Assessing the Environmental Impact of End of Life High Voltage Products

A case study of Hitachi Energy's EoL transformers in Sweden

Master's thesis in Sustainable Energy Systems

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Abstract

High voltage (HV) products respond to increased needs for long distance electricity transmission from decentralised power generation systems such as solar and wind power generation. With the expected increase in electricity production from renewable energy and electricity consumption in line with electrification in the industrial and transport sectors, the demand of HV products is expected to increase. Hitachi Energy is a leading manufacturing company in electric power products, and HV products are the main products in one of their main business areas at the company. Currently, there is little knowledge about the disposal of HV products and the levels of material recovery and recyclability. Recycling of metals and materials is important both in terms of resource use and environmental impact. The aim of this project is to perform an extensive survey of the current end-of-life management of the high voltage products and to assess its environmental impact. To achieve this, a literature study was performed, covering regional regulations and directives in waste handling, primary and secondary metal production, hazardous substances, and concepts of circular economy. Interviews were then conducted with EoL service providers. The environmental assessment was then made based on these results, and on data collection through environmental reports. The results showed high recycling rates for metals and uncontaminated transformer oil, while the small amounts of conventional waste are sent directly to landfill or to incineration for energy recovery. Overall, the materials have an even higher recyclability potential and present opportunities to save large amounts of energy and emissions by replacing primary production. The decontamination of hazardous substances, such as PCB contaminated oil and components, is an energy intensive process, but incineration of them results in greater emissions and environmental harm. The hazardous substances should be eliminated or replaced in the products, both for environmental reasons but also because handling them constitutes a risk to human health. Replacing hazardous substances with alternative substances, product design that facilitates recycling at EoL stage, optimising current recycling process in disassembly, separation and sorting stages, and dialogues between the product manufacture and EoL service providers are important factors for increasing the level of material recycling and recyclability, and for reducing the environmental impact on a product level.

Keywords: End of life, EoL, high voltage products, material recycling, energy recovery, Life cycle analysis, LCA, circular economy, waste management

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Akiho Tamura and Tim Johansson, Gothenburg, June 9, 2022

List of Abbreviations

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BOF	Basic Oxygen Furnace
CEAP	Circular Economy Action Plan
CRMs	Critical Raw Materials
DR	Direct Reduction
EAF	Electric Arc Furnace
ECHA	European Chemicals Agency
EEE	Electrical and Electronic Equipment
ELV	End of Life Vehicles
EoL	End-of-life
EOL-RIR	End-of-life Recycling Input Rate
EOL-RR	End-of-life Recycling Rate
EoW	End-of-Waste
EPA	Environmental Protection Agency
EPR	Extended Producer Responsibility
ETP	Electrolytic Tough-Pitch
EU	European Union
GCB	Generator circuit breaker
GHGRP	Greenhouse Gas Reporting Program
GIS	Gas-Insulated switchgear
GWP	Global Warming Potential
HCl	Hydrochloric acid
HF	Hydrogen Fluoride
HVDC	High Voltage Direct Current
HV	High Voltage
HYBRIT	Hydrogen Breakthrough Ironmaking Technology
ICT	Information and Communication Technology
IEW	Industrial Electrical Equipment Waste
IPCC	Intergovernmental Panel on Climate Change
ISRI	Institute of Scrap Recycling Industries
LCA	Life Cycle Assessment

MFA	Material Flow Analysis
N_2	Nitrogen
NOx	Nitrogen Oxides
NTP	Non Thermal Plasma
O_2	Oxygen
PBB	Polybrominated Biphenyls
PBDE	Polybrominated Diphenyls Ethers
PCBs	Polyclorinated Biphenyls
PE	Polyethylene
POPs	Persistent Organic Pollutants
PP	Polypropylene
PVC	Polyvinyl Chloride
RMI	Raw Materials Initiative
R&D	Research and development
REACH	Registration, Evaluation, Authorisation, Restriction of Chemicals
RCRA	The Resource Conservation Recovery Act
RoHS	Restrictions of Hazardous Substances
SDGs	Sustainable Development Goals
SF_6	Sulfur hexafluoride
SO_2	Sulfur dioxide
TSCA	Toxic Substances Control Act
UHVDC	Ultrahigh Voltage Direct Current
US	United States
WEEE	Waste Electrical and Electronic Equipment
WFD	Waste Framework Directive

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Introduction

Hitachi Energy is a pioneering technology leader that is helping to increase access to affordable, reliable, sustainable and modern energy for all. High voltage products are the main products in one of their main business areas at the company. These products respond to increased needs for long distance electricity transmission from remote power sources such as decentralised power systems using solar and wind energy. With the expected increase in electricity consumption in the coming decades, the demand for these products is also expected to rise. To perform the high level of quality of power transmission, high voltage products need specific materials that are important both economically and environmentally. Currently, there is little knowledge about how these products are disposed of and the level of recyclability of the materials. Recycling is important both in terms of resource use and environmental impact. Additionally, with the rise of circular economy principles and ideas, recycling is one of the main methods that can be used to close material flows. This is especially important for electrical equipment, as it often requires metals and critical raw materials of limited supply. The products have a lifetime of 30-40 years, so there is a large time gap between the production and recycling of the products. It is therefore relevant to investigate both current and emerging recycling technologies when investigating the end-of-life management. For these reasons, there is a need for a greater understanding of the current end-of-life practices and to assess its environmental impact, both from the side of society and for Hitachi as a company. This knowledge can then be used to change the design and handling of the products in order to improve resource efficiency and enhance profits through more effective use of waste flows and by utilizing emerging recycling technologies. Implementing these changes would be beneficial both for the company from an economic perspective, and for society as a whole from an environmental perspective.

1.1 Aims

The aim of this project is to perform an extensive survey of the current end-of-life management of the high voltage products as it is conducted by end-of-life service providers, and to assess its environmental impacts. The project also aims to provide comprehensive knowledge of this management by analysing material flows and comparing end-of-life practices and environmental impacts both for different management processes as well as in different regions in the world, where the end-of-life management may differ for high voltage products. Furthermore, the project aims to suggest changes on the product design and material flows over the product supply chain, and to the end-of-life management practices with the goal of mitigating the environmental impacts through the product life cycle, and increasing rates in reusing, recycling and recovering of each material for the current and future high voltage products.

1.2 Objectives

The objectives of the project can be divided into three parts. In the first part of the project, the main objective is to provide a measurement of the environmental impact of the current end-of-life handling. This is achieved by defining the important material groups in the products and analysing their methods of production and recycling. This is followed by investigating hazardous substances, and regulations relating to these substances and to waste from high voltage products in general. Finally, interviews are performed with end-of-life service providers in the relevant regions. The results are then compared between the different regions and emerging recycling technologies are evaluated.

In the second part of the project, the objective is to identify changes and improvements to facilitate recycling and increase recyclability rates of the products. This is done by reviewing the R&D process in order to find potential design changes, and by analysing the entire recycling process. The environmental impact of the suggested changes compared with the current processes is then assessed and evaluated.

In the third and final step of the project, the objective is to document the outcomes in a technical report, and to provide guidelines for the production unit at Hitachi energy and for customers, in order to establish better handling of the high voltage products from an environmental point of view.

1.3 Research questions

The research questions are made based on the aims and the objectives. The following questions are used as a basis for the research:

- How are the high voltage products currently managed at their end-of-life stage by the end-of-life service providers in the different regions in the world?
- What are the rates in recycling, reusing and recovering of the material groups in the high voltage products today in the different regions, where the different end-of-life management are conducted?
- What kind of environmental impacts are there when the high voltage products are managed at their end-of-life stage?
- What are the differences in the end of life management practices and the environmental impacts between the different regions?
- How much do the changes on products design, on material flow over the product supply chain, and on end-of-life management practices contribute to mitigate the environmental impacts and to increase rates in reusing, recycling, and recovering of the material groups for current and future high voltage products?

2
Theory

This chapter covers the key theoretical concepts necessary for this study. It begins with the high voltage products and sustainability goals of Hitachi Energy, and the regulations and directives that are most relevant to the waste generated by this category of products. From there, major materials and hazardous substances, and their roles in the products are described, in combination with their current methods of recycling or disposal. Finally, to contextualise the study and its results, background and key concepts associated with environmental assessments and circular economy are explained. All information in this chapter was retrieved through a literature study, either using academic and technical reports, internal documents at Hitachi Energy, or educational material from Chalmers University of Technology.

2.1 High voltage products

High voltage (HV) products play an important role in the emerging power trends such as compact and intelligent substations, high voltage direct current (HVDC) and ultrahigh voltage direct current (UHVDC) transmission links between cities and countries, and integration of renewable energies in an existing energy system [1]. High voltage products can be defined as products that can be used with voltage levels from 52 kV up to 1 500 kV. The advantages with the HV products are that the HV products can reduce the losses in transmitting power over the long distance, the use of conductors where metals are used, and the land use [2]. On the other hand, disadvantages of HV products include that equipment used in the HV products tends to be expensive and large. This means that losses, conductor use and land use can be minimised with the HV products, however high investment cost and large equipment are required for manufacturing and installing them. The HV products that are mainly focused and analysed in the project are presented in the Figure 2.1, where different products are divided by its application and functions.

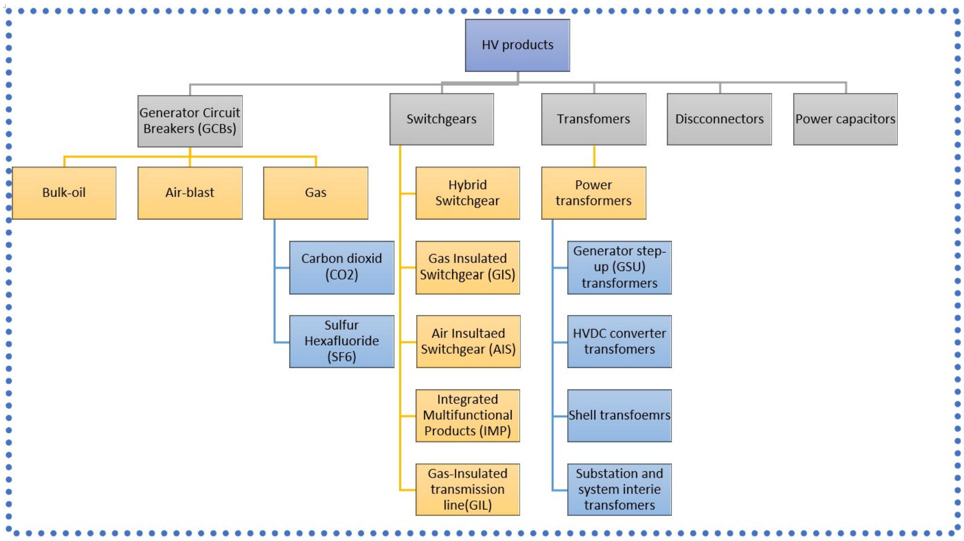

Figure 2.1: Simplified chart of Hitachi Energy's high voltage products. The focus in the project is on all high voltage products on a general level, which is highlighted with the dotted line.

As seen in Figure 2.1, Hitachi Energy's main HV products are generator circuit breakers (GCBs), switchgears, transformers, disconnectors and power capacitors. The focus in the project is the environmental impact of all high voltage products at their end of life stage on a general level. Generator circuit breakers can further divided by the insulation medium such as oil-, air- and gas insulated generator circuit breakers [1]. Switchgears are also divided by the insulation medium, hybrid-, air- and gas insulated switchgears. At substations, different kinds of power transformers are used depending on applications such as generator step-up transformers, HVDC converter transformers, shell transformers and substation and system interie transformers.

The main function of generator circuit breakers is to stop the flow of current in case of imbalance in power production and load or faults in a power generation system [2]. Switchgears are used as interconnection points between the different lines by connecting from one line to another with switching possibilities. The key function of transformers is to change the voltage levels either to increase or decrease to transmit and distribute power to electricity consumers. Disconnectors are used to ensure that an electrical circuit is completely disconnected for maintenance and services. Power capacitors are used to shift the voltage in relation to current to maintain voltage levels.

2.2 Sustainability goals of Hitachi Energy

Hitachi Energy has their own sustainability goals, so called Sustainability 2030, which is a strategic plan for a sustainable society aligned with the UN's Sustainable Development Goals (SDGs) [3]. Sustainability 2030 consists of short and medium-term concrete and measurable targets. Regarding the planet, Hitachi Energy has the following targets, which the company aims to achieve by 2030 using 100% fossil-free electricity in operations:

- 50% reduction of CO2 equivalent emissions along the value chain compared to 2019.
- 50% reduction of waste disposed compared to 2013.
- 25% reduction of freshwater use compared to 2013.
- 25% reduction of hazardous substances and chemicals compared to 2022.

Furthermore, the company emphasises collaboration across stakeholders, geographies and sectors as a key success factor for achieving carbon neutrality in society, mitigating climate change, promoting circular economy and accelerating energy transition [3].

2.3 Hazardous substances

HV products use hazardous substances as insulation medium. In this section, the major hazardous substances in HV products, sulfur hexafluoride (SF_6) and polychlorinated biphenyls (PCBs), are described along with potential future alternatives.

2.3.1 Sulfur hexafluoride

Sulfur hexafluoride (SF_6) is a non-flammable, non-toxic gas of high chemical stability. Because of its unique dielectric properties, it is used as an electrical insulator and arc suppressant in high voltage equipment. It is also an extremely potent greenhouse gas with a very long atmospheric lifetime.

The gas is used in several types of electrical equipment, including circuit breakers, gas-insulated substations, and high voltage switchgear. Gas-insulated switchgear (GIS) is one form of switchgear, where conductors and contacts are insulated using pressurized SF_6 gas. Compared to air, its insulating properties are much better, resulting in more compact equipment, which in turn reduces land use, energy consumption and waste [1].

Sulfur hexafluoride is one of the six greenhouse gases listed in the Kyoto Protocol. It is the most potent greenhouse gas ever evaluated according to the IPCC, with a global warming potential that is 23 900 times greater than carbon dioxide [4]. The gas is also inert in the lower parts of the atmosphere, resulting in an atmospheric lifetime of approximately 800 - 2 300 years [5]. Due to the increasing usage of electricity, which results in an increased demand for equipment using the gas, emission rates of SF_6 are increasing rapidly. As the gas is mostly used in well-sealed installations, the primary source of emissions is leakage, mainly caused by aging of for example sealing elements [6].

SF_6 usually poses a low risk for health issues, although it could cause suffocation at high concentrations in poorly ventilated areas. However, thermal stress as a consequence of electric arcing in the gas-insulated equipment can cause the gas to break down into other compounds that are far more toxic and hazardous. These by-products are also produced upon incineration of SF_6. Examples of by-products include sulfur pentafluoride (SF_5), sulfur tetrafluoride (SF_4), nitrogen dioxide (NO_2), nitric oxide (NO), nitrous oxide (N_2O), sulfur dioxide (SO_2), and hydrogen fluoride (HF) [7].

Alternative insulation solutions include dry air, oil, vacuum, nitrogen, and carbon dioxide. Gas mixtures also occur, for example the addition of SF_6 to nitrogen or air to improve insulation capacity. These solutions are well-researched and commercially viable but limited by their low breakdown voltages compared to pure SF_6. This means they are better suited for low to medium voltage equipment, but more challenging to use at higher voltage levels [8].

2.3.2 Polychlorinated biphenyls

Polychlorinated biphenyls (PCBs) are man-made chemical substances that were continually produced and used on a large scale across the world between the 1930s and 1980s [9]. PCBs were used mainly as electrical insulating fluid in transformers because they have suitable technical characteristics such as high dielectric strength, high thermal conductivity, chemical stability, non-flammability and ability to withstand high temperatures [10].

Beside these technical strengths, PCBs have drawbacks as they are classified as persistent organic pollutants (POPs) due to their persistence in the environment, and risks for bio-accumulation in an organism and bio-magnification via the food chain, as they have been detected in soil, surface, ground water and in food, which in turn causes adverse effects to human health and the environment [9]. To minimise the risks of toxic effects to human health and the environment caused by both intentional and unintentional production (i.e. by-products of industrial processes), the commercial use and production of PCBs has been restricted in many countries since the 1980s [9]. However, there are still a large number of transformers that contain considerable amount of PCBs contaminated transformer oil in the world today [10].

According to 40 years of studies on PCB pollution, food safety, health risks and human health in an electronic waste (E-waste) recycling area in China, soil and fish samples indicated higher concentration levels of PCBs than sediments, air, water and food items [11]. The study also found that agricultural soils near the E-waste recycling sites showed more higher concentration levels of PCBs than industrial soils and urban soils [11]. The study also mentions that the body burden of PCBs increased especially in children living nearby the E-waste recycling area, and these pollutants could cause various abnormalities in human health, such as kidney injury, hematology and affected thyroid hormone levels in the body [11].

Natural and synthetic esters have been introduced and used as an alternative electrical insulating fluid instead of PCBs in transformers [12]. Natural esters are derived from seeds of different plants such as rapeseed oil, soya oil, or sunflower while synthetic esters are artificially manufactured from certain raw materials. Natural esters are suitable in the temperate environment due to their high pour point and low oxidation stability, while synthetic esters are suitable in the cold climates due to their low pour point and high oxidation stability [12]. According to a study conducted by

Mahanta [12], the application of ester oil in transformer reduces the failure of a transformer in the power system network and reduces the cost involved with transformer condition monitoring due to its numerous advantages over conventional mineral oil, such as high biodegradability, high-temperature stability, high viscosity index, lower temperature flow-ability, low toxicity, low flammability and reduced friction.

2.4 Regulations and directives

This section covers the relevant regulations and directives associated with different types of waste in the chosen global regions or countries. Only directives that apply to all waste, or specifically to waste originating from or relating to high voltage products, industrial electrical equipment, or adjacent product categories are covered. As the primary focus of the project is the EU, directives and regulations within the union are mentioned by their title and described in further detail than for other regions.

2.4.1 EU Waste Framework Directive

The Waste Framework Directive (WFD) is an EU directive that establishes a legal framework for the treatment of waste in the European Union. The aim of the framework is to prevent and reduce the negative impact of waste generation and management, and to improve the use of resources [13]. The directive introduces concepts such as the Extended Producer Responsibility (EPR) and the "polluter-pays principle", specifies End-of-waste (EoW) criteria for certain waste materials, and sets recovery and recycling targets for both household waste and construction and demolition waste. Furthermore, it defines the European waste hierarchy, which indicates the preferred order of action for the reduction and management of waste [14]. The five steps in the hierarchy are:

1. **Prevention:**
   Measures taken before a substance becomes waste, that reduce the quantity or adverse impact of the waste, or its content of hazardous substances.
2. **Reuse and preparation for reuse:**
   Operations by which products that are not waste are used again for their original purpose, or prepared for such use.
3. **Recycling:**
   Recovery operations through which waste materials are reprocessed into new products.
4. **Recovery for other purposes, such as energy:**
   Operations where the principal result is the waste serving a useful purpose by replacing other materials.
5. **Disposal:**
   Any operation which is not recovery, even if the secondary consequence of the operation is reclamation of substances or energy.

The hierarchy applies as a priority order for waste management legislation and policies, but specific waste streams may depart from it if justified by life-cycle thinking and overall environmental impact [13]. The waste hierarchy is often represented as an inverted pyramid, as shown in Figure 2.2. To clarify, energy recovery through for example waste incineration is not considered recycling, neither in this project, nor by EU standards.

Figure 2.2: Illustration of the European waste hierarchy [14]

2.4.2 EU Ecodesign directive

The EU Ecodesign directive establishes a framework to set requirements on energy-related products in order to reduce the energy consumption and environmental impact occurring throughout their life cycle. The life cycle phases of a product, as defined by the Ecodesign directive [15], are:

- Selection and use of raw materials
- Manufacturing
- Packaging, transport, and distribution
- Installation and maintenance
- Use
- End of life

For every phase, an identification and assessment of several different types of environmental aspects must be made. Examples of such aspects include consumption of energy and natural resources, emissions to air, water, or soil, waste generation, and opportunities for reuse, recycling, and recovery of materials or energy.

The directive is implemented through regulations that apply to specific products and product groups. The motivation of the directive is that energy-related products account for a significant share of the consumption of energy and natural resources in society. Energy efficiency improvements are therefore an important part of reaching the emission reduction targets of the EU. This is especially important as electricity use is expected to rise within the coming decades.

2.4.3 Waste regulations in the US

The Resource Conservation and Recovery Act (RCRA) is a federal law that creates a framework for the management and disposal of hazardous and non-hazardous solid waste. The regulations of the RCRA are enforced by the U.S. Environmental Protection Agency (EPA) and on the state level. RCRA sets national goals for the protection of human health and of the environment, conservation of energy and natural resources, reduction of waste generation, and an environmentally sound waste management [16].

There is no national law that mandates recycling, but specific recycling regulations or legislation often exists at the state or city level. These regulations may take the form of recycling goals or landfill bans, or may apply to certain products or product categories.

2.4.4 Waste regulations in China

In China, solid waste and its management is regulated by the Law of the People's Republic of China on Prevention and Control of Environmental Pollution by Solid Waste. The law was enacted in 1995 but has seen two major amendments, the most recent in 2020. The goals of the law is to prevent environmental pollution caused by solid waste, to safeguard public health and ecological security, and to promote sustainable economic and social development [17]. It establishes a comprehensive framework on waste management, including the collection, sorting, transport, import, storage, treatment, and disposal of several types of waste.

Over the past 15 years, more policies and standards have been formulated to improve and promote waste management through reduction, recycling, and harmless treatment of solid waste. The speed of standard formulation has been increasing and previous standards have seen revisions [18]. Examples of relevant standards include the Standard for pollution on the storage and disposal site for general industrial solid waste (GB 18599-2001) and the Standard for pollution control on hazardous waste storage (GB 18597-2001). This trend shows that the policy situation in China is rapidly changing, which can be explained by state emphasis on waste management in response to increasing waste generation [18].

2.4.5 Regulations on metal scrap

The management of copper scrap in the EU falls under the waste regulations, such as the Waste Framework Directive and the EU Waste Shipment Regulation [19]. Additionally, the EU Regulation No 715/2013 establishes EoW criteria that determine when copper scrap ceases to be waste and may be used as input for recovery processes as a secondary raw material. These criteria regulate what type of scrap may be used as input, its quality and composition, and what pre-treatment processes must be completed [20]. Certain types of copper-containing waste may also be regulated by more specific directives, such as the WEEE directive.

Specifications and standards for copper and copper alloy scrap also exist on international, regional, and national levels, and are used as references for price setting, classification, and quality control. European Standard EN 12861 specifies the requirements for several quality aspects of copper scrap used for direct melting. The US trade association Institute of Scrap Recycling Industries (ISRI) has developed specifications that distinguish between different grades of copper scrap. These specifications are internationally accepted and used as standards throughout the world. In contrast to EN 12861, the specifications also cover lower grade copper that requires smelting and refining [19].

Aluminium scrap is largely covered by the same EU waste regulations as copper scrap. The corresponding regulation that determines the waste status of the scrap is EU Regulation No 333/2011, which also covers iron and steel scrap. The regulation establishes criteria on the quality, pre-treatment, impurity levels, and composition of the scrap used in recycling processes [21]. The most relevant product-specific EU directives are the WEEE directive and the ELV directive. Same as for copper, there are specifications and standards for aluminium scrap on all levels. The most important are the ISRI specifications and European Standard EN 13920. These classify the scrap metal by its chemical composition, impurity levels, shape and size, and homogeneity [22].

2.4.6 EU RoHS directive

Restrictions of Hazardous Substances (RoHS) directive is an EU directive that restricts the use of hazardous substances in electrical and electronic equipment (EEE) to protect the environment and public health [23]. The main reasons why the EU established this directive in 2003 are that the amount of waste electrical and electronic equipment (WEEE) is increasing every year in the EU and EEE contains hazardous substances, which in turn has risks for release during the use, collection, treatment and disposal phases. Restricting the use of hazardous substances in EEE promote even the possibilities and economic profitability of recycling of WEEE.

RoHS directive restricts certain hazardous substances in EEE such as lead, cadmium, mercury, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE), which can cause serious environmental and health problems and are required to be substituted by safer alternatives [23]. All manufactures of products with an electrical and electronic equipment have to follow these restrictions unless products are specifically excluded in the directive.

The directive can be considered to be adjacent to high voltage products and its waste, as it does not apply to a majority of the waste from the product category. Both the RoHS directive and the WEEE directive excludes EEE from large-scale fixed installations, which includes a large share of transformers, switchgear, and equipment pertaining to electrical substations. The only exception to this exclusion is equipment specifically designed as part of those installations. Nonetheless, the RoHS directive is relevant as the aforementioned exclusion does not apply to all types of EEE, and the terms of the directive may see changes or updates in the future.

2.4.7 EU REACH regulation

REACH is an EU regulation that stands for Registration, Evaluation, Authorisation and Restriction of Chemicals. REACH was adopted in 2007 and aims to improve the protection of human health and the environment from the risks caused by chemical substances used both in industries and our daily lives, while enhancing the competitiveness of EU chemical industry [24]. The main reasons why the EU adopted the REACH regulation are that there has been insufficient information on a large number of chemical substances which are manufactured and placed on the EU market for many years and therefore it is necessary to fill the information gaps to ensure that industry can assess hazards and risks of chemical substances, and to identify and implement risk management measures to protect human health and the environment [25].

Manufactures, importers, and downstream users of chemical substances are obliged to gather information on the properties of their chemical substances and to register information in a central database governed by European Chemicals Agency (ECHA)[25]. ECHA evaluates individual registration and assesses whether the risks of substances can be managed or not.

2.4.8 Regulations on sulfur hexafluoride

Use of sulfur hexafluoride (SF_6) in the EU falls under the F-gas directive, which regulates fluorinated gases. The directive controls several aspects of the usage of the compound, including containment measures such as:

- Emission control and leakage detection
- Recovery of the gas prior to disposal of the equipment
- Record keeping on recovery, recycling, reclamation, and disposal of the gas

The objective of these measures is to establish rules on all steps of the life cycle in order to reduce emissions of the gas [26].

In the USA, SF_6 is covered by the Greenhouse Gas Reporting Program (GHGRP) of the EPA. The GHGRP requires reporting of greenhouse gas data and other relevant information from large emission sources and industrial gas suppliers, including the supply and emission of SF_6 in electrical equipment [27]. In addition to this program, there are also regulations on the state and regional level that set maximum emission rates from and target the service of electrical equipment containing SF_6.

China has no mandatory regulations on consumption or emissions of SF_6. However, national plans and policies adopted by the government address climate change with the aim to reduce greenhouse gas emissions in general.

2.4.9 Regulations on polychlorinated biphenyls (PCBs)

Regarding production and use of polychlorinated biphenyls (PCBs), different regulations are applied either on international, regional or country levels. The Stockholm Convention is an international agreement that aims to protect human health and the environment from the effects of persistent organic pollutants (POPs). The convention was adopted by the international community and entered into force in 2004 [28]. The convention regulates currently 29 POPs and PCBs are ones of POPs listed in the convention. The convention prohibits the international production and use as well as unintentional exposures of PCBs. The countries are required to eliminate the use of PCBs in existing equipment by 2025 and to ensure the environmentally sound disposal of waste that contain PCBs by 2028 [28].

Persistent Organic Pollutants (POPs) Regulation regulates strictly use of PCBs in the EU. The regulation requires that all remaining PCBs within dielectric equipment in concentrations above 0.005 % and in volumes greater than 50 ml must be decomposed or transformed by 2025 [9].

Regarding disposal of PCBs in the EU, the directive on the disposal of PCBs/PCTs are applied, which aims to ensure the environmentally friendly disposal of these chemicals and of the equipment containing them [9]. As it is a directive, each EU member state has to implement this directive into national legislation. In Sweden, disposal of PCBs has to be followed by the waste regulation (Avfallsförordningen, 2020:614) and the PCB ordinance (Förordning, 2007:19 om PCB) [29].

Production and use of PCBs in the U.S. was banned in 1979 by the Toxic Substances Control Act (TSCA) and disposal of PCBs are regulated by TSCA PCB regulations [30]. The United States Environmental Protection Agency (EPA) states that although PCBs are no longer commercially produced and used, PCBs are present in products such as transformers and materials produced before the TSCA was introduced [30].

PCBs were neither widely produced nor used in China before they became the subject of international bans on use and production by the Stockholm convention [31]. Rather, pollution linked to PCBs has emerged in China through imported electronic waste (E-waste) and informal waste management such as open dumping and uncontrolled waste recycling. Local residents are suffering serious health and the environmental problems, where PCB containing waste is stored and managed in an improper manner [31]. Due to emerging PCB pollution to human health and in the environment, the State Environment Protection Authority has continuously issued rules and regulations regarding pollution from PCB containing waste since 1990s. One of the regulations is Pollution Control Standard for PCB-containing waste, which was issued in 1992 and different PCB containing waste handling are described depending on PCB concentration [32].

2.5 Recycling technologies

In this section, the secondary production and recycling processes of the most important materials in high voltage products are described. When relevant, the primary production processes are also described to allow for comparison between primary and secondary production.

2.5.1 Copper

Copper is used as an electrical conductor in many different types of electrical equipment, including high voltage products such as transformers, electrical cable and wiring, and busbars in for example switchgear. The type of copper used for electrical conductors is mainly electrolytic tough-pitch copper (ETP), which is a high purity copper (>99.9% Cu) that contains a small amount of oxygen as alloying agent [33]. The high purity in combination with a high price on copper results in very high recovery and recycling rates for the copper in these products.

2.5.1.1 Recycling technologies

Copper can be recycled without loss of quality. Recycling copper requires between 80-90% less energy than primary production and is associated with reduced costs and environmental impact [34][35]. In copper extraction, primary production refers to output from virgin ore, while secondary production refers to output from recycling scrap or direct melt of waste generated during the manufacturing process. Secondary production is an important source of copper, accounting for roughly 15-18% of all refined copper worldwide [36]. Copper can be recovered from a large variety of scrap metal sources, and the recycling process is highly dependent on the type of scrap and its purity. To use the scrap effectively, it therefore needs to be analyzed, sorted, and processed prior to recycling.

The process of producing recycled copper from scrap can be divided into three steps: collection of waste, sorting and separation, and metallurgical metal recovery [37]. The collection of the copper waste refers to the process of making EoL products available for recovery by separating them from other waste flows [19]. This process usually lies outside of the copper recycling process. The collection may be dependent on the price of copper. When the price is low, collection of scrap may be delayed, while when the price is high, the incentive for collection and recycling rises [38]. After the scrap has been collected, mechanical or manual pre-treatment may be necessary, depending on the material source. This could be the case if the scrap has coatings or attachments or is otherwise entwined with other materials. Examples of pre-treatment methods include manual and automatic sorting, magnetic separation, crushing, grinding, and shredding of the scrap [19]. The metallurgical metal recovery process is largely the same as for primary production, but it requires fewer steps. High grade, clean copper can be recovered directly through remelting, while lower grade copper needs further processing similar to primary copper production. Recycling through direct remelting is much more energy- and cost efficient compared to smelting and refining, but it is highly restricted by the requirements on low contaminant and impurity levels [37].

High voltage products at end of life belong to the waste category called Industrial Electrical Equipment Waste (IEW). The relative amount of this type of scrap is low compared to other sources, but the copper content is typically high. The high grade of the copper in IEW increases the profitability of processing and recycling, resulting in high recovery rates [39]. Electrical grade copper should not be mixed with copper of lower purity grade, as this could lead to contamination by for example phosphorus which significantly reduces electrical conductivity [19].

2.5.1.2 Pyrometallurgical processing

Pyrometallurgical processing is the main method of copper extraction, accounting for about 80% of all production from ore [39]. It is also the dominating method used in secondary production. The pyrometallurgical route of production is based on extraction of ore followed by concentration through flotation. The copper concentrates are then transformed into a matte in a smelting process which takes place in a furnace. The molten matte is processed in a converter where residual sulfur and impurities are removed, resulting in blister copper with a copper content of 98,5-99,5% [19]. The final refining of the copper can be further divided into fire refining in an anode furnace, where sulfur and oxygen is removed from the blister copper to ensure that it reaches a purity of 99,5%, and electrorefining, which results in copper cathodes of 99,99% purity. An overview of the primary production process is shown in Figure 2.3. The cumulative energy input for primary production is approximately 25 GJ/t, but the energy consumption is dependent on the ore grade of the native mineral [40].

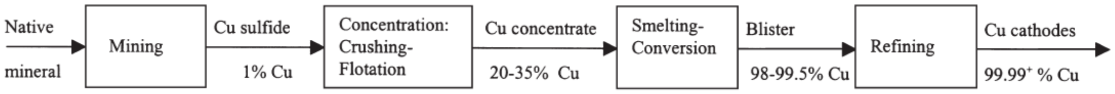

Figure 2.3: Overview of the steps in primary copper production [40]

Secondary copper can be added at three different points in the primary production process: the smelting furnace, the converting furnace, and the anode furnace. Where the copper is added depends on the quality and size of the scrap. Converting furnaces require higher quality scrap, and while the scrap may be added to anode furnaces, the melting process can be slow, making directly recycled scrap anodes the most common addition at this step. An alternative recycling route is to reprocess the secondary copper in secondary smelters that are specifically designed to handle that type of material. Secondary smelters can be divided into two categories: metal smelters, which only treat high grade scrap, and black copper smelters, which process lower grade scrap as well [39].

Compared to primary production, copper recycling has several environmental benefits, mainly a large reduction in energy consumption. Other environmental aspects associated with copper production include: depletion of natural resources and minerals, global warming, acidification (caused by SO_2, NOx, HCl, etc.), eutrophication, and emissions to air, water and soil. The impact of these factors is either reduced or eliminated for secondary copper production [35]. The key environmental sensitivities of the recycling process are the distance that the scrap is transported, and the electricity mix used in the furnace [41]. Opportunities for increasing recycling rates of copper mainly lie outside of the copper industry. Examples of such opportunities include changes in product design and in the collection and sorting of EoL products.

2.5.2 Steel

Steel is one of the most recycled materials and recycling of steel also contributes to conservation of energy, emissions, raw materials and natural resources. Physical properties of steel also enable it to be recycled continuously without loss of quality or strength [42].

2.5.2.1 Steel scraps and recycling rates

There are three types of steel scrap based on where steel scrap is generated: home scrap, new scrap and old scrap [43]. Home scrap is generated within a steel production facility. New scrap is generated by manufacturers of steel containing products while old scrap, also called obsolete scrap or EoL scrap, is generated at EoL by end users [44]. Home scrap and new scrap are usually well sorted and of high purity while EoL scrap is usually contaminated with fragments of metals and non-metal debris [45]. Therefore, only well sorted EoL scrap can be recycled back into the same end uses. In fact, EoL scrap is often downcycled to end uses such as building and infrastructure materials where lower quality steel can be tolerated.

A technical report by American Iron and Steel Institute shows that the recycling rate in appliances sector (i.e., electrical device and equipment) was 78% including both new scrap and old scrap in 2019 [44]. The report also mentions that the average recycled content of steel production in 2019 was estimated at 82% for Electric Arc Furnace (EAF) production and 23% for Basic Oxygen Furnace (BOF) production. For the recycling rates for steel containers in 2019, the recycling rate for new steel scrap containers was 98% while the recycling rate for old steel scrap containers was 58% [46].

2.5.2.2 Primary and secondary production process

Steel production can be divided into two production routes: primary and secondary steel production. The primary steel production uses iron ore as ferrous resource and technologies are usually characterised as high energy demand per tonne of steel produced [45]. The overall processes in the primary production is that iron ore is reduced to iron in a blast furnace (BF), where large amounts of coal is required as reduction agent, the iron is then refined into steel in a BOF. There are also direct reduction (DR) technologies, where iron ore is directly reduced to steel. The primary steel production technologies results in high CO_2 emissions due to usage of large amounts of coal. However, research and development in the sector today focus on reduction of emissions by optimising current process and developing innovative approaches such as BF with top gas recycling with Carbon Capture and Storage (CCS) or direct reduction to steel using hydrogen as reduction agent with electrolysis [47]. One of the ongoing industrial projects is the "HYBRIT" project in the north of Sweden, where coal is replaced with hydrogen as reducing agent, and fossil free iron and steel production is produced in an industrial scale [48].

On the other hand, the secondary steel production uses steel scrap as ferrous resource and technologies are characterised less energy intensive compared to the primary steel production since the scrap resource has already gone through the reduction process, where high energy demand is required [47]. Scrap is then refined into steel using EAF. The secondary production could be theoretically CO_2 emissions free production since electricity is the main source of energy in EAF.

The primary production requires a cumulative energy input of 15-24 GJ/t while the secondary production of steel requires only 1.3-6.0 GJ/t [45]. Today, only 40% of global steel production is covered by secondary steel production. Achieving the higher share of secondary steel production depends on several factors such as the fraction of EoL scrap that is collected for recycling, the effectiveness in sorting different steel alloys, the effectiveness in separating EoL steel from other materials and the effectiveness in recycling processes [45]. However, according to Morfeldt, the secondary steel production would not be enough to meet the future demand, which is expected to increase in the future, for steel products by considering the current growth rate of consumption [47].

2.5.2.3 Ferrous alloys in HV products

As HV products consist of a number of different ferrous alloys, in which iron is the main constituent. Recovering of those ferrous alloys and non ferrous metals (e.g., copper and aluminium) is the most interest from material supply and environmental points of view. Some relevant ferrous alloys for HV products are listed, major elements in the composition and material properties are described shortly. Ferrous alloys that are highly relevant for HV products and major elements in the composition on mass basis are listed in Table 2.1.

Table 2.1: List of ferrous alloys and major elements in the composition [49]

Metal alloys	**Elements in the composition on mass basis**
Electrical steel	Iron and silicon (1-6.5 %)
Carbon steel	Iron and carbon (0.1-1 %)
Stainless steel	Iron, chromium (15-20 %) and nickel (5-12 %)

Electrical steel is an iron-silicon alloy with high amount of silicon. Addition of silicon in the steel improves magnetic properties and increases electrical resistance as well as permeability [50]. Carbon steel is an iron-carbon alloy and it can be divided into three categories depending on its carbon content: low-, medium- and high carbon steel with carbon content from 0.1% to 1.0%. Carbon steels can be used in many applications with high ductility, strength and relatively low production cost [51]. Stainless steel is a high chromium content steel with corrosion resistance. Nickel is often added to improve the corrosion resistance in oxidising conditions [49].

2.5.3 Aluminium

Aluminium is nearly infinitely recyclable as long as the build-up of impurities is kept to a minimum, and the secondary production is much more energy efficient than primary production. Production of aluminium through recycling requires up to 95% less energy [52]. Secondary aluminium is estimated to require an energy input of 5-7 GJ/t [22], compared to 200 GJ/t for primary aluminium. The reason for these energy savings is that secondary production simply involves remelting of the metal, avoiding several of the energy intensive steps of primary production, including electrolysis. Because of the reduced consumption of fuel and electricity, the carbon footprint of secondary aluminium is also much lower. Recycling can reduce the CO_2 emissions from aluminium by up to 93% [53]. The energy savings in combination with the relative value of the metal and its ease of recycling has resulted in high recovery rates. In 2019, the collection rate for new scrap was 95%, and 70% for old scrap [54].

2.5.3.1 Recycling and the secondary production process

The recycling process begins with the collection of aluminium scrap. Upon collection, primary sorting is often done before the scrap is transported to treatment plants. The scrap is then cut up and shredded to facilitate further processing. This is followed by physical separation and preparation of the scrap. Examples of separation techniques include magnetic separation to remove steel and iron, air separation to remove light weight materials such as rubber, plastic, and foams, sink/float techniques, eddy current separation, and spectroscopy [53]. If the scrap is covered by contaminants such as oil, paint, and coatings, these are removed using centrifuges or de-coating machines. The goal of the mentioned technologies is to separate different scrap materials to obtain high-quality aluminium scrap for the refining process. The sorting process also aims to separate the scrap by composition, as its alloying agents and contaminant levels determine how it can be re-purposed and the processes that are used. After preparing and sorting the scrap, it is melted in a furnace, the type of which depends on the type of scrap and the quality of the desired product. Examples of furnaces used for remelting include rotary furnaces, reverbatory furnaces, and induction furnaces.

2.5.3.2 Primary production process

Primary production of aluminium takes place in three stages. First, bauxite is extracted by mining. The bauxite is then converted to aluminium oxide (Al_2O_3), commonly called alumina, using the Bayer process. Primary aluminium is produced by converting the alumina using the Hall-Héroult process. After primary aluminium has been obtained, it is alloyed to produce cast and wrought aluminium, which in turn is used for fabrication and manufacturing [55]. An overview of the complete process is shown in Figure 2.4.

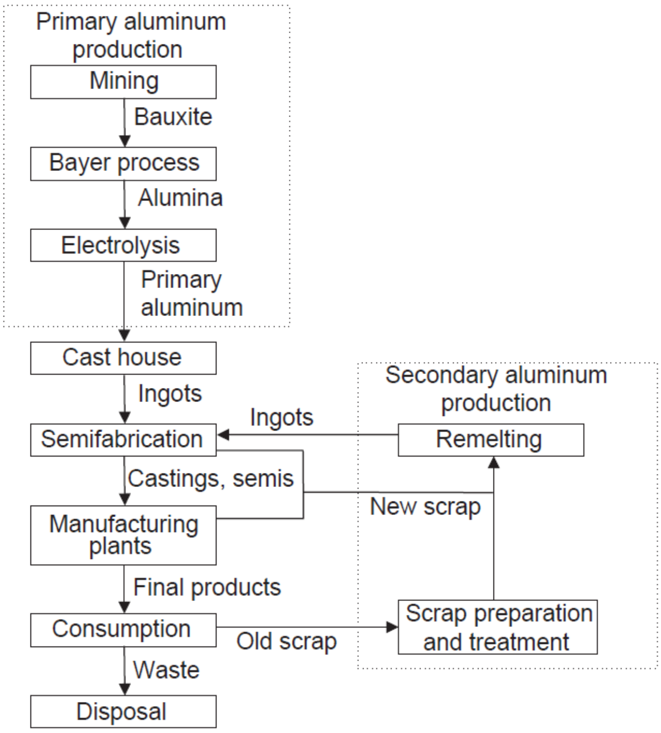

Figure 2.4: Overview of the steps and material flow in aluminium production [55]

The Bayer process is a hydrometallurgical process used for nearly all alumina production. Initially, bauxite is washed and ground. It is then dissolved in sodium hydroxide at high pressure (>35 bar) and high temperature (120-300 °C) [55]. The resulting liquor is clarified in a settling tank to remove residues and impurities. The residues contain iron, titanium, and silicon, and are called red mud. The clarified liquor is then cooled in precipitation tanks, where solid crystals of aluminium hydroxide are added as precipitation seed. In the final step of the process, the aluminium hydroxide is calcined in a rotary kiln or fluid bed at high temperatures (up to 1 300 °C) to produce alumina [55][56][57].

The Hall-Héroult process is the basis for all primary aluminium smelting plants. The process involves the dissolution of alumina in molten cryolite (Na_3AlF_6) at 960 °C inside an electrolytic cell [55]. The cell consists of two electrodes: one cathode and one anode. An electric current of low voltage and high amperage is passed between the electrodes through the electrolyte, which reduces the alumina and produces liquid aluminium and oxygen gas [56]. The oxygen gas reacts with the carbon anodes to form carbon dioxide, which uses up the anodes.

Primary aluminium production is one of the most energy intensive processes in the industry. The cumulative energy input for primary production is approximately 200-220 GJ/t [55][57][58], which is at least eight times higher than for iron and seven times higher than for copper. The Hall-Héroult process in itself is very energy intensive, requiring 13-17 kWh per kg aluminium. Overall, electrolysis represents almost all the electricity and a significant portion of the energy consumption of the production of primary aluminium [55]. In addition to the energy consumption, another important aspect to consider regarding primary aluminum production is the extraction of bauxite. Bauxite is considered a critical raw material by the European Commission due to its strategic importance. The EU is heavily reliant on import to meet their demands, which creates the risk of supply chain disruptions, and further incentivizes increased recycling of the material.

2.5.4 Polymers

Polymers and plastics include a wide range of materials with varying properties and characteristics. There are three principal polymer classes: thermoplastics, thermosets, and elastomers. The classes are mainly differentiated by their mechanical properties and their response to heat. Many different polymers from all three classes are used in high voltage products. In these products, they are used for a wide variety of purposes, including insulation, construction material, and adhesives. From the thermoplastics class, common polymers include polypropylene (PP), polycarbonate, polyvinyl chloride (PVC), polyurethane, polyamide (nylon, PA), and polyethylene (PE). The main thermoset used is epoxy or epoxy resin. Finally, the elastomers used are mostly synthetic rubbers such as EPDM rubber and silicone rubber.

2.5.4.1 Recycling technologies

Mechanical recycling is the simplest and most common form of plastic recycling. It is the most effective method in terms of economic cost, carbon footprint, and environmental impact [59]. However, since the method involves melting the plastic materials, not all polymers can be recycled this way. For example, thermosets are very difficult to recycle mechanically since they cannot be remelted.

Collection and sorting of waste are the first steps of mechanical recycling. Primary sorting according to color and type is often done at the source. Preferably, the plastic waste is sorted into specific polymers. If the sorting and processing take place in different locations, the plastic is often baled to facilitate transporting. The initial sorting is followed by fine sorting and separation of polymers, which takes place at dedicated recycling facilities. The sorting and separation methods can either be manual or automatic. The primary sorting at the source is usually manual and may be required before the automatic methods can be initiated, in order to prevent foreign materials from obstructing and blocking the machines. Examples of large-scale automatic separation methods include density separation, electrostatic separation, and spectroscopic sorting. Several methods are typically used, but the sorting depends both on the feed and the quality requirements. The separation is followed by size reduction, for example through grinding, shredding, or milling to produce plastic fragments or flakes. These fragments are washed and dried to remove impurities. The clean fragmented material is melted and extruded after adding new polymer additives, if required. The final product of the whole mechanical recycling process is pellets that can be used as raw material for new plastics. It is worth noting that the process steps may occur in different order, multiple times, or removed entirely, depending on the waste stream [60].

Polymer degradation is an issue that affects all plastics, both naturally over time, and during the recycling process. The degradation refers to a reduction of the physical properties of the polymer, such as molecular weight, strength, and mass. It is caused by heating and mechanical shearing during the melt processing. Degradation rate depends on the circumstances of the recycling methods, additives present, and of course the polymer type itself. It can be abated by regulating the techniques and compensated for by adding different additives, but never avoided completely without restoring the polymer on a molecular level [60].

Chemical or feedstock recycling is an alternative plastic recycling method which has seen increasing research and attention in recent years. It involves converting polymers into monomers, which can then be polymerized back into new plastic materials. There is no loss of properties, making it a potential way to create a circular polymer economy [61]. This method is very promising but currently far less common than mechanical recycling. It also has a higher carbon footprint, as the process of transforming polymers to monomers and back again can be energy intensive. However, this may change if the process achieves an industrial scale.

2.5.4.2 Disposal methods

Energy recovery through incineration is a common method of disposal for plastics, particularly in Sweden. Plastic has a relatively high energy content and can be used as a secondary fuel. Compared to recycling, this option is less favourable from an environmental point of view, as reflected in the EU waste hierarchy. Additionally, incineration requires advanced pollution control, as dioxins and other hazardous substances are generated during the combustion process. The process is under strict regulation by the EU Hazardous Waste Incineration Directive.

Landfill is the final option for polymers and plastics. It is the least-preferred alternative, and should be avoided at all costs. In general, it should only be used if recycling or energy recovery is not possible.

2.5.5 Sulfur hexafluoride

To prevent leaks to the atmosphere, special care must be taken when servicing or disposing of equipment containing sulfur hexafluoride (SF_6) gas. When dismantling for example high voltage products, any enclosures containing SF_6 must be identified and isolated as soon as possible to avoid damage that could result in leakage. The gas itself may then be removed using vacuum pumps [62]. After draining the gas, there are two principal routes of management for SF_6 gas: disposal or recycling.

2.5.5.1 Disposal methods

Incineration is the most common method of disposal. Through this method, the release of greenhouse gases is reduced. However, the process is costly and energy intensive, and produces toxic by-products, as previously mentioned. Removing these compounds after the incineration requires advanced and complicated air pollution control that adds to the total cost [7].

A more advanced disposal technique is decomposition through non-thermal plasma (NTP) approaches. These novel techniques remain mostly on the research stage and focus on small-scale systems, but they have remarkable potential in terms of their low cost and energy requirements. The by-products produced NTP decomposition depend on the additive gases and the power supplied. In general, the by-products are less harmful than those produced through incineration, and they can be removed using a wet scrubber system. Examples of NTP approaches include radio frequency plasma, microwave plasma, dielectric barrier discharge, and electron beam decomposition [7].

2.5.5.2 Recycling technologies

Depending on the quality of the gas, it may also be recycled after the end-of-life of the products. This is achieved using reclamation processes that purify it to the required technical standards. Compared to incineration, implementing recycling can result in reduced cost, energy consumption and carbon footprint, and avoids the formation of toxic by-products.

One of the more promising methods of recycling is cryogenic separation. By using liquid nitrogen to freeze the SF_6 gas below its melting point, impurity gases are removed and high purity SF_6 is obtained. Prototype purification systems show that the method is capable of processing large amounts of SF_6 gas at a time, which indicates that it can easily be scaled up to a commercial scale [63]. The first step of the system is analysis of the gas. Through the analysis, the levels of moisture and impurities such as O_2, N_2, SO_2 and HF are detected. Because some of these impurities cannot be removed in the cryogenic process, a pre-cleaning system consisting of filters and scrubbers is required. The next step of the process is freezing of the gas. The gas is cooled to around the freezing point of SF_6, which is relatively high at -64 °C. Therefore, as the gas freezes on the tube coils in the separation vessels, the impurity gases can be vented to the atmosphere. In the final step, the SF_6 gas is melted, collected, and refilled.

2.5.6 Polychlorinated biphenyls (PCBs)

To minimise eventual risks of toxic effects on human health and in the environment nearby recycling plants, PCBs need to be removed from transformer oil and disposed of in a proper manner. A disposal method and a promising recycling technology for PCBs contaminated oils are described.

2.5.6.1 Disposal methods

Incineration is the most widely used method to dispose of transformer oils contaminated with PCBs. However, the incineration method generates hazardous byproducts such as dioxins classified as persistent organic pollutants (POPs), which in turn causes negative impact in the environment and human health in case emissions from combustion process are not controlled [64].

2.5.6.2 Recycling technologies

To reuse transformer oils contaminated with PCBs, transformer oils need to be cleaned and decontaminated before being reused. There are various decontamination methods using thermal-, chemical-, biochemical- and radiolytic techniques [64].

Among different decontamination methods, a reduction method has been developed as an alternative method to detoxify PCBs and to recycle transformer oils. Especially the method that uses catalytic hydrodechlorination approach as this reduction method is relatively simple, safe, and effective, and also has been proven that no hazardous byproducts are generated [64]. The overall process in a reduction method is that transformer oils are firstly segregated by filtering, washed with water, dehydrated under vacuum and finally centrifuged. After the centrifuging step, detoxified transformer oils are produced and reused for new applications.

In the catalytic hydrodechlorination method, noble metal catalysts such as palladium (Pd), platinum (Pt) are used. Choi et al found that these metal catalysts are effective for the catalytic hydrodechlorination method at relatively low temperature (<80°C) [64]. However, because of the high cost of noble metals, a large scale commercial application with these noble metals catalysts is limited. Relatively cheap transition metal catalysts such as nickel (Ni), silica or carbon composite are also found as effective metal catalysts. However, with these metal catalysts, relatively high reaction temperature (>200°C) and high hydrogen pressure (>2MPa) are required to achieve significant hydrodechlorination activity.

Organic liquid solvents such as methanol, ethanol and hexane are also used in the catalytic hydrodechlorination method. In fact, these organic liquid solvents generate toxic organic waste [64]. Moreover, it requires time-consuming and energy intensive process to remove the organic liquid solvents once the hydrodechlorination step is carried out.

Super critical fluids (SCFs) have been found as potential alternatives for organic liquid solvents because of its high diffusivity and low viscosity properties as a fluid. According to the study by Choi et al [64], 100% PCB conversion (where the PCBs concentrations before and after the hydrodechlorination reaction were compared) was achieved with Nickel/silica-alumina metal catalyst under the reaction temperature (200°C) and the reaction time (1h). Furthermore, 100 % PCBs conversion was achieved at the reaction temperature 175°C with super critical CO_2 fluid as the reaction medium [64]. The study indicates that PCBs in transformer oils can be detoxified and the treated oil can be reused without using noble metal catalysts and conventional organic liquid solvents.

2.6 Environmental assessment

This section covers previous LCA studies on the HV products of Hitachi Energy, resource depletion for metal production and critical raw materials.

2.6.1 Previous LCA studies

The power consulting team at Hitachi Energy conducts a life cycle assessment (LCA) on the company's main products. According to the LCA report on a specific HV product published in 2020, the energy consumption during the operation phase and material production phase (especially metals such as steel, copper and aluminium) have the highest contribution on the total CO_2 emissions over the product life cycle.

The LCA report also shows that how much renewable energy sources are integrated in an electricity grid determines which life cycle phase has the most contribution on the total CO_2 emissions. The operation phase was the highest contribution on the total CO_2 emissions over the product life cycle for a scenario using an average EU-28 electricity grid mix. On the other hand, the material production phase and the operation phase contributed equally to the total CO_2 emissions for a scenario, where renewables energy sources (i.e., hydro-, wind- and solar energy) are integrated in the electricity grid mix.

The LCA report concludes that energy efficiency to minimise power loses during the operation phase and strategic selection of material suppliers are the most important factors to reduce the total CO_2 emissions over the product life cycle.

Based on results from the LCA report, material production phase generates the most CO_2 emissions over the product life cycle. It indicates that integration of secondary metals on current and future HV products can reduce significantly the overall environmental impact over the life cycle for the scenario where renewables energy sources are dominated in the electricity grid mix.

2.6.2 Resource depletion for metal production

Resource depletion caused by metal production has been increasing over the time to meet growing global metals demand and this trend is expected to continue in the future. In fact, the report Global Resource Outlook 2019 showed that if the historical metals extraction path continues unchanged, metal extraction is expected to increase to 18 billion tonnes in 2060, compared to 9.1 billion tonnes in 2017 [65].

The report mentions that the iron-steel production chain has the largest climate change impacts, with about 66% of the the total climate change impact from metal production due to the large volumes of steel produced annually and the energy intensive processing of the ore into iron and steel [65]. Aluminium production has the second largest climate change impacts, at 25% of the total climate change impacts. Additionally, copper and precious metals production causes 30-45% of the toxicity impacts from metal production such as sulfidic mining tailings, where unused processed materials from mining are stored in tailing impoundment dams and contaminants in the materials can leach into soil and groundwater.

The report also mentions that the efficient use of metals in manufacturing, low-impact processing technologies in metal production, circular economy business models for products and metal recycling, remanufacturing and refurbishing of products are highly effective in reduction of the environmental impacts of the metals group [65]. However, the report emphasises that the amount of scrap metals is not enough to meet the global metals demand especially in countries where population and economic activities are expanding, meaning that the primary metal production continues in order to meet global metals demand.

2.6.3 EU Critical raw materials

To address the growing concern of securing valuable raw materials, European commission launched the Raw Materials Initiative (RMI) in 2008 [66]. One of the main actions of the RMI is to establish a list of critical raw materials (CRMs) at EU level. The fist list was published in 2011 and since then it has been updated every three years to access the criticality of raw materials for the EU. Criticality is evaluated based on two main factors, economic importance and supply risk for the EU [67]. Critical raw materials and non-critical raw materials identified in the 2020 criticality assessment are presented in the Figure 2.5. As seen in the Figure 2.5, 30 out of 83 material candidates are classified as CRMs.

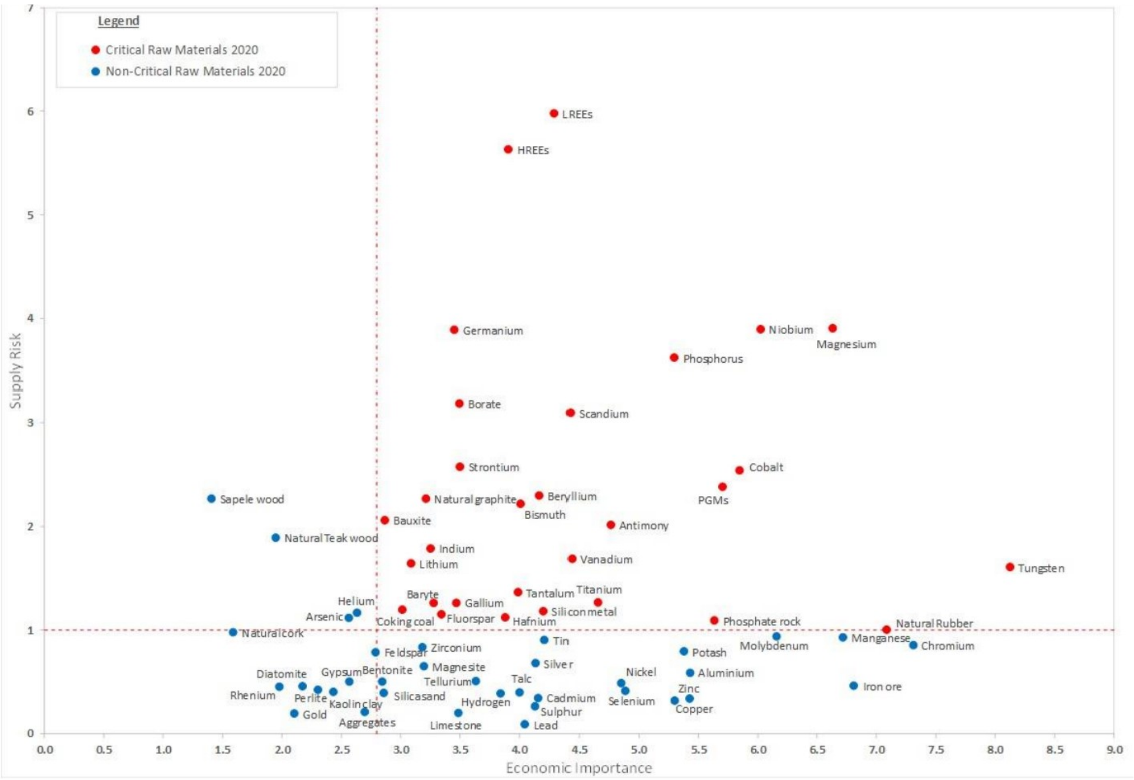

Figure 2.5: Critical raw materials and non-critical raw materials identified in the 2020 criticality assessment by RMI in the EU [67]

CRMs are highly relevant for HV products and electrical and electronic equipment (EEE) products since CRMs are used for material production such as bauxite for the primary aluminium production and silicon metal for the primary steel production. Minimising dependence of CRMs in EEE products and substituting new raw materials to replace CRMs are important from material supply and economic growth points of view.

2.7 Circular economy

Conventionally, the linear economy models of production and consumption have characterised economic systems, where raw materials are extracted, processed and transformed into products [65]. Products are then consumed, disposed of, and handled as waste. According to the Circular Gap Reporting Initiative (CGRI), only 8.6% of the total extracted materials is circulated within the world economy in 2020, meaning that over 90% of the total extracted materials and feedstock are either wasted or accumulated in the global material flows [68]. In the linear economy, the value and functionality are lost once products are turned into waste. On the other hand, products and materials are restored while maintaining their value and functionality as long as possible in a circular economic system [69]. In this section, circular principles, circular strategies and EU circular economy action plan are described.

2.7.1 Circular principles

There are three important principles in the circular economy that help business increase resource efficiency and maintain products with high value and functionality: "Narrowing loops", "Slowing loops" and "Closing loops" [69]. "Narrowing loops" is about reducing the amount of materials per product or service and this strategy can be achieved through using fewer resource per product and during the production process, which in turn increases resource efficiency. An example of this is "Lean manufacturing", a production method that constantly optimises the efficiency of production processes while reducing costs and environmental impacts. "Slowing loops" is about continuous reuse of materials and products over time and this can be achieved through the design of long life products or the design of product life extension, which in turn results in a slowdown of the flow of resources. Examples of this strategy are reusing, repairing, refurbishment and remanufacturing. "Closing loops" is about to close the loop between disposal and production, resulting in a circular flow of resources and this strategy can be achieved through recycling. Metal recycling is an example of "Closing loops" as they can be recycled continuously without losing its value and functionality [65].

2.7.2 Circular strategies

There are different circular strategies that can be taken depending on different life cycle phases: extraction/production, use and post use. For the extraction/production phase, process-related strategies and design-related strategies, where the concept of "Narrowing loops" described previously is widely used, can be taken [70]. Process-related strategies include reducing amount of waste during extraction and production, reducing use of material resources and energy while design-related strategies include design of products to use less material and to easily repair or recycling. Material substitution is also one of the design strategies taken in the early product design phase. For the use phase, there are two ways to increase resource efficiency, either to use products more efficiently and effectively or to extend their use [70]. To use products more efficiently means to deliver or acquire function according to the user's needs and to make sure that products are used for intended purpose while using products more effectively means to reduce use of energy during use, which is only applicable for durable products (i.e. not disposal products) such as HV products as they use energy during the use phase. To extend the use of products include many practices in the concept of "Slowing loops" such as reusing, repairing, refurbishment and remanufacturing, which is also only applicable for durable products. For the post use, recycling, which is an example in the concept of "Closing loops", is an effective way that recovers and returns materials to use. Depending on properties of materials different waste management can be taken. Biodegradable materials can be digested anaerobically or composted, or processed to generate biogas, plant nutrients and soil enhancers [70]. Energy recovering recovers combustible materials into energy carriers such as used for heat and electricity generation. Controlled landfills control emissions to air, soil and water from disposed waste.

When introducing circular strategies in the different product life cycle phase, there is always a risk for potential environmental trade-offs. For the extraction/production phase, there are some potential trade-offs associated with design for durability and repairability. More durable products may require more and higher quality material and results in complexity of products, which in turn requires additional separation processes in the post use phase [70]. For the use phase, although most durable products can be given a longer life time through restorative strategies such as maintenance, repairing, refurbishment and remanufacturing, these strategies require transport, either staff delivering the maintenance service and spare parts need to be produced and transported. Thus, there is a risk that the associated environmental impact caused by additional transport and production outweighs the benefit of longer life time of products. For the post use phase, although post use processes such as recycling and energy recovery improve resource efficiency as long as their impacts are smaller than the impacts from alternative solutions, there is a risk of keeping hazardous substances in circulation if materials are recycled to direct use.

2.7.3 EU Circular Economy Action Plan

The European Commission adopted new Circular Economy Action Plan (CEAP) in 2020 as a main part of the European Green Deal, Europe's new agenda for sustainable growth [71]. The aims of this CEAP are to reduce pressure on natural resources, and create sustainable growth and jobs in Europe. CEAP is also recognised as a precondition to achieve the EU's 2050 climate neutrality target and to stop biodiversity loss. The differences compared to the first CEAP are that the new CEAP focuses on initiatives along the entire life cycle, targets how products are designed, promotes circular economy processes, encourage sustainable consumption, and aims to ensure that waste is prevented and the resource use are maintained within the EU economy [71]. This new CEAP also focuses on the sectors that use most resources and where the potential for circularity is high such as sectors in electronics and information and communication technologies (ICT)[71].

3

Method

In this chapter, the methodology of the project is described. First, the scope and selection of the method is defined, and the strategies used for data collection are described. This is followed by definitions of terms relating to recycling and recycling rates, and description of the methodology of the material flow analysis of the project. Finally, the modelling and simulation for the LCA analysis, including how emissions of the recycling processes are quantified.

3.1 Scope and selection

In this section, the scope of the project and the areas of focus are described, including which regions, companies, and products were selected for investigation and analysis. When further delimitations were made compared to the aims and objectives, they are described and motivated accordingly.

3.1.1 Selection of regions and companies

An initial survey on the global markets and regions was performed, primarily based on the market for high voltage products and the presence and activity of Hitachi Energy. This survey showed that the most important regions are North America, East Asia, and the EU. Within these regions, the US, Sweden, Germany, Spain, and China were selected for further study. Due to a lack of available information and difficulty establishing contact with EoL service providers in other countries, the scope was later limited to recycling within the EU, with a particular focus on the recycling process in Sweden.

Individual companies were selected for investigation and interviews in order to gain insight into each recycling process step. EoL service providers were the primary target, in particular those that work with high voltage products and power transformers. The aim was to find technical experts that could provide information and data on the recycling process, preferably at least one for each major step. The selection process was based on research on the market for recycling high voltage products and electrical equipment. Stena Recycling was a natural choice given the already existing cooperation between them and Hitachi Energy. In addition to disassembly of high voltage products, Stena Recycling also manage several other relevant processes, such as scrap metal collection and management of hazardous waste. The cooperation in combination with their role on the recycling market therefore constituted the basis for this choice. Similarly, AGR company was selected based on contacts within Hitachi Energy, and because of their significant presence in the recycling of transformer oil in Europe. After the initial contact with these recycling companies, other actors further down the processing chain were contacted as well, mainly smelters and secondary metal producers, companies working with recycling hazardous waste, and local waste incineration and energy recovery facilities. At this point, Fortum Waste Solutions was identified as an important actor, since they manage hazardous waste through incineration, which is an alternative route compared to the previously mentioned recycling processes at AGR.

3.1.1.1 Stena Recycling in Sweden

Stena Recycling is an EoL service provider that has a business cooperation with Hitachi Energy in collection and recycling of obsolete transformers. The company is one of the leading recycling companies in Nordic countries with nearly 90 plants and manages 3.4 million tonnes of material annually [72]. The company provides services in collecting, material recycling, and managing a wide variety of waste such as hazardous waste, paper, metal and other residual materials that arises from operations and production. The waste management at the company includes customised solutions in sorting, decontamination, disassembly and transport marking. At the recycling plant in Karlstad, the handling and dismantling of old transformers, including those containing oils, the handling of components containing SF_6 and other electronic equipment such as capacitors and cables from the power and energy sector are taken place.

3.1.1.2 AGR company in Spain

AGR company is an EoL service provider offering services in management and destruction of transformer equipment contaminated with PCB, and decontamination of transformer oils up to 2 500 ppm for reuse [73]. The company manages even other types of hazardous and non-hazardous waste at the request from clients. AGR is the first company founded in 1995 in Spain with the largest capacity in treatment and decontamination of transformer oils contaminated with PCB using metallic sodium. The details of decontamination method are described in detail in the next chapter.

3.1.1.3 Fortum Waste Solutions in Sweden

Fortum Waste Solutions is a Nordic recycling company with more than 30 recycling facilities in the Nordic countries. The company provides waste handling for hazardous waste from industrial- and households sector. One of the recycling facilities located in Kumla, Sweden for example does a final treatment for hazardous waste such as transformer sand, PCB contaminated oil and hazardous components from other recycling companies. The majority of hazardous waste that are transported to the recycling site in Kumla, are incinerated for energy recovery to produce electricity and heat till local residents and industry. Except for incineration for energy recovery, wet chemical-, biological-, soil washing-, and water purification treatment are typical methods for handling of hazardous waste. Since 2020, the company has collected and stored lithium ion batteries as intermediate storing before they are being further transported to the external recycling facilities [74].

3.1.2 Selection of HV products

When collecting data and analysing previous internal reports from Hitachi, an example high voltage product was used for this project. Selecting a single product as an example allows for further investigation and detailed analysis of material composition, and facilitates communication with EoL service providers during interviews. This product was also used to approximate recycling rates for an example of an entire high voltage product, using calculations based on recycling rates and waste management methods of the individual materials. When specific product data was difficult to find or track, transformers in general were used as the primary category of products for data collection. The selected product was the Hitachi Energy 40 MVA Liquid Filled Power Transformer. The material composition and components of the product are presented in Table 3.1. Note that "other parts and accessories" are not included in the total mass, since they have a supporting role and are not considered to be part of the original product.

Table 3.1: Material composition of Hitachi Energy 40 MVA Liquid Filled Power Transformer

Material	**Mass [kg]**	**Mass [%]**
Transformer cooling liquid (tank)	18 698	25
Core - electrical steel	18 055	24
Windings - copper	13 196	18
Tank and tank assembly parts - carbon steel	11 312	15
Radiators - carbon steel	5 654	8
Other parts and accessories	2 677	4
Core clamps and core parts - carbon steel	1 952	3
Tank shunts - electrical steel	1 484	2
Transformer cooling liquid (radiators)	1 549	2
Pressboard	1 532	2
Conductor insulation - kraft paper	435	1
Laminated wood	413	1
Total mass (excl. other parts and accessories)	**74 281**	

The motivation for this choice is that transformers are among the most important high voltage products for Hitachi Energy with a large number produced and delivered, and that the cooperation between Hitachi Energy and Stena Recycling mainly concerns the handling and recycling of transformers. Internal LCA reports have been made on this specific product, which aids in the environmental analysis of it. Furthermore, transformers belong to a category of products that require special management due to hazardous substances, in this case oil containing PCBs, which is an important aspect to investigate. Because of the concerns regarding human health and the environment caused by the substance, it is vital to examine how the handling and recycling is implemented in practice.

3.2 Data collection

Numerical data was collected from annual environmental reports at Stena Recycling, Fortum Waste Solutions, and secondary material production facilities, as well as from public reports and statistics from for example government authorities. The data was used to calculate recycling rates, and to estimate the amount of emissions and energy consumption at the EoL life cycle stage for the high voltage products. Where data on recycling rates and energy consumption was lacking, the information was retrieved from relevant academic reports instead, in which case the source will be clearly referenced. The main purpose of the data collection was to obtain actual data from the EoL service providers, which allowed for the analysis of environmental impacts at EoL stage using reliable numbers.

The data collection from the aforementioned sources focused on the following topics:

- Recycling rates for different materials used in transformers
- Energy consumption for recycling of different materials
- Emissions related to recycling process

The most important primary sources used are listed in Table 3.2 below. In addition to the collection of numerical data, interviews and workshops were conducted with experts at the previously mentioned companies.

Table 3.2: List of primary sources targeted for data collection and interviews

Actor	Description
Stena Recycling	Disassembly and recycling of products
Stena Metall	Recycling of metal and oil
Fortum Waste Solutions	Management of hazardous waste
Celsa Steel Services	Steel producer
SSAB	Steel producer
Boliden	Copper producer
Geological Survey of Sweden, SGU	Authority for issues relating to bedrock, soil, and groundwater

3.2.1 Interviews

Interviews with EoL service providers were conducted remotely using tools such as Microsoft Teams, and all interviews were recorded after asking permission to do so. In cases where the interviewees were not available to talk, they were instead contacted through email. The targets of the interviews were technical experts, production managers, project managers, and other people with similar roles that possess knowledge into the EoL management and recycling process. The main purposes were to gain deeper understanding of EoL management by different EoL service providers, its environmental impacts, to obtain understanding of emerging recycling technologies, and to gain input on future product design to facilitate recycling of materials. The EoL service providers that were interviewed were Stena Recycling in Sweden, AGR company in Spain and Fortum in Sweden. The other sources from

Table 3.2 were contacted, but attempts at collecting information from them was either unsuccessful, had very limited results, or the information was considered not to be relevant to the objectives of this project.

The questions of the interviews focused on the following topics:

- The recycling process and the methods used
- Disassembly of the products
- Difficulties and challenges in the recycling process
- Safety measures relating to hazardous substances
- Environmental risks
- Energy consumption and emissions
- Potential future recycling technologies

Following the interviews, environmental reports for the companies or facilities were also gathered, primarily to further investigate energy consumption, recycling rates, and the fate of materials after leaving the recycling facilities.

3.3 Definitions of recycling rate and related terms

When presenting recycling data, there are two important indicators that describe the recycling rate of raw materials:

- **EOL-RIR:** End-of-life Recycling Input Rate, which is defined as the secondary production flows divided by the total production flows, which in turn consists of the primary production flows, the secondary production flows, and the imports flows.
- **EOL-RR:** End-of-life Recycling Rate, which is defined as the secondary production from old scrap divided by the total available material at end-of-life and imports of end-of-life products.

These terms are widely used in documentation and statistics in the EU, as well as by international and European metal groups and institutes, but the definitions and methods of calculation may vary. Examples of variations could be whether or not new scrap is included in the primary production flows, and the inclusion of imports of materials or products. The definitions described above are retrieved from a technical report by the Joint Research Centre (JRC) of the European Commission, which are the same as those used in the Raw Material System Analysis (MSA) and Raw Materials Information System (RMIS) of the European Commission [75]. In this project, the term recycling rate refers to EOL-RR, unless stated otherwise. This indicator is most relevant when analysing the efficiency of the recycling process, and for investigating how much material is lost between the end-of-life stage and the manufacturing stage.

In addition to the two recycling rate terms, it is also important to distinguish between collection rate and recycling processing rate when it comes to recycling. Collection rate refers to the ratio of collected materials or products for recycling purposes, for example the amount of metal collected from scrap compared to the amount of available metal. Processing rate refers to the ratio of recycled materials to collected materials. This means that the recycling rate (EOL-RR) can be seen as a combination of the collection rate and the processing rate, as the total recycling efficiency depends on both how much material is collected, and how efficiently it is processed and taken care of.

3.4 Material flow analysis (MFA)

Material Flow Analysis (MFA) was used to visualise waste flows and recycling processes as well as to evaluate different recycling types. The system boundary for the MFA is limited to the EoL stage. No accumulation of materials was assumed in the system. A simplified system boundary is presented in the Figure 3.1.

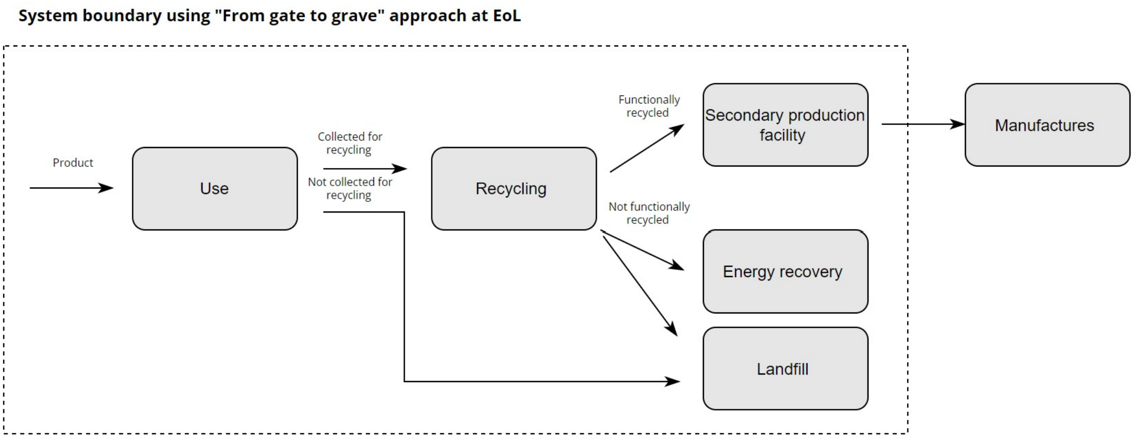

Figure 3.1: A simplified system boundary using the product life cycle scope "from gate to grave" at the EoL stage [76]

The MFA was based on an annual environmental report from Stena Recycling. The technology boundary is limited to the obsolete power transformers of Hitachi Energy. Furthermore, as the numerical data used for the MFA was collected from Stena Recycling, the geographical boundary of the MFA is limited to Sweden.

Different recycling types can be applied when assessing material recycling in material flows. In this project, the following recycling types are assessed on material level;

(a) Functional recycling
(b) Non-functional recycling in carrier metal
(c) Non-functional recycling in other materials
(d) No recycling
(e) Unknown

Functional recycling means that material properties such as physical or chemical properties are utilised in a new material production cycle, while non-functional recycling refers to material properties that are not utilised, e.g. materials are considered as impurities in a new material production cycle [77]. For example, metals entering secondary production facilities are categorised as functional recycling, while materials that are dispersed in construction materials or backfilling materials are assessed as non-functional recycling in carrier metal. Furthermore, materials entering energy recovery facilities are categorised as non-functional recycling in other materials while materials entering landfills are considered as no recycling.

3.5 Modelling and simulation for LCA analysis

GaBi software is a software which is specialised for a life cycle assessment of a product or services in business context [78]. GaBi software was used to estimate CO_2 emissions generated in electricity, heat and fuel production as recycling facilities consume energy in the form of electricity, heat and fuel for operation of recovering materials. Although conducting an LCA analysis is not included in the objectives of this project, it is important to mention that the previous LCA study for the Hitachi Energy's liquid power transformer has been conducted using GaBi software and results from this project such as recycling rates for each material, energy consumption of recycling of different materials and emissions related to recycling process are implemented into the existing LCA models in GaBi software.

3.5.1 Quantifying CO_2 emissions

Data for energy consumption in each recycling process was sourced from environmental reports and interviews. Total $CO_{2\text{eq}}$ emissions for each recycling process were calculated using database and models in GaBi. Firstly, how much energy is consumed to recycle 1 ton of incoming waste at each recycling process was listed. The recycling processes that were analysed were disassembly, decontamination and incineration process. Thereafter, energy consumption in each recycling process were converted to $CO_{2\text{eq}}$ emission with an emission factor.

The emission factor for electricity, heat and fuel (diesel) production was sourced from a database called Sphere LCA database which is available in GaBi software. Emissions caused by electricity, heat and fuel production were assumed to take place within an EU-28 electricity grid mix, an EU-28 heat (natural gas) mix and an EU-28 diesel mix at filling station, which are available as models in GaBi. As the incineration facility produces electricity and heat, emissions caused by electricity and heat production at the incineration facility were assumed as an average European municipal solid waste thermal facility, which is also available in GaBi. The emission factor for each energy type is presented in Table 3.3.

Table 3.3: The emission factor for each energy type sourced from the Sphere LCA database in GaBi sofware [79].

Emission source	Emission factor	Unit
Emission in electricity production	0.406	kg $CO_{2\text{eq}}$/kWh
Emission in heat production	0.002	kg $CO_{2\text{eq}}$/kWh
Emission in diesel production	0.515	kg $CO_{2\text{eq}}$/kg
Emission in electricity and heat production	0.716	kg $CO_{2\text{eq}}$/kWh

4

Results

In this chapter, the main results are presented, including the recycling process for the liquid power transformer, material recycling rates, energy consumption and CO_2 emissions, environmental impacts, and emerging recycling technologies.

4.1 Recycling process for the liquid power transformer

In this section, the results of the MFA over the recycling processes from collecting old transformers all the way to the final destination at the EoL stage and detailed recycling steps with focus on disassembly, decontamination, separation and sorting, and incineration are presented.

4.1.1 Material flow analysis

In 2020, Stena Recycling collected 7 000 tonnes of obsolete transformers, out of which 4 700 tonnes of metals and 1 000 tonnes of oils were recovered. Incoming waste flows to the recycling facility in Karlstad are presented in the form of Sankey diagram in Figure 4.1.

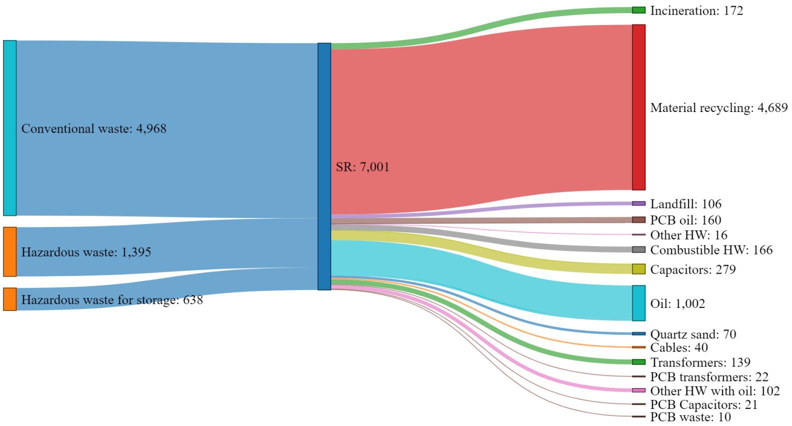

Figure 4.1: Incoming waste flows to the recycling facility in Karlstad and different waste types before they are further sent to either Stena's internal recycling facilities or external EoL service providers are presented in the form of a Sankey diagram. SR in the figure stands for the Stena Recycling facility in Karlstad, HW stands for hazardous waste, and numbers are presented in tonnes per year.

As described in the method, the obsolete transformers from Hitachi Energy are transported to the recycling facility in Karlstad as the first step of recycling processes, where the dismantling, mechanical and chemical separation, and sorting of waste are mainly taking place. Transformer waste that is collected by Stena Recycling can be divided into the broader categories of conventional waste, hazardous waste and hazardous waste for storage as seen in Figure 4.1. After sorting the waste into the different waste types, each waste type is sent to different recycling facilities within the Stena Recycling group or to other EoL service providers within the country, depending on waste types. For example, sorted metal scrap such as steel, copper, and aluminium scrap, that are indicated as Material recycling (4 689 ton/year) in Figure 4.1, are sent to internal facilities at Stena, where metal scrap are further treated before being sold in the scrap market. Similarly, transformer oils, that are indicated as Oil (1 002 ton/year) and as PCB oil (160 ton/year) in Figure 4.1, are sent to either internal Stena Metal facilities or other EoL service provider, such as incineration facilities, depending on PCB contamination levels on oil. Combustible waste such as wood and paper are sent directly to incineration facilities (172 ton/year) for energy recovery while ceramics are sent to landfill (106 ton/year). Hazardous waste (HW) that is temporarily stored at the recycling facility in Karlstad (638 ton/year) include small transformers, PCB contaminated transformers, other HW with oil, capacitors, PCB contaminated capacitors, oil, PCB contaminated oil and PCB waste. Hazardous waste (1 395 ton/ year) including PCB oil, combustible HW, capacitors, oil, quartz sand, and cables are distributed to different external EoL service providers within the country.

An overview of the material flows and processes involved in the recycling of transformers, from collecting the obsolete transformers at end-users, all the way to final destinations for each waste type are presented in Figure A in Appendix 1.

As seen in Figure A, after the first step (dismantling, chemical and mechanical separation, and sorting of waste) of the recycling processes, 66.96 % of the total incoming waste based on mass basis is sent to internal metal facilities at Stena for metal recycling, and metal scrap is thereafter further sent to their respective metal production facilities located both inside and outside of Sweden, depending on metal types. Metals that are functionally recycled with the current recycling systems are steel, aluminium, copper and silicon sheets.

29.05 % of the total incoming waste is hazardous waste, out of which sand, capacitors and PCB contaminated oil (corresponding to 6.25 % of the total incoming waste) are sent to an external waste solution facility at Fortum Waste Solutions, where final handling for hazardous waste takes place such as incineration. This hazardous waste is not considered to be functionally recycled since the material properties are not utilised once the waste is incinerated. Therefore this is assessed as non-functional recycling in other materials. On the other hand, transformer oil that is not contaminated with PCB (corresponding to 14.20 % of the total incoming waste) is sent to internal oil facility at Stena for functional recycling. This means that it is the contamination levels that decide whether or not the oil is functionally recycled.

Paper and wood that stand for 2.47 % of the total incoming waste are sent to incineration facilities for energy recovery, which as before is assessed as non-functional recycling in other materials. On the other hand, ceramics (corresponding to 1.52 % of the total incoming waste) are sent to landfills and this is categorised as no recycling. Both the energy recovery and landfilling are operated by local municipal energy utility companies.

4.1.2 Recycling steps in the disassembly process

After reaching its end-of-life, the first step in the recycling process of transformers is disassembly. The transformers are usually transported to a recycling or waste management facility beforehand, but the largest models may have to be dismantled on site to facilitate transportation. Prior to dismantling, the transformer oil is removed and tested by analysing samples of the oil. This is done to determine the PCB levels, as the oil and the materials require decontamination if the levels are too high. An overview of the steps in the recycling process is shown in Figure 4.2.

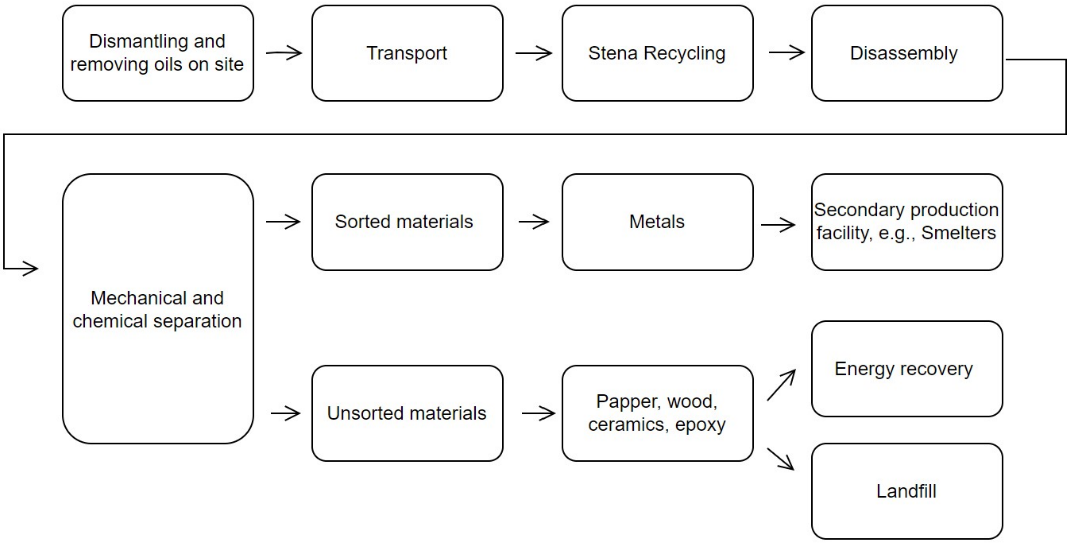

Figure 4.2: Simplified process diagram in the recycling of transformers at Stena Recycling in Sweden

Due to the large variety in characteristics between different models, the disassembly is performed manually, by hand. All manufacturers use different designs, and the transformers can range in size from 0.5 tons to 100 tons, making it nearly impossible to automatise the process. At Stena Recycling, mechanical dismantling methods are most common, including for example screwing apart the transformers when possible, or cutting them up using scrap shears. Chemical separation methods also occur, but mechanical methods are usually sufficient, and material separation is not currently a problem in the recycling process.

The materials are then separated and sorted into their respective material groups. If necessary, the materials are cleaned and decontaminated, for example if they have been in contact with oil with PCB. Certain materials cannot be decontaminated, for example porous materials such as paper or wood, and must be discarded. Metals are highly prioritised for recycling because of their recyclability, high price, and limited supply. Additionally, the purity is often high, further incentivising recycling. The metals are milled and sold to secondary production facilities, such as smelters, where the scrap is further processed to produce new raw materials. One exception is the silicon sheet in the transformer core, which is usually exported, mainly to China, India, and Pakistan, and reused in the manufacturing of new transformers. It is worth noting that typically, the disassembly and secondary production take place at different facilities, which means that transport is required after the sorting and separation of materials. Intermediary steps may also occur after the initial sorting and separation. For example, scrap wholesale companies may buy the metal scrap after it has been sorted. This process can occur internally at the recycling company, meaning that the scrap is transported to other plants at for example Stena Recycling or Stena Metall, or the scrap can be sold and transported to external actors, or even exported, as the previously mentioned transformer cores. However, the metals are usually not processed further in these intermediary steps.

The potential recycling rate for the materials in the transformers is very high. Almost all materials can be recycled or reused, with the main exceptions being paper, wood, and ceramics, which are either used for energy recovery or sent to landfill. Polymers such as epoxy are also difficult to recycle, and may complicate the recycling process as a whole.

4.1.3 Recycling steps for decontamination

Transformer oils that are contaminated with PCB containing more than 50 ml must be decontaminated by 2025 under the POPs regulation in the EU. The technologies for decontamination are available on an industrial scale. AGR in Spain uses metallic sodium for decontamination of transformer oils at their recycling plants. A simplified process diagram using metallic sodium is presented in Figure 4.3. The overall process is that PCB contaminated oil stored in a tank is dried by two filtering equipment until the concentration of water falls below 5 parts per million (ppm), after which the oil is introduced into a reactor. In the reactor, PCB contaminated oil reacts with pre-treated metallic sodium, and finally decontaminated oil and sodium chloride are produced as products. The decontaminated oil is then used as base oil for the manufacture of other types of oils by adding the desired additives, or reused as dielectric oil, while the sodium chloride is deposited in landfills. According to the director at AGR, nearly 95% of the total incoming contaminated oils is currently decontaminated for reuse and only 5% is deposited through other methods. This percentage is calculated based on the total amount of incoming oil mass and the total mass that is sent to incineration. The figure itself can vary depending on the concentration of PCB in the incoming oil. In case a transformer contains over 3 000 mg PCB/kg oil, the cost of decontamination is deemed too high and the oil is therefore sent to incineration instead.

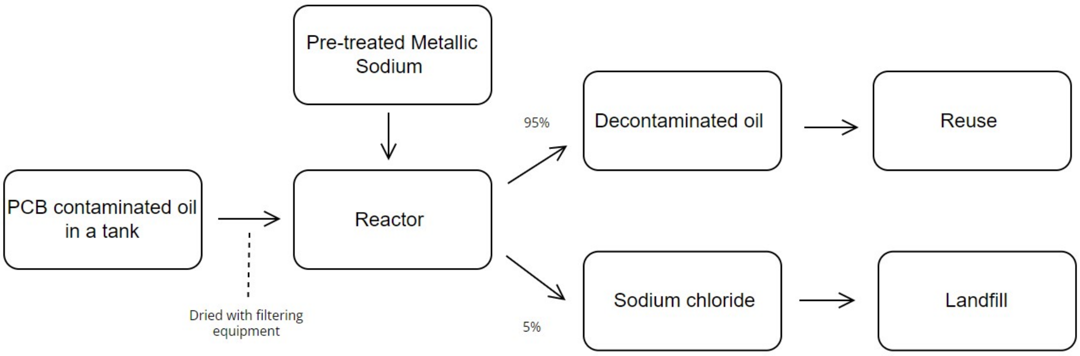

Figure 4.3: Simplified process diagram in the decontamination process at AGR in Spain

The main reasons why all transformer oils cannot be decontaminated are due to compounds such as water, particles, and gases present in the oils, and porous materials used in transformers such as paper, wood that make it difficult to decontaminate them completely. Additionally, it is not always economically viable to treat the oils, as previously described. A notable difficulty of the decontamination is the metallic sodium used in the process, as the substance requires extra care due to its highly reactive nature and the risk of reactions with humidity in the ambient air.

4.1.4 Separation and sorting methods

Separation and sorting of different materials from the obsolete transformers are important steps in the recycling process, and thereby it is highly relevant for manufacturers of HV products to have detailed knowledge of the physical separation technologies at the shredding plant. The methods of sorting and separation for each material are presented based on literature studies, interviews, and dialogues with the production manager at the Stena Recycling facility in Karlstad.

The shredding plant in Karlstad consists of a series of different stages: the dismantling, shredding, and sorting stages. Simplified material flows and the methods of separation and sorting are presented in Figure 4.4. As the material flows and process diagram are simplified, any residues from each stage are excluded from the figure.

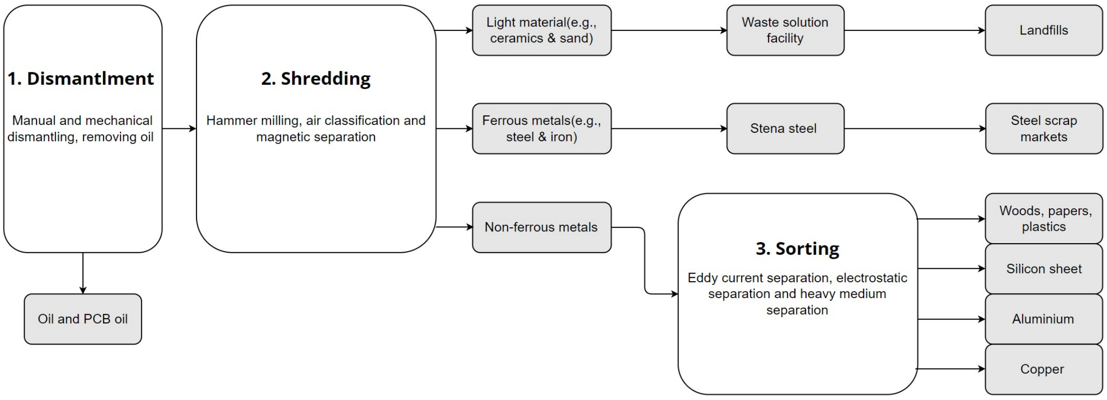

Figure 4.4: Material flows and how each material is separated and sorted at the shredding plant in Karlstad

Dismantling is the first stage at the shredding plant, and this stage includes manual and mechanical dismantling, as well as removing transformers oils. As described earlier, dismantling can occur on site if it is necessary in order to reduce transport costs for the recycling company. Manual dismantling is an effective method when dealing with a wide variety of transformers that differ in size and design. Manual dismantling is also preferred if the HV products contain precious metals since mechanical dismantling of these metals can result in losses of a large part of these metals with the current dismantling technologies [82]. On the other hand, mechanical dismantling is preferred when dealing with a large amount of transformers, and it is carried out by screwing apart transformer components and cutting them up using scrap shears. After this step, transformer oils are removed and sent to either an oil recycling facility or an industrial waste solution facility depending on the PCB contamination levels, while solid dismantled materials are sent to the shredding stage.

Shredding is the second stage and different methods can be applied in this stage. The main goal of this stage is to separate solid waste into light materials, ferrous materials and non-ferrous materials based on material properties such as weight and magnetic properties using different technologies such as hammer milling, air classification and magnetic separation [77]. The air classification separates milled particles, that are obtained by hammer milling, based on weight so that light and heavy fractions are separated [77]. The light fractions consist of low density materials such as sand, ceramics and a small fraction of light metals that contain magnesium and aluminium. Sand is sent to an external industrial waste facility, ceramics are sent to landfills that are operated by local municipal energy utility companies, while the small fraction of light metals is sent to eddy current separation [80]. On the other hand, the heavy fractions mainly consist of a mixture of ferrous- and non-ferrous metals such as iron, steel, aluminium and copper. The heavy fractions are sent to magnetic separation. The magnetic separation separates heavy fractions into ferrous materials (i.e., steel and iron that have magnetic properties) and non-ferrous materials (i.e., copper and aluminium that have no magnetic properties). Magnetically separated steel and iron are sent to an internal steel facility at Stena for the final treatment before they are being sold in the steel scrap market, while non-ferrous materials are sent to the sorting stage.

Sorting is the final stage at the shredding plant and the main goal of this stage is to separate non-ferrous materials into their respective material group using separation technologies such as eddy current separation, electrostatic separation, and heavy medium separation. The eddy current separation and the electrostatic separation methods are used to separate a mixture of non-ferrous materials into non-ferrous metals (i.e., aluminium and copper) and other non-ferrous material (i.e., woods, papers, rubber, plastics) based on differences in material conductivity. The main problem in these methods is that the particle size must be relatively small, preferably smaller than 5 mm for the eddy current separation method, and even smaller than 75 μm for the electrostatic separation method, in order to achieve an efficient separation [81], [82]. The heavy medium separation is used to separate different types of plastics, as well as to separate metals from plastics, based on differences in density of the materials in a liquid medium with a specific density [82]. The main problems in this method are that heavy liquids medium are costly and hazardous, since they are mixtures of different minerals like calcite, barite and ferrosilicon [83]. Wood, paper and plastics are sent to a local utility companies for energy recovery while the silicon sheets, aluminium and copper are either sent to internal facilities at Stena before being sold in the scrap market, or to external smelters for each metal group [80].

4.1.5 Incineration of hazardous waste for energy recovery

All hazardous waste that cannot be decontaminated is sent to waste incineration facilities for disposal, and energy is recovered in the process. In the case of transformers, the main example of such waste is PCB contaminated material and components. If the contamination of the waste exceeds the levels specified by the POPs regulation and other related regulations, it must be treated using irreversible processes to convert it into harmless substances before any materials can be used for other purposes or sent to landfill. The Fortum Waste Solutions facility in Kumla is the final destination for many types of hazardous waste, including PCB contaminated transformer oil and condensers from high voltage products. A simplified process diagram at the facility in Kumla and final destinations for residues that are generated during the combustion process are presented in Figure 4.5.

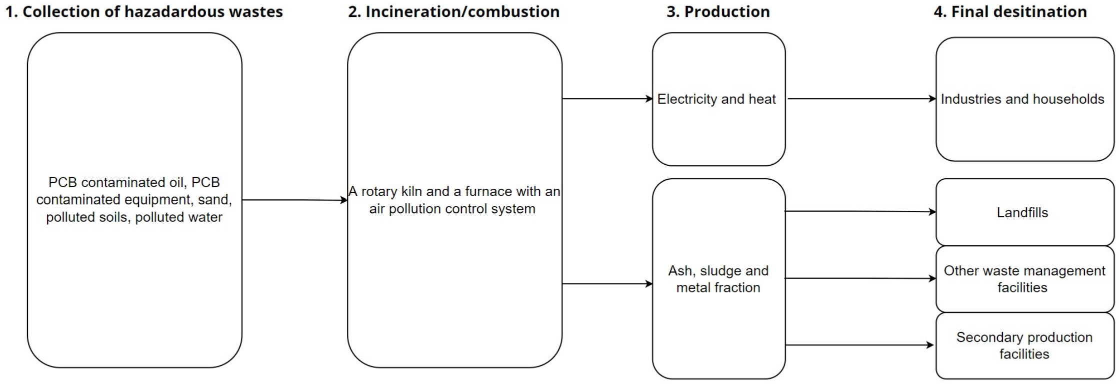

Figure 4.5: A simplified process diagram at the facility in Kumla and final destinations for residues generated in the combustion process

When the hazardous waste reaches the facility in Kumla, it is typically not disassembled or separated, and any waste containers are left unopened. Instead, the waste and the containers are incinerated in their original states. This is done to reduce emissions to air and water, and to prevent unnecessary exposure of hazardous substances to the employees. In some cases, the materials may be crushed and reduced in size, if it is possible to do so without increasing substance exposure.

At the Fortum Waste Solutions facility, there are two incineration alternatives: high temperature incineration in a rotary kiln at 1 200 - 1 400 °C, and a furnace with a lower operating temperature of 850 °C. Which alternative is chosen depends on the type of waste and its contents. At this stage, the mix and properties of the waste must also be considered to achieve a good combustion process, resulting in the mixing of different categories and types of waste. The waste incineration results in production of electricity and district heating, so while the facility requires a significant amount of energy for processes such as heating and flue gas cleaning, the entire system is net positive in terms of energy consumption.

To prevent emissions of dioxins, particles, and other harmful substances, an advanced air pollution control system is used to clean the flue gases produced in the incineration process. The first step is absorption, which occurs through the addition of a lime slurry in a lime reactor. There, halogens and acidic gases such as sulphur compounds bind to the lime and are removed in the form of dry matter. This is followed by the addition of active carbon to remove dioxins. The flue gases are then passed through textile filters to remove soot and other particles. After the textile filters, the gases are transferred to a wet scrubber, which is the final treatment step. In the scrubber, the gases are cooled to approximately 70 °C and saturated with water. Through scrubbing with water and hydrogen peroxide, substances such as mercury and hydrochloric acid are trapped. Before the treated gases are emitted through the stack, the emission levels of different relevant substances are measured to ensure that the levels are acceptable and that all systems are working properly.

After the incineration, the residuals mainly consist of ashes, sludge, and metals. Large metal pieces are extracted and sent to secondary production facilities, while the sludge, which also contain metal fractions, is sent to other waste management facilities for further processing. Other residuals that cannot be recycled or used for construction and other purposes are sent to landfill. The environmental reports from Fortum Waste Solutions showed that landfill was the most common final fate for the materials sent to the incineration facility, with the total waste disposed to landfill from all sources reaching 1 620 000 m^3 during 2021.

Incineration and energy recovery as a final solution of handling hazardous waste is more common in Nordic countries as well as in France and Germany since there are the same level of advanced air pollution control systems available in these countries. As the method requires an advanced air control system in the combustion process, it also varies in different countries depending on available technologies on recycling sites.

4.2 Material recycling rates

This section covers the material recycling rates for the main material categories of the HV products. Due to limitations in time and scope for this project, the presented recycling rates are combinations of the results from both the conducted interviews and data collection through literature studies.

4.2.1 Metals

The recycling rates for the three main metals covered in this study are presented in Table 4.1. As there is a certain degree of uncertainty when calculating recycling rates, and the figures vary geographically and over time, several figures are presented for each metals. The sources of the figures is presented in the rightmost column, with the order of the sources corresponding to the order the figures are presented in the centre column.

Table 4.1: Recycling rates for the most common metals in HV products.

Material	**Recycling rate (EOL-RR) [%]**	**Sources**
Steel	69, 71, 75	[84], [85], [86]
Copper	61, 65	[86], [87]
Aluminium	69, 73, 76	[86], [88], [89]

The recycling rates are averages based on the recycling from all sources of the material. For individual product categories, the rates may be higher or lower depending on factors such as the collection rate and ease of separation of the materials.

4.2.2 Material recycling rates on the product level

Approximative recycling rates for each material in the Hitachi Energy 40 MVA Liquid Filled Power Transformer are presented in the Table 4.2. In the third and fourth columns, the resulting ranges of the EOL-RR and amounts of recycled materials are presented. As recycling rates for the metals vary depending on which sources are used, there is also a certain degree of uncertainty in recycling rates for each material. Furthermore, ferrous alloys such as carbon steel and electrical steel in the composition were assumed as steel in general due to lack of available sources for each ferrous alloy type. For the recycling rates of the transformer cooling liquid, including both tank and radiators, figures for the recycling rates for decontamination of PCB oil at AGR were used. As kraft paper and laminated wood are incinerated as combustible waste for energy recovery purposes, the recycling rate for these materials was set to 0%. Due to lack of data on recycling rates for other parts and accessories as well as pressboard, the recycling rates for these materials were not applicable.

Based on recycling rates for each material group in the composition, the recycling rate on product level was finally estimated to range from 72.5 % to 76.5 %. It should be noted that due to the reasons previously described, the level of uncertainty for the recycling rates in Table 4.2 is rather high. Furthermore, as the numbers used for metals are industry averages, the rates for this particular type of waste (HV products and electrical waste) is likely slightly higher, because of factors like collection rate, which is typically higher for metals originating from industrial electrical waste than from WEEE and other consumer waste types.

Table 4.2: Approximative material recycling rates on product level

Material	**Mass** [kg]	**EOL-RR** [%]	**Recycled material** [kg]
Transformer cooling liquid (tank)	18 698	95 - 96	17 763 - 17 950
Core - electrical steel	18 055	69 - 75	12 458 - 13 541
Windings - copper	13 196	61 - 65	8 050 - 8 577
Tank and tank assembly part - carbon steel	11 312	69 - 75	7 805 - 8 484
Radiators - carbon steel	5 654	69 - 75	3 901 - 4 241
Other parts and accessories	2 677	n/a	n/a
Core clamps and core parts - carbon steel	1 952	69 - 75	1 347 - 1 464
Tank shunts - electrical steel	1 484	69 - 75	1 024 - 1 113
Transformer cooling liquid (radiators)	1 549	95 - 96	1 472 - 1 487
Pressboard	1 532	n/a	n/a
Conductor insulation - kraft paper	435	0	0
Laminated wood	413	0	0
Total (excl. other parts and acc.)	**74 280**	**72.5 - 76.5**	**53 820 - 56 857**

4.3 Energy consumption

The energy consumption is calculated using data provided by technical experts and environmental reports at Stena Recycling, AGR and Fortum waste solutions. The consumption is sorted into three categories: electricity, district heating where applicable, and fuel, referring to fossil fuels used directly in the process. The calculations for the disassembly process are based on the annual consumption of the different types of energy, in combination with the annual amount of material handled by the facility. Because of this, the energy consumption should be seen as an average for all types of transformers. The consumption is dependent on the disassembly time and the required tools, and as the recycled transformers come in a wide range of weights and sizes, the time spent on each product also varies. There is no documentation on the exact time and energy spent on each product, so this simplification is necessary in order to get actual results. The resulting energy consumption is presented in Tables 4.3, 4.4, and 4.5 which show the consumption during the disassembly process, the recycling of the oil and final handling of hazardous waste, respectively.

Table 4.3: Energy consumption per ton of disassembled material at the recycling site in Karlstad [105]

Energy type	**Amount**	**Unit**
Electricity	34.52	kWh/ton
District heating	41.20	kWh/ton
Fuel (diesel)	0.357	kg/ton

Table 4.4: Energy consumption per ton of transformer oil at AGR in Spain

Energy type	**Amount**	**Unit**
Electricity	155	kWh/ton
Fuel (diesel)	13	kg/ton

Table 4.5: Energy consumption per ton of hazardous waste at Fortum in Kumla [106],[107]

Energy type	**Amount**	**Unit**
Electricity	8.22	kWh/ton
District heating	0.36	kWh/ton
Fuel (diesel)	3.87	kWh/ton

As the disassembly and incineration processes are taken place in Sweden, energy consumption for district heating is included in the energy consumption for each recycling facility. Regarding the incineration process at Fortum Waste Solutions in Kumla, electricity and heat are also produced. It should be noted that the energy consumption listed in Table 4.5 is the energy input required for the facility itself, the air pollution control, and other internal processes. This energy consumption represents only a very small part of the total emissions in the process, as waste incineration causes a large amount of emissions through combustion. The decontamination process has the highest energy consumption per ton of processed waste out of all recycling processes, mainly in the form of electricity. This is because the decontamination process is based on chemical separation, which in turn requires more energy per ton of processed waste compared to disassembly process, where mechanical separation is dominated in a large part of the process. Both the disassembly and decontamination processes rely on electricity for the most part, in contrast to the incineration process.

4.4 CO_2 emissions

The emissions were calculated using databases and models in GaBi, based on the energy consumption of the recycling processes. To convert the production of electricity, heat and fuel (diesel) into emissions, the EU-28 energy mix database was used in the software. All emissions and environmental effects were calculated as CO_{2eq} directly using the emission factors described in the method chapter. The results from the impact assessment are presented in Tables 4.6, 4.7, 4.8, and 4.9.

Table 4.6: CO_2 emission per ton of processed waste at the recycling site in Karlstad

Energy type	**Amount**	**Unit**
Electricity	14.015	$kgCO_{2eq}/ton$
District heating	0.083	$kgCO_{2eq}/ton$
Fuel (diesel)	0.183	$kgCO_{2eq}/ton$
Total	**14.282**	$kgCO_{2eq}/ton$

Table 4.7: CO_2 emission per ton of processed waste when proceeding decontamination process at AGR in Spain

Energy type	**Amount**	**Unit**
Electricity	62.930	$kgCO_{2eq}/ton$
Fuel (diesel)	6.695	$kgCO_{2eq}/ton$
Total	**69.625**	$kgCO_{2eq}/ton$

Table 4.8: CO_2 emission per ton of processed waste when handling hazardous waste at Fortum Waste solutions in Kumla

Energy type	**Amount**	**Unit**
Electricity	3.337	$kgCO_{2eq}/ton$
Fuel (diesel)	1.993	$kgCO_{2eq}/ton$
District heating	0.0007	$kgCO_{2eq}/ton$
Total	**5.331**	$kgCO_{2eq}/ton$

Table 4.9: CO_2 emission per ton of processed waste when electricity and heat are produced via incineration at Fortum Waste solutions in Kumla

Emission source	**Amount**	**Unit**
Electricity & heat production	80.283	$kgCO_{2eq}/ton$

The tables above clearly show that the waste incineration cause the highest CO_{2eq} emissions per ton of waste out of all the separate processes. These emissions are in the form of CO_2, SO_2, and NOx emissions, among others. The emissions from all the facilities cannot simply be summarized as different fractions of the waste require different types of treatment. Only the PCB contaminated waste is sent to the decontamination or incineration facilities, while the metals and uncontaminated oil can be sold to other markets with much less processing required. To allow for a fair summary of the investigated processes, the mass percentages sent to different facilities as shown in Figure A are taken into account. Approximately 6.25% of the total transformer waste is hazardous waste that requires final treatment of some kind, and the emissions from these processes are allocated accordingly. The results of this summary is presented in Table 4.10, which therefore should be seen as a summary of the total emissions from the investigated processes per ton of transformer waste that is sent to the first EoL management step (disassembly and dismantling).

Table 4.10: The overall CO_2 emission per ton of transformer waste at all waste facilities after allocating emissions according to mass percentages

Emission source	Amount	Unit
Disassembly	14.282	$kgCO_{2eq}/ton$
Sum, decontamination route	**18.633**	$kgCO_{2eq}/ton$
Sum, incineration route	**19.633**	$kgCO_{2eq}/ton$

The emissions are slightly higher when choosing incineration rather than decontamination of the hazardous waste, which is expected as the emissions per ton are higher for the former process. Referring back to the MFA and the complete waste management process shown in Figure A, it should be noted that not all processes are included in the calculations of total energy consumption and emissions, primarily due to a lack of information. Waste storage at the waste management facilities is not taken into account, as it is difficult to determine the treatment and fate of this waste before it is sent to other facilities. Emissions from transportation are also excluded, meaning that the actual total emissions are higher than shown in the tables above. Similarly, metal recycling and secondary production of metals are excluded from the emissions due to a lack of information from metal producers and inexact figures for the metal recycling rates.

4.5 Environmental impact at recycling sites

In this section, possible environmental impacts when handling of hazardous chemical substances SF_6 and PCBs at recycling sites are presented.

4.5.1 Handling of SF_6

SF_6 is still used in the production of new breakers and switchgears, and can therefore be expected to be an issue in the recycling process for the foreseeable future. While SF_6 does not pose a risk to human health, it is an extremely potent and long lived greenhouse gas. Leaks must therefore be prevented, and the gas must be handled in a closed loop system.

If the pressure in the equipment exceeds 2 bar, it cannot be transported and must instead be emptied on site. In Norway, Stena Recycling empties the equipment of SF_6 themselves, while in Sweden there is a collaboration with Vattenfall Services to perform this service instead. After emptying, the gas itself is transported to another facility, where it is typically incinerated. All handling of SF_6 gas in the EU requires authorisation and management according to the F-gas directive, and must be documented accordingly.

4.5.2 Handling of PCBs

Toxic effects from PCB contamination in transformer oils is the single biggest risk when managing old transformers, especially for workers at the recycling plants and for the environment near the recycling plants. As described in the previous chapter, PCBs are classified as POPs due to its persistence in the environment and risks for bio-accumulation and bio-magnification, which in turn causes diverse effects on human health and the environment. All the investigated recycling companies, Stena Recycling, AGR, and Fortum Waste Solutions have employed extensive safety measures to protect their workers and the environment from those risks.

A majority of obsolete transformers that are managed at the recycling plant in Karlstad was produced between 1950 and 1960 in Sweden before the ban of production of PCBs was introduced, meaning that PCB contaminated oils can be present in these transformers. To minimise the risks, all materials in transformers are examined either at sites of end-users or at recycling plants and all oils are removed from transformers and samples are taken for measuring concentration of PCBs in oils before moving on further recycling steps. In Sweden, if concentration of PCBs in oils is more than 2 ppm, decontamination is necessary. In case the concentration of PCBs in oils is less than 2 ppm, the oils can be reused for new applications. PCB contamination can be present even in other WEEE such as capacitors and switches, which must be considered during the recycling of these components.

Workers at Stena recycling wear protection cloths and masks to avoid direct contact with PCBs when handling contaminated materials. All workers are obliged to have samples taken once every two years to check if they are contaminated with PCBs or not during the recycling processes.

As the decontamination process at the AGR facility is automated, the process itself is relatively safe for workers. However, every worker is well trained for handling PCB contaminated oils.

Fortum Waste Solutions is the waste handling facility for a wide array of hazardous waste coming from industries and households, and therefore safety measures are important for the protection of workers and the environment. Emissions to air, soil and water from the recycling site are strictly controlled by the local municipal authorities as the facility in Kumla is the only facility that is legally permitted to handle hazardous waste in Sweden. Workers at the recycling site wear protection cloths, masks, glasses, and gloves to avoid direct contact with PCBs when handling PCB contaminated waste. To minimise the risks, higher PCB contaminated waste is directly sent to the incineration process without having any pre-treatment by workers in order to prevent exposure. Solid hazardous waste is stored in a warehouse while liquid hazardous waste is stored in tanks, and the process water is cleaned before it goes back to the municipal waste water system. Particulate matter and pollutants generated in the combustion process go through the flue gas control system before they are emitted into the air.

4.6 Emerging recycling technologies

In this section, emerging technologies related to disassembly, primary and secondary material production (copper, steel, aluminium and polymer), recycling of hazardous substances and alternative substances are summarised based on literature studies.

4.6.1 Disassembly of products

There are several emerging disassembly technologies that are designed to protect human health and the environment through the minimisation of manual labor. Automatised disassembly is a technology that can reduce work involving manual disassembly, and minimise the contamination risk from hazardous substances on workers and the environment. Robotised dismantling is another emerging technology that can replace human work, while managing large quantities of electrical and electronic waste [82]. Additionally, the materials extracted with this technology can achieve better quality compared to those obtained with manual dismantling.

Another promising technology is the integration of semi-automatic disassembly cell after manual dismantling [90]. This technology can only be applied to one part of WEEE and is designed to remove printed circuit boards from the flames. Reusable parts and toxic components on the printed circuit boards are identified with the data based image processing. After that, the toxic components are removed by laser dissoldering technology while the reusable parts are removed by robot grippers. Although this technology is primary designed for the certain part of WEEE, technologies and methods are applicable for other WEEE such as transformers and other HV rpoducts.

4.6.2 Primary and secondary material production

Although secondary material production reduces significantly energy consumption in the production phase, primary material production is expected to continue to meet growing material demand. Therefore, promising emerging technologies related to primary and secondary material production for copper, aluminium, steel and polymers are investigated and presented based on findings from literature studies.

Even though the pyrometallurgical process dominates 80% of the current world copper production, the hydro-metallurgical process and secondary copper production will play an important role in the near future in terms of environmental impact and quality of material as the secondary copper production consumes less energy while the hydro-metallurgical produces relatively high purity of copper [39]. Furthermore, the hydro-metallurgical process generates less solid particles compared to the pyrometallurgical process and reagents can be reused [91]. However, the hydro-metallurgical process requires large amount of water. Waste water contains soluble metal compounds, chelating compounds and organic solvents, which in turn increases risks for contamination. Therefore, the hydro-metallurgical process needs more further research in order to increase utilisation of water in the process so that the process ensures less water usage and lower risk of contamination.

Secondary aluminium production that involves remelting of aluminium scrap in a furnace has a potential to reduce significantly energy consumption and CO_2 emissions in the material production phase compared to its primary production. In addition, secondary aluminium production does not generates any bauxite residue so called Red mud, that is generated during the Bayer process in the primary production. Red mud is disposed in artificial impoundments, which in turn can cause serious environmental impacts [91]. However, byproducts that are generated in the secondary aluminium production such as off gas and black dross need to be treated so that the production can be carried out in an environmentally safe manner.

Blast furnace (BF) technology with top gas recycling with Carbon Capture Storage (CCS) and direct reduction (DR) using hydrogen as reduction agent with electrolysis are emerging technologies to reduce CO_2 emissions in the primary steel production. For secondary steel production, refining steel scraps in Electric Arc Furnace (EAF) is a promising method since this technology has the potential to produce steel without generating CO_2 emissions over the production phase.

Due to loss of properties and limited application of recycled polymers and plastics produced via mechanical recycling method, chemical recycling method is a more promising method to maintain material properties and to increase application of recycled material. Feedstock recycling that involves converting polymers into monomers and then polymerising into new plastics is one of the methods that is under development. However, this method is an energy intensive technology and therefore needs further research to optimise energy consumption during the recycling process [61].

4.6.3 Recycling of hazardous substances

Recycling of the hazardous substances used in HV products, mainly SF_6 and PCBs, should be prioritised over incineration for energy recovery, as dictated by the EU Waste Hierarchy. Incineration results in large amounts of emissions while also wasting materials and natural resources, and it should therefore be avoided if other options are available. Despite this, the research of this project show that incineration remains the most common management route for hazardous substances, and it can therefore be concluded that the recycling methods of these materials need further investigation, investment, and development so that the environmental impact of the EoL management of the products can be reduced. The most important recycling methods for SF_6 and PCB contaminated materials are presented below.

For the recycling of SF_6, cryogenic separation is the most promising method, as it can result in highly purified SF_6 through the removal of impurity gases using liquid nitrogen. However, little information could be found in this project regarding the prevalence of this method, and its industrial applicability has not been assessed.

For decontamination of PCB contaminated oil, the catalytic hydrodechlorination method using nickel/silica-alumina catalyst and super critical CO_2 fluid is one of the promising methods on a laboratory scale, since this method reached 100 % PCB conversion. Furthermore, the method relies neither on noble metal catalysts nor on conventional organic liquid solvents, and therefore the method is profitable both economically and environmentally due to lower economical costs and the lack of generation of organic waste [64].

4.6.4 Alternative chemical substances

The hazardous substances used in high voltage products need to be replaced by alternative chemical substances in order to reduce the negative environmental impact over the life cycle of the products. The substances are dangerous in different ways, as SF_6 is a very potent greenhouse gas, while PCBs constitute a biological risk, and seeing as even their management results in environmental harm due to the prevalence of incineration, continued usage cannot be considered sustainable. Alternative solutions to SF_6 and PCBs are summarised below, based on findings from literature studies.

The extreme global warming potential of SF_6 makes it imperative to find environmentally friendly alternatives. Nonetheless, the material properties, for example insulation properties, decomposition properties, physiochemical properties, and compatibility with metals and materials in the products of any replacement must be comparable or better than for SF_6 [92], and these criteria ultimately dictate if the alternative is viable as an insulating gas. Common alternative insulation solutions include dry air, oil, vacuum, nitrogen, and carbon dioxide, and these solutions are well researched and commercially viable. Though more environmentally friendly, these alternatives are limited by their comparatively low breakdown voltages, resulting in better suitability for low and medium voltage equipment than for high voltage equipment [8]. Another possible alternative is to use gas mixtures consisting of SF_6 combined with nitrogen or helium, resulting in lower consumption of the gas and thereby reduced environmental risks. The mixtures may use either equal parts of both substances, or lower concentrations of SF_6, depending on the practical applications [93]. However, gas mixtures cannot completely solve the problems that come with SF_6, as they will still have significant GWPs.

Using new insulation gases is another option that has seen increasing attention and research in recent years. The most promising new gases include perfluorinated ketones ($C_5F_{10}O$ and $C_6F_{12}O$) and fluoronitrile (C_4F_7N) [92][94]. These gases have low GWPs and high dielectric strength, and they may be able to compete with the performance of SF_6, either in their pure form or when used with CO_2 as a buffer gas. Mixing with CO_2 may be necessary in order to reduce the minimum operating temperature of the equipment to an acceptable level. Studies indicate problematic aspects regarding other properties of the gases, however, including for example compatibility, leaking rate, and interruption performance [92][94][95]. In conclusion, finding a single solution among the all the alternative gases and gas mixtures to replace SF_6 on a large scale requires far more investigations and experimental studies to be carried out, especially when it comes to high voltage applications.

For the insulating fluid in transformers, natural and synthetic esters are potential alternative substances to PCBs. As natural esters are derived from organic seeds of plants, this type of ester oil is favourable from an environmental point of view. Studies also show that the application of ester oils in transformers leads to both reduced failure in the transformers in the power system network, and reduced cost associated with transformer condition monitoring due to their property advantages, such as high temperature stability and high viscosity index [12].

5

Discussion

In this chapter, the main findings from the results chapter are reflected upon and discussed. The chapter covers analysis of the recycling process, challenges for recycling companies, challenges for a circular economy, the LCA studies and sustainability goals of Hitachi Energy, as well as the quality of data in the project and potential future studies.

5.1 Analysis of the recycling process

The energy consumption during the disassembly process is roughly divided equally between electricity and district heating. Due to a lack of data, the direct causes for the electricity consumption cannot be determined, making it difficult to analyse the process further and suggest improvements. At the AGR facility, there is no need for heating due to the climate in Spain, which is a point of uncertainty in the data, as there would likely be a district heating consumption if the decontamination took place in Sweden. The energy consumption at the incineration facility is very low compared to the other processes. This is due to the local production of heat and electricity, which drastically reduces the need for purchasing from the grid. When comparing all three processes, it is clear that the decontamination requires the most energy, with just the electricity consumption requiring more than twice the sum of the electricity and district heating of the disassembly.

The decontamination of the transformer oil stands for a significant portion of the $CO_{2\text{eq}}$ emissions. This is mainly due to the high energy consumption required by the decontamination process. The emissions from this process primarily come from the electricity consumption, with less than 10% coming from consumption of fossil fuels. Compared to incineration, decontamination of the oil therefore has a greater potential for reduced emissions in the future, if the European electricity mix transitions towards fossil-free energy sources. The waste incineration, on the other hand, cannot lower its air emissions to the same degree without implementing CCS systems. Furthermore, incineration requires air pollution control systems to prevent emissions of hazardous substances. In addition to CO_2, significant amounts of NOx, SO_2, and small amounts of metals are released despite the presence of these systems. If the systems fail or are not present at all due to lack of regulations or available technologies, the emissions become much greater and constitute a serious risk to human health and to the environment. Decontamination of hazardous waste should therefore be seen as the more environmentally friendly alternative out of the two waste management methods.

Overall, avoiding the use of hazardous substances is the most sustainable option, as it eliminates the need for final treatment altogether, which reduces the environmental risks. This process is already underway, as legislation banning PCB forces manufacturers to choose alternative substances. Phasing out these substances is also in alignment with the sustainability goals of Hitachi Energy, and will likely result in reduced energy consumption and emissions, as shown by the results of this study. Nonetheless, it is important to consider that PCB contaminated oil and components still remain in old products, and must be handled responsibly at their end-of-life. SF_6 also remains an issue, and while it is under strict regulations, there is no ban underway in the foreseeable future.

Because of the phase-out of PCB, there is a risk that recycling companies are reluctant to invest in new decontamination facilities, as they are expected to become obsolete. For comparison, waste incineration facilities are more versatile and can be used for many types of waste. Further analysis of the PCB contaminated products still on the market is necessary, as all such products require treatment, but the most economically viable method depends on their amount and expected lifetime.

5.2 Challenges for recycling companies

The material flow analysis (MFA) showed that all major metals used in transformers, such as steel, copper, aluminium, and the silicon sheet can be functionally recycled using current recycling technologies, mainly by utilizing mechanical separation techniques. However, due to contamination of the metals and materials through contact with insulation mediums in the transformers, the actual handling of these materials is categorised as either non-functional recycling in carrier metal or non-functional recycling in other materials, since the material properties are not utilised in a new material production cycle. Materials with higher contamination levels are often incinerated today, as this is deemed more economically profitable. This indicates that more metals and materials could be functionally recycled without losing material properties if there was less contamination on materials caused by the hazardous substances in transformers. For recycling companies, this is a challenge because contamination on metals and materials reduces the amount of materials that can be recycled. A possible solution to this is to introduce alternative chemical substances such as biodegradable natural esters to replace PCBs in transformer oils. This is a promising solution to reduce the contamination risk of the materials, and more materials can be functionally recycled.

There are some materials that are difficult to recycle due to their composition and structure. For instance, sand, ceramics and plastics are difficult to recycle functionally given the current recycling technologies. Today, ceramics are often landfilled while sand and plastics are incinerated for energy recovery. Contaminated porous materials are also difficult to recycle, as the contaminants are nearly impossible to remove from the materials because of their material structures. Incineration is an effective method to handle waste that cannot be recycled and contain hazardous substances to avoid circulation of hazardous substances in a new material production cycle. However, incineration method requires an advance air pollution control system and value of material are completely lost once materials are incinerated.

Another challenge for recycling companies is to increase recycling rates for materials and quality of recycled materials. As the results for material recycling rates showed, the highest average industrial recycling rates for copper and steel are today around 75%, while for aluminium it is around 65%. This is partly because manual dismantling is still taking place in a large part of the disassembly stage. A possible solution to increase recycling rates for materials and the quality of recycled materials is to either introduce emerging technologies such as automated dismantling in the disassembly stage, or to improve or optimise the current separation and sorting technologies. Due to limited data, it is difficult to identify and quantify which minor components and or materials are currently lost during the recycling process. However, the aforementioned solution can potentially contribute to the improvement of both recovery of minor components and minor metals. Moreover, it can contribute to increase the quality of recycled materials by reducing impurity levels, which leads to fewer treatment steps at the remelting stage during the secondary material production.

Another aspect related to challenges for recycling companies is that there is a trade off relationship between high functionality and recyclability. Due to high functionality on products, products performance is maintained. However, from a recyclability point of view, this can be challenging. One example is that there are several joining methods that can be used to connect different materials. Disassembly process can be complicated depending on which joining method is used. A possible solution to increase recyclability on product level is to use joining methods that facilitate disassembly. Mechanical joining methods are favourable compared to chemical joining methods since it helps to increase recovering valuable materials and reduces contamination risk during recycling process. This is also a reason why product design is important since this design stage determines how much materials can be recovered at the end of life stage.

5.3 Challenges for a circular economy

One major challenge for a circular economy of high voltage products is the lack of communication between key actors at different phases of the life cycles of the products. This is especially true for the design phase and the end-of-life phase. The interviews with the EoL service providers indicated that there is no dialogue between them and the product development departments, which complicates recycling as the products are less likely to be designed with the issues of EoL management in mind. This makes it difficult for recycling facilities to adjust their equipment and processes to fit the products, impedes automation, and generally reduces recycling efficiency. A related issue is that each different phase of the product life cycle may be handled by a new company, and in the end-of-life phase, there are even different companies for every step of the process. For power transformers, decommissioning and disassembly, handling of hazardous materials, waste disposal and energy recovery, and secondary material production are all handled by different actors. This high level of fragmentation complicates communication and may result in unnecessary transportation, and increases the risk of material being lost along the way. The companies may also be competitors providing overlapping services, which disincentivizes communication and sharing of information.

There is also a large number of manufacturers on the market, which results in a wide variety of designs and products. Additionally, certain products such as transformers vary in size and design depending on the application. Increased standardisation could be one way of solving these problems, but due to the varying demands between applications, the manufacturers can never be expected to adhere to one uniform design. The variety in design results in higher costs, reduced recycling rates and recycling efficiency, and makes automation nearly impossible. This leads to higher resource and energy use and complicates strategies aiming to "close loops" and achieving a circular material and resource flow.

Another challenge to evaluating and ultimately achieving circularity is the fact that materials and components are exported to other countries. This could result in a net negative balance for certain materials, for example metals or critical materials, and complicates the analysis and monitoring of material flows.

Because of the long life time of high voltage products, there is a large time gap between the manufacturing phase and the end-of-life phase. While a long product life time could naturally be seen as a positive aspect, as more durable products result in higher resource efficiency, better use of materials, and usually present more opportunities for reuse, repair, and refurbish the products, the time gap can also cause a number of problems. For example, the original manufacturers may no longer be in business, making original drawings and product components unavailable. This complicates both reparation of the products as well as potential reuse of individual components after end-of-life. It also means that changes made at the beginning of the life cycle, for example to the product design and selection of materials, will not come into effect until up to 50 years later when those products are decommissioned. Fully implementing the necessary measures for a circular economy for these products will therefore take a long time, at least if done through changes in the initial life cycle phases.

Another aspect to consider is that due to economic growth, recycled products and recovered materials may be insufficient to meet the future demand of materials. Even with a recycling rate of 100% for all materials, new raw materials will have to be extracted if the demand keeps rising. As the electrical grid is expected to expand in response to the ongoing electrification, the demand for high voltage products will likely rise as well. This effect will be exacerbated by the use of new materials and substances in the manufacturing process. As complex materials and new insulation medias are introduced to the products, significant shares of the material reserves originating from decommissioned products will be obsolete and must be recovered or recycled for other purposes.

5.4 LCA studies and the sustainability goals

Mapping material flows and visualising recycling process using MFA helped to obtain insights into the current EoL management in Sweden. Results from MFA, energy consumption and estimated amount of CO_2 emissions in each recycling process can be used as raw data when modeling the EoL stage as these aspects have been uncertain points in the previous LCA models. Alternatively, results from this project can be compared with the current LCA models.

An important aspect that needs to consider when implementing results from this project into the LCA models is that recycling process requires long distance transport and waste market is global. For instance, silicon sheet that are sorted at the recycling facility in Karlstad are exported to China, India and Pakistan. To do a comprehensive LCA analysis, it is important to take into account this global waste market. This global waste market also makes it difficult to trace materials at the EoL stage and to specify final destinations especially for metals.

Regarding the sustainability goals of Hitachi energy, there is a potential to achieve certain targets such as the target for reductions in $CO_{2\mathrm{eq}}$ emissions, the disposed waste reduction target, and the hazardous substance and chemical reduction target. CO_2 emissions along the value chain can be reduced if the fraction of secondary metals is increased in the products, since secondary metal production significantly reduces the total CO_2 emissions in the material production phase compared to primary metal production. The amount of disposed waste can also be reduced using different circular strategies, implemented at either the life cycle phase or through product design changes, in order to facilitate the recycling of materials at the EoL stage. The fraction of hazardous substances can also be reduced by replacing them with alternative chemical substances, for example biodegradable ester oils for the liquid power transformers, or replacement gases for switchgears.

5.5 Quality of data

The project used environmental reports from recycling companies and relevant authorities. Data quality is therefore difficult to assess since available data is limited, some data from recycling companies are confidential, and other available sources are few. This makes it difficult to compare data quality with other available data.

The results that were obtained are not specific to any single high voltage product, and should be mainly be seen as representative for transformers as a category. When calculating the energy consumption and subsequent emissions at the recycling facilities, annual averages of the material and total energy were used. The energy consumption includes sources such as light and heat for the premises, and while these are important contributions to the total, data for the specific tools and separation processes would allow for differentiation between different product types and models, which would give more detailed results. Furthermore, after the initial recycling steps, the materials are separated, and the material streams from the high voltage products are mixed with those of other products. Because of this, it is not possible to distinguish between materials from different products once they leave the first recycling facility. The materials from the original product are very difficult to track and there is no way to guarantee which secondary production facility the materials from the transformers actually reach.

The scope of this study was limited to Sweden, but the results are mostly applicable to the Nordic countries in general, and to some extent the rest of the EU. The energy mixes of the Nordic countries are comparable in terms of composition and environmental impact, and there is also a high degree of material flow between the countries, meaning that due to exports of material to for example Norway or Finland, the results of the material flow analysis cannot be considered to be completely limited to Sweden. Actors like Stena Recycling are present in other Nordic and European countries, and collect and recycle products from all over Europe. In other regions, however, the recycling processes may differ and recycling rates are expected to be lower.

The fates of the metals were difficult to establish with certainty. While it is reasonable to assume that nearly all metals are sent to smelters for secondary production, while most likely remaining in Sweden, the material flows for the transformers were not fully charted all the way to the secondary production facilities. Furthermore, there is a lack of data regarding the processing rates of scrap metal at the smelters. This means that the steps between the scrap collection and the secondary production of metals is a point of uncertainty that requires further investigation. The data from Stena Recycling indicated that all or nearly all scrap metal was sent to scrap collectors or directly to smelters, but studies of recycling rates of these materials show that these figures are closer to 70-80% (EOL-RR) in reality, and even that is considered high estimates. It is clear that there is an information and knowledge gap in this area, and that metals are lost along the recycling process.

5.6 Future studies

For future studies, the environmental assessment should be expanded to other global regions, such as North America, South America, and East Asia. Both the regulations and the maturity of the market for recycling and EoL services vary globally, and as the EU is only one of many markets, a complete assessment is necessary to identify all potential improvements. Comparing the recycling processes and their environmental impacts in other regions would give perspective to the results and would allow for comparison of how high voltage products are recycled around the world. It is also important to investigate more products, including for example a deeper analysis of switchgear, generator circuit breakers, disconnectors, and power capacitors. These products are important both for Hitachi Energy and for the electric power system in general.

To gain more insight into the material recovery rates, the secondary raw materials market should be explored further. This could show how much recycled materials can be used in the manufacturing of new products, and what the current theoretical limit is for the recycling input rate. Investigation into these areas could also help set targets or regulations for recycling rates. By determining how much recycled material is currently used in new products, potential reductions in energy consumption and emissions can also be calculated.

The recycling rates need further investigation, so that they reflect the material recovery for the product category of high voltage products, and transformers specifically if possible. In this project, industry averages were mostly used for the metal recycling rates, and a complete material flow analysis may be necessary to obtain more specific figures. For example, it would be relevant to further investigate the collection rate of high voltage products by comparing the amount of products that reach their end-of-life, or are expected to do so, to the amount that is decommissioned and collected for recycling. Furthermore, to find the recycling rate for all high voltage products in Sweden, the collection and recycling process could be compared to that of other companies and suppliers. It could naturally also be relevant to expand this comparison to other countries within the EU, to find regional differences that could be improved, given the established global material flows.

Due to time constraints in this project, certain necessary simulation work required to investigate how much changes to product design, material flow over the product supply chain, and end-of-life management practices can mitigate the environmental impacts was not performed. Such simulations should therefore be included in the future studies, in order to fully assess the maximum environmental potential that changes to the EoL management of HV products could bring about.

6

Conclusions

The mapping of waste and material flows is an important step in increasing circularity and provides knowledge that can be used to reduce the environmental impact of high voltage products, and by extension, the electric power grid at large. Recycling is a complex process, however, as global material flows and long distance transports create a complicated network of processes, from which it is difficult to collect information and gain a complete overview.

The materials in the switchgear and transformers have a high potential for recyclability and achieving high recycling rates saves large amounts of energy compared to extraction and primary production. High voltage products in general are composed mainly of metal, for which the recycling methods are straightforward and well established. The insulation mediums used present more of a problem, as they are typically hazardous by nature and must be handled with care. The strict regulations for these substances force EoL service providers to utilize irreversible treatment methods, which in practice usually results in disposal through incineration, even when decontamination or recycling would be viable alternatives.

The disassembly and dismantling process is not an issue in the current recycling process, but manual disassembly dominates, with mechanical separation of materials being the most common method. Due to variety in product size and design, automatisation is difficult to implement. Furthermore, changes in material and manufacturing choices in more recent products could create problems in the future due to the rise of complex materials. Dialogue between the actors and subsequent changes in product design would help facilitate automatisation and dismantling in general, which in turn could lead to higher recycling rates.

One of the difficult parts when mapping and visualising material flows at the EoL stage was that it was nearly impossible to identify material pathway for each material and to specify final destinations for materials, especially metals. This is because the waste market exists on a global scale and a large number of actors are involved in the recycling market and the secondary metal market, which makes it difficult to obtain relevant data for each metal type. Furthermore, confidential data and lack of data at EoL service providers made it difficult to comprehensively map waste flows over the EoL stage. Therefore, mapping the material flow needs further investigation to identify possible pathway where metals are lost and their final destinations. This kind of investigation would give better insights into current and potential maximum recycling rate for metals and materials.

When it comes to CO_2 emissions during the recycling process, handling of hazardous substances causes the most energy consumption and emissions since a large part of hazardous waste is incinerated or treated with energy intensive recycling methods. To reduce energy consumption and emissions during the recycling process, amount of hazardous substances used in HV products need to be reduced and replaced with alternative chemical substances.

Regarding potential environmental risks when handling obsolete power transformers at recycling facilities, PCB contamination caused by hazardous substances is the biggest risk. All recycling facilities that were interviewed have safety measures in place to protect workers and environment nearby the recycling cites from direct contact and leakage of contaminants and pollutants from hazardous waste.

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Appendix 1

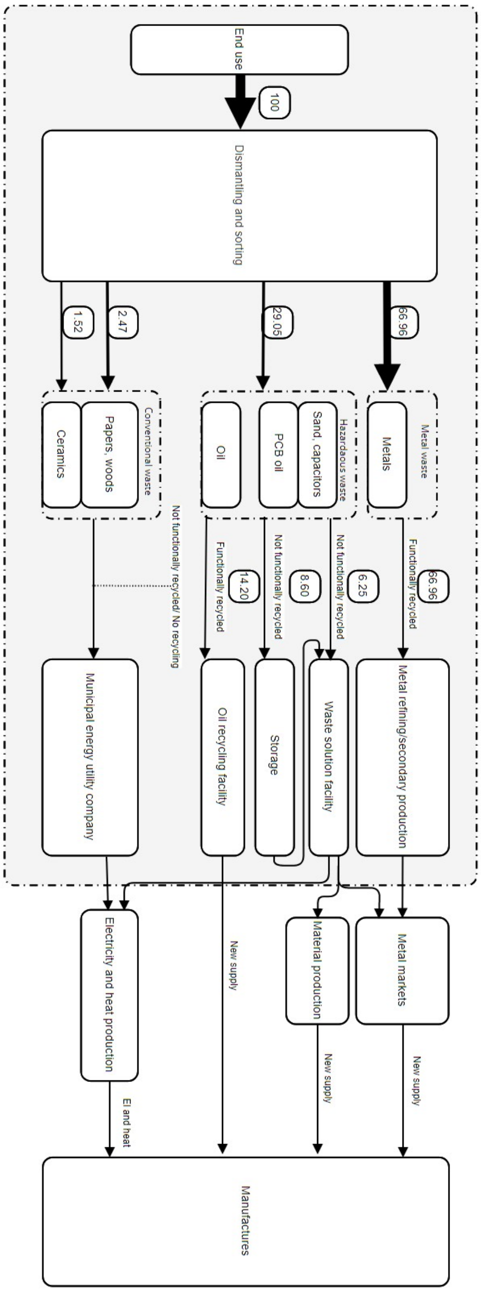

Figure A.1: Material flows and processes in recycling of transformers in Sweden. Numbers in the figure are presented in percentages of the incoming flow that are collected and managed annually at the recycling facility in Karlstad.

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