possible for the financing of the collection systems to be more economically viable and logistically easier to manage compared with individual take-back schemes (Miliute-Plepiene & Youhanan, 2019). Some of the examples of such organisations in Europe include Erion in Italy, El-Kresten in Sweden, and UFH in Austria. The detailed role of EPR organisations will be explained in the following section of this chapter which talks about different actors involved in the value chain of e-waste management.

4.3 Actors Involved in the Value Chain

The value chain of WEEE starts once the product has been discarded by the consumer with the intention of no further use. In the value chain, there are usually following phases involved:

- Collection: The activity of how the discarded waste is collected
- Transportation: From collection points to processing facilities
- Sorting: Sorting of WEEE into categories that undergo the same processing
- Pre-Process: Manual or automated disassembly & shredding of WEEE
- Transportation: From pre-processing to post-processing facilities
- Post-Processing: Activities carried out to handle any fraction received from pre-processing

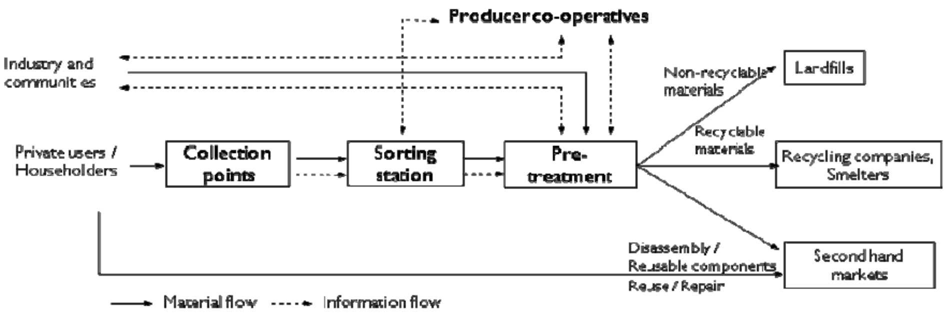

***Figure 4.2**: Value Chain of WEEE. (*Román et al., 2008*)*

Every actor of the chain can take charge of one or more phases and there may be various players involved along the chain. In the section below some of the most important actors along the chain are highlighted and their roles have been explained.

1- Waste Suppliers

As highlighted before the value chain for WEEE starts when the users have decided to discard it off without an intent of further use. The actors involved at this stage may be various, the author has decided to divide them in two groups for the sake of simplicity and better understanding.

Private Individuals – These are the private consumers using EEE in the household or for personal use. Such end users may have several ways to discard off their e-waste. These include:

- They may hand it over at a municipal facility for recycling. By European law they must not be asked for any fee to leave the electronic waste at such facilities.
- They may hand it over to any large retailer who are selling EEE. In some European countries even small EEE retailers collect WEEE from the end consumers to hand it

over to the next player in the chain. Even for this case, the consumers are not asked to pay a fee for discarding.

- As another option, consumers may even sell their discarded EEE items to some commercial collector or recycler for a fee.

Businesses, Governments & Municipalities – In addition to consumers, businesses and governments also make use of EEE for their work purposes and they discard such equipment at some point after the use. These are also not obliged to take care of their discarded WEEE by themselves and are rather free to choose any option of discarding as mentioned above. Similarly, they are not required to pay any fee at this stage for recycling of EEE at its EoL.

The waste suppliers are not asked for any compensation at this stage as they have already paid a certain premium to the producers for the EoL management, with any EEE product they are buying on the European market. The flow of the material and the cost structure among various actors will be explained in more detail in the following sections. For now, the reader must keep in mind that the producers use such premiums to pay for the EoL management to the EPR organisation which in turn take care of the recycling responsibility of the producers. The section below explains the role of an EPR organisation in more details.

2- EPR Organisations

As highlighted in the above sections that according to the EPR principle, the European Law assigns the responsibility to the producers to organise take back of their equipment when it reaches EoL stage. Such producers may be OEMs, importers, and distributors, and according to the Law, they may either setup their own system, or assign a third party to execute these regulations. The role of EPR organisations comes as such third-party organisations that collectively represent a group of producers to fulfil their legal requirements on management of e-waste. This in turn allows the producers to better focus on their core competencies of design, production, and marketing etc.

During the literature review, the author came across multiple examples where such EPR organisation have also been called Producer Responsibility Organisations (PROs). The main roles of such organisations, include managing the EoL operation on WEEE starting from collection to recycling. They often sign agreements with municipalities or set up their own collection points across the country where waste may be collected. In the figure 4.3 a sketch has been provided of the relationship between such EPR organisations and producers through to the municipalities.

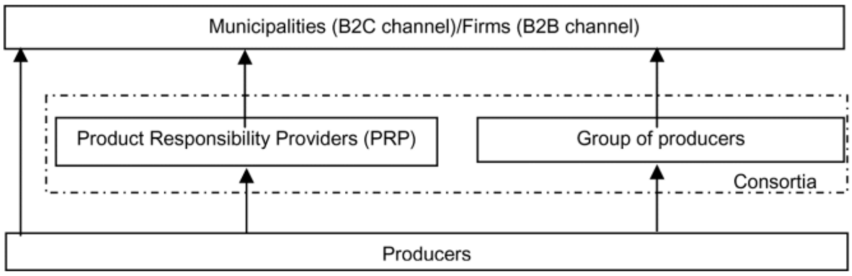

Figure 4.2: Principle of EPR. (Melacini et al., 2010)

Moreover, they work with transporters or setup their own logistics networks to collect that waste from the collection points and deliver to designated recycling facilities. Such recycling facilities may be either operated by EPR itself or they may sign agreements with different recycling companies. They often have such agreements that recyclers take the responsibility of properly dealing with the waste including material extraction and then disposal into landfills in controlled conditions. The recyclers in this case make money by selling the recycled materials. In case it is not economical feasible to extract the materials for further sale, EPR organisations may often have to pay to the recyclers to take care of the recycling part of WEEE.

In the end EPR organisation also work with the governments to report & register the recycling targets achieved. As mentioned during the Legislation chapter the new targets for WEEE collection after 2019 have been set at 65% of POM or 85% of WG. For carrying out all these activities, the financing framework comes from the producers who are placing their EEE on the market.

3- Recycling Companies

In general, once the e-waste is collected and dismantled, the reusable materials parts is then sent on to recycling companies which extract such materials with specialised techniques for a new use. Often, such recycling companies may be divided into two categories, the first which sorts and pre-treats the WEEE and the second which performs the end processing as will be explained in the following section where the flow of material during the recycling process has been described. For now, the reader must understand that there may be a single company performing all the stage of the recycling process or usually multiple companies involved such that the transport may occur during various stage of the recycling process.

Recycling companies may be part of an EPR organisation, or they may be an independent company working within an EPR system such that they have agreements with the EPR organisations. They have to meet the local and European legislation and be part of Authorised Treatment Facilities (ATF), which means they are formally accredited, permitted, and equipped to collect/take back and/or recycle WEEE or the materials ensuing from WEEE (New_InnoNet, 2016).

Various recycling companies working at the end-process stage and specialising in certain materials' extraction may include metallurgical industry specialising in metal smelting, plastic recyclers, and miscellaneous recycling companies specialised in materials such as mercury, lead etc.

4.4 Cost Structure and Swedish Example

In this section we look at the division of costs among various players involved in the value chain of WEEE. Moreover, we look into the Swedish WEEE management system as an example to what we have seen in the above sections. For the cost structure, following sketch in figure 4.4 may be helpful for the reader in getting a perspective about it.

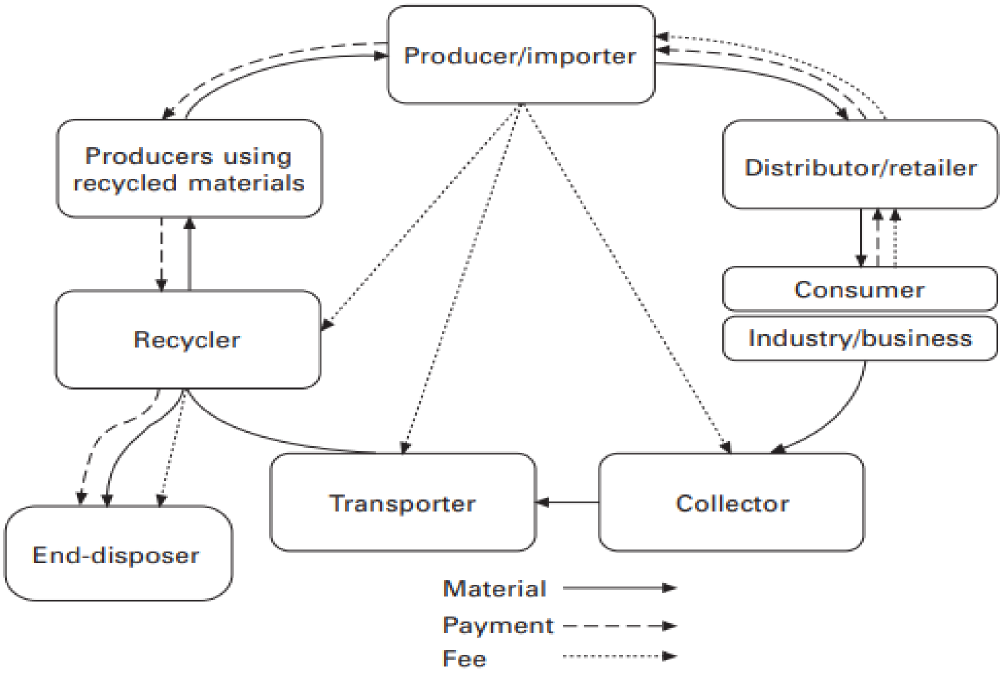

Figure 4.4: Cost structure division (source: Román, 2012)

It can be seen that at the EoL stage of EEE, the waste suppliers such as consumers & small businesses are not required to pay any fee for discarding their waste. Rather they have paid a certain fee while they were purchased the product from the European market. On the other hand, the producers pay a fee to the collectors, transporters and recyclers, often through EPR organisations or a consortium of group of producers as shown in figure 4.2. In cases where the value of extracted materials from WEEE is sufficient, the recyclers may often not receive a fee from the producers or EPR organisations. They instead sustain the economic activity of their businesses through selling reusable parts, components, and materials back to the producers. Moreover, recyclers are also responsible for disposing off any extra materials without causing any damage to the environment. For this they may often do it by themselves or pay to specialised end-disposers for doing that.

Looking into the Swedish WEEE management system, the main actor involved in the collection and recycling of WEEE is El-Kresten. It is basically an EPR organization that was established in 2001 as a result of an agreement between the producers' association and the country's administration. It functions as a non-profit organization, and it is financed by the affiliated producers on their costs & equipment placed on the market.

The way El-Kresten works is that it makes contracts with municipalities and other collecting organizations for collecting the waste. It has a network of 600 such collection centers, also called recycling centers, where households and businesses can hand over their e-waste. It is important to know that no fee is charged to them at this stage. Moreover, since 2015 retailers of EEE, both physical & online stores, are obliged to accept WEEE. It means that consumers can also hand over their e-waste directly to the retailer, who then submits it to the recycling centers.

At the recycling centers, products are sorted into various categories. The reuse possibility of products is checked and accordingly, they may be sold to various second-hand market actors and refurbishing companies (e.g. Swappie). The rest of the stock is transported to recycling facilities for further treatment. El-Kretsen makes contracts with transportation companies and treatment plants i.e recycling service providers, for carrying out these activities. Such contracts are based on five different WEEE categories of (1) fridges & freezers, (2) small electrical & electronic products, (3) large appliances, (4) low energy & fluorescent luminaries, and (5) LED & light bulbs. Moreover, the country has been divided into various collection areas based on volume, logistics costs, and the location of pre-treatment plants. Single-sourced contracts are made with one treatment plant in every collection area and the procurement is conducted through an open tender procedure. The transport procurement is implemented in the same manner, except that the transportation volume of a collecting area is divided between two to three transportation companies to optimize transportation routes.

The cash flow between El-Kretsen and a recycling service provider is based on the material value and is totally business-based. However, in the case of large white goods and television sets, when there is a negative material value, El-Kretsen pays the recycler.

The basic feature of the Swedish system is efficient material flow; the recycling operations are centralized, and the transportation is optimized. In 2007, a web-based system was introduced in the country to disseminate and cover information. The actors in the value chain from collectors, to transporters, and recyclers are connected through online portals. The statistical data about the collected e-waste is analyzed to better optimize the logistics costs as well as extract information about the value of the collection as well as the cost of handling it. In fact, big-data analytics in waste management and recycling is appearing in many advanced countries to better manage their waste management systems and optimize their costs.

5. Recycling Techniques for WEEE

In this chapter, some of the most important recycling techniques have been explored. The first section gives an overview of the process starting from collection to pre-treatment and then end-process stages. Later into the chapter those techniques have been reviewed with somewhat technical details.

5.1 Overview

So far, the reader must have got an idea about various actors involved in the value chain of WEEE management, this section gives an overview how the recycling processes are carried out. The formal e-waste recycling industry usually consists of 3 main phases: collection, pre-processing, and end-processing. Although all of these phases may be carried out by a single company, it is common that several specialised companies are involved in this chain as we have seen in the above section.

1. Collection

The collection of the e-waste is very crucial to secure cost effectiveness in recycling. The collected e-waste needs to be free from other materials and should preferably include uniform types of e-waste. This phase of waste treatment does not depend much on technical solutions such as type of collection transport and the available infrastructure, it rather depends on socio-economic factors such as knowledge of households about waste management and their engagement in sorting different waste fractions. Furthermore, the engagement of the producers according to EPR principle is also very important to secure high rates of waste collection for recycling. It is because the collection efficiency is usually the weakest link in e-waste recycling. Even at very high yields of recycled materials, low collection rates significantly reduce the total recovered materials as compared to the share of total e-waste generated. For example, in Austria in 2015, a collection rate of 49% with its high pre-processing and end-processing efficiencies of 75% and 99% respectively, resulted in only 38% material recovery of the total e-waste generated (Miliute-Plepiene & Youhanan, 2019).

2. Pre-processing

The second phase in the recycling process of e-waste is that of pre-processing or in other words preparation for recycling. This phase may be summarised as depicted in figure 5.1.

In the first step different parts of the products which may be reusable (e.g. hard drives in laptops), or which may contain hazardous components (e.g. batteries) are separated from the waste. It is mainly done by manual dismantling where valuable and hazardous components are sorted out manually at fairly high rates. The second step is mechanical dismantling where the products are first crushed & shredded into smaller size followed by manual sorting of wiring, metals, and plastics on conveyor belts. These two steps are also termed as de-pollution of the e-waste.

Once reduced in size the shredded components in e-waste undergo mechanical sorting, by making use of a vibrating screen. From that point onwards, the ferrous metals such as iron & steel are separated using magnets, while the non-ferrous metals such as copper & aluminium are separated by applying the electro-magnetic fields, the so-called Eddy-Current technology.

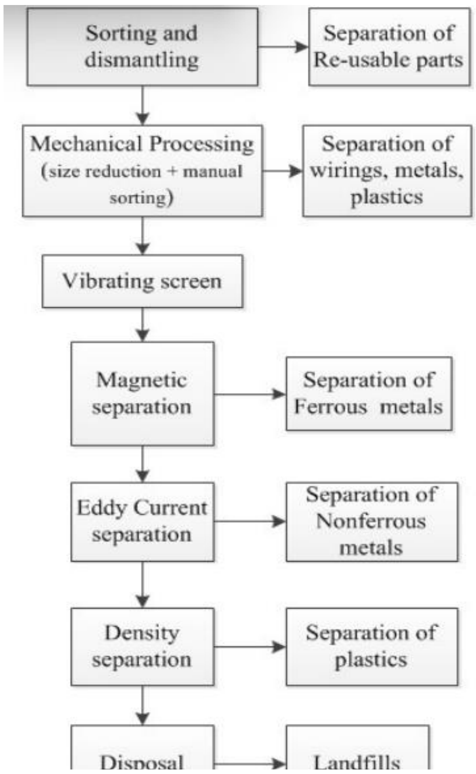

***Figure 5.1**: Tree of pre-treatment steps (Khaliq et al., 2014)*

Plastics which make up a large share of the materials by weight, are sorted mostly using mechanised sorting techniques such as floating technologies and optical spectrometry. In floating technologies, the plastics are sorted by blowing air or in liquid batches according to their stoichiometric weights, while in optical spectrometry, different plastic types are mechanically separated by making use of different colours through optical recognition technologies. At the end, we get residual waste that is not suitable for recycling.

In summary, regardless of the approach and the chosen technology, in the pre-processing stage, following four groups of materials are extracted:

a. Hazardous materials – Examples could be things like batteries which contain hazardous materials, and they cannot be pre-processed together with the other materials to avoid contamination
b. Valuable parts – parts or components of the products which can be re-used/re-sold on the market after dismantling
c. Valuable recyclable materials – materials like copper, aluminium, and plastics etc that will be sold for further material recovery
d. Residues – non-hazardous materials like ceramics, and some kinds of plastics that are not suitable for recycling, and hence are most likely to be disposed of in landfills or incinerated.

3. End-processing

This phase of recycling is rather technologically intensive and requires a substantial capital investment to setup. It basically aims to recover metals and plastics, often back to their virgin material properties or convert them into useful materials in case of plastics.

For the metal recovery, two of the most commonly used techniques in Europe include pyrometallurgical processing and hydrometallurgical processing. The technical aspects and details of these technologies will be discussed in the following sections. It is to mention for now that the ferrous metals are directed to steel smelters to recover iron, while non-ferrous metals such as aluminium rich fractions and copper rich components are sent to aluminium smelters and copper smelters respectively. In the end, up to 30 different metallic fractions can be recovered through such techniques (Miliute-Plepiene & Youhanan, 2019). Other emerging technologies for this purpose include bio-metallurgy and electro-metallurgy, but currently they still lack cost-efficiency and sufficient installed capacity (Miliute-Plepiene & Youhanan, 2019).

For the plastics found at this stage, they may either be incinerated for energy recovery, or they may undergo chemical recycling. During chemical recycling plastics are converted into lower molecular weight products to be used as fuels, original monomers, or valuable chemicals. The most common treatment in chemical recycling is that of pyrolysis, in which plastics are heated at high temperatures to degrade them into lower molecular weight products.

5.2 Depollution

The first step after the collection of electric waste management is the sorting and shredding of the waste material into components that can be recycled and then reused in the same form or reformed to produce new material. The sorting process is generally done manually where operators are separating the waste into different categories depending on various components that can be recycled from them. This stage can also be performed using robots that have special sensors and cameras to sort the waste materials automatically.

The next step is dismantling of the waste. The separately collected WEEE has to be treated unless that appliance can be utilized again as a whole. The selection for reuse is done in the early stages of the WEEE management and special handling measures are applied to take that appliance as a whole for storage. These items can then be refurbished or delivered to resellers.

The treatment can only be performed once all the hazardous material and fluids are removed. The guidelines to consider a material as hazardous have been defined by the legislation. Some items have to be removed as a whole like Capacitors containing polychlorinated biphenyls (PCBs), components containing mercury, asbestos, toner cartridges, CR tubes, gas discharge lamps, internal hazardous batteries etc. While some items can be removed as materials, for example, plastic containing brominated flame retardants, CFCs, HCFCs, HFCs and HCs, external electric cables, circuit boards, LCDs etc. The removed substance is then disposed in accordance with the legislations provided or it can be delivered to reprocessing to turn into useful products.

After sorting and dismantling, next process is the shredding to reduce the volume of the waste. This can be done in different types of shredding machines, most usual being the 2-shaft industrial shredding machine. This volume reduction phase processes the waste for next phases and for subsequent separation of the materials to recover metals, plastics, and precious materials.

5.3 Mechanical sorting treatment

In these techniques, firstly the waste coming from shredding stage is passed through screening. The vibrating screens ensures uniform particle size for metallurgical process in metal recovery stages. The screens separate the waste by allowing permissible sized particles to pass through while restricting the others. The end output fractions are uniformed in size and also enriched in metal are returned in recovery stage.

- Ferrous – The next procedure is magnetic separation of ferro-magnetic metals from non-ferrous metals and other non-magnetic materials. It is done by using the principle of magnetic attraction with the help of magnetic separator. Such magnetic separators may be of various types depending upon the quantity and size of the ferrous metals.

- Non-ferrous – Eddy current and corona electrostatic are two of the most commonly used methods to separate non-ferrous metals from the rest of the waste feed. They both work by making use of the conductivity properties of such metals. In case of eddy currents, an alternating magnetic field induces electrical eddy currents on non-ferrous metal particles. This results in a secondary magnetic field which is opposite to the direction of the primary magnetic field. The exchange interactions between the magnetic fields result in repulsive forces able to separate the conducting particles from the product stream. On the other hand, in corona electrostatic separation, high voltage electric field is used which attracts the conducting metals to electrostatic plate and results in their separation from non-conductor materials such as plastics.

- Plastics – In order to separate the plastics, there may be various techniques that can be used. Two of the most commonly used techniques include floating sorting and image-processing. In case of floating technology, the density properties of plastics are used such that light and heavy fractions of polymers are separated. It works by using a tank of water and passing the waste stream from one end to the other. The material separation occurs by sinking or floating in the tank depending upon density concentration. The density of the water can be altered by adding various chemicals and often tanks are set up in series using different solutions, each one coping with different material density to separate the waste with increasing levels of purity. On the other hand, in case of image-processing, which is also called colour sorting, colour of different particles is sensed with the help of optical means and computer control is used to mechanically divert particles of identical colour out of the waste stream separating different kinds of plastics. One of the common issues in these techniques is that shredding results in mixtures of particles that show a distribution in composition, size, shape, texture, coating etc such that identification becomes complicated (Van schaik & Reuter, 2012).

5.4 Metal Recovery

For metal recovery two of the most commonly used techniques are desribed below:

1- Pyrometallurgy

Pyrometallurgy is one of the most commonly used thermal treatments that can be used for the recovery of metals from WEEE. The process includes smelting the metal scraps received from the pre-processing stage of WEEE in a plasma arc furnace, blast furnace or copper smelter, incineration, and high heat roasting in the presence of selective gases to recover mainly non-ferrous as well precious metals. During the process, the crushed scraps are burned in a furnace or in a molten bath to remove plastics, and the refractor oxides form a slag phase together with some metal oxides (Cui & Zhang, 2008).

While looking into the WEEE management practices in Sweden, the author came across an application of pyrometallurgical process at Boliden Smelters for recovery of metals from e-waste. According to their website, in 2021, the recovery of metals through this process included 223 kilo ton (kt) of copper, 34 kt of zinc clinker, 27 kt of lead, 483 ton of silver, and 11 ton of gold (Boliden Rönnskär - Boliden, n.d.). The schematic diagram of their pyrometallurgical process is shown below.

As

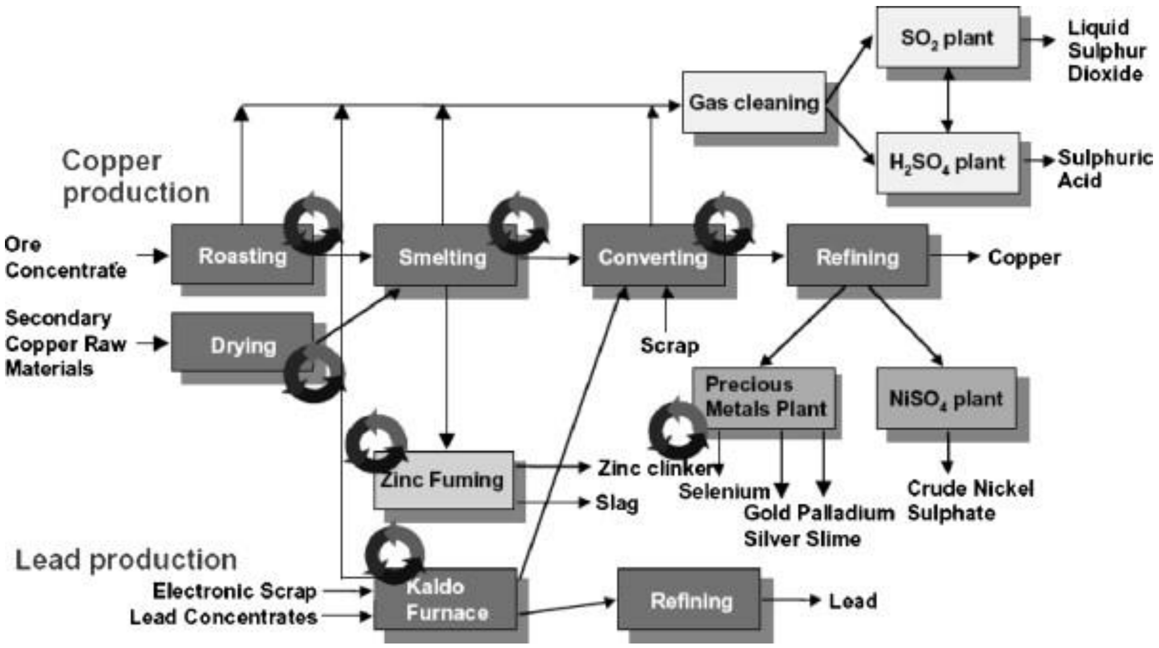

Figure 5.2: *Schematic for Rönnskår Smelter (Cui & Zhang, 2008)*

shown in the schematic, crushed metal scraps are fed into the process depending on their purities. High copper containing scrap is fed into converting process directly while low grade waste is first fed into the Kaldo furnace. The blended feed material is charged by skip hoist and an oxygen lance supplies the needed oxygen for combustion. Off-gases are subjected to additional combustion air at around 1200 degree Celsius in post-combustion. The Kaldo furnace produces a mixture of copper alloy that is sent to the copper converting for recovery of metals such as Cu, Ag, Au, Pd, Ni, Se, and Zn. In contrast, the other metals in the form of dust containing Pb, Sb, In, and Cd are sent to other operations for metal recovery (Cui & Zhang, 2008).

The process of pyrometallurgy is known to have some limitations as well, particularly with regards to the sustainability goals. It is because it is a highly energy intensive process with the additional possibility of releasing toxic materials into the environment such as dioxins and industrial slags. Therefore, it needs to be operated in an advanced control emission system which requires substantial capital investments. Moreover, as this process cannot be used for the recovery of metals such as Al and Fe, there is a possibility of higher loss of such metals in the slag concentrations leading to less efficiency (Cui & Zhang, 2008).

2- Hydrometallurgy

Due to several drawbacks of pyrometallurgy as mentioned above, hydrometallurgy has been used as an alternative route to metal recovery from WEEE. It is more controllable and predictable as compared to pyrometallurgy as well as it is characterized by low energy consumptions and high recovery rates. During the process there is no emission of gases, but large quantities of liquid slags are generated as a result of the extraction procedure which may contain toxic, corrosive and flammable reagents.

The main stages in hydrometallurgy include first a leaching stage, where the metals of interest are transferred into the liquid solutions, and during the second stage those metals are separated in the leaching solution using various techniques. Due to the lack of technical acumen of the author in the said chemical methods, only the available techniques for hydrometallurgy will be highlighted during the scope of this work. Moreover, a tree has been attached in the figure 5.3, where all the available techniques have been enlisted in their proper order.

1- Leaching of metals

Leaching is the first stage of hydrometallurgy, and it is the process of extracting a soluble constituent from a solid by means of a solvent. The most common conventional leaching agents used in the recovery of metals from WEEE include cyanide, acid, thiourea, and thiosulfate. In the attached picture there have been indicated some additional leaching methods including bioleaching and etching, these are in fact the emerging methods in the process with the purpose of being more environmentally friendly.

2- Recovery of metals from leachate

There are various techniques which are used these days for the purpose of recovering the metals from leaching solution. As shown in the picture, some of the most commonly used methods include cementation, ion exchange, solvent extraction, adsorption on carbon, and electrorefining etc.

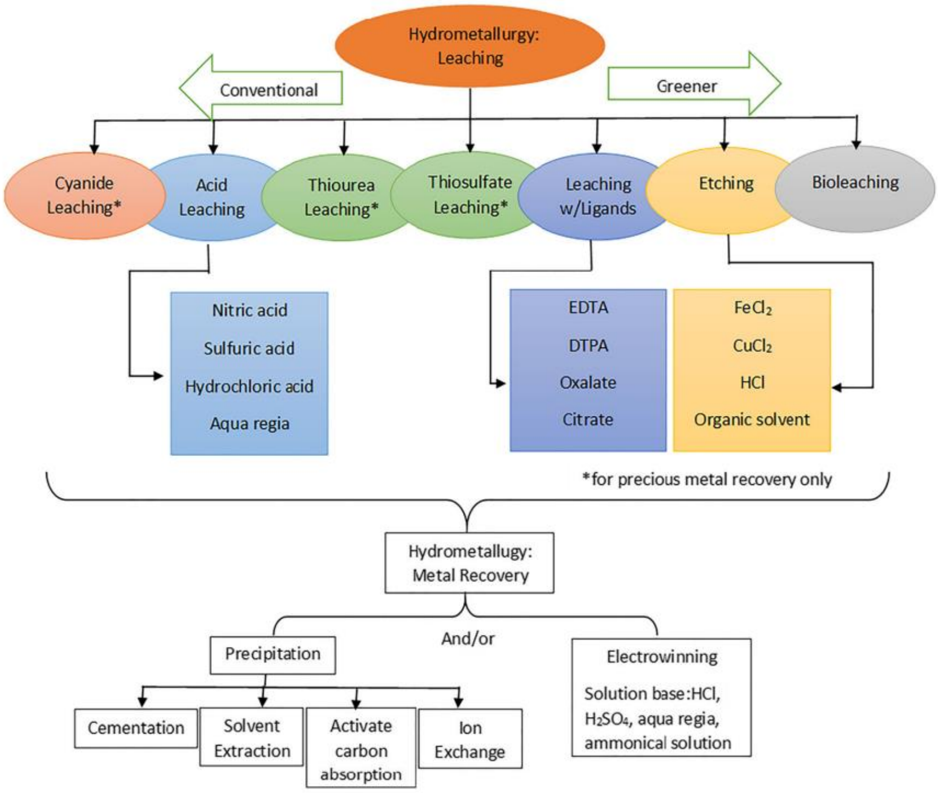

Figure 5.3*: Tree of hydrometallurgical techniques. (Ambaye et al., 2020)*

5.5 Plastic Recovery

As seen in the previous section that after the e-waste goes through depollution and mechanical processing stages, plastics are found to be one of the biggest fractions ready to be processed further in the chain of recycling. It may then be either incinerated for energy recovery, or it may undergo chemical recycling.

Chemical recycling is essentially the conversion of plastic waste materials into lower molecular weight products to be used as fuels, original monomers, or valuable chemicals. It is carried out by the use of chemical reactions while applying different methods such as solvolysis and thermolysis. Its tree has been shown in the figure 5.4.

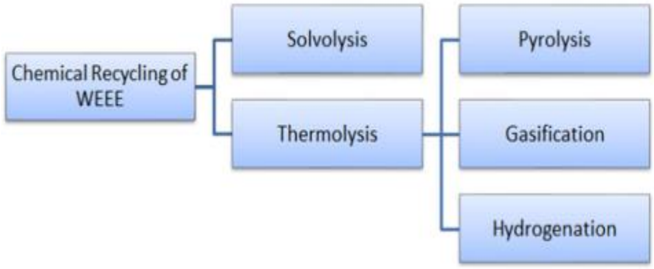

Figure 5.3*: Schematic presentation of WEEE's chemical recycling techniques (source: Charitopoulou et al., 2020)*

While solvolysis is more of a laboratory technique, thermolysis has been increasingly used on industrial scale. In thermolysis plastics polymers are heated in an inert atmosphere in the absence of air and oxygen (Al-Sabagh et al., 2016). It may be carried out by various processes such as pyrolysis, gasification, and hydrogenation. Among the three, pyrolysis is the best method as only 10% of the energy content of the waste plastic is used to convert the scrap into valuable hydrocarbon products (Charitopoulou et al., 2020). Therefore, during the scope of this report, the author reviews only the process of pyrolysis as it is the most common method used in the industry.

1- Pyrolysis

Pyrolysis is the process of separating the carbon-based organic products into smaller molecules by exposing them to high temperatures in the absence of oxygen. The decomposition occurs due to the limited chemical bonding of materials allowing them to disintegrate after heat (*Pyrolysis Process*, n.d.). In case of plastics, the temperature acts as a crucial parameter as high temperatures (above 500 C) favour the production of chars and gases, while lower temperatures (300-500 C) favour the production of liquid fractions.

Although pyrolysis is a thermal process which may be used for variety of different materials in different applications. In case of pyrolysis of the WEEE plastics there needs to be considered a special aspect that they may also contain toxic flame retardants like BFRs. Therefore, during the pyrolysis of WEEE plastics they are first pre-treated to remove BFRs. There are different techniques used for pyrolysis of WEEE plastics which also deal with Br fixation. Some of such techniques include solvent extraction, co-pyrolysis, catalytic pyrolysis, and microwave-assisted pyrolysis.

In solvent extraction, various solvents such as isopropanol, toluene, and methanol etc are used to efficiently remove BFRs from WEEE. Their choice affects the efficiency of extraction of different materials from the plastics. Usually this technique requires high operational costs and large amounts of energy, which restricts the industrial use of this method (Charitopoulou et al., 2020).

In case of co-pyrolysis, two or more materials are processed together without making use of any solvents or catalysts such that the aim is to improve the quality and quantity of the oils derived (Charitopoulou et al., 2020). The limiting factor in this technique is that it depends on synergistic effect of various materials that react together such that not all plastics can be used in co-pyrolysis.

For the catalytic pyrolysis, catalysts are used to carry out cracking reaction such that plastic waste is converted into the liquid oil at lower temperatures. It is reported to have shown different advantages compared with normal pyrolysis techniques which are usually carried out higher temperatures. Some of those benefits include lower energy consumption, enhanced selectivity of derived products, and inhibited formation of undesired products such as chlorinated hydrocarbons (Aguado et al., 2007).

Microwave-assisted pyrolysis (MAP) is another technique used for the pyrolysis of WEEE plastics, but it is more like an emerging technique that offers some advantages over conventional heating such as uniform and efficient heating with a better control (Charitopoulou et al., 2020). In MAP, WEEE plastics may either be converted into petrochemical products that can be further used as fuel, or they may be used for producing raw chemical feedstock that can be reused. However, due to the hazard of microwave radiation and the difficulties in handling MW reactors, this technique hasn’t seen a widespread use so far (Charitopoulou et al., 2020).

6. WEEE Management in the World

In this chapter, we take a brief look at the WEEE Management in the world. We mainly look at some of the statistics from the regions, the legislative infrastructure and institutions present in various countries, and lastly the WEEE management systems implemented in various countries of the regions.

6.1 Africa

In the continent of Africa, according to the global monitor report in 2019, 2.9 Mt of WEEE was generated with an average of about 2.5 kg per capita. Out of the total WEEE generated only 0.03 Mt of WEEE was reported to have been collected and recycled in a proper documented way. It made only 0.3&% of the total waste generated, while the fate of the rest of the waste is mostly unknow which is believed to have been collected and treated in a non-environmentally sound way. The potential release of greenhouse gas emissions from undocumented waste fridges and air conditioners was estimated to be equivalent of around 9.4 Mt CO2. In addition to that the amount of various toxic materials such as mercury and BFR from undocumented flows of waste were estimated to be around 0.01 kt and 5.6 kt respectively. On the other hand, the total value of raw materials present in the WEEE generated in Africa, was estimated to be at about 3.2 billion USD (Forti et al., 2020).

1- Legislation

Although in the past years there have been made substantial improvements in the legal and institutional infrastructure and framework to tackle the issue of e-waste management in various countries of the continent. There still lacks the framework in majority of countries as according to the global monitor 2020, 49 countries in the continent were analysed, only 13 of them were found to have a national e-waste legislation/policy or regulation in place. Some of the countries who have adopted a WEEE management policy recently include Ghana, Nigeria, Egypt, South Africa, Rwanda, and Cameroon etc.

In Ghana, for example, Technical Guidelines on Environmentally Sound E-Waste Management for all the actors of WEEE value chain including collectors, collection centres, transporters, treatment facilities, and final disposal have been adopted and enforced. In Nigeria, the first EPR organisation for e-waste management, EPRON, was formed in 2018 by various electronic producers in Nigeria such as HP, Dell, Phillips, Microsoft, and Deloitte. It is contributing towards the establishment of a proper WEEE management system in the country. The East African Community (EAC) including countries such as Tanzania, Rwanda, Uganda, Burundi, Kenya, South Sudan, and Democratic Republic of Congo adopted a common regional strategy in 2017 to achieve a sustainable e-waste management system. The strategy prioritizes strengthening of legal framework, establishing infrastructure, and promoting R&D for e-waste management in the community countries.

2- WEEE Management Systems

When it comes to the operational aspects of e-waste management in Africa, there is a thriving informal sector of collectors and recyclers in most countries. In such cases, there are neither organised take-back systems, nor licensed provisions for sorting & dismantling of e-waste. The e-waste is often processed in the backyards by manual stripping and electronic boards are removed for resale. The wires are burnt to recover few materials such as copper, aluminium, and iron, causing the deposition of other bulk components in the open dumpsites. Although most of the valuable materials are recovered and sold for another use, the biggest downside is the deposition of hazardous compounds in the environment.

On the other hand, there are in place formal e-waste recycling facilities in some of the countries like South Africa, Morocco, Egypt, and Rwanda etc, but they are often not functioning within a proper take-back system, and rather co-exist with a large informal sector to receive their feeds. In such cases it may often be challenging for such recyclers to progress due to inconsistent volumes, but new initiatives being taken in the form of pilots are expected to be helpful in this regard.

In conclusion, the e-waste management problems are somewhat similar in various sub regions of the continent. Major problems include the lack of public awareness about the topic, lack of legislative framework, lack of collection & EPR systems, lack of recycling facilities, dominance of informal sector often polluting the environment, and finally poor financing for carrying out proper waste management activities.

6.2 Americas

According to statistics in the year 2019, in the Americas a total of 13.1 Mt of e-waste was generated. In terms of per capita it stood at 13.3 kg per capita, placing it higher than Asia and Africa. On the other hand, only 9.4 % is reported to have been collected and recycled in a proper documented manner. The rest of nearly 90% is either exported to other countries or disposed of in a non-environmental friendly manner, placing the continent lower than Asia and Europe with regards to recycling. The potential release of greenhouse gas emissions from undocumented waste fridges and air conditioners was estimated to be equivalent of around 26.3 Mt of CO_2. Lastly the amount of the amount of mercury from undocumented flows of e-waste was estimated at 0.01 kt and that of BFR was estimated at 18kt. The total value of raw material present in the e-waste was estimated at 14.2 billion USD which is higher than all the other regions except Asia.

1- Legislation

For the region of Americas, 34 countries were analysed by the monitor and only 10 were found to have a national e-waste legislation or policy. If looked at the countries in North America, both the countries, the United States and Canada do not have a national legislation on the WEEE management. Rather some of the states in the US and majority of the provinces in Canada have enacted some form of their own legislation. The laws among various state and provinces vary strongly from one to another and consequently it affects the management systems within the two countries. Majority of the states and provinces in both countries follow an EPR approach but there may be found different approaches such as public sector programmes and shared responsibility.

In Latin America, on the other hand, only few countries have managed to establish legislation for e-waste management. The monitor reported that the region has seen considerable progress regarding the implementation of e-waste regulations in the past 5-10 years. but that is only limited to a few countries. Apart from Mexico, Costa Rica, Colombia, and Peru, only Brazil and Chile are laying the groundwork for the implementation of a formal regulatory framework. Brazil implemented its national policy in 2020 and Chile, although has a national policy, is working further to enact specific e-waste regulations targeted at collection & recycling targets as well as proper implementation of a formal collection system. The list of other countries who have had established systems for a while and are looking for further improvements, include Peru, Ecuador, Costa Rica, Mexico, and Colombia.

2- WEEE Management Systems

In the US, although, there is no federal level legislation for proper take-back system, but there are measures to prevent the adverse effects posed by unappropriated disposal and treatment of e-waste. Only certified recyclers are allowed to operate in the country and for that purpose two different programmes are in place, namely Responsible Recycling (R2) and Steward standards. Hundreds of recycling facilities are certified to one or both of these programmes, whose standards been continuously updated since their inception in 2010. Similarly, there is a product stewardship programme in Canada and the recyclers have to follow its standards in order to reduce the harmful effects of recycling to the environment.

In Latin America, as mentioned earlier, there are numerous countries without any sort of regulation. From the ones which do have a legal framework in place, there are some which have established take-back systems and mandatory collection targets such as Colombia and Peru, while the others such as Brazil and Chile, are still not able to implement effective take back systems and achieve certain targets. In any of these two cases, there is a wide range of companies involved in e-waste management and disposal activities especially the recycling process to recover valuable materials from WEEE. One of the problems other than lower volumes available for such recycling companies is that most of them are still at the bottom of the learning curve (Forti et al., 2020). On the other hand, very large quantities are still handled by the informal sector and that contributes to the labour structure of Latin America.

6.3 Asia

The total amount of e-waste generated in Asia in 2019 was estimated at 24.9 Mt with an average of 5.6 kg per capita (Forti et al., 2020). Out of that only 2.9 Mt was collected and treated in a proper documented manner. This fraction makes 11.7% of the total generated WEEE placing the region on second position after Europe with regards to the proper waste treatment. On the other hand, the potential release of greenhouse gases emissions from undocumented waste fridges and air conditioners was estimated to be equivalent of 60.8 Mt of CO2, which is the highest compared with all the other regions. Similarly, toxic elements such as mercury and BFR are also the highest at 0.04 kt and 35.3 kt respectively. Lastly, the value of raw material present in the e-waste was also estimated to be the highest of all regions at 26.4 billion USD (Forti et al., 2020).

1- Legislation

This region has the most densely populated countries of all the other regions and of the 46 countries analysed by the monitor only 17 were found to have a national e-waste policy. In South Asian countries, only India has a legislation for the proper management of e-waste. The other countries are also beginning to recognise the importance of the issue and several countries are considering the legislation for e-waste management. Pakistan, for example, has enacted an initial draft for WEEE management to be initially implemented in the province of Punjab. In Southeast Asia on the other hand, some of the countries are comparatively more advanced compared to South Asian countries. The Philippines doesn't have a specific regulation for e-waste, but they do have range of regulations regarding hazardous wastes and are working towards drafting specific legislation for e-waste. Cambodia has a specific law relating to e-waste management and it covers all activities regarding disposal, storage, collection, recycling, and dumping of WEEE.

China has a national legislation for the management of WEEE including both collection and treatment. Like the EU, China has divided the WEEE into various product categories and some of those have special regulations for their treatment to protect the environment from any harmful effects of recycling and disposing. Other East Asian countries such as Japan and South Korea have well-established WEEE management legislation and policy. Japan was one of the first countries to implement an EPR approach for WEEE management. In Western and Central Asian countries, on the other hand, WEEE management legislation is relatively poor and e-waste management infrastructure is mostly absent. Some of the highlights may include the development of new legislation in Kyrgyzstan applying the EPR concept to e-waste and new legislation in Kazakhstan considering the implementation of a manufacturer's extended liability to cover part of the costs for collection and disposal of WEEE.

2- WEEE Management Systems

The WEEE management systems found in Asia are rather diverse, ranging from very advanced systems in countries like Japan, South Korea, and the province of Taiwan, to notorious informal sectors of India and China. Although in both these countries, there are also advanced recycling systems with coexist with informal activities and often depend upon them for receiving their feeds.

In South Asian countries the WEEE management is largely based on informal activities for collection, dismantling, and recycling. Several recycling companies and EPR organisations have erupted in India over the past few years, but their capacity remains mostly underutilised as a large majority of the WEEE is handled by the informal players. Some of the challenges include enforcing rules, lack of proper collection & transportation infrastructure, limited awareness of consumers, and lack of standards etc.

In China, the formal e-waste recycling industry has shown considerable growth recently due to the efficient enforcement of the regulations. According to the Chinese Ministry of Ecology and Environment more than 70 million e-waste units were dismantled properly in China in 2019. The informal sector and illegal importation of WEEE have been drastically declining due to stricter controls from the government. However, due to increasing gap between funding and subsidies, some challenges for e-waste funding policy are emerging. In Taiwan, WEEE collection and recycling rates achieved in 2018 were significantly high at 64% of the waste being treated according to the legislation. It is mainly due to the efficient implementation of EPR concept to recycling system as well as high capacity of e-waste recycling facilities. Japan and South Korea both have advanced collections systems and developed infrastructure for recycling the waste.

In Central Asia, most of the generated WEEE ends up in landfills or illegal dumping sites without any sorts of proper treatment. It is a common practice in the entire region, that consumers send their discarded equipment to small companies, which dismantle them to extract certain reusable components, while disposing the rest in a non-environmental friendly manner. In Kazakhstan, some official collection and recycling sites have been developed under the Green Economy Transition plan, but their capacity is not sufficient to according to the needs of the country due to its enormous size. In Western Asia, despite the fact that the countries range from very rich to very poor, WEEE management systems are mostly informal. In the rich countries like UAE, there are large migrant workers that make use of the donated used-EEE from the richer households, a thing unique to the region (Forti et al., 2020). In Palestine there are several landfills where WEEE is dumped without adequate treatment.

6.4 Oceania

According to the statitics of e-waste monitor, in the year 2019, the e-waste generated in Oceania was among one of the highest as per capita. The average per capita waste generated was 16.1 kg per capita, while in total less wast was generated at 0.7 Mt due to less population. Even from this low amount of e-waste produced, the properly treated fraction stands very low at 0.06 Mt i.e only 8.8% of the toal generated. The amounts of toxic substances in the environment are relatuvely lower compared with the other regions, but so is the value of raw materials present in WEEE found at 0.7 billion USD (Forti et al., 2020).

1- Legislation

The only country in the region which has a national legislation in place is Austrailia, while all the other countries in the region including smaller island nations as well as New Zealand don’t have any national regulation for WEEE management. Even in Austrailia the regulation came into effect only a decade ago in 2011, and that too only for the categories televisions and computers. Government’s Product Stewardship Act 2011 requires the producers of televisions and computers to arrange the financing and operating activities for recycling. This essentially provides the private households and small business with free acces to collection and recycling activities for the televisions and computers.

2- Waste Management Systems

For the management of e-waste, it is a common practice in Austrailia that the computers and television producers are carrying out their legislative responsibilities through Producer Responsibility Organisations (PSOs). Such PSOs in the country are licensed and regulated by the governmnet authorities such that they are required to provide annual audit reports to the government department. Furthermore, some of the states are taking some initiatives individually to manage WEEE in their own state. One such example is that of the government of Victoria, which in 2019, banned WEEE disposal in landfills without carrying out a safe management of hazardous materials. It is not clear how they plan to put the responsibility on the producers or the indiviuals as so far the government has been setting aside a budget to deal with it by itself.

In New Zealand, on the other hand, the government is considering deeloping a national plan for managing the WEEE produced in the country. So far the practice largely involves the disposal of such waste into landfills without any special prior treatment or extraction of valuables. It is mainly due to lack of a mandatory legislation and lack of a formalised system for managing the e-waste (Blake, Farrelly, and Hannon 2019).

7. Future Trends and Conclusion

In this chapter, a brief look has been taken into the future trends for WEEE management and the report is finally concluded with remarks about further research options into the subject matter of WEEE management.

7.1 Future Trends

In the case of future trends, there may be different elements which may be considered important for the WEEE management sector. In this section, three of them are briefly reviewed.

1- Business

Businesses these days are increasingly realizing the importance of sustainability and including it as an important aspect of their strategies. It is mainly due to consumer awareness and a lot of global as well as local initiatives and policies for that. In that scenario, a lot of new business models are emerging for EEE producers, which are termed so-called Circular Economy Business Models (CEBMs). Some of the important aspects of CEBMs are the consumption of resources & energy, the origin of materials & their transportation, biodiversity & social impacts, and EoL aspects of the products including toxic waste emissions & their re-use/recycling.

The operation undertakings of businesses for dealing with such EoL aspects are therefore not limited only to the end phase, rather they begin at the material selection & design phase to efficiently implement their CEBMs. According to Tischner and Hora, some of the important operational & design strategies that businesses are increasingly using for their new business models may include:

Modular design – such that products are made from various modules enabling easy replacement for repairing, upgrading, and refurbishing if necessary.

Design for recycling – recyclable materials with low toxicity are chosen such that valuable materials may easily be recycled without deposing harmful substances to the environment

Design for disassembly and assembly – products are manufactured in such a way that easily detachable components are made without possibly using joints & screws such that dismantling is non-destructive. The ideal assembly process for such purpose is called to be reversible.

Design of product-service systems – different kinds of service mechanisms are designed in the companies including maintenance, renting, leasing, take back, and reverse supply chain systems etc.

These are some of the important operational undertakings that businesses take to implement their CEBMs. Looking at the list of such emerging CEBMs in the field of EEE, one of the most important trends which the companies are following is that of moving from products to services. What it means is that the producers of EEE don't sell their products rather they hand them out to the users, both for B2C transactions as well as for their B2B clients. During the use phase, the producers are responsible for carrying out any maintenance activities or upgrading the equipment after a certain time period. Moreover, at the end phase, the service offering companies are responsible for proper treatment such as reusing the equipment in some other place or recycling in a proper way. Some examples of the application of this business model may include the installation of coffee machines at workplaces or the installation of washing machines in university dormitories. Once the EEE products are offered as a service or leased instead of sold, there are better opportunities for product lifetime extension and effective take-back & treatment at the EoL.

2- Technology

The use of e-products is growing substantially over the years. This is not limited only to stand-alone equipment in households but growing e-products are being used in buildings, transport systems, and for personal use. This trend is expected to grow over the years as more and more new kinds of smart products appear on the market. Not just that, the concept of smart cities largely depends on the installation of a large number of smart sensors and devices, also known as IoT devices. According to some estimates, the number of such devices is expected to grow to 100 billion in 2050 (Haroon et al., 2016). Recently the EU has also commissioned a report on evaluating the potential effects of IoT devices. Although it is expected that IoT will have significant economic and social advantages, one big concern is that of WEEE generation from it.

One the other hand, as technology develops, new and advanced materials will be used in e-products. This could include, for example, substitution of critical resources and the introduction of more recycling friendly and biodegradable materials. Innovation and geopolitical issues will play a role in this, which would affect EoL material recovery effort.

3- Consumer Awareness

Consumer awareness regarding the overall environmental footprint of human production has been increasing over the past decade. Especially in Europe, where even political parties with green and sustainable agendas are starting to become more and more popular. One of the most important factors in environmental sustainability is the use and disposal of EEE at their EoL. Therefore, there is a trend of growing demand for sustainable and environmentally friendly electrical & electronic products. This trend in turn is leading more and more companies to start putting eco-labels on their products and coming up with Circular Business Models (CBMs) to cater to consumers' needs.

Not just the environmental concerns, there are growing social concerns as well largely due to social media. Such that customers demand transparency in the value chain the whole life cycle starting from material extraction to EoL treatment. We have seen in recent years that some of the biggest EEE manufacturers faced a backlash due to such social issues of child labour for example in the far-east countries like China. This in turn is leading many companies to be more transparent about their value chains. So far it hasn't been very common except for a few cases here and there. It is expected that in the coming years companies will have to take the issue seriously due to growing demand from consumers. One of the technologies which may be used for this purpose is Blockchain such that the data from all points of importance in a value chain is stored on a decentralised database. In recent years some start-ups have emerged with this idea, which makes it possible to trace the transparency of a supply chain (*Building a Transparent Supply Chain*, 2020).

7.2 Conclusion

Although there are always uncertainties about how the future evolves, the use of e-products, however, will almost certainly grow during the coming years. It is true for both developed countries, where smart cities with billions of IoT devices will be developed, and for growing economies where the use of e-products will be substantial due to the enhanced economic prosperity that comes along with it. This means more e-waste, which means more challenges and opportunities for all players in the global e-waste arena, including producers, users, e-waste collectors, recyclers, and policymakers. Under these conditions, making sure of a sustainable production and consumption system for e-products will necessitate significant efforts on the part of all stakeholders.

With insights into the future, producers probably have the best opportunity to design a future-proof electronics sector that is economically and environmentally sustainable. Besides manufacturing and recycling, innovative businesses can also tap into the huge product and component reuse potential. Many new circular economy business models (CEBMs) can be established, such as offering products as a service or leasing them instead of selling them. Such business models can provide better opportunities for product lifetime extension and smoother take-back at the EoL. There is also a demand for more sustainable products, which can be attributed to growing consumer awareness. Businesses will certainly be better off by proactively addressing users' demands.

There is an opportunity for policymakers as well to facilitate the transition towards a more circular system. Many developing countries lack effective policies and proper infrastructure for WEEE management. This situation offers a great opportunity for such countries in Asia, Africa, and South America, where more rapid technological growth is expected. Institutionalising informal recycling activities can help create a safer working environment for waste workers, less environmental impact, and a more sustainable recycling industry. The lessons learnt during the last two decades from the EU in developing and implementing WEEE regulations and setting up management systems can be of value in this process.

In the EU, on the other hand, the EPR-based take-back system has been a noteworthy milestone in e-waste management. However, the current e-waste management systems still need to capture the functional and material value of EoL products fully. In order to achieve its circular economy goals as set out under the EU Green Deal, the EU will need to take further legislative and operational steps. Separate targets for reuse may be introduced as reuse saves higher rates of GHG emissions as compared to recycling. Under the current scenario, however, recycling is more incentivised due to higher economic gains for manufacturing companies.

Furthermore, digitalisation can help to achieve the circular economy targets as it has the potential to support the circular management of e-waste. It can help in all stages, including prevention, collection, and treatment, by enhancing information transfer, improving processes, and connecting the relevant actors across the value chain. AI, for example, can improve the gathering & processing of information to enable the circular design of EEE. Blockchain-enabled solutions can provide safe & transparent tools for sharing information about WEEE across its value chain. Robots, sensors and digital twins can improve e-waste sorting & dismantling. Further research work can be focused on developing new use cases of such digital technologies and, consequently, new business models for the companies operating in the WEEE management chain. Research can also be conducted into looking for ways to how the EU financial instruments and institutions may be used to support the development and deployment of these digital technologies in the WEEE value chain.

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