RECYCLING OF WASTE FROM ELECTRICAL AND ELECTRONIC EQUIPMENT

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Abstract of the Thesis

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Recycling gained an increasing importance due to the growing awareness of the need for a more economical and ecological future. Therefore, this thesis intended to raise awareness of recycling and to analyse the currently used methods for recycling of waste from electrical and electronic equipment. Thereby, a comparative study of Finland and Austria was conducted to evaluate the effectiveness and suitability of the used recycling methods. In addition, old electronic components were selected and analysed to determine if they were still suitable for recycling.

This thesis aimed to show the current economic and environmental situation regarding the recycling of waste from electrical and electronic equipment on a global scale, with a particular focus on Finland and Austria. By reflecting on the situation in different countries and analysing the reasons for these differences, this thesis identified the best practices and potential strategies to improve the recycling rates and reduce the environmental impact. Globally, only 22.3 per cent of e-waste was formally collected and recycled in an environmentally sound manner in 2022, which highlighted the need for improvements both in Europe and worldwide.

The main findings indicated that both compared countries had a better recycling rate than the average of the European Union. The recycling rate was calculated by comparing the total e-waste collected in 2022 to the average amount of EEE placed on the market in the last three years. Furthermore, both countries applied similar recycling techniques and shared common implementation methods. During the component analysis, an initial optical microscope inspection revealed that the components were largely intact prior to processing. Areas of interest that were identified at this stage were then further analysed by using an x-ray microscope.

Key words recycling, waste from electrical and electronic equipment, sustainability, legislations, microscopic analysis

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FOREWORD

I would like to express my sincere gratitude to the Lapland University of Applied Sciences for giving me the opportunity to write this thesis.

My special thanks go to my supervisor, Ari Pikkarainen, for his constant guidance, support and valuable feedback throughout this thesis. I would also like to thank my commissioner, Katri Hendriksson, for suggesting this interesting and highly relevant topic for my thesis. In addition, I am very grateful to Soile Sääski for her assistance with the microscopic analyses and help with laboratory equipment and procedures.

SYMBOLS AND ABBREVIATIONS

ADC	Analogue-to-Digital Converter
Billion	Defined as $10*10^9$
e-waste	electronic waste
EEE	Electrical and Electronic Equipment
ERP	Extended Producer Responsibility
EU	European Union
ITU	International Telecommunication Union
Million	Defined as $10*10^6$
WEEE	Waste from Electrical and Electronic Equipment

1 INTRODUCTION

With the increasing awareness about a circular economy and a greener, more regenerative future during these past few years recycling became more and more important to all aspects of the economy. In order to reach the European Union's goal to achieve a minimum annual collection rate of at least 65 per cent of the average weight of electrical and electronic equipment placed on the market in the last three years, or alternatively 85 per cent of all waste from electrical and electronic equipment generated, each country relies on different methods and strategies (European Union 2012). To contribute to this growing importance, this thesis will raise awareness of recycling and summarise currently used recycling methods of electrical and electronic equipment.

Due to different industries within the nations, every country focuses on different parts of recycling. This thesis aims to compare the recycling strategies of Finland and Austria, with a focus on their different approaches to the recycling of electrical and electronic equipment and the factors influencing their effectiveness.

Although Finland does recycle municipal waste, the main waste generation arises through industrial waste due to their mining industry throughout the country. In comparison Austria is one of the countries of the European Union which recycles the most from urban waste. (Yanatma 2023; European Environment Agency 2024.) Due to these different approaches a comparison between both countries will show the effectiveness and how the strategy can be implemented in another country or whether it even serves any purpose at all. Additionally, the increasing relevance of recycling and a circular economy has led to the introduction of more regulations by the European Union and individual countries.

One main aspect which also needs to be considered is the regional economy, where recycling will help to create jobs and support the local industries as well as the innovation of waste management technologies. Furthermore, the rising need of resource efficiency, energy savings and the reduction of the usage of raw materials has driven the development department to be more focused on the reuse of components.

Although the recycling process has already significantly improved during the last few years, it still needs to be continuously improved to ensure a better recovery rate of materials. One main aspect will be to make the process as economically and technically efficient as possible. Another important factor is the reduction of dependence on other countries regarding the rare metals used in the electrical and electronic components. This thesis will identify the best methods and scenarios to reduce the environmental impact of waste from electrical and electronic equipment.

2 THEORETICAL REVIEW

2.1 Definition of Waste from Electrical and Electronic Equipment

Electrical and electronic equipment, EEE, refers to products which operate with circuitry or electrical components and a power supply. They include electrical products, for example refrigerators, washing machines, hairdryers, but also smaller electrical devices like smartphones, tablets, e-cigarettes or wireless headphones. Electrical appliances are everywhere in people's everyday life. Therefore, in high-income countries the number of appliances per person is about 109 products, excluding lamps, while in low-income countries there are only four items per capita. When electrical equipment gets thrown away by its owner, without the intent to use it again, it turns to waste from electrical and electronic equipment, WEEE, or electronic waste, e-waste. (UNITAR 2024, 20-21.)

Not everything which has electrical or electronic components is officially considered as electrical and electronic equipment. For example, batteries and electrical storage devices are not declared as EEE due to their different end of life treatment. Other examples such as built-in-car electronics, military devices or space waste is also not considered as EEE. The definition of waste from electrical and electronic equipment is equally difficult. Not everything which is declared as waste is unusable. Some components are still functional or can easily be repaired, while on the other hand, not everything that can be reusable still has a market value. Another crucial point is the declaration of e-waste. For repairs and the extend of the product life, e-waste is sometimes shipped overseas. However, care should be taken to ensure that only products that can be repaired or reused are shipped, to avoid sending them to places without a real market and therefore to contribute to an increase in the global e-waste. (UNITAR 2024, 22-23.)

2.2 Historical and Current Situation of Recycling in Finland and Austria

The first directives and regulations for WEEE date back to 2002 and have been revised repeatedly since then. But even before that there were similar directives which focused on recycling in general, such as the directive 94/62/EC, which deals with packaging and packaging waste. These guidelines were the starting point for the following WEEE directives. (European Environment Agency 2024.)

The main guidelines which are currently used in the European Union are the directive of the waste from electrical and electronic equipment from 2012, 2012/19/EU (European Union 2012), guidelines for the waste framework and the waste hierarchy from prevention to elimination (European Communities 2008) and packaging guidelines (European Union 1994). These directives serve as a basis for national laws in the member states as well as a template for any amendments to these or new guidelines. (European Environment Agency 2024.)

The first guidelines on WEEE collection and recycling were incorporated into Finnish national law in 2004, in the waste act 452/2004, which revised the 1993 waste act. Afterwards there were a few changes in the waste act in 2011 and in 2014 which were implemented to meet and adapt to the standards of the WEEE directive from the European Union, 2012/19/EU. The latest amendments concern the waste act from 2014 to bring it up to date and update it to act 1026/2021. (Ylä-Mella et al. 2014; WtERT 2025.)

One of the first guidelines for WEEE in Austria has been in place since 2005, the regulation on waste of electrical equipment 121/2005. Since then, it repeatedly got adapted to the newest regulations. As in other European countries, the regulation 2012/19/EU was also implemented and has since then formed the basis for the latest amendments to the regulations. Other related directives are the waste management act, AWG 2002, the ordinance on waste electrical and electronic equipment, EAG-VO, and the waste treatment obligations ordinance. (BMLUK 2025; Bitkom Compliance Solutions 2019.)

2.3 Current Global Trends and Figures on E-Waste Recycling

2.3.1 Global Overview of E-Waste Generation and Recycling

The recovery of e-waste, the global term for waste of electronic equipment, reached around 62 billion kilograms worldwide in 2022. This corresponds to approximately 7.8 kg per capita per year. Out of this mass, only 22.3 per cent of e-waste were formally documented, collected and recycled in an environmentally safe way. In comparison, the global volume of e-waste in 2010 was only around 34 billion kg, which indicates an annual increase of around 2.3 billion kg. Similarly, the formal collection and recycling rate also increased with around 0.5 billion kg per year until it reached 13.8 billion kg in 2022. This increase indicates that the generation of the total e-waste exceeds the numbers for the formal recycling rate by a factor of almost five. (UNITAR 2024, 12; Holuszko, Kumar & Espinosa 2022, 3.)

The total amount of e-waste, 62 billion kilograms in 2022, is divided into four areas. 13.8 billion kg are collected and recycled in an environmentally safe way, about 16 billion kg are gathered and recycled outside of a formal system in high to middle income countries, 18 billion kg is handled in middle to low-income countries with no developed infrastructure and 14 billion kg are disposed of as residual waste, mostly in landfills. These numbers reveal that a large percentage of waste is still not disposed of in an environmentally friendly way and that there is still a lot of potential for improvements in the collection and recycling of e-waste. The composition of e-waste in 2022 reveals that the largest share with 31 billion kg are metals, followed by 17 billion kg of plastic and 14 billion kg of other materials, such as composite materials, alloys, glass or concrete. Out of these 31 billion kg only 19 billion kg of metals were recovered and recycled. The metals that occur most frequently in e-waste are iron with 24 billion kg followed by aluminium and copper with 4 and 2 billion kg per metal. Rare earth elements which are needed for renewable energy technologies are often only used in small quantities and low concentrations which makes them difficult to recycle. Therefore, the recycling rate for these elements is less than one per cent. (UNITAR 2024, 13, 46-49; Lapland UAS 2025, 7.)

Based on the data presented in figure 1, it can be seen that Africa has the lowest e-waste generation rate but also has the most difficulties in recycling them. Asia on the other hand generates half of the annually e-waste totally, 30 billion kg, but has due to its large population a better e-waste generation per capita than for example Europe, Oceania or America. However, due to the lack of policies, Asia still has a relatively low recycling rate. Europe, Oceania and America are the continents with the highest amount of the e-waste generated per capita. However, they are also the continents with the highest documented collection rate per capita of e-waste. This contributes to the fact that they each have an annual average formal collection and recycling rate of over 30 per cent. (UNITAR 2024, 14.)

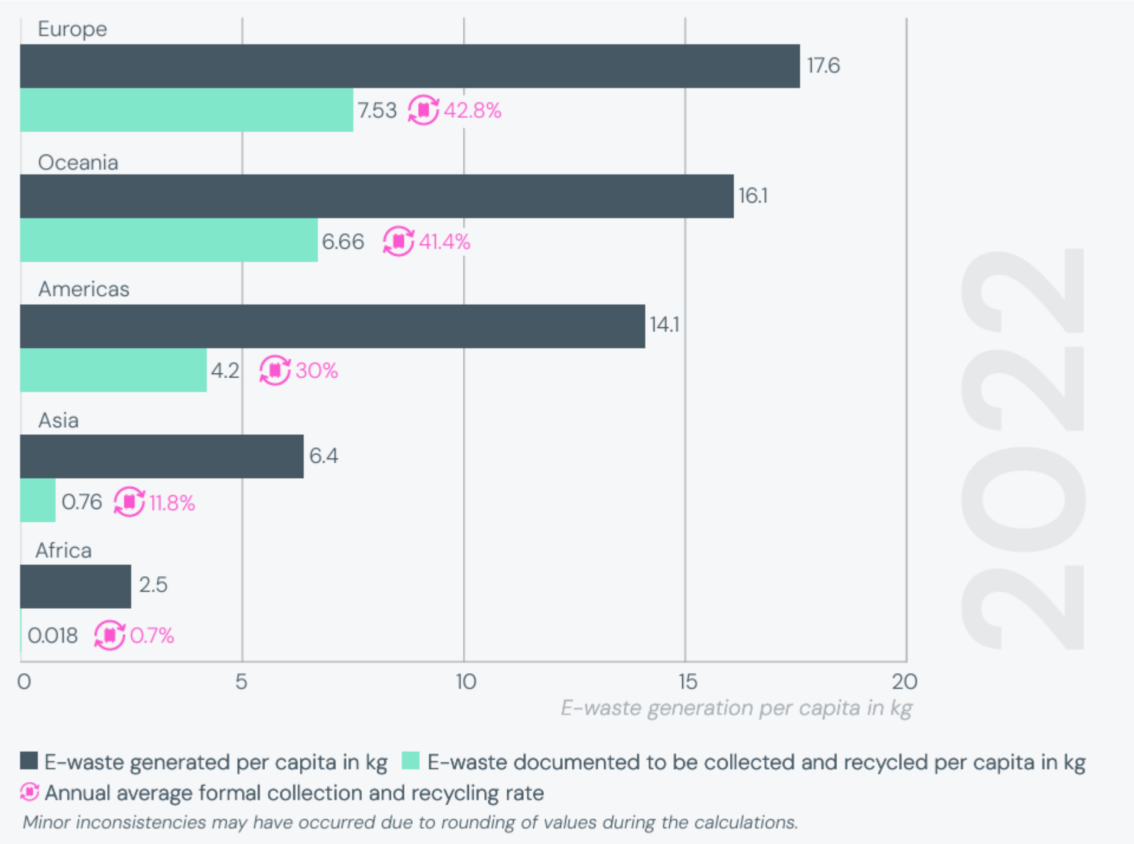


Figure 1. Amount of e-waste generated and collected in 2022 (UNITAR 2024, 14)

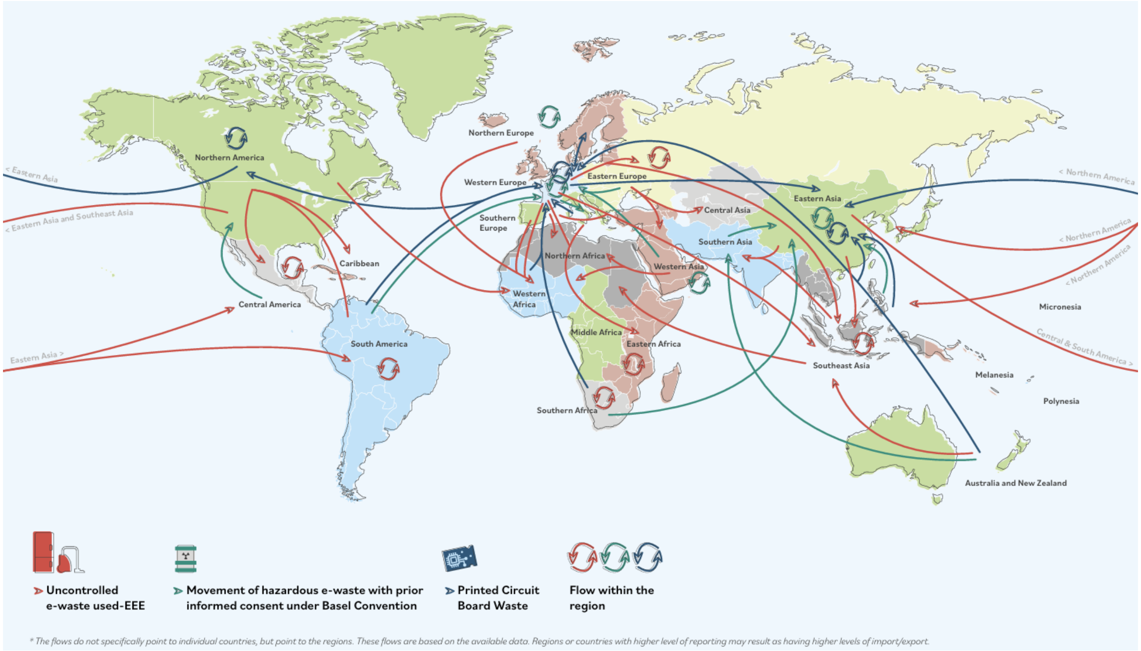
Another important point which is often overlooked is the breakdown of electronic waste. It can be recognised that one-third of e-waste, around 20 billion kg, consists of small equipment such as microwave ovens, e-cigarettes and vacuum cleaners. The problem, however, is that the recycling rates for these devices only remains at 12 per cent globally. Other smaller but slightly bigger electronic components, such as smartphones or laptops, account for around 5 billion kg and only around 22 per cent get recycled. Larger and heavier electronic parts for example monitors or cooling and freezing equipment are more frequently collected and recycled. (UNITAR 2024, 14.)

2.3.2 Global E-Waste Flow

In 2019, 5.1 billion kg of e-waste was moved between different countries. Of these, 65 per cent were transferred uncontrolled which means that the handling process was not monitored and may not have been environmentally friendly. However, there are components which are reasonably transported, for example circuit boards whose recycling facilities are located in other countries or e-waste that cannot be disposed of in its own country. The main justification for exporting e-waste is to close the digital divide between rich and poor countries. (UNITAR 2024, 40-43; Holuszko et al. 2022, 18-19; Baldé, D’Angelo, Luda, Deubzer & Kuehr 2022, 9.)

The goal of the Basel convention is the control of transboundary movements of hazardous wastes and their disposal. It was adopted in 1989 and entered into force in 1992. The reason was the public appeal to react to the discovery in 1980 of the disposals of toxic waste from other regions in developing countries. The overall goal of the convention is to protect the environment and the human health against the effect of hazardous waste. To achieve this goal, there are three main objectives: the reduction of hazardous waste generation and the promotion of an environmentally sound management system regardless of the disposal place, the restriction of transboundary movements unless it is necessary for an environmentally sound management and a regulatory system for cases in which transboundary movements are acceptable. (Basel Convention 2025.)

The global e-waste flow can be seen in figure 2, where the map shows the flows within the region, the paths of uncontrolled e-waste and used EEE, the movement of hazardous e-waste prior informed consent under the Basel convention and the path of printed circuit board waste. It can be recognised that a large amount of uncontrolled e-waste is sent from developed countries to developing regions, such as Southeast Asia, Eastern Asia, Africa and South America. An important shift, however, is the export of high-end components from regions like Australia, Africa and South America to countries with an established downstream recycling industry. This indicates that these countries are key players in the recycling process whilst also being in a challenging situation. They are focused on the separation of high value components such as printed circuit boards, hard drives and processors to send them back to developed countries while they continue to receive low value e-waste. Together with the leftovers of the high value components these countries are producing increasingly more e-waste, as they are not capable of continuing the recycling process. This results in them exporting more high value components whilst keeping the low value ones. In addition to exchanges between developed and developing countries, exchanges are also taking place between developed countries themselves and within individual regions. (UNITAR 2024, 40-43; Holuszko et al. 2022, 18-19.)



* The flows do not specifically point to individual countries, but point to the regions. These flows are based on the available data. Regions or countries with higher level of reporting may result as having higher levels of import/export.

Figure 2. Global import and export flows (Baldé et al. 2022, 13)

2.4 Significance and Importance of Recycling

2.4.1 Importance of Recycling

Negative impacts due to improper handling, in particular the release of harmful substances and greenhouse gases, need to be avoided in order to minimise the long-term impacts on human health. These indirect costs mainly concern workers and residents in developing countries. One way to prevent environmental destruction and minimising health risks is urban mining which is the extraction of resources from waste rather than from the earth's crust as in conventional mining.

A major impact of mining on human health is a respiratory disease caused by air pollution from the use of mercury to extract gold. Other problems of mining are the use of child labour and the violation of basic human rights as well as illegal mining activities and the involvement of organised crimes. Reasons as to why mining is difficult are the large volumes of difficult to extract stones which are necessary to produce a sustainable amount of metals. For example, three million kilograms of rocks must be mined to produce one kilogram of gold. This demonstrates the importance of recycling as fewer raw materials are required. (UNITAR 2024, 52-53.)

2.4.2 The Role of Circular Economy in Recycling

Circular economy and recycling are closely linked together. The main concept of a circular economy is to create a closed loop system that aims to reduce waste, reuse old components, improve the durability of products and reduce the demand for new materials. The need for a change can be seen in the global overall recycling rate, where only 9 per cent of materials are recycled back and only 14 per cent of municipal waste gets collected. However, these numbers relate to general waste streams and not specifically to waste from electrical and electronic equipment. A difference can also be seen between the categories of materials which are recycled such as paper, metals or plastics as well as the countries that recycle them. For example, the European Union has an average general recycling rate of about 43 per cent whereas China only recycles 22 per cent. (Holuszko et al. 2022, 299.)

With the increasing digitalisation more and more electronic devices get involved in our everyday business. Although the digitalisation creates many opportunities to network worldwide and access information, the recycling rate at the end of the devices service life remains negligible. While the manufacturers focus on making electronic devices more functional, they often neglect the material efficiency and the recyclability of the product. This makes it harder to create a recycling system which leads to an increasing number of devices being produced without the old appliances being recycled. (Holuszko et al. 2022, 301-302.)

The aim of a circular economy is to focus on reusing and extending the lifespan of devices. Therefore, the whole life cycle of a device needs to be changed. At first the device needs to be designed recyclable, then the use of less raw material needs to be considered and at the end of the devices lifespan there needs to be a good take-back system to ensure proper recycling. (Holuszko et al. 2022, 302-304; Alexander, Pascucci & Charnley 2023, 97-100.)

2.4.3 Economic Benefits of Recycling

The total amount of metals in e-waste had an estimated amount of USD 91 billion in 2022. Nearly half of the total value of metals came from copper, gold and iron followed by another quarter from nickel and aluminium. However, due to inefficient recycling technologies, landfilling or incineration only around USD 28 billion worth of metals were recovered and returned to the economy. The overall loss of USD 37 billion in 2022 was calculated by comparing the economic benefits with the costs associated to e-waste. The benefits were calculated with the recovery of metals and the avoided greenhouse gas emissions while the costs were measured with the treatment of e-waste along with the hidden externalised costs for the environment and human health. These externalised costs were divided into four different sections. The largest part with a value of USD 36 billion were the long-term socio-economic environmental costs caused by the greenhouse gas emissions followed by USD 22 billion for the costs of illnesses and an estimated value of working lives caused by mercury emissions. The third largest area amounting to USD 19 billion came from the compensation of plastic released into the environment. Finally, the smallest share, at USD 1 billion, resulted from lead being discharged into nature. (UNITAR 2024, 54-56.)

2.4.4 Environmental Benefits of Recycling

Conventional mining causes many serious environmental damages such as air and water pollution as well as a destruction of land and a loss of biodiversity. To reduce these damages, the recovery of secondary raw materials from e-waste plays an important role. This implies that 900 billion kg of ore were not produced by normal mining but by recovery and 52 billion kg of CO_2 -equivalent emissions could be avoided. In addition, 41 billion kg of CO_2 -eq. emissions were avoided through the proper disposal of refrigerants. However, not only CO_2 -eq. emissions should be used as a benchmark for environmental damage. The used substances also need to be considered such as flame retardants, mercury or unmanaged cooling and freezing equipment. Flame retardants have an impact of 45 million kg of e-waste plastics which are not managed under appropriate conditions and are mainly used in plastics for screens, monitors, cables and housings. Among them, brominated flame retardants are especially difficult to recycle, as they must first be separated from the plastic itself. Mercury, on the other hand, is present in lamps, screens and IT devices and is responsible for 58 tons of mercury emissions due to insufficient e-waste management. (UNITAR 2024, 52-53.)

2.5 Improvement and Outlook for the Future of Recycling

The International Telecommunication Union, ITU, is a specialised agency from the United Nations which sets global targets for the collection and recycling of e-waste. Unlike the European Union's WEEE directive, these targets are not binding. Compared to the target of the 2008 EU directive which defines a collection rate of 65 per cent of the average weight of EEE sold on the market in the previous year or the directive from 2019 which defines the target from the past three years or an alternative target of 85 per cent of the annually generated WEEE, the ITU's targets are significantly lower. The ITU aims for a collection and recycling rate of just 30 per cent. The different future outlooks for 2030, which are presented in the United Nations report with different scenarios, are summarised in figure 3. (UNITAR 2024, 58-63; Commission of the European Communities 2008, 75; European Union 2012.)

The worst scenario, business-as-usual, would not consider any changes in the behaviour. By not making any adjustments, the recycling rate would even decrease, as the rate of the e-waste production would outpace any improvements in the e-waste management. On the other hand, the progressive scenario relies on a voluntary collection scheme in countries with no current legislation to reach the 38 per cent goal. Another measure required to achieve this target would be to increase the formal collection rate to 85 per cent in countries that already have legislation and a formal collection rate for e-waste. To achieve the third scenario, a collection rate of 44 per cent, a worldwide improvement in the collection and treatment of e-waste would be necessary. Furthermore, the working conditions in the voluntary sector, particularly in low-income countries, would have to be improved. To achieve the most aspirational scenario, several changes would be required. These would include a high level of global cooperation to organise the recycling efficiently in all regions. (UNITAR 2024, 60-63.)

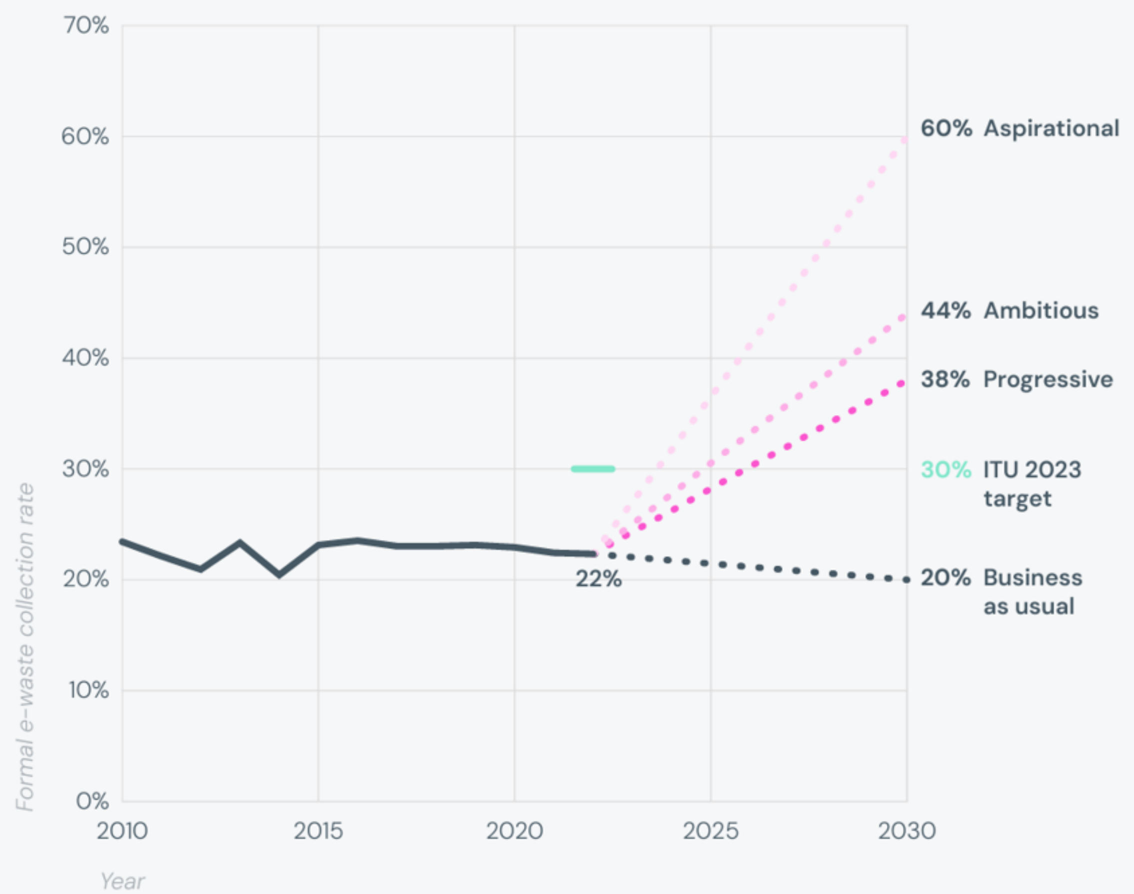


Figure 3. Possible future formal e-waste collection and recycling rates according to different scenarios (UNITAR 2024, 58)

The targets vary greatly depending on the scenario, with a difference of up to 38 billion kg, or a 40 per cent difference, from formally collected e-waste in 2030. The variations in the amount of recovered or lost metals as well as the avoided or released CO_2 -eq. emissions caused by the environmentally unsound management of refrigerants for every scenario is visualised in figure 4. (UNITAR 2024, 58-63.)

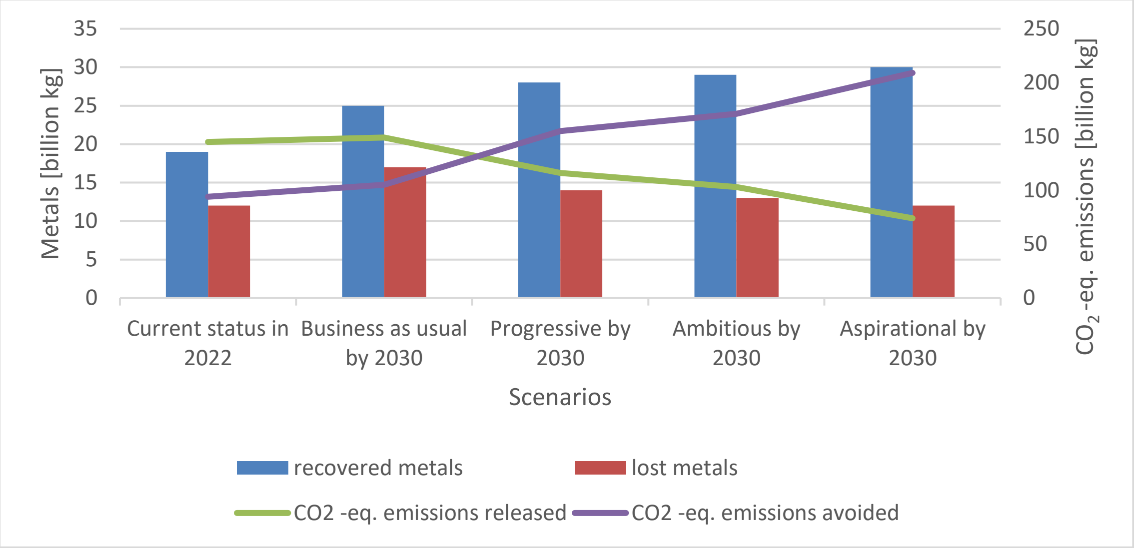


Figure 4. Recovered or lost metals and environmental impact in different scenarios (UNITAR 2024, 60-63)

One way to avoid the loss of metals is to increase the overall recycling rate to ensure that more e-waste ends up in the recycling process and therefore more metals can be recovered by optimising the recycling processes. Also, the use of informal collectors and recyclers, if they are properly trained, can help to ensure that more metals are returned to the recycling process. Similarly, the reduction of e-waste is closely connected to the recovery of CO_2 -eq. emissions. The more refrigerators and other appliances with environmentally damaging coolants are properly recycled, the more emissions can be avoided. The recycling process therefore requires less energy than the original production which indirectly contributes to the reduction of CO_2 -eq. emissions. (UNITAR 2024, 52, 58-63, 139.)

Another important outlook is the economic situation. Based on the predictions, this could result in either a minus of USD 40 billion in the business-as-usual scenario or a plus of USD 38 billion in the aspirational scenario. Even if the progressive scenario will be reached by 2030, the economic will still lose USD 4 billion. This loss will result from the value of recycling costs, environmental and health costs due to pollutant emissions, plastic pollution and refrigerants. Only from the ambitious scenario onwards the economic impact will be positive with around USD 10 billion. (UNITAR 2024, 60-63.)

3 OVERVIEW OF RECYCLING METHODS

3.1 Recycling Technologies

The different recycling methods vary between mechanical, thermal and chemical processes. The selection criteria depend on the material structure, the economic efficiency and the environmental factors. Some recycling processes for electrical and electronic waste are physical separation, pyrometallurgical processes, hydrometallurgy, biohydrometallurgy and processes for non-metal fractions. The recycling technologies can roughly be categorised into preprocessing and end processing. Preprocessing or mechanical recycling recovers the metals without destroying the nonmetal components and minimises operating costs. Physical recycling technologies consume less energy and reduce the overall mass of the devices which makes them easier to be transported. Preprocessing techniques focus on size reduction and physical separation of metals from e-waste to reduce the amount that needs to be processed in the following, more costly stages. On the other hand, end processing techniques use the recovered metals from the preprocessing stage to produce high-purity metals with the recycling methods pyrometallurgy, hydrometallurgy and biometallurgy. (Holuszko et al. 2022, 95-230.)

Pyrometallurgical processes use heat to produce liquid phases, such as molten metal which serves as reactive media to melt and dissolve WEEE, enabling the separation and recovery of valuable metals. Due to the high temperature and therefore the possibility to recover different metals at the same time, pyrometallurgical processes are an efficient method for recycling large volumes. Hydrometallurgy processes consist of chemical reactions in aqueous mediums. This involves dissolving metals from the solid material using acids, bases or other types of solvents and then recovering the metals by using various methods such as extraction or electrolysis. These processes produce less emissions than pyrometallurgical processes and are capable of an energy-efficient recovery process, even for metals in a very small concentration. Biohydrometallurgy uses microorganisms and their metabolites in aquatic environments for the processing of recovering metals from different materials. The main processes are bioleaching, biosorption, bioflotation and bioreduction which help to extract, separate and recover metals from various raw materials and waste products in an efficient and environmentally friendly method. All the non-metal parts, which amount to around 70 per cent, also need to be recycled, otherwise they will end up in landfills and cause serious environmental and health risks. Table 1 provides an overview of the various recycling methods based on the used recycling technology and illustrates the variety of processes. (Holuszko et al. 2022, 95-230; Picazo-Rodriguez et al. 2023, 2-7.)

Table 1. Detailed list of the processes of the various recycling technologies (Holuszko et al. 2022, 95-230; Picazo-Rodriguez et al. 2023, 2-7)

Recycling Technology	**Process of the various recycling technologies**
Physical Separation	Dismantling, Comminution/ Size Reduction (Shredders, Hammer Mills, High-Voltage Fragmentation, Knife Mills, Cryogrinding), Particle Size Analysis, Size Separation / Classification (Screening, Classification, Centrifugal Classifier, Gravitational Classifiers), Magnetic Separation (Low-Intensity Magnetic Separators, High-Intensity Magnetic Separators), Electrical Separation (Corona Electrostatic Separation, Triboelectric Separation, Eddy Current Separation), Gravity Separation (Jigs, Spirals, Shaking Tables, Zig-Zag Classifiers, Centrifugal Concentrators, Dense Medium Separation), Froth Flotation, Sensor-Based Sorting
Pyrometallurgical Processes	Smelting (Copper-Smelting, Lead-Smelting), Electrochemical Processes (High-Temperature Electrolysis, Low-Temperature Electrolysis), Other Operations (Roasting, Molten Salt Oxidation Treatment, Distillation, Pyrolysis)
Hydrometallurgy	Chemical Reactions, Leaching, Concentration/ Purification of metals and recovery

Biohydrometallurgy	Bioleaching, Biosorption (Biosorption via Metal Selective Peptides, Chelators Derived from Nature), Bioflotation, Bioreduction and Bioaccumulation,
Nonmetal Fraction	Physical Recycling (Size Classification, Gravity Separation, Magnetic Separation, Electrical Separation, Froth Flotation), Chemical Recycling

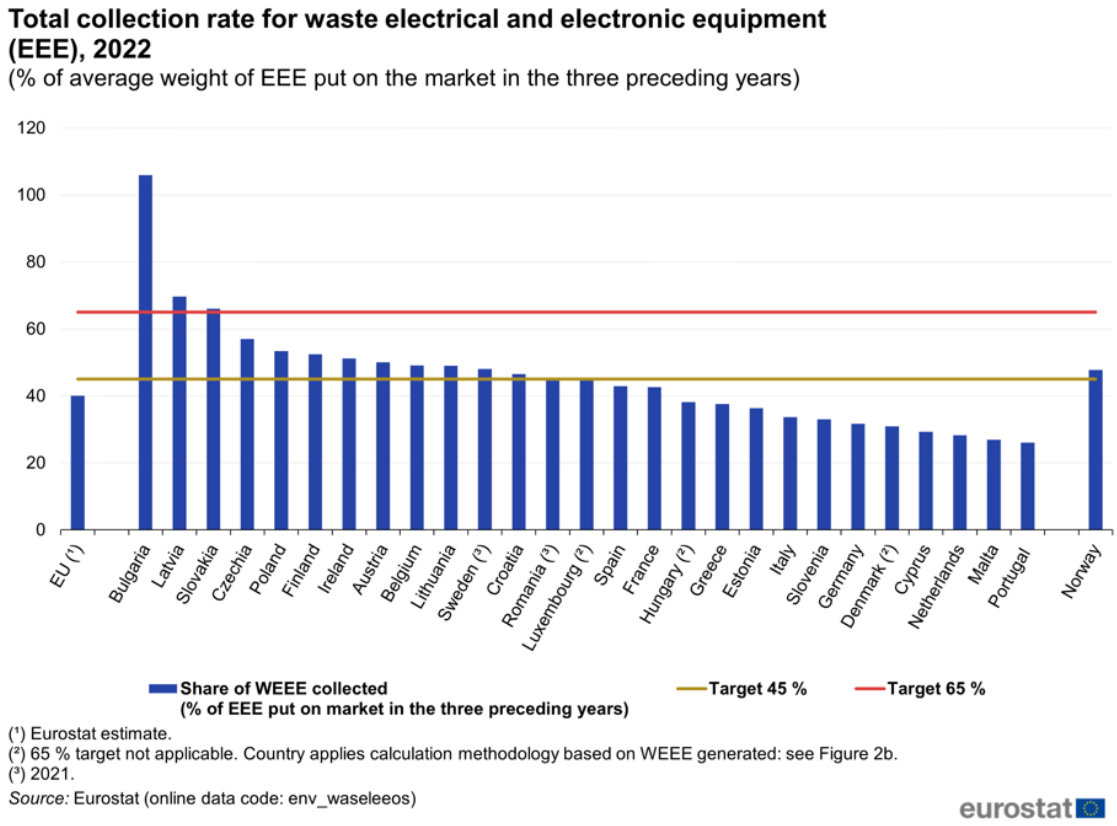
3.2 Health Consequences in Recycling

Due to pollutants and hazardous substances in electronic components a controlled and accurate recycling process is an important step to reduce health risks to the exposed persons. The risk for health consequences increases with improper disposal methods. Similarly, environmental contamination occurs when components are improperly recycled. Thereby the hazardous substances seek into the soil and contaminate the surrounding terrain. The main intake of hazardous substances occurs over ingestion, inhalation or dermal contact. In addition, there may also be a more unconscious absorption through the earth, water, food or air due to environmental contaminations. Groups of people such as children, pregnant women, seniors, people with disabilities and workers in the informal recycling industry are particularly at risk. Resulting health issues due to the exposure to heavy metals or organic pollutants from e-waste include thyroid dysfunction, lung damage, infertility, growth retardation in children and mental health disorders. In addition, DNA damage, an increased risk of cancer and the development of chronic diseases such as diabetes and cardiovascular diseases can be observed. (Grant et al. 2013, 350-358.)

4 COMPARISON OF RECYCLING RATES

4.1 Comparison of WEEE Collection Rates with Overall Recycling Rates

In alignment with data from the UNITAR global e-waste monitor from 2024, it can be seen that the collection rate of all EEE products collected in the EU over the last three years is approximately 40 per cent. The ratio is calculated by comparing the share of total e-waste collected in 2022 to the average amount of EEE placed on the market between 2019-2021. In comparison between Finland and Austria, as can be seen in figure 5, it is noticeable that Finland already has a percentual collection rate of around 52 per cent whereas Austria only lies at around 50 per cent. (UNITAR 2024, 96; Eurostat 2024.)



Total collection rate for waste electrical and electronic equipment (EEE), 2022

(% of average weight of EEE put on the market in the three preceding years)

(¹) Eurostat estimate.

(²) 65 % target not applicable. Country applies calculation methodology based on WEEE generated: see Figure 2b.

(³) 2021.

Source: Eurostat (online data code: env_waseleeos)

Figure 5. Total percentage collection rate for WEEE in 2022 (Eurostat 2024)

The total amount of general waste generated in 2020 is 116.1 million tonnes in Finland and 68.9 million tonnes in Austria. For the recycling of waste from electrical and electronic equipment, the numbers are 118 000 tonnes for Finland and 175 000 tonnes for Austria. The waste generation per capita in 2020, 4.8 tonnes per capita as an average for the European Union, results from 1.7 tonnes of waste excluding the major mineral waste and 3.1 tonnes of major mineral waste. However, in terms of waste generation per capita, Finland is the leading country of waste generated with a total amount of 21 tonnes. As for Austria, it is also above the European average with 7.7 tonnes. However, it can be seen that the distribution between both countries is different. Figure 6 shows the biggest part of waste generation per capita in Finland. It comes from major mineral waste, such as from mining, where they extract nickel, zinc, lithium, cobalt and gold from the mines. (Yanatma 2023.)

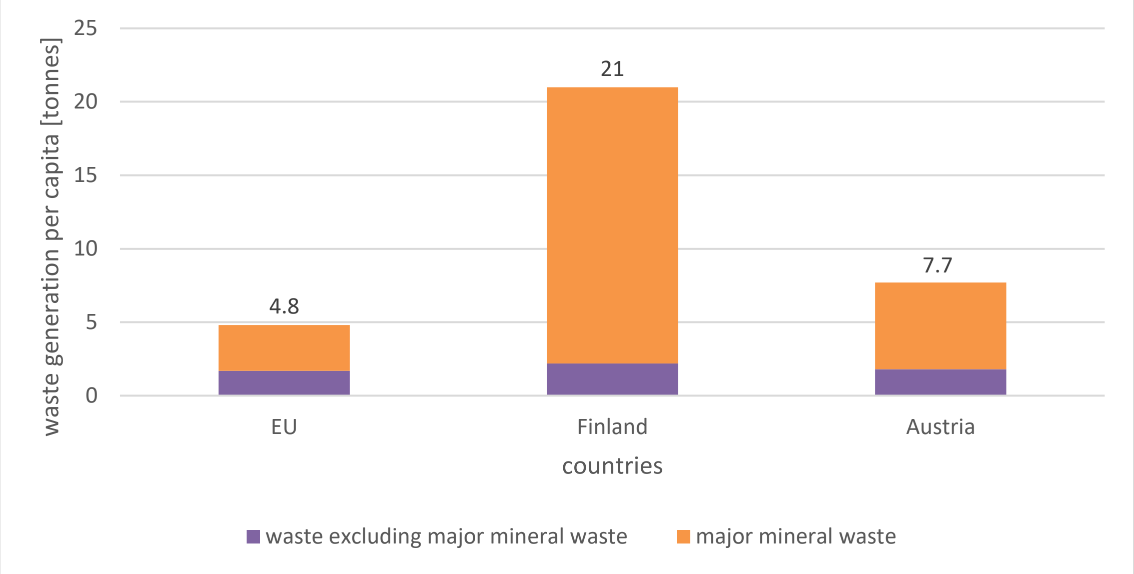


Figure 6. Compared waste generation per capita (Yanatma 2023)

While the global recycling rate of formally collected and recycled e-waste is 22.3 per cent, the normal general recycling rate in 2020 and the WEEE recycling rate in 2022 in the European Union is around 40 per cent. The recycling rate for municipal waste in the European Union in 2021 is 49.6 per cent. In Finland, the general recycling rate is 9.5 per cent, while the recycling rate for municipal waste in 2021 is 37.1 per cent. In comparison, Austria has a normal recycling rate of 34 per cent in 2020 and 62.3 per cent for municipal waste in 2020 since the data for 2021 is not available. (Yanatma 2023; Eurostat 2024.)

4.2 Implemented Recycling Systems

The Finnish recycling system varies depending on who is responsible for the waste. If the waste comes from private households, it is reused at the second-hand market and can become a device in a private household again. If the waste is not reused, it can be returned to different collection points, such as mobile collection points, permanent collection points, receptions in stores or B2B collection points. From there, they are then further sorted and processed in pretreatment plants before being returned to the second-hand market or categorised as recoverable, hazardous or disposable material and treated accordingly. The other alternative options include contracting private service providers for waste management, or producers fulfilling their extended producer responsibility, EPR, individually. From there, the waste is returned to the cycle of sorting and pretreatment. This cycle can be seen in figure 7. (Ylä-Mella et al. 2014, 6-7.)

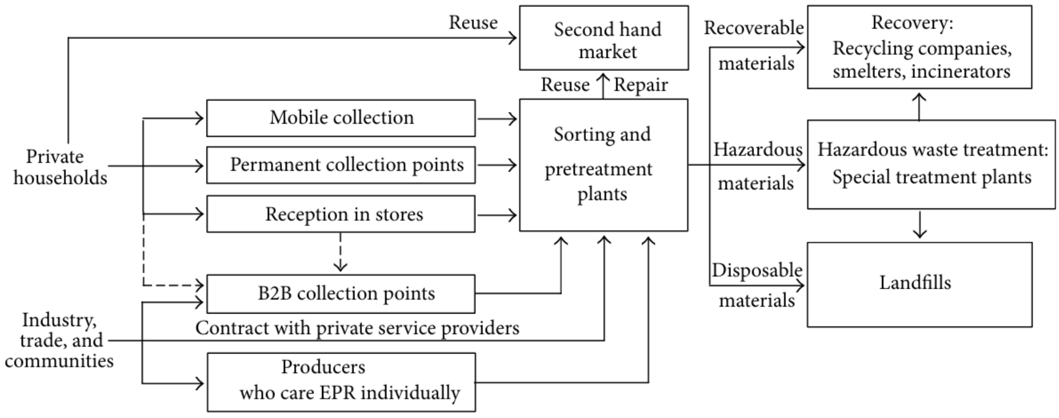


Figure 7. The main stages of the WEEE recovery system in Finland (Ylä-Mella et al. 2014, 7)

From the collection points, the waste is then first taken to regional sorting and pretreatment stations where it is manually separated. Reusable parts are then manually sorted, stored and forwarded, while recyclable appliances are sent directly to pretreatment processes. In the pretreatment process, WEEE is manually disassembled to fulfil the requirements for selective treatment for hazardous material. These hazardous materials must be removed before the actual treatment of WEEE. After the manual sorting and crushing, the material is then mechanically sorted before it is sent to recycling. Some materials are transported to smelters for further processing or used as energy in incinerators. Other methods for materials which cannot be processed are treatments in a physiochemical treatment plant or disposal in special landfills. (Ylä-Mella et al. 2014, 8.)

Similarly, the main recycling method in the Austrian recycling system is the removal of harmful substances. This involves manual dismantling with a screwdriver, hammer and pliers or mechanical dismantling methods followed by manual sorting. The second major method is the recycling of old appliances, which can then be resold on the second-hand market, the internet or flea markets. In addition, there are mechanical treatment processes including separators, recycling of metals and plastics, thermal treatment of hazardous waste and special processes for refrigerators and monitors. Likewise, attention is paid to fair storage and transport conditions as well as the export of certain fractions. (Tesar & Öhlinger 2008, 11-21.)

These recycling efforts are also reflected by the approaches of the Austrian companies to incorporate the concept of a circular economy. Surveys done by the Austrian federal ministry show that the biggest strategy for implementing the circular economy are repair and reuse. This is followed by the strategies of a circular design, resource-efficient production and material recovery. According to the survey, the strategies of remanufacturing or new business models are not as relevant. This company survey provides a good indication of how the current strategies are being accepted and perceived as important in the economy. The assessments of the importance of the various circular economy strategies for specific business sectors are presented in figure 8. It is possible for the companies to make multiple selections. (Granzer-Sudra, Pollak, Reinberg & Wagner 2024, 35-36.)

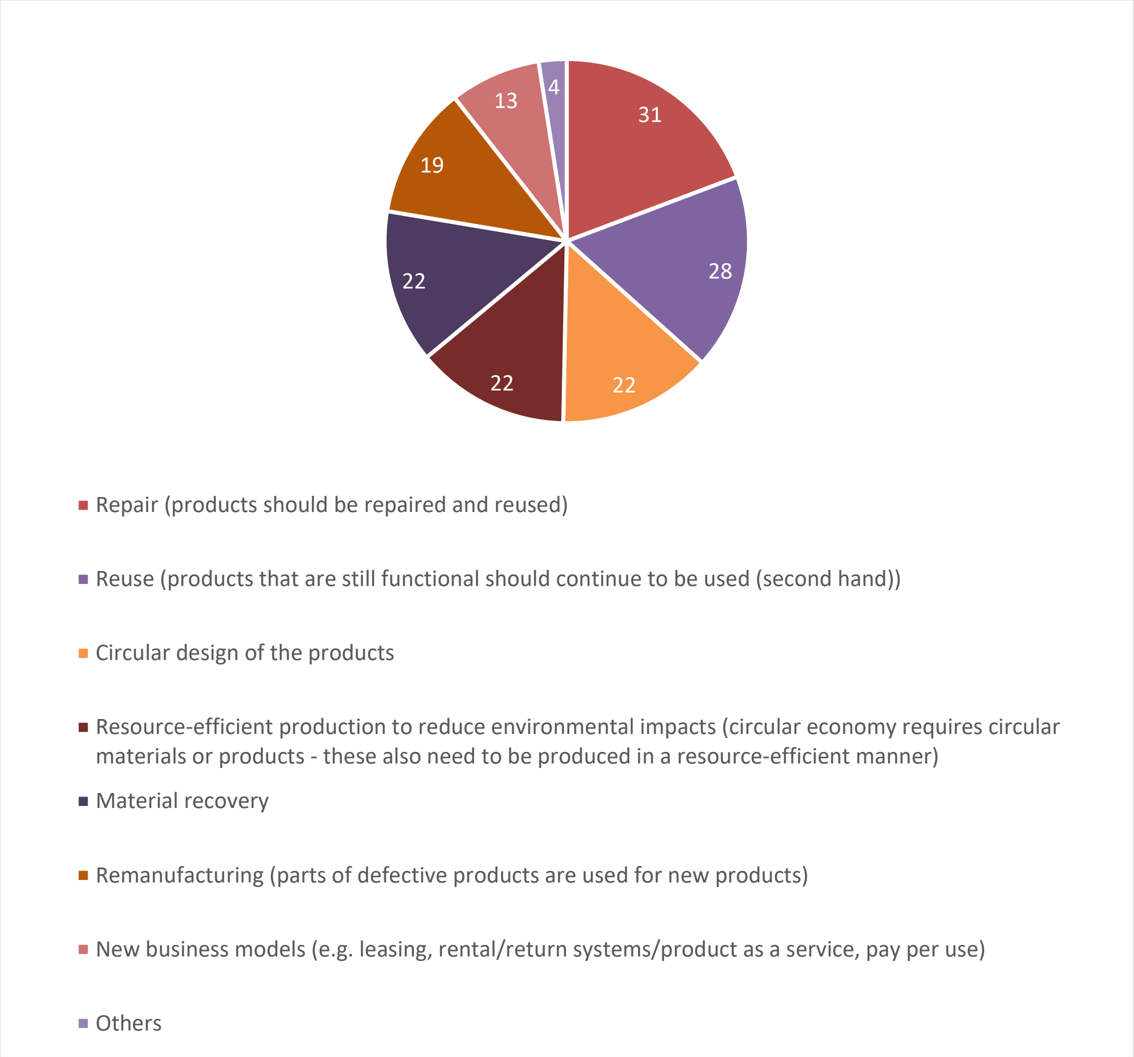


Figure 8. Assessment of the importance to companies of the various circular economy strategies for the electrical, electronics & information and communication technologies sectors (multiple selection possible) (Granzer-Sudra et al. 2024, 35)

The overall WEEE recycling process follows general process steps that are applied similarly in several countries and therefore represent a largely standardised procedure. After collection of the old devices, they are first manually sorted into specific product groups or forwarded directly to specialised recycling plants. The appliances are then passed on if they are still functional or if the capacities, technical capabilities or permits of the primary treatment plant are exceeded. Equipment that is accepted for further processing undergoes systematic pre-sorting and is prepared for dismantling. In the dismantling phase the individual components are separated in a specific manner. Depending on the type and purity of the material, the material is either reused, recycled for material or energy recovery or, if recycling is not technically or economically suitable, sent for environmentally friendly. The whole recycling process is illustrated in figure 9. (Gramatyka, Nowosielski & Sakiewicz 2006.)

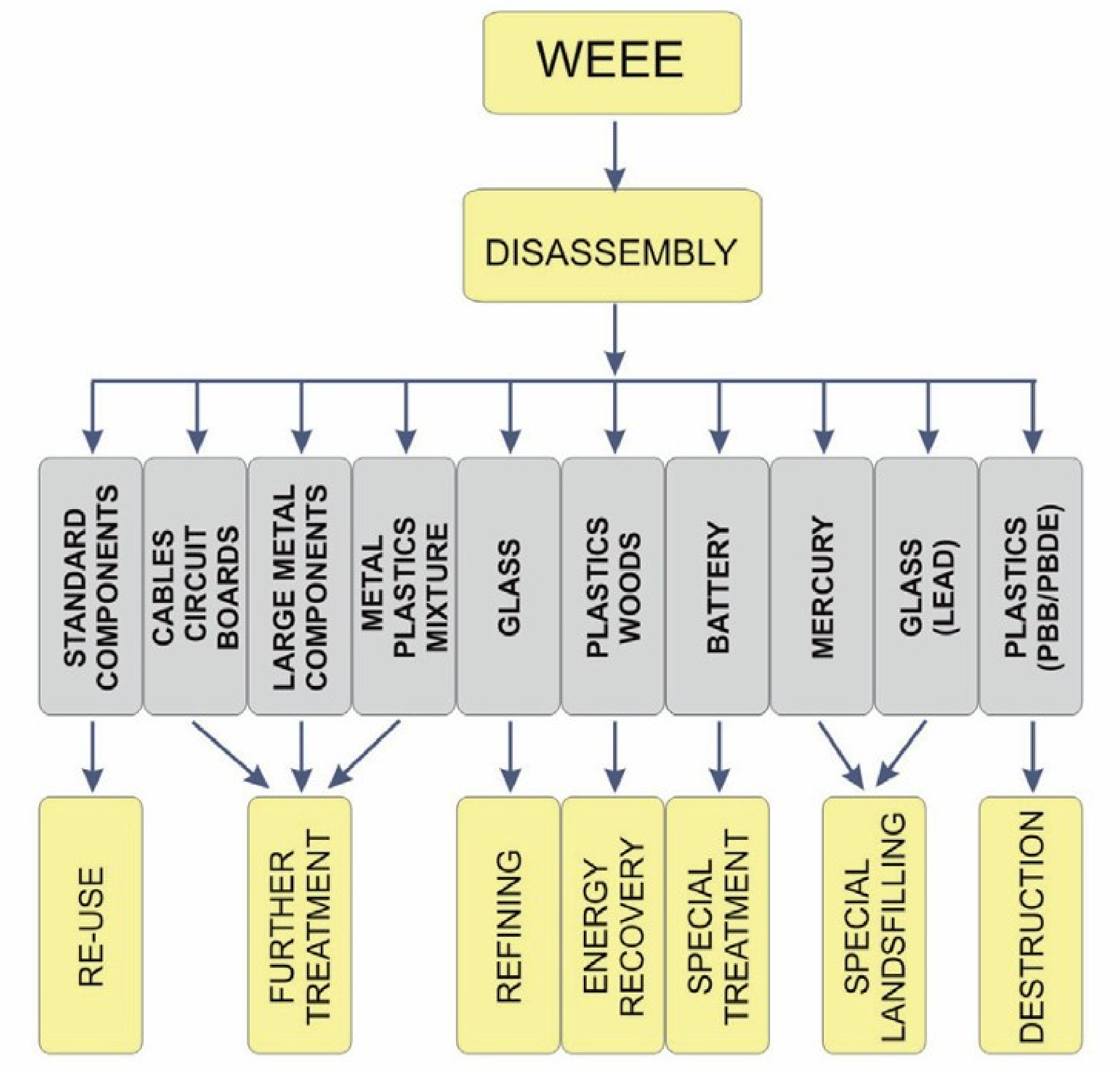


Figure 9. Typical WEEE recycling process (Gramatyka et al. 2006)

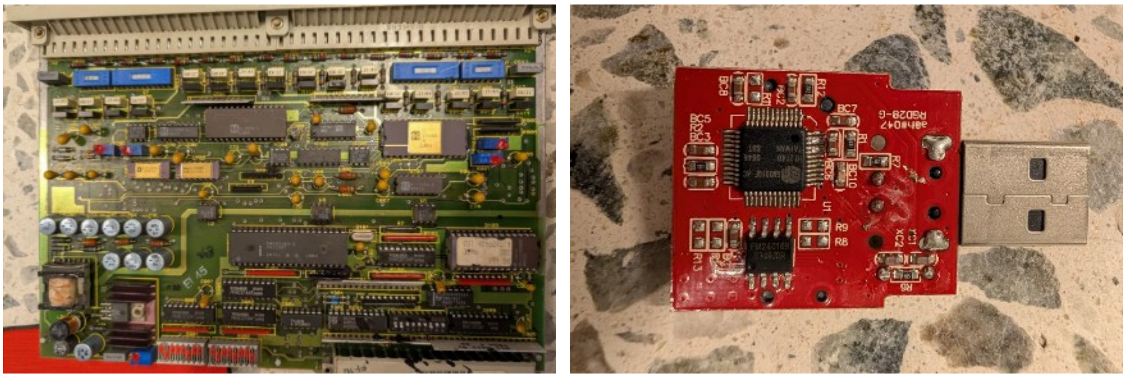
5 METHODOLOGY

5.1 Selection of Electronic Components for Visual Inspection

The analysed components for the visual inspection of material wear on old electronic components were selected according to availability. However, it was desirable for the components to be old and preferably damaged. This meant that the devices no longer operated. Unfortunately, the exact reason why the devices no longer worked could only be assumed and was probably not due to defects in the electronic components.

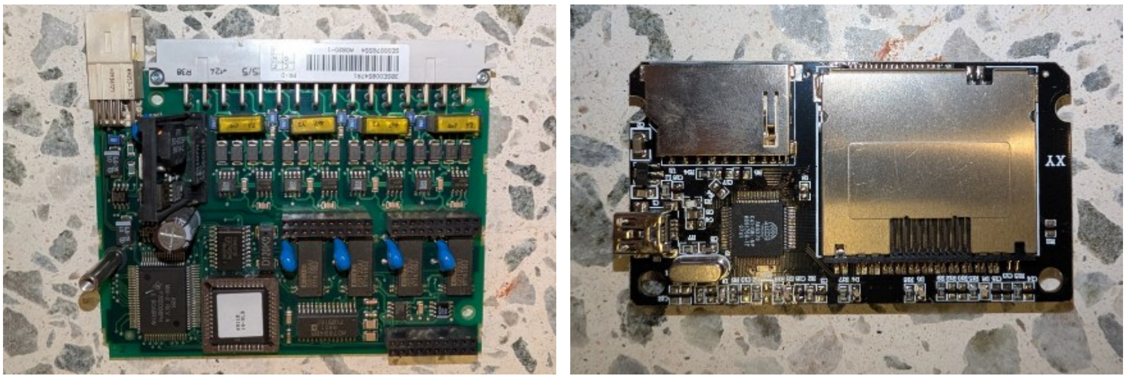
In total there are five old electronic components which were examined under the Leica MZ16 stereomicroscope, an optical microscope for small magnifications. This microscope features a zoom magnification range from 0.71x to 11.5x and was used in combination with two different auxiliary objectives, the PLANAPO 1.6x and the PLAN 0.5x. The PLANAPO 1.6x objective was used to increase the magnification for a more detailed view, while the PLAN 0.5x magnification was chosen to achieve a wider field of view. To capture good images of the components, the LEICA MC170 HD microscope camera was attached to the microscope. Therefore, the images of the components could be captured with the corresponding software, the Leica Application Suite. Furthermore, noticeable areas which could not be observed easily with the light microscope were examined with the x-ray microscope, phoenix nanome|x to see inside the components.

The first analysed component, the Siemens Simatic 6ES5 466-3LA11, appears to be an analogue input circuit board which may have previously been installed in automation technology applications. It is not known whether the board was still functioning at the time of removal or whether it was already defective. The second provided device is an old Lexar USB 2.0 SDHC reader that was previously used as a personal device. Its functionality could not be determined at the time of analysis, but it was stated that it was no longer working. In addition to the previously mentioned components, a third component was also made available for examination. This component is another circuit board, from the company ABB, which consists of two smaller boards that were plugged together. It is assumed that it was also used in the industrial automation technology sector. The fourth component is a Gembird USB 2.0 all-in-1 card reader, which was used to read several memory data formats via a USB interface. The assumed failure of this device was presumably a system error. The last component is a circuit board which was already cut in half in order to see the different layers of the board. All the analysed components can be seen in Figure 10 a-e.



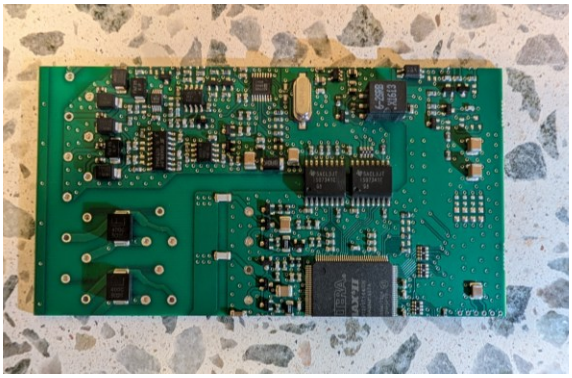
a) Siemens Simatic circuit board

b) Lexar USB 2.0 SDHC reader



c) ABB circuit board

d) Gembird USB 2.0 card reader



e) Circuit board

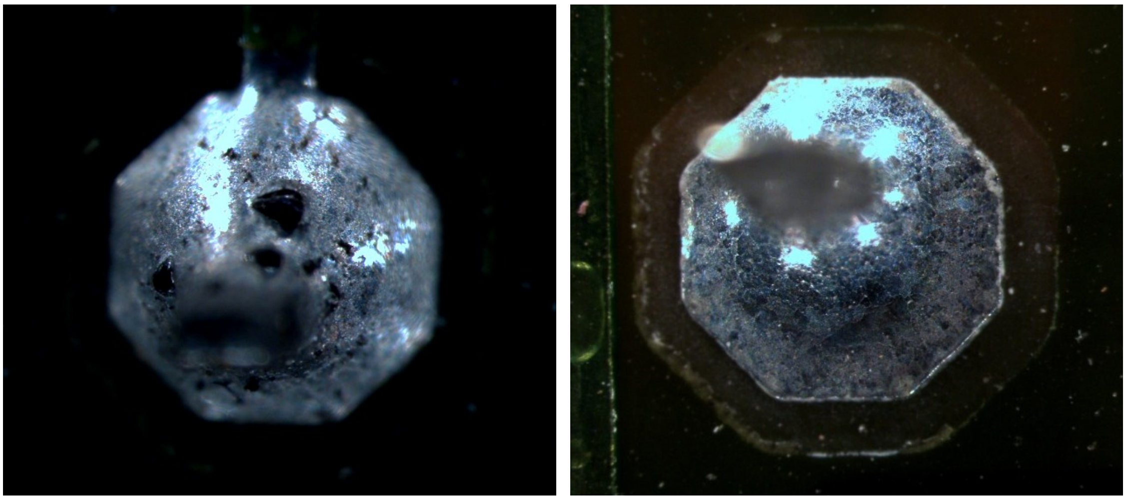
Figure 10. Pictures of the components

5.2 Inspection of Old Electronic Components Prior Further Processing

Because the components had already stopped functioning before they were selected, a microscopic investigation was performed to determine the possible cause of failure. During this analysis both auxiliary objectives as well as various zoom magnifications were used in order to be able to view everything as accurately as possible. In addition to the light microscope, an x-ray microscope was also used to allow for a non-destructive internal inspection. To be able to compare the results in the best possible way, the analysis focused on various selected positions on the components before and after the processing.

5.2.1 First Component: Siemens Simatic Circuit Board

In Figure 11 a-b, on the first selected position of the first component, it could be seen that the contacts on the back have a slightly greyish discolouration and an uneven surface which may indicate signs of pitting corrosion or oxidation. Possible reasons for these assumptions could be the soldering process or a higher thermal exposure due to overheated components on the front side.



a) with greyish discolouration b) without greyish discolouration

Figure 11. Contacts from the back of the Siemens Simatic circuit board

The second selected position are resistors in the top left corner on the frontside of the circuit board. The resistors R524 and R504 and their solder joints were examined more closely. In addition, the capacitor C33 was also selected to be analysed. The last component which was viewed was the analogue-to-digital converter, HI1-574AKD-5, in the top right corner on the frontside of the component. Except than in the first selected position, the contacts, no material wear or failures could be detected.

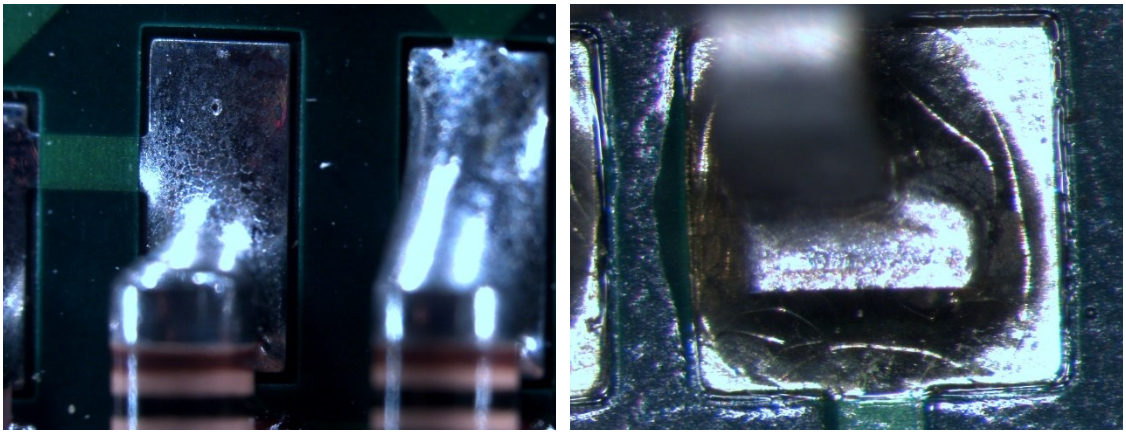
5.2.2 Second Component: Lexar USB 2.0 SDHC Reader

The second component was also examined on the front and back. However, there weren't any apparent signs of defects. The overall inspection showed no signs of any breakage in the solder joints or on the entire part. Similarly, there were no signs of any individual parts overheating. Only some minor surface irregularities, at the back of the device at some solder joints could be found and visualised in figure 12.

Figure 12. Material degradation on the back of the Lexar USB reader

5.2.3 Third Component: ABB Circuit Board

Because the third part, the ABB circuit board, consisted of two circuit boards which were assembled together, it had to be dismantled first before it could be inspected. The boards showed no severe signs of corrosion, some other defects or any broken components. Externally, the items appeared to be in an overall good condition, but it too was supposedly broken. As can be seen in figure 13 a-b, there are no major defects recognisable which could be an indication as to why the device is not working anymore. The only minor defects that have been found is a small, localised hole at the soldered joint as well as a few small cracks in other areas.



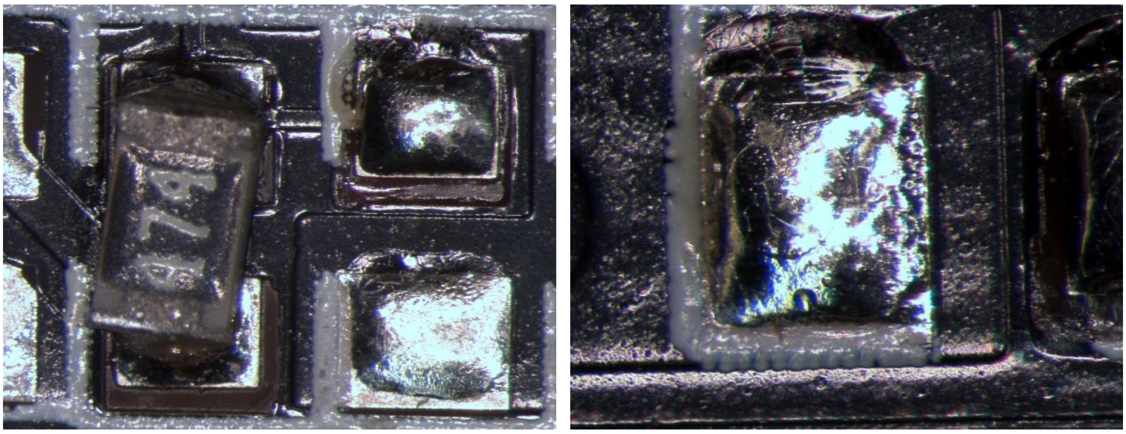
a) small localised hole at the soldered joint

b) cracks at the joint

Figure 13. Findings on the ABB circuit boards

5.2.4 Fourth Component: Gembird USB 2.0 All-in-1 Card Reader

The fourth component, the Gembird USB card reader, was also inspected on the front and back. Whilst no obvious causes for the damage could be found on the component, which would confirm the suspicion of a system error, there too were various points selected for further inspection. Although no major damage could be detected, it was found that one solder joint had been soldered on at an angled position, although it is not known whether that was intentional or not. Also, some cracks had formed at the solder joints, which can be observed in figure 14 a-b.



a) angled position of a resistor   b) cracks at the joint

Figure 14. Findings on the Gembird USB card reader

5.2.5 Fifth Component: Circuit Board

The detailed information about the manufacturer or the prior application of the last component is not known. It is a circuit board which was already cut in half in order to investigate the different layers of the component. Therefore, the board was not examined for further damaged areas on the surface, as the focus of the investigation on this component was on the different layers and the material in between.

5.3 Controlled Damage of Electronic Components

As all the components, except the last component, were in an already good condition and no major defects were detected during the microscopic analysis, the first four components were intentionally exposed to different stresses. One test was that the components were bent to see if the solder joints would break or form cracks. Furthermore, certain components, such as capacitors or resistors on the circuit boards, have been additionally exposed to an overload to test their resistance. To simulate a realistic situation, some of the parts were also dropped down or tested to potentially withstand a certain weight load, if someone were to accidentally step on them. This can particularly occur for USB readers as they are smaller and more mobile and therefore have to withstand a larger amount of external stress. For the bigger parts, it was assumed that the connections on the devices could potentially be bent and therefore be damaged during their normal usage. The method used for controlled damage to the individual devices is listed in more detail in the following table 2.

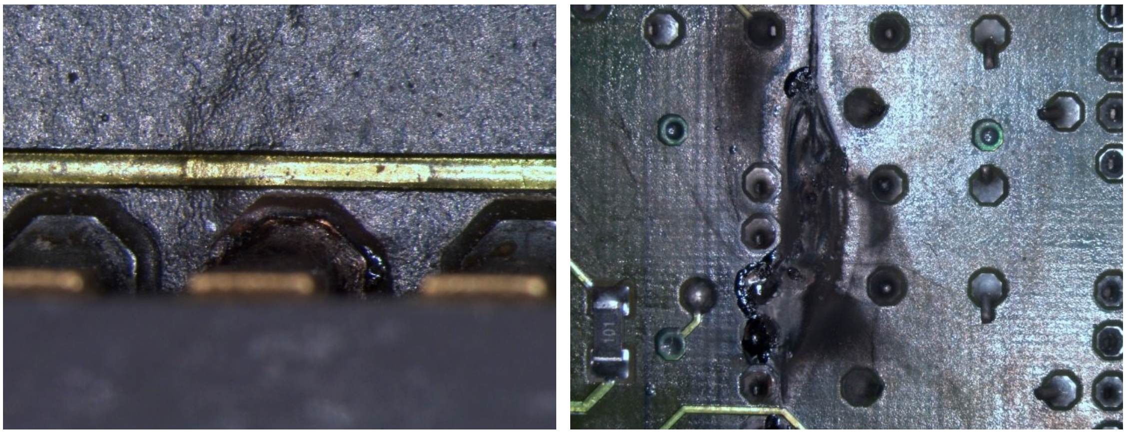
Table 2. Overview of the used method for controlled damage

	components			
Used Method of controlled damage	**Siemens Simatic circuit board**	**Lexar USB 2.0 SDHC reader**	**ABB circuit board**	**Gembird USB 2.0 all-in-1 card reader**
Bending			x	x
Dropping		x		x
Weight load		x		
Overload	x	x		

6 RESULTS

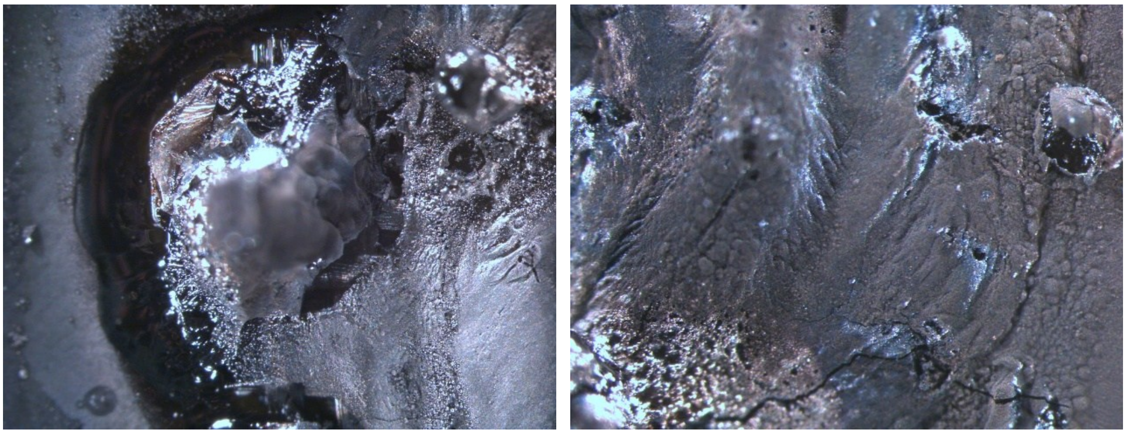
6.1 First Component: Siemens Simatic Circuit Board

To investigate the response of various components to overloading conditions, different locations on the circuit board were chosen to demonstrate the influence of the applied current. First, the resistors R524 and R504 were overloaded by soldering the power supply directly to the contacts of the resistors on the back of the board. However, no visible changes on the resistor or the solder joints could be observed, the assumption is that the power source wasn't strong enough to affect the resistors. Subsequently, the power supply got soldered onto the contacts on the back of the capacitor. During the power input, a slight expansion of the capacitor was observed indicating a physical reaction to the applied current. However, once the power was cut off, the capacitor returned to its original shape. It is assumed that the amount of current was not large enough. For the final test involving this component, the power supply was soldered onto another, smaller capacitor. This was to assess whether the reduced size of the capacitor would result in a different reaction to the applied current. As a result, it was observed that the capacitor exploded as soon as the power supply was turned on, causing a small electric fire in the nearby analogue-to-digital converter, ADC. This resulted in some damages to the nearby components that can be visualised with an optical microscope. They include burnt areas on the front and back of the circuit board as well as burnt contacts and a melted material surface on the underside of the board. The damage is documented in the figure 15 a-d.



a) Frontside of the burnt ADC

b) Back of the burnt ADC

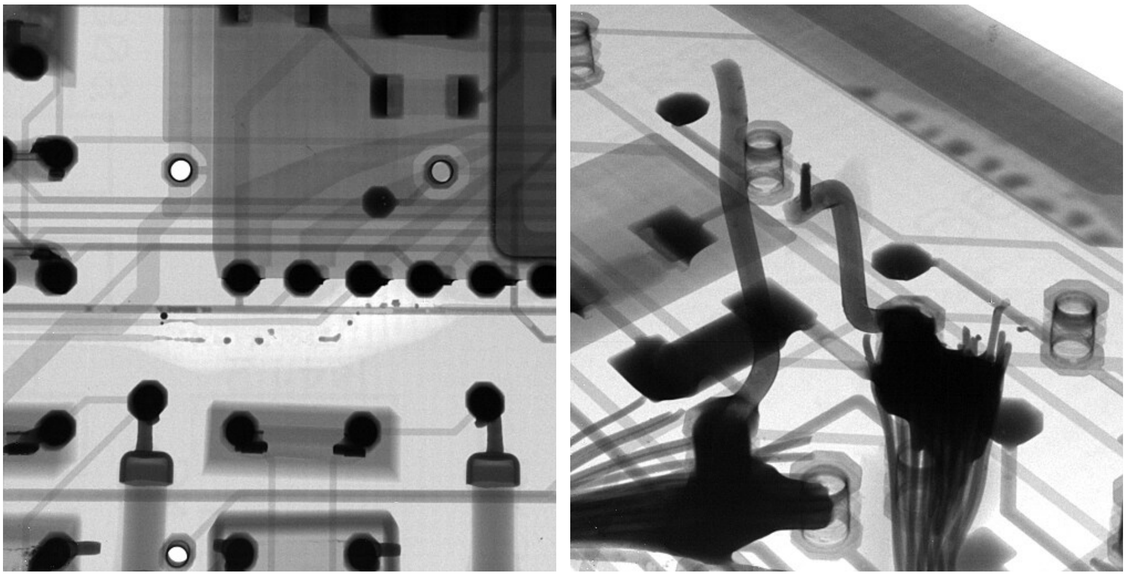


c) Detailed view of a contact from the back

d) Detailed view of the burnt material surface on the back

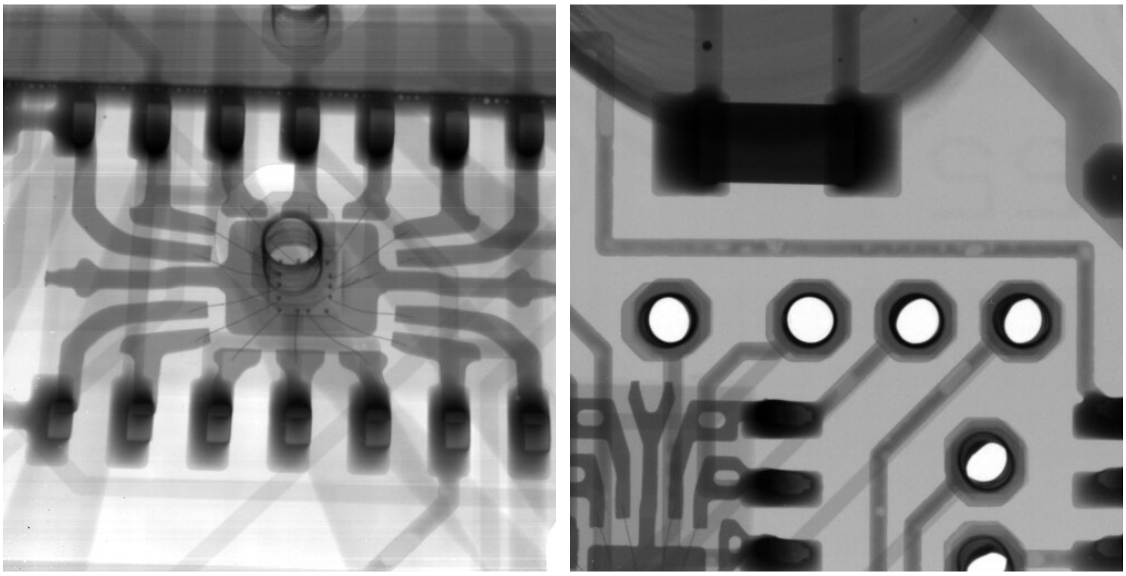
Figure 15. Stereomicroscope images of the Siemens Simatic circuit board after processing

Furthermore, by using an x-ray microscope, it can be seen more precisely that the solder connections to the ADC have melted. However, it is observed that only the connections close to the ADC have dissolved, while the ones near the ruptured capacitor are still intact. Inside the ADC, where according to the investigation at least one or two connections have melted, it can be observed that a connection at the top right contact inside the chip itself has been damaged. However, this cannot be confirmed, and it is only an assumption that this was caused by the experiment. In addition, the ruptured capacitor legs can be seen where the capacitor was before the experiment. Another assumption was that the brighter spots on the circuit board could also have been caused by the experiment. However, further investigations using the x-ray microscope revealed that the lighter coloured spots occur on the entire component and could therefore have been created during the production process. The results from the x-ray microscope can be seen in figure 16 a-d.



a) Melted connections near the ADC

b) Ruptured capacitor legs



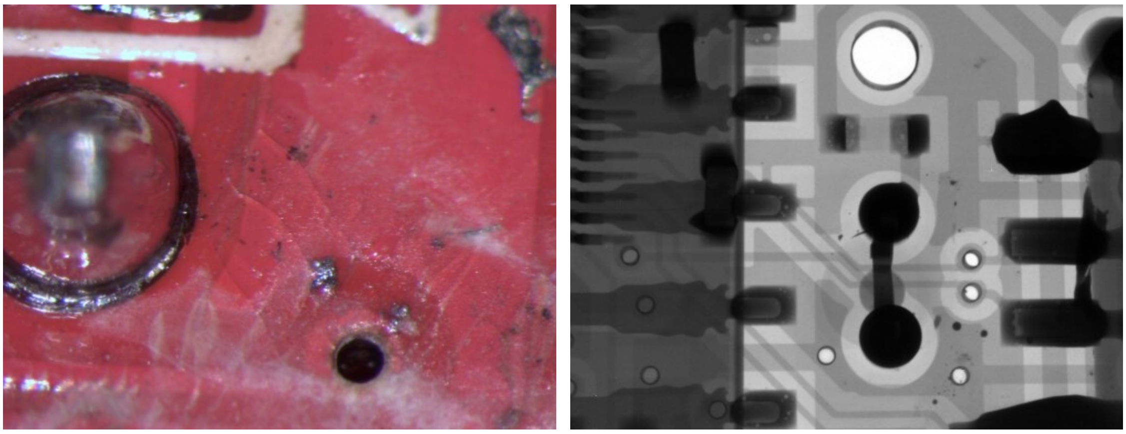
c) Damaged connection in the top right contact inside the ADC

d) Independent solder connection on the circuit board

Figure 16. X-ray images of the Siemens Simatic circuit board after processing

6.2 Second Component: Lexar USB 2.0 SDHC Reader

Initial attempts to destroy the Lexar USB reader as a result of overloading it remained unsuccessful, likely due to an insufficient power supply. Consequently, the USB reader was then exposed to mechanical stress by repeatedly dropping it from a low height to simulate real handling scenarios. In addition, a strength test was carried out to evaluate the device's resistance to pressure, including being stepped on. As a result of the stereomicroscopic analysis, only a few additional cracks are observed on the back of the component. It is assumed that these cracks only appear to affect an adhesive material on the surface of the component, rather than the circuit board itself. However, it is important to note that this assumption and the presence of an adhesive is only made by visual inspection and has not been confirmed by further testing. In addition, a second investigation with the phoenix nanome|x was performed to visualise the inside of the component. In this image, no cracks can be seen at the selected position. This may indicate that the cracks only occur in the assumed adhesive layer and do not directly affect the board. The comparison of the same location with different investigation methods can be viewed in figure 17 a-b.



a) Stereomicroscope image

b) Phoenix nanome|x image

Figure 17. Investigation of possible cracks at the Lexar USB reader

6.3 Third Component: ABB Circuit Board

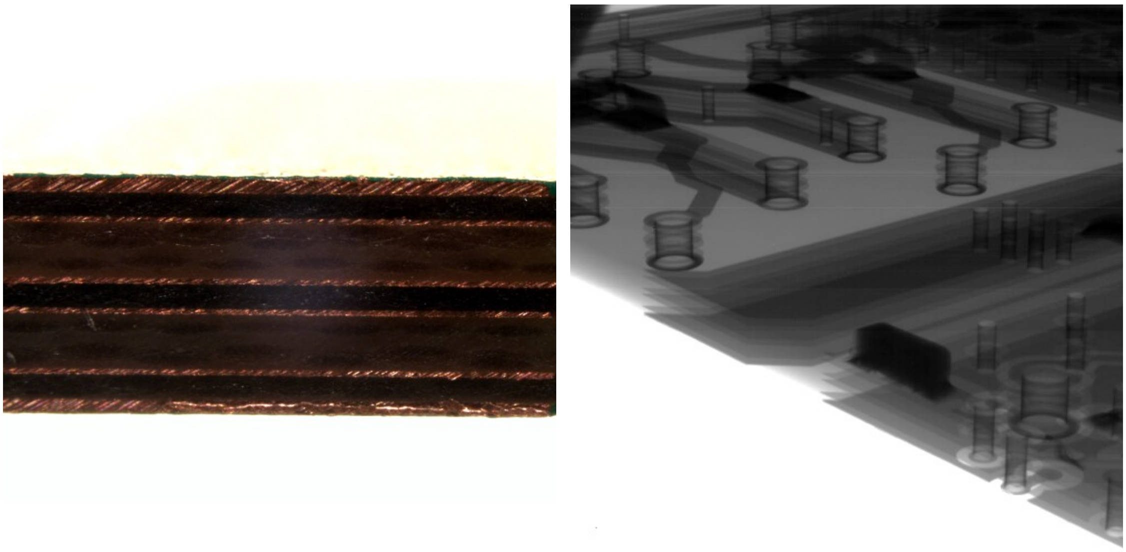
On the third part, the ABB circuit board, no changes at the board are detected as a result of bending them. All solder joints appear unchanged and show no additional cracks or other defects compared to their pre-test condition. Only the pre-testing cracks at certain solder joints remain visible.

6.4 Fourth Component: Gembird USB 2.0 All-in-1 Card Reader

As with the ABB circuit board, there is no recognisable damage to the Gembird USB card reader caused by the bending process. The solder joints remained intact and show no further cracks than in the pictures that were taken prior testing.

6.5 Fifth Component: Circuit Board

Since the part had already been cut, no further damaging processes were carried out. The investigation only focused on the cut-through part of the component whereby it can be seen in figure 18 a-b that the printed circuit board consists of six different layers. The material in between is assumed to be copper. To verify the presence of copper, a more detailed elemental analysis would have to be carried out.



a) Stereomicroscope image b) Phoenix nanome|x image

Figure 18. Detailed images of the circuit board layers

7 DISCUSSION

This chapter discusses the results of this thesis in relation to the initial research questions. The aim is to raise awareness and show the importance of recycling as well as how electrical and electronic waste is handled worldwide, in the European Union and especially in Finland and Austria. It also aims to demonstrate the various environmental and economic benefits of recycling and the future prospects for different recycling scenarios in order to achieve a higher recycling rate. Furthermore, the different recycling methods and the different recycling rates in the countries Finland and Austria are discussed. At last, the goal is to analyse the condition of electronic components before they get recycled, to determine whether the components are still functional or show visible defects and therefore cannot be recycled.

Raising awareness of recycling is especially important when it is considered to affect people's health, environmental sustainability and economic development. Traditional mining, especially in developing countries, is associated with significant health risks, the use of child labour and violations of basic human rights. It also contributes to environmental degradation through the release of toxins and greenhouse gas emissions. Therefore, urban mining is often presented as a more sustainable alternative. It involves the recovery of valuable materials from existing waste, rather than the extraction of new raw materials. With this shift environmental and health impacts could potentially be reduced. However, it is important to note that the implementation of urban mining remains complex. The overall effectiveness of urban mining depends not only on the availability of waste as a resource, but also on efficient collection, sorting and processing systems. Worldwide, there are still considerable differences between wealthy and low-income countries. In some cases, e-waste gets exported to low-income countries for dismantling, but only the valuable parts are then reclaimed back by other countries. The remaining waste is then left behind in the developing countries, which often don’t have access to suitable treatment facilities. This increases the environmental impact on the local population.

Significant environmental and economic benefits from recycling are evident. The estimated value of recyclable metals in e-waste was about USD 91 billion. But due to inefficient recycling technologies, landfilling or incinerations, only about USD 28 billion were returned to the economy. Future scenarios predict an economic loss of up to USD 40 billion in a business-as-usual scenario, while a coordinated and aspirational global approach could lead to a potential gain of USD 38 billion. However, whether such high recycling rates can be achieved is uncertain and depends heavily on international co-operations, investments and policy implementations. In environmental terms, effective recycling methods help to reduce the CO_2-equivalent emissions as well as to minimise the negative effects of conventional mining, such as air and water pollution, the destruction of land and the loss of biodiversity. However, with only 22.3 per cent of e-waste being formally documented, collected and recycled in an environmentally safe way in 2022, current efforts remain insufficient. Therefore, future scenarios highlight the urgent need to significantly increase the recycling efficiency and system-wide commitment.

The European Union is trying to increase the recycling rates with various different directives. These regulations also apply to all member states, including Finland and Austria. Based on the overall collection rate for WEEE in 2022, it becomes evident, that both Finland and Austria perform above the European Union’s average. This evaluation is carried out by comparing the share of total e-waste collected in 2022 to the average amount of EEE placed on the market in the last three years. While Finland achieved a collection rate of around 52 per cent, Austria reported around 50 per cent, which in both cases is above the European Union’s average of around 40 per cent. These numbers reflect the effectiveness of the national collection systems which shows that both countries have established a functioning infrastructure for the disposal of WEEE. Nevertheless, there is still room for improvements to achieve higher collection rates. To increase these rates, both countries focus on similar recycling methods, such as manual dismantling, mechanical processing and the recovery of raw materials. This involves various techniques, including physical separation, pyrometallurgical and hydrometallurgy treatment, biohydrometallurgy as well as processes for non-metal fractions.

The component analysis showed that the first component, the Siemens Simatic 6ES5 466-3LA11 circuit board, was in a good overall condition even before the investigation began. There were no major damages found during the first inspection. However, some greyish discolouration on the contacts on the back of the component could be detected. Whilst their exact condition could not be determined by visual inspection alone, they could indicate early signs of material degradation. To determine the existing defects more precisely, further in-depth analyses would be required, for example an examination of the surface composition. With the exception of one part, the destruction by overloading did not succeed, which was probably due to the current being too low. The one part that could be damaged is a capacitor, which has ruptured and destroyed a nearby solder connection to the analogue-to-digital converter. Therefore, the first assumption, that the damage was directly at the capacitor, could be disproved. It is also suspected that the internal connection within the chip has been damaged, possibly as a result of the burst capacitor, however, this cannot be confirmed without further analyses. Furthermore, the x-ray images showed that there were small bright spots along the line, which were also initially thought to be caused by the capacitor. However, after examining the entire circuit board with the x-ray microscope, it was found that they were present on the entire board. The current assumption is that these lighter spots happened during the production process of the printed circuit board and are not an indication of possible defects.

On the second component, a Lexar USB 2.0 SDHC reader, small irregularities and cracks on the solder joints can be detected. However, more detailed tests need to be carried out to determine the precise cause of the damage. During testing, an attempt was made to destroy the components by overloading them. However, this was not successful, and no visible results were obtained. By performing the bending test as well as the test for a normal wear of a USB reader, it could be seen that small cracks occurred on the back of the component after these tests. These cracks, however, are not visible with the x-ray microscope, which means that they can be situated on a possible adhesive layer or that the cracks are perhaps in a material that is not recognised by the x-ray microscope. This could occur because the material is being suppressed by the microscope.

However, it should be noted that if there is an adhesive layer on it, it may become damaged by external influences and might affect the function of the board.

On the third and fourth component, a circuit board from ABB and a Gembird USB 2.0 all-in-1 card reader, only a few minor cracks could be found on the investigation prior processing. As the bending tests were only carried out with normal force, as it can occur during assembly, the force was not directed specifically at one point. As a result, no detachment of an individual joint is to be expected. Due to the low force, the solder joints still look good after the stress without any further cracks appearing on the component.

The last component, another printed circuit board, was investigated due to the different layers of the board. It was recognised that it consists of different layers with different materials in between. This material is assumed to be copper, but this can only be confirmed by further testing. However, with this investigation it can be recognised, that the different layers must also be considered during recycling. They need to be separated before the start of the process, which makes it more complex.

In summary, it can be concluded that the examined components were still in a relatively good condition prior processing and showed no severe damages. Even if the parts no longer functioned, the physical condition of the parts suggested that they are still suitable for recycling. This underlines the importance of informing the public about the recyclability of devices. Although some devices may no longer work, it is still important that they get disposed of properly. In addition, smaller devices such as e-cigarettes should also be recognised by the public as e-waste and therefore disposed of in the recycling system. However, while the analysed components in this thesis only show minor damages, it should be considered, that a visual inspection alone is not sufficient. Further investigations of the irregularities at the solder joints would be elemental analyses to determine the exact cause of the degradation. This would also provide important information if the parts have reuse potential. This clarification could help to adapt the recycling process or change the recycling method altogether. Another further possibility for improvement is to increase the test volume of the analysed components to obtain a broader overview and to be able to make more reliable conclusions. Overall, it is important to note that recycling needs to be carefully managed to be as effective as possible.

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