CIRCULAR ECONOMY: MANAGEMENT OF WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT (WEEE) IN EUROPE

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INDEX

FIGURES INDEX

CHART INDEX

1. INTRODUCTION

The management of Waste Electrical and Electronic Equipment (WEEE) in Europe is a pressing issue, as the growing volume of electronic waste poses significant challenges for sustainable waste management (Salhofer et al., 2018). WEEE consists of a complex mixture of materials, including hazardous substances such as heavy metals, plastics, and valuable resources like rare earth elements (Hsu et al., 2019). Safely handling and disposing of WEEE is crucial to mitigate environmental and health risks while also promoting resource recovery.

In Europe, the management of WEEE is governed by a comprehensive set of directives and policies aimed at minimising its adverse effects and fostering the principles of the circular economy (European Union, 2012; European Union, 2018). These regulations provide guidelines for the collection, treatment, and recycling of WEEE to ensure the proper handling of hazardous components and the recovery of valuable materials (Pekarkova et al., 2018; Tunsu & Retegan, 2016).

However, the implementation of WEEE management regulations across European countries and regions exhibits variations and challenges (Habib et al., 2021; Salhofer et al., 2018). Different approaches and practices can impact the effectiveness and efficiency of WEEE management systems. For instance, the availability and accessibility of collection points, the effectiveness of recovery networks, and the involvement of various stakeholders can vary (Bruno et al., 2017; Joshi et al., 2019).

To address these issues and enhance the management of WEEE, ongoing research and technological advancements play a crucial role. Studies have explored various aspects, such as the development of sustainable metal recovery techniques (Bertuol et al., 2020; Chen et al., 2021), the application of laser-induced breakdown spectroscopy for chemical analysis (Câmara Costa et al., 2017), and the potential of bioleaching as a metal extraction method (Faramarzi et al., 2020). These investigations contribute to the development of innovative approaches for WEEE treatment and recycling, aiming to improve resource efficiency and minimise environmental impacts.

This thesis aims to explore and analyse the management of WEEE in Europe, with a focus on the policies, practices, and challenges related to its collection, treatment, and disposal. Specifically, this thesis will:

- Define WEEE and highlight its significance in Europe.
- Examine the European Union directives governing WEEE management, including the WEEE Directive 2012/19/EU, RoHS Directive 2011/65/EU, and Circular Economy Package 2018.
- Investigate national policies and regulations concerning WEEE management in different regions of Europe.
- Explore Extended Producer Responsibility (EPR) systems in Europe, including producer obligations and the implementation of EPR.
- Analyse WEEE collection methods, targets, and recycling methods.
- Address challenges, opportunities, and future scenarios in WEEE management in Europe, such as illegal WEEE exports, technological advancements, and future developments.
- Summarise the importance of responsible WEEE management in Europe and discuss future developments and opportunities

The thesis is structured as follows. It begins with an overview and conceptual framework of WEEE management in Europe. This is followed by an examination of European Union directives on WEEE, national policies and regulations, and Extended Producer Responsibility systems. The thesis then explores WEEE collection and recycling practices, including targets and methods. It also discusses challenges, opportunities, and future scenarios in WEEE management. The conclusion summarises the key findings and implications, highlighting areas for further research.

2. CONCEPTUAL FRAMEWORK

This section provides a conceptual framework for understanding the management of WEEE. It begins with the definition of WEEE, which encompasses discarded or obsolete products powered by electricity or batteries that contain circuitry. The definition of WEEE is essential in guiding its proper management.

2.1. Definition of WEEE

Waste Electrical and Electronic Equipment refers to any discarded or obsolete products that are powered by electricity or batteries and contain circuitry, such as computers, televisions, smartphones, refrigerators, and lighting equipment (Baldé et al., 2017; European Union, 2012). WEEE is a rapidly growing waste stream, driven by technological advances, short product lifetimes, programmed obsolescence, and consumer behaviour (Parajuly et al., 2019). It presents both challenges and opportunities for waste management, as it contains hazardous substances that can pose risks to the environment and human health (World Health Organization, 2014). International organisations have provided definitions and classifications for WEEE to guide its management:

Figure 1. Evolution of e-products in the last century

Source: unep.org

European Union directives and policies have defined Waste Electrical and Electronic Equipment as discarded or obsolete electrical and electronic products, including those powered by electricity or batteries, containing hazardous substances that pose risks to the environment and human health (European Union, 2011; European Union, 2012).

The United Nations Environment Programme (UNEP) provides a comprehensive definition of electronic waste as discarded electrical or electronic devices, including their parts, components, and consumables, which have reached the end of their life cycle. E-waste is a global concern, with an estimated annual generation of 50 million metric tonnes and a rising trend due to increased consumption and short product life cycles (UNEP, 2019).

According to the World Health Organization (WHO), e-waste or Waste Electrical and Electronic Equipment refers to electrical or electronic devices, including their components, subassemblies, and consumables, which become waste at the end of their useful life. This encompasses a wide range of items such as computers, monitors, wireless devices, printers, telephones, televisions, lamps, household appliances, toys, and medical devices. E-waste contains hazardous substances, including lead, cadmium, mercury, and arsenic, which can pose risks to human health and the environment if not properly managed. The WHO recognizes the importance of addressing e-waste issues and has initiated efforts to increase awareness, enhance health sector capacity, and promote policies to protect public health, particularly focusing on the health of children (World Health Organization, 2021).

To put it concisely, WEEE refers to discarded or obsolete products powered by electricity or batteries that contain circuitry. WEEE is a rapidly growing waste stream fueled by technological advances, short product lifetimes, programmed obsolescence, and consumer behaviour. It presents both challenges and opportunities for waste management due to the presence of hazardous substances that can pose risks to the environment and human health. The European Union, United Nations Environment Programme (UNEP), and World Health Organization (WHO) have provided comprehensive definitions of WEEE, emphasising the need for proper management to mitigate the adverse impacts of e-waste. These definitions highlight the broad range of electronic devices and components that fall under the category of WEEE, as well as the importance of raising awareness, strengthening health sector capacity, and implementing policies to protect public health and the environment

2.2. Importance of managing WEEE in Europe

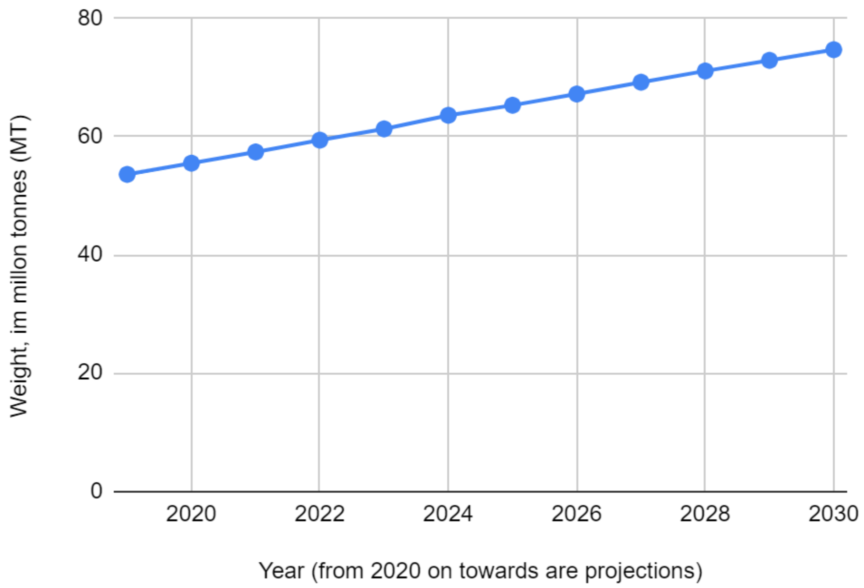
The management of WEEE is crucial in Europe for a number of reasons, as outlined by several experts in the field. Here are a few authors and their thoughts on the importance of managing WEEE in Europe:

Pekarkova et al. (2018) highlights the importance of managing WEEE in Europe due to the economic and environmental consequences of incorrect disposal. The authors suggest that the current WEEE management system in Europe does not effectively address the issue of incorrect disposal, resulting in significant economic costs and environmental impacts. The incorrect disposal of WEEE contributes to the release of hazardous substances into the environment, which can negatively affect human health and ecosystems. The authors estimate the economic cost of these impacts to be around €143 million per year in Europe. Furthermore, the incorrect disposal of WEEE also has significant climate change impacts, as it contributes to greenhouse gas emissions. The authors estimate that these emissions are equivalent to approximately

3.5 million tonnes of CO_2 per year, which is equivalent to the annual emissions of more than 700,000 passenger cars. Therefore, effective WEEE management is crucial in mitigating the economic and environmental impacts associated with the incorrect disposal of WEEE.

Shittu, Williams, and Shaw (2016) discuss how e-waste is a growing global problem and estimate that by 2018, the world's e-waste generation will reach 50 million metric tons annually. They explain that Europe has taken a proactive approach to WEEE management by introducing the WEEE Directive, which requires manufacturers to take responsibility for the disposal and recycling of their products. The authors note that although the WEEE Directive has helped to improve the situation, more needs to be done to ensure proper e-waste management across Europe. They suggest that increasing public awareness, improving enforcement of regulations, and promoting sustainable design practices can help address the e-waste problem in Europe and globally, as we can see in the graph below.

Figure 2. WEEE generation between 2019 and 2030.



Source: own elaboration according to Shittu et. al (2016).

Ismail and Hanafiah (2019) emphasise the relevance of Life Cycle Assessment (LCA) as a tool to identify environmental impacts of WEEE management practices. According to the article, Europe is among the regions with the highest WEEE generation and is also a pioneer in adopting policies and regulations for WEEE management. LCA studies can help assess the environmental impacts of these policies and guide decision-making towards more sustainable solutions. The authors also highlight the challenges faced by the industry in implementing sustainable WEEE management practices, such as the need for more effective recovery and recycling techniques. Therefore, managing WEEE in Europe is of great importance to minimise the environmental impacts of e-waste and ensure sustainable development.

In summary, it is essential to stress that the importance of managing WEEE in Europe cannot be underestimated. Economic and climate impacts from the incorrect disposal of WEEE, such as loss of resources, environmental pollution, and adverse health effects, highlight the need for proper management and disposal. Furthermore, the extended producer responsibility model and regulations put in place in Europe have resulted in significant progress in WEEE management, including improvements in collection, treatment, and recovery rates. However, challenges and opportunities remain in achieving a circular economy for WEEE, particularly in developing effective collection schemes and promoting the sustainable use of resources. Therefore, it is crucial to continue advancing in the field of WEEE management through technological innovations, policy improvements, and public awareness campaigns.

3. EUROPEAN UNION DIRECTIVES ON WEEE

The European Union (EU) has taken a leading role in tackling the environmental and health risks associated with Waste Electrical and Electronic Equipment (WEEE) disposal. Through the development of directives and policies, the EU aims to reduce the generation of WEEE, promote appropriate treatment and disposal methods, and facilitate the recovery and reuse of valuable resources (European Union, 2012; European Union, 2018). These directives establish a comprehensive regulatory framework that spans the entire life cycle of electrical and electronic equipment, encompassing aspects from design and manufacturing to collection and recycling (European Union, 2012). Since their implementation, these directives have significantly influenced the management of WEEE in Europe and have contributed to the adoption of a circular economy approach to waste management (European Union, 2018).

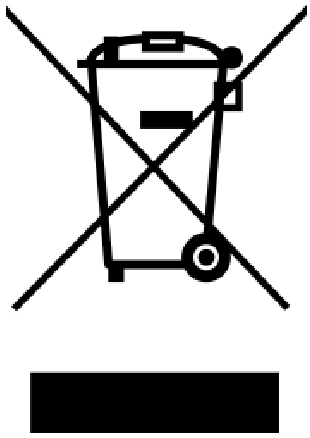
3.1. WEEE Directive 2012/19/EU

The WEEE Directive 2012/19/EU[1] is a key piece of legislation in the EU that aims to reduce the environmental and health risks associated with the disposal of electrical and

[1] https://eur-lex.europa.eu/eli/dir/2012/19/oj accessed in March 2023

electronic waste. The directive sets out a regulatory framework for the entire life cycle of electrical and electronic equipment, from design and manufacturing to collection and recycling.

Figure 3. WEEE label: crossed out wheelie bin symbol



Source: europa.eu

The crossed out wheelie bin symbol means that you are required by law to dispose of this equipment separately from unsorted municipal waste. The WEEE marking must appear on any electrical and electronic equipment placed on the EU market. Batteries or rechargeable cells that are not permanently installed must be removed beforehand and disposed of separately. A bar under the trash can means that the product was released after August 13, 2005.

One of the main objectives of the WEEE Directive is to increase the collection, reuse, and recycling of WEEE. To achieve this, the directive establishes binding targets for the collection of WEEE, ranging from 45% to 85% of the average weight of electrical and electronic equipment put on the market in each member state over the preceding three years. The Member States of the EU can annually choose either method for the calculation of the WEEE collection targets. For the WEEE Generated method, the target is 85%, and for EEE POM, the target has been 65% since 2019. These two methods for collection targets will be explained in the section “6.1 Collection targets”.

The WEEE Directive also introduces a number of requirements for the treatment and disposal of WEEE. It requires member states to ensure that WEEE is properly treated and recycled, and that hazardous substances are removed and disposed of safely. The directive sets out specific treatment standards for various types of WEEE, such as refrigerators, televisions, and photovoltaic panels, and requires member states to establish monitoring and enforcement measures to ensure compliance with these standards.

In addition to collection and treatment targets, the WEEE Directive also introduces requirements for the design and manufacture of electrical and electronic equipment. It requires manufacturers to take into account the environmental impact of their products, and to design products that are easier to reuse, repair, and recycle. The directive also promotes the use of eco-design principles, such as energy efficiency and the use of recycled materials, to reduce the environmental footprint of products throughout their life cycle.

The WEEE Directive places responsibility on producers and importers of electrical and electronic equipment for meeting the costs of collection, treatment, and disposal of WEEE. Member states are required to establish systems for the financing of WEEE management, such as extended producer responsibility schemes, in which producers contribute to the costs of managing WEEE based on the amount and type of products they put on the market.

The WEEE Directive is one of the key policy instruments for promoting a circular economy approach to waste management in the EU. It seeks to reduce the environmental and health impacts of WEEE, promote the recovery and reuse of valuable resources, and create a more sustainable and efficient use of resources. However, the implementation of the WEEE Directive is not uniform across EU member states, and there are still challenges and opportunities for improvement in the collection, treatment, and disposal of WEEE. Effective implementation and enforcement of the directive, as well as further research and innovation in WEEE management, are needed to address these challenges and fully realise the benefits of a circular economy approach to waste management in Europe.

3.2. RoHS Directive 2011/65/EU

The Restriction of Hazardous Substances (RoHS) Directive 2011/65/EU[2] is a EU directive that restricts the use of certain hazardous substances in electrical and electronic equipment (EEE). The directive aims to reduce the environmental and health risks associated with the use of hazardous substances in EEE, as well as to promote the recovery and reuse of valuable resources.

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[2] https://eur-lex.europa.eu/eli/dir/2011/65/oj accessed in March 2023.

Figure 4. RoHS compliant label

Source: certification-company.com/

The RoHS Directive restricts the use of six hazardous substances in EEE: lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB), and polybrominated diphenyl ethers (PBDE). These substances are known to have harmful effects on human health and the environment, and their use in EEE can pose a risk to workers involved in their production, users of the equipment, and to the environment during its disposal.

The RoHS Directive applies to a wide range of EEE, including large household appliances, small household appliances, IT and telecommunications equipment, consumer equipment, lighting equipment, and electrical and electronic tools. The directive places the responsibility for compliance with the restrictions on manufacturers, importers, and distributors of EEE, and requires them to ensure that their products do not contain the restricted substances above a certain threshold. The manufacturer or importer guarantees that their electrical or electronic equipment, along with its components, is free from hazardous substances by adhering to the RoHS Directive and applying the marking, shown in Figure 4.

The RoHS Directive also establishes procedures for the assessment of the compliance of EEE with the restrictions. These procedures involve the use of conformity assessment procedures, testing, and documentation requirements, and they are intended to ensure that the EEE placed on the market complies with the requirements of the directive. The directive also provides for market surveillance and enforcement measures to ensure that non-compliant products are removed from the market and that manufacturers and importers who violate the directive are subject to penalties.

The RoHS Directive is an important tool for promoting a circular economy approach to EEE. By restricting the use of hazardous substances, the directive promotes the recovery and reuse of valuable resources, and reduces the environmental and health risks associated with the disposal of EEE. The directive has also stimulated innovation and the development of new technologies that are free from hazardous substances and that are more sustainable and efficient.

However, the RoHS Directive is not without its challenges. The regulation of hazardous substances in EEE is a complex and constantly evolving issue, and the effectiveness of the RoHS Directive depends on the ability of regulators to keep pace with technological advancements and to address emerging environmental and health risks. Additionally, the implementation and enforcement of the RoHS Directive varies across EU member states, and there are concerns about the reliability and consistency of conformity assessment procedures and testing methodologies. Ongoing research and innovation, as well as continued collaboration and coordination among stakeholders, are needed to address these challenges and to promote the sustainable and safe use of EEE in the EU.

3.3. Circular Economy Package 2018

Figure 5. Circular Economy Package logo

Source: environment.ec.europa.eu

The Circular Economy Package 2018[3] is a set of legislative proposals by the European Union aimed at promoting a more sustainable and resource-efficient economy. The

[3] https://ec.europa.eu/environment/circular-economy/index_en.htm accessed in March 2023

package includes a number of measures aimed at reducing waste, increasing recycling rates, and promoting the use of renewable resources.

One of the key measures is the revision of the Waste Electrical and Electronic Equipment Directive. The new WEEE Directive sets higher collection targets for member states, with a goal of collecting 65% of all WEEE generated by 2022 and 85% by 2035. The directive also aims to increase the reuse and refurbishment of WEEE, with a target of 10% by 2030.

The revised WEEE Directive also includes a number of measures aimed at improving the traceability of WEEE and increasing the responsibility of producers for the management of their products throughout their lifecycle. This includes the establishment of a product passport for certain categories of EEE, which will provide information on the environmental performance and repairability of products.

Another key measure of the Circular Economy Package 2018 is the introduction of a set of rules on the design and production of products, known as eco-design. The eco-design rules aim to improve the environmental performance of products, including EEE, by reducing their resource consumption, extending their lifespan, and increasing their recyclability. The rules also aim to promote the use of renewable materials and energy in the production of EEE.

Also includes a number of measures aimed at promoting the use of secondary raw materials in the production of new products. This includes the establishment of a framework for the recognition of end-of-waste criteria, which will facilitate the recycling and recovery of secondary raw materials. The package also includes measures aimed at promoting the use of recycled materials in new products, including the establishment of a minimum requirement for the use of recycled materials in certain products, such as plastic bottles.

Overall, the Circular Economy Package 2018 is an important step towards a more sustainable and resource-efficient economy in the EU. The revision of the WEEE Directive, in particular, has the potential to significantly increase the collection and recycling of WEEE, as well as to improve the environmental performance and lifespan of EEE. The package also has the potential to stimulate innovation and the development of new technologies that are more sustainable and efficient. However, the successful implementation of the package will require ongoing collaboration and coordination among stakeholders, as well as continued research and innovation.

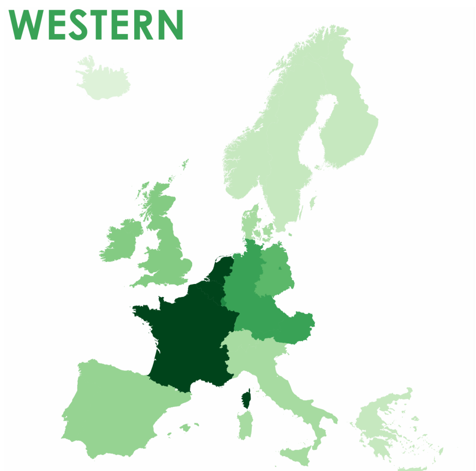
4. NATIONAL POLICIES AND REGULATIONS IN EUROPE

In recent years, the European Union has made significant progress in regulating and managing the waste of electrical and electronic equipment. However, the implementation and enforcement of WEEE policies and regulations vary among EU member states, resulting in differences in WEEE management practices and outcomes across different regions.

This section will provide an overview of the national policies and regulations related to WEEE management in five different regions of Europe, including Northern Europe, Southern Europe, Eastern Europe, Western Europe, and Central Europe. It will also highlight some of the key differences in WEEE policies and regulations among these regions. By examining the diverse approaches and practices in WEEE management across Europe, we can gain a better understanding of the strengths and weaknesses of different policies and regulations and identify areas where improvements can be made to enhance WEEE management and promote a more sustainable future.

4.1. Western Europe

Figure 6. Western Europe countries



Source: Vividmaps.com

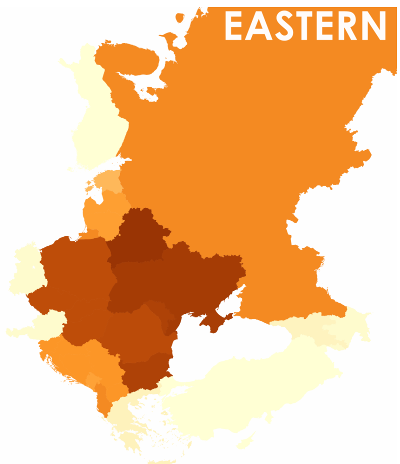
Western Europe, which includes countries like Germany, France, and Belgium, is known for having some of the strictest regulations on WEEE management in Europe. The WEEE Directive has been implemented in all Western European countries, which establishes obligations for producers, distributors, and consumers of electrical and electronic equipment. This directive mandates that producers are responsible for financing the collection, treatment, and recycling of WEEE. Many countries in this region have also implemented additional regulations beyond the WEEE Directive, such as the United Kingdom, which has implemented more stringent recycling targets for WEEE management.

One of the strengths of WEEE management in Western Europe is the high level of awareness and engagement of stakeholders in the process. Governments, producers, and consumers are generally well-informed and committed to the proper handling and disposal of WEEE. In addition, many countries have well-developed recycling infrastructure and technologies, which enable the recovery of valuable resources from WEEE.

However, one of the challenges in Western Europe is the high cost of compliance with regulations. Producers face high fees for financing the collection and recycling of WEEE, which can lead to increased costs for consumers. This cost can be a barrier for some producers, particularly for smaller businesses. In addition, illegal dumping and exports of WEEE to developing countries continue to be issues in some areas.

4.2. Eastern Europe

Figure 7. Eastern Europe countries



Source: Vividmaps.com

In Eastern European countries, WEEE management is still developing, and many countries have only recently implemented regulations for the proper handling and disposal of WEEE. The WEEE Directive has been implemented in all Eastern

European countries, but enforcement and compliance with regulations are still challenging in some areas. The collection of WEEE is often limited, and illegal dumping is still prevalent in some countries.

Despite these challenges, some countries like Poland and Romania have made significant progress in developing their WEEE management systems and infrastructure. Poland has implemented regulations for the separate collection and recycling of WEEE, while Romania has established a national collection system and has worked to increase awareness and engagement of stakeholders in the process.

One of the challenges for WEEE management in Eastern Europe is the lack of financial resources for the proper handling and disposal of WEEE. Governments and producers face financial constraints, which limit the implementation of effective WEEE management systems. In addition, the lack of public awareness and engagement can be a barrier to the success of WEEE management initiatives.

4.3. Northern Europe

Figure 8. Northern Europe countries

Source: Vividmaps.com

In Northern European countries, such as Sweden, Denmark, and Finland, WEEE management is closely linked to the concept of circular economy, with a focus on reducing waste and promoting sustainable practices. These countries have implemented strict regulations for the handling and disposal of WEEE, with some countries like Finland requiring mandatory take-back of WEEE from consumers by retailers.

One of the strengths of WEEE management in Northern Europe is the high level of public awareness and engagement. Governments and producers work closely with consumers to promote the proper handling and disposal of WEEE, and consumers are generally well-informed and committed to the process. In addition, the implementation of deposit systems for WEEE has been successful in promoting proper recycling and reducing waste.

However, one of the challenges in Northern Europe is the high cost of compliance with regulations. Producers face high fees for financing the collection and recycling of WEEE, which can lead to increased costs for consumers. In addition, the collection of WEEE can be limited in some areas, which can be a barrier to effective WEEE management.

4.4. Southern Europe

Figure 9. Southern Europe countries

Source: Vividmaps.com

The region comprises countries such as Portugal, Spain, Italy, Greece, and Cyprus, all of which have implemented the EU WEEE Directive. However, the implementation of these policies has not been consistent across the region, resulting in both high and low points.

One of the high points is the increased awareness of the importance of managing e-waste properly, which has led to the establishment of several recycling plants and programs in the region. In addition, Southern European countries have implemented measures such as extended producer responsibility and a mandatory fee for the disposal of electronic devices. These policies have helped to reduce the amount of e-waste in landfills, resulting in a lower environmental impact.

On the other hand, some countries in Southern Europe have struggled with the implementation of WEEE policies due to economic and logistical challenges. For instance, smaller countries such as Cyprus and Greece have limited resources and have faced difficulties in collecting and recycling e-waste effectively. Moreover, the lack of standardisation across the region has resulted in disparities in the application of WEEE policies.

Nevertheless, WEEE policies in Southern Europe offer significant opportunities for the region, especially in terms of the circular economy. E-waste contains valuable resources that can be recovered and reused in the production of new products. Thus, effective e-waste management can create job opportunities, reduce environmental pollution, and contribute to the region's economic growth.

In comparison to other European regions, Southern Europe lags behind in terms of WEEE policy implementation, with Northern Europe leading the way. However, there is potential for collaboration and knowledge sharing between the regions to improve the effectiveness of WEEE

4.5. Central Europe

Figure 10. Central Europe countries

Source: Vividmaps.com

Central European countries such as Austria, the Czech Republic, Hungary, Poland, Slovakia and Slovenia have implemented the European Directive to varying degrees.

The high point of the WEEE policies and regulations in Central Europe is that they have been successful in reducing the amount of WEEE sent to landfills. The EU has set a target of recycling 65% of WEEE by 2019, and some Central European countries such as Austria, have already surpassed this target. Furthermore, these policies and regulations have led to the development of a circular economy where valuable resources can be recovered and reused.

However, the low point is that some Central European countries are still struggling to meet the recycling targets set by the EU. Insufficient resources and a lack of infrastructure are some of the challenges that need to be addressed to ensure the proper management and disposal of WEEE.

Opportunities exist for Central Europe to work with other European regions to share best practices and improve the implementation of WEEE policies and regulations. Collaboration and cooperation can lead to a more efficient and effective waste management system across the continent. Moreover, the development of new technologies for recycling and recovery of valuable resources can also create new economic opportunities for the region.

As a summary we can see Chart 1 which shows a summary of the policies applied in each European region, their strengths and challenges.

Chart 1. Comparative chart of WEEE management in the different regions of the European Union

Region	Strengths	Challenges
Western Europe	- Strict regulations and obligations for producers, distributors, and consumers	- High cost of compliance with regulations
	- High level of awareness and engagement of stakeholders	- Illegal dumping and exports of WEEE to developing countries
	- Well-developed recycling infrastructure and technologies	
Eastern Europe	- Progress in developing WEEE management systems and infrastructure	- Lack of financial resources for handling and disposal
	- Implementation of regulations and national collection systems in some countries	- Limited collection of WEEE

		- Lack of public awareness and engagement
Northern Europe	- Strong focus on circular economy and sustainable practices	- High cost of compliance with regulations
	- High level of public awareness and engagement	- Limited collection of WEEE
	- Successful implementation of deposit systems for WEEE	
Southern Europe	- Establishment of recycling plants and programs	- Economic and logistical challenges
	- Extended producer responsibility and mandatory fee for disposal of electronic devices	- Lack of standardisation in the application of WEEE policies
		- Disparities in policy implementation
Central Europe	- Success in reducing WEEE sent to landfills	- Struggling to meet recycling targets
	- Development of circular economy and resource recovery	- Insufficient resources and infrastructure
		- Need for collaboration and knowledge sharing to improve policy implementation

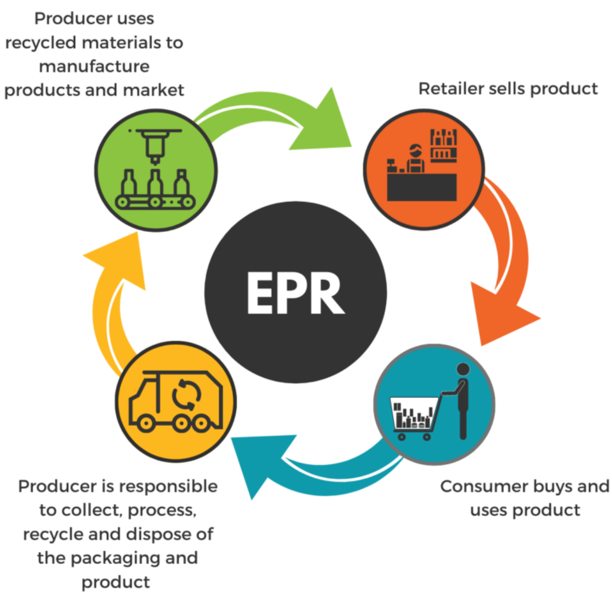
Source: Own elaboration.

In conclusion, WEEE policies and regulations in Central Europe have been successful in reducing the amount of electronic waste sent to landfills, but challenges remain in meeting recycling targets. Collaborative efforts and the development of new technologies can provide opportunities for the region to improve waste management practices and create economic benefits.

5. EXTENDED PRODUCER RESPONSIBILITY (EPR) IN EUROPE

Extended Producer Responsibility (EPR) is a key policy instrument for the management of WEEE in Europe. The WEEE Directive of the EU introduced the concept of EPR, making producers of electronic equipment responsible for the entire life cycle of their products. This includes financing the collection, transportation, and environmentally sound treatment of WEEE. EPR has proven to be an effective mechanism for promoting the sustainable management of WEEE, encouraging producers to design products that are easy to recycle and reducing the environmental impact of electronic waste. As a result, many countries in Europe have adopted EPR policies and regulations, recognizing the significant role that producers can play in promoting the circular economy and reducing the environmental impact of WEEE. In Figure 11, we can see in summary the cycle of how the product leaves from and to the producer.

Figure 11. EPR System summary



Source: www.iastoppers.com

5.1. EPR systems in Europe

In Europe, there are two main types of EPR systems for WEEE: individual and collective. The key differences between the two systems are outlined below:

- Individual EPR systems: Under an individual EPR system, each producer is responsible for financing the collection, transportation, and treatment of the WEEE generated by their products. This means that the producer must ensure that the WEEE generated by their products is collected, transported, and treated in an environmentally sound manner, either directly or through a contracted service provider. The producer is also responsible for reporting on their WEEE management activities to the relevant authorities.

- Collective EPR systems: In a collective EPR system, multiple producers of WEEE products join together to form a collective scheme. This scheme is responsible for financing the collection, transportation, and treatment of WEEE generated by the products of its members. This system allows producers to pool their resources and share the costs of WEEE management. The collective scheme is responsible for ensuring that the WEEE generated by its members is collected, transported, and treated in an environmentally sound manner. The collective scheme is also responsible for reporting on the WEEE management activities of its members to the relevant authorities.

One key difference between individual and collective EPR systems is the level of responsibility and control that producers have over the management of their WEEE. Under an individual EPR system, producers have direct control over the management of their WEEE, while under a collective EPR system, the management of WEEE is outsourced to a collective scheme.

Another difference is the costs of compliance. Under an individual EPR system, each producer must bear the full cost of WEEE management. This means that smaller producers may struggle to comply with the regulations, as they may not have the financial resources to manage their WEEE effectively. In a collective EPR system, the costs of WEEE management are shared among the members of the scheme. This can make compliance more affordable for smaller producers.

In summary, individual and collective EPR systems for WEEE in Europe have different levels of responsibility, control, and costs of compliance. However, both systems are designed to ensure that producers take responsibility for the environmentally sound management of their products throughout their entire life cycle, from production to disposal.

5.2. Producer obligations

The producer obligations under the EPR system for WEEE in Europe are outlined in the WEEE Directive of the European Union. These obligations include:

- Financing the management of WEEE: Producers are responsible for financing the collection, transportation, and environmentally sound treatment of WEEE. They must ensure that the costs of WEEE management are covered, either individually or through a collective scheme.

- Registration with a national WEEE management organisation: In some European countries, producers are required to register with a national WEEE management organisation, which manages the collection and treatment of WEEE on behalf of producers.

- Designing products for easy recycling: Producers are encouraged to design products that are easy to recycle and to reduce the use of hazardous materials. This can help to increase the recovery of valuable materials and reduce the environmental impact of WEEE.

- Meeting collection and recycling targets: Each member state of the European Union is required to set collection targets for WEEE. Producers must ensure that they meet these targets.

- Reporting on their WEEE management activities: Producers must report on their WEEE management activities, including the amount of WEEE collected and treated, and the costs associated with this.

- Providing information to consumers: Producers must provide information to consumers on the environmentally sound disposal of WEEE, including the availability of collection points and the procedures for returning WEEE.

Overall, the producer obligations under the EPR system for WEEE in Europe are designed to hold producers responsible for the entire life cycle of their products, from production to disposal. By requiring producers to finance the collection, transportation, and treatment of WEEE, and to design products that are easy to recycle, the EPR system promotes the sustainable management of WEEE and the circular economy.

5.3. Implementation of EPR in Europe

The implementation of WEEE EPR in Europe varies by country, and each country has adopted its own specific system. The steps involved in implementing a WEEE EPR system in Europe can be broadly outlined as follows:

- Develop legislation: A country must develop national legislation to implement the EU WEEE Directive. This legislation outlines the obligations of producers, the requirements for the management of WEEE, and the penalties for non-compliance.

- Choose an EPR system: The country must decide which type of EPR system to adopt - individual or collective. This decision will depend on factors such as the size of the market, the number of producers, and the available resources.

- Establish a producer responsibility organisation (PRO): If the country chooses to adopt a collective EPR system, a PRO must be established. This is an organisation that is responsible for managing the collection, transportation, and treatment of WEEE on behalf of producers.

- Develop collection and recycling infrastructure: The country must develop infrastructure for the collection and recycling of WEEE. This may involve the establishment of collection points and recycling facilities, as well as the development of transportation networks.

- Establish a monitoring and reporting system: The country must establish a system for monitoring and reporting on the collection, transportation, and treatment of WEEE. This system is used to ensure that producers are meeting their obligations under the legislation.

Each country in Europe has its own specific implementation of WEEE EPR. For example, Germany has adopted a collective EPR system, where producers are required to join a PRO that is responsible for managing the collection and recycling of WEEE. France has also adopted a collective system, while Italy has adopted an individual EPR system, where producers are responsible for managing the collection and recycling of their own products. Spain has adopted a hybrid system, where larger producers are required to manage their own WEEE, while smaller producers are allowed to join a collective scheme.

Overall, the implementation of WEEE EPR in Europe involves a combination of legislative, organisational, and infrastructural measures. The specific implementation of EPR systems varies by country, depending on the national context and resources available.

6. WEEE COLLECTION AND RECYCLING IN EUROPE

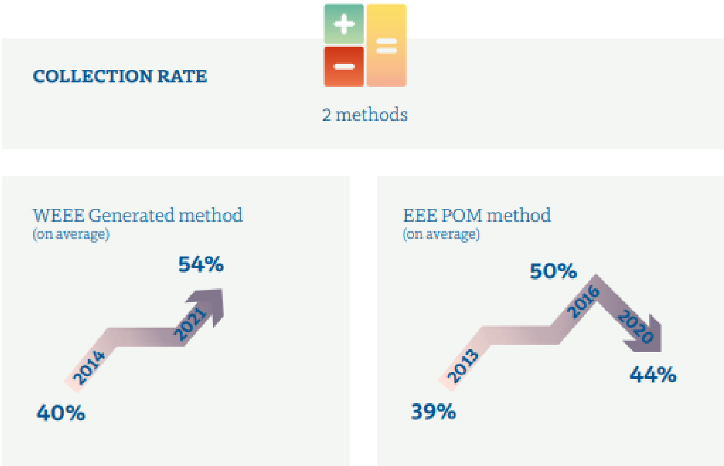
One of the key objectives of these previously mentioned policies is to promote the collection and recycling of WEEE, with specific objectives set for each member state. Methods for collecting and recycling WEEE vary by country and type of waste, but generally involve a mix of government-led programs, producer responsibility schemes, and private sector initiatives.

6.1. Collection targets

The WEEE Directive of the European Union mandates two methods for calculating the collection rate in the EU Member States, as shown in Figure 12 below. The first method, referred to as the "WEEE Generated method," involves calculating the mass of WEEE collected in a given year and dividing it by the mass of WEEE generated in the same year. Between 2014 and 2021, the collection rate using this method increased from 40% to 54%. This significant increase is mainly driven by the substantial increase in the WEEE collection compared to the WEEE Generation during the same period.

On the other hand, the second method, the "EEE POM method," calculates the collection rate as the mass of WEEE collected divided by the average amount of Electrical and Electronic Equipment (EEE) Placed on Market (POM) in the three preceding years. From 2013 to 2016, the collection rate using this method increased from 39% to 50%. However, from 2016 to 2020, the collection rate using the EEE POM method dropped to 44%. Despite the significant increase in the WEEE collection, the decrease in the collection rate is caused by even larger increases in EEE POM, causing the collection rate to decrease using this method.

Figure 12. Collection rate methods



Source: Baldé et al. (2021)

It is important to note that the two methods have their advantages and disadvantages, depending on the data available and the context. The WEEE Generated method provides a more up-to-date collection rate based on the actual WEEE generated and collected in a particular year. However, this method may be affected by factors such as the accuracy of the data on WEEE generated and the timing of the data collection.

The EEE POM method, on the other hand, provides a longer-term perspective on the collection rate and is less sensitive to short-term fluctuations in WEEE generation and collection. However, this method may be affected by factors such as the accuracy of the data on EEE POM and changes in the product mix of EEE placed on the market.

The WEEE Directive also sets specific collection targets for certain types of WEEE, including large household appliances, small household appliances, IT and telecommunications equipment, consumer equipment, lighting equipment, and electrical and electronic tools. These collection targets range from 35% to 85% of the weight of equipment placed on the market:

- Large household appliances (LHA): This includes items such as refrigerators, freezers, washing machines, and dishwashers. The collection target for LHA is 85% of the weight of equipment placed on the market.

- Small household appliances (SHA): This includes items such as toasters, vacuum cleaners, and electric shavers. The collection target for SHA is 35% of the weight of equipment placed on the market.

- IT and telecommunications equipment: This includes items such as computers, laptops, tablets, mobile phones, and televisions. The collection target for this category is 45% of the weight of equipment placed on the market.

- Consumer equipment: This includes items such as audio and video equipment, cameras, and musical instruments. The collection target for consumer equipment is 65% of the weight of equipment placed on the market.

- Lighting equipment: This includes items such as fluorescent tubes and LED bulbs. The collection target for lighting equipment is 80% of the weight of equipment placed on the market.

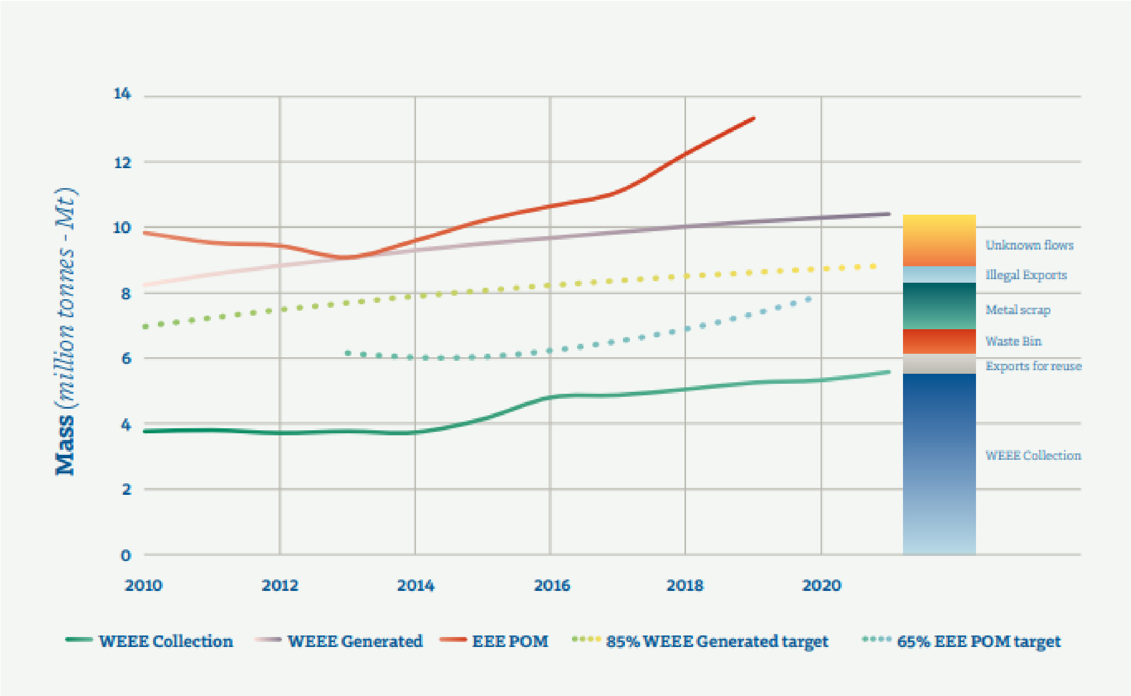
- Electrical and electronic tools: This includes items such as drills, saws, and sewing machines. The collection target for electrical and electronic tools is 50% of the weight of equipment placed on the market.

It's important to note that these targets are minimum requirements, and some EU member states have set higher collection targets for certain types of WEEE.

Governments typically rely on information reported by producers and importers to determine how much weight of appliances are placed on the market. Producers and importers are required to report the quantities of electrical and electronic equipment that they place on the market to national authorities in accordance with the WEEE Directive. The authorities then use this information to determine whether the collection targets for different types of WEEE have been met.

A study made by Baldé et al., (2021), found that EEE Placed on the Market (EEE POM) decreased from 9.8 Mt in 2010 to 9.1 Mt in 2013 and increased steadily to 13.3 Mt in 2019. However, the data for 2020 and 2021 could not be reasonably estimated with the provided data. Due to the overall increases in volumes of EEE POM in the past, the generated WEEE showed an increase of 1.8 Mt (from 8.3 Mt in 2010 to 10.4 Mt – 19.6 kg/inhabitant – in 2021). Alongside the growth of the generated WEEE, the formal collection of WEEE grew from 3.8 Mt to 5.6 Mt (10.5 kg/inhabitant) in 2021. Figure 13 provides a visualisation of the main findings of the study.

Figure 13. Development of the WEEE generated, WEEE collection, WEEE flows, and targets for the Member States of the EU-27

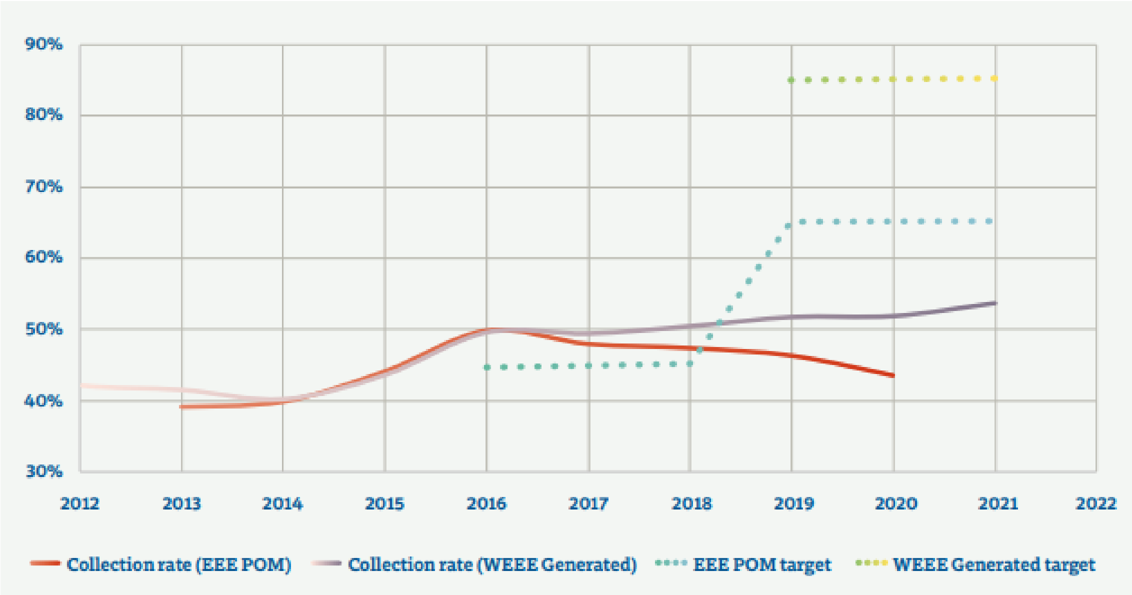


Source: Baldé et al. (2021)

The initial approach to calculate the collection rate involved dividing the mass of WEEE collected by the average amount of EEE POM in the preceding three years, which was implemented in 2016. Since then, the collection target has been determined as the ratio between the collected amount and the average weight of EEE placed on the market in the previous three years. The collection target was set at 45% for 2016 and was increased to 65% in 2019.

Figure 13 displays the progress of the collection rates for both calculation methods and their respective targets. The method that calculates the collection rate as the mass of WEEE collected in relation to the average amount of EEE POM in the preceding three years showed an increase from 39% to 50% between 2013 and 2016. However, the collection rate declined to 44% from 2016 to 2020, due to the increase in the EEE POM in the previous three years as depicted in Figure 12. On the other hand, the method that calculates the collection rate as the mass of WEEE collected in relation to the average amount of WEEE generated exhibited a steady increase from 40% in 2013 to 54% in 2021, which is attributed to the rise in WEEE collection as observed in Figure 14.

Figure 14. Collection rates in the EU-27, United Kingdom, Norway, Switzerland, and Iceland using two methods (EEE POM and WEEE Generated) and their respective targets.



Source: Baldé et al. (2021)

Based on the current collection rates, it is apparent that the region (EU-27, United Kingdom, Norway, Switzerland, and Iceland) has not met either collection target.

6.2. Collection methods

WEEE collection methods in Europe can be divided into three main categories: curbside collection, bring systems, and producer take-back systems. Curbside collection is a method in which WEEE is collected along with other municipal waste from households and transported to a central location for sorting and treatment. Bring systems involve the establishment of designated drop-off points for WEEE in public areas, such as parking lots, and households can bring their WEEE directly to these points. Producer take-back systems require producers to take back their products at the end of their life cycle and ensure that they are properly recycled or disposed of.

We will try to describe each of these methods including their advantages and disadvantages as well as seeing their contribution to WEEE collection objectives.

6.2.1. Curbside collection

Curbside collection of WEEE is an important method of waste management in Europe. It involves the collection of household electrical and electronic waste at the curbside or doorstep by designated collection trucks or municipal collection vehicles. We can see an example in Figure 15.

According to a study by Habib et al. (2021), curbside collection is the primary method of WEEE collection in the European Union (EU), accounting for approximately 50% of total collection. This is due to the convenience and accessibility of curbside collection for households, as well as the ease of implementation for local authorities. The study notes that countries such as Belgium, the Netherlands, and Sweden have particularly high rates of curbside collection.

Figure 15. Collection banks for small electrical items.

Source: www.scambs.gov.uk

Similarly, the article by Ismail and Hanafiah (2019) highlights the importance of curbside collection in the management of WEEE, citing it as one of the most effective methods for reducing the amount of WEEE sent to landfills. The authors note that curbside collection can be implemented at a low cost and can result in a high recovery rate of WEEE materials, which can then be recycled or reused. Also emphasise the need for proper segregation and sorting of WEEE materials during curbside collection, as this can significantly improve the efficiency and effectiveness of the process.

One of the main advantages of curbside collection is that it is a convenient and accessible way for households to dispose of their WEEE. By placing WEEE at the curb, people can easily get rid of their old or broken electronic devices without having to go to a special collection point. This convenience can encourage more people to properly dispose of their WEEE, reducing the amount of WEEE that ends up in landfills or illegal dumping sites.

Another advantage of curbside collection is that it allows for efficient and cost-effective collection of WEEE. Curbside collection routes can be optimised to cover a large area with minimal travel time and fuel consumption, reducing the overall costs of collection. Additionally, curbside collection can be integrated into existing waste collection systems, making it more manageable and cost-effective for local authorities.

However, there are also some disadvantages to curbside collection of WEEE in Europe. One of the main disadvantages is that it can lead to contamination of other waste streams. Improperly discarded WEEE can contain hazardous materials, such as heavy metals and toxic chemicals, which can pose a risk to human health and the environment. If WEEE is not properly sorted and handled, these hazardous materials can contaminate other waste streams, leading to additional environmental and health risks.

Another disadvantage of curbside collection is that it may not always be effective in reaching all households, particularly in rural or remote areas. Additionally, some people may still choose to discard their WEEE improperly, even if curbside collection is available, leading to potential environmental and health risks.

In conclusion, curbside collection of WEEE in Europe presents both advantages and disadvantages. While it can be a convenient and cost-effective way to collect WEEE, it can also lead to contamination of other waste streams and may not be effective in reaching all households. Therefore, it is important to implement proper sorting and handling procedures and to continue to promote awareness and education on proper WEEE disposal practices.

6.2.2. Bring systems

WEEE bring systems, also known as drop-off systems, involve consumers bringing their electronic waste to designated collection points. These collection points are typically located at municipal waste facilities, retail stores, or other public locations as we can see in Figure 16. In Europe, WEEE bring systems are commonly used alongside curbside collection and other methods to manage electronic waste.

Figure 16. Drop-off point in Spain

Source: santacruzlimpia.es

However, there are also some disadvantages associated with WEEE bring systems. One of the main challenges is ensuring that the collection points are easily accessible for all members of society, particularly those who are elderly or disabled. Additionally, WEEE bring systems may be more expensive to operate and maintain compared to curbside collection, particularly in rural areas where collection points are sparsely located.

Habib et al. (2021) conducted a study on the WEEE bring systems in the European Union and found that these systems have been effective in increasing the collection of WEEE. The bring systems involve setting up collection points at convenient locations, such as supermarkets and community centres, where consumers can bring their WEEE for proper disposal. These systems have been successful in motivating consumers to dispose of their WEEE properly, leading to an increase in the amount of WEEE collected. However, the study also notes that the effectiveness of these systems varies widely depending on the location, infrastructure, and level of enforcement. For example, some regions may have a well-established infrastructure, making it easier to implement and enforce these systems, while other regions may lack the necessary infrastructure, resulting in lower participation rates and effectiveness.

Forti et al. (2020) argue that WEEE bring systems are an essential component of the circular economy, which aims to reduce waste and promote sustainability. The study notes that the implementation of these systems can contribute to the creation of jobs and economic growth, as it requires the establishment of collection points, transportation, and recycling facilities. Moreover, the study emphasises the importance of collaboration between various stakeholders, including policymakers, producers, and consumers, to ensure the success of WEEE bring systems. Policymakers can set regulations and provide incentives to encourage the implementation of these systems, while producers can take responsibility for the collection and recycling of their products. Consumers can also play a role by properly disposing of their WEEE and supporting the implementation of these systems.

Overall, WEEE bring systems have shown to be effective in increasing the collection of WEEE in the European Union. However, the success of these systems depends on several factors, including the location, infrastructure, and level of enforcement. Additionally, the implementation of these systems requires collaboration between various stakeholders to ensure their success and contribution to the circular economy.

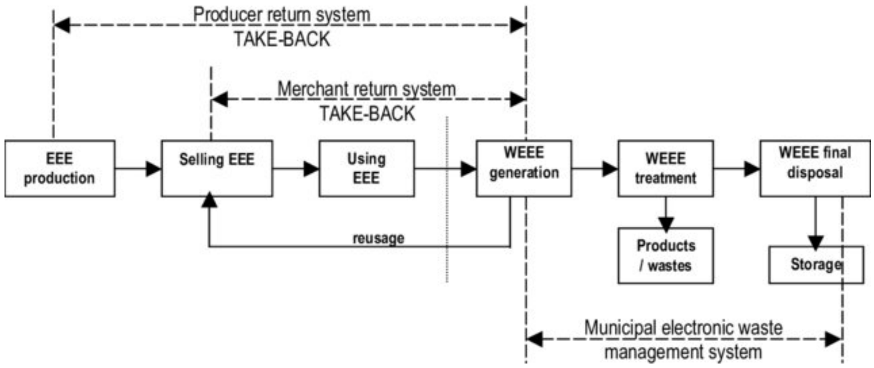
6.2.3. Producer take-back systems

Producer Take-Back System (PTBS) is a policy approach where the producers of a product are responsible for its entire lifecycle, including the collection, treatment, and disposal of the product after its use. PTBS is a common approach used in managing WEEE in Europe, where producers are required to finance and operate the collection and recycling of WEEE.

The most common policy instrument for WEEE collection and recycling in the European Union is the producer take-back system (PTBS), as pointed out by Salhofer et al. (2018). This policy approach requires producers to take responsibility for the products they put on the market and motivates them to design products that are easier to repair and recycle. The authors also suggest that PTBS can be used as a tool to encourage eco-design and extended producer responsibility.

As we can see in Figure 17, the mapping of the "collection and transportation" system to the life cycle of electrical and electronic equipment involves various components. One of the major options is the producer's "take-back" system, which can cover the entire life cycle, starting from EEE production and extending to WEEE/E-waste disposal.

Figure 17. WEEE collection and transportation systems



Source: researchgate.net

However, Nigam et al., (2021) argue that the current PTBS approach has its limitations, such as the lack of standardisation across different countries and difficulties in enforcing the policy. They propose a different approach where producers are required to design products that can be easily disassembled, repaired, and upgraded, and the responsibility of end-of-life treatment should be shared between producers and consumers.

The study by Ryan-Fogarty et al., (2019) highlights the importance of PTBS in preventing the loss of mercury from WEEE. The authors found that a significant amount of mercury is lost to the environment from WEEE in scrap metal and municipal waste, which can be prevented through the proper collection and treatment of WEEE under a PTBS approach. This indicates the importance of properly collecting and treating WEEE through PTBS to prevent hazardous substances from being released into the environment.

The effectiveness of the PTBS approach in Italy, which is largely based on the spatial access to recovery networks, was studied by Bruno et al., (2017). The authors found that the accessibility and availability of collection points play a significant role in the success of the PTBS approach. To ensure maximum coverage and convenience for consumers, collection points should be strategically located. These findings indicate that the accessibility and availability of collection points are crucial to maximise the effectiveness of the PTBS approach.

Overall, PTBS is a widely adopted approach in Europe for managing WEEE, and it has the potential to incentivize producers to design products that are easier to repair and recycle. However, there are limitations to the current approach, and there is a need for standardisation and enforcement. The effectiveness of the approach also depends on the accessibility and availability of collection points for consumers.

Below and as a summary, we can see Chart 2 where the different WEEE collection methods mentioned above are compared.

Chart 2. Comparative chart between WEEE collection methods

	Curbside Collection	**Bring Systems**	**Producer Take-Back Systems**
Collection Process	Trucks visit curbside or doorstep to collect WEEE from households.	Consumers bring WEEE to designated collection points at municipal waste facilities, retail stores, or other public locations.	Producers are responsible for collection, treatment, and disposal of WEEE.
Convenience for Households	Convenient and accessible, no need to visit special collection points.	Requires consumers to bring WEEE to designated collection points.	Consumers are not directly involved; responsibility lies with producers.
Cost-Effectiveness	Efficient and cost-effective collection, integrated into existing waste collection systems.	May be more expensive to operate and maintain, especially in rural areas.	Costs borne by producers, may incentivize eco-design and extended producer responsibility.
Collection Coverage	Covers a large area, but may not reach all households, particularly in rural or remote areas.	Depends on the location, infrastructure, and level of enforcement; may vary in effectiveness.	Accessibility and availability of collection points play a significant role in success.

Environmental Impact	Improper disposal can contaminate other waste streams, leading to additional environmental and health risks.	Proper collection and treatment can prevent loss of hazardous substances into the environment.	Proper collection and treatment prevent hazardous substances from being released into the environment.
Circular Economy	Can contribute to the circular economy by increasing recycling and creating jobs.	Essential component of the circular economy. Requires collaboration between stakeholders.	Incentivizes producers to design products that are easier to repair and recycle.

Source: Own elaboration.

6.3. Recycling targets

The Directive 2002/96/EC established the targets for the collection, recycling, and recovery of WEEE. The recast Directive (2012/19/EU) increased these targets in stages. According to Article 7 of Directive 2012/19/EU, the collection rate targets for WEEE vary depending on the reference year. Until 2015, each member state was required to collect at least 4 kilograms of WEEE per inhabitant annually from private households or the same amount of weight collected in the three previous years, whichever was greater. From 2016 to 2018, the minimum collection rate was set at 45% of the total weight of WEEE collected in a given year, expressed as a percentage of the average weight of EEE placed on the market in the three previous years in the member state concerned. From 2019 onwards, the minimum collection rate must be 65% of the average weight of EEE placed on the market in the three previous years in the member state concerned, or alternatively 85% of WEEE generated in that member state. Member states are free to choose the preferred measurement method. The minimum targets for recovery and recycling/preparing for reuse for WEEE collected separately are set separately for each category of WEEE.

Figure 18. Minimum targets for recovery and recycling/preparing for reuse for WEEE separately collected from the reference year 2019 onwards

Category of EEE	Recovery target	Recycling / preparing for reuse
Temperature exchange equipment	85	80
Screens, monitors, and equipment containing screens having a surface greater than 100 cm^2	80	70
Lamps	n.a.	80
Large equipment (any external dimension more than 50 cm)	85	80
Small equipment (no external dimension more than 50 cm)	75	55
Small IT and telecommunication equipment (no external dimension more than 50 cm)	75	55

Source: ec.europa.eu

Figure 18 provides an overview of the EU targets for the recovery and recycling of different types of WEEE. The targets are set by the EU directives and aim to increase the amount of WEEE that is recovered and recycled to reduce the environmental impact of electronic waste. Shows that the targets for the recovery and recycling of WEEE vary depending on the type of equipment. For example, the target for the recovery of small household appliances is 50% by weight, while for large household appliances, the target is 85% by weight. This is because larger appliances, such as refrigerators and washing machines, contain more valuable materials that can be recovered and recycled.

6.4. Recycling methods

WEEE recycling has become increasingly important due to the significant amount of e-waste generated globally. In recent years, various WEEE recycling methods have been developed to minimise environmental impact and to recover valuable materials from e-waste. This section will provide a detailed description of four main WEEE recycling methods: mechanical recycling, pyrometallurgical recycling, hydrometallurgical recycling and biometallurgy recycling.

6.4.1. Mechanical recycling

Mechanical recycling is one of the most widely used WEEE recycling methods in Europe, and it involves the disassembly of WEEE followed by the mechanical separation of different components. This process is often used for large household appliances such as refrigerators, washing machines, and dishwashers, which contain large quantities of metal components (Habib et al., 2021).

The mechanical recycling process involves several steps. First, the WEEE is manually or automatically disassembled to separate the different components. Next, the separated components are shredded into smaller pieces, and the different materials are mechanically separated from each other using techniques such as magnetic separation, eddy current separation, and density separation. Finally, the separated materials are processed into secondary raw materials that can be used in the production of new products (Ismail & Hanafiah, 2019).

Figure 19. PCB recycling machine

Source: www.sunygroup.cn

According to Figure 19, a PCB recycling machine is designed to recycle and separate various types of waste printed circuit boards (PCBs) that come from various electronic devices, including computers, cell phones, and televisions. The PCB recycling machine utilises a dry mechanical process, which involves shredding, crushing, and separating the materials using air gravity separation and electrostatic separation. The process starts by feeding the waste PCBs into the shredder, which breaks the boards into smaller pieces. The pieces are then fed into a crushing machine, which reduces the size of the pieces even further.

Next, the crushed PCB pieces are conveyed into the airflow separation chamber, where the airflow separates the materials based on their specific gravity. The heavier materials like metals and plastics fall down, while the lighter materials like dust are carried away by the air. After that, the separated materials are passed through an electrostatic separator, which uses an electrostatic charge to separate the metal from non-metal materials. The final products obtained are metal and non-metal powders. The metal powders can be sold directly to metal smelters, while the non-metal powders can be reused for other industrial applications.

Mechanical recycling is considered a sustainable WEEE recycling method because it reduces the amount of waste sent to landfills and conserves natural resources. In addition, the production of secondary raw materials using mechanical recycling requires less energy than the production of virgin materials, leading to reduced greenhouse gas emissions and energy consumption (Habib et al., 2021).

However, there are also some challenges associated with mechanical recycling. One of the main challenges is the presence of hazardous substances in some WEEE components, such as flame retardants and heavy metals. These substances can cause environmental pollution and pose health risks to workers involved in the recycling process. Therefore, it is important to ensure that these hazardous substances are properly handled and disposed of during the mechanical recycling process (Shittu et al., 2018).

Another challenge is the quality of the secondary raw materials produced through mechanical recycling. The quality of the secondary raw materials depends on the purity of the separated materials, which can be affected by factors such as the design of the WEEE products and the efficiency of the mechanical separation techniques used. If the quality of the secondary raw materials is not high enough, they may not be suitable for use in the production of high-quality products, limiting the economic benefits of mechanical recycling (Ismail & Hanafiah, 2019).

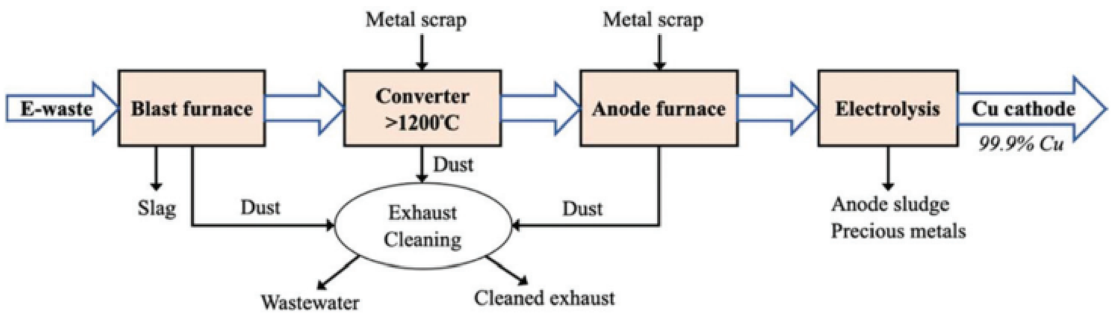
Overall, mechanical recycling is an important WEEE recycling method in Europe that has the potential to reduce environmental impact, conserve natural resources, and promote a circular economy.

6.4.2. Pyrometallurgical recycling

Among various recycling methods for WEEE, pyrometallurgical recycling has gained attention due to its efficiency in recovering valuable metals from WEEE. In Europe, pyrometallurgical recycling has been widely adopted for WEEE treatment and is regulated by the Waste Incineration Directive (WID) and the Industrial Emissions Directive (IED).

Pyrometallurgical recycling involves a high-temperature process that involves smelting and refining of WEEE components. Chen et al., (2021) investigated the possibility of handling trace elements in WEEE recycling through copper smelting, and their results suggested that copper smelting is a feasible method for the recovery of valuable metals and the removal of hazardous substances. In the process, WEEE is first dismantled, and the separated components are crushed and then fed into a smelter furnace. The smelting process involves melting and reduction of the components to obtain a molten metal alloy that contains precious metals such as copper, silver, and gold. The molten alloy is then further refined using various methods such as electrolysis and precipitation to remove impurities and obtain pure metal. The recovered metals can be sold as raw materials for the production of new electronic products, reducing the demand for virgin materials and mitigating the environmental impact of mining activities.

Figure 20. Pyrometallurgical processing scheme based on e-waste smelting process



Source: Hsu et al (2019)

In Figure 20 we can see this process where electronic waste is collected, and the valuable copper is extracted through a series of steps. First, the waste is fed into a blast furnace, where it is heated to around 1200 degrees Celsius. This causes the copper-containing materials to melt and separate from the other waste materials. The copper-rich materials are then transferred to an anode furnace, where they are further heated to remove impurities and form a copper matte. This matte is then refined through electrolysis, which involves passing an electric current through the matte to separate the copper from other metals. The copper that is collected during electrolysis is then cast into a copper cathode, which can be used for further processing or sold as a raw material. The other metals that were separated during electrolysis can also be collected and processed for further use.

Salhofer et al., (2018) compared the WEEE management practices in Europe and China and found that pyrometallurgical recycling is the dominant recycling method in Europe, accounting for over 50% of the total WEEE treatment. The authors highlighted the importance of implementing advanced smelting technologies and optimising the process to improve metal recovery rates and reduce environmental impacts. Moreover, the authors emphasised the need for strict monitoring and control of emissions and residues generated during the process to ensure compliance with the environmental regulations.

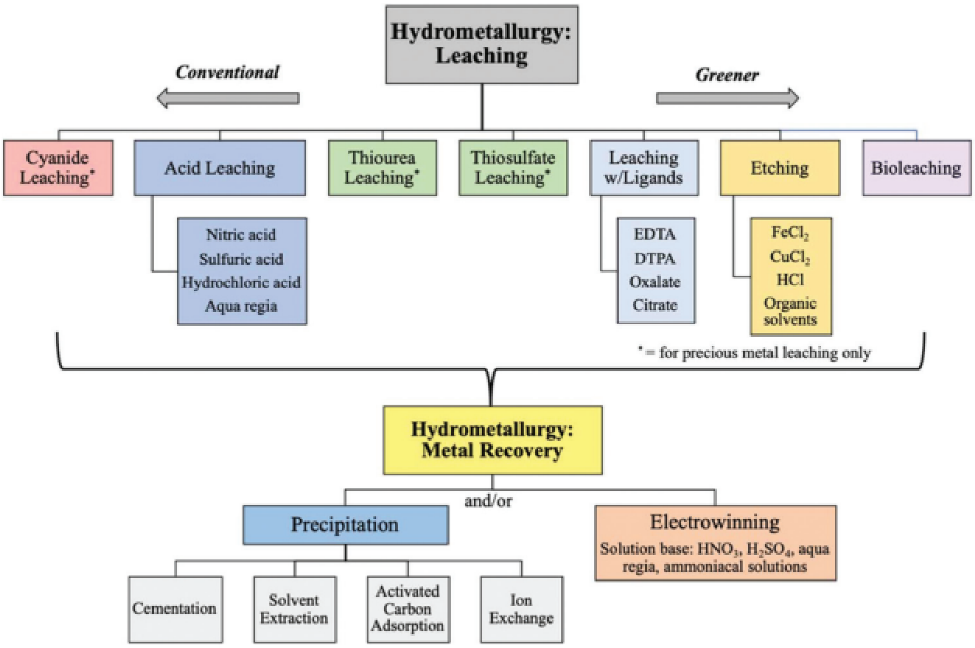
In summary, pyrometallurgical recycling is a promising method for the treatment of WEEE in Europe, and its efficiency and environmental performance can be improved through the adoption of advanced technologies and strict compliance with regulations. However, the process requires careful handling of hazardous substances and proper monitoring to prevent environmental pollution.

6.4.3. Hydrometallurgical recycling

Hydrometallurgical recycling is one of the promising approaches for the recovery of valuable metals and the treatment of hazardous components in WEEE. In Europe, the hydrometallurgical recycling of WEEE has gained increasing attention in recent years due to the implementation of the European Union directives, such as the RoHS and WEEE Directives.

The hydrometallurgical recycling process consists of several stages, including pretreatment, leaching, solvent extraction, electrowinning, and precipitation. The pretreatment stage aims to remove the plastic, glass, and other non-metallic materials from the WEEE, reducing the volume of the material and increasing the concentration of the target metals. After pretreatment, the WEEE is subjected to a leaching process using acids or other reagents to dissolve the metals. The leachate is then subjected to a solvent extraction process to separate and purify the metals of interest. The purified metals are subsequently recovered through electrowinning or precipitation, depending on the metal and the concentration in the leachate.

Figure 21. Summary of hydrometallurgical leaching and metal recovery techniques.



Source: Hsu et al., (2019)

Figure 21 illustrates the different stages of hydrometallurgy used for metal recovery from e-waste. The process involves a series of acid or caustic leaches followed by separation and purification techniques, such as cementation, solvent extraction, ion exchange, and activated carbon adsorption, to isolate and concentrate the metals from the leached solutions. Chemical leaching processes, especially acid leaching, are commonly used, and cyanide leaching is no longer considered due to its high toxicity. Thiourea and thiosulfate leaching are considered greener alternatives to caustic acid leaching. After leaching, various metal recovery routes are utilised, where precipitation is the most commonly used technique. Electrowinning shows potential as an electrochemical technique that can be staged efficiently after chemical leaching, especially through simultaneous routes of leaching and electrodeposition. Overall, hydrometallurgical techniques have gained traction, and recent research has shown that bioleaching is becoming an interesting and promising option.

The hydrometallurgical recycling of WEEE can recover several valuable metals, such as gold, silver, copper, and platinum-group metals (PGMs). The recovery of these metals can not only reduce the environmental impact of WEEE but also contribute to the supply of critical metals. Moreover, the hydrometallurgical process can also treat the hazardous components in WEEE, such as lead, cadmium, and mercury, through selective precipitation or stabilisation.

In recent years, there has been a growing interest in the hydrometallurgical recycling of WEEE in Europe. One such study by Chen et al., (2021) examined the recovery of trace elements from WEEE through copper smelting. The study reported high recovery rates for copper, gold, and silver, which are valuable metals found in many electronic devices. Another study by Tunsu and Retegan (2016) reviewed various hydrometallurgical processes for the recovery of metals from WEEE, and emphasised the importance of pretreatment and solvent extraction for the recovery of precious group metals (PGMs). This study highlighted the need for the development of more efficient and effective recycling technologies. Additionally, Habib et al., (2021) conducted an analysis of the WEEE flows in the European Union and emphasised the need for improving the collection and recycling systems for WEEE. The study noted that current collection and recycling practices are insufficient to meet the EU's goals for sustainable development and circular economy.

Although challenges remain, such as the presence of hazardous substances, European regulations have played a crucial role in ensuring the safe and sustainable management of WEEE. As such, hydrometallurgical recycling is expected to continue to play a significant role in the circular economy of electronic devices in Europe.

6.4.4. Biometallurgy recycling

The increase in WEEE generation and the need for sustainable management of these wastes have led to the development of various recycling technologies. One such technology is biometallurgy, which involves the use of microorganisms for metal recovery. Biometallurgy is a promising approach to WEEE recycling due to its eco-friendly and cost-effective nature. In this section, we will review the current state of WEEE biometallurgy recycling in Europe, its advantages and limitations, and the challenges involved.

Several researchers have reported the potential of biometallurgy for metal recovery from WEEE in Europe. For instance, Faramarzi et al., (2020) used a mixed culture of bacteria to recover copper, nickel, and cobalt from printed circuit boards (PCBs). The study showed that the bacterial consortium had a high leaching efficiency for copper (98%), nickel (88%), and cobalt (90%). Similarly, Okonkwo et al., (2021) used a mixed culture of microorganisms to recover copper, zinc, and nickel from WEEE. The results showed that the biometallurgical process was effective in the recovery of metals, with copper having the highest recovery rate of 93%.

The biometallurgical process involves the use of microorganisms to dissolve or transform metal-containing minerals into soluble forms that can be recovered. The process is divided into two main stages: leaching and recovery. In the leaching stage, the microorganisms dissolve the metals from the WEEE materials. The leachates are then processed to recover the metals in their metallic or salt forms. The recovery stage involves the use of chemical and physical methods to recover the metals.

The advantages of biometallurgy include its eco-friendly nature, lower energy consumption, and lower greenhouse gas emissions compared to conventional metallurgical processes. Additionally, it is a cost-effective process due to its simplicity and the use of microorganisms as catalysts. However, the process has some limitations, such as low leaching rates for some metals, long processing times, and the need for optimised process conditions. Moreover, the cost-effectiveness of biometallurgy depends on the availability and cost of microbial cultures, which may vary depending on the region.

In conclusion, biometallurgy has great potential for the recovery of metals from WEEE in Europe. However, more research is needed to optimise the process conditions and increase the leaching efficiency for some metals. The cost-effectiveness of the process also needs to be assessed in terms of the availability and cost of microbial cultures. Biometallurgy can complement other recycling technologies to achieve a sustainable management of WEEE in the EU.

Below and as a summary, we can see Chart 3 where the different WEEE recycling methods mentioned above are compared.

Chart 3. Comparative chart between WEEE recycling methods

Method	**Mechanical Recycling**	**Pyrometallurgical Recycling**	**Hydrometallurgical Recycling**	**Biometallurgy Recycling**

Process Description	Disassembly of WEEE followed by mechanical separation of components.	High-temperature smelting and refining of WEEE components.	Leaching of metals from WEEE, followed by solvent extraction and recovery.	Use of microorganisms to dissolve or transform metal-containing minerals for recovery.
Key Steps	1.Disassembly of WEEE components. 2. Shredding and mechanical separation of materials. 3. Processing of separated materials into secondary raw materials.	1. Dismantling of WEEE components. 2. Crushing and smelting to obtain a molten metal alloy. 3. Refining of the alloy to obtain pure metal.	1. Pre-treatment to remove non-metallic materials. 2. Leaching of metals using acids or reagents. 3. Solvent extraction and purification of metals. 4. Recovery through electrowinning or precipitation.	1. Leaching of metals from WEEE using microorganisms. 2. Recovery of metals from leachates through chemical and physical methods.
Advantages	Reduces waste sent to landfills. Conserves natural resources. Requires less energy and reduces greenhouse gas emissions.	Efficient recovery of valuable metals. Reduces demand for virgin materials. Mitigates environmental impact of mining activities.	Recovery of valuable metals. Treatment of hazardous components. Contributes to critical metal supply.	Eco-friendly and cost-effective. Lower energy consumption and emissions. Complements other recycling technologies.

Challenges	Presence of hazardous substances. Quality of secondary raw materials.	Handling of hazardous substances. Control of emissions and residues.	Presence of hazardous substances. Optimising process conditions.	Low leaching rates for some metals. Long processing times. Cost and availability of microbial cultures.

Source: Own elaboration.

7. CHALLENGES, OPPORTUNITIES AND FUTURE SCENARIOS IN WEEE MANAGEMENT IN EUROPE

In the realm of WEEE management in Europe, several challenges, opportunities, and future scenarios shape the landscape. One pressing challenge is the illegal export of WEEE to developing countries, which continues to pose environmental and health risks. Factors such as inadequate regulatory frameworks, economic incentives, lack of awareness, and corruption contribute to this issue (Oteng-Ababio, 2020). Illegal exports result in environmental damage, health hazards, and economic burdens for affected communities (Puckett et al., 2002). However, advancements in technology offer promising solutions. Laser-Induced Breakdown Spectroscopy (LIBS) enables the analysis of WEEE composition (Câmara Costa et al., 2017), while blockchain ensures a transparent and secure supply chain (Joshi et al., 2019). Supercritical carbon dioxide extraction facilitates the recovery of valuable metals (Bertuol et al., 2020). Looking ahead, three future scenarios emerge: linear growth, reactive approach, and proactive pathway (Parajuly et al., 2019). By addressing the challenges and embracing opportunities, Europe can establish a sustainable and responsible WEEE management system for the benefit of society and the environment.

7.1. Illegal WEEE exports

The European Union has implemented regulations to control the proper handling and disposal of WEEE to ensure environmental sustainability. However, the illegal export of WEEE from Europe to developing countries continues to pose significant environmental and health risks.

According to Oteng-Ababio (2020), the illegal exportation of waste electrical and electronic equipment from Europe to developing countries is caused by several factors. These include the lack of adequate regulatory frameworks, economic incentives, a lack of awareness, and corruption.

One factor contributing to the illegal export of WEEE is the lack of sufficient legal frameworks to enforce WEEE management policies in some European countries. This makes it easier for illegal exports to take place. Additionally, economic incentives have been established in some European countries to increase the cost of WEEE management, leading to companies exporting their waste to developing countries where disposal costs are lower.

Furthermore, many consumers and producers in Europe are not aware of the potential environmental and health hazards associated with improper disposal of electronic waste, which has contributed to the growth of the illegal WEEE trade. Finally, corruption may be a factor in illegal WEEE exports from Europe, with some officials susceptible to bribery or other forms of corruption.

The effects of illegal WEEE exportations from Europe to developing nations are carefully examined, according to Puckett et al., (2002). One of the primary consequences of these exports is environmental damage. Improper disposal of electronic waste can lead to soil and water pollution, which can have long-term impacts on the environment and surrounding ecosystems. This pollution can also contaminate food and water sources, which poses a significant health risk to local communities.

In addition to environmental damage, electronic waste often contains hazardous materials that can pose serious health risks to workers and local communities. Exposure to heavy metals, such as lead and mercury, can cause long-term health problems, including cancer and reproductive disorders. The informal sector in developing countries is often involved in the processing of electronic waste, and these workers may be exposed to hazardous materials without adequate protection. This puts their health and wellbeing at risk, and can have significant long-term consequences for both workers and local communities.

Illegal WEEE exports can also have economic impacts, as local communities may bear the costs of waste disposal and cleanup efforts. These costs can be significant, and may ultimately limit economic development in affected areas. In addition, the illegal WEEE trade can contribute to corruption and undermine regulatory efforts to promote sound waste management practices.

Addressing these consequences requires a concerted effort from all stakeholders, including policymakers, producers, consumers, and law enforcement agencies. By promoting sound WEEE management practices, ensuring that electronic waste is disposed of in an environmentally responsible manner, and providing adequate protection for workers and local communities, the negative consequences of illegal WEEE exports can be minimised.

7.2. Technological advancements

Technological advances in the field of WEEE have led to significant improvements in the way electronic waste is managed and recycled. The increasing amount of electronic waste generated globally has become a significant environmental concern. Hence, it is necessary to develop efficient and sustainable methods for recycling and recovery of valuable metals and other materials from WEEE. In this section, we will discuss some of the technological advancements in the field of WEEE, including their contexts and results achieved.

One of the most promising technologies in WEEE management is Laser-Induced Breakdown Spectroscopy (LIBS), as demonstrated by Câmara Costa et al. (2017). This technology offers a non-destructive and fast way of analysing the chemical composition of WEEE. In their study, the researchers used LIBS to analyse different WEEE samples, including printed circuit boards (PCBs), cathode ray tubes (CRTs), and computer mice. The results showed that LIBS can detect the presence of hazardous substances such as lead and bromine in WEEE. The authors suggested that LIBS could be an effective tool for quality control and process optimization in WEEE recycling facilities. Moreover, the technology can provide a quick and accurate assessment of the metal content in WEEE, which can help in determining the economic viability of WEEE recycling.

Another promising technology in WEEE management is blockchain, which can be used to establish a closed-loop supply chain for WEEE. Joshi et al. (2019) explored the challenges of implementing blockchain in WEEE management in developing countries. The authors argue that blockchain can help to create a transparent and secure supply chain for WEEE, thereby reducing the chances of illegal trade, fraud, and corruption. They also suggest that blockchain can enable stakeholders to trace the origin and flow of WEEE from the point of collection to the recycling facility. This transparency can help to ensure that WEEE is recycled responsibly, and valuable materials are recovered efficiently. The authors suggest that blockchain can contribute to the development of a circular economy for WEEE, which can reduce the environmental impact of electronic waste.

Supercritical carbon dioxide (SC-CO2) extraction is another innovative technology that can be used to recover metals from WEEE. Bertuol et al. (2020) discuss the use of SC-CO2 for metal recovery from WEEE. The authors argue that SC-CO2 can be a viable alternative to traditional extraction methods, such as hydrometallurgy and pyrometallurgy, which can be energy-intensive and environmentally damaging. The authors suggest that SC-CO2 can be used to extract valuable metals, such as copper and gold, from WEEE in a clean and efficient manner. Moreover, SC-CO2 extraction can also help to remove hazardous substances, such as brominated flame retardants, from WEEE, which can reduce the environmental impact of electronic waste.

In conclusion, technological advancements in the field of WEEE have led to the development of innovative and sustainable methods for electronic waste management. Laser-induced breakdown spectroscopy, blockchain, and supercritical carbon dioxide extraction are some of the technologies that have shown promising results in the analysis, management, and recycling of WEEE. These technologies can contribute to the development of a circular economy for WEEE, which can help to reduce the environmental impact of electronic waste and promote resource efficiency. Further research and development of these technologies can help to establish a sustainable and responsible electronic waste management system globally.

7.3. Future scenarios for WEEE management

According to a report published by Parajuly et al., (2019), there are three possible future scenarios for Europe regarding the management of WEEE.

The first scenario, linear growth, envisions a future in which WEEE management remains unchanged, with a continuation of the current linear growth pattern of WEEE generation and management practices. In this scenario, the EU would focus mainly on meeting recycling targets and improving collection rates, without implementing significant changes in the WEEE management system. The linear growth scenario assumes that the current legal framework will remain unchanged, and there will be no substantial technological advancements. As a result, this scenario foresees an increase in the amount of WEEE generated and a lack of infrastructure and resources for proper treatment and recycling.

The reactive approach scenario envisions a future where the EU would respond to issues only after they occur, without anticipating them. This approach would result in a patchwork of regulations and policies that address specific WEEE-related problems as they arise, without a coordinated strategy. This scenario assumes that the EU will experience moderate growth in WEEE generation and manage to meet the recycling targets, but not with optimal efficiency. The reactive approach scenario also assumes that the EU will continue to rely on the existing WEEE management infrastructure without significant changes or upgrades. As a result, this scenario could lead to an inadequate response to WEEE-related issues and a lack of innovation in the WEEE management system.

The proactive pathway scenario envisions a future in which the EU would adopt a holistic and integrated approach to WEEE management, embracing innovation and circular economy principles. This scenario assumes a reduction in WEEE generation through eco-design and sustainable consumption patterns. It also assumes a robust legal framework that promotes extended producer responsibility, eco-design, and the use of secondary raw materials. In this scenario, the EU would invest in new technologies, infrastructure, and systems for efficient and effective WEEE management. As a result, the proactive pathway scenario could lead to a more sustainable and circular economy, with reduced environmental impacts and increased economic opportunities.

In conclusion, the future of WEEE management in Europe depends on the decisions made by stakeholders in the coming years. The linear growth scenario assumes that current practices will continue, leading to an unsustainable and inefficient WEEE management system. The reactive approach scenario foresees moderate improvement but lacks a coordinated strategy. The proactive pathway scenario is the most desirable, as it embraces innovation and circular economy principles, leading to a more sustainable and efficient WEEE management system. The EU and its member states must work together to ensure a sustainable and efficient WEEE management system for the benefit of society and the environment.

8. CONCLUSION

In conclusion, this thesis has effectively addressed all the objectives set out in the introduction. It has provided a comprehensive exploration and analysis of the management of WEEE in Europe, covering various aspects related to its collection, treatment, and disposal. The significance of WEEE in Europe was clearly defined, emphasising its environmental and economic implications. The European Union directives governing WEEE management, including the WEEE Directive, RoHS Directive, and Circular Economy Package, were examined highlighting their role in shaping WEEE policies and practices.

The thesis thoroughly investigated national policies and regulations in different regions of Europe, providing an overview of the diverse approaches and practices in WEEE management across the continent. It also delved into Extended Producer Responsibility (EPR) systems, discussing producer obligations and the implementation of EPR schemes in Europe. The analysis of WEEE collection methods, targets, and recycling techniques provided valuable insights into current practices and identified areas for improvement.

Challenges, opportunities, and future scenarios in WEEE management were addressed comprehensively. The thesis highlighted the persisting issue of illegal WEEE exports, the potential of technological advancements in recycling and resource recovery, and discussed potential future developments and opportunities in responsible WEEE management.

8.1 Importance of responsible WEEE management in Europe

Effective management of WEEE is of utmost importance for the environment, human health, and the economy. The EU directives on WEEE, RoHS, and Circular Economy Package provide a strong regulatory framework for WEEE management in Europe. Extended Producer Responsibility (EPR) systems, which are implemented across Europe, have played a critical role in increasing the collection and recycling of WEEE. However, there are still many challenges that need to be addressed, such as illegal

WEEE exports, lack of awareness among consumers, and limited recycling infrastructure in some regions.

The WEEE collection and recycling rates in Europe need to be further improved, and the implementation of EPR needs to be strengthened. National policies and regulations should be harmonised to ensure consistency across Europe. Effective enforcement of regulations and continuous monitoring of the supply chain are crucial to prevent illegal WEEE exports. Moreover, the adoption of advanced recycling technologies such as biometallurgy can lead to a more sustainable WEEE management system in Europe.

8.2 Future developments and opportunities.

The future of WEEE management in Europe is full of opportunities. Technological advancements such as artificial intelligence, robotics, and machine learning have the potential to revolutionise the recycling industry and increase the efficiency of WEEE collection and recycling. The shift towards a circular economy and the adoption of a zero-waste approach can lead to a more sustainable future for WEEE management in Europe.

Moreover, the development of new business models and the emergence of circular supply chains can create new economic opportunities for the WEEE sector. Collaborative efforts between governments, businesses, and civil society can lead to more effective and sustainable WEEE management in Europe. The promotion of eco-design and the implementation of green public procurement policies can encourage the production of eco-friendly products and reduce the environmental impact of WEEE. Overall, the future developments and opportunities in WEEE management in Europe are promising and offer potential for a more sustainable future.

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