Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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Environmental impacts of treating e-waste in Norway

Master's thesis in Nordic Master in Environmental Engineering with a specialisation in Residual Resources Engineering and Industrial Ecology
Supervisor: Johan Berg Pettersen & Anders Damgaard
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Abstract

E-waste is a very complex waste stream consisting of complex mixtures of different materials containing hazardous and valuable materials. These are important to recover to avoid the environmental impacts of improper disposal. Although iron is the most recoverable element by mass, the greatest environmental advantage in e-waste metal recovery lies in the retrieval of valuable metals such as gold, silver, palladium, copper, and nickel.

This report examines the environmental impacts of treating electronic waste in Norway, focusing on waste flows, material compositions and environmental impacts on an annual basis. Material flow analysis is used as the base of understanding the material flows of e-waste in Norway followed by a Life cycle assessment conducting the environmental impacts of the system. The annual collection of 107,000 tonnes of e-waste is carried out by return companies organised by Extended Producer Responsibilities. The e-waste undergoes various treatments including reuse, material recovery, landfilling, energy recovery, thermal destruction, and other methods. Of the total collected e-waste, 82% is towards material recovery, 2% reused, and 12% undergoing energy recovery.

The environmental impact assessment reveals that the overall system of e-waste treatment in Norway leads to environmental savings in most midpoint categories, with steel recovery demonstrating significant climate change impact reduction. Contradictory findings are observed in copper recovery, highlighting the need for further investigation.

Endpoint categories highlight the negative impacts of steel recovery on ecosystems and the performance of benefitting human health impacts is lower than the performance for reuse, aluminium recovery and recovery of other metals. For the LCA model of this project gold, silver and nickel are recovered from other metal recovery. The system shows high uncertainties for especially recovery of other metals. Nonetheless, the overall e-waste treatment system in Norway annually carries an uncertainty level of 12%, which indicates high limitations of the system model.

The prioritisation of material recovery based on environmental impacts suggests caution with steel recovery due to negative implications for ecosystems, while aluminium recovery and reuse show positive performance for all endpoint categories. The study recommends prioritising the treatment of lost waste and waste found in residual waste streams, as they hold a high potential for recovery. Further research is essential to refine prioritisation strategies and gain a deeper understanding of the environmental implications associated with different materials and recovery approaches. The findings need to be futher reseached and improved to be able to provide insights for decision-makers and stakeholders in designing effective e-waste management strategies in Norway. Addressing the identified knowledge gaps and uncertainties is crucial for improving the environmental performance of e-waste treatment practices in Norway.

Sammenfatning

Elektronik affald er en meget kompleks affaldsstrøm, der består af forskellige materialer, der indeholder farlige og værdifulde materialer. Disse er vigtige at genindvinde for at undgå miljømæssige konsekvenser ved uansvarlig bortskaffelse af elektronik affaldet. Selvom jern er det mest genindvindelige materiale i forhold til total masse, ligger den største miljømæssige fordel ved metalgenvinding af e-affald i genvindingen af værdifulde metaller som guld, sølv, palladium, kobber og nikkel.

Denne kandidatafhandling undersøger de miljømæssige konsekvenser ved behandling af elektronisk affald i Norge og fokuserer på affaldsstrømme, materiale sammensætning og miljøpåvirkninger årligt. Materialestrømsanalyse bruges som grundlag for at forstå materialestrømmene af elektronik affald i Norge, efterfulgt af en livscyklusvurdering, der undersøger systemets miljøpåvirkninger. Årligt indsamles 107.000 ton elektronik affald i Norge, udført af returselskaber der er organiseret af Udvidet Producentansvar (Extended Producer Responsibility). Elektronik affaldet bliver sendt til forskellige behandlinger, herunder genbrug, materialegenvinding, deponering, energigenvinding, termisk destruktion og anden behandling. Af det samlede indsamlede elektronik affald går 82% til materialegenvinding, 2% genbruges og 12% gennemgår energigenvinding.

Miljøpåvirkningsvurderingen viser, at det overordnede system til behandling af elektronik affald i Norge resulterer i miljømæssige besparelser i de fleste midtpunktskategorier, hvor genvinding af stål viser betydelig reduktion af klimapåvirkning. Modstridende resultater observeres ved kobbergenvinding, hvilket understreger behovet for yderligere undersøgelser.

Endpoint kategorien fremhæver de negative påvirkninger af stålgenvinding på økosystemer, og effekten på sundhedsmæssige fordele er lavere end effekten for genbrug, aluminiumsgenvinding og genvinding af andre metaller. I LCA-modellen for dette projekt genindvindes guld, sølv og nikkel fra genvinding af andre metaller. Systemet viser høj usikkerhed, især ved genvinding af andre metaller. Ikke desto mindre har det overordnede system til behandling af elektronik affald i Norge årligt et usikkerhedsniveau på 12%, hvilket indikerer betydelige begrænsninger ved systemmodellen.

Prioriteringen af materielgenvinding baseret på miljømæssige påvirkninger indikerer forsigtighed med hensyn til stålgenvinding på grund af negative konsekvenser for økosystemer, mens aluminiumsgenvinding og genbrug viser positiv præstation for alle endpoint kategorier. Resultaterne fra dette projekt anbefaler prioritering af behandling af mistet affald fra tyveri og eksport og affald fundet i restaffald, da de har et stort potentiale for genvinding. Yderligere forskning er afgørende for at opstille prioriterings strategier og opnå en dybere forståelse af de miljømæssige konsekvenser forbundet med genvinding af forskellige materialer. Resultaterne skal yderligere undersøges og forbedres for at kunne levere indsigt til beslutningstagere og interessenter i udviklingen af effektive strategier for håndtering af elektronik affald i Norge. Det er afgørende at adressere de steder der mangler information om industrien og de usikkerheder der er for at forbedre modellen for behandling af elektronik affald i Norge.

Preface

This project is written in the spring semester of 2023 (from the 2nd of January 2023 to the 2nd of June 2023) as the final project of the Nordic Master in Environmental Engineering with a specialisation in Residual Resources Engineering and Industrial Ecology. This master thesis is written by Lærke Lindgreen Lauritsen, master student in the joint Nordic master programme at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU) and DTU Sustain at the Technical University of Denmark (DTU). This master's thesis corresponds to 30 ECTS points and is supervised by Johan Berg Pettersen (Associate Professor, NTNU Industrial Ecology Programme), Anders Damgaard (Senior Researcher, DTU Sustain), and co-supervised by Kim Rainer Mattson (Ph.D. Candidate, NTNU Industrial Ecology Programme).

The overall objective of the project was to understand the flows and waste treatment of electrical and electronic waste streams in Norway. From understanding the system of handling electrical and electronic waste in Norway, the environmental impacts were found using the life cycle assessment software EASETECH. The focus of the project was to understand the value of recycling specific materials such as precious metals in comparison to recycling rates based on total mass recovery, by looking into the different recovery processes and the environmental impacts and uncertainties associated with the recovery process.

This master thesis was accomplished with great guidance and help from several people, whom I would like to thank. I would like to thank Kim, Johan, and Anders for their patience, support, advice, guidance, and interest in the project throughout the whole process. Their positive inputs have provided me with plenty of motivation. I would also like to thank the people in the industry who have taken the time to provide me with valuable input for my analysis. Especially, a big thanks to Knut Sælid (Operations Manager/Technical Manager WEE in the WEEE department at Stena Recycling AS) and Charlotte Andresen (Norsk Gjenvinning AS - NG metal) who dedicated their time to provide me with valuable insights that elevated my overall understanding of the complex system of electrical and electronic waste management in Norway.

Abbreviations

APOS Allocation at the point of substitution
AT Terrestrial acidification
DALY Disability-adjusted life year
EF Freshwater eutrophication
EM Marine eutrophication
EPR Extended Producer Responsibility
e-waste Electrical and electronic waste
FET Freshwater eco-toxicity
FRS Fossil resource scarcity
FU Functional unit
GWP Global warming potential
HTC Human toxicity: cancer
HTNC Human toxicity: non-cancer
IR Ionising radiation
LCA Life cycle assessment
LCI Life cycle inventory analysis
LCIA Life cycle impact assessment
LU Land use
MET Marine eco-toxicity
MFA Material flow analysis
MRS Mineral resource scarcity
OD Ozone depletion
PE Personal equivalent
PM Fine particulate matter formation
POFE Photochemical oxidant formation: ecosystem quality
POFHH Photochemical oxidant formation: human health
POM Put-on-market
SD Standard deviation
SR Sensitivity ratio
TET Terrestrial eco-toxicity
WEEE Waste electrical and electronic equipment
WU Water use

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1 Introduction

Electrical and electronic waste (e-waste) is a fast-growing global concern that has increased in recent years and is projected to continue growing (Forti et al., 2020). E-waste is defined as anything with a battery, plug, or electric cord which has reached its end-of-life phase (World Economic Forum, 2019). In 2019, the generated e-waste was 53.6Mt globally, which corresponded to 7.3 kg per capita (Forti et al., 2020). E-waste is a complex mixture of different materials and contains hazardous and valuable materials that are important to recycle, as the improper disposal of these can have high environmental and health impacts (John Baxter, Lyng, et al., 2016). Even though the management of e-waste benefits both depletion of raw materials and lowers the emissions of improper disposal, only 17.4% of e-waste is collected for recycling globally (Forti et al., 2020).

Today's recycling goals are primarily based on the mass recovery of materials. This approach assumes that increasing the availability of recoverable materials will automatically create a robust market for secondary raw materials. However, this approach does not consider complex materials such as electronic equipment containing up to 60 different elements of the periodic table (World Economic Forum, 2019), nor the fact that some materials are difficult to recycle efficiently (Marianne Bigum, Brogaard, and Christensen, 2012). This may result in lower-quality materials, that do not substitute the same primary materials used in the production of the products. This alternative approach of recycling complex materials will be referred to as value recycling in this project.

The environmental benefits of saving specific materials in terms of value recycling compared to total mass recovery can reduce the total impact. While it has been found that iron is the most recoverable element by mass, the biggest environmental benefit, when recovering metals from e-waste, is in fact achieved through the recovery of gold, silver, palladium, copper, and nickel (Marianne Bigum, Brogaard, and Christensen, 2012). Rather than focusing solely on mass recovery, looking into recycling some of the most valuable elements in e-waste can lead to higher economic value as well as a lower environmental impact (Marianne Bigum, Brogaard, and Christensen, 2012). It is estimated that one tonne of smartphones contain 100 times more gold than a tonne of gold ore (World Economic Forum, 2019) which indicates the huge potential of recycling valuable materials from e-waste.

Norway, a country with a highly developed economy and technological industries, is not free from the challenges concerning e-waste. Globally, Norway is among the countries with the highest consumption of electronics per capita (Eurostat, 2023) and it is also the country that generates the most e-waste per capita with an average of 26.0kg per capita (2019) (Forti et al., 2020). The collection of e-waste in Norway is mostly driven by national regulation (Avfallsforskriften, 2004) and is organised by the concept of Extended Producer Responsibility, which implies that the manufacturer of electronic products is responsible for the end-of-life treatment of these products (Sander et al., 2007). Through national regulations, Norway is required to recycle at least 75% of the collected e-waste for energy or material recovery, and for some e-waste product categories, this number is even higher (Avfallsforskriften, 2004). However, there is still room for improvement in terms of reducing the environmental impact of e-waste, as some of it ends up in residual waste and some is stolen or exported (Baxter et al., 2021). This thesis will look into the current state of treating e-waste in Norway and the potential environmental impacts of this treatment. The potential environmental savings of prioritising value recycling compared to mass recycling in Norway will be investigated.

1.1 Objective

The purpose of this project is to investigate the flows of collecting and treating electrical and electronic waste streams in Norway. The environmental consequences of the Norwegian handling of e-waste will be assessed from the flows and waste treatment of e-waste. The benefits of treating different materials that either focus on maximising the total recycling yield (mass recycling) or maximising the recovery and recycling of highly valuable and critical materials (value recycling) will be investigated. The following research questions define the aim of the project.

> **RQ 1:** What is the current flow of electronic waste generation and what downstream treatment options are available and used in Norway?

To answer this, material flows and the composition of electronic waste in Norway will be investigated. This will be done by setting up an Material flow analysis (MFA) through a literature review, and by contacting industry representatives and researching the e-waste industry in Norway.

> **RQ 2:** What is the environmental impact of collecting and treating electronic waste annually in Norway?

From the investigated MFA and the material composition of e-waste, it is possible to research the environmental impacts through Life cycle assessment (LCA). With the LCA software EASETECH, the e-waste system in Norway will be quantified and the resulting environmental impacts will be investigated. The system boundaries of the LCA will be from the collection of e-waste to the treatment of e-waste including the substitution of virgin material by recycled material.

> **RQ 3:** How can the prioritisation of material recovery of certain materials be effectively determined according to environmental impacts?

This will be investigated by calculating the environmental impacts for endpoint impacts and discussing the different potentials of recovering different materials in e-waste. The uncertainty of the system will be discussed to estimate if some material recovery processes can be prioritised over other processes.

2 Background

In this section, the electrical and electronic waste system of Norway will be described from the collection phase through regulation, and finally to the treatment of the waste. Background concepts for the project will also be described to provide a clear understanding of the potential of recovering e-waste.

2.1 Purpose of recycling electrical and electronic waste

Prevention of waste is the most preferred waste management strategy, followed by reusing, recycling, recovery and the least preferred management strategy is disposal (World Economic Forum, 2019). Generally, incineration and landfill have been two primary methods of disposal of e-waste, but researchers suggest these two disposal methods should be the least considered to conserve valuable materials of e-waste (Ismail and Hanafiah, 2019).

E-waste is often seen as a problem that only occurs after consumers discard their devices. However, the issue involves the entire life cycle of the devices. Various stakeholders, such as designers, producers, investors, traders, miners, raw material producers, consumers, and policymakers, all have an important part to play in reducing waste (World Economic Forum, 2019). This includes keeping value within the system, prolonging the economic and physical lifespan of items, and promoting their repair, recycling, and reuse (World Economic Forum, 2019).

Recycling electronics has a considerable environmental advantage in comparison to other disposal options for e-waste. One of the advantages is that improper disposal is avoided which could lead to direct environmental impacts, as electronic waste can consist of hazardous materials and other materials that can lead to an environmental burden (John Baxter, Lyng, et al., 2016). A second advantage is that recycling e-waste can recover valuable materials that bring both economic advantages as well as secondary materials that can substitute primary production (John Baxter, Lyng, et al., 2016).

Electronic waste is an underutilised but rapidly expanding valuable resource. Almost all the e-waste has the potential for recycling. Nowadays, urban mining, which involves extracting resources from complex waste streams, can be more financially feasible than traditional mining, and it is less energy intensive. There is a huge material potential, it is as an example estimated that e-waste potentially holds up to 7% of the world's gold (World Economic Forum, 2019).

2.1.1 End-of-life management

The end-of-life management of electronic waste is complex. The management is associated with both economic opportunities and potential environmental impacts (Ismail and Hanafiah, 2019). The management of electronic waste is unique because electronics have distinct chemical and physical properties compared to other types of waste streams, as they can contain more than 60% of valuable materials and can contain more than 100 varieties of hazardous and toxic fractions (Ismail and Hanafiah, 2019).

Secondary raw material markets are important for a circular economy, if it should be possible to keep the high quality of materials, and at the same time minimise the extraction of natural materials. The "Investigating Europe's secondary raw material markets" report from European Environment Agency looks into eight different secondary raw material markets and finds that only the secondary raw material markets for aluminium, paper, and glass are well functioning (EEA et al., 2022). On the other hand, the report states that the secondary raw markets of plastic, wood, bio waste, textiles, and aggregates from construction and demolition waste markets are not well-functioning (EEA et al., 2022).

Electrical and electronic products encompass a diverse range of materials, including metals such as iron, copper, gold, cobalt, and aluminium, which can be extracted from e-waste and recycled. Beyond these commonly recognised metals, the category of metals known as rare earth metals remains unfamiliar to many individuals (Norsirk, 2023). However, these rare earth metals are experiencing a surge in demand due to their critical importance in numerous emerging technologies and advancements. Consequently, their market value has been consistently rising each year, as demand outpaces supply, and new technologies and developments require these rare metals (Norsirk, 2023). Different high-tech innovation products are, or could be, dependent on rare earth metals. In the periodic table, 17 elements are characterised as rare earth metals such as Scandium, Yttrium, Praseodymium, and Neodymium (Norsirk, 2023).

Rare earth metals are in e-waste however, it is uncertain to what extent rare earth metals are recovered compared to gold and silver. Research shows that precious metal recycling is considerable globally, but the recycling of rare earth metals is nearly nonexistent (John Baxter, Lyng, et al., 2016). Specific data on the LCA of rare earth metals is limited. However, recent analysis suggests that, in terms of greenhouse gas emissions and commonly used indicators, rare earth metals may be of secondary importance compared to precious metals. This reinforces the understanding that even small quantities of precious metals have a considerable environmental impact. However, if other factors like resource use, toxicity, and occupational health were considered, rare earth metals would likely be more important (John Baxter, Lyng, et al., 2016).

The recycling industry for e-waste follows a pyramid structure. It consists of a small number of refiners recovering the different materials (fewer than 10 in Europe), a larger number of dismantlers and pretreatment facilities, and even larger numbers involved in the initial collection of e-waste (EEA et al., 2022). Currently, there are significant losses of critical raw materials during the collection, pretreatment, and recycling of e-waste (EEA et al., 2022). Some materials, like magnesium, have high losses during pre-processing, while others, like neodymium, lack proper recycling processes at an industrial scale. The rising value of scarce metals like indium and tellurium may eventually justify investments in large-scale recovery for e-waste (EEA et al., 2022).

2.1.2 Misplaces e-waste

Misplaced waste in residual waste might not make up a high proportion of the total amount, but the related impacts might have consequences (M. Bigum et al., 2017). Misplaced special waste in residual waste might, by mass, be less than 1% of the total amount, but it is the most significant fraction according to the metal content when iron and aluminium are excluded. When residual waste, including misplaced electronics, is incinerated, an increase of mercury and cadmium in flue gas can be seen and so can levels of emitted dioxides and furans to mention a few (M. Bigum et al., 2017). The recovery of metals in ashes is limited and most full-scale technologies can only handle ferrous metals, aluminium, and to some extent copper (M. Bigum et al., 2017). The metals that are not recovered from ashes are not available for re-entering the material cycle.

Recovery of iron and aluminium from bottom ash can be 80% iron and 55% aluminium for an incineration plant equipped with a wet flue gas cleaner (M. Bigum et al., 2017), the rest of the bottom ash was used for road construction, and the fly ashes and air pollution control residues were landfilled (M. Bigum et al., 2017). Approximately 96% of the resources lost through ashes come from special waste in residual waste. The majority of these losses are attributed to platinum(85%), with smaller contributions from copper (7%), gold, and silver(M. Bigum et al., 2017).

2.1.3 Environmental impacts

Metals obtained through the recycling of e-waste are two to ten times more energy-efficient than metals extracted from fresh ore (World Economic Forum, 2019). Additionally, urban mining of e-waste results in 80% less CO_2-eq emissions per unit of gold compared to traditional mining of gold (World Economic Forum, 2019).

In 2016, a study on Elretur (now called Norsirk) was conducted to understand the environmental impacts of responsible disposal of e-waste considering refrigerators, mobile telephones, and LCD screens separately (John Baxter, Lyng, et al., 2016). The study showed that the recovery of critical materials is vital for the environmental impact of e-waste. It showed that for all waste types investigated, the benefit of recovering materials and recovering energy exceeded the negative consequences of irresponsible disposal (John Baxter, Lyng, et al., 2016). The recycling of the three different products showed Global warming potential (GWP) savings. If refrigerators are irresponsibly disposed, refrigerants can be released into the atmosphere, which has a high environmental impact and could account for 96% of the total GWP burden of the refrigerator end-of-life treatment. This shows the importance of proper handling of hazardous waste fractions (John Baxter, Lyng, et al., 2016).

2.2 Electrical and electronic waste in Norway

The general trend in Europe is that the collected electronic waste has been increasing from 2010 to 2018 (Baxter et al., 2021). The Nordic countries, however, do not follow that trend. In Norway, the collected waste has been somewhat steady during 2012 to 2021 at about 0.14 Mt annually (Statistisk Sentralbyrå, 2022). National regulation on waste mostly drives the collection of e-waste in Norway (Avfallsforskriften, 2004). The collection is organised by the concept of Extended Producer Responsibility (EPR) (Sander et al., 2007). The companies who are subject to EPR in Norway are expected to manage waste according to the principle of one-for-one, meaning the companies selling or producing electronics need to collect the same amount of e-waste in kg or units as the sold amount (Recipo, 2023). Producers and importers of electrical and electronic equipment in Norway must be a member of one of the four authorised return companies (EEregisteret, 2019). The four authorised return companies are

Recipo, Renas, Norsirk, and ERP Norway. The four different return companies are then responsible for the proper collection and treatment of e-waste. The return companies are responsible for the safe collection and recovery of different e-waste product categories in accordance with the national regulations (Avfallsforskriften, 2004). The return companies are obligated to document and report to the 'Produsentansvar' (owned by the Norwegian Environmental Agency), their collected amounts and quantities that have been sent to different waste treatments (Miljødirektoratet, 2023).

2.2.1 Regulations of electrical and electronic waste system in Norway

In 1999 the national waste regulations for electronic and electrical waste were introduced in Norway to prevent and reduce environmental and health problems related to e-waste by regulating the collection and end-of-life treatment of e-waste. The regulations reduce the use of primary resources, ensures that hazardous waste from electronic waste is managed in an environmentally sound way and ensures sustainable management of e-waste (Norsirk, 2022).

There are different requirements for involved stakeholders in the electronic waste system. Stores that sell electronic products must accept e-waste corresponding to products they sell in the store and ensure safe and correct storage of the e-waste until collected by an authorised company such as the four different return companies. Furthermore, the stores are required to tell customers that e-waste must be disposed of separately from other waste. Municipalities are required to offer collection facilities for residents, so they have a place to return their electronic waste free of charge. Producers and importers are required to have binding agreements with the return companies covering the potential e-waste equal to the total amount of electrical and electronic equipment imported to or produced in Norway (Avfallsforskriften, 2004). Producers and importers must report to the return company, the total quantities of electrical and electronic equipment they place on the market in Norway each year (Norsirk, 2022).

In the national regulations, there are specific requirements for the recovery of eight different product categories. These requirements are set as a percentage of the total mass of each product category to be either recovered in the form of reuse, material recovery, or energy recovery (incineration), and a different recovery percentage is given for reuse or material recovery. The regulations are based on the product category, and they vary from 75% to 85% for the recovery when including energy recovery, and they vary between 55% and 80% when excluding energy recovery (Avfallsforskriften, 2004).

2.2.2 The management system for Norwegian electrical and electronic waste

The management system for Norwegian e-waste is complex due to geographical factors and varying treatment pathways for different types of e-waste. The return companies' responsibilities begin at different collection points all around Norway including collection facilities run by municipalities, stores selling electronics, and other collection facilities. A more detailed description of "other collection facilities" and what it is, has not been defined or documented by the industry (Miljødirektoratet, 2023). Depending on the collection point, the waste might have already been separated into different product categories, or otherwise, sent on to the different regional reception centers for sorting and potential pretreatment (John Baxter, Lyng, et al., 2016). At the pretreatment facilities, the hazardous waste groups are removed, and the different materials are sent on to recovery treatment - most often in Scandinavia, but at times, elsewhere in Europe (John Baxter, Lyng, et al., 2016). The treatment includes material recovery, energy recovery, and landfilling, where the recovered materials and energy are considered to replace equivalents on the European market (John Baxter, Lyng, et al., 2016).

Information on treatment outcomes, for instance, recycling rates or waste to incineration, is reported from EPR companies to governmental bodies (Environmental Agency) and based on internal reporting between the EPR company and the respective recycling facilities. The benefit of thorough reporting is to provide some insight into most of the value chain, but this is challenging, as electronic waste and different material fractions are sent on to different treatment places with some materials being treated outside of Norway (Renas, 2020). This portal has only been in use since 2019, as electronic waste was previously reported differently (Miljødirektoratet, 2023) (EEregisteret, 2019). Before 2019, the collection of e-waste in Norway was reported across 14 different product categories with 11 falling within the scope of the EU regulations. However, starting in 2019, the collection data shifted to a revised framework consisting of eight different product categories (Baxter et al., 2021). The total collected mass of e-waste and collection points are reported in the database, and so are the different treatments of the collected e-waste. Documentation on what material fractions are treated and the different shares of material fractions are not given in the database (Miljødirektoratet, 2023).

2.2.3 Product categories

In Norway, electronic waste is split into eight different categories of electronic types. For a systematic overview of the different categories, see Table 1. The table shows examples of the different products collected in each of the eight product categories. All product categories are shown in the table, but Category 4 is split into two different subgroups; large products except for solar panels and solar panels separately. It is considered as one category for this project. The same accounts for Category 5 where ionic smoke detectors is a subgroup of Category 5, but is considered as part of Category 5 for this project.

Table 1: Overview of the different product categories (Avfallsforskriften, 2004)

Product category	Products included in category
Category 1: Heating and cooling equipment	Refrigerators, freezers, air conditioners, dehumidifiers, heat pumps, water heaters, radiators containing oil and other products and equipment of a similar nature and size.
Category 2: Screens, monitors and equipment containing screens with a surface of more than 100 cm^2	Monitors, television sets, electric and electronic photo frames, laptops, electric and electronic reading boards and other products and equipment of a similar nature and size.
Category 3: Light sources	Incandescent lamps, compact fluorescent lamps (energy-saving lamps), fluorescent lamps, high-pressure lamps, LEDs and other products and equipment of a similar nature and size.
Category 4: Other large products where one of the outer dimensions is over 50 cm	Washing machines, dryers, dishwashers, electric cooking appliances, electric stoves, musical equipment, weaving and knitting machines, large computers and printers, toys, leisure and sports equipment, vending machines, medical equipment, solar panels, other consumer products and other products and equipment of a similar nature.
Category 5: Other small products where the longest outer dimension is less than 50 cm	Vacuum cleaners, carpet cleaners, sewing machines, microwave ovens, ventilation equipment, irons, toasters, watches, shavers, calculators, radios, video cameras, toys, smoke detectors, other consumer products and other products and equipment of a similar nature.
Category 6: Smaller IT and telecommunications equipment where the longest outer dimension is less than 50 cm	Mobile phones, GPS devices, routers, computers, printers, telephones and other products and equipment of a similar nature
Category 7: Large industrial equipment	Large stationary industrial tools such as winches, large fixed installations such as elevators and escalators, non-road industrial machinery, transformers, large electric motors and other products and equipment of a similar nature and size.
Category 8: Large industrial cables	All cables

The different product categories are treated differently. For Category 1, steel, metals, cables, and plastics are separated from the e-waste and recycled into new raw materials (Norsk Gjenvinning, 2023). For Category 2, screens are first disassembled to remove lamps and other elements. The CRTs can contain items like phosphor powder, leaded glass, copper, and other rare metals that can be recycled and used for new production (Norsk Gjenvinning, 2023). For Category 3, the light sources are crushed and washed or treated in different processes. Materials such as glass, metals, and plastics are obtained. Special machines are used to remove hazardous materials like mercury or phosphorus (Norsk Gjenvinning, 2023). For Category 4, Category 5 and Category 7, liquids, oil and hazardous fractions are removed either mechanically or manually. In a mechanical treatment, fractions such as circuit boards, capacitors, and more are removed. After this, a mechanical sorting process separates iron, metals, and plastics that can be recycled (Norsk Gjenvinning, 2023). For Category 6 fractions such as light sources, batteries and monitors are removed. In the same way as for the other categories useful fractions are removed and subsequent separation of iron, metals and plastics takes place for material recycling (Norsk Gjenvinning, 2023). For Category 8, fractions such as bitumen, oil, grease, plastic, copper, aluminium, lead, and iron are separated. The fractions arising after treatment are delivered to approved smelters and incinerators both within Norway and outside Norway. Cables containing oil and grease are classified as hazardous waste and are treated accordingly to the classification (Norsk Gjenvinning, 2023).

2.2.4 The different return companies

The different return companies handle different amounts of e-waste annually and have different capacities. The distribution of how much of the total generated waste the different return companies collect can be seen in Figure 1, based on an average of four years (2019-2022) (Miljødirektoratet, 2023). As can be seen on the figure, Norsirk is responsible for most electronic waste management with a share of 47% of the total collected waste followed by Renas which collects 29%. Recipo collects 16% and Serva collected about 1% during the two years it was operating and is now part of ERP Norway who collects about 6% of the total waste.

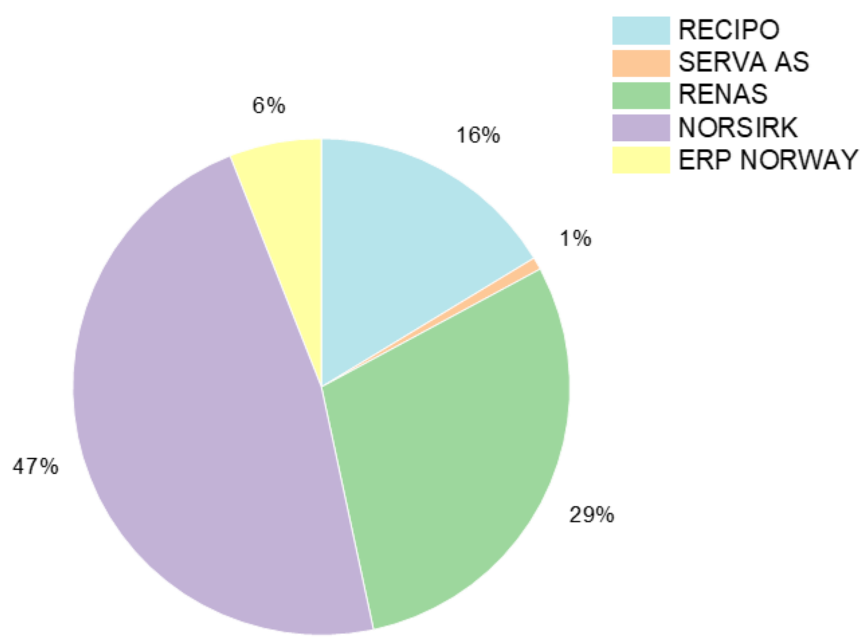

Figure 1: Distribution of the total amount of e-waste collected by the different return companies (Miljødirektoratet, 2023)

Most e-waste is collected at the collection facilities with a share of 45% of the total collected e-waste. 29% of the total e-waste is collected at stores and the last 26% is collected at other collection facilities. It differs between the different return companies where they collect most of their waste. Recipo collects 56% of the total e-waste collected at stores, where Norsirk collects 63% of the total waste collected at collection facilities, and Renas collects 50% of the total waste collected from other collection facilities. All the different return companies report collection of waste from all three different collection options except Recipo, which does not collect waste from other collection facilities.

Norsirk (formerly known as Elretur) has been handling e-waste since 1998 and is the biggest return company in

Norway. It provides different solutions and services for the collection, transportation, and recycling of e-waste, batteries and packaging (Norsirk, 2023).

Renas is the second largest e-waste return company in Norway. Renas was founded in 1999 and has 100 collection points around Norway. Renas collaborates with eight operators with a total of 14 treatment facilities. Renas carries out producer responsibility for around 2,700 producers and importers of e-waste in Norway. The company collaborates with AS Batteriretur and Grønt Punkt Norge (Renas, 2023).

The third biggest return company in Norway is Recipo, a Nordic Producer Responsibility Organisation that assists companies in Sweden, Norway, and Denmark. Recipo was founded in 2007 and has more than 150 collection sites in Norway. Recipo has its own plastic recycling plant and recycles plastics from e-waste. The recycling plant handles end-of-life electronic products, recycles the plastics, and turns the recycled plastic into pellets ready for the secondary market. Recipo recycles different types of plastics, and sells ABS Pellets, PS Pellets, ABS/PC Pellets, and PMMA (Recipo, 2023).

The last operating return company is ERP Norway which is part of the Landbell Group. ERP is short for European Recycling Platform and is an international company operating in different countries. ERP states that it has more than 38,600 members across 62 countries. It was one of the first return companies to be authorised to operate across borders, and it has been operating since 2002 (ERP, 2023). For the years 2019 and 2020 a fifth return company, Serva, is included in the data. However, as of 2021 (Brønnøysundregistrene, 2021), Serva was acquired by ERP Norway (Serva, 2021).

2.2.5 Collection of e-waste

Norway has the highest amount of electrical and electronic equipment Put-on-market (POM) per capita annually compared to other countries (Eurostat, 2023). However, Norway does also have the highest collection rates of e-waste per capita annually. Even though the collection rates are high in Norway, there are some problematic losses in the system (Baxter et al., 2021). These problems occur before the counted collection, as losses of e-waste happen through theft, illegal export, or through it ending up in residual waste (Baxter et al., 2021). Some questionable problems are e-waste in business-to-business collection, legal export, and electronic waste ending in scrap metals (Baxter et al., 2021). Stakeholders indicate that theft and scavenging of e-waste remain a concern in Norway. Even though municipalities have improved the security of e-waste at collection facilities by fencing and other measures, the increasing number of electrical and electronic equipment stores receiving e-waste can be reasons for losses. Stores are obligated to receive electronic equipment corresponding to the products they are selling, and to make this easy for the consumer, the collection container is usually placed outside stores with limited security which can facilitate theft and scavenging (Baxter et al., 2021). It is estimated that about 2-5% of the POM is lost to theft and scavenging (Baxter et al., 2021).

E-waste also ends up in residual waste which is an issue as e-waste contains hazardous substances such as lead, mercury, barium and brominated flame retardants. Also, in this case, the potential for material recovery is lost and potential pollution of other waste streams occurs (Marianne Bigum, Petersen, et al., 2013). The special waste such as batteries and e-waste ending up in residual waste is not very well documented, and better data is needed to understand how this can be improved (Marianne Bigum, Petersen, et al., 2013). Bigum et al. found that special waste ending in residual waste accounted for 0.34% (w/w) of the total generated residual waste from 3,129 households in Denmark (Marianne Bigum, Petersen, et al., 2013). Not all product categories of e-waste were discarded as residual waste. By mass, the product category most likely to be found in residual waste is Category 5 (small household electronics). Of the e-waste discarded as residual waste, 49% by mass were products from Category 5 (Marianne Bigum, Petersen, et al., 2013). Other product categories found in residual waste are Category 3 (light sources), Category 4 (larger household electronics) and Category 6 (communication equipment) (Marianne Bigum, Petersen, et al., 2013). Compared to other studies, a study from Germany found the content of electronic waste to be 1.27% in residual waste (Dimitrakakis et al., 2009). A third study from the Netherlands found that 0.88% of the residual waste was electronic waste (Huisman et al., 2012).

It is estimated that a total of 7,000 tonne of e-waste ends in the residual waste annually in Norway, which is around 0.8% of the total residual waste (Baxter et al., 2021). In 2021, sampling of residual waste in two areas was done in Norway, here it was found that e-waste and hazardous waste were 1.1% of the total residual waste (Fagerheim, Mikkelborg, and Bjørnerud, 2021).

2.2.6 Treatment of e-waste

The treatment of e-waste is a very complex system as there are many different treatment places. Some separate the e-waste and make it ready for transportation to the next treatment, some treatment facilities remove substances such as oils or hazardous fractions, and lastly, some actually perform recovery treatment of different materials (personal communication with Charlotte Andresen, Appendix II B).

The first step of the treatment process of e-waste is to remove hazardous fractions of the e-waste which is often done manually (Renas, 2020). If not done before transportation to the facility, all liquids, as well as any toner cartridges and color toner, need to be removed before further treatment. Batteries are removed and cables are cut off and collected for separate treatment. A number of components containing environmentally hazardous substances need to be removed, documented and reported to the authorities (Renas, 2020). Sorted e-waste with hazardous fractions removed is sent to further treatment where it goes through different treatments including grinders, magnets, sieves, and sensor technology etc. (Renas, 2020).

Two treatment places are responsible for treating the largest share of e-waste in Norway, namely Revac in Revetal and Stena Recycling in Frogner. The treatment process at Revac includes grinding, manual and mechanical sorting, dismantling, magnetic sorting and granulation. Plastic is recovered to plastic granulate. Metals are melted and recovered as iron, gold and aluminium. Copper ore and printed circuit boards are melted together and cast into sheets which then go through pyrolysis before copper sheets are ready for the secondary market (Revac, 2023).

The second large recycling facility of e-waste in Norway is Stena Recycling. Stena Recycling has different collection facilities in Norway where the treatment starts, and then the company has a larger facility in Frogner (Stena

Recycling, 2023). They collect, transport, dismantle, sort, remove hazardous waste, process manually, process mechanically, fragment secondary raw material, quality controls, pack and deliver to the production industry (personal communication with Knut Sælid, Appendix II A).

At Stena Recycling the e-waste is sorted at reception point to remove environmentally harmful components from products before the remaining materials are recycled. Iron, metals, plastics and cables from e-waste are separated and recycled. All hazardous waste is recycled or safely destroyed by certified and authorised operators. Functioning products are sent to reuse, where the products are stripped of information, refurbished, upgraded and then put back on the market (Stena Recycling, 2023). Stena Recycling's large treatment facility in Halmstad, Sweden, covering 433,000 m^2, equivalent to 80 football fields, receives the material fraction ready for recovery (Stena Recycling, 2023) (personal communication with Knut Sælid, Appendix II A).

In addition to the two larger recycling facilities, there are also smaller treatment places around Norway. These facilities are usually pretreatment facilities, where the different products are separated and some fractions are removed and sent to different treatments before being sent to material recovery. Metallco, Østbø and Hellik Teigen are good examples of "Stage 1 processors" (personal communication with Tom Erland Schjørlin, Appendix II C). They ensure that all environmental toxins are removed in accordance with the regulations (Renas, 2020).

Norsk Gjenvinning is one of Norway's largest providers of recycling and environmental services. They collect and receive all types of e-waste and transport the products to a separate facility for sorting, reloading, and for classifying the e-waste into the eight product categories (Norsk Gjenvinning, 2023). Norsk Gjenvinning treats large industrial equipment at their own treatment facilities at NG Metall Drammen and KMT Linnestad and treats all types of e-waste at their new facility located in Katrineholm in Sweden. Zirq Solution recycles complex cables and transformers at their treatment facility in Linnestad and is part of Norsk Gjenvinning (Zirq Solution, 2023) (personal communication with Charlotte Andresen, Appendix II B).

3 Methodology

This section describes the different methodologies employed and how they are used for this project. Firstly, the design of this project is described after which the methodology of the material flow analysis (MFA) is presented. The MFA quantifies the different masses in the system and forms the basis for investigating the environmental impacts of the system through a life cycle assessment (LCA). The LCA performed in this study follows the official guidelines ISO 14040 (European Committee for Standardization and CEN national members, 2006a) and ISO14044 (European Committee for Standardization and CEN national members, 2006b). The four phases of the LCA set forth in the ISO guidelines will be thoroughly described in this section. The LCA will be performed using the software EASETECH, where a sensitivity analysis and an uncertainty analysis will also be run.

3.1 Research design

The research for this project was split into three important milestones to fully complete the analysis. The first milestone of the project was to explore literature and data to be able to quantify the flows of e-waste in Norway today. The second milestone was to set up the MFA based on the found literature and data. The last milestone was to set up the model in EASETECH using the constructed MFA and data from Ecoinvent. From the system model in EASETECH, the system's environmental impacts were found and a sensitivity analysis was carried out. The research design of this project, including all the small steps on the way, can be seen in more detail in Figure 2.

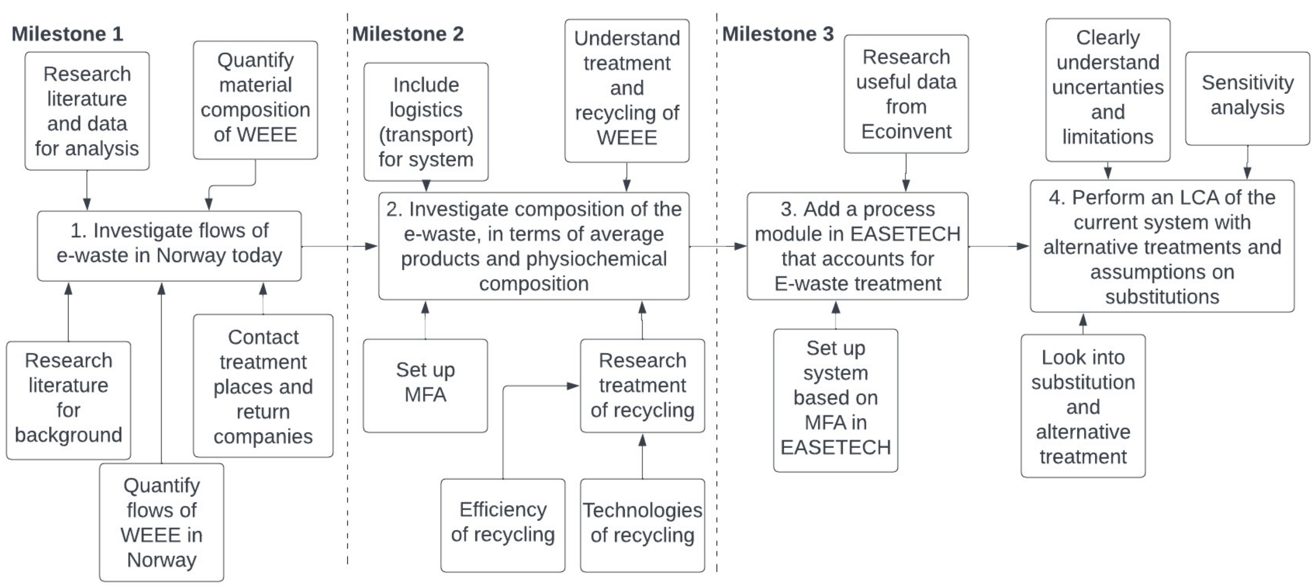

Figure 2: The research design of this project

The MFA is first carried out to understand the system of e-waste flows in Norway today. The MFA is based on found data from literature and will be used as input data for the subsequent LCA along with input data from Ecoinvent. An overview of how the data is used for the performed MFA and LCA, and the flow of the project can be seen in Figure 3. To quantify the MFA, data on the material composition of e-waste [kg/kg WW] is estimated and the overall flows [ton/yr] of e-waste in Norway are determined. The results of the MFA complete the e-waste flows of the system that is used for the inventory of the LCA. Missing data on treatment processes and substitution is added to the inventory to be able to fulfill the LCA.

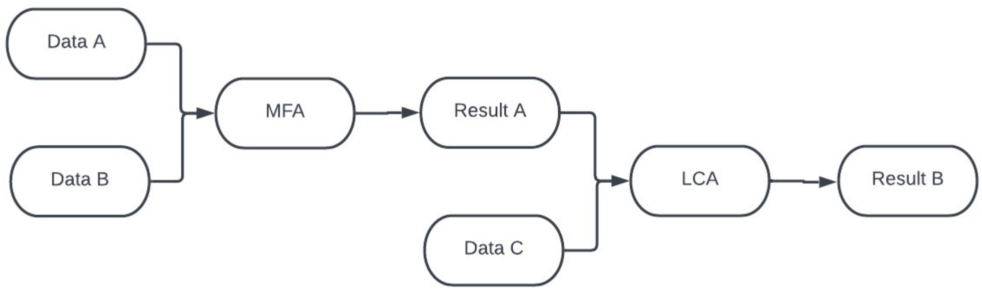

Figure 3: Outline of the used data for both the MFA and LCA of this project

3.2 Material flow analysis

An MFA is a systematic assessment of a system to understand the flows and stocks of materials defined in space and time (Brunner and Rechberger, 2016). The full MFA system for e-waste in Norway includes the POM value until the final treatment process of e-waste. However, the focus of this project, and thus also the system boundaries of the LCA, starts with the collection of e-waste, at either stores, collection facilities, other collection facilities or residual waste until the e-waste has been treated. The system considers the total amount of e-waste generated annually in Norway excluding industrial e-waste and large industrial cables, as the material composition of these waste types varies a lot from consumer-related e-waste. To be able to quantify the system and understand the complexity of the system, different companies in the industry such as return companies and treatment facilities were contacted. In Appendix I, a contact matrix can be found. A teams meeting with Stena Recycling and NG Metal Drammen helped understand the system and in combination with literature and databases it was possible to set up the MFA. Meeting summaries can be found in Appendix II. In Figure 4, the MFA for this project can be seen including the system boundaries.

Figure 4: The MFA system showing the system boundaries of this project

3.2.1 Quantification of flows

Data and assumptions for all the different flows of the system are needed to understand and estimate the flows of e-waste in Norway. All flows seen in the simple MFA system in Figure 4 are mostly quantified by data from 'Produsentansvar' (Miljødirektoratet, 2023). These data are reported from different return companies. The first year of data reported in the newest format is 2019. Data on e-waste in Norway have been reported since 2006, but in 2019 the product categories and the reporting changed (EEregisteret, 2019), and the earlier years are therefore excluded from this project.

The "Put on market" flow in Figure 4 is only included in this project to be able to calculate the "Loss: Theft/export" flow. The data for the POM are from Eurostat (Eurostat, 2023) and as e-waste is unlikely to be disposed the same year as the electronics are purchased, an average of four years is calculated from 2014-2017. The generated e-waste consists of many different types of electronics of various sizes, and with very different lifetimes. Some products have a long lifetime while some do not. For the POM flow, a conservative estimate is made based on an average lifetime of five years. The lifetime of five years is based on the report "A Stock-Driven Model for Assessing Environmental Benefits of Product Lifetime Extension in Norwegian Households" (Krych and Pettersen, 2021) as it was found that a freezer has a long lifespan of around 25 years, and a vacuum cleaner has one of the shortest lifespans of about five years. The lifetime of products is only used to calculate the loss flow from theft and export for the MFA, and the conservative choice of a lifetime of five years does not affect the results of the LCA. As the POM value is not used for the LCA of this project, it will not be further discussed, even though, the lifetime of different products varies, and the physical composition of electronic products becomes more and more complex in the development of newer products (Krych and Pettersen, 2021) (World Economic Forum, 2019).

Process 1 "Use phase (consumer)" in Figure 4 is a stock for the MFA as there are electronic products in use and also many products stored in private homes. There are many reasons why products are stored in people's homes, but some of the reasons could be the potential value, the challenge of getting to a return place, or the worries of what happens to personal data on the device when disposed (World Economic Forum, 2019).

The data on loss for export and theft, flow "Loss: Theft/export" in Figure 4, are estimated by the report "Collection of Electronic Waste (Innsamling av EE-avfall)" (Baxter et al., 2021). The repair of products or secondhand sale is not quantified as it is hard to estimate, and is thus, only included in the use phase.

The flow "Residual waste for energy recovery" in Figure 4 is quantified by the report "Collection of Electronic Waste (Innsamling av EE-avfall)" (Baxter et al., 2021) and the sampling of e-waste in residual waste by 1.1% (Fagerheim, Mikkelborg, and Bjørnerud, 2021). The composition of the different e-waste categories ending in residual waste is estimated to be the same as in the study by Bigum et al. (2013) of e-waste in residual waste in Denmark (Marianne Bigum, Petersen, et al., 2013).

The collection of correctly disposed e-waste happens from three different main sources; collection facilities run by municipalities, stores, and other collection facilities. Data on collected e-waste at stores, recycling stations and other are from 'Produsentansvar' and so are the data of the masses sent to the different treatments or final disposal (Miljødirektoratet, 2023). The flows are quantified as an average of the years 2019, 2020, 2021, and 2022 as data were reported differently for the previous years.

The total mass flows of generated e-waste are based on data from the Norwegian Environmental Agency reported by the return companies (Miljødirektoratet, 2023). In total, 142,000 ton of e-waste is collected annually (based on a four-year average of 2019-2022) in Norway, which contains all eight product categories including the large industrial equipment and large industrial cables which are not considered in this project. The large industrial equipment is approximately 13% of the collected e-waste and the large industrial cables are approximately 12%.

Excluding the industrial waste, the amount of collected e-waste that will be considered in this study is 107,232 ton yearly. The data used for the quantification of collected waste for treatment can be seen in Table 2. The information in this table is used to quantify the flows for the different product categories and the total collected waste. These flows are seen in Figure 4 as the flows to 6 category processes and the flow from collection point to process 12. The masses are given in ton per year in Table 2 and the shares of the different product categories are shown as well.

Table 2: Total quantities of the different product categories collected in ton per year and the percentage share of each product category (Miljødirektoratet, 2023).

Product category	2019 (ton)	2020 (ton)	2021 (ton)	2022 (ton)	Avarage of collected E-waste (ton)	Percentage share of E-waste (%)
1. Heating and cooling equipment	18,168	19,440	22,915	24,068	21,148	20%
2. Screens, monitors and equipment containing screens with a surface of more than 100 cm²	6,843	7,634	6,249	6,730	6,864	6%
3. Light sources	1,099	907	1,168	1,043	1,054	1%
4. Other large products where one of the outer dimensions is over 50 cm	38,304	34,608	37,916	41,836	38,166	36%
5. Other small products where the longest outer dimension is less than 50 cm	32,773	32,951	29,711	32,692	32,032	30%
6. Smaller IT and telecommunications equipment where the longest outer dimension is less than 50 cm	6,398	8,032	8,648	8,794	7,968	7%
Total	103,585	103,571	106,606	115,164	107,232	100%

The collected e-waste is sent to pretreatment and here sent on to different treatments which is also reported by the five different return companies to the Norwegian Environmental Agency (Miljødirektoratet, 2023). Table 3 shows the share of different treatment types for the different product categories. The data in this table is used for the flows from process 12, "other treatment", "Reuse", "Deposition/landfilling", "Energy recovery", "thermal destruction" and the flow to process 12 in Figure 4. The recovery rates of different material fractions are not available, and it is therefore assumed that all material fractions are equally sent to the different treatment types.

Table 3: Percentage share of different treatment types for the different product categories (Miljødirektoratet, 2023)

Product category	Other treatment	Reuse	Deposition / Landfilling	Energy recovery	Material recovery	Thermal destruction
1. Heating and cooling equipment	0.1%	1.8%	1.4%	14.0%	82.4%	0.3%
2. Screens, monitors and equipment containing screens with a surface of more than 100 cm²	0.0%	11.9%	3.5%	6.6%	77.5%	0.6%
3. Light sources	0.0%	0.0%	3.9%	0.0%	96.0%	0.0%
4. Other large products where one of the outer dimensions is over 50 cm	0.1%	1.0%	4.9%	10.3%	83.6%	0.1%
5. Other small products where the longest outer dimension is less than 50 cm	0.1%	0.1%	4.9%	14.1%	80.7%	0.2%
6. Smaller IT and telecommunications equipment where the longest outer dimension is less than 50 cm	0.1%	7.9%	4.6%	13.3%	73.9%	0.2%
Total	0.1%	2.0%	4.1%	12.1%	81.6%	0.2%

3.2.2 Requirements of mass recovery

The different product categories have different regulations on the share that needs to be sent to reuse or material recovery or energy recovery (Avfallsforskriften, 2004). There are requirements for recycling rates for the different product categories in Norway. There is both a recycling rate for total recovery which includes the mass sent to reuse, energy recovery and material recovery from pretreatment and a recycling rate for reuse and material recovery. The requirements are given as "For EE waste in product Category 1 and Category 4, at least 85% of the collected amount of waste must be recycled, of which at least 80% of the waste must be prepared for reuse or material recovery." (Avfallsforskriften, 2004). The recycling rates are given in percentage of the total mass to be recycled. The recycling requirements must be met every year by the return companies for the individual product categories (Avfallsforskriften, 2004). The requirements for each product category both including energy recovery and without can be seen in Table 4 (Avfallsforskriften, 2004). The actual shares in percentage sent to the different treatments after pretreatment reported to the Norwegian Environmental Agency (Miljødirektoratet, 2023) can also be seen in Table 4.

Table 4: Norwegian requirements of recycling rates for recovery including reuse, energy recovery and material recovery and the requirement for recovery including reuse and material recovery. The percentage of recycling reported by the return companies with and without energy recovery is also shown in this table. [a](Avfallsforskriften, 2004), [b](Miljødirektoratet, 2023)

Product category	Requirement for recovery (reuse, energy and material recovery) (a)	Total recovery (b)	Requirement for material recovery and reuse (a)	Total material recovery and reuse (b)
1. Heating and cooling equipment	85%	98.2%	80%	84.1%
2. Screens, monitors and equipment containing screens with a surface of more than 100 cm^2	80%	95.9%	70%	89.4%
3. Light sources	-	96.1%	80%	96.0%
4. Other large products where one of the outer dimensions is over 50 cm	85%	94.9%	80%	84.6%
5. Other small products where the longest outer dimension is less than 50 cm	75%	94.8%	55%	80.8%
6. Smaller IT and telecommunications equipment where the longest outer dimension is less than 50 cm	75%	95.1%	55%	81.8%
Total	-	95.6%	-	83.6%

The return companies report what treatments the e-waste is sent to after pretreatment, but there is little visibility on what treatment places, the waste is sent to. Furthermore, the type of treatment, the e-waste is sent to, is only reported in total masses, and no information is given on the material composition of the treated e-waste. The e-waste is sent to different locations for treatment based on category and according to contracts between companies. Some treatments following the pretreatment are the final end treatment for some fraction, and for other materials or treatments, the waste is sent to further treatment in Norway or exported for treatment within Europe. The system for e-waste treatment in Norway is complex, and there is no visibility within the sector, so it is impossible to have a detailed understanding of the actual e-waste flows without direct contact with treatment facilities. The share of e-waste sent to different treatments, based on reporting by the return companies, can be seen in Table 5. For this project it is considered that all material fractions are equally recovered from the pretreatment, as the actual recovery rates of individual material fractions are not given.

Table 5: Percentage of total e-waste sent to different treatments from the 5 different return companies (Miljødirektoratet, 2023)

Percentages of e-waste from cat 1-6 sent to treatment from returncompanies (%)					
	Recipo	Serva	Renas	Norsirk	EPR Norway
Other treatment	0%	0%	0%	0%	0%
Reuse	2%	14%	1%	3%	0%
Deposition / Landfilling	5%	2%	5%	3%	0%
Energy recovery	11%	12%	12%	13%	2%
Material recovery	82%	71%	82%	81%	11%
Thermal destruction	0%	1%	0%	0%	0%
Total amount of e-waste cat 1-6 collected (ton/annually)	17,537	777	38,413	44,112	5,993

3.2.3 Material Composition

The six product categories focused on in this assessment is assumed to be handled as one total mass and undergo the same treatment processes. For this project, one product is chosen to represent each product category. These products are chosen to somewhat represent the differences in composition between the different product categories, but they are not fully representative of the actual generated e-waste, as there is big variation of products and material composition within the product categories. The products chosen to represent each category are the following; 1. Refrigerator, 2. Television (LCD screen), 3. Compact fluorescent lamp (CFL lamp), 4. Dishwasher, 5. Microwave and 6. Smartphone.

To simplify the material lists of the products, all plastic types are combined into one material fraction and so are other metals not including aluminium, steel, and copper. The modelled material composition does not fully represent the actual material composition, some products consist of many different plastic types such as flame retardant or polystyrene (PS) etc. The different plastic types are most likely not treated as one mass in reality, but they are combined into one material fraction in the model in order to understand the flows and to simplify the assessment. This applies to glass, where ceramics and all different glass types pooled into one fraction. Aluminium, steel and copper are material fractions by themselves. Ideally, all other metals in the material composition would be identified individually, but are combined as one material fraction named "other metals" in this project. Dependent on the product, this fraction includes precious metals, nickel, mercury, lead, gold, silver, palladium, and other metals. The importance of the individual different metals will be further discussed.

The compositions of the used material fractions for each of the six products are estimated based on found literature and databases. Table 6 shows the material composition of the products chosen for each product category and the source of the material list for each product. The categories of materials included are steel, aluminium, plastic (including all different types of plastic), glass (including ceramics and all glass types), copper, and other metals (including all other metals than steel, aluminium and copper).

Table 6: Material composition for chosen products representing the different product categories. [a](John Baxter, Lyng, et al., 2016), [b](Filimonau, 2021), [c](Fulvio and Peiro, 2015), [d](Gallego-Schmid, Mendoza, and Azapagic, 2018)

Product	Steel	aluminium	Plastic	Glass	Copper	Other metals	Source
Refrigerator	74%	1%	25%	0%	1%	0%	(a)
Television (LCD screen)	35%	8%	45%	6%	2%	5%	(a)
CFL Lamp	12%	8%	23%	46%	7%	4%	(b)
Dishwasher	79%	1%	17%	0%	3%	0%	(c)
Microwave	66%	6%	7%	11%	6%	3%	(d)
Smartphone	3%	2%	59%	16%	15%	5%	(a)

To understand the flows and recovery of some metals, layers of the MFA are made. These layers include the content of aluminium, steel/iron, copper as well as palladium, silver, gold, and nickel which are included in the fraction "other metals". The information in Table 6 is used to quantify flows of steel, aluminium, and copper for all flows before process 14-18 (Figure 4). From studies of e-waste, it is estimated that, of the total mass of e-waste, 0.0007% is palladium, 0.0022% is gold, 0.0313% is silver, and 0.3% is nickel (Marianne Bigum, Brogaard, and Christensen, 2012). The recovery of palladium, gold, silver, nickel, aluminium, copper, and iron for the pretreatment and recovery process for the MFA layers are based on the study by Bigum et al. (2012), and the recovery rates can be seen in Table 7. The table also shows the overall mass composition of total generated e-waste assumed for the layers based on Bigum et al. (2012) and the material fraction of steel/iron, copper, aluminium, other metals, glass and plastic according to the material composition of the chosen products.

Table 7: Material composition for total generated e-waste and the recovery rates for pretreatment and recovery process for the different materials. [a](Marianne Bigum, Brogaard, and Christensen, 2012), [b]Table 6

	Total mass	Recovered from pretreatment	Recovered from recovery process
Palladium	0.0007% (a)	26% (a)	98% (a)
Gold	0.0022% (a)	26% (a)	98% (a)
Silver	0.0313% (a)	12% (a)	97% (a)
Nickel	0.3% (a)	100% (a)	90% (a)
Aluminium	3.0% (b)	86% (a)	79% (a)
Copper	4.3% (b)	60% (a)	95% (a)
Iron	65.1% (b)	96% (a)	100% (a)
Other metals	1.7% (b)	-	-
Glass	5.4% (b)	-	-
Plastic	20.6% (b)	-	-

3.3 Life cycle assessment

The life cycle assessment (LCA) performed in this project follows the Norwegian standards that are based on the ISO 14040 European standard and the ISO 14044 European standard. LCA evaluates the environmental impacts of a system. According to the official International Standard Organization (ISO) guidelines, an LCA consists of four different phases; goal and scope, Life cycle inventory analysis (LCI), Life cycle impact assessment (LCIA), and interpretation (European Committee for Standardization and CEN national members, 2006a).

3.3.1 Goal and scope

The goal and scope definition phase first defines the goal of the LCA followed by defining the Functional unit (FU) of the system, and then, it defines the system boundaries. The goal of the LCA study states the intended application of the study, the motivation for making the study, and the intended audience (European Committee for Standardization and CEN national members, 2006a).

The intended application of the LCA for this project is to understand the environmental impacts of the waste management system of e-waste in Norway. The study is carried out to gain insights into the e-waste management system in Norway as a whole in order to represent and understand possible environmental impacts and identify possible areas of improvement. The LCA performed in this study can form the basis for further research due to the simplified nature of the performed LCA which has a low level of detail and a use of many generalisations. Further research is required to obtain more detailed findings that can be relevant for stakeholders and policymakers who are following the electronics and raw materials markets in Norway and the EU closely.

Functional unit: The FU describes the objective of the LCA and links the input to the output. A FU is important for the comparability between different LCA studies, as studies can easily be compared if the FU is the same (European Committee for Standardization and CEN national members, 2006a). The LCA carried out in this project will investigate the environmental impacts of the e-waste management system in Norway from the collection of e-waste to its treatment and does not consider the production of electronics. The total amount of e-waste collected excluding large industrial waste and large industrial cables is 107,232 t per year based on an average of the years 2019, 2020, 2021, and 2022 (Miljødirektoratet, 2023). The FU of this LCA study is defined as "the treatment of the e-waste collected annually in Norway excluding large industrial equipment and large industrial cables, i.e. 107,323 t per year".

System boundaries: The result of the LCA study is dependent on the chosen system boundaries. Depending on the goal and scope of the study, the system boundaries are defined according to the intended application and audience (European Committee for Standardization and CEN national members, 2006a). For this LCA study, the input to the process is the e-waste collected by different return companies at either stores, recycling stations, or other, and the e-waste ending up in residual waste. Losses from theft or legal/illegal export are not included in the system boundaries of the LCA. Furthermore, production, sale, use phase, repair, and secondhand sale are not included in the LCA study. Transportation from the collection point to the treatment facility and further on to other treatment processes are included in the system boundaries. The unit for the system of collected e-waste in Norway is kg annually for the EASETECH model based on the value given in Table 2 but denoted in tonnes. The output is the potential recovery of materials and the potential substitution of virgin production. In Figure 5, the system boundaries of the LCA are shown.

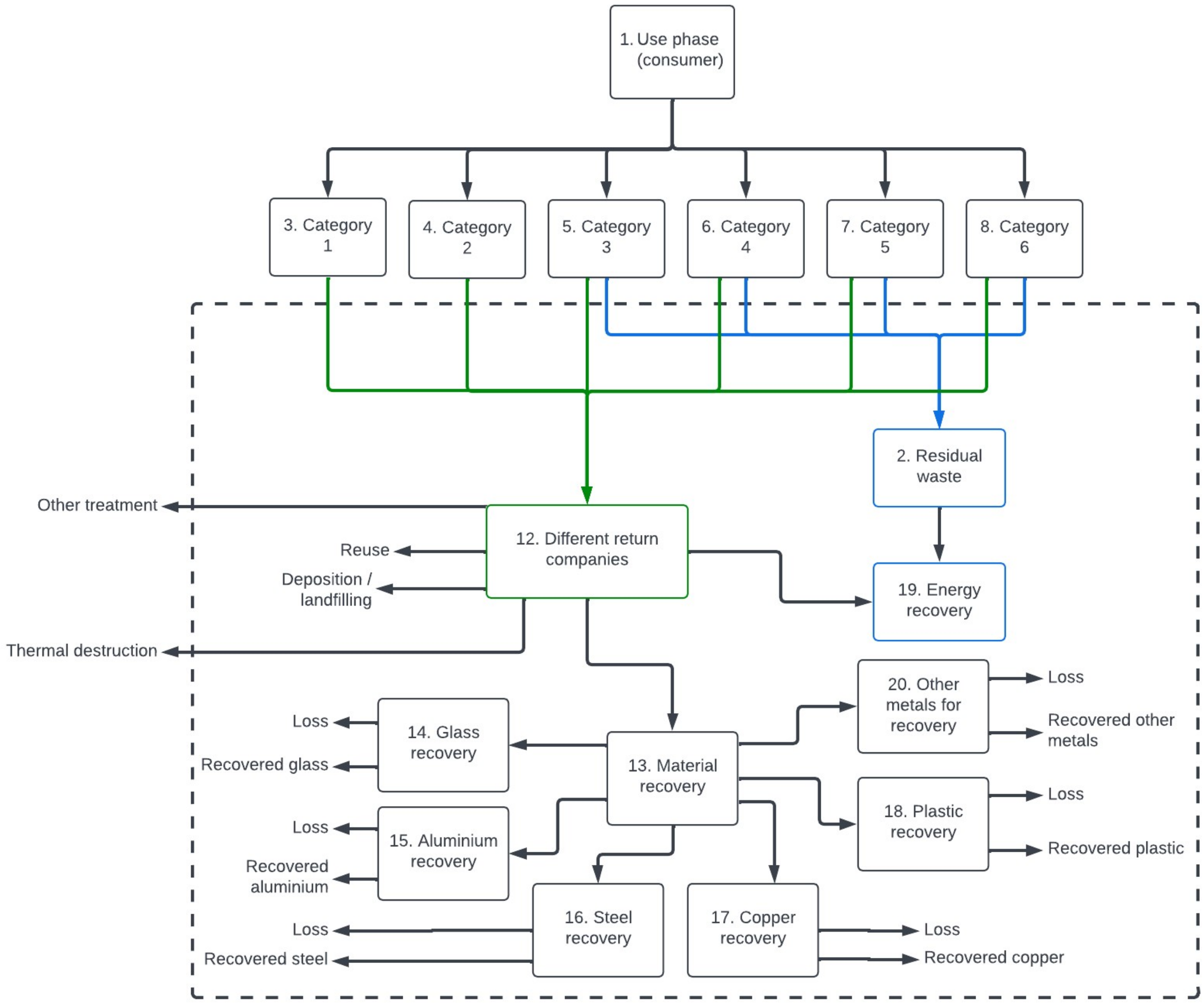

Figure 5: The LCA system showing the system boundaries of this project

Allocation: Allocation is the act of dividing the input and/or output flows of a studied activity to the product system that is being studied (European Committee for Standardization and CEN national members, 2006b). In the attributional approach, allocation is the method used to convert multi-product activities into single-product activities (Ecoinvent, 2022). For this study, the system model "Allocation at the point of substitution (APOS)" is used for the data from Ecoinvent v3.8 used in the LCA model. APOS follows the attributional approach of allocation, and this database is chosen instead of the other attributional approach "Allocation cut-off by classification", because this system considers the value of the recycling. The responsibility of waste production in the cut-off system model lies with the producer under the principle of "polluter pays", and there is a reward for using recyclable products that are available without any additional cost (Ecoinvent, 2022), while the APOS system allocates the valuable by-products from the treatment system in combination with the activity of producing waste (Ecoinvent, 2022). APOS is a better fit for this project compared to cut-off as it includes emission credits from the recycling and treatment of e-waste, thereby, including additional environmental costs or the benefits of recycling. Since the study looks at waste management systems, using the cut-off system is not as relevant, as it considers the benefits for the producer.

3.3.2 Life cycle inventory analysis

The life cycle inventory analysis (LCI) considers what is produced, the inputs to the production, what the product contains, and the emissions from these activities (European Committee for Standardization and CEN national members, 2006b). The LCIanalysis involves data collection and calculation procedures for quantifying the relevant inputs and outputs of the system. Due to limitations, uncertainties, and data gaps, this phase must also include qualified assumptions if needed. Data calculations follow the collection of data and include data validation, unit consistency, and ensuring that the data is related to the FU. Furthermore, considerations of the allocation method for the system should be made according to the output of the system (European Committee for Standardization and CEN national members, 2006a).

The data collection for the LCIanalysis is mainly based on the MFA data which forms the foundation for the LCA study and is the primary data to complete the LCA. The composition of e-waste seen in Table 6 for the different products representing each product category is used for the LCI. The total amount of collected e-waste and the different percentages for the treatment processes seen in Table 2 and Table 3 are also used for the LCI. The data for the MFA is given in ton e-waste collected annually, where the unit used for the LCA is kg e-waste collected annually. Transport distances of e-waste from the collection point to treatment are included in the LCA modelling.

3.3.3 Life cycle impact assessment

The life cycle impact assessment (LCIA) defines the impact categories and the different impacts of the system within the different categories. Using the LCIresults, the significance of potential environmental impacts can be evaluated. To accomplish the LCIA, the inventory data is related to specific environmental impact categories and indicators. The LCIAhas different limitations as it only addresses the environmental issues specified in the goal and scope. Limiting dimensions of the LCIcan lead to the LCIAresults being uncertain (European Committee for Standardization and CEN national members, 2006a).

For the LCIAthe ReCiPe 2016 impact assessment method is used. This method addresses 18 different environmental concerns at the midpoint level and aggregates the midpoints into three different endpoint categories. The endpoint categories are "damage to human health", "damage to ecosystems" and "damage to resource availability" (EU and BB, 2021). Endpoint characterisation measures the impact of a stressor on human health, ecosystems, and resources. It quantifies the damage caused in terms of human life-years lost and years lived with disabilities (DALY), species disappeared (Species*yr), and resource depletion (USD2013). The midpoint impacts measure the damage to one of the areas, whereas the endpoint impacts measure the consequences of certain emissions until it causes damage (EU and BB, 2021). The midpoint indicators will be calculated for the system through the use of EASETECH. All impact categories will be discussed and compared in Personal Equivalents (PE) for the normalised impacts, and some impact categories will be discussed for the characterised results. The impact categories that will be discussed at a midpoint level will especially be the global warming potential in CO_2-eq. The 18 impact categories will be used to calculate and understand the endpoint impacts. The endpoint impacts are calculated based on the ReCiPe 2016 v1.1 calculation sheet for the three different endpoint categories (Huijbregts et al., 2017).

3.3.4 Interpretation

The interpretation phase is the final discussion of the analysis and includes the discussion on the weaknesses of the system as well as recommendations for improvement such that a conclusion to the analysis can be reached. The interpretation phase considers the LCIand the LCIAtogether. The interpretation phase considers the LCIand LCIAin relation to the goal and scope, and it concludes on the findings and discusses limitations and recommendations. The interpretation should clearly state the uncertainties and that the LCIAresults reflect potential environmental impacts and does not predict actual impacts. The interpretation reflects the overall results and findings of the LCA (European Committee for Standardization and CEN national members, 2006a). For the interpretation for this project, the LCIand LCIAresults need to be in place, then the different midpoint impacts and endpoint impacts will be discussed and so will the sensitivity analysis and the uncertainty analysis.

3.4 EASETECH

To implement the LCA for this project, the software EASETECH is used. EASETECH is an LCA model developed at DTU Environment and DTU Compute at the Technical University of Denmark. EASETECH stands for "Environmental Assessment System for Environmental TECHnologies" (DTU, 2021). EASETECH can be used to perform LCA of complex systems handling diverse material flows. Through the programme, it is possible to model resource use and recovery and find the environmental impacts associated with environmental management in a life-cycle context (DTU, 2021) (Clavreul, Baumeister, et al., 2014). EASETECH V.3.4.4 is used for this project.

EASETECH has different qualities than other LCA software, as it focuses on material flow modelling of heterogeneous flows as the basis for the LCA calculations (Clavreul, Baumeister, et al., 2014). EASETECH can provide tools for sensitivity and uncertainty analysis and has a toolbox of processes that can be used for different LCA modelling. These forms a basis for building the different technologies. Different modules from the toolbox are used for this project such as incineration modules and landfilling modules. The input of the modelled LCA system uses the material fraction catalogue, where material properties are defined, for the material composition of collected e-waste. EASETECH provides the different impact categories of the LCIAmethods: EDIP97, EDIP2003, ReCiPe 2016, CML (CML, 2013), USEtox and IPCC 2007 (Clavreul, Baumeister, et al., 2014). For the LCIAfor this project, the ReCiPe 2016 impact categories are used for midpoint and endpoint impacts for the system annually. For uncertainty analysis, the IPCC 2021 impact category for global warming potential (GWP100) is used for a less heavy simulation.

3.4.1 LCA Model

For the EASETECH model made of the e-waste system in Norway, different processes, assumptions, and parameters are used. The system is modelled such that the input to the system is the total collected e-waste annually divided into the different product categories by the material composition of the chosen products to represent the different product categories, see Table 6. A different input to the system is the e-waste ending in residual waste. This input is divided into the different product categories that are mostly being disposed in residual waste by mass. The material catalogue in EASETECH is used for the different materials. Steel is represented by the material fraction "Food cans (tinplate/steel)", for aluminium, the material fraction "Beverage cans (aluminium)" is used, glass is represented by "Clear glass", plastics by "Hard plastic", other metals by "Other metals" and a new material fraction is added separately for copper. These material fractions used from the basic material catalogue in EASETECH do not fully represent the material fractions, but the data offer valuable insight into the current situation.

Transportation is included in the model. Transport distance from the collection point to the reception point, from the reception point to pretreatment, and from pretreatment to material recovery treatment is based on (John Baxter, Lyng, et al., 2016). The transport distances are given for the collection, pretreatment and treatment for three different products, a television, a refrigerator, and a smartphone in Norway (John Baxter, Lyng, et al., 2016). An average of the first transport distance for all three products are used for the transportation distance for this project and the same is done for the second and third transportation distance (John Baxter, Lyng, et al., 2016). There are regulations to new vehicles put on the market to follow exhaust pollution limits, known as the euro emission standards(The AA, 2017). The latest standard, 'Euro 6', has been applied since 2015 (The AA, 2017), and this emission standard is considered for the transportation of e-waste for this project. All transport is assumed to be by truck. In reality some e-waste is also transported by rail and boat. For the treatment processes: reuse, landfilling, and incineration, a transportation distance of 50km is assumed, as it is expected that these treatments happen locally.

A pretreatment module is added in EASETECH, and for this module, it is assumed that 10% of the e-waste is manually sorted and removed for specific treatment or reuse. The last 90% of the e-waste is assumed to go through shredding, magnetic separation and Eddy-current separation. The different material fractions are then sent on to incineration, landfilling, reuse and material recovery. The masses sent to thermal destruction and other treatment are included in the pretreatment, but the specific treatment is not considered as these treatment processes are unknown. All material fractions are evenly sent to the different treatments even though this is not reality, but the recovery values for different materials are unknown.

The incineration module is based on the template module in EASETECH based on a Danish plant. Adjustments are made as a Norwegian incineration plant is a bit different. In Norway, the energy loss is higher than in Denmark and is adjusted to be 16% energy loss (Kauko et al., 2022) (Egging-Bratseth et al., 2021). The electricity production mix is mostly attributed to hydropower in Norway, and the substitution value of substituting electricity in Norway is much lower than the electricity mix covered by coal or natural gas (Norwegian Ministry of Petroleum and Energy, 2021). It is considered that there is a heat loss in the substitution of heat and a 20% heat loss is included (Kauko et al., 2022) (Egging-Bratseth et al., 2021).

The total mass, going to reuse, is split into the different product categories. The products representing the different product categories are substituting new production of those products. It is assumed that a reused product substitutes 25% of new production, as the reuse does not fully substitute the production of a new product, but it extends the lifetime of the product and lowers the need for new production. The reuse percentage differs for the different product categories, and as the reuse is highest for product categories 1,2,4,6 by mass, substitution is only considered for these four products. The e-waste sent to landfilling is considered landfilled using the template modules in EASETECH, "landfill of plastics", "landfill of metals" and "landfilling of glass".

Material recovery is the most complex process of the system. The materials sent for recovery are assumed to be fully split into different material fractions; plastic, steel, other metals, copper, aluminium and glass. The different material fractions are treated differently and for aluminium, glass, plastic and steel the recycling modules in EASETECH are used. For copper recycling Ecoinvent data is used for the recovery, and for other metals, only silver, nickel and gold are considered recovered. These recovery processes are based on Ecoinvent data. The losses of the different recovery processes are considered sent to landfilling, the reality probably also includes incineration.

Throughout most of the system in EASETECH the template modules of different treatment has been used. EASETECH does not have specific modules on electronic waste, and different treatment processes has therefore been added from Ecoinvent v3.8. The databases used for different treatments and production for the substitution of materials and products are found in Ecoinvent(Ecoinvent, 2022). In Table 8, an overview of the used sources for the different processes and fractions can be found. In Appendix III, a more detailed list of the used Ecoinvent data can be found.

Table 8: Sources for the different flows and processes used for the EASTECH model

Comment	Source
System input	
Collected e-waste information from 'Produsentansvar'	Table 2
Material composition of product categories	Table 6
E-waste in residual waste	(Marianne Bigum, Petersen, et al., 2013)
Transportation	
Transportation (collection, reception point, pretreatment)	(Marianne Bigum, Petersen, et al., 2013)
Transportation for incineration, landfilling and reuse	Assumption
Transportation by truck	EASETECH
Pretreatment	
Treatment including shreddering, magnetic separation and Eddy-current separation	Ecoinvent
E-waste sent to different treatments	Table 3
Reuse	
Different categories being reused	Table 3
Substitution of new production of products	Ecoinvent
Material recovery	
Plastic recovery process	EASETECH
Glass recovery process	EASETECH
Copper recovery process	Ecoinvent
Gold recovery process	Ecoinvent
Silver recovery process	Ecoinvent
Nikel recovery process	Ecoinvent
Aluminium recovery process	EASETECH
Steel recovery process	EASETECH
Landfilling	EASETECH
Incineration	
Incineration process	EASETECH
Landfilling	
Landfilling	EASETECH

3.4.2 Substitution

In LCA, substitution refers to the avoided burden credited based on the expected displacement of a material or product (Vadenbo, Hellweg, and Astrup, 2017). The recycled material replaces and avoids primary production. By substituting products, the impacts that arise in the recycling process are compared with the impacts of the primary production of a material or product. This way, it is easier to understand the environmental benefits or drawbacks of different recycling and management options (Viau et al., 2020). There are different challenges and limitations of substitution modelling, as factors such as resource potential, recovery efficiencies, and displacement rates can be hard to assure accuracy in waste management (Viau et al., 2020). The substitution potential can be described as a function of four different factors (Vadenbo, Hellweg, and Astrup, 2017), and the function is:

$$\gamma = U^{rec} \cdot \eta^{rec} \cdot \alpha^{rec:dis} \cdot \pi^{disp} \tag{1}$$

where U^{rec} is the physical resource potential of the waste stream, which represents the quantity of potentially recoverable material accessible in the waste stream. The factor η^{rec} is the recycling efficiency, $\alpha^{rec:dis}$ is the substitution ratio and π^{disp} defines the market response (Vadenbo, Hellweg, and Astrup, 2017).

For this project, substitution is considered for reuse, material recovery, and energy recovery. For the material sent to reuse, the product categories 1, 2, 4, and 6 are considered to substitute some of the primary production of refrigerators, televisions, dishwashers, and smartphones according to the mass recovery rates in Table 3. It is considered that the production of these products is substituted 25% as reuse only extends the lifetime of the products and does not replace materials in production. For material recovery, it is considered that the recovery of metals fully replaces the primary production of aluminium, steel, copper, gold, nickel, and silver. Plastic and glass do not fully substitute primary production. Furthermore, energy recovery of electricity and heat is also assumed to substitute heat and electricity production according to the Norwegian energy mix, as the energy recovery activity occurs in Norway.

3.4.3 Sensitivity analysis

As described, different parameters are defined for the system. EASETECH allows the use of parameters in all input fields, and the parameters can be used to run a sensitivity analysis and an uncertainty analysis (Clavreul, Baumeister, et al., 2014). A sensitivity analysis will be carried out to understand the sensitivity of the analysis and flag the uncertainties of the system. The sensitivity analysis is done for all the used parameters in EASETECH. Sensitivity analysis assesses how variations in input parameters impact the outcomes of a model (Clavreul, Guyonnet, and Christensen, 2012). Sensitivity analysis helps identify which input variables have a significant impact on the results (Clavreul, Guyonnet, and Christensen, 2012). In EASETECH, a perturbation analysis is run for the different parameters to assess the influence of the parameters' uncertainty. The perturbation analysis is run with an increase of 10% as the base for the calculations. 55 parameters for this system, are tested and analysed according to the Sensitivity ratio (SR). The SR is calculated following the equation (Clavreul, Guyonnet, and Christensen, 2012):

$$SR = \frac{\frac{\Delta result}{initial\_result}}{\frac{\Delta parameter}{initial\_parameter}} \tag{2}$$

The sensitivity ratio SR, is the relative sensitivity that is comparable between the different parameters (Clavreul, Guyonnet, and Christensen, 2012).

3.4.4 Uncertainty analysis

The different parameters used for this project are defined with a mean value and distribution, which allows running an uncertainty analysis. The user can define a probability distribution of triangular, uniform, lognormal, or normal shape for each parameter (Clavreul, Baumeister, et al., 2014). With the defined parameters, a Monte Carlo simulation can be run. For more precise results, the Monte Carlo simulation can run large sample values (Clavreul, Baumeister, et al., 2014). All parameters used in the LCA model are considered normally distributed for this project.

Standard deviation (SD) is included for all parameters. Most of the SD are calculated based on available data. SD is calculated with the following equation:

$$SD = \sqrt{\frac{\sum |x - \mu|^2}{N}} \tag{3}$$

In the equation 3, the data value μ is the mean of the data set and N is the amount of data points. The standard deviation is calculated for most parameters, and for some, the SD is found in the literature. As an example, the standard deviation will be calculated based on the data for the four different years for all the parameters based on data from 'Produsentansvar' (Miljødirektoratet, 2023). For a few parameters, the standard deviation was assumed to be 10% as the parameter was not certain. The uncertainty analysis is run for all parameters by Monte Carlo of 10,000 simulations. The uncertainty is only run for IPCC 2021 w LT to get the uncertainty for the global warming potential (GWP100), as the uncertainty analysis for all midpoint impact categories for ReCiPe 2016 was too heavy.

4 Results and Discussion

Following the description of the methodology used for this project, the results will be presented in this section. Here, the findings and outcomes of the study will be presented and interpreted, allowing readers to understand the significance and implications of the research. Both the MFA and LCA results will be presented and discussed. This section includes both results and discussion but also focuses on several key points and findings related to treating e-waste.

4.1 Material flow analysis

The conducted MFA will be presented for the total system annually in Norway, but also an MFA quantified for the flows of seven different metals in e-waste. The limitations of the conducted MFA will be addressed according to treatment shares, material composition and potential recovery.

4.1.1 Quantified material flow analysis

An MFA was constructed of the total e-waste system in Norway on an annual basis based on the collected data. In Figure 6, the conducted MFA can be seen with flows in kt per year in Norway. The input data is quantified according to the different product categories collected at the different collection points. A flowchart showing the MFA differently can be found in Appendix IV. A table of the different flows, flow names, total mass, and comments including sources can be found in Appendix V.

To understand the material composition of metals in the electronic waste and how they are recovered, different layers of seven different metals (aluminium (Al), Copper (Cu), Steel (Fe-C), Palladium (Pd), Gold (Au), Silver (Ag) & Nickel (Ni)) were added to the MFA. The recovery rates of the metals are based on Bigum et al. study (Marianne Bigum, Brogaard, and Christensen, 2012). The metal content of the waste is based on the material composition in Table 7. The masses of the different metals can be seen in Figure 7. It is assumed that all different materials are equally divided into the different treatment types for the overall MFA, where the MFA with metal layers, shows the recovery of the seven different metals, including the different mass recoveries of the metals from Bigum et al. study (Marianne Bigum, Brogaard, and Christensen, 2012). In Appendix VI all flows of the different layers can be seen. This figure is not mass balanced as the total quantity is based on data from 'Produsentansvar' (Miljødirektoratet, 2023) and the recovery of the different metals are based on Bigum et al. study (Marianne Bigum, Brogaard, and Christensen, 2012). In Appendix VII all the data used for quantifying the different metal layers can be found.

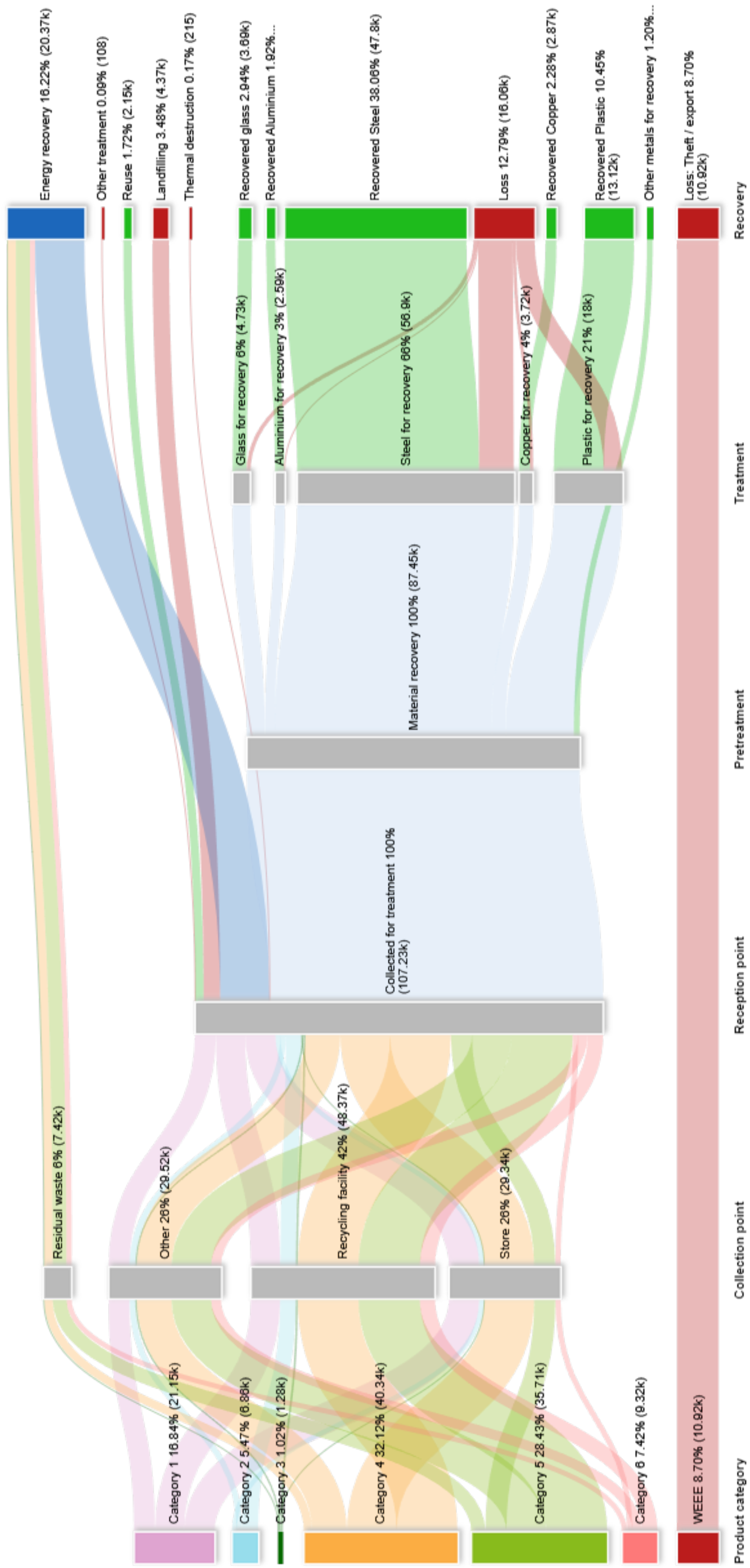

Figure 6: Sankey chart of annual mass flows of e-waste in Norway. The masses are shown in ton. The six product categories are represented by the following products: 1 - Refrigerator, 2 - LCD-screen, 3 - CFL Lamp, 4 - Dishwasher, 5 - Microwave & 6 - Smartphone

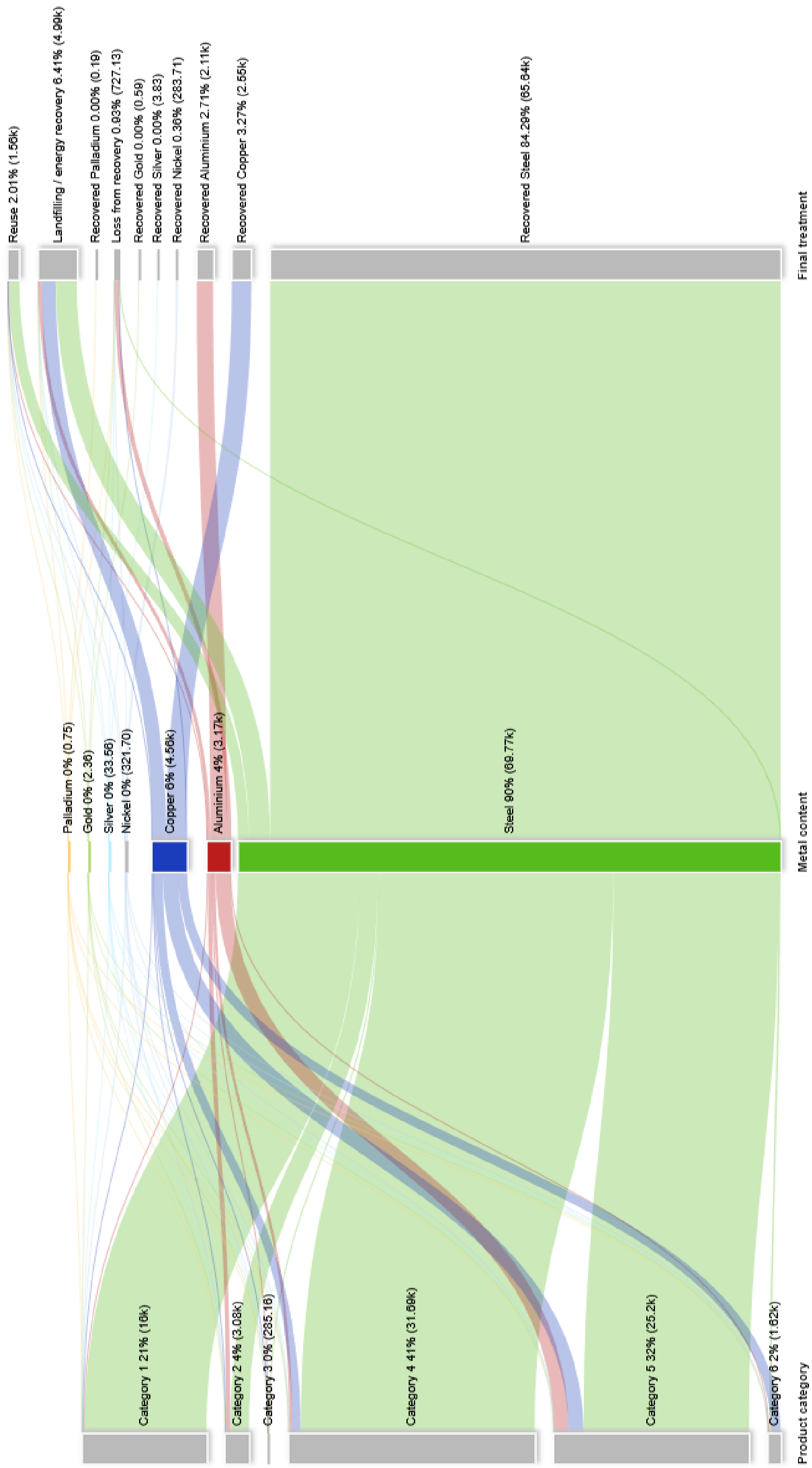

Figure 7: Sankey chart of annual metal recovery of e-waste in Norway. The masses are shown in ton

4.1.2 Treatment shares

In Table 5, the percentage of the mass sent to different treatments for the different return companies can be seen. Recipo, Renas, and Norsirk, it is interesting to see that the waste sent to energy recovery is somewhat steady for all return companies, but looking into reuse, Norsirk reuses 3% of the total collected mass, where Renas reuses about 0% of their total collected mass. Renas, furthermore, has the highest percent share of e-waste sent to landfilling by 11%. Recipo and Norsirk only landfill 4-5%. Renas also has the lowest percentage sent to material recovery of 77%, whereas Recipo sends 82% for material recycling.

For the MFA, it is considered that all material fractions are equally sent to different treatment options. This is unlikely as some materials are more likely sent to incineration and other treatment types compared to other materials. It is estimated that in the Nordic countries, well under 30% of the plastics in e-waste are recycled (John Baxter, Wahlstrom Margareta, et al., 2014). The system of this study considers 78% of the plastic to be sent to material recovery (Miljødirektoratet, 2023), and it is then expected that 73% of the plastic sent to recovery is actually recovered (EASETECH process) and can substitute primary materials on the market. This gives an overall recovery percentage of 57% for plastics which is much higher than estimated by (John Baxter, Wahlstrom Margareta, et al., 2014). The collection and treatment system of electronic waste in Norway is complex as so many different stakeholders are involved. Here waste is sent on to different treatment places and then reported back to the collection companies. This is a huge limitation for the actual MFA, as the final treatment and recovery cannot be fully documented but is, instead, based on different assumptions such as the different materials being treated equally.

One thing is that the different material fractions are treated differently, but so are the different product categories. A different perspective on the MFA could be to follow each of the different product groups, as these are also treated differently. For the MFA, it is just about 2% of the total mass that is reused, where actually around 12% of product Category 2 is being reused and about 8% of product Category 6 is being reused (Table 3). The reuse for the different product groups is considered for the LCA for the substitution potential, but not for the material fractions. The material composition is different for each product category and higher reuse of smartphones would potentially lead to a lower recovery of copper than the MFA system indicates. How much is sent for energy recovery is also different across the product categories which can imply lower levels of recycling of some material fractions.

4.1.3 Comparison of material composition

The material composition of the different product categories is used for the overall material fraction of the total generated waste. This is not fully representative as one product for each product category is chosen, when in reality, the different product categories include many different products and product ages which results in a more diverse material composition than what is used for this project. It is estimated in this project that 20.6% of the total mass of electronic waste consists of plastics. This is somewhat close to the 17.5% that (John Baxter, Wahlstrom Margareta, et al., 2014) estimates the overall plastic percentage of e-waste to be in the Nordic countries.

If the copper, aluminium, and steel content is compared to the composition of electronic waste by Bigum et al. (Marianne Bigum, Brogaard, and Christensen, 2012), the fractions match quite well. For this project, it is considered that aluminium is 3.0% of the total mass of generated e-waste, copper is 4.3% and iron/steel is 65.1%. In the paper by Bigum et al., it is estimated that aluminium is 3.3%, copper is 4.4% of the total mass and iron is 40.2% of the total mass (Marianne Bigum, Brogaard, and Christensen, 2012). The copper content and aluminium content align very well with Bigum et al., but the steel content of e-waste in this project is much higher.

For this project, only one product per product category is used and the variety is therefore not fully representable for the actual composition of e-waste. For further research, it could be a good idea to validate the choice of products by doing a visual inspection of e-waste. This way it could be validated what product best represents the actual waste stream or if the product categories are highly mixed. This would also make it possible to see if products are old or newer according to the complexity of products, as the complexity is getting higher and higher over the years. A different approach could also be by constructing average compositions for each category based on multiple samples of products.

4.1.4 Potential recovery

The POM flow is included for the MFA even though this is not included in the system boundaries for the LCA. This flow is only used to enable the calculation of the losses from theft and legal/illegal export (Baxter et al., 2021), to understand the potential improvement of the system. In the Sankey chart in Figure 6 (supported by Appendix IV and Appendix V), it can be seen that more than 10,000 ton of electronic waste is lost to theft and legal/illegal export, and about 7,500 ton ends up in residual waste. The waste that is not collected for recycling is a loss for the potential recovery and can have a high environmental burden if disposed incorrectly.

4.2 Life cycle assessment

The findings from the conducted LCA in EASETECH will be presented. This section will present the different findings of midpoint impacts, impacts in Personal equivalent (PE), endpoint categories, results of the sensitivity analysis and uncertainty analysis. The discussions of the results from the LCA will follow in the next section "Interpretations".

4.2.1 Life cycle inventory

The system is set up in EASETECH with different processes of the model. The system is divided into 11 different processes for the different impacts in the LCIA. In Appendix IX the EASETECH model can be seen. The model has six different product categories as input to the collection point. This waste stream is transported to the reception point and further transported to pretreatment. At the pretreatment, the waste is split into different treatments; reuse, landfill, material recovery, and energy recovery. The different inputs to the process are the four different product categories that are misplaced in the residual waste and sent directly to energy recovery. The life cycle inventory of the model can be seen in Table 8 and the used parameters for the LCIin Table Appendix VIII.

4.2.2 Life cycle impact assessment

After setting up the model in EASETECH, the LCIA for the ReCiPe 2016 data was run for all 18 midpoint impacts. When running the LCIA, the impacts of each category were given for each of the processes in the system. To simplify and understand the impacts of each treatment process, the impacts were combined into 11 different treatment processes. The 11 different processes are; aluminium recovery, copper recovery, glass recovery, landfill, other metal recovery (including silver, gold, and nickel recovery), plastic recovery, pretreatment, reuse, steel recovery, transportation, and energy recovery. For more understandable tables and graphs, abbreviations for the 18 different impact categories are used. The different abbreviations can be found in Table 9. The different midpoint impact categories for the 11 different processes and the total for the whole system (annually in Norway) can be found in Appendix X. For most categories, the overall environmental impact of the whole system has negative values which indicates environmental savings. Only for the impact categories Marine eutrophication (EM), Ozone depletion (OD), and Terrestrial eco-toxicity (TET) are the environmental impacts for the system positive indicating an environmental burden.

Table 9: Abbreviation of midpoint impact categories

Name of midpoint impact category	**Unit**	**Abbreviation**
Climate change	kg CO_2-eq	GWP
Fine particulate matter formation	kg PM2.5-eq	PM
Terrestrial acidification	kg SO_2-eq	AT
Freshwater eutrophication	kg P-eq	EF
Marine eutrophication	kg N-eq	EM
Mineral resource scarcity	kg Cu-eq	MRS
Fossil resource scarcity	kg oil-eq	FRS
Ozone depletion	kg CFC-11-eq	OD
Ionising radiation	kBq Co-60-eq	IR
Photochemical oxidant formation: ecosystem quality	kg NOx-eq	POFE
Photochemical oxidant formation: human health	kg NOx-eq	POFHH
Terrestrial eco-toxicity	kg 1,4-DCB-eq	TET
Freshwater eco-toxicity	kg 1,4-DCB-eq	FET
Marine eco-toxicity	kg 1,4-DCB-eq	MET
Human toxicity: cancer	kg 1,4-DCB	HTC
Human toxicity: non-cancer	kg 1,4-DCB	HTNC
Land use	m2*yr annual crop land-eq	LU
Water use	m3 water consumed	WU

To sum up data for graphs for the four different impact categories, Appendix X can be seen. The chosen impact categories are GWP in kg CO_2-eq, Fine particulate matter formation (PM) in kg PM2.5-eq, Terrestrial acidification (AT) in kg SO2-eq, and OD in kg CFC-11-eq. All the impacts are calculated as the total emission of e-waste treated in Norway annually. The graphs can be seen in Figure 8. In the graphs, it can be seen that for GWP, PM, and AT, there is a total saving of emissions in the system, where the system has positive emission according to OD. A summary of the data used for the four different graphs can be found in Table 10 For the full list of impact per EASETECH process see Appendix XI.

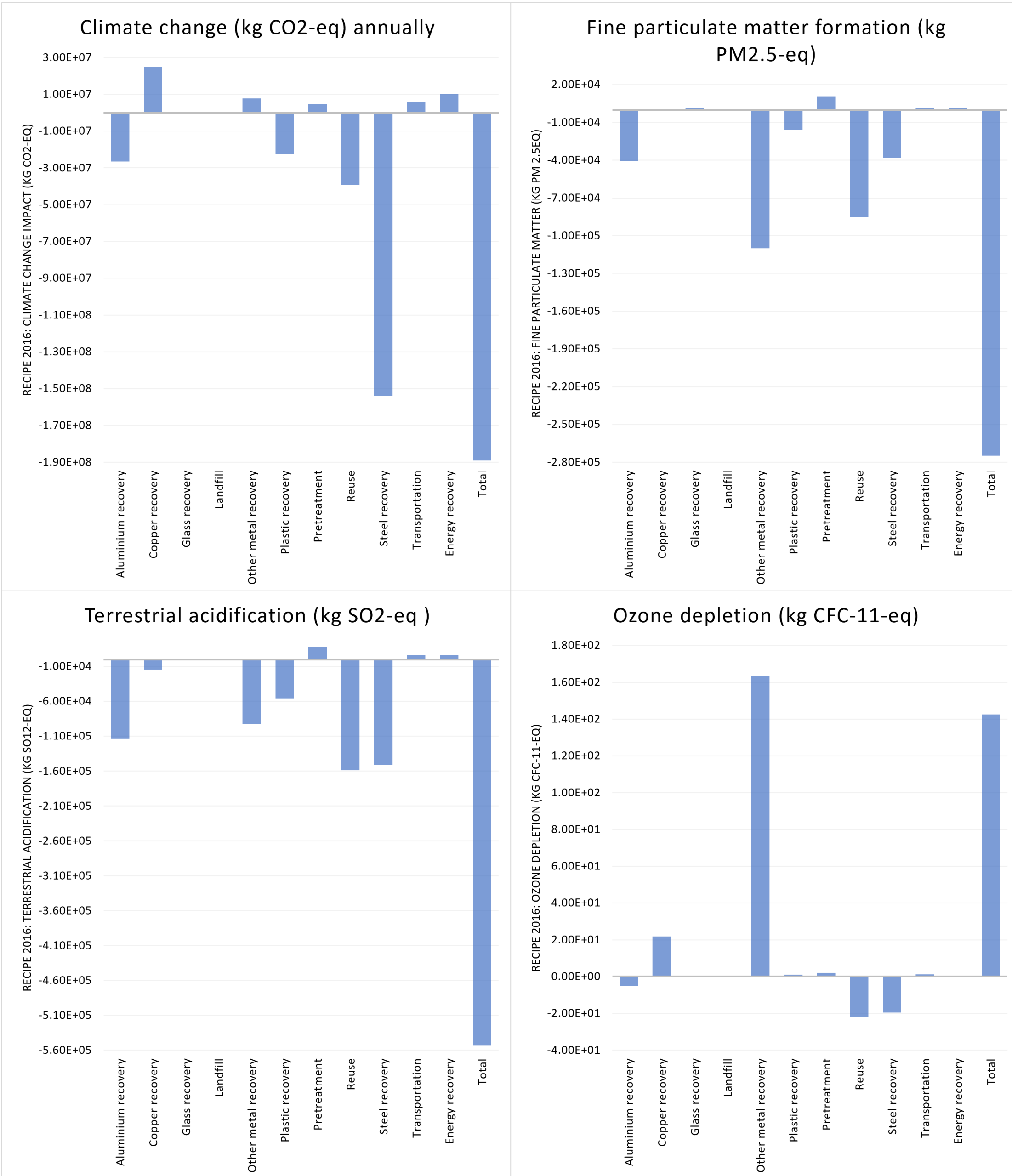

Figure 8: Emissions for four different midpoint impact categories, GWP, PM, AT and OD, for the different processes annually in Norway

Table 10: Data summary of the emissions for each process for the four different impact categories, GWP, PM, AT and OD, shown in Figure 8

Name	**Climate change (kg CO_2-eq)**	**Fine particulate matter formation (kg PM2.5-eq)**	**Terrestrial acidification (kg SO_2-eq)**	**Ozone depletion (kg CFC-11-eq)**
Aluminium recovery	-2.66E+07	5.26E+04	1.54E+05	5.62E+01
Copper recovery	2.48E+07	-8.79E+04	-2.64E+05	-3.93E+01
Glass recovery	-7.22E+05	-5.55E+03	-1.88E+04	-6.34E-01
Landfill	1.21E+05	2.35E+05	6.52E+05	2.41E+02
Other metal recovery	7.83E+06	-3.41E+05	-7.32E+05	-7.67E+01
Plastic recovery	-2.25E+07	-8.94E+03	-4.92E+04	1.98E+00
Pretreatment	4.82E+06	-8.66E+02	-2.07E+03	-3.46E-01
Reuse	-3.93E+07	-6.20E+04	-1.04E+05	-1.77E+01
Steel recovery	-1.54E+08	-3.36E+05	-7.57E+05	1.19E+02
Transportation	6.01E+06	1.77E+03	6.35E+03	1.21E+00
Energy recovery	1.01E+07	1.75E+03	5.92E+03	-3.43E-01
Total	-1.89E+08	-5.51E+05	-1.11E+06	2.85E+02

To better compare the different impact categories the LCIA results are normalised in EASETECH. The normalised results in PE can be seen in Appendix XII. The results for the normalised impacts can be seen in Figure 9, where the full graph is shown on the left and the graph for a zoomed view is to the right.

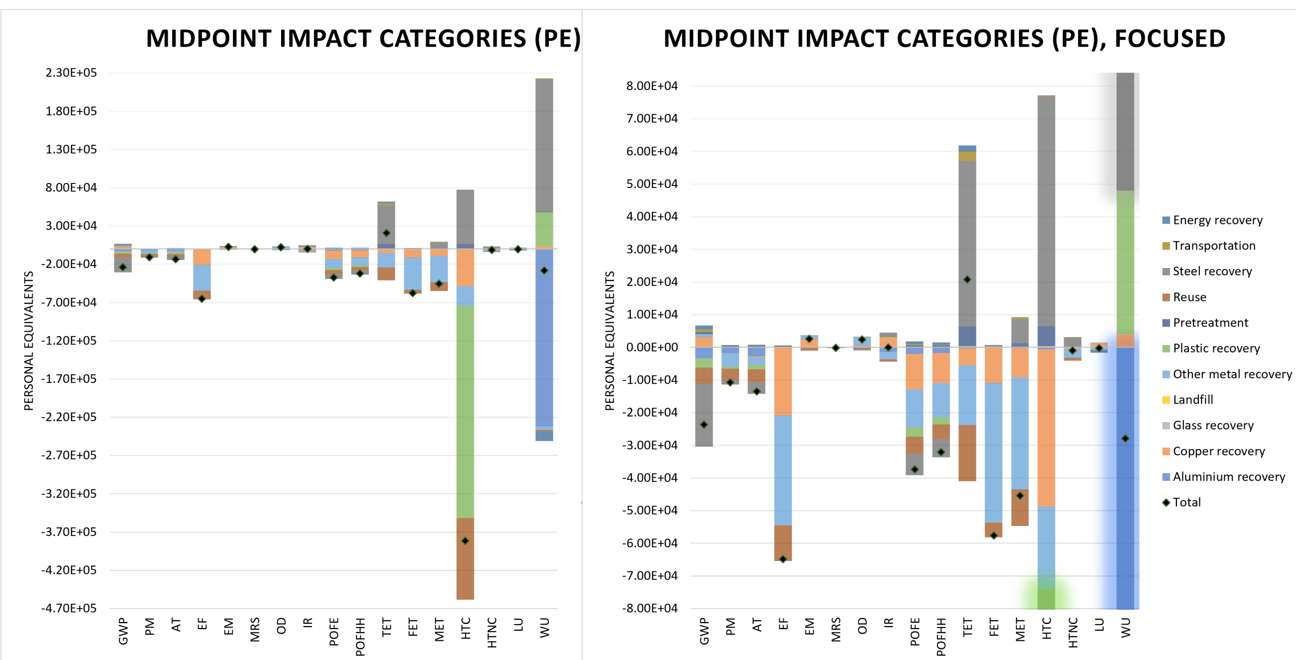

Figure 9: Normalised results for the different impact categories in PE

For the normalised impacts. it can be seen that the system leads to emission savings for most impact categories. The most significant impact inPEis the Human toxicity: cancer (HTC) impact category where the biggest saving for the system is seen.

The endpoint categories are calculated for the whole system (annually in Norway). There are three different endpoint categories, human health, ecosystems, and resource depletion. The different categories include different midpoint categories that are timed with a specific conversion factor to be calculated in the unit for the different endpoint categories. The first endpoint category that is calculated is human health which is calculated in Disability-adjusted life year (DALY). The graph of the different midpoint categories contributing differently for the 11 different processes can be seen in Figure 10. In the graph it can be seen that the emission savings from GWP and PM contribute the most to the overall calculated DALY. In Figure 11 the total contribution of each process to the human health endpoint impact can be seen. The aluminium recovery, followed by the reuse process, contributes most to savings for the human health impact. Other metal recovery also contributes to a large saving in DALYs.

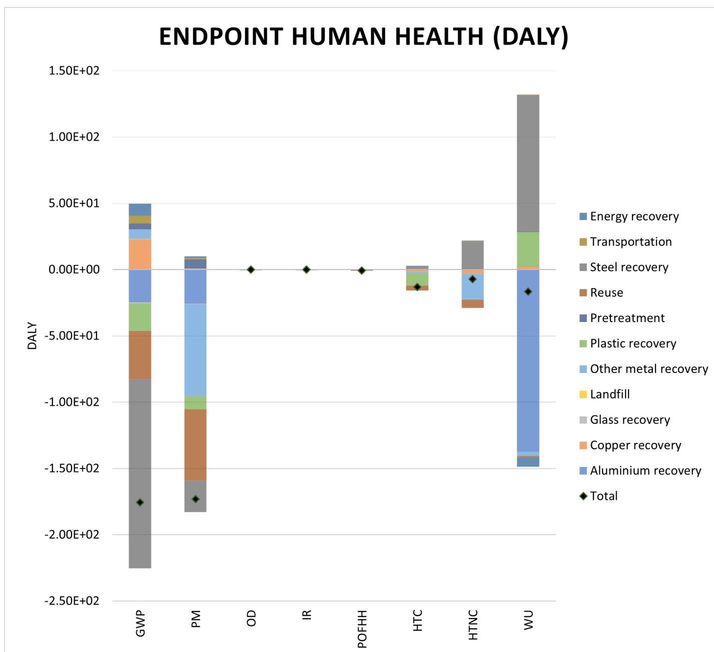

Figure 10: Endpoint impact for human health per impact category in DALY per year

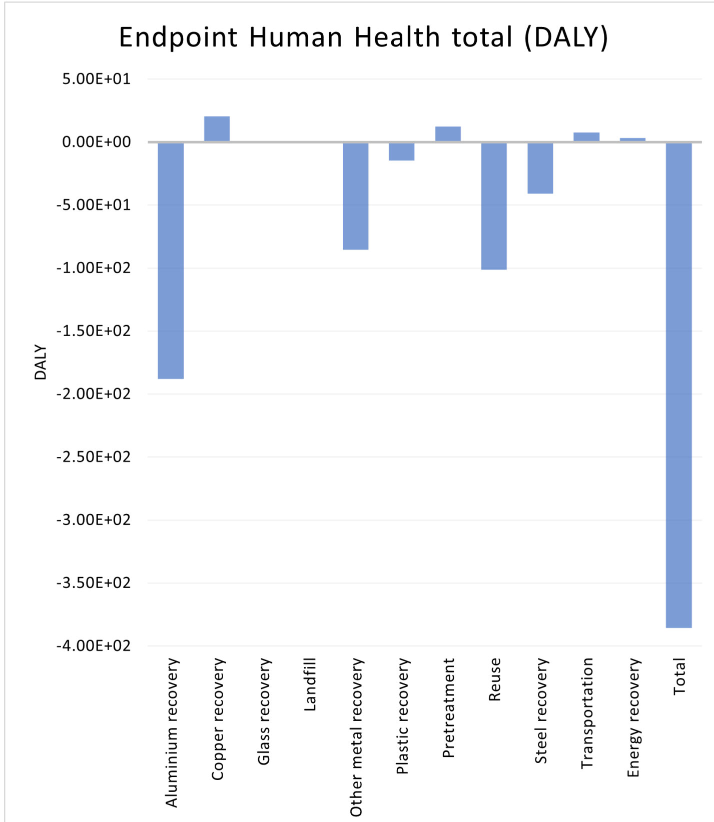

Figure 11: Endpoint impact for human health per process in DALY per year

The second endpoint category is the ecosystem impact. The ecosystem impact is calculated individually for the terrestrial ecosystem, freshwater ecosystem and marine ecosystem. The graph showing the ecosystem impacts can be seen in Figure 12. The impact of the terrestrial ecosystem has the highest contribution to the total ecosystem impact. The contribution to the ecosystem impact by processes can be seen in Figure 13. Aluminium recovery has the highest contribution to impact savings, where steel recovery has the highest gaining impact to ecosystems.

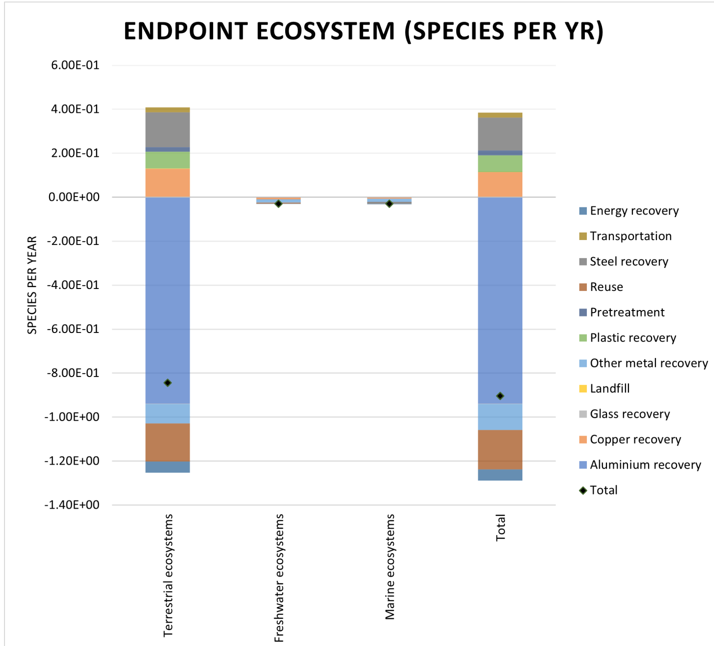

Figure 12: Endpoint impact for ecosystems per impact category in species per yearr

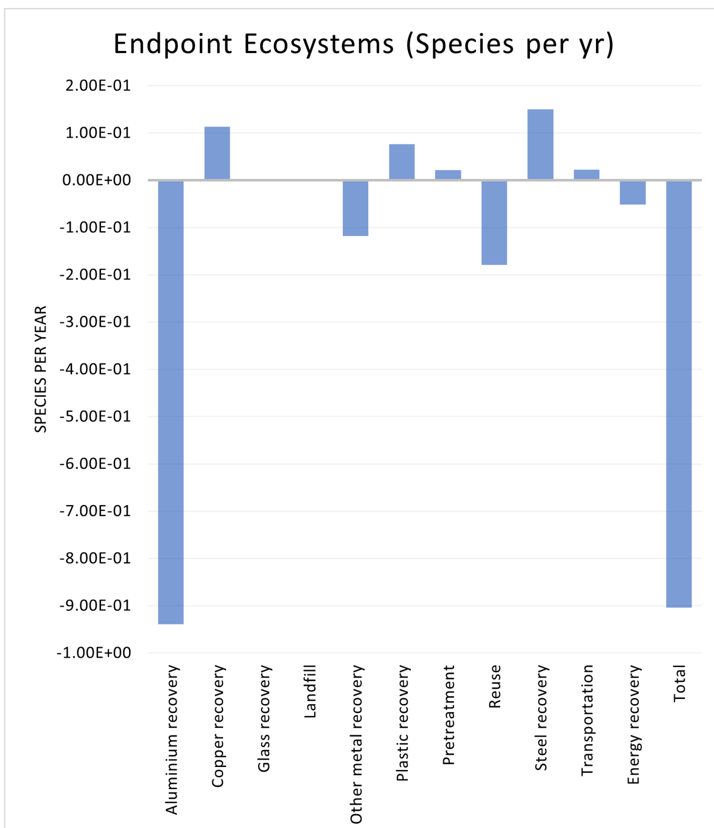

Figure 13: Endpoint impact for ecosystems per process in species per year

The last endpoint category is resource depletion in USD2013. The result for each process and the total impact can be seen in Figure 14. The largest savings are seen for the plastic recovery followed by steel recovery. Other metal recovery and copper recovery contributes to the resource depletion endpoint category.

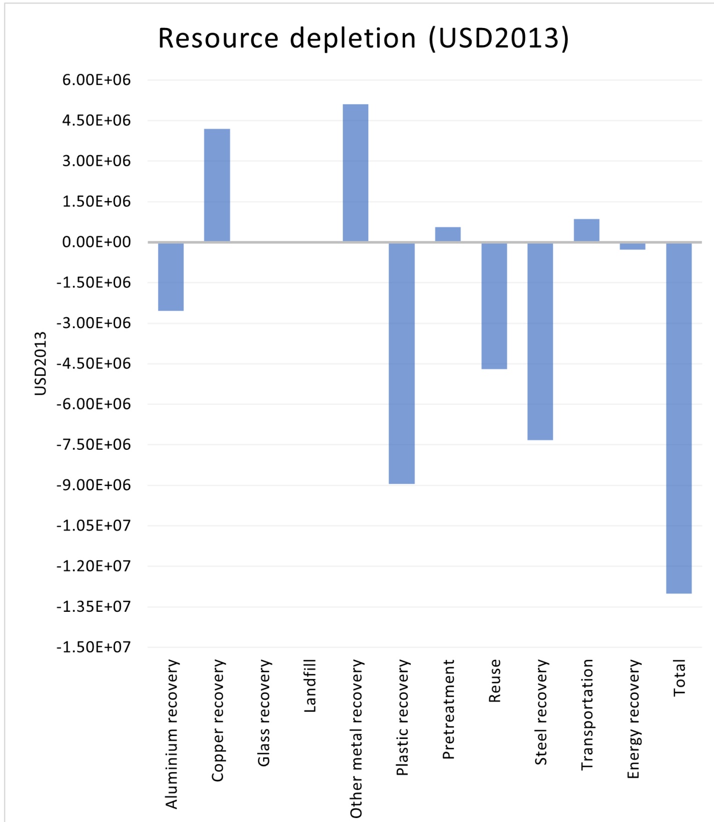

Figure 14: Endpoint impact for resource depletion per process in USD2013 per year

4.2.3 Sensitivity analysis and uncertainty analysis

The perturbation analysis is run for all parameters with an increase of 10%. The results of all parameters for all the midpoint categories can be seen in Appendix XIII, where the sensitivity ratio higher than 0.2 and lower than -0.2 is marked in red. The majority of the different impact categories have an overall negative impact score for the sensitivity analysis, which indicates that an overall increase in parameters of 10% would result in higher environmental savings. All midpoint impact categories except EM, OD, and TET has an overall negative impact score if increasing all parameters by 10%.

To highlight the most sensitive parameters according to the sensitivity analysis, the most sensitive parameters for three chosen impact categories can be seen in Table 11. The three impact categories chosen are GWP, Ionising radiation (IR), and Water use (WU). Climate change is an interesting midpoint impact category, and the two others are shown as these had the most sensitive parameters. In the table, only SR values higher than 0.1 and lower than -0.1 are shown for the three different impact categories. The five most sensitive parameters for each category are shown and the most sensitive parameter for each category is marked in bold. For climate change the most sensitive parameter is total_WEEE (total mass of generated e-waste) of 1.02, meaning that the climate change impact increases by 1.02% when the total_WEEE parameter increases 1%. The most sensitive parameter according to the change of ionising radiation is the Pt_MR_Copper (Share of copper sent to material recovery from pretreatment). The most sensitive water use parameter is the Recycling_Aluminium (recycling efficiency of aluminium).

Table 11: Highlights sensitive ratios (SR) for most sensitive parameters. The five most sensitive parameters per impact category and the largest for each impact category are marked in bold. SR values higher than 0.1 and lower than -0.1 are included in the table

Parameter name	Climate change (SR)	Ionising radiation (SR)	Water use (SR)
PT_MR_Alu	1.40E-01	2.84E+01	8.32E+00
PT_MR_Copper	-1.32E-01	**-6.60E+01**	-1.43E-01
PT_MR_Other		5.19E+01	1.73E-01
PT_MR_Steel	8.03E-01	-2.16E+01	-6.25E+00
Recycling_Aluminium	1.45E-01	2.85E+01	**8.33E+00**
Recycling_gold		3.22E+01	2.96E-01
Recycling_other		5.51E+01	
Recycling_steel	8.90E-01	1.12E+00	
Share_Cat4	4.12E-01	-1.62E+01	-2.18E+00
Share_Cat5	3.09E-01	1.26E+01	2.97E+00
Total_WEEE	**1.02E+00**	1.07E+00	8.43E-01

The list of parameters and the used standard deviation for each parameter can be seen in Appendix XIV. The uncertainty analysis is run for the IPCC 2021 w LT (GWP100), where the ReCiPe 2016 was used in previous results. To see the differences in the results of climate change impacts (in kg CO_2 eq) for the two methods, consult Figure 15.

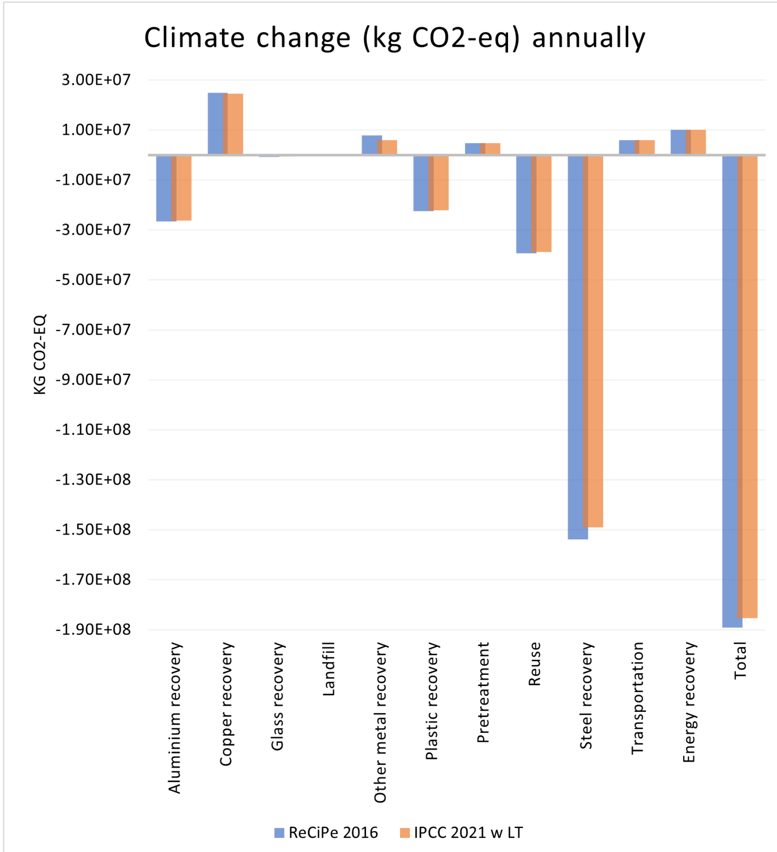

Figure 15: Comparison of results for climate change impacts for the ReCiPe 2016 method and IPCC 2021 (GWP100) method in kg CO_2-eq annually

In Appendix XIV the relative standard deviation in percent can be seen for each parameter. The most uncertain parameter is Reuse_Cat1, which is the percentage share of product Category 1 that is sent to reuse. This parameter is uncertain as the amount of product Category 1 sent to reuse varies over the four years. 17 parameters have a relative standard deviation of more than 25%, which shows high parameter uncertainty. The uncertainty analysis is run for all parameters for 10,000 Monte Carlo simulations. The results for the found mean, standard deviation, and variations can be seen in Appendix XV for each EASETECH flow. The results, including the uncertainty for the 11 different processes and the total climate change impact, can be seen in Figure 16. Here, it can be seen that there is especially high uncertainty for the other metal recovery. The total climate change impact found based on the LCA model of treating e-waste in Norway annually is high.

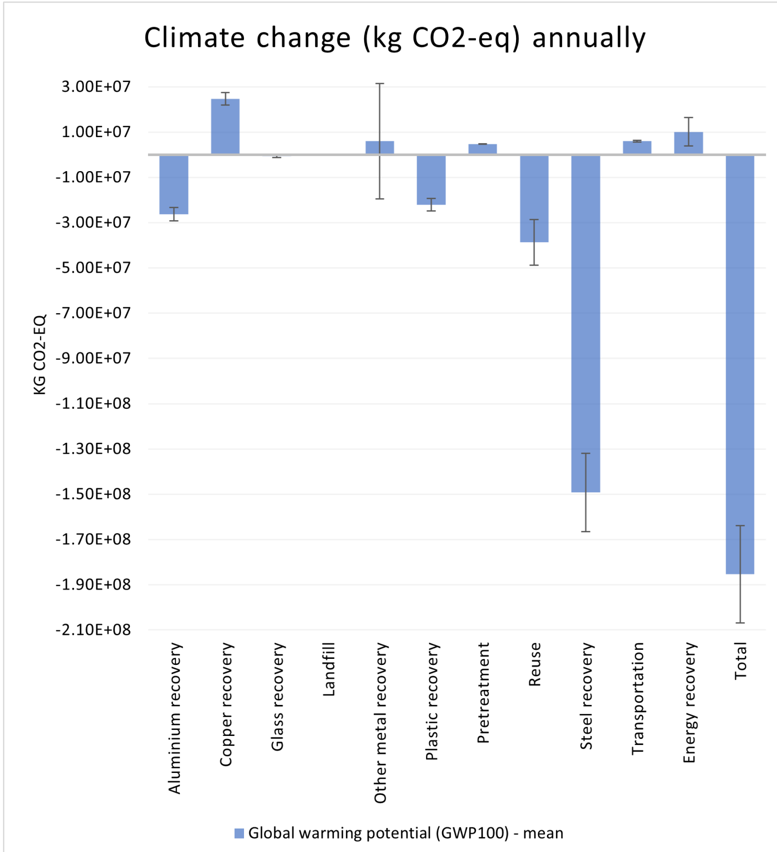

Figure 16: Climate change impacts for the 11 different processes and the total in kg CO_2-eq annually including the uncertainties for each process

4.2.4 Product categories

The material composition of the different product categories is different and the global warming potential (IPCC 2021) is found for each product category annually in comparison to the other product categories. In Figure 17, the global warming potential for the different processes across the different product categories can be seen. The steel recovery has the most significant impact on product categories 1, 4, and 5, whereas the copper recovery and plastic recovery have the most significant impact on product Category 6. In Figure 18, the uncertainty for the GWP is included for all product categories. In Table 12, the mean, standard deviation, and relative standard deviation for the global warming potential across each product category can be seen.

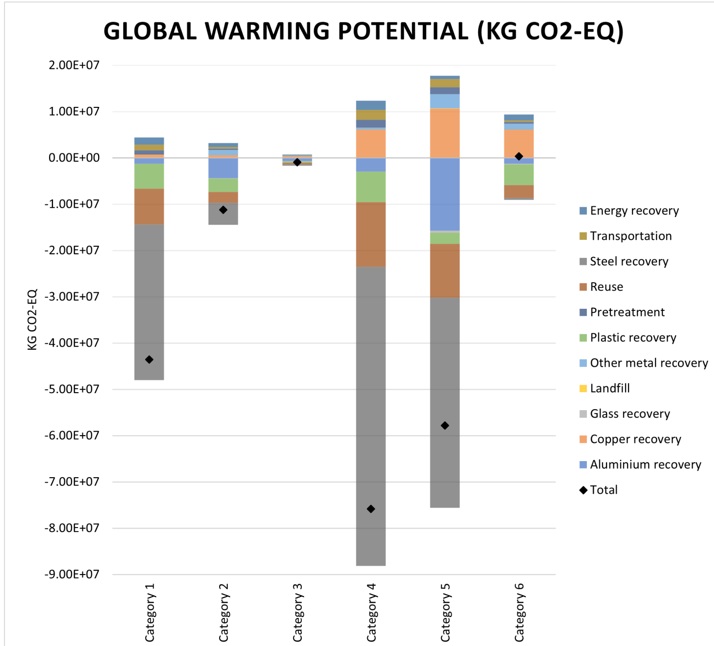

Figure 17: Global warming potential for the different processes for each product category

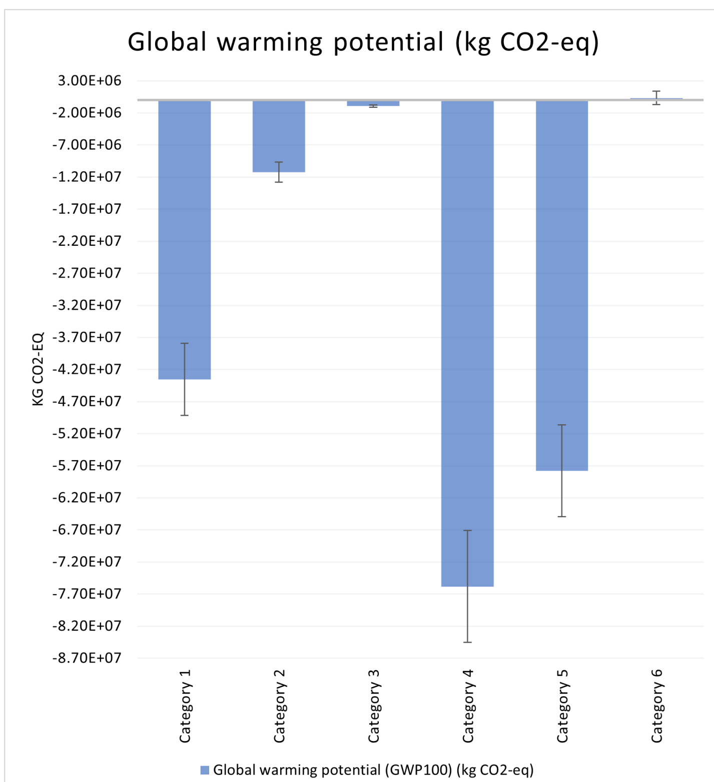

Figure 18: Global warming potential for each product category and the uncertainty

Table 12: GWP100 data for the different product categories, showing mean, standard deviation, relative standard deviation and the global warming potential per kg e-waste

Name	**Global warming potential (GWP100) (kg CO_2-eq)**	**Standard Deviation**	**Relative Standard Deviation**	**Global warming potential (GWP100) (kg CO_2-eq/kg waste)**
Category 1	-4.35E+07	5.60E+06	-13%	-2.06
Category 2	-1.12E+07	1.57E+06	-14%	-1.64
Category 3	-9.44E+05	1.63E+05	-17%	-0.90
Category 4	-7.58E+07	8.73E+06	-12%	-1.99
Category 5	-5.78E+07	7.17E+06	-12%	-1.80
Category 6	3.33E+05	1.06E+06	316%	0.04
Total	-1.89E+08	2.09E+07	-11%	-1.76

4.2.5 Potential savings

All the given results are for the annual system in Norway. This includes the e-waste that is misplaced in residual waste and incinerated. If losses from e-waste in residual waste and losses of e-waste to theft and export are avoided, the climate change savings are quantified for one tonne of e-waste to understand the potential of saving the environmental impact by collecting and treating the lost e-waste. In Figure 19 the savings of collecting and treating one tonne of e-waste can be seen, the material composition is the same as for the total amount of collected e-waste in Norway used for the LCA.

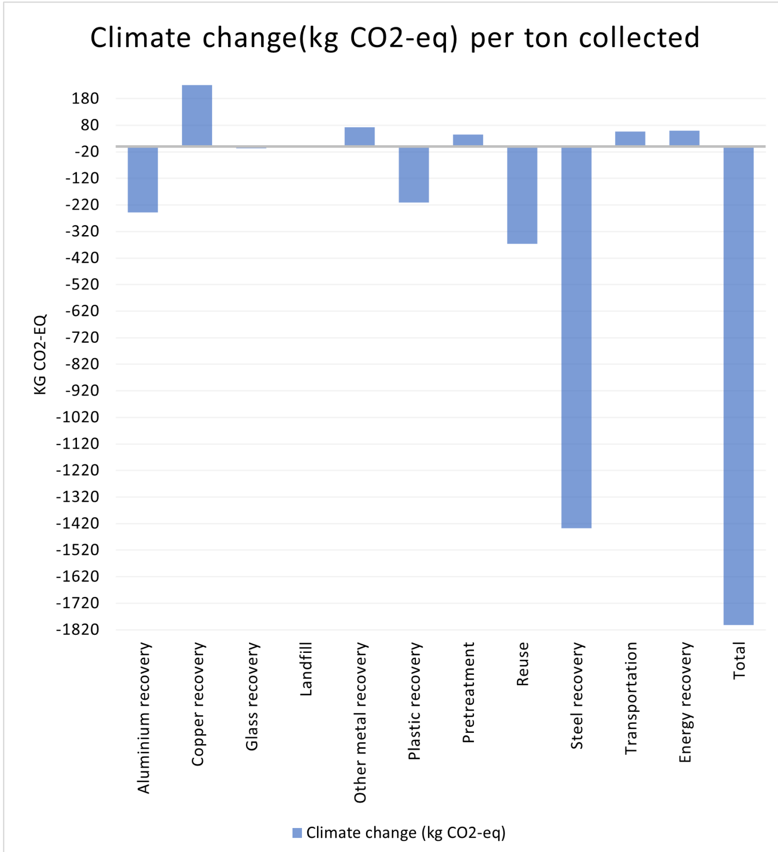

Figure 19: Climate change impact of collecting and treating 1 ton of e-waste

4.3 Interpretations

The interpretations section will discuss the results of the LCA. It addresses the different midpoint impacts of the different processes and looks into endpoint impacts to compare the different recovery processes in the system.

4.3.1 Midpoint impacts from the system

Looking at the different midpoint impacts shown in Figure 8, the highest environmental savings for climate change are most significant for steel recovery, but reuse and plastic recovery do also have high impact savings. It thus shows that copper recovery is the process that emits the most kg CO_2-eq annually. Other metal recovery also emits CO_2-eq annually instead of saving emissions as expected. The processes landfilling, pretreatment, transportation, and energy recovery lead to CO_2-eq annually. From the found climate change impacts, the system questions if it makes sense to recover copper and other metals as these processes lead to climate change emissions.

The causes of this may be the chosen Ecoinvent processes for the recovery treatment of copper and the recovery treatment of other metals as well as the production of primary copper, gold, silver, and nickel that is being substituted in the system. For the system, the total mass of other metals sent to material recovery is treated according to Ecoinvent data for "treatment of precious metal from electronics scrap, in anode slime, precious metal extraction". This process causes high emissions that, potentially, are not showing a realistic picture, but the highest emissions are from treating gold, silver, and nickel individually. In the model, only silver, nickel, and gold are recovered, but there is a potential of higher substitution of other metals in this material fraction such as lead, zinc, mercury etc. So for the recovery of other metals, there is a potential of including more metals to be recovered which could potentially lead to lower emissions.

Looking into other midpoint impacts, it is found that steel recovery has the highest CO_2-eq savings for GWP while it also has the highest impact of all 11 processes for 6 of the 18 impact categories (TET, Freshwater eco-toxicity (FET), Marine eco-toxicity (MET), HTC, Human toxicity: non-cancer (HTNC) and WU).

Recovery of other metals leads to emissions of CO_2-eq and also the highest impact of all processes for OD. However, the other metal recovery is the process saving the most emissions for 8 out of 18 impact categories (PM, Mineral resource scarcity (MRS), IR, TET, FET, MET, HTNC and Land use (LU)).

Copper recovery has the highest impacts of all processes for GWP, EM, Fossil resource scarcity (FRS), IR, and LU. However, Copper recovery saves the most emission of all processes for Photochemical oxidant formation: ecosystem quality (POFE) and Photochemical oxidant formation: human health (POFHH). From the found midpoint results, it is hard to estimate the most important recovery process in terms of environmental impacts.

4.3.2 Personal Equivalents

To better compare and understand the different impact categories side by side, the normalised impacts in PE are reviewed. Looking at the normalised impacts in personal equivalents for the system, the highest environmental benefit in PE is the "human toxicity: cancer" impact category. For the normalised impacts, steel has a significant bad influence on terrestrial ecotoxicity, human toxicity: cancer and water use, whereas plastic recovery has the most significant benefit to human toxicity: cancer. Reuse, copper recovery, aluminium recovery and other metal recovery have a highly visible beneficial impact on different impact categories.

The findings, showing that the recovery of copper and recovery of other metals for the model leads to climate change emissions, contradict the findings of Bigum et al. (Marianne Bigum, Brogaard, and Christensen, 2012). Here it was found that recovering aluminium, copper, gold, iron, nickel, palladium, and silver from e-waste offers environmental savings across all impact categories (Marianne Bigum, Brogaard, and Christensen, 2012). The normalised results in personal equivalences showed that the recovery of metals palladium, gold, silver, nickel, and copper appeared to have a greater significance compared to the recovery of iron and aluminium, despite the fact that larger quantities of iron and aluminium are recovered (Marianne Bigum, Brogaard, and Christensen, 2012). This indicates that the metal recovery of precious metals is an important aspect of e-waste treatment, even though the recovery rates are low. This emphasises the importance of setting recycling targets based on the recovery of individual metals by value rather than a general weight-based approach (Marianne Bigum, Brogaard, and Christensen, 2012). This is not at all clearly shown in the results of the system model. This could be further investigated by looking at the per kg treatment of each material instead of the total amount of treated e-waste annually, as it would help understand the different impacts per material in equal amounts.

4.3.3 Endpoint impacts from the system

From the found midpoint results, it is hard to rank which process is the most beneficial process from an environmental perspective. The endpoint is more efficient to be able to compare the different processes and their following environmental impact.

The calculated human health impact based on the midpoint impacts shows that the human health impact is mostly influenced by climate change impacts and particulate matter formation impacts. The overall human health impact of treating e-waste in Norway from this system saves DALYs. The savings in DALYs is mostly contributed by the recovery of aluminium, followed by the reuse and recovery of other metals. According to these findings, the importance of recycling aluminium and other metals is seen. Even though steel is recovered in much larger quantities, the benefit of recovering steel according to the human health impacts in DALYs is not as high as prioritising reuse, recovery of aluminium, and recovery of other metals. These results also show that copper recovery leads to an increase in DALYs and indicate that if this system showed the reality, copper recovery should be reduced in order to save DALYs annually. For further investigation, the copper recovery would need to be explored to understand how much lower the environmental impact of copper recovery could be.

If looking at the impact on ecosystems, the decision-making of which processes of e-waste treatment to prioritise would look a bit different. The overall endpoint impact for ecosystems shows savings of treating e-waste in Norway. The recovery of aluminium has the highest beneficial impacts on the ecosystems, where copper recovery, plastic recovery and steel recovery lead to losses of species per year for the ecosystems. Reuse and other metal recovery are both processes that benefit the ecosystems. From an ecosystem point of view, aluminium recovery, reuse, and other metal recovery should be prioritised, whereas copper recovery, plastic recovery and steel recovery should be lowered. Furthermore, energy recovery is also benefitting the ecosystems. For the model, it is assumed that all material fractions are equally sent to material recovery, in reality, more plastic is sent to incineration and more steel is sent to material recovery. If more plastic is sent to energy recovery, the overall ecosystem impact would benefit more from energy recovery and less from the losses from plastic recovery.

The third endpoint category is resource depletion which indicates the extent of resource depletion caused by the system. Copper recovery and other metal recovery causes the most resource depletion in the system reducing the availability of resources in the future. Plastic recovery, steel recovery and reuse are negative indicating resource savings or avoidance. The processes are contributing to resource savings or avoidance of further resource depletion.

Even though the endpoint impacts do not give a clear answer on what process of the e-waste recovery system is most important to all endpoint impacts, it is clear that reusing e-waste and recovering aluminium has positive impacts on all three impact categories. Other metal recovery has savings of both human health and ecosystem impacts, which does show the potential of recovering gold, silver and palladium from other metals. These benefits to the system are potentially higher if more metals are considered recovered in this material fraction.

4.3.4 The sensitivity and uncertainty of the system

The sensitivity analysis showed that some parameters were more sensitive than others and that the sensitivity of the analyses differed between impact categories. A parameter being sensitive does not necessarily mean that the parameter is uncertain. The input flows of the system are dependent on the total collected e-waste. This parameter is the most sensitive parameter for the climate change impact, but the relative standard deviation of the parameter is 0% showing that the parameter is not uncertain but most sensitive. Steel is, by mass, the biggest material fraction throughout the system and has a high share of the climate change benefits in CO_2-eq which gives the second and third highest sensitivity for the parameters of the recycling efficiency of steel as well as the highest share of steel sent to material recovery from pretreatment. These two parameters control big mass flows and it therefore makes sense that these are sensitive.

The size of the standard deviations indicates that the uncertainty of the model is high. The total climate change impact has a relative sensitivity of 12 % and looking at the different processes, the highest uncertainty is seen for the recovery of other metals by a relative sensitivity of more than 400%. The recovery of glass is, furthermore, also very uncertain by a relative sensitivity of 81%. From these high uncertainties of especially other metals that have a meaningful impact on ecosystems and human health, it is difficult to conclude from the found results if this process should be recovered, as it is very uncertain. The uncertainty of this process could lead to higher or lower climate change impacts.

4.3.5 Impact by product categories

The impact of treating e-waste from the different product categories does have different impacts, as the material composition varies for the different product categories. When looking at the total impact of each product category being treated annually in the model, the highest environmental savings are for the two largest product categories by mass (categories 4 and 5). All product categories have a net savings of CO_2-eq annually except Category 6 which leads to emissions. Smartphones (Category 6) have a high copper content, and as this process leads to emissions in the system, the overall impact of treating Category 6 leads to emissions as well. According to the LCA made of treating a refrigerator, LCD-screen, and smartphone in Norway, it was found that recycling of all three products leads to environmental savings for the climate change impact category (John Baxter, Lyng, et al., 2016).

The environmental impacts per product was found to be -0.4 kg CO_2-eq per kg refrigerator (John Baxter, Lyng, et al., 2016), -1.5 kg CO_2-eq per kg LCD screen (John Baxter, Lyng, et al., 2016) and -6.1 kg CO_2-eq per kg smartphone (John Baxter, Lyng, et al., 2016). From the EASETECH model, it was found that recycling 1 kg LCD screen (Category 2) saved -1.64 CO_2-eq, where recycling 1 kg smartphone lead to emissions of 0.04 kg CO_2-eq. These findings can be seen in Table 12. The findings of this project contradict the findings from (John Baxter, Lyng, et al., 2016). There are multiple possible reasons for this. One of the most important reasons is the copper recovery leading to emissions, instead of lowering emissions as Bigum et al. study shows (Marianne Bigum, Brogaard, and Christensen, 2012). High uncertainties of the system also have limitations. The most expected limitation of this project is the assumption of material fractions evenly being sent to material recovery.

4.3.6 Potential savings from losses

In the MFA system, the losses of waste being lost before collection is estimated to be more than 10,000 t and furthermore, 7,500 t are lost as misplaced in electronic waste. The e-waste ending in residual waste is included in the LCA model and sent to energy recovery. The energy recovery leads to higher environmental impacts that could potentially be prevented if e-waste in residual waste was avoided - either on the consumer side or before energy recovery. This shows a huge potential for improving the system. If the lost e-waste was prevented from theft or legal/illegal export, the potential of saving emissions from treating e-waste in Norway would have an even higher potential. The model reflects a potential saving of 1,802kg CO_2-eq per treated tonne of e-waste. Preventing losses from e-waste in residual waste and e-waste being lost under other circumstances has a high potential. Lastly, there is also a potential of the e-waste being stored in private households.

4.4 Further work

The outcomes of this project provide a foundation for future investigations, given the simplified approach used in the conducted MFA and LCA. Different things could be improved by more detailed research, but different recommendations to further work can be estimated after the findings of this project.

The environmental savings of value recovery should be further studied to uncover the full potential and benefits of including value recovery in recycling regulations of e-waste. The LCA model did show that the human health impact and ecosystems impact benefitted more from recovering gold, silver, nickel and aluminium than the recovery of high quantities of steel, which potentially shows benefits of value recovery over mass recovery. The uncertainty of this study is though very high, and this cannot be concluded from these investigations.

Reuse shows environmental savings for all impact categories. The overall reuse in Norway is only about 2% and the potential of reusing products, components, and materials within the electronic equipment industry should be further investigated. A way to prevent losses from theft and export, losses of e-waste ending in residual waste, and potential e-waste stored in private households could be a paid take-back collection, where consumers get money back for returning e-waste. Some stores do this, and it could be valuable for further analyses to investigate how efficient and popular this is, and if the reuse potential of products and components increases.

There is no working secondary raw material market for e-waste. This could indicate that the materials recovered from e-waste are not going back into the same industry and are instead being downcycled or sold to different industries. This would be interesting to investigate, as it could potentially validate the use of substitution of the model. In the system model, the recovery materials are considered to be of quality to directly replace primary materials, but this would need to be further researched to fully understand the actual substitution potential.

The industry is not that transparent and the most accessible information are the ones the industry is obligated to give. The information given by the industry about the recovery of materials lacks supporting evidence of actual recovery efficiencies and what materials that are recovered. This is a limitation to the data collection and results in high uncertainties. It was attempted to get into contact with the industry several times, but most companies, both return companies and treatment facilities did not respond. The ones that did respond, gave very useful information, but there are still remaining knowledge gaps in the industry that need to be better understood.

The regulations of e-waste are detailed to some points, but there are still questions that are unanswered in the national regulations on e-waste. One question the user sits back with is what the different treatments that are being documented are. Thermal destruction and other treatment, are two treatment types that are not described for the user to understand. Furthermore, the return companies report that some e-waste is collected at other collection facilities, which are not stores or collection facilities run by municipalities.

The highest limitation of this project is the material recovery of different material fractions. The material recovery process modelled is based on assumptions with varying degrees of certainty. More precise data provided on these processes would significantly improve the representativeness of the model. For example, 82% of other metals are sent to material recovery but Bigum et al. states that only 26% of gold is recovered from pretreatment (Marianne Bigum, Brogaard, and Christensen, 2012). The same accounts for plastic where it is estimated that less than 30% of plastics in e-waste are recovered (John Baxter, Wahlstrom Margareta, et al., 2014). It is expected that the recovery of steel is even higher than considered in this system (Marianne Bigum, Brogaard, and Christensen, 2012). Improving the material recovery process could potentially show more beneficial results for different processes or the upper set.

5 Conclusion

In conclusion, the current flow of electronic waste generation in Norway involves the collection of approximately 107,000 tonnes of e-waste annually by four different return companies. The collected waste is then directed toward various treatment options, including reuse, material recovery, landfilling, energy recovery, thermal destruction, and other treatments. The material recovery differs between the different material fractions. From the found composition of electronic waste including precious metals, aluminium, steel, and copper, the mass flows of different metals are found. These flows show a potential for higher recovery rates of metals of high quantity such as steel, where the recovery efficiencies of palladium, gold, and silver are much lower. An even higher potential of material recovery is from lost waste ending in residual waste or ending up stolen or exported. These losses make up 17,000 tonnes annually and state an option for improvement.

The environmental impact of collecting and treating electronic waste annually in Norway results in overall environmental savings for almost all midpoint categories. Notably, steel recovery leads to significant savings in climate change impact, while copper recovery and recovery of other metals show emissions gain, which differs from some previous studies. These contradictory findings emphasise the need for further research and consideration.

Determining the prioritisation of material recovery based on environmental impacts requires careful evaluation. The analysis indicates that steel recovery has negative implications for ecosystems and is less favorable compared to other metal recovery and aluminium recovery. Copper recovery shows negative environmental impacts according to the model. The modelled system has high uncertainties, especially for other metal recovery. The overall system of treating e-waste in Norway annually exhibits a 12% level of uncertainty. Reuse emerges as a highly beneficial approach, and aluminium recovery demonstrates positive performance in terms of endpoint categories.

To effectively prioritise material recovery, it is recommended to focus on treating lost waste and waste found in residual waste, as these sources possess high potential for recovery. Further research and analysis are necessary to refine the prioritisation process and gain a more comprehensive understanding of the environmental impacts associated with different materials and recovery methods.

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7 Appendix

7.1 Appendix I

Table 13: Reach out matrix

Company	Contact form and status	Response
Produsentansvar (Miljødirektoratet)	1. Email sent with questions 25-01-2023 2. Response the 25-01-2023 that I should fill out contact form 3. Contact form filled out the 25-01-2023 4. Email sent again 07-02-2023 to hear about answer time on contact form 5. No response to second email or contact form	No
REVAC	1. Email sent with questions 25-01-2023 2. Email sent again with questions 08-02-2023 (vekt@revac.no) 3. Contact formular with direct email contact sent with questions 20-04-2023 4. No response to any of the three emails	No
Norsk gjenvinning	1. Contact formular filled out 25-01-2023 2. Filled out again the 08-02-2023 3. No response to the 2 sent contact forms	No
Norsk gjenvinning metal (NG metal)	1. Email sent with questions 08-02-2023 2. Teams meeting with Charlotte 02-03-2023 to understand NG metal process	Yes - very usefull
Zirq Solutions	1. Email sent with questions 08-02-2023 2. Email sent again with questions 23-02-2023 3. No response to the 2 emails	No
Recipo	1. Email sent with questions 08-02-2023 2. Email sent again with questions 23-02-2023 3. No response to the 2 emails	No
Renas	1. Email sent with question 08-02-2023 2. Answer from Renas 10-02-2023. Kind and quick response refering to producentansvar and article from 2016 and saying that I could return with specific questions 3. New email with specific questions sent 13-02-2023 4. No response to second email	Yes
Heimdal gjenvinningsstation	1. Email sent with questions 23-02-2023	No
Metallco EE	1. Email sent with questions to Metallco Trondheim the 27-02-2023 2. Answer from Metallco 27-02-2023 sending me on to Metallco Gjørvik 3. Email sent with questions to Metallco Gjørtvik the 27-02-2023 4. Answer from Metallco 27-02-2023 with a short description of the process 5. More questions sent to 01-03-2023 6. Answer with good information 01-03-2023	Yes - very usefull
Hellik Teigen AS	1. Email sent with questions 27-02-2023	No
Stena recycling	1. Email sent with questions to Stena Recycling Hommelvik 27-02-2023 2. Response from Stena Recycling Hommelvik 28-02-2023 sending me on to Stena Recycling Frogner 3. Email sent with questions to Stena Recycling Frogner 01-03-2023 4. Teams meeting with Knut 08-05-2023 to understand Stena recycling processes	Yes - very usefull
Østbø	1. Email sent with questions 27-02-2023	No

7.2 Appendix II

Appendix II A

Meeting summary from Teams meeting the 08-05-2023 with Knut Sælid, Operations Manager/ Technical Manager WEE in the WEEE department at Stena Recycling AS:

In a meeting with Knut he tells about how the Stena Recycling concern works. Stena Recycling has 13 different treatment places in Norway, some are small collection points where a bit of sorting of the received waste happens and some are bigger with different treatment capacities and expertise. The treatment of electronic waste mainly happens at the Stena Recycling Ausenfjellet in Frogner, Norway. At Ausenfjellet they are taking the first steps of treating the electronic waste and ensuring that all hazardous elements are removed, waste is taken out and different material fractions are sorted out before the different material fractions are sent to Stena Recycling Halmstad in Sweden for further recycling treatment. The only hazardous waste that is not removed before Halmstad is flame-retardant plastics that can be treated in Halmstad. The treatment of different material fractions in Halmstad is the final treatment for most materials before the materials go on to the market as secondary materials. All the 13 different branches in Norway can receive all types of electronic waste, some of the electronics of specific categories are sorted at the first branch, some are sent on for dismantling/sorting at Ausenfjellet and some categories need mechanical dismantling/sorting which is done at Stena Recycling in Halmstad. In Ausenfjellet the fractions for reuse and the hazardous waste fractions are removed and then the waste is shredded. After the shredding process, the iron is removed and sent on to a smelting plant in Norway, other useful materials are sent on to treatment in Halmstad and the waste fractions are sent to incineration and landfilling in Norway.

Stena Recycling takes in all product categories of electronic. Stena Recycling has a strong desire to recycle as much as possible, including precious metals. Knut said that Stena Recycling Halmstad have about 32 subgroups of materials that are being treated. For example, about 9 subgroups of different plastic types. 4 of these are sent directly to incineration where other plastic groups are recycled and can be used and recycled up to 7-8 times. Stena Recycling has contracts with the return companies, Renas, Norsirk and EPR Norway. The last return company Recipo has contracts with Revac. Stena Recycling and Revac is taking care of about the same amount of electronic waste (around 50.000-60.000 ton annually). It is different from year to year who has the highest share but at the moment Stena Recycling treats more e-waste than Revac he says. The key numbers reported by the return companies should show the reality of most of the value chain as the numbers Stena Recycling reports to the return companies include both Norway and Sweden treatment to some extent.

The industry of treating electronic waste in Norway is somewhat kept very secret. No one is sharing information on the recovery of materials, the different capacities and treatment processes are kept secret. Only information on the total masses collected and the treatment type the waste is sent on to is shared, for the return companies to report to 'Produsentansvar'. Knut does not understand why the industry is so secret because all companies are checked to see if they follow the regulations on electronic waste and it is not that they are doing anything illegal. His experience is though that the industry is less secret than it was earlier at least his experience is though that it is less a secret now than it was back in the day. It was a more simple system before. Then there were only 2 different return companies (Renas and Norsirk (Elretur at that point)). Norsirk collected consumer electronics and Renas took care of industrial and large electronics. Today it is a much more complex system as more return companies are competing and all have the same responsibilities and no clear allocation /distribution. Even though he was very willing to share information on the processes at Stena Recycling he is not interested in sharing all Stena Recycling recovery treatments, recycling options and capacities with the competitors in the industry.

Even though the electronic waste industry in Norway is very secret to the public they are required to follow the regulations and are controlled by different stakeholders. Stena Recycling and other treatment places require lots of documentation that are then checked. The company is monitored by both the return companies, public administrators and the Norwegian Environmental Agency to keep checking the process, permits etc. of Stena Recycling to make sure all actors in the value chain follow the national regulations. This industry is subject to the requirement of controls/monitoring and it is therefore very important that everything is reported.

Knut tells that the newest focus of Stena Recycling is to recover and recycle critical earth metals. The process of recovering earth metals is a very demanding process and in collaboration with return companies, this is being researched more deeply. All recycling processes are time-consuming and developments of recovery do not happen overnight, so there is no timeline for when it is possible and if possible to recover rare earth metals in electronic waste at Stena Recycling, but for now it is their focus area. Furthermore, there is also a focus on improving the reuse of electronic waste.

Appendix II B

Meeting summary from Teams meeting the 01-03-2023 with Charlotte Andresen, Norsk Gjenvinning AS - NG metal:

Charlotte Andresen from Norsk Gjenvinning AS - NG metal Drammen took her time to share some information on their operation at NG Metal Drammen. Since 2013 Charlotte has been working with electronic waste and throughout those years there has been a big development within the collection, treatment and composition of electronic waste. Charlotte tells that her experience is that electronic waste now consists of a lower quantity of steel and a higher quantity of plastic. The electronic product becomes more and more complex and there is a higher use of different materials. The focus on treating electronic waste has increased to reduce the environmental impacts of disposing of electronic waste and bring secondary materials back into the market. NG Metal Drammen treats electronic waste and as they are handling electronic waste they have to follow the Norwegian regulations which require lots of paperwork when waste is sent across borders for further treatment.

NG metal Drammen mostly treats large industrial electronic waste, such as elevators and escalators which is not included in the analysis of this project. They start demolishing the waste and removing hazardous waste, oils etc. Manual sorting is used to remove this and for big fractions, machines are used for dismantling. NG Metal Drammen is the first step of the treatment process unless the dismantling has started earlier but this requires a permit. Some businesses have the possibility to separate the waste - but the recycling facilities run by municipalities, for example, are only allowed to receive waste and sort it into different categories, but they are not allowed to separate electronic waste (e.g. a lamp, if the consumer who delivers it splits it into bulb, stand and cable, it is best, otherwise it ends up as a whole lamp and must first be disassembled at a treatment facility that has permission to do so). The different plants have either permission to treat the waste (separate etc.) or only permitted to receive waste.

Residual waste is sent to incineration for energy recovery. Plastic is both treated for recycling but some plastic is also sent directly to incineration. Charlotte could not tell where the different materials were sent on to different treatments as she was not working closely with the department sending it on to different treatment processes/places, but it is sent on to different treatment facilities from NG Metal Drammen. Copper, cables, aluminium, oils, condensates, steel, wood and other metals are sent for recovery. Materials are shredded and is sent to other treatment places including Norsk gjeninvinnings metal treatment place NG metal AB Katrineholm in Sweden. NG Metal has a plant in Sweden as well, which takes care of different electronics where NG Metal in Drammen mostly handles large electronic waste. This plant is relatively new and is similar to REVAC and Stena Recycling

At the moment NG Metal has a contract with Renas and earlier on had a contract with Norsirk (the contract ended in 2019). They have different contracts with companies through Renas, but sometimes logistics is playing a role, so even though NG metal has a contract with a company but there is a treatment place closer by, the logistics and shorter transportation is usually preferred to include the environmental point of view. Drammen then also treats some of their competitor's electronic waste if NG metal Drammen is the closest option.

Appendix II C

Summary of emails back and forth (end february/start march 2023) with Tom Erland Schjørlin from Metallco Gjørvik:

Metallco EE Norge AS in Gjøvik, process about 10,000 tons of electronic waste per year per year. They pick out a good part of it for reuse of individual components. They run a lot of iron in their own shredder at the facility. It is a mixture of iron, metals and other waste that is being shreddedBatteries and other hazardous waste are decontaminated and sent to an approved treatment facility. Cables are cut and recycled at Metallco's plant in Fredrikstad. Residual product is crushed and sorted into different fractions for recycling and is sent to different treatment facilities in both Norway and Sweden. Plastic and other waste is sent to energy recovery.

7.3 Appendix III

Table 14: Ecoinvent data used for LCA model

Name	Reference Product	Location	Time period	Amount	Unit	Per
Pretreatment						
treatment of waste electric and electronic equipment, shredding	waste electric and electronic equipment [kg]	GLO	1/1/2005 – 12/31/2021	0.9	kg	kg Total Wet Weight
Reuse						
consumer electronics production, mobile device, smartphone	consumer electronics, mobile device, smartphone [unit]	GLO	1/1/2014 – 12/31/2021	-0.25/50	unit	kg Total Wet Weight
television production	television [unit]	GLO	1/1/2008 – 12/31/2021	-0.25/30	unit	kg Total Wet Weight
dishwasher production	dishwasher [unit]	GLO	1/1/2007 – 12/31/2021	-0.25/0.16345	unit	kg Total Wet Weight
refrigerator production	refrigerator [unit]	GLO	1/1/2015 – 12/31/2021	-0.25/60	unit	kg Total Wet Weight
Other metals recovery						
treatment of precious metal from electronics scrap, in anode slime, precious metal extraction	precious metal from electronics scrap, in anode slime [kg]	SE	1/1/2000 – 12/31/2021	1	kg	kg Total Wet Weight
treatment of metal part of electronics scrap, in copper, anode, by electrolytic refining	nickel, class 1 [kg]	SE	1/1/2000 – 12/31/2021	Recycling_nickel	kg	kg Total Wet Weight
treatment of precious metal from electronics scrap, in anode slime, precious metal extraction	silver [kg]	SE	1/1/2000 – 12/31/2021	Recycling_silver	kg	kg Total Wet Weight
treatment of precious metal from electronics scrap, in anode slime, precious metal extraction	gold [kg]	SE	1/1/2000 – 12/31/2021	Recycling_gold	kg	kg Total Wet Weight
gold mine operation and gold production, unrefined	gold, unrefined [kg]	RoW	1/1/2012 – 12/31/2021	-1	kg	kg Total Wet Weight
primary zinc production from concentrate	silver [kg]	RoW	1/1/2015 – 12/31/2021	-1	kg	kg Total Wet Weight
cobalt production	nickel, class 1 [kg]	GLO	1/1/2012 – 12/31/2021	-1	kg	kg Total Wet Weight
Copper recovery						
treatment of copper scrap by electrolytic refining	copper, cathode [kg]	RER	1/1/1994 – 12/31/2021	1	kg	kg Total Wet Weight
copper production, cathode, solvent extraction and electrowinning process	copper, cathode [kg]	GLO	1/1/1994 – 12/31/2021	-1	kg	kg Total Wet Weight

7.4 Appendix IV

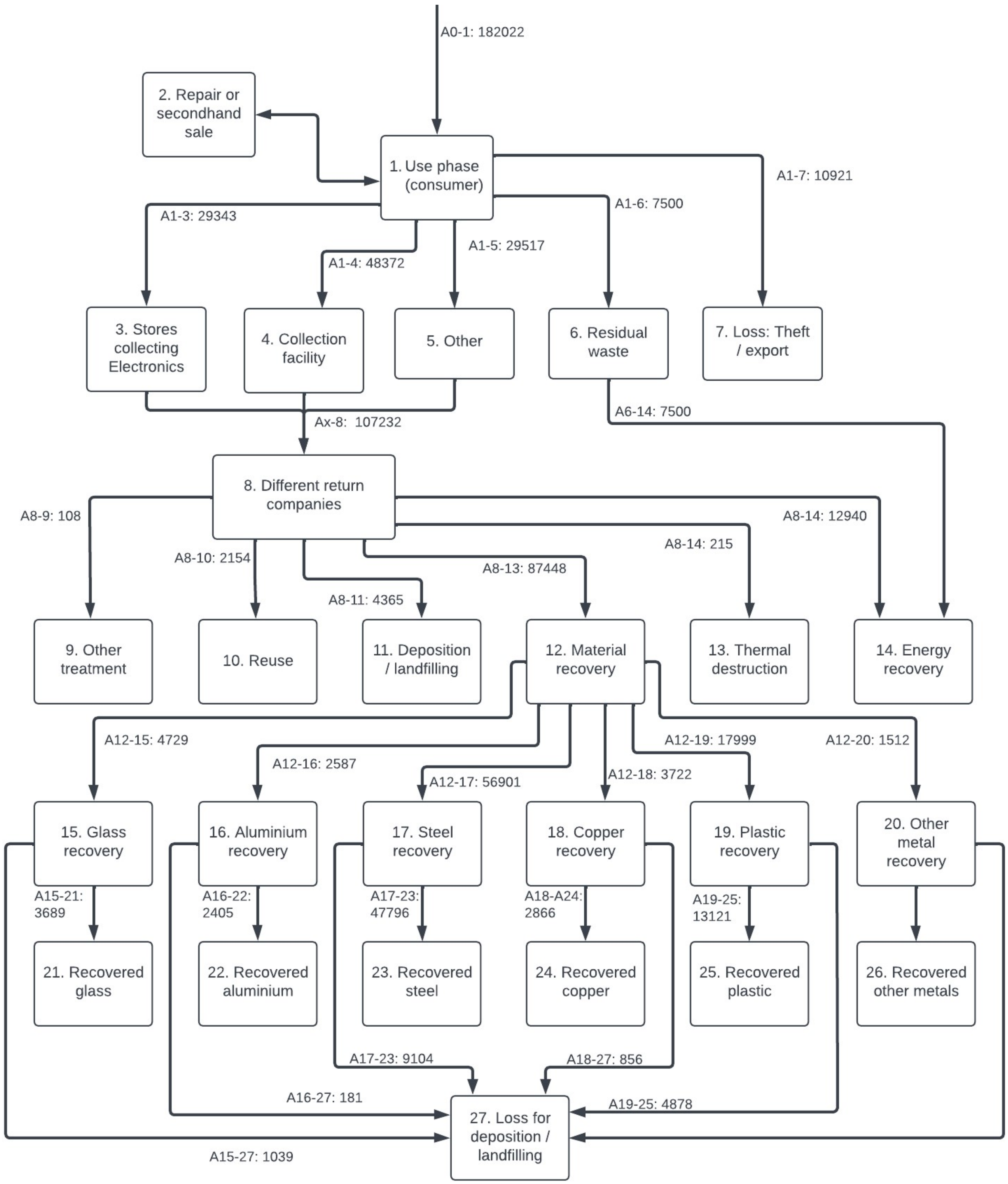

Figure 20: Quantified MFA of the system, flows are in ton per year

7.5 Appendix V

Table 15: List showing all flows of the MFA for total masses of e-waste. [a] (Miljødirektoratet, 2023), [b] (Eurostat, 2023), [c] (Baxter et al., 2021), [d] (Marianne Bigum, Petersen, et al., 2013), [e] (Fagerheim, Mikkelborg, and Bjørnerud, 2021). TheTable continues on the next page.

Flow	Flow name	Total mass	Unit	Comment
A0-1	Put on the market	182022	Ton	Eurostat data average from 2014-2017 (4 year average period with a 5 year delay) (b)
A1-3	Generated e-waste of product category 1	21148	Ton	Percentage collected based on the average of 2019-2022 (20%) (a)
A1-4	Generated e-waste of product category 2	6864	Ton	Percentage collected based on the average of 2019-2022 (6%) (a)
A1-5	Generated e-waste of product category 3	1054	Ton	Percentage collected based on the average of 2019-2022 (1%) (a)
A1-6	Generated e-waste of product category 4	38166	Ton	Percentage collected based on the average of 2019-2022 (36%) (a)
A1-7	Generated e-waste of product category 5	32032	Ton	Percentage collected based on the average of 2019-2022 (30%) (a)
A1-8	Generated e-waste of product category 6	7968	Ton	Percentage collected based on the average of 2019-2022 (7%) (a)
A3-9	Cat 1 collected at store	7980	Ton	Percentage collected based on the average of 2019-2022 (38%) (a)
A3-10	Cat 1 collected at recycling facility	7684	Ton	Percentage collected based on the average of 2019-2022 (36%) (a)
A3-11	Cat 1 collected at other	5483	Ton	Percentage collected based on the average of 2019-2022 (26%) (a)
A4-9	Cat 2 collected at store	1248	Ton	Percentage collected based on the average of 2019-2022 (18%) (a)
A4-10	Cat 2 collected at recycling facility	4097	Ton	Percentage collected based on the average of 2019-2022 (60%) (a)
A4-11	Cat 2 collected at other	1519	Ton	Percentage collected based on the average of 2019-2022 (22%) (a)
A5-9	Cat 3 collected at store	100	Ton	Percentage collected based on the average of 2019-2022 (10%) (a)
A5-10	Cat 3 collected at recycling facility	530	Ton	Percentage collected based on the average of 2019-2022 (50%) (a)
A5-11	Cat 3 collected at other	424	Ton	Percentage collected based on the average of 2019-2022 (40%) (a)
A6-9	Cat 4 collected at store	13078	Ton	Percentage collected based on the average of 2019-2022 (34%) (a)
A6-10	Cat 4 collected at recycling facility	15966	Ton	Percentage collected based on the average of 2019-2022 (42%) (a)
A6-11	Cat 4 collected at other	9122	Ton	Percentage collected based on the average of 2019-2022 (24%) (a)
A7-9	Cat 5 collected at store	5555	Ton	Percentage collected based on the average of 2019-2022 (17%) (a)
A7-10	Cat 5 collected at recycling facility	16091	Ton	Percentage collected based on the average of 2019-2022 (50%) (a)
A7-11	Cat 5 collected at other	10386	Ton	Percentage collected based on the average of 2019-2022 (32%) (a)
A8-9	Cat 6 collected at store	1382	Ton	Percentage collected based on the average of 2019-2022 (22%) (a)
A8-10	Cat 6 collected at recycling facility	4004	Ton	Percentage collected based on the average of 2019-2022 (46%) (a)
A8-11	Cat 6 collected at other	2582	Ton	Percentage collected based on the average of 2019-2022 (31%) (a)
A9-12	E-waste collected at stores	29010	Ton	Percentage collected based on the average of 2019-2022 (27%) (a)
A10-12	E-waste collected at collection facilities	48336	Ton	Percentage collected based on the average of 2019-2022 (45%) (a)
A11-12	E-waste collected at others	29886	Ton	Percentage collected based on the average of 2019-2022 (28%) (a)
A1-2	E-waste in residual waste	7500	Ton	Based on (c) and (e)
A1-0	Theft, Legal export, Illegal export	10921	Ton	Based on (c) where theft is 2-5% POM and Export is 2-4% (6% of POM used)
Ax-12	Total generated waste	107232	Ton	Total average collected e-waste from 2019-2022 (a)
A2-0	Residual waste for incineration	7500	Ton	Based on (c) and (e)

Flow	Flow name	Total mass	Unit	Comment
-	Product category 3 in residual waste	225	Ton	(d)
-	Product category 4 in residual waste	2175	Ton	(d)
-	Product category 5 in residual waste	3675	Ton	(d)
-	Product category 6 in residual waste	1350	Ton	(d)
A12-0a	Waste sent to other treatment	108	Ton	Percentage of treatment based on the average of 2019-2022 (0.2%) (a)
A12-0b	Waste sent to reuse	2154	Ton	Percentage of treatment based on the average of 2019-2022 (1.8%) (a)
A12-0c	Waste sent to landfilling	4365	Ton	Percentage of treatment based on the average of 2019-2022 (8.1%) (a)
A12-0d	Waste sent to energy recovery	12940	Ton	Percentage of treatment based on the average of 2019-2022 (11.7%) (a)
A12-13	Waste sent to material recovery	87448	Ton	Percentage of treatment based on the average of 2019-2022 (77.9%) (a)
A12-0e	Waste sent to thermal destruction	215	Ton	Percentage of treatment based on the average of 2019-2022 (0.3%)(a)
A13-14	Glass for recovery	4729	Ton	Overall composition share (4.7%) (Table 7)
A13-15	Aluminium for recovery	2587	Ton	Overall composition share (2.5%) (Table 7)
A13-16	Steel for recovery	56901	Ton	Overall composition share (56%) (Table 7)
A13-17	Copper for recovery	3722	Ton	Overall composition share (12.9%) (Table 7)
A13-18	Plastic for recovery	17999	Ton	Overall composition share (22.4%) (Table 7)
A13-0	Other metals for recovery	1512	Ton	Overall composition share (1.5%) (Table 7)
A14-0a	Recovered glass	3689	Ton	Based on EASETECH recycling process (78% recovery)
A14-0b	Glass loss	1039	Ton	Glass not recovered (input-output)
A15-0a	Recovered aluminium	2405	Ton	Based on EASETECH recycling process (93% recovery)
A15-0b	Aluminium loss	181	Ton	Aluminium not recovered (input-output)
A16-0a	Recovered steel	47796	Ton	Based on EASETECH recycling process (84% recovery)
A16-0b	Steel loss	9104	Ton	Steel not recovered (input-output)
A17-0a	Recovered copper	2866	Ton	Based on EASETECH recycling process (77% recovery)
A17-0b	Copper loss	856	Ton	Copper not recovered (input-output)
A18-0a	Recovered Plastic	13121	Ton	Based on EASETECH recycling process (73% recovery)
A18-0b	Plastic loss	4878	Ton	Plastic not recovered (input-output)
A19-0a	Recovered other metals	-	Ton	No data
A19-0b	Other metal loss	-	Ton	No data

7.6 Appendix VI

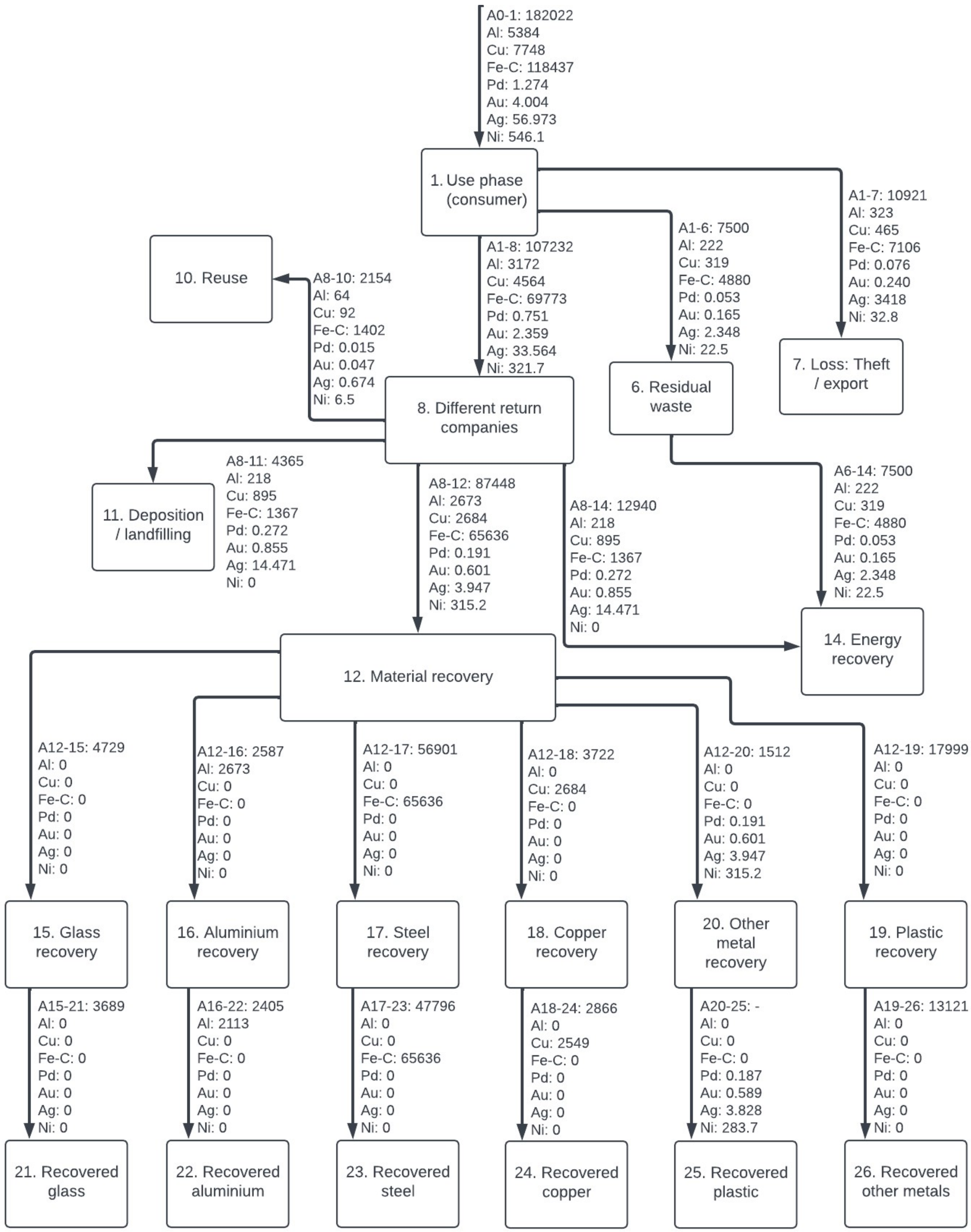

Figure 21: Quantified metal flows for the MFA system in ton per year. The first flow "Ax-x" shows the total mass flow, the other flows are for the following metals, Al for aluminium, Cu for copper, Fe-C for steel, Pd for palladium, Au for gold, Ag for silver and Ni for nickel

7.7 Appendix VII

Table 16: List showing all metal flows. [a](Marianne Bigum, Brogaard, and Christensen, 2012), [b](50:50 incineration / landfilling), [c](Clean fractions is considered). The table continues on the next page.

Flow	Flow name	Total mass	Steel	Aluminium	Copper	Palladium	Gold	Silver	Nickel	Unit	Comment
A0-1	Put on the market	182022	118437	5384	7748	1.274	4.004	56.973	546.065	Ton	Table 7
A1-3	Generated e-waste of product category 1	21148	15639	155	133	0.148	0.465	6.619	63.443	Ton	Table 7
A1-4	Generated e-waste of product category 2	6864	2381	555	119	0.048	0.151	2.149	20.593	Ton	Table 7
A1-5	Generated e-waste of product category 3	1054	128	82	71	0.007	0.023	0.330	3.163	Ton	table 7
A1-6	Generated e-waste of product category 4	38166	30110	352	1097	0.267	0.840	11.946	114.498	Ton	table 7
A1-7	Generated e-waste of product category 5	32032	21275	1868	1949	0.224	0.705	10.026	96.095	Ton	table 7
A1-8	Generated e-waste of product category 6	7968	239	159	1195	0.056	0.175	2.494	23.904	Ton	table 7
A3-9	Cat 1 collected at store	7980	5902	58	50	0.056	0.176	2.498	23.941	Ton	table 7
A3-10	Cat 1 collected at recycling facility	7684	5683	56	48	0.054	0.169	2.405	23.053	Ton	table 7
A3-11	Cat 1 collected at other	5483	4055	40	34	0.038	0.121	1.716	16.449	Ton	table 7
A4-9	Cat 2 collected at store	1248	433	101	22	0.009	0.027	0.391	3.744	Ton	table 7
A4-10	Cat 2 collected at recycling facility	4097	1421	332	71	0.029	0.090	1.282	12.291	Ton	table 7
A4-11	Cat 2 collected at other	1519	527	123	26	0.011	0.033	0.476	4.558	Ton	table 7
A5-9	Cat 3 collected at store	100	12	8	7	0.001	0.002	0.031	0.301	Ton	table 7
A5-10	Cat 3 collected at recycling facility	530	64	41	36	0.004	0.012	0.166	1.589	Ton	table 7
A5-11	Cat 3 collected at other	424	52	33	29	0.003	0.009	0.133	1.272	Ton	table 7
A6-9	Cat 4 collected at store	13078	10317	121	376	0.092	0.288	4.093	39.233	Ton	table 7
A6-10	Cat 4 collected at recycling facility	15966	12596	147	459	0.112	0.351	4.997	47.899	Ton	table 7
A6-11	Cat 4 collected at other	9122	7197	84	262	0.064	0.201	2.855	27.366	Ton	table 7
A7-9	Cat 5 collected at store	5555	3690	324	338	0.039	0.122	1.739	16.665	Ton	table 7
A7-10	Cat 5 collected at recycling facility	16091	10688	938	979	0.113	0.354	5.036	48.273	Ton	table 7
A7-11	Cat 5 collected at other	10386	6898	606	632	0.073	0.228	3.251	31.157	Ton	table 7
A8-9	Cat 6 collected at store	1382	41	28	207	0.010	0.030	0.433	4.146	Ton	table 7
A8-10	Cat 6 collected at recycling facility	4004	120	80	601	0.028	0.088	1.253	12.011	Ton	table 7
A8-11	Cat 6 collected at other	2582	77	52	387	0.018	0.057	0.808	7.747	Ton	table 7
A9-12	E-waste collected at stores	29010	18876	858	1235	0.203	0.638	9.080	87.030	Ton	table 7
A10-12	E-waste collected at collection facilities	48336	31451	1430	2057	0.338	1.063	15.129	145.007	Ton	table 7
A11-12	E-waste collected at others	29886	19446	884	1272	0.209	0.657	9.354	89.658	Ton	table 7
A1-2	E-waste in residual waste	7500	4880	222	319	0.053	0.165	2.348	22.500	Ton	table 7
A1-0	Theft, Legal export, Illegal export	10921	7106	323	465	0.076	0.240	3.418	32.764	Ton	table 7
Ax-12	Total generated waste	107232	69773	3172	4564	0.751	2.359	33.564	321.695	Ton	table 7
A2-0	Residual waste for incineration	7500	4880	222	319	0.053	0.165	2.348	22.500	Ton	table 7

Flow	Flow name	Total mass	Steel	Aluminium	Copper	Palladium	Gold	Silver	Nickel	Unit	Comment
-	Product category 3 in residual waste	225	27	18	15	0.002	0.005	0.070	0.675	Ton	table 7
-	Product category 4 in residual waste	2175	1716	20	63	0.015	0.048	0.681	6.525	Ton	table 7
-	Product category 5 in residual waste	3675	2441	214	224	0.026	0.081	1.150	11.025	Ton	table 7
-	Product category 6 in residual waste	1350	41	27	203	0.009	0.030	0.423	4.050	Ton	table 7
A12-0a	Waste sent to other treatment	108	-	-	-	-	-	-	-	Ton	Excluded
A12-0b	Waste sent to reuse	2154	1402	64	92	0.015	0.047	0.674	6.463	Ton	table 7
A12-0c	Waste sent to landfilling	4365	1367	218	895	0.272	0.855	14.471	0.000	Ton	(b)
A12-0d	Waste sent to energy recovery	12940	1367	218	895	0.272	0.855	14.471	0.000	Ton	(b)
A12-13	Waste sent to material recovery	87448	65636	2673	2684	0.191	0.601	3.947	315.232	Ton	(a)
A12-0e	Waste sent to thermal destruction	215	-	-	-	-	-	-	-	Ton	Excluded
A13-14	Glass for recovery	4729	-	-	-	-	-	-	-	Ton	(c)
A13-15	Aluminium for recovery	2587	-	2673	-	-	-	-	-	Ton	(a)
A13-16	Steel for recovery	56901	65636	-	-	-	-	-	-	Ton	(a)
A13-17	Copper for recovery	3722	-	-	2684	-	-	-	-	Ton	(a)
A13-18	Plastic for recovery	17999	-	-	-	-	-	-	-	Ton	(c)
A13-0	Other metals for recovery	1512	-	-	-	0.191	0.601	3.947	315.232	Ton	(a)
A14-0a	Recovered glass	3689	-	-	-	-	-	-	-	Ton	(c)
A14-0b	Glass loss	1039	-	-	-	-	-	-	-	Ton	(c)
A15-0a	Recovered aluminium	2405	-	2112	-	-	-	-	-	Ton	(a)
A15-0b	Aluminium loss	181	-	561	-	-	-	-	-	Ton	(a)
A16-0a	Recovered steel	47796	65636	-	-	-	-	-	-	Ton	(a)
A16-0b	Steel loss	9104	0	-	-	-	-	-	-	Ton	(a)
A17-0a	Recovered copper	2866	-	-	2549	-	-	-	-	Ton	(a)
A17-0b	Copper loss	856	-	-	134	-	-	-	-	Ton	(a)
A18-0a	Recovered Plastic	13121	-	-	-	-	-	-	-	Ton	(c)
A18-0b	Plastic loss	4878	-	-	-	-	-	-	-	Ton	(c)
A19-0a	Recovered other metals	-	-	-	-	0.187	0.589	3.828	283.709	Ton	(a)
A19-0b	Other metal loss	-	-	-	-	0.004	0.012	0.118	31.523	Ton	(a)

7.8 Appendix VIII

Table 17: List of parameters used for the EASETECH model of treating Waste electrical and electronic equipment (WEEE). [a](Miljødirektoratet, 2023), [b](Marianne Bigum, Petersen, et al., 2013), [c](Baxter et al., 2021) & Fagerheim, Mikkelborg, and Bjørnerud, 2021, [d](John Baxter, Lyng, et al., 2016), [e](Marianne Bigum, Brogaard, and Christensen, 2012)

Parameter	Parameter name	Value used for EASETECH	Unit	Comment
Total_WEEE	Total mass of generated e-waste	1.07E+08	kg	Average of 4 years (a)
Share_Cat1	Mass share of category 1 of total mass	0.20	%	Share calculated based on average of 4 years (a)
Share_Cat2	Mass share of category 2 of total mass	0.06	%	Share calculated based on average of 4 years (a)
Share_Cat3	Mass share of category 3 of total mass	0.01	%	Share calculated based on average of 4 years (a)
Share_Cat4	Mass share of category 4 of total mass	0.36	%	Share calculated based on average of 4 years (a)
Share_Cat5	Mass share of category 5 of total mass	0.30	%	Share calculated based on average of 4 years (a)
Share_Cat6	Mass share of category 6 of total mass	0.07	%	Share calculated based on average of 4 years (a)
Share_RW3	Mass share of category 3 of e-waste in residual waste	0.03	%	(b)
Share_RW4	Mass share of category 4 of e-waste in residual waste	0.29	%	(b)
Share_RW5	Mass share of category 5 of e-waste in residual waste	0.49	%	(b)
Share_RW6	Mass share of category 6 of e-waste in residual waste	0.18	%	(b)
Total_RE	Total mass of e-waste in residual waste	7.50E+06	kg	(c)
Trans1	Transportation from collection point ton reception point	115	km	Average of 3 distances (d)
Trans2	Transportation from reception point to pretreatment	374	km	Average of 3 distances (d)
Trans3	Transportation from pretreatment to material recovery	613	km	Average of 3 distances (d)
Trans_general	General transportation to treatment places except material recovery	50	km	Assumption
PT_Other	Share of total mass for other treatment from pretreatment	0.10	%	(a)
PT_Reuse_Plastic	Share of plastic for reuse from pretreatment	2.01	%	(a)
PT_Reuse_Other	Share of other metals for reuse from pretreatment	2.01	%	(a)
PT_Reuse_Steel	Share of steel for reuse from pretreatment	2.01	%	(a)
PT_Reuse_Copper	Share of copper for reuse from pretreatment	2.01	%	(a)
PT_Reuse_Glass	Share of glass for reuse from pretreatment	2.01	%	(a)
PT_Reuse_Alu	Share of aluminium for reuse from pretreatment	2.01	%	(a)
PT_Land_Plastic	Share of plastic for landfilling from pretreatment	4.07	%	(a)
PT_Land_Other	Share of other metals for landfilling from pretreatment	4.07	%	(a)
PT_Land_Steel	Share of steel for landfilling from pretreatment	4.07	%	(a)
PT_Land_Copper	Share of copper for landfilling from pretreatment	4.07	%	(a)
PT_Land_Glass	Share of glass for landfilling from pretreatment	4.07	%	(a)
PT_Land_Alu	Share of aluminium for landfilling from pretreatment	4.07	%	(a)
PT_MR_Plastic	Share of plastic for material recovery from pretreatment	81.55	%	(a)
PT_MR_Other	Share of other metals for material recovery from pretreatment	81.55	%	(a)
PT_MR_Steel	Share of steel for material recovery from pretreatment	81.55	%	(a)
PT_MR_Copper	Share of copper for material recovery from pretreatment	81.55	%	(a)
PT_MR_Glass	Share of glass for material recovery from pretreatment	81.55	%	(a)
PT_MR_Alu	Share of aluminium for material recovery from pretreatment	81.55	%	(a)
PT_TD	Share of total mass for thermal destruction from pretreatment	0.20	%	(a)
PT_ER_Plastic	Share of plastic for energy recovery from pretreatment	12.07	%	(a)
PT_ER_Other	Share of other metals for energy recovery from pretreatment	12.07	%	(a)
PT_ER_Steel	Share of steel for energy recovery from pretreatment	12.07	%	(a)
PT_ER_Copper	Share of copper for energy recovery from pretreatment	12.07	%	(a)
PT_ER_Glass	Share of glass for energy recovery from pretreatment	12.07	%	(a)
PT_ER_Alu	Share of aluminium for energy recovery from pretreatment	12.07	%	(a)
Reuse_Cat1	Category 1 for reuse	16.85	%	(a)
Reuse_Cat2	Category 2 for reuse	36.75	%	(a)
Reuse_Cat4	Category 4 for reuse	17.93	%	(a)
Reuse_Cat6	Category 6 for reuse	28.47	%	(a)
Recycling_plastic	Recycling efficiency of plastic	90	%	EASETECH Process
Recycling_other	Recycling efficiency of other metals	90	%	Assumption
Recycling_gold	Total share of mass of gold in other metals	0.127	%	Mass % given for total e-waste (e)
Recycling_silver	Total share of mass of silver in other metals	1.811	%	Mass % given for total e-waste (e)
Recycling_nickel	Total share of mass of nickel in other metals	17.354	%	Mass % given for total e-waste (e)
Recycling_steel	Recycling efficiency of steel	84	%	EASETECH Process
Recycling_copper	Recycling efficiency of copper	77	%	Ecoinvent - copper process
Recycling_glass	Recycling efficiency of glass	94	%	EASETECH Process
Recycling_Aluminium	Recycling efficiency of aluminium	93	%	EASETECH Process

7.9 Appendix IX

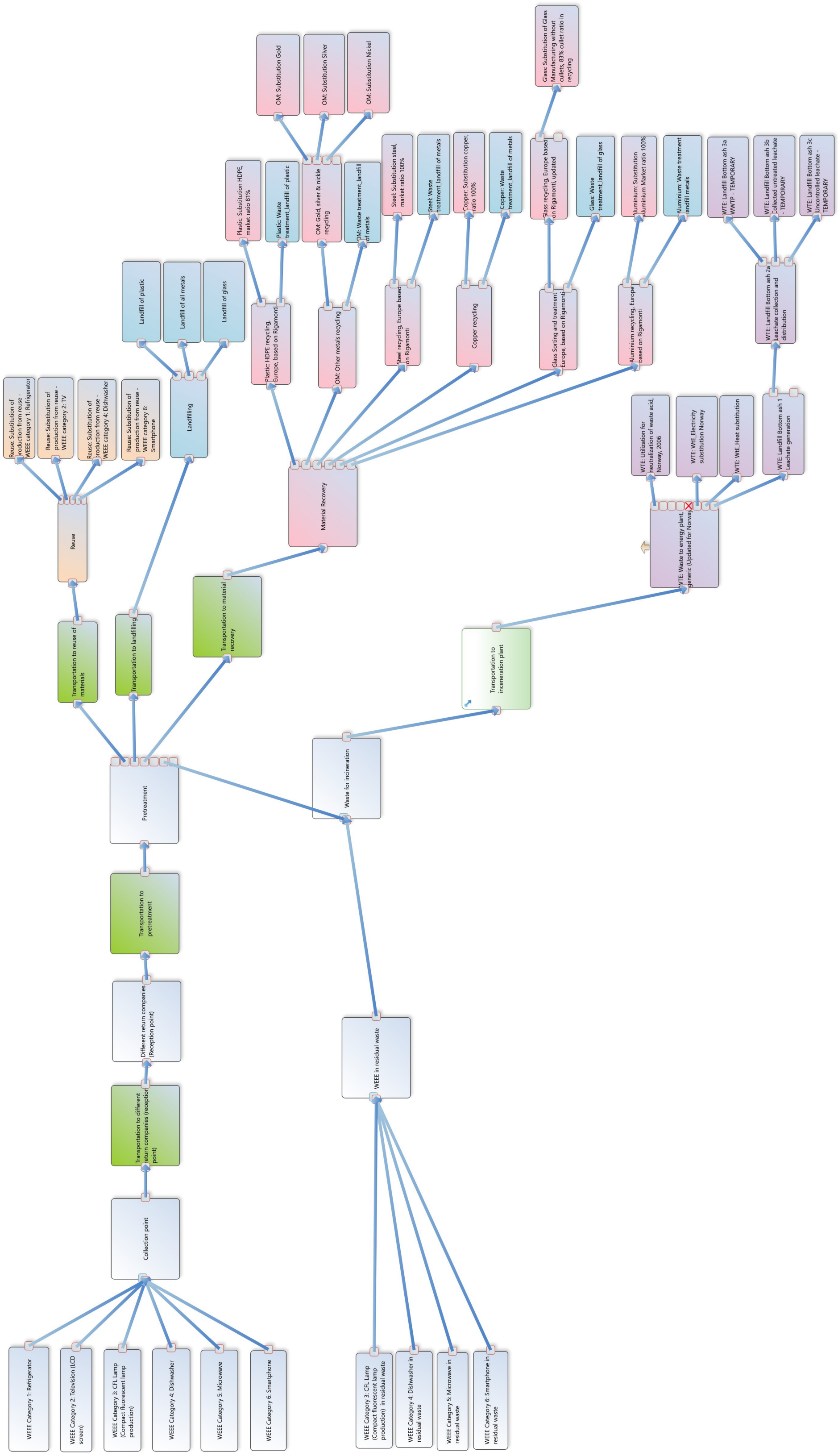

Figure 22: Appendix IX: EASETECH model

7.10 Appendix X

Table 18: Total emission for each product category for the different processes annually in Norway. Abbreviations and units can be seen in theTable 9. The processes that lead to emission savings for the different categories are marked in green and the processes leading to emission gains are marked in red.

Process Name	GWP	PM	AT	EF	EM	MRS	FRS	OD	IR
Aluminium recovery	-2.66E+07	-4.08E+04	-1.13E+05	-3.61E+00	-7.00E+01	-1.23E+04	-5.55E+06	-5.08E+00	-6.20E+05
Copper recovery	**2.48E+07**	-5.40E+02	-1.45E+04	**-1.35E+04**	**1.18E+04**	-3.91E+06	**1.12E+07**	2.19E+01	**1.44E+06**
Glass recovery	-7.22E+05	1.41E+03	1.13E+03	-2.83E+01	-4.21E+01	-2.99E+01	5.83E+04	-4.58E-01	-1.95E+04
Landfill	1.21E+05	9.11E+01	2.99E+02	2.78E+01	1.97E+01	1.19E+03	3.22E+04	1.58E-02	2.21E+03
Other metal recovery	7.83E+06	**-1.10E+05**	-9.24E+04	-2.19E+04	4.56E+03	**-8.48E+06**	1.55E+07	**1.64E+02**	**-1.13E+06**
Plastic recovery	-2.25E+07	-1.59E+04	-5.56E+04	4.04E+01	3.51E+00	2.01E+03	**-1.96E+07**	1.05E+00	1.33E+05
Pretreatment	4.82E+06	**1.08E+04**	**1.81E+04**	**2.57E+02**	3.47E+01	**1.56E+04**	1.21E+06	1.96E+00	4.96E+04
Reuse	-3.93E+07	-8.55E+04	**-1.59E+05**	-7.04E+03	**-4.57E+03**	-4.55E+05	-1.01E+07	**-2.16E+01**	-3.53E+05
Steel recovery	**-1.54E+08**	-3.81E+04	-1.51E+05	-8.24E-01	6.69E+01	-4.87E+06	-1.36E+07	-1.96E+01	4.71E+05
Transportation	6.01E+06	1.77E+03	6.35E+03	5.04E+00	8.96E+01	3.61E+02	1.88E+06	1.21E+00	1.61E+03
Energy recovery	1.01E+07	1.75E+03	5.92E+03	-1.59E+00	2.25E+00	-1.17E+03	-5.91E+05	-3.43E-01	3.91E+03
Total	-1.89E+08	-2.75E+05	-5.53E+05	-4.21E+04	1.19E+04	-1.77E+07	-1.95E+07	1.43E+02	-2.18E+04

Process Name	POFE	POFHH	TET	FET	MET	HTC	HTNC	LU	WU
Aluminium recovery	-3.66E+04	-3.66E+04	-5.55E+06	-1.22E+03	-8.66E+03	-6.51E+03	-3.96E+05	-1.33E+02	**-6.19E+07**
Copper recovery	**-1.91E+05**	**-1.88E+05**	-7.75E+07	-2.74E+05	-3.87E+05	-4.96E+05	-1.28E+07	**8.39E+06**	1.06E+06
Glass recovery	-2.01E+03	-1.91E+03	5.17E+06	-2.05E+02	1.97E+03	3.80E+03	4.97E+05	0.00E+00	4.51E+04
Landfill	3.57E+02	3.53E+02	8.20E+03	1.72E+02	1.40E+02	7.12E+02	5.61E+03	0.00E+00	1.32E+02
Other metal recovery	-2.04E+05	-2.15E+05	**-2.79E+08**	**-1.08E+06**	**-1.49E+06**	-2.60E+05	**-8.68E+07**	**-4.86E+06**	-1.29E+06
Plastic recovery	-5.10E+04	-4.50E+04	6.87E+05	-6.79E+02	-1.27E+01	**-2.86E+06**	5.44E+04	0.00E+00	1.17E+07
Pretreatment	1.11E+04	1.10E+04	9.11E+07	3.94E+03	5.05E+04	6.27E+04	3.76E+06	1.31E+05	3.74E+04
Reuse	-9.40E+04	-9.14E+04	-2.61E+08	-1.15E+05	-4.83E+05	-1.10E+06	-2.67E+07	-8.72E+05	-4.94E+05
Steel recovery	-1.15E+05	-1.15E+05	**7.72E+08**	**1.06E+04**	**3.20E+05**	**7.23E+05**	**8.97E+07**	-5.32E-04	**4.65E+07**
Transportation	5.69E+03	5.58E+03	4.22E+07	8.37E+02	2.28E+04	3.04E+03	1.32E+06	0.00E+00	2.18E+05
Energy recovery	**1.49E+04**	**1.50E+04**	2.81E+07	5.03E+02	7.71E+03	1.79E+03	8.30E+02	-4.45E+06	-3.24E+06
Total	-6.62E+05	-6.61E+05	3.16E+08	-1.45E+06	-1.97E+06	-3.93E+06	-3.13E+07	-1.66E+06	-7.45E+06

7.11 Appendix XI

Table 19: Summary of all LCIA data from EASETECH used for the four midpoint impact graphs.

Name	**Climate change (kg CO_2-eq)**	**Fine particulate matter formation (kg PM2.5-eq)**	**Terrestrial acidification (kg SO2-eq)**	**Ozone depletion (kg CFC-11-eq)**
Sum	-1.89E+08	9.52E+02	3.16E+03	9.53E-02
Aluminium recycling, Europe based on Rigamonti	8.00E+05	-4.18E+04	-1.16E+05	-5.17E+00
Aluminium: Substitution Aluminium Market ratio 100%	-2.74E+07	2.01E+00	6.58E+00	2.70E-04
Aluminium: Waste treatment landfill metals	2.85E+03	9.43E+04	2.70E+05	6.13E+01
Copper recycling	4.41E+07	-9.49E+04	-2.84E+05	-3.94E+01
Copper: Substitution copper, ratio 100%	-1.93E+07	9.55E+00	3.13E+01	1.29E-03
Copper: Waste treatment_landfill of metals	1.36E+04	6.99E+03	2.01E+04	1.81E-01
Glass recycling, Europe based on Rigamonti, updated	3.09E+06	4.90E+01	1.50E+02	1.20E-02
Glass Sorting and treatment Europe, based on Rigamonti	4.60E+04	-5.64E+03	-1.91E+04	-6.51E-01
Glass: Substitution of Glass Manufacturing without cullets, 83% cullet ratio in recycling	-3.86E+06	5.36E+00	1.77E+01	3.61E-04
Glass: Waste treatment_landfill of glass	3.51E+03	3.66E+01	1.20E+02	4.92E-03
Landfill of all metals	5.20E+04	4.46E+00	1.48E+01	3.01E-04
Landfill of glass	2.92E+03	5.01E+01	1.64E+02	1.06E-02
Landfill of plastic	6.56E+04	2.35E+05	6.52E+05	2.41E+02
OM: Gold, silver & nickel recycling	1.43E+08	9.14E+02	2.54E+03	2.82E-01
OM: Other metals recycling	3.91E+05	-2.81E+05	-5.63E+05	-6.05E+01
OM: Substitution Gold	-1.11E+08	-1.60E+04	-4.71E+04	-4.55E+00
OM: Substitution Nickel	-4.25E+06	-4.90E+04	-1.37E+05	-1.29E+01
OM: Substitution Silver	-2.02E+07	1.66E+00	5.45E+00	2.24E-04
OM: Waste treatment_landfill of metals	2.36E+03	3.83E+03	1.17E+04	1.03E+00
Plastic: HDPE recycling, Europe, based on Rigamonti	4.21E+06	-1.99E+04	-6.77E+04	-1.12E-07
Plastic: Substitution HDPE, market ratio 81%	-2.68E+07	1.00E+02	3.29E+02	2.12E-02
Plastic: Waste treatment_landfill of plastic	1.31E+05	1.08E+04	1.81E+04	1.96E+00
Pretreatment	4.82E+06	-8.66E+02	-2.07E+03	-3.46E-01
Reuse: Substitution of production from reuse - WEEE category 1: Refrigerator	-3.88E+05	-9.56E+03	-2.40E+04	-1.52E+00
Reuse: Substitution of production from reuse - WEEE category 2: TV	-2.54E+06	-1.05E+03	-1.90E+03	-1.27E-01
Reuse: Substitution of production from reuse - WEEE category 4: Dishwasher	-2.84E+05	-7.40E+04	-1.31E+05	-1.96E+01
Reuse: Substitution of production from reuse - WEEE category 6: Smartphone	-3.61E+07	2.26E+04	5.29E+04	3.59E+00
Steel recycling, Europe based on Rigamonti	1.37E+07	-6.08E+04	-2.04E+05	-2.32E+01
Steel: Substitution steel, market ratio 100%	-1.68E+08	1.03E+02	3.39E+02	1.39E-02
Steel: Waste treatment_landfill of metals	1.47E+05	-2.75E+05	-5.53E+05	1.43E+02
Transportation to different return companies (reception point)	6.90E+05	2.04E+02	7.29E+02	1.39E-01
Transportation to incineration plant	5.70E+04	1.68E+01	6.02E+01	1.15E-02
Transportation to landfilling	1.22E+04	3.61E+00	1.29E+01	2.46E-03
Transportation to material recovery	3.00E+06	8.86E+02	3.17E+03	6.03E-01
Transportation to pretreatment	2.24E+06	6.63E+02	2.37E+03	4.51E-01
Transportation to reuse of materials	6.03E+03	1.78E+00	6.37E+00	1.21E-03
WTE: Landfill Bottom ash 1 Leachate generation	2.04E+04	1.57E+01	5.34E+01	1.01E-02
WTE: Landfill Bottom ash 3a WWTP - TEMPORARY	2.16E+02	3.02E-01	4.06E-01	1.15E-03
WTE: Landfill Bottom ash 3c Uncontrolled leachate - TEMPORARY	0.00E+00	0.00E+00	0.00E+00	0.00E+00
WTE: Utilization for neutralization of waste acid, Norway, 2006	1.26E+04	1.53E+01	4.57E+01	4.41E-03
WTE: Waste to energy plant, generic (Updated for Norway)	1.19E+07	2.09E+03	6.87E+03	9.51E-02
WTE: WtE_Electricity substitution Norway	-4.24E+04	-5.93E+01	-7.98E+01	-2.26E-01
WTE: WtE_Heat substitution	-1.81E+06	-3.15E+02	-9.71E+02	-2.28E-01

7.12 Appendix XII

Table 20: Normalised results in PE for all different impact categories for the different processes, marked from low (green) to high (red).

Name	**GWP**	**PM**	**AT**	**EF**	**EM**	**MRS**	**FRS**	**OD**	**IR**
Aluminium recovery	-3.33E+03	-1.59E+03	-2.76E+03	-5.55E+00	-1.51E+01	-1.02E-01	0.00E+00	-8.46E+01	-1.29E+03
Copper recovery	3.11E+03	-2.11E+01	-3.53E+02	-2.08E+04	2.55E+03	-3.26E+01	0.00E+00	3.65E+02	3.00E+03
Glass recovery	-9.04E+01	5.49E+01	2.75E+01	-4.36E+01	-9.11E+00	-2.49E-04	0.00E+00	-7.63E+00	-4.06E+01
Landfill	1.51E+01	3.56E+00	7.29E+00	4.27E+01	4.25E+00	9.93E-03	0.00E+00	2.64E-01	4.60E+00
Other metal recovery	9.80E+02	-4.30E+03	-2.25E+03	-3.36E+04	9.86E+02	-7.07E+01	0.00E+00	2.73E+03	-2.36E+03
Plastic recovery	-2.82E+03	-6.22E+02	-1.36E+03	6.22E+01	7.60E-01	1.67E-02	0.00E+00	1.75E+01	2.78E+02
Pretreatment	6.04E+02	4.23E+02	4.42E+02	3.95E+02	7.52E+00	1.30E-01	0.00E+00	3.26E+01	1.03E+02
Reuse	-4.92E+03	-3.34E+03	-3.88E+03	-1.08E+04	-9.89E+02	-3.79E+00	0.00E+00	-3.61E+02	-7.35E+02
Steel recovery	-1.92E+04	-1.49E+03	-3.68E+03	-1.27E+00	1.45E+01	-4.06E+01	0.00E+00	-3.27E+02	9.82E+02
Transportation	7.52E+02	6.93E+01	1.55E+02	7.75E+00	1.94E+01	3.01E-03	0.00E+00	2.01E+01	3.36E+00
Energy recovery	1.26E+03	6.82E+01	1.44E+02	-2.44E+00	4.87E-01	-9.73E-03	0.00E+00	-5.72E+00	8.15E+00
Total	-2.37E+04	-1.07E+04	-1.35E+04	-6.48E+04	2.57E+03	-1.48E+02	0.00E+00	2.38E+03	-4.55E+01

Name	**POFE**	**POFHH**	**TET**	**FET**	**MET**	**HTC**	**HTNC**	**LU**	**WU**
Aluminium recovery	-2.07E+03	-1.78E+03	-3.65E+02	-4.83E+01	-1.99E+02	-6.32E+02	-1.26E+01	-2.15E-02	-2.32E+05
Copper recovery	-1.08E+04	-9.14E+03	-5.10E+03	-1.09E+04	-8.93E+03	-4.82E+04	-4.08E+02	1.36E+03	3.96E+03
Glass recovery	-1.14E+02	-9.26E+01	3.40E+02	-8.12E+00	4.54E+01	3.69E+02	1.59E+01	0.00E+00	1.69E+02
Landfill	2.02E+01	1.71E+01	5.40E-01	6.83E+00	3.23E+00	6.91E+01	1.79E-01	0.00E+00	4.93E-01
Other metal recovery	-1.15E+04	-1.04E+04	-1.84E+04	-4.27E+04	-3.44E+04	-2.52E+04	-2.77E+03	-7.88E+02	-4.83E+03
Plastic recovery	-2.88E+03	-2.19E+03	4.52E+01	-2.70E+01	-2.92E-01	-2.78E+05	1.74E+00	0.00E+00	4.38E+04
Pretreatment	6.25E+02	5.32E+02	5.99E+03	1.56E+02	1.16E+03	6.09E+03	1.20E+02	2.13E+01	1.40E+02
Reuse	-5.31E+03	-4.44E+03	-1.72E+04	-4.56E+03	-1.11E+04	-1.07E+05	-8.54E+02	-1.41E+02	-1.85E+03
Steel recovery	-6.51E+03	-5.56E+03	5.08E+04	4.19E+02	7.37E+03	7.02E+04	2.87E+03	-8.63E-08	1.74E+05
Transportation	3.21E+02	2.71E+02	2.78E+03	3.32E+01	5.25E+02	2.96E+02	4.23E+01	0.00E+00	8.17E+02
Energy recovery	8.41E+02	7.28E+02	1.85E+03	2.00E+01	1.78E+02	1.74E+02	2.65E-02	-7.21E+02	-1.21E+04
Total	-3.74E+04	-3.21E+04	2.08E+04	-5.76E+04	-4.54E+04	-3.81E+05	-1.00E+03	-2.69E+02	-2.79E+04

7.13 Appendix XIII

Table 21: Results for sensitivity analysis for all parameters increased by 10% for all midpoint categories. TheTable continues on the next page

Name	GWP	PM	AT	EF	EM	MRS	FRS	OD	IR
All	-1.89E+08	-2.75E+05	-5.53E+05	-4.21E+04	1.19E+04	-1.77E+07	-1.95E+07	1.43E+02	-2.18E+04
PT_ER_Alu	-4.11E-05	-1.44E-04	-2.36E-04	-1.64E-07	5.16E-06	-5.20E-08	-1.01E-04	1.63E-05	-3.83E-03
PT_ER_Copper	-6.69E-05	-2.13E-04	-3.48E-04	-6.19E-07	9.18E-06	-9.80E-08	-1.70E-04	2.89E-05	-5.58E-03
PT_ER_Glass	-8.42E-05	-2.69E-04	-4.41E-04	-7.57E-07	1.15E-05	-1.22E-07	-2.13E-04	3.63E-05	-7.04E-03
PT_ER_Other	-2.42E-05	-8.37E-05	-1.37E-04	-1.15E-07	3.08E-06	-3.13E-08	-5.99E-05	9.73E-06	-2.22E-03
PT_ER_Plastic	-3.31E-02	-1.20E-04	-4.06E-04	2.79E-05	2.45E-05	4.34E-05	2.15E-02	-1.93E-03	-9.60E-03
PT_ER_Steel	-9.03E-04	-3.23E-03	-5.29E-03	-2.59E-06	1.11E-04	-1.09E-06	-2.21E-03	3.51E-04	-8.58E-02
PT_Land_Alu	-1.26E-05	-5.58E-06	-9.16E-06	-1.55E-08	6.49E-05	-6.67E-07	-2.74E-05	1.85E-06	-1.08E-03
PT_Land_Copper	-1.83E-05	-8.09E-06	-1.33E-05	-2.24E-08	9.40E-05	-9.66E-07	-3.97E-05	2.68E-06	-1.56E-03
PT_Land_Glass	-1.89E-05	-1.69E-05	-2.79E-05	-7.03E-05	1.41E-06	-5.05E-06	-5.49E-05	3.03E-06	-2.06E-03
PT_Land_Other	-7.32E-06	-3.23E-06	-5.30E-06	-8.95E-09	3.76E-05	-3.86E-07	-1.59E-05	1.07E-06	-6.23E-04
PT_Land_Plastic	-3.60E-04	-1.85E-04	-3.01E-04	-5.89E-04	1.30E-05	-4.53E-05	-1.09E-03	7.78E-05	-7.16E-02
PT_Land_Steel	-2.85E-04	-1.26E-04	-2.06E-04	-3.48E-07	1.46E-03	-1.50E-05	-6.17E-04	4.17E-05	-2.43E-02
PT_MR_Alu	1.40E-01	1.48E-01	2.04E-01	8.40E-05	-5.79E-03	6.92E-04	2.83E-01	-3.55E-02	2.84E+01
PT_MR_Copper	-1.32E-01	1.83E-03	2.59E-02	3.21E-01	9.92E-01	2.21E-01	-5.74E-01	1.54E-01	-6.60E+01
PT_MR_Glass	2.97E-03	-5.29E-03	-2.34E-03	6.69E-04	-3.35E-03	1.14E-06	-5.55E-03	-2.99E-03	8.91E-01
PT_MR_Other	-4.17E-02	4.00E-01	1.67E-01	5.19E-01	3.84E-01	4.79E-01	-7.94E-01	1.15E+00	5.19E+01
PT_MR_Plastic	1.16E-01	5.73E-02	9.93E-02	-9.71E-04	1.06E-03	-1.15E-04	9.93E-01	8.21E-03	-6.11E+00
PT_MR_Steel	8.03E-01	1.36E-01	2.69E-01	-1.96E-05	8.11E-03	2.75E-01	6.63E-01	-1.35E-01	-2.16E+01
PT_Other	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PT_Reuse_Alu	6.04E-03	9.04E-03	8.35E-03	4.86E-03	-1.12E-02	7.48E-04	1.50E-02	-4.42E-03	4.70E-01
PT_Reuse_Copper	8.75E-03	1.31E-02	1.21E-02	7.04E-03	-1.62E-02	1.08E-03	2.17E-02	-6.40E-03	6.81E-01
PT_Reuse_Glass	1.11E-02	1.66E-02	1.53E-02	8.93E-03	-2.06E-02	1.37E-03	2.76E-02	-8.12E-03	8.64E-01
PT_Reuse_Other	3.50E-03	5.23E-03	4.83E-03	2.81E-03	-6.49E-03	4.33E-04	8.68E-03	-2.56E-03	2.72E-01
PT_Reuse_Plastic	4.22E-02	6.31E-02	5.83E-02	3.39E-02	-7.82E-02	5.22E-03	1.05E-01	-3.08E-02	3.28E+00
PT_Reuse_Steel	1.36E-01	2.04E-01	1.88E-01	1.10E-01	-2.52E-01	1.69E-02	3.38E-01	-9.95E-02	1.06E+01
PT_TD	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Recycling_Aluminium	1.45E-01	1.52E-01	2.10E-01	8.60E-05	-7.21E-03	7.08E-04	3.00E-01	-3.63E-02	2.85E+01
Recycling_copper	1.02E-01	3.45E-01	5.14E-01	4.13E-01	-8.81E-02	2.50E-01	2.37E-01	-2.77E-01	6.14E+00
Recycling_glass	4.37E-03	-4.61E-03	-1.23E-03	2.08E-03	-3.58E-03	1.05E-04	-1.57E-03	-3.34E-03	1.01E+00
Recycling_gold	-2.02E-02	3.34E-01	7.00E-02	4.88E-01	3.91E-01	3.05E-01	-6.33E-01	9.36E-01	3.22E+01
Recycling_nickel	-1.65E-02	1.43E-02	2.45E-02	-7.73E-04	-5.92E-02	8.04E-02	-5.54E-02	5.54E-02	9.25E+00
Recycling_other	-3.92E-02	4.03E-01	1.72E-01	5.19E-01	3.83E-01	4.79E-01	-7.88E-01	1.15E+00	5.51E+01
Recycling_plastic	1.48E-01	7.55E-02	1.28E-01	1.08E-02	-1.53E-03	9.29E-04	1.08E+00	-1.34E-03	1.29E+00
Recycling_silver	-2.66E-03	5.49E-02	7.72E-02	3.21E-02	5.21E-02	9.38E-02	-1.00E-01	1.54E-01	1.36E+01
Recycling_steel	8.90E-01	2.23E-01	3.72E-01	4.07E-05	-2.79E-02	2.76E-01	8.62E-01	-1.64E-01	1.12E+00
Reuse_Cat1	2.05E-03	3.15E-03	3.73E-03	4.28E-04	-1.40E-03	5.22E-04	5.84E-03	-2.43E-03	6.79E-02
Reuse_Cat2	1.34E-02	3.48E-02	4.34E-02	9.20E-03	-7.43E-03	1.01E-02	3.54E-02	-1.07E-02	9.83E-01
Reuse_Cat4	1.50E-03	3.81E-03	3.44E-03	5.16E-04	-7.56E-04	6.74E-04	3.73E-03	-8.92E-04	7.82E-02
Reuse_Cat6	1.91E-01	2.69E-01	2.36E-01	1.57E-01	-3.76E-01	1.44E-02	4.71E-01	-1.38E-01	1.50E+01
Share_Cat1	2.37E-01	1.05E-01	1.44E-01	4.10E-02	-4.53E-02	7.33E-02	4.74E-01	-5.30E-02	-4.15E+00
Share_Cat2	5.90E-02	1.26E-01	1.02E-01	1.13E-01	7.18E-02	1.04E-01	6.45E-02	1.99E-01	1.21E+01
Share_Cat3	4.88E-03	1.75E-02	1.41E-02	2.04E-02	2.19E-02	1.69E-02	-6.10E-03	2.97E-02	1.15E+00
Share_Cat4	4.12E-01	2.14E-01	2.73E-01	1.70E-01	1.38E-01	2.14E-01	5.76E-01	3.11E-03	-1.62E+01
Share_Cat5	3.09E-01	4.20E-01	3.83E-01	4.56E-01	5.13E-01	4.35E-01	-6.06E-02	5.56E-01	1.26E+01
Share_Cat6	-3.26E-03	1.20E-01	8.86E-02	1.99E-01	3.00E-01	1.57E-01	-5.91E-02	2.66E-01	-4.47E+00
Share_RW3	-6.76E-04	-6.95E-05	-1.18E-04	4.01E-07	3.20E-06	8.31E-07	3.75E-04	-2.97E-05	-1.95E-03
Share_RW4	-4.86E-03	-7.07E-04	-1.19E-03	3.32E-06	2.74E-05	5.87E-06	2.55E-03	-1.97E-04	-1.97E-02
Share_RW5	-3.81E-03	-1.32E-03	-2.18E-03	1.28E-06	4.98E-05	4.02E-06	1.30E-03	-5.11E-05	-3.56E-02
Share_RW6	-1.01E-02	-2.52E-04	-4.75E-04	7.94E-06	1.63E-05	1.31E-05	6.36E-03	-5.59E-04	-8.57E-03
Total_RE	-1.95E-02	-2.35E-03	-3.96E-03	1.29E-05	9.68E-05	2.38E-05	1.06E-02	-8.36E-04	-6.58E-02
Total_WEEE	1.02E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.89E-01	1.00E+00	1.07E+00
Trans_general	-3.98E-04	-8.08E-05	-1.44E-04	-1.50E-06	9.47E-05	-2.56E-07	-1.21E-03	1.06E-04	-9.27E-04
Trans1	-3.65E-03	-7.41E-04	-1.32E-03	-1.37E-05	8.68E-04	-2.34E-06	-1.11E-02	9.74E-04	-8.49E-03
Trans2	-1.19E-02	-2.41E-03	-4.28E-03	-4.47E-05	2.82E-03	-7.62E-06	-3.59E-02	3.17E-03	-2.76E-02
Trans3	-1.59E-02	-3.22E-03	-5.72E-03	-5.97E-05	3.77E-03	-1.02E-05	-4.80E-02	4.23E-03	-3.69E-02

Name	POFE	POFHH	TET	FET	MET	HTC	HTNC	LU	WU
All	-6.62E+05	-6.61E+05	3.16E+08	-1.45E+06	-1.97E+06	-3.93E+06	-3.13E+07	-1.66E+06	-7.45E+06
PT_ER_Alu	-5.00E-04	-5.01E-04	8.18E-05	-7.03E-06	-1.22E-05	-1.69E-05	-1.44E-05	-3.07E-04	-3.61E-04
PT_ER_Copper	-7.36E-04	-7.37E-04	4.53E-02	-5.93E-05	-3.07E-03	-6.91E-05	-3.98E-05	-1.37E-03	-6.83E-04
PT_ER_Glass	-9.33E-04	-9.33E-04	7.64E-05	-3.68E-05	-3.93E-05	-8.62E-05	-3.44E-05	-1.67E-03	-8.45E-04
PT_ER_Other	-2.90E-04	-2.90E-04	1.10E-04	-5.17E-06	-1.21E-05	-1.34E-05	-2.63E-05	-2.27E-04	-2.18E-04
PT_ER_Plastic	-6.14E-04	-7.21E-04	-6.52E-05	6.95E-06	1.48E-03	2.07E-04	2.14E-04	1.72E+00	2.87E-01
PT_ER_Steel	-1.12E-02	-1.12E-02	1.50E-03	-1.01E-04	-2.03E-04	-2.82E-04	-3.61E-04	-4.27E-03	-7.52E-03
PT_Land_Alu	-1.23E-05	-1.22E-05	8.23E-06	-4.26E-06	-2.75E-06	-5.30E-06	-8.12E-06	0.00E+00	-1.93E-06
PT_Land_Copper	-1.79E-05	-1.77E-05	1.19E-05	-6.17E-06	-3.99E-06	-7.68E-06	-1.18E-05	0.00E+00	-2.80E-06
PT_Land_Glass	-2.68E-05	-2.65E-05	1.54E-05	-2.81E-07	-2.11E-06	-2.42E-07	-7.61E-06	0.00E+00	-3.65E-06
PT_Land_Other	-7.14E-06	-7.06E-06	4.76E-06	-2.47E-06	-1.59E-06	-3.07E-06	-4.70E-06	0.00E+00	-1.12E-06
PT_Land_Plastic	-2.15E-04	-2.13E-04	7.13E-05	-1.07E-05	-2.21E-05	-4.72E-05	-5.01E-05	0.00E+00	-2.41E-05
PT_Land_Steel	-2.78E-04	-2.75E-04	1.85E-04	-9.59E-05	-6.20E-05	-1.19E-04	-1.83E-04	0.00E+00	-4.36E-05
PT_MR_Alu	5.52E-02	5.53E-02	-1.56E-02	8.30E-04	4.23E-03	1.65E-03	1.20E-02	7.99E-05	8.32E+00
PT_MR_Copper	2.88E-01	2.85E-01	-2.42E-01	1.89E-01	1.96E-01	1.26E-01	4.07E-01	-5.05E+00	-1.43E-01
PT_MR_Glass	2.81E-03	2.66E-03	1.99E-02	1.26E-04	-1.31E-03	-9.87E-04	-1.70E-02	0.00E+00	-6.84E-03
PT_MR_Other	3.08E-01	3.25E-01	-8.81E-01	7.42E-01	7.58E-01	6.61E-02	2.77E+00	2.93E+00	1.73E-01
PT_MR_Plastic	7.62E-02	6.73E-02	1.57E-02	4.10E-04	-1.17E-03	7.28E-01	-6.03E-03	0.00E+00	-1.57E+00
PT_MR_Steel	1.71E-01	1.71E-01	2.49E+00	-7.46E-03	-1.66E-01	-1.84E-01	-2.88E+00	3.21E-10	-6.25E+00
PT_Other	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PT_Reuse_Alu	4.13E-03	4.02E-03	-2.40E-02	2.30E-03	7.12E-03	8.14E-03	2.48E-02	1.53E-02	1.93E-03
PT_Reuse_Copper	5.99E-03	5.82E-03	-3.48E-02	3.33E-03	1.03E-02	1.18E-02	3.60E-02	2.21E-02	2.79E-03
PT_Reuse_Glass	7.60E-03	7.39E-03	-4.41E-02	4.23E-03	1.31E-02	1.50E-02	4.56E-02	2.81E-02	3.54E-03
PT_Reuse_Other	2.39E-03	2.33E-03	-1.39E-02	1.33E-03	4.13E-03	4.71E-03	1.44E-02	8.85E-03	1.12E-03
PT_Reuse_Plastic	2.89E-02	2.81E-02	-1.68E-01	1.61E-02	4.98E-02	5.69E-02	1.73E-01	1.07E-01	1.35E-02
PT_Reuse_Steel	9.31E-02	9.06E-02	-5.41E-01	5.18E-02	1.61E-01	1.83E-01	5.60E-01	3.44E-01	4.35E-02
PT_TD	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Recycling_Aluminium	5.95E-02	5.91E-02	-1.76E-02	9.37E-04	4.52E-03	6.11E-03	1.29E-02	7.99E-05	8.33E+00
Recycling_copper	5.07E-01	4.98E-01	-1.23E+00	2.54E-01	3.40E-01	5.14E-01	1.04E+00	1.40E+00	3.18E-02
Recycling_glass	3.67E-03	3.51E-03	1.63E-02	1.47E-04	-9.76E-04	-9.54E-04	-1.58E-02	0.00E+00	1.58E-02
Recycling_gold	2.26E-01	2.39E-01	2.49E+00	1.90E-01	-4.98E-02	-1.16E+00	-6.93E-01	2.55E+00	-1.93E-02
Recycling_nickel	-9.46E-03	-8.54E-03	-9.58E-01	2.00E-04	5.57E-02	-4.31E-02	2.15E-01	1.10E-02	1.40E-01
Recycling_other	3.11E-01	3.28E-01	-9.11E-01	7.44E-01	7.63E-01	1.92E-01	2.83E+00	2.95E+00	1.75E-01
Recycling_plastic	9.09E-02	8.18E-02	-4.39E-04	8.31E-04	8.53E-04	7.30E-01	1.10E-03	0.00E+00	3.32E-02
Recycling_silver	9.47E-02	9.73E-02	-2.44E+00	5.54E-01	7.57E-01	1.39E+00	3.30E+00	3.90E-01	5.43E-02
Recycling_steel	2.29E-01	2.28E-01	-3.91E-02	2.40E-03	5.59E-03	9.60E-03	2.33E-02	3.21E-10	2.96E-01
Reuse_Cat1	1.46E-03	1.41E-03	-2.43E-02	7.09E-04	2.40E-03	1.08E-02	1.60E-02	5.93E-03	6.61E-04
Reuse_Cat2	1.72E-02	1.63E-02	-2.29E-01	1.69E-02	9.44E-02	4.67E-02	1.81E-01	8.96E-02	4.05E-03
Reuse_Cat4	1.31E-03	1.27E-03	-3.00E-02	9.30E-04	3.63E-03	1.41E-02	1.91E-02	1.47E-02	4.52E-04
Reuse_Cat6	1.22E-01	1.19E-01	-5.42E-01	6.05E-02	1.45E-01	2.08E-01	6.37E-01	4.15E-01	6.12E-02
Share_Cat1	8.95E-02	8.63E-02	4.65E-01	1.90E-02	1.09E-02	1.92E-01	-4.97E-01	3.62E-01	-1.32E+00
Share_Cat2	9.55E-02	9.72E-02	-1.17E-01	1.46E-01	1.53E-01	1.21E-01	4.75E-01	6.72E-01	1.05E+00
Share_Cat3	1.67E-02	1.69E-02	-2.48E-02	2.32E-02	2.48E-02	1.43E-02	7.95E-02	1.88E-02	1.99E-01
Share_Cat4	2.33E-01	2.28E-01	8.06E-01	1.19E-01	1.02E-01	2.70E-01	-7.14E-01	-3.88E-01	-2.18E+00
Share_Cat5	4.11E-01	4.16E-01	7.87E-02	4.86E-01	4.91E-01	1.92E-01	9.43E-01	-3.63E-01	2.97E+00
Share_Cat6	1.63E-01	1.64E-01	-2.51E-01	2.07E-01	2.20E-01	2.11E-01	7.14E-01	-2.71E-01	1.21E-01
Share_RW3	-2.45E-04	-2.47E-04	1.30E-03	-7.90E-06	-6.46E-05	-1.30E-05	-5.05E-06	3.37E-02	5.49E-03
Share_RW4	-2.49E-03	-2.50E-03	5.55E-03	-2.68E-05	-1.89E-04	-3.72E-05	-4.92E-05	2.41E-01	3.88E-02
Share_RW5	-4.60E-03	-4.61E-03	1.92E-02	-8.16E-05	-1.21E-03	-1.57E-04	-1.40E-04	1.75E-01	2.65E-02
Share_RW6	-9.32E-04	-9.65E-04	1.69E-02	-3.41E-05	-7.10E-04	3.45E-06	2.83E-05	5.20E-01	8.65E-02
Total_RE	-8.26E-03	-8.33E-03	4.30E-02	-1.50E-04	-2.17E-03	-2.03E-04	-1.66E-04	9.69E-01	1.57E-01
Total_WEEE	1.01E+00	1.01E+00	9.57E-01	1.00E+00	1.00E+00	1.00E+00	1.00E+00	3.06E-02	8.43E-01
Trans_general	-1.08E-04	-1.06E-04	1.67E-03	-7.23E-06	-1.45E-04	-9.71E-06	-5.30E-04	0.00E+00	-3.67E-04
Trans1	-9.87E-04	-9.69E-04	1.53E-02	-6.62E-05	-1.33E-03	-8.90E-05	-4.86E-03	0.00E+00	-3.36E-03
Trans2	-3.21E-03	-3.15E-03	4.98E-02	-2.15E-04	-4.32E-03	-2.90E-04	-1.58E-02	0.00E+00	-1.09E-02
Trans3	-4.29E-03	-4.21E-03	6.66E-02	-2.88E-04	-5.77E-03	-3.87E-04	-2.11E-02	0.00E+00	-1.46E-02

7.14 Appendix XIV

Table 22: Standard deviation for each parameter used in EASETECH. [a](Miljødirektoratet, 2023), [b](Marianne Bigum, Petersen, et al., 2013), [c](Baxter et al., 2021) & Fagerheim, Mikkelborg, and Bjørnerud, 2021, [d] (John Baxter, Lyng, et al., 2016), [e] (Marianne Bigum, Brogaard, and Christensen, 2012)

Parameter	Value used for EASETECH	Standard deviation (SD)	Unit	Relative SD (%)	Comment
Total_WEEE	1.07E+08	4744	kg	0%	SD based on data for the 4 years (a)
Share_Cat1	0.20	0.0160	%	8%	SD based on data for the 4 years (a)
Share_Cat2	0.06	0.0063	%	10%	SD based on data for the 4 years (a)
Share_Cat3	0.01	0.0009	%	10%	SD based on data for the 4 years (a)
Share_Cat4	0.36	0.0134	%	4%	SD based on data for the 4 years (a)
Share_Cat5	0.30	0.0181	%	6%	SD based on data for the 4 years (a)
Share_Cat6	0.07	0.0074	%	10%	SD based on data for the 4 years (a)
Share_RW3	0.03	0.0129	%	43%	SD given in paper of 43% (b)
Share_RW4	0.29	0.1247	%	43%	SD given in paper of 43% (b)
Share_RW5	0.49	0.2107	%	43%	SD given in paper of 43% (b)
Share_RW6	0.18	0.0774	%	43%	SD given in paper of 43% (b)
Total_RE	7.50E+06	500	kg	0%	Assumption for SD (c)
Trans1	115	1	km	1%	SD based on the given 3 distances (d)
Trans2	374	177	km	47%	SD based on the given 3 distances (d)
Trans3	613	434	km	71%	SD based on the given 3 distances (d)
Trans_general	50	5	km	10%	Assumption (SD +/-10%)
PT_Other	0.10	0.04	%	39%	SD based on data for the 4 years (a)
PT_Reuse_Plastic	2.01	0.41	%	21%	SD based on data for the 4 years (a)
PT_Reuse_Other	2.01	0.37	%	18%	SD based on data for the 4 years (a)
PT_Reuse_Steel	2.01	0.37	%	18%	SD based on data for the 4 years (a)
PT_Reuse_Copper	2.01	0.37	%	18%	SD based on data for the 4 years (a)
PT_Reuse_Glass	2.01	0.37	%	18%	SD based on data for the 4 years (a)
PT_Reuse_Alu	2.01	0.37	%	18%	SD based on data for the 4 years (a)
PT_Land_Plastic	4.07	1.59	%	39%	SD based on data for the 4 years (a)
PT_Land_Other	4.07	1.96	%	48%	SD based on data for the 4 years (a)
PT_Land_Steel	4.07	1.96	%	48%	SD based on data for the 4 years (a)
PT_Land_Copper	4.07	1.96	%	48%	SD based on data for the 4 years (a)
PT_Land_Glass	4.07	1.96	%	48%	SD based on data for the 4 years (a)
PT_Land_Alu	4.07	1.96	%	48%	SD based on data for the 4 years (a)
PT_MR_Plastic	81.55	1.37	%	2%	SD based on data for the 4 years (a)
PT_MR_Other	81.55	1.37	%	2%	SD based on data for the 4 years (a)
PT_MR_Steel	81.55	1.37	%	2%	SD based on data for the 4 years (a)
PT_MR_Copper	81.55	1.37	%	2%	SD based on data for the 4 years (a)
PT_MR_Glass	81.55	1.37	%	2%	SD based on data for the 4 years (a)
PT_MR_Alu	81.55	1.37	%	2%	SD based on data for the 4 years (a)
PT_TD	0.20	0.06	%	29%	SD based on data for the 4 years (a)
PT_ER_Plastic	12.07	1.51	%	13%	SD based on data for the 4 years (a)
PT_ER_Other	12.07	1.23	%	10%	SD based on data for the 4 years (a)
PT_ER_Steel	12.07	1.23	%	10%	SD based on data for the 4 years (a)
PT_ER_Copper	12.07	1.23	%	10%	SD based on data for the 4 years (a)
PT_ER_Glass	12.07	1.23	%	10%	SD based on data for the 4 years (a)
PT_ER_Alu	12.07	1.23	%	10%	SD based on data for the 4 years (a)
Reuse_Cat1	16.85	13.10	%	78%	SD based on data for the 4 years (a)
Reuse_Cat2	36.75	5.09	%	14%	SD based on data for the 4 years (a)
Reuse_Cat4	17.93	8.29	%	46%	SD based on data for the 4 years (a)
Reuse_Cat6	28.47	7.12	%	25%	SD based on data for the 4 years (a)
Recycling_plastic	90	9.00	%	10%	Assumption (SD +/-10%)
Recycling_other	90	9.00	%	10%	Assumption (SD +/-10%)
Recycling_gold	0.13	0.01	%	10%	Assumption (SD +/-10%)
Recycling_silver	1.81	0.18	%	10%	Assumption (SD +/-10%)
Recycling_nickel	17	1.74	%	10%	Assumption (SD +/-10%)
Recycling_steel	84	8.40	%	10%	Assumption (SD +/-10%)
Recycling_copper	77	7.69	%	10%	Assumption (SD +/-10%)
Recycling_glass	94	9.40	%	10%	Assumption (SD +/-10%)
Recycling_Aluminium	93	9.30	%	10%	Assumption (SD +/-10%)

7.15 Appendix XV

Table 23: Results of uncertainty analysis for each flow

Global warming potential (GWP100) - Uncertainty analysis				
Flow	**Mean**	**Standard deviation (SD)**	**Variation**	**Relative SD**
Unit	kg CO_2-eq	kg CO_2-eq	kg CO_2-eq	%
Aluminium recycling, Europe based on Rigamonti	8.01E+05	3.53E+04	1.25E+09	4%
Aluminium: Substitution Aluminium Market ratio 100%	-2.71E+07	2.96E+06	8.74E+12	-11%
Aluminium: Waste treatment landfill metals	2.75E+03	3.60E+03	1.30E+07	131%
Copper recycling	4.40E+07	1.78E+06	3.18E+12	4%
Copper: Substitution copper, ratio 100%	-1.94E+07	2.10E+06	4.39E+12	-11%
Copper: Waste treatment_landfill of metals	1.30E+04	4.37E+03	1.91E+07	34%
Glass recycling, Europe based on Rigamonti, updated	3.07E+06	3.40E+05	1.16E+11	11%
Glass Sorting and treatment Europe, based on Rigamonti	4.56E+04	2.17E+03	4.70E+06	5%
Glass: Substitution of Glass Manufacturing without cullets, 83% cullet ratio in recycling	-3.78E+06	4.19E+05	1.76E+11	-11%
Glass: Waste treatment_landfill of glass	3.45E+03	5.50E+03	3.03E+07	160%
Landfill of all metals	4.97E+04	2.11E+04	4.45E+08	42%
Landfill of glass	2.95E+03	1.43E+03	2.05E+06	49%
Landfill of plastic	6.42E+04	3.04E+04	9.25E+08	47%
OM: Gold, silver & nickel recycling	1.39E+08	1.93E+07	3.72E+14	14%
OM: Other metals recycling	3.90E+05	1.78E+04	3.16E+08	5%
OM: Substitution Gold	-1.09E+08	1.65E+07	2.71E+14	-15%
OM: Substitution Nickel	-4.18E+06	6.22E+05	3.87E+11	-15%
OM: Substitution Silver	-2.00E+07	2.98E+06	8.89E+12	-15%
OM: Waste treatment_landfill of metals	2.26E+03	2.03E+03	4.11E+06	90%
Plastic: HDPE recycling, Europe, based on Rigamonti	4.16E+06	1.57E+05	2.48E+10	4%
Plastic: Substitution HDPE, market ratio 81%	-2.64E+07	2.83E+06	8.00E+12	-11%
Plastic: Waste treatment_landfill of plastic	1.28E+05	1.15E+05	1.33E+10	90%
Pretreatment	4.75E+06	1.37E+05	1.89E+10	3%
Reuse: Substitution of production from reuse - WEEE category 1: Refrigerator	-4.38E+05	3.51E+05	1.23E+11	-80%
Reuse: Substitution of production from reuse - WEEE category 2: TV	-2.50E+06	4.75E+05	2.25E+11	-19%
Reuse: Substitution of production from reuse - WEEE category 4: Dishwasher	-2.86E+05	1.37E+05	1.87E+10	-48%
Reuse: Substitution of production from reuse - WEEE category 6: Smartphone	-3.54E+07	1.00E+07	1.01E+14	-28%
Steel recycling, Europe based on Rigamonti	1.42E+07	4.83E+05	2.33E+11	3%
Steel: Substitution steel, market ratio 100%	-1.64E+08	1.73E+07	3.01E+14	-11%
Steel: Waste treatment_landfill of metals	1.40E+05	7.36E+04	5.41E+09	53%
Sum	-1.85E+08	2.14E+07	4.59E+14	-12%
Transportation to different return companies (reception point)	6.87E+05	7.44E+04	5.53E+09	11%
Transportation to incineration plant	5.68E+04	1.92E+04	3.68E+08	34%
Transportation to landfilling	1.22E+04	4.26E+03	1.82E+07	35%
Transportation to material recovery	2.99E+06	3.11E+05	9.70E+10	10%
Transportation to pretreatment	2.23E+06	2.31E+05	5.31E+10	10%
Transportation to reuse of materials	6.00E+03	9.87E+02	9.73E+05	16%
WTE: Landfill Bottom ash 1 Leachate generation	2.03E+04	9.45E+03	8.92E+07	46%
WTE: Landfill Bottom ash 3a WWTP - TEMPORARY	2.10E+02	9.77E+01	9.54E+03	46%
WTE: Landfill Bottom ash 3c Uncontrolled leachate - TEMPORARY	0.00E+00	0.00E+00	0.00E+00	0%
WTE: Utilization for neutralization of waste acid, Norway, 2006	1.25E+04	3.84E+03	1.48E+07	31%
WTE: Waste to energy plant, generic (Updated for Norway)	1.19E+07	6.16E+06	3.80E+13	52%
WTE: WtE_Electricity substitution Norway	-4.15E+04	2.17E+04	4.73E+08	-52%
WTE: WtE_Heat substitution	-1.81E+06	9.49E+05	9.01E+11	-52%

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