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Engineering Sustainability: The Development of Design Criteria and Policy for Electric Motor Recycling

Master's thesis in Mechanical Engineering
Supervisor: Anna Olsen
Co-supervisor: Alexey Matveev
June 2023

Master's thesis

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Engineering Design and Materials, Master's Thesis

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Preface

This master's thesis is the result of my research project on recycling and disassembling procedures for Electrical motors, conducted at the Norwegian University of Science and Technology (NTNU), in 2023. This Master's thesis has been carried out by Sverre Andreas Helland, specialising in product development and production. The objective of this thesis is twofold. The first objective is to establish specific design criteria for electric motors with a focus on handling after End of life. The second objective is to establish a recycling policy for Alva Industries.

The research was conducted using a combination of literature review, case study, interviews, a survey, and analytical methods. The details of these are presented in the subsequent chapters.

I would like to take this opportunity to thank my supervisor from Alva Industries, Alexey Matveev. He has shown great interest in the project and his knowledge, insight, and support were greatly appreciated throughout the project process. I would also like to thank my internal supervisor from NTNU, Anna Olsen, for her help with my research and for her valuable guidance, feedback, and support throughout the thesis.

I would also like to express my gratitude to Stena Recycling for taking the time to provide me with insights into their processes and for their support throughout the course of this project. Additionally, I would like to express my appreciation to my colleagues students and friends who provided constructive discussions and encouraging words.

Lastly, I want to thank my family and girlfriend for their support and belief in me.

Sverre Andreas Helland
Trondheim, June 2023

Abstract

This master's thesis underscores the importance of sustainable design in relation to the recycling of electric motors. Given the escalating number of electric motors, this study focuses on the development of recycling-oriented design criteria and the establishment of a recycling policy, with particular emphasis on Alva Industries.

The methods employed include a comprehensive literature review, business surveys, interviews, and a detailed case study at Stena Recycling. The analysis of the information gathered from these sources provides insight into the current recycling process and identifies the challenges and opportunities associated with the sustainable management of end-of-life electric motors. Based on these findings, a policy for recycling and reuse was developed. A literature review of assembly techniques and materials formed the basis for the established design criteria.

The results of this work have resulted in a policy that Alva Industries can use to raise awareness around recycling and initiate measures to establish a robust recycling culture. The established design criteria can contribute to informed design choices for future electric motors, with the goal of optimizing and increasing recyclability. The potential for future research is also identified, such as exploring new materials and assembly methods for implementation in Alva Industries' electric motors.

The policy and case study illustrates recycling possibilities and can assist companies in discovering unknown recycling opportunities. The study theoretically contributes to the understanding of the current recycling process for electric motors and how it can be improved.

However, the study has some limitations. Access to detailed information on design and a specific epoxy resin blend was limited due to intellectual property rights, making comparisons with potential alternatives challenging. Finding relevant cost data, especially related to the production and transportation of recycled and raw materials was also challenging.

Overall, by highlighting the significance of environmentally friendly design and recycling, this study establishes the way for the electric motor manufacturing industry that is more sustainable in the future. The results may encourage additional study and development in this area.

Keywords

Electric motor recycling, Sustainable design, End of life Management, Recycling policy, Case study, Stena Recycling.

Sammendrag

Denne masteroppgaven fremhever betydningen av bærekraftig design i sammenheng med resirkulering av elektriske motorer. Gitt det økende antallet av elektriske motorer, fokuserer denne studien på utviklingen av designkriterier for resirkulering og etableringen av en resirkuleringspolicy, med et spesielt fokus på Alva Industries.

Metodene som ble benyttet inkluderer en omfattende litteraturstudie, bedriftsundersøkelser, intervjuer og en detaljert case-studie hos Stena Recycling. Analysen av informasjonen hentet fra disse kildene gir innsikt i dagens resirkuleringsprosess og identifiserer utfordringene og mulighetene forbundet med bærekraftig håndtering av elektriske motorer ved slutten av deres levetid. På grunnlag av disse funnene ble det utviklet en policy for resirkulering og gjenbruk. En litteraturgjennomgang av sammensetningsteknikker og materialer dannet grunnlaget for de etablerte designkriteriene.

Resultatene fra denne oppgaven har resultert i en policy som Alva Industries kan benytte for å øke oppmerksomheten rundt resirkulering og iverksette tiltak for å etablere en robust resirkuleringskultur. De etablerte designkriteriene kan bidra til informerte designvalg for fremtidige elektriske motorer, med mål om å effektivisere og øke resirkulerbarheten. Potensialet for fremtidig forskning er også identifisert, som for eksempel utforskning av nye materialer og monteringsmetoder for implementering i Alva Industries' elektriske motorer.

Policyen og case-studien illustrerer resirkuleringsmulighetene og kan hjelpe bedrifter med å oppdage ukjente resirkuleringsmuligheter. Studien bidrar teoretisk til forståelsen av den nåværende resirkuleringsprosessen for elektriske motorer og hvordan den kan forbedres.

Studien har imidlertid noen begrensninger. Tilgangen til detaljert informasjon om design og spesifikk epoxy-resin-blanding var begrenset på grunn av immaterielle rettigheter, noe som gjorde sammenligning med potensielle alternativer utfordrende. Det var også utfordrende å finne relevante kostnadsdata, spesielt knyttet til produksjon og transport av resirkulerte og råmaterialer.

Samlet sett baner denne studien vei mot en mer bærekraftig fremtid for produksjonen av elektriske motorer ved å fremheve betydningen av bærekraftig design og resirkulering. Det er et håp om at funnene vil inspirere ytterligere forskning og innovasjon innen dette feltet.

Contents

List of Figures

List of Tables

1 Introduction

The production of electrical permanent magnet (PM) motors has seen significant growth due to the rising demand for energy and the expansion of the electrical industry. These motors are used in a wide range of applications, from small appliances to large industrial systems. However, the disposal of these motors at the end of their life contributes to the challenges of electronic waste (e-waste). The increased production of electrical PM motors has led to a substantial rise in the generation of e-waste. These motors have a limited lifespan and are eventually discarded, resulting in considerable environmental and economic consequences.

The extraction and production of valuable materials, such as rare earth elements and precious metals, often have adverse impacts on the environment, including soil degradation, air and water pollution, and the depletion of non-renewable resources. The lack of standardized design criteria for recycling electrical PM motors exacerbates the e-waste problem and undermines the potential environmental and economic benefits of recycling.

Establishing requirement specifications for the design of electric motors with a focus on recycling electrical PM motors would offer a structured approach to the recycling process and promote sustainable and environmentally friendly practices. Maximizing the recovery of valuable materials would reduce the demand for newly mined resources and support the circular economy. Additionally, the recovery of valuable materials would generate revenue, fostering the growth of the recycling industry and creating job opportunities.

Therefore, the development of such requirement specifications for the design of electric motors with a focus on recycling electrical PM motors is crucial for addressing the growing e-waste problem and promoting sustainable practices. This research would have significant environmental and economic implications, as it would contribute to a more sustainable future by reducing waste, promoting the recovery of valuable materials, and supporting the circular economy.

1.1 Motivation and Background

The motivation for this thesis lies in the increasing demand for sustainable and eco-friendly practices, which necessitates effective methods for recycling electrical PM motors. Currently, the recycling process for these motors is inconsistent and does not incorporate a uniform set of design criteria. This results in inefficiencies and restricts the retrieval of valuable materials. The aim of this thesis is to establish a comprehensive set of design criteria for the recycling of electrical PM motors, taking into account the different materials used in their construction and the importance of safe and efficient recovery.

1.2 Stakeholders Involved

A stakeholder analysis was conducted to identify the key parties involved in the recycling of electric motors. The stakeholders are classified into primary and secondary stakeholders based on their roles and interests:

- **Primary Stakeholders:** These stakeholders are directly involved in the production, use, or recycling of electric motors. Their actions and decisions have a significant impact on the recycling process and its outcomes.
- **Secondary Stakeholders:** These stakeholders are indirectly involved in the electric motor recycling process. They are often affected by the outcomes of the primary stakeholders' actions and decisions, and they can influence the process to some extent.

Table 1: Stakeholder analysis for electric motor recycling

Stakeholder	Example	Primary Secondary
Environmental organizations	Greenpeace, ZERO (Zero Emission Resource Organization), Basel Action Network, Naturvernforbundet	Primary
Government	Politicians working towards achieving the UN's SDGs on climate change.	Primary
Electric motor manufacturers	Alva Industries, KDE Direct, Maxon ABB, General Electric, Tesla Motors.	Primary
Consumers of electric motors	Car manufacturers, electric motor repair companies, electronics manufacturers.	Secondary
Waste management companies	Stena Recycling, Veolia, SUEZ, Norsk Gjennvinning.	Primary
Workers in the recycling industry	Employees at recycling facilities, workers involved in dismantling and recycling electric motors.	Secondary
Research and development institutions	SINTEF (Norwegian independent research organization), MIT Materials Research Laboratory, Chalmers University of Technology, NTNU (Norwegian University of Science and Technology), IFE (Institute for Energy Technology, Norway).	Secondary
Investors and shareholders	Investors in motor manufacturing and recycling companies.	Secondary

1.3 Problem Statement

The escalating amount of electric motors and other electrical equipment used in different applications has generated a growing demand for sustainable and environmentally friendly practices, which describe how the current recycling process works. Currently, many manufacturers of electrical equipment remain unaware of the various options available, which has led to an inefficient and varied approach to how valuable materials are recycled. There is also a significant issue that electric motors are primarily designed with an emphasis on performance and durability rather than recyclability. This has caused the recycling process of electric motors to be less profitable and efficient

1.4 Objectives and Research Question

The thesis aims to establish a set of design criteria specifications intended to make the recycling process of electric motors more sustainable and efficient. In addition, the thesis seeks to develop a recycling and reuse policy specifically tailored for Alva Industries, which could also serve as a benchmark for the broader industry. To achieve these objectives, several sub-objectives have been defined::

- Conduct a case study to gain a comprehensive understanding of the existing recycling processes.
- Identify the various challenges and limitations of the current recycling process.
- Investigate different assembly methods for electric motors.
- Analyze the existing regulations and standards related to recycling of WEEE and their impact on sustainable practices.
- Assess the environmental and economic impacts of electric motor production and recycling to identify opportunities for sustainable development.

The following research question is established:

- What are the necessary steps the industry needs to take in order to prepare for recycling electric motors?

1.5 Approach

This study uses a systematic, iterative, and comprehensive methodology to examine the recycling procedures of electric motors. It aims to develop a set of design principles that simplifies recycling processes and establish a recycling and reuse policy for Alva Industries.

The initial stage of the research involves an exhaustive review of the current literature on the recycling of Electrical and Electronic Equipment (WEEE), and the design of electric motors. The review's goal is to comprehend the present practices, spot challenges, and to uncover potential opportunities associated with the recycling processes of electric motors.

In addition to the literature review, a survey was carried out among companies using a significant number of electric motors. The survey intended to unveil their understanding and practices of recycling end-of-life (EOL) motors, with a focus on dismantling and recycling techniques, current challenges, and their awareness of these aspects.

To gain more in-depth insights, a detailed case study was conducted at Stena Recycling, a leading company in the recycling field. The study sought to understand their recycling processes, the challenges they face, and their viewpoints on potential improvements. An interview was also conducted with one of their partners, Norsirk. These efforts provided a deeper understanding of EOL treatments for electric motors.

Data obtained from the literature review, industry survey, case study, and the interview were then thoroughly analyzed and evaluated. This process involved forming conclusions about the challenges and opportunities associated with the sustainable management of EOL electric motors. Based on these insights, a policy for recycling and reuse was developed, aiming to foster best practices in electric motor recycling, mitigate environmental impact, and enhance resource recovery.

The final stage of the study integrates the findings and implications derived from the implemented methodologies. Key insights are summarized, offering a succinct yet comprehensive overview of the current situation and potential future of electric motor recycling. Furthermore, a recycling policy for Alva, informed by our research findings, is proposed to initiate a more structured recycling process within the company.

The research concludes by recommending future research directions to improve understanding and implementation of sustainable EOL electric motor management.

1.6 Limitations and Assumptions

Three main categories of limitations were encountered during this thesis: those relating to confidential design and material information, those relating to specific cost information and the limitations of the necessary equipment to perform experiments on the epoxy resins.

Access to thorough information was restricted in the area of design and materials because of issues with intellectual property. For instance, Alva Industries withheld information about the specifics of its electric motors to protect its distinctive design elements and proprietary materials. This includes a unique epoxy mixture that they use in their products. As a result, comparing the material quality to potential alternatives was difficult due to these factors.

The analysis was somewhat uncertain in terms of cost data due to the lack of precise figures for the production and transportation of recycled and raw materials. Due to the geographic distribution of recycling facilities within Europe, it was assumed that transportation costs for recycled raw materials might be lower; however, these assumptions inevitably add a layer of complexity and the possibility of error. Therefore, obtaining more precise data in these areas would help future research by enhancing its thoroughness and precision.

It was planned to carry out experiments on the epoxy mixture used by Alva based on the experiments investigated in the project report [1]. After talking to a number of professors at NTNU, it was concluded that this was not possible to achieve with the available equipment.

2 Electric motors

This chapter provides a comprehensive overview of electric motors, covering different types, design principles, components, and materials disassembly processes and presents potential alternative materials for epoxy. These key aspects lay the foundation for discussion about design criteria for electric motors presented in Chapter 9.

2.1 Fundamentals and Varieties of Electric Motors

Electric motors are machinery that transforms electrical energy into mechanical energy that is primarily rotational motion. Their usefulness comes from being able to produce high levels of drive output simply and effectively, as well as from having the capacity to be easily scaled down in size, allowing them to be incorporated into a variety of machinery and equipment [2]. Electric motors have become an incredibly vital part of today's technological advancement and are now found in a wide array of applications in both industrial and daily contexts.

An electric motor is composed of a stationary component called the stator and a rotating component called the rotor. The stator includes copper windings that are energized to generate a magnetic field. On the other hand, the rotor consists of either permanent magnets or electromagnets that interact with the magnetic field produced by the stator. When an electric current is applied to the windings, a magnetic field is created, causing the rotor to rotate [3]. This rotational motion generates mechanical power that can be utilized to perform various types of work.

The functionality of an electric motor can be explained through the principle of electromagnetic induction. When an electric current flows through a conductor, it creates a magnetic field around the conductor. Conversely, when a conductor moves within a magnetic field, it generates an electric current in the conductor. In an electric motor, this principle is used to create a rotating magnetic field that interacts with the magnetic field of the rotor. The resulting force produces the rotation of the rotor, which in turn generates mechanical power. Figure 1 shows an illustration of a basic setup of a DC motor[3].

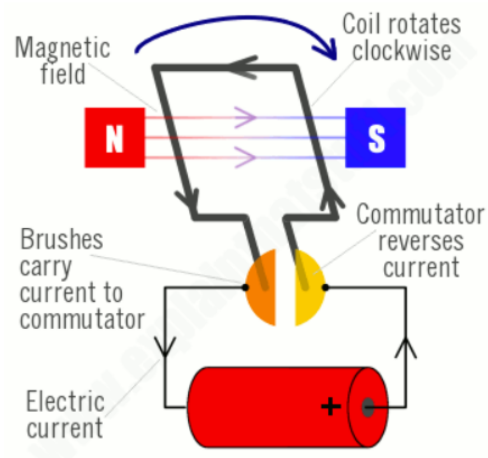

Figure 1: Basic setup of a DC motor [3].

In this thesis, electric motors have been categorized into three main types, as illustrated in Figure 2.

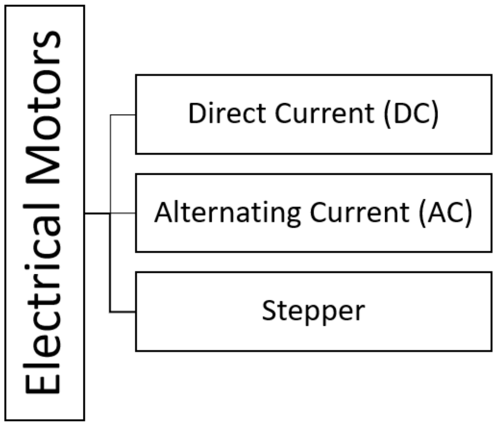

Figure 2: The categories of electric motors.

2.1.1 Direct Current (DC) Motors

DC motors are electric motors that convert electric power into mechanical energy [4]. These motors work based on the principle of Lorentz force, which states that a current-carrying conductor placed in a magnetic field experiences a force perpendicular to both the current and the magnetic field. DC motors have a commutator that switches the current direction in the rotor coil, creating a constant rotational torque.

DC motors, especially Permanent Magnet DC (PMDC) motors, find common use in applications like electric vehicles, industrial machines, and consumer electronics due to their high torque output and overall efficiency [4].

2.1.2 Alternating Current (AC) Motors

An AC motor is an electric motor that consists of a stator with a coil that is supplied with alternating current to convert electric current into mechanical power. These types of motors can be single or three-phase, where three-phase are often used for bulk power conversion and single phase is used for smaller power conversions [5].

AC motors fall into two primary categories: synchronous and induction motors. In synchronous motors, the rotation of the rotor is synchronized with the frequency of the applied current, and a rotating magnetic field is produced by multi-phase AC electromagnets situated on the stator. An induction motor, also known as an asynchronous motor, employs a mechanism where an electric current is only applied to the stator. The magnetic flux from the stator then interacts with the rotor's short-circuited coil, inducing a torque that drives the rotor's rotation.

AC motors are known for their versatility, efficiency, and quiet operation, making them a popular choice for a wide array of applications, such as water heaters, pumps, garden equipment, compressors, and various household appliances. Their design predominantly revolves around a copper-wound stator, over which a rotating magnetic field is created [5].

2.1.3 Stepper Motors

Unlike the continuous rotation seen in many other electric motors, stepper motors can rotate in precise increments. They are a type of brushless synchronous DC motor. They are built in a way that allows a phased array of coils to be quickly turned on and off, allowing the motor to move through fractions of a full rotation at a time. These individual phases are referred to as 'steps' including full-step, half-step, and micro-step [6].

Stepper motors are typically digitally controlled and function as key components in an open-loop motion control positioning system. They are commonly used in holding or positioning applications where their ability to provide clearly defined rotational positions, speeds, and torques make them ideally suited for tasks requiring extremely precise motion control, such as robotics, 3D printers, and CNC machines [6].

2.2 Design of Electric PM Motors

2.2.1 Components and Materials Used in Electric motors

The electric motor X60 - Kv120 from Alva as shown in Figure 3, has been used as a reference point for the recycling process and the possibilities in terms of the material composition and how it is made. The motor is mainly utilized in unmanned aerial vehicles and autonomous underwater vehicles.

Figure 3: The electric motor X60 - kv120 [7].

The electric motor is composed of several components and subassemblies. Table 2 provides an overview of the various parts and the corresponding materials used in the construction of the motor. The primary materials utilized in the electric motor, such as aluminium, steel, stainless steel, copper, plastic, and epoxy, are displayed in the table. These materials are critical for the construction and operation of the motor, and their composition can significantly impact its performance and durability [1].

Table 2: Components and materials for X60-Kv120 [7] [1].

Components	**Material**
Stator housing	Aluminum
Cover stator	Aluminum
Axle stator	Stainless steel
Rotor	Aluminum
Axle	Plastic
Bearing	Steel
Bolt	Steel
Pin to axle	Steel
Magnet	NdFeB
Windings	Copper
Windings protector	Epoxy
Back iron ring	Steel

An electric permanent magnet (PM) motor typically consists of several primary components, including the stator, rotor, impeller, bearings, windings, shaft, housing, and PM [8]. Supplementary to these primary components, there are several auxiliary but critical parts, such as insulation for the windings, top cover, and bolts to secure the housing. An exploded view of Alva's X60-kv120, depicting the different components with their respective names, is shown in Figure 4.

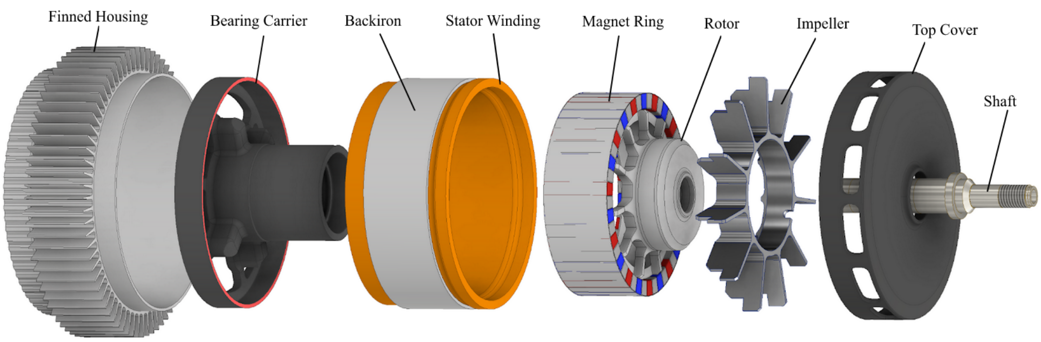

Figure 4: Exploded view of electric PM motor [7].

The **stator** of an electric motor is a stationary component. This component consists of several small components assembled together to form the stator. The stator of an electric PM motor includes the stator core, windings, insulation, end bells and bearings. The primary function of the stator is to create a magnetic field that interacts with the rotating magnetic field of the rotor to generate torque.

The **cores** of electric motors consist of laminated electric steel that is precisely engineered to exhibit desired magnetic properties, such as low Eddy current loss, small hysteresis losses, and high permeability [8]. Insulation varnish is utilized between the lamination layers to prevent electric losses. Electric steel is an iron that is alloyed with silicon to lower the material's conductivity and reduce eddy current losses, while simultaneously narrowing the hysteresis loop, leading to lower hysteresis losses.

Soft Magnetic Composites (SMCs) are an alternative to traditional electric steel lamination. SMC is composed of ferromagnetic powder particles surrounded by an electrically insulating film, providing good relative permeability, magnetic saturation, and high electric resistivity [9]. SMC is suitable for high-speed permanent magnet (PM) machines, for which the magnetic reluctance of the magnet dominates the magnetic circuit, making the performance of such motors less sensitive to the core permeability [9].

Table 3 provides a comparison of laminated electric steel and SMCs for electric motors, based on their composition, magnetic properties, design flexibility, thermal conductivity, and particle size. The table highlights the advantage and disadvantages of each type, making it easier to choose the best option based on specific application requirements.

Table 3: Comparison of laminated electric steel and soft magnetic composites for electric motor [10].

Properties	**Laminated electric Steel**	**SMCs**
Composition	Iron alloy with added silicon	Ferromagnetic powder particles surrounded by an electrically insulating film
Magnetic Properties	Low eddy current loss, small hysteresis losses, high permeability	Good relative permeability, magnetic saturation, and high electric resistivity
Design Flexibility	Limited due to stack lamination process	Greater flexibility in shaping and design
Thermal Conductivity	Higher	Lower
Particle Size	Thickness between 200-1000 µm	Typically smaller, ranging from 5-200 µm

Stator windings are an important component in an electric motor, and are usually made of copper, are wound around the stator core slots and carry the electric current that produces the magnetic field. The copper windings generate the magnetic field that is necessary to drive the motor. When current is supplied to the stator windings, it creates a rotating magnetic field that drives the rotor to rotate and transfer torque to other machine components. Copper is a suitable material for stator windings due to its excellent electric conductivity and low electric resistance, which minimizes heat loss and enhances the efficiency of the motor. Additionally, copper windings are flexible and can be tightly wound around the stator core, which increases the magnetic field and improves motor performance.

For encapsulated electric motors such as Alva's X60-kv120, the windings are encapsulated with epoxy resin (Orange part in Figure 4), and attached around the stator core slots. The stator windings are usually first placed in the stator before the epoxy resin is applied, as illustrated in Figure 8. When the epoxy has hardened, it provides a protective casing around the stator windings and the stator and helps to protect the motor against external influences, as well as to dampen vibrations and noise.

Bearings in electric motors are designed to support the rotor to keep the air gap between the rotor and the stator as well as transfer the loads from the shaft to the motor frame [8]. Selecting the correct bearing design for the specific motor ensures the design efficiency of the motor is maintained with minimal friction and power losses. Bearings in electric motors require minimal friction and should be durable to meet specific requirements for strength and dimensions. The material utilized for bearing production depends on the size and design of the electric motor. In addition to this, the properties of the motor such as speed and environment also affect the choice of material [8].

The **Shaft** is the component of the electric motor that transfers torque from the motor to the attached machine part. The shaft is often mounted on bearings to reduce friction and wear. The shaft used in electric motors is often produced in carbon steel SAE 1045, hot or cold-rolled. This medium carbon is often used due to its favourable properties such as good strength, toughness and wear resistance. Alternative materials that are also commonly used for the shaft in electric motors include SAE 1117, SAE 1137, SAE 1144, hot-rolled SAE 1035, and cold-rolled SAE 1018 [8].

Impeller is a component that is used to move air or fluid through the motor for cooling or other purposes. In addition to cooling, impellers may also be used to create pressure or suction within the motor for various purposes, such as ventilation or fluid circulation.

The materials used to make impellers can vary depending on the specific application and requirements of the motor. Common materials include metals such as aluminium or steel, as well as various plastics or composites that offer specific properties such as corrosion resistance or high-temperature performance.

End bells are crucial components in an electric motor as they play an important role in securing the stator windings and rotor to the motor shaft. Their primary function is to ensure proper alignment and enable smooth and reliable rotation of the motor. In addition to this, end bells provide essential protection against dust, dirt and moisture, while also effectively dampening motor vibration and reducing noise levels [11].

They are typically made of strong and heat-resistant metal, such as steel or aluminium, and usually have a circular shape that fits over the ends of the stator core and rotor.

The rotor is a cylindrical component that rotates inside the stator and is attached to a shaft that provides the torque to other machine parts. The rotor consists of several permanent magnets arranged in a specific configuration to create a magnetic field that interacts with the rotating magnetic field generated by the windings in the stator. In addition to permanent magnets, rotors can also have soft magnetic material poles, such as iron or steel, which are used to reinforce the magnetic field and increase the motor's torque. The rotors in small PM motors are often made of cast aluminium or steel, while larger motors may have rotors made of laminated steel sheets or powdered metal.

Permanent magnets (PMs) are used in electric motors due to their ability to provide a constant and strong magnetic field without the need for external electric power. This results in higher efficiency and power density compared to machines that use only electromagnetic windings [8]. PMs play a crucial role in the design of high-performance electric motors, as they determine the machine's torque density, efficiency, and weight. There are three classes of PMs currently used for electric motors:

- *Alnicos (Al, Ni, Co, Fe)*
- *Ceramics (ferrites)*
  - Barium ferrite $BaO \times 6Fe_2O_3$
  - Strontium ferrite $SrO \times 6Fe_2O_3$
- *Rare-earth materials*
  - SmCo (Samarium-Cobalt)
  - NdFeB (Neodymium-Iron-Boron)

Alva Industries are currently using NdFeB. This rare-earth PM has excellent magnetic properties, such as high energy products and coercivity, which is a measure of the magnet's resistance to becoming demagnetized. A magnet with a high coercivity can resist demagnetization and maintain its magnetization in the presence of external magnetic fields. These characteristics enable the development of small and light designs [7].

2.3 Construction and Assembly Techniques of Electric Motors

The selection of assembly technique is an important decision to optimize the mechanical performance of different aspects, such as stability, vibration, reliability and thermal conductivity. The selection should also consider the ease of motor disassembly in terms of recycling, repair, and reuse.

This section aims to explore the assembly techniques employed in electric motors, with a specific focus on epoxy-encapsulated bonding, as implemented by Alva. The advantages and disadvantages of these methods, provide a comprehensive evaluation of their applicability in motor construction. Furthermore, the disassembly process of Alva's motors will be presented and investigated considering its implication for recycling, repair and reuse. This can give a deeper understanding of the assembly and disassembly aspects of electric PM motors and result in highlighting the potential challenges and opportunities they present.

2.3.1 Assembly Techniques

There are several types of fasteners that can be used to assemble components. Permanent and non-permanent fixings are the two main categories of engineered fasteners [12]. Permanent fasteners, such as adhesives, welding, thermal shrink fit, locking nuts, and others are used to join things together permanently. A non-permanent fix allows for the disassembly of the system without damaging the parts. Metal makes up the majority of non-permanent fasteners; nuts and bolts are popular choices. In this study, an examination of various fastening methods appropriate for electric motors will be conducted. Specifically, the methods investigated include adhesive bonding, threaded fasteners, Press fit, and snap fit. The consideration of these methods was based on their potential for ease of recycling and current widespread use in industry. Adhesive bonding, for example, is a widely adopted technique currently in use, hence its inclusion. Meanwhile, threaded fasteners, press fit, and snap fit were chosen due to their inherent recyclability attributes, which align with the growing emphasis on sustainability in engineering practices.

Adhesive Bonding

Starting with adhesive bonding, this technique is widely used in the aerospace industry and involves the joining of components using adhesives, substances that hold materials together by surface attachment and form a durable bond when cured or hardened [13]. There are different types of adhesives used in bonding, including epoxy, polyurethane, acrylic, cyanoacrylate, and silicone, among others [14]. The choice of adhesive depends on the materials being bonded, the required bonding strength, and application requirements. A specific method for applying adhesives, encapsulation, is employed by Alva Industries, as elaborated in section 2.4.1.

There are several application methods for adhesives. This is a simplified procedure for the adhesive bonding process:

1. **Clean and Prepare Surfaces:** Thoroughly clean and prepare the surfaces to be bonded to ensure optimal adhesion. Remove any contaminants such as oil, grease, or loose particles. Consider surface treatments like sanding, degreasing, or chemical priming to enhance adhesion.

2. **Apply the Adhesive:** Apply the adhesive to one or both surfaces being joined. The application method may vary based on the adhesive type and bonding requirements. Common techniques include manual application using brushes or rollers, spray application, or automated dispensing systems. Ensure even and adequate coverage on the bonding surfaces.

3. **Press or Clamp Components:** Bring the adhesive-coated surfaces together and firmly press or clamp them. Apply sufficient pressure to create intimate contact between the adhesive and the surfaces. This helps ensure proper wetting and eliminates air bubbles or voids that may compromise the bond strength.

4. **Allow Curing or Hardening:** Follow the manufacturer's instructions for curing or hardening the adhesive. This can involve natural air drying, exposure to heat or UV light, or the addition of a curing agent. During the curing process, the adhesive undergoes a chemical reaction that forms a strong and durable bond between the joined components.

This assembly technique has several advantages when used in electric motors. Firstly, it allows for a uniform distribution of loads across the entire bonded area. This contributes to increasing the strength and stiffness of the structure. This is important in electric motors, where it is necessary to maintain structural integrity and minimize deformations during operation. Secondly, by employing adhesive bonding instead of traditional mechanical fastening methods, weight reduction and improved efficiency can be achieved.

There are also some disadvantages to the use of adhesive bonding. One of the challenges is achieving reliable and long-lasting adhesion between different materials with varying thermal expansion coefficients. Temperature variations in the motor can result in thermal stresses and potential weaknesses in the adhesive, which can affect the performance and reliability of the bond over time.

Additionally, the adhesive bonding process can be more time-consuming and costly compared to mechanical fastening methods, especially if specialized tools or additional steps such as surface treatment are required. Another challenge arises from the limited feasibility of directly reusing and repairing components bonded using this fastening method due to the inherent difficulty of disassembling adhesives.

Threaded Fasteners

Transitioning to threaded fasteners, this category includes fasteners with a helix-formed tread that wraps around the axes, allowing for the reliable and adjustable fastening of materials. Examples of these fasteners include screws, bolts, and nuts. Each of these fasteners has a unique combination of thread profile, pitch, and lead, depending on their intended use [15].

Threaded fasteners have several advantages in the context of electric motor assembly:

- **Assembly Flexibility:** Their design allows for both tightening and loosening of connections, which provides flexibility during assembly and disassembly processes.
- **High Load Bearing:** The mechanism of engaging the threads forms a secure connection that can bear substantial loads, crucial for the assembly of electric motors that often operate under high mechanical stress.
- **Variety of Designs:** They come in various sizes and configurations, which means they can accommodate a wide range of assembly requirements. Furthermore, their installation and removal are usually straightforward, facilitating maintenance and repair tasks.
- **Reliability Strategies:** Several strategies can be employed to ensure the reliability of threaded fasteners in electric motors:
  - Proper torque control during installation can help achieve the correct preload and reduce the risk of loosening.
  - The use of locking mechanisms or adhesives can enhance fastener security.
  - Understanding the material properties of the fastener and choosing materials that can withstand the operating conditions of the motor can mitigate issues such as thermal expansion and electrolytic corrosion.

However, threaded fasteners also present several challenges in electric motor assembly:

- **Precise Alignment:** Precise alignment is required to avoid cross-threading, which can damage the fastener and the component it's being attached to.
- **Vibration:** Threaded fasteners may also loosen under vibrations if not properly secured.
- **Thread Wear:** Repeated assembly and disassembly can lead to thread wear, reducing their holding power.
- **Corrosion:** They may be prone to rusting or corrosion, particularly in harsh environmental conditions.

Overall, despite the fact that threaded fasteners offer a flexible and customizable method of joining components, their use necessitates careful attention to details like alignment, the possibility of wear and tear, and the particular environmental circumstances of the application [15].

Press Fit

Press fit or interference fit is a fastening method used for assembling two components that relies on normal force, cold welding and friction. The method works by tightly inserting a shaft (Male) into a slightly smaller hole (Female) in another part, which creates interference and holds the parts in place as illustrated in Figure 5. Press fit technology is often employed in electronic and electro-mechanical component manufacturing processes [16].

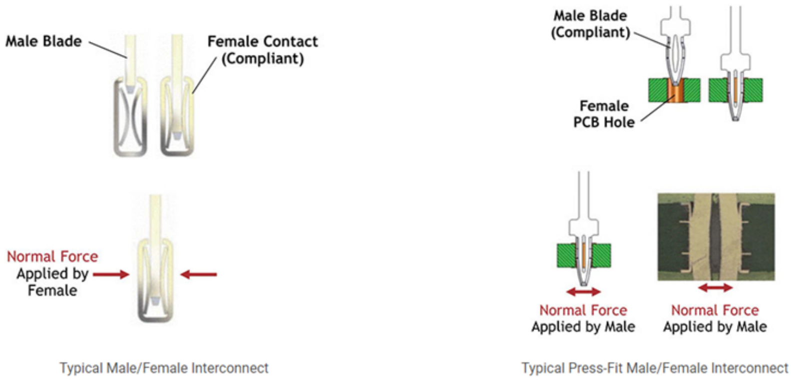

Figure 5: Schematic of Male Blade and Female Contact in Various Press Fit Configurations [16]

The advantages of using press fit:

- **Simple and cost-efficient installation:** Press fit method does not require additional fastening mechanisms or materials.
- **High mechanical strength:** Properly dimensioned press fit connections can achieve high mechanical strength and security, which can be crucial in high-load applications.
- **Electrical and thermal conductivity:** Press fit connections enable direct contact between components, providing good electrical and thermal conductivity in electrical and electronic applications.
- **Possibility of disassembly and repair:** By using appropriate press fit tolerances, components can be disassembled and repaired if necessary.

The disadvantages of using press fit:

- **Precise tolerance control is necessary:** To achieve a reliable press fit connection, accurate tolerance control is important for both the components and the mating holes.
- **Challenging production processes:** Manufacturing precise mating holes can be a challenging task, especially for small or complex components.
- **Risk of deformation and damage:** Improperly applied force or inaccurate tolerances can result in deformation or damage to the components.
- **Limited adjustability:** Press fit connections allow for limited adjustability after installation, and any adjustments can be time-consuming and demanding.

Snap Fit

Snap fit is a mechanical assembly method that involves joining at least one flexible component with another. This process employs particular design features, such as protrusions and undercuts, which allow the flexible component to deform elastically. When aligned, these flexible features are temporarily deformed, allowing them to bypass each other. Once in position, the elastic recovery of these features produces a locking effect. This action results in the component snapping securely into place, creating a solid assembly as illustrated in Figure 6 [17]. The design of the snap fit eliminates the need for additional fasteners, as the components are held together by their very shape, ensuring a secure and reliable connection.

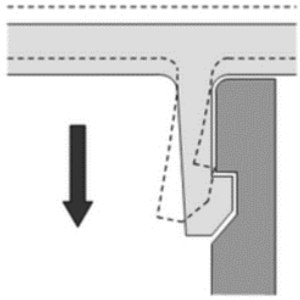

Figure 6: Schematic of the interconnection of two components with the use of snap fit [17]

Advantages of Snap-fit Joints [17]:

- **Easy assembly/disassembly:** Snap-fit connections facilitate quick and efficient assembly and disassembly processes, allowing for easy maintenance or repairs.
- **Cost-effectiveness:** Snap-fit joints often eliminate the need for additional fasteners, reducing material and assembly costs.
- **Design flexibility:** Snap-fit designs offer versatility in component integration and can accommodate various geometries and sizes.
- **Rapid assembly/disassembly:** Snap-fit connections facilitate easy and efficient assembly and disassembly processes, allowing for quick maintenance or repairs.
- **Damping and vibration absorption:** Snap-fit joints can provide damping properties, reducing vibration and enhancing the overall stability of the assembly.

Disadvantages of Snap-fit Joints [17]:

- **Complex production process:** The design and manufacturing of snap-fit joints can be more intricate and challenging compared to other assembly methods, requiring careful attention to ensure proper fit and functionality.
- **Easy to break:**Snap-fit joints may be more susceptible to damage or breakage if subjected to excessive force or stress.
- **Weaker than permanent joints:** Snap-fit joints may have lower load-bearing capacities compared to permanent joints, making them more suitable for lighter-duty applications.
- **Material selection:** The choice of materials for snap-fit components is critical to ensure sufficient flexibility, strength, and durability.
- **Tolerance control:** Precise tolerances are necessary to achieve proper fit and assembly, which may require careful attention during the manufacturing process.
- **Aging and wear:**Over time, the flexibility of snap-fit components may diminish due to aging or repetitive assembly/disassembly, potentially affecting their long-term performance.

2.4 Construction and Disassembly of Alva Industries Electric Motors

The assembly technique is an important process in the construction of electric motors. The process involves the fitting and fastening of various components to create a functional motor. Alva's electric motors are known as "epoxy-encapsulated motors" or "epoxy-encased motors". This means that epoxy is used to hold different parts together. Figure 7 shows an exploded view of Alva's electric motor with Rotor [1], Windings [2], and Backiron [3] numbered.

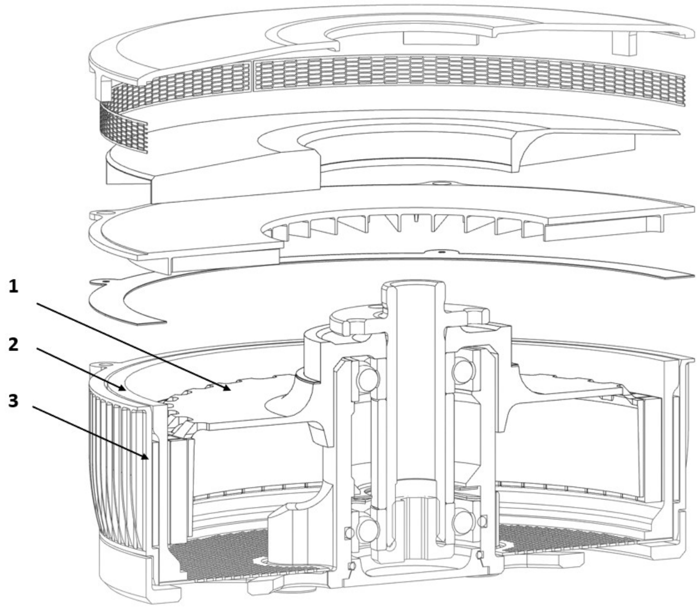

Figure 7: Exploded view of Alva's electric motor with Rotor(1), Windings(2), and Stator(3) numbered.

2.4.1 Epoxy-Encapsulated Motors

The rotor (1) and stator (3) are placed inside a mould and then liquid epoxy resin is poured into the mould to create epoxy-encapsulated motors as illustrated in Figure 8. Encapsulation with high Glass Transition Temperature (Tg) epoxy systems provides sufficient crack resistance and good mechanical strength at the operating temperature [18]. For Alva's electric motor, the epoxy blends it also used to encapsulate the windings (2). Epoxy is also used to laminate several layers of steel that are placed on the outside of the stator in the component called back-iron, which is attached to the stator. This method protects the components from external elements including moisture, dust and vibrations once the epoxy has dried and hardened to form a firm and long-lasting encapsulation [19]. It can also be an effective barrier against electromagnetic interference (EMI). The epoxy also provides stiffness and strength to the motor structure, which can improve its mechanical stability, an important factor in avoiding vibrations and noise in the motor [20]. Epoxy-encapsulated motors are often used in environments with high-reliability requirements, such as aerospace and underwater applications, due to the high degree of protection and robustness they offer. This type of motor is also advantageous when the motor needs to be very compact. An overview of the advantages can be seen in Table 4

Figure 8: Encapsulation process: Liquid epoxy being applied to copper wires, providing insulation and protection [21]

While epoxy encapsulation has numerous advantages, it also presents a huge disadvantage related to recycling. The use of high Tg epoxy to attach different components makes it extremely difficult to separate them without causing damage or affecting their properties. Due to this challenge, repairing or reusing particular components within an epoxy-encapsulated system turns into a time-consuming and expensive process.It is a difficult task because it requires careful extraction of the components without causing damage, which increases its complexity. Due to these challenges, repairing or reusing particular components within an epoxy-encapsulated system turns into a time-consuming and expensive process.[22]. The epoxy encapsulation also restricts the motor's ability to get repairs. The only alternative, which can be expensive and time-consuming, is to replace the complete motor. Epoxy has the additional drawback of not being environmentally friendly. Epoxy includes materials that, if improperly disposed, could harm the environment [23].

Table 4: Advantages and Disadvantages of Epoxy Encapsulation in Electric Motors

Advantages	**Disadvantages**
Higher heat dissipation [19]	Difficult disassembly[22]
Increased longevity [20]	Limited repair options [22]
Decreased noise and vibrations [23]	Leakage of harmful materials [24]
Protection of internal components	Not environmentally friendly
Improved mechanical stability	contribute to the degradation of other materials

2.4.2 Disassemble of Electric Motors

The encapsulation with epoxy makes it challenging to disassemble the electric motors without resorting to mechanical processes for certain components. Some parts can be manually disassembled efficiently and safely by hand, such as end caps, bearings, and shafts [25]. These components are frequently held in place by screws that can be removed with a screwdriver. The end caps, which are normally constructed of metal or plastic, keep the bearings in position. The rotor may spin smoothly on the shaft thanks to the bearings.

However, it is important to recognize that the disassembly time and which parts can be disassembled for electric motors can vary depending on different factors such as the design, size, and complexity of the motor. Additionally, certain parts of electric motors, such as those embedded in unrecyclable epoxy, may be difficult to disassemble, potentially affecting the direct reuse of different components and also repairs of electric motors.

Electric motor parts that are epoxy-bonded together, such as the stator, rotor, and core, can't be taken apart without causing damage [19]. Due to the use of epoxy, it is challenging to recycle or repair these parts without causing damage. When it comes to disassembly, various motor constructions may pose specific difficulties. For instance, it might be challenging to remove individual components from epoxy-encapsulated motors because the entire motor is frequently encased in a solid block of epoxy [22]. In contrast, modular motors have sections that are made to be easily put together and taken apart, enabling quick repairs and part replacement [26].

Table 5 presents an overview of the manually disassembled parts and the corresponding disassembly time for general epoxy-encapsulated electric motors. Table 6 provides a specific example with the Alva X60-kv120 motor. The disassembly time values given in Table 5 are an average estimate taken from various types of encapsulated electric motors and should be considered as indicative.

Table 5: Manually disassembled parts of an electric motor and estimated time for disassembly.

Part	**Description**	**Time (min)**
Stator housing	Outer casing of the stator	10
Cover stator	Protective cover for the stator	5
Rotor	Rotating part of the motor	15
Axle	Central shaft of the motor	5

Table 6: Manually disassembled parts of X60-kv120 and estimated time for disassembly.

Part	**Time (min)**
Motor housing	5
Impeller	2-3
Separate rotor from stator	1
Separat bearings from the rotor	1

Components that are typically bonded with epoxy and cannot be disassembled without causing damage:

1. The stator (including stator windings)
2. The rotor (including rotor windings and magnetic poles)
3. Bearings encapsulated in epoxy
4. Wire terminals and connections within the epoxy

Information on the parts and disassembly time of electric motors, such as the data presented in Table 6, can be useful in planning and optimizing the disassembly process to maximize the recovery of high-quality materials. However, some of the enchanted epoxy components, such as the winding and the rotor as seen in 9, are difficult to direct reuse or repair.

2.5 Alternative substitutes for Epoxy

Epoxy resins are very important in electric motors to perform several functions such as insulation among different components, thermal stability, adhesion, encapsulation and mechanical strength. Epoxy is used for this purpose because of the high transition temperature, better electrical resistance, chemical resistance and lubricants, and ease of processing The importance of epoxy resins in electric motors adhesives with lower temperatures might be a solution. These could be thermoplastic resins [27]. However, several challenges when recycling components of precious electric motors such as titanium, copper and stainless steel raise the necessity to go for substitutes [28]. This chapter aims to provide a thorough and deep understanding of the alternatives that may be possible to use instead of epoxy with all the advantages and drawbacks it will possess in comparison.

Figure 9: Windings and stator from Alva's X60-Kv120 [7].

The selection of materials for insulation, thermal stability, adhesion, encapsulation and mechanical strength is crucial when it comes to electric motors. Although epoxy resins have historically been preferred, alternative materials provide special benefits in service with the necessary properties as well as the simplicity of disassembling and recycling. The essential properties of epoxy required in service are the three-dimensional cross-linked structure for high structural integrity, high glass-transition temperature providing mechanical strength even at moderately higher temperatures, adhesion strength with other components, low water absorption and good chemical resistance [29]. An in-depth exploration of various alternatives will be undertaken, specifically focusing on the ease of recycling electric motors. The analysis will evaluate the advantage and disadvantages factors associated with these alternatives, providing detailed insights into their recyclability.

2.5.1 Polymers

Polymers are ideal for applications where the free flow of material is required to encapsulate the individual components with bearing moderately high temperatures (180-300 °C) in service because of their good mechanical qualities and great thermal stability and fluidity [30].

Table 7: Tg for several polymers for high-temperature service

Polymer	Glass-Transition-Temperature (Tg)	Reference
Polyetherimide (PEI)	218°C	[31]
Polyimide (PI)	200-400°C	[32]
Liquid-Crystal-Polymers	230-400°C	[31]
Polybenzimidazole (PBI)	400-430°C	[33]
Polyaryletherimide (PAEI)	230-245°C	[34]
Polyurethane (PU)	>200°C	[35]

T_g values provided in Table 7 have approximate ranges and can vary depending on the specific formulation and testing condition.

Polyyrethane

The substitution of epoxy with polyurethane (PU) resins represents a potential alternative for the utilization of electric motors. PU have strong mechanical strength, thermal stability, and electrical insulating qualities. They are appropriate for encapsulating and potting applications because of their good adherence to a variety of surfaces. PU resins are certainly be identified as thermoset elastomers or thermoplastic [36], which makes them very good materials for disassembling and recycling electric motors. The polyurethane (PU) material's specific formulation and composition can affect the T_g. The T_g of polyurethane normally ranges from -10 to 250 °C or greater, which is a wide range [37]. However, all the physical and mechanical properties resonate with the requirements only if the structure of PU is designed and modified to obtain thermoplastic properties.

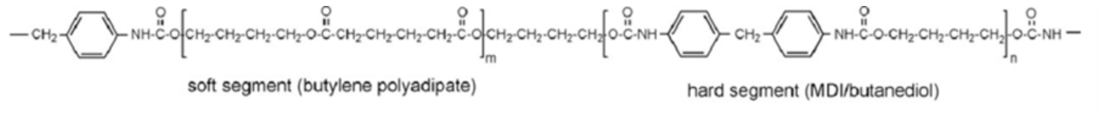

Figure 10: Thermoplastic-PU elastomer structure [38].

Figure 10 shows the blend of hard PU segments providing high strength, hardness and mechanical rigidity to the structure, whereas soft segments provide toughness and ease of recyclability to the structure [39]. Studies are being done to develop more efficient and sustainable recycling structures for PU to minimize waste and promote a circular economy approach while keeping the mechanical properties intact.

Silicone-Based Resins

Silicone-based materials, such as silicone resins or elastomers, are renowned for their superior electrical insulating capabilities and good tolerance to high temperatures in electric motors. They can resist very high temperatures without degrading their mechanical or electrical capabilities. Additionally, flexible silicone materials can be employed for conformal coating, encapsulating applications and free flow to even intricate areas where epoxies cannot flow [40]. Wang et al. synthesized triglycidyloxy-phenyl-silane (TGPS) mixed with EPON-828 and DER-732 to form a silicone-based epoxy. Among all, TGPS has the highest Tg of 430°C. However, adding other components reduces the Tg, enhancing the elasticity, which might provide ease of disassembling during electric motor recycling [41].

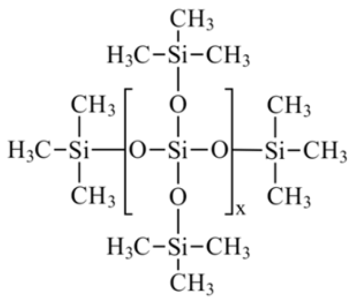

Figure 11: Silicone-resin monomer structure[42].

Lv et al. reported that the recycling of silicone-based resins is as difficult as epoxy resins, however, the scrap after disassembling is usable for sustainable projects such as steel slag removal [43]. Rupasinghe discussed the limitations of silicone-based resin recycling by providing suitable solutions for depolymerization and scission of silicone bonds by radical extraction, catalytic bond breaking, hydrolysis and thermal depolymerization [44]. Therefore, even the recycling is challenging but studies have been done to provide efficient solutions by providing the waste material for beneficial usage.

Polyester

Polyester resins are often employed in electric motor applications, especially in smaller motors. They have strong mechanical qualities, thermal stability, and electrical insulation. Karnoub et al. suggested a further increase in the mechanical strength of polyester resins, with frequent use in conjunction with mica or fibre-glass reinforcements [45]. Thermal studies (TGA and DSC) of the polyester resin by Calabrese et al. prove tremendous thermal resistance and stability at higher temperatures up to 320 °C. The impedance spectroscopy and electrical resistance results prove the excellent electrical resistance by 10-10 Sm-1 [46]. Goetter and Winkeler show the limited amount of monomers in unsaturated polyester resins makes it less volatile organic content [47].

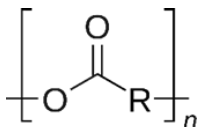

Figure 12: Polyester structure[45].

In contrast to epoxy resins, which have a cross-linked structure, polyester resins have a linear structure, making them more suitable for recycling. Polyester resins may be melted and treated once again more readily since cross-linking is not present. Yoon et al. proposed the depolymerization of unsaturated polyester using propylene glycol and further the recycled monomers were able to polymerize again by adding maleic anhydride. The curing of recycled resin was also observed to be quicker than that of fresh resin [48]. Nakagawa and Goto were able to recover a high yield of styrene-fumaric-acid-copolymer (SMC) by hydrolyzing the thermoset network of polyester resins with an accelerated reaction provided by potassium hydroxide [49]. Wang et al. obtained SMC by the comprehensive and selective bond breaking of polyester resins by submerging the sample in glycol with potassium carbonate as a catalyst for degradation at 185°C for approximately 5 hours [50]. The specific recyclability and techniques for recycling might still differ based on the composition, additives, and particular kind of polyester resin used, even though polyester resins usually have superior recyclability than epoxy resins. Thus the polyester resin providing the ease of disassembling also offers very good thermal and mechanical properties to use as an alternative to epoxy resins in electric motors.

Polyimide

Polyimide is a high-performance polymer with remarkable thermal stability and superior electrical insulating qualities. It is resistant to high temperatures without suffering much damage. Polyimide films or coatings are utilized in the electronic industry as a protective layer in motors running at high temperatures or as insulation between components [51]. Miwa et al. discussed that epoxy resin is a versatile material, but if it is needed to replace polyimide in an application, several concerns will be under concentration such as processing of making polyimide, reactants used along with (hardener, curing agent and solvent) and curing conditions [52]. Despite these resemblances, it's crucial to remember that polyimide and epoxy resin have different chemical compositions, manufacturing processes, and performance traits. Therefore, while choosing amongst them, thorough thought and examination of the application's particular needs are required, which may be useful in electric motors.

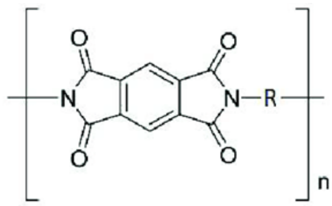

Figure 13: Polyimide structure][53].

Olifirov et al. discussed polyimide recycling by following the solid-state approach of mechanochemistry. A planetary ball mill at low energy was used for mixing composition by following it at high energy for the treatment of polyimide waste [54]. Due to their highly crosslinked and thermally stable structure, polyimides are renowned for their difficult recycling but are less difficult as compared to epoxy resins [55]. However, several methods have been investigated for recycling polyimide materials. Even though none of these techniques has been extensively used in the industry yet, the current research attempts to enhance polyimide recycling.

Hybrid Epoxy Resins

Hybrid epoxy resins refer to epoxy resins that have been combined with other materials, including reversible thermosetting resins. Among the various types of hybrid epoxy resins investigated, a noteworthy example is bio-based epoxy resin.

Bio-Based Epoxy Resin

The use of VAN-AC-EP/DDM, a bio-based epoxy, is a potential alternative. In comparison to its petroleum-based counterpart, DGEBA/DDM, this epoxy system exhibits a variety of advantageous characteristics, according to recent research in the fields of bio-based polymers and sustainable materials science. [56]. These include enhanced energy efficiency, better thermal and mechanical qualities, the potential for recycling, and eco-friendly waste disposal. This substance has a lower environmental impact than epoxy made from petroleum products because it is bio-based.

When comparing specific attributes of the VAN-AC-EP/DDM epoxy system to conventional epoxy, the benefits of that material become more obvious. For instance, compared to DGEBA/DDM, it has been discovered that the curing process of VAN-AC-EP/DDM requires lower onset temperatures and releases less enthalpy, which suggests increased energy efficiency and environmental sustainability. It is a more practical option in terms of energy consumption during the curing process due to the lower temperatures, which range from 94.19°C to 116.54°C depending on the heating rate.

Additionally, VAN-AC-EP/DDM's thermal performance is superior, with a higher glass transition temperature (Tg) of 146°C compared to DGEBA's 202°C. VAN-AC-EP/DDM has a lower initial degradation temperature, but the high residual carbon rate at 800°C (R800) of 25.8% suggests a potential use as a flame retardant.

Applications for VAN-AC-EP/DDM can also be deduced from how the compound behaves in various solvents. For example, compared to DGEBA/DDM, it showed lower swelling ratios and higher gel contents in most solvents, indicating improved chemical resistance. Additionally, it had a relatively high contact angle in water (66.1°), indicating some hydrophobicity, which might be advantageous in applications requiring moisture resistance.

In conclusion, the VAN-AC-EP/DDM system emerges as a viable and sustainable alternative to traditional petroleum-based epoxy.

3 Recycling techniques for electric motors

3.1 Overview of the Life Cycle

The life cycle of electric motors can be presented in several ways. The most common process is presented in Figure 14 [57]. This represents the process of electric motors from natural resources used in production to recycled motors [1].

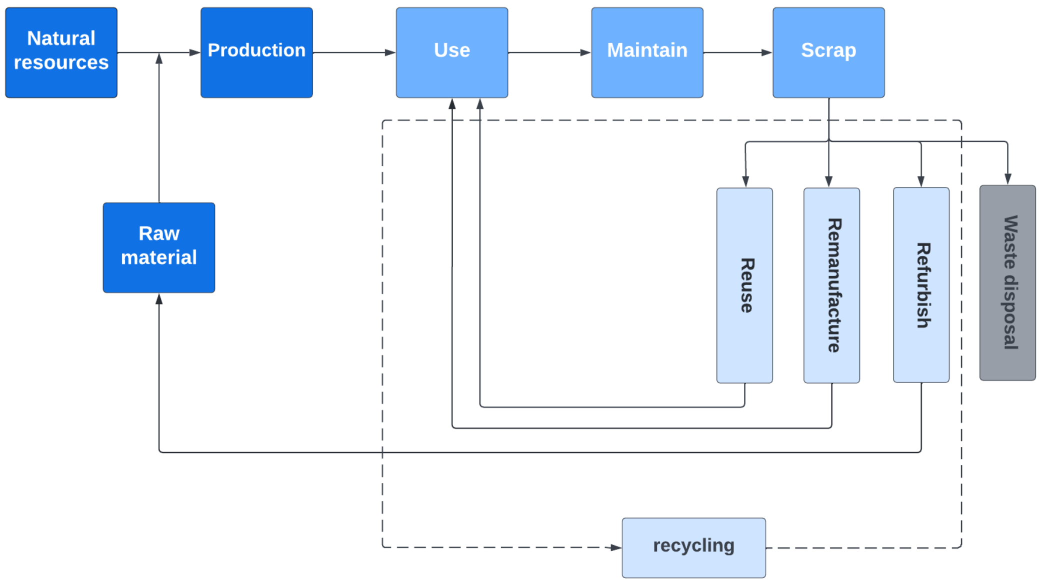

Figure 14: Life Cycle of electric motors [57] [1].

Hasanuzzaman, Rahim, Saidur *et al.* [58] proposed four strategies for minimizing scrap:

- Reuse
- Refurbishment
- Remanufacturing
- Recycling

The technique used is determined by the condition of the motor, and frequently a combination of these techniques is used. For instance, certain materials that cannot be recycled might be thrown away, whereas broken down parts are turned into raw materials. The remainder of the components are then inspected to determine if they can be directly reused or used in the remanufacturing of new motors. A thorough investigation should be carried out to determine the malfunction's cause in order to determine the best strategy for each motor.

The recycling diagram denoted by the "dashed square" in Figure 14 provides an overview of the process. Alva wants to develop a more thorough strategy for the EOL motors depicted in Figure 15 [1].

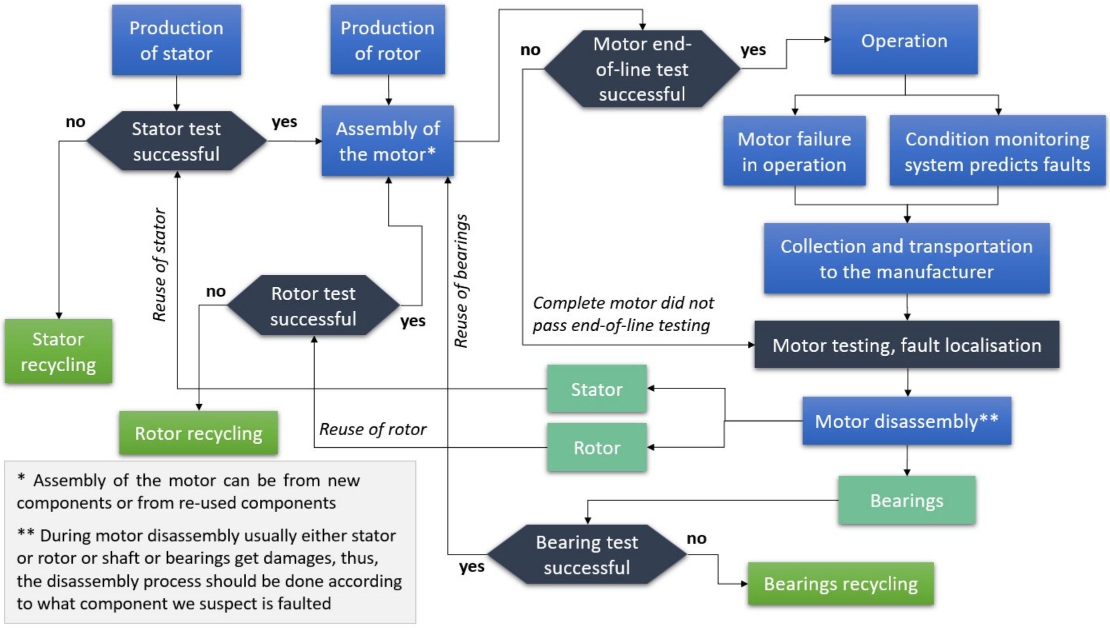

Figure 15: Recycling process for Alva's electric motors [1].

The purpose of the testing process for EOL motors is to determine their potential for reuse in operational settings. If a motor passes the EOL test, it can be incorporated into new products. However, if it fails the test, it must undergo further analysis to determine the root cause of the issue. The motor's constituent parts, such as the stator, rotor, and bearings, are disassembled and tested individually to assess their functionality. If these parts are found to be functioning optimally, they can be reused in the assembly of new motors, thus extending their lifespan. In contrast, faulty parts are collected and accumulated before being sent for recycling to minimize waste and promote sustainability [1].

3.1.1 Reuse of Electric Motor Components

From the preliminary research, the reuse of electric motors was investigated to be one of the most beneficial ways to recycle. There are several reasons for this. Firstly, it reduces the demand for raw materials, such as copper and steel, which are finite resources. Secondly, it reduces the amount of pollution and waste produced when hazardous materials, such as lubricants and coolants, are not disposed of. This reduces the risk of environmental harm to wildlife and ecosystems. Thirdly, reusing components can be a cost-effective and efficient method of recycling materials and can enhance the profitability of businesses that implement this practice. To ensure profitability, careful and safe disassembly of components is necessary to prevent damage to the functioning parts. Moreover, the reuse of components can enhance the sustainability of operations and bolster the reputation and public image of the company [1]. However, there are challenges associated with reusing components from electric motors, including difficulty in determining whether a motor can be safely reused and the time-consuming and costly process of testing and repairing motors. Disassembling the components from each other can also be a time-consuming process, and there is no specific solution for how this should be done yet for all types of electric motors.

Alva can serve as an example to illustrate how various components can be reused following the process outlined in Section 3.1. As noted by Bonnett and Young [59], approximately 50% of motor failures at EOL is due to faulty bearings, which suggests that other components, such as the stator and rotor, can be repurposed.

Alva currently (December 2022) experiences a scrap rate of 15% during production due to two specific reasons, which are delamination of the winding from the back iron during bonding and thermistor problems [1]. These issues affect the stator assembly, and therefore it is worth noting that all other components from scrapped motors during production that do not include the stator assembly can be directly reused.

3.1.2 Remanufacturing & Refurbishing

These are two strategies for extending the life of products. Remanufacturing involves restoring components to a like-new condition and providing the same warranty and quality as newly made components. In contrast, refurbishing restores items to a usable condition but with a shorter warranty than a new product. Both processes follow the same steps as reuse but also include component repair. The steps of these processes are presented in Figure 16. The major benefit of remanufacturing and refurbishing electric motors is that they help prolong the motor's lifespan and decrease the need for disposal. Reusing parts can also decrease many energy-consuming steps in the production process of new components.

Figure 16: The overall steps in remanufacturing and refurbishing [1].

Nonetheless, remanufacturing and refurbishing electric motors have their challenges. The cost of the process, which can be higher than simply replacing the motor with a new one, is one challenge. Another challenge is the availability of specialized equipment and expertise required for the process. Thorough consideration of the costs and challenges linked with the process is essential to determine whether it is the right choice for a given situation. The costs associated with these methods vary greatly depending on motor size, design, construction method, etc.

The motors that do not pass the tests can not be reused, refurbished or remanufactured. Hence, the production facility gathers these motors in a designated collection and dispatches them to a recycling plant such as Stena Recycling.

4 Methodology

This chapter describes the methodology adopted for the study, including the research approach, Literature review, data collection and data analysis.

4.1 Overview of the Research Approach

This study employed a mixed-methods approach to investigate the challenges and potential solutions related to the recycling of electric motors. The mixed-methods approach was chosen for its capacity to provide a comprehensive understanding of the research questions by combining both qualitative and quantitative research methods. The use of multiple data sources allowed for a more in-depth examination of the complex issues surrounding electric motor recycling and for generating empirical evidence to support the research hypotheses

An extensive literature search was conducted as an essential part of the research process. This included reviewing academic publications, industry reports, and relevant legislation to identify the current state of knowledge regarding electric motor recycling and the challenges and opportunities associated with the disassembly process. The main themes explored during the literature search included: the composition and construction of electric motors, various recycling methods and technologies, environmental and economic aspects of motor recycling, and the role of policy and regulation in promoting sustainable practices. The literature review informed the development of the research questions and helped to identify gaps in existing knowledge that the study aimed to address.

The qualitative data collection methods consisted of semi-structured interviews with a purposeful sample of experts in electric motor recycling, including those with experience in recycling EEE, such as electric motors. The participants were selected based on their expertise in the field and willingness to participate in the study.

Quantitative data collection was carried out through a survey that was distributed to industries that use electric motors. The survey aimed to obtain an overview of their thoughts and experiences regarding recycling electric motors and their practices after the EOL of electric motors. The survey included closed-ended questions with numerical data or Likert scale responses, which allowed for quantitative analysis.

The mixed-methods approach allowed for a comprehensive exploration of the research questions and contributed to a more robust understanding of the challenges and potential solutions related to electric motor recycling. The integration of qualitative and quantitative data, along with the insights gained from the literature search, provided valuable information to address the research questions.

4.2 Literature Review

The research in this thesis focuses on five main topics related to the design and recycling of electric motors, as shown in Figure 17. These were selected to cover the various objectives that had been set. The first topic explores the design of electric motors, with a particular emphasis on their components, materials, and performance requirements. The second topic investigates existing recycling processes for electric motors, including disassembly methods, component separation, and material recovery techniques. The third topic concerns material selection for the design of electric motors, with a focus on how material properties impact motor performance and the feasibility of material recovered during recycling. The fourth topic explores the application of design for recycling principles and methodologies to the design of electric motors. The fifth topic focuses on life cycle engineering, with an emphasis on the environmental impact of electric motor production, use, and disposal. In addition to these main areas, relevant literature within sub-areas has also been conducted.

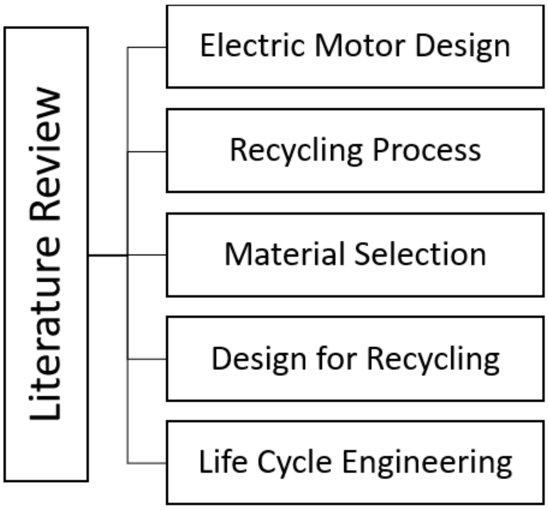

Figure 17: Overview of literature review topics.

4.2.1 Searchwords

The literature review was conducted by using a series of combinations of searchwords in Google Scholar(GS). The aim was too out which keywords and how many were needed to get a broad but relevant result. The relevance of the results was examined by looking at the title and abstract. The same search was then carried out in the Oria and Scopus databases.

Table 8, 9, 10, 11 and 12 present a summary of one of the search procedures for the five main subjects of the literature review. These subjects are broad; therefore, several searches were performed using different keywords. The tables show the databases used for the searches, the keywords used, and the number of results obtained.

Table 8: Summary of literature on design of electric motors.

Search engine	**Search word 1**	**Search word 2**	**Search word 3**	**Search word 4**	**Search word 5**	**Search word 6**	**Number of hits**
GS	Electrical	Motor	Design	Components	Materials	Composition	381 000
Oria	Electrical	Motor	Design	Components	Materials	Composition	70
Scopus	Electrical	Motor	Design	Components	Materials	Composition	8

Table 9: Summary of literature on recycling processes for electrical machines.

Search engine	**Search word 1**	**Search word 2**	**Search word 3**	**Search word 4**	**Search word 5**	**Search word 6**	**Search word 7**	**Number of hits**
GS	Recycling	Techniques	Electrical	Machines	Separation	Recovery	Disassembly	22 600
Oria	Recycling	Techniques	Electrical	Machines	Separation			16
Scopus	Recycling	Techniques	Electrical	Machines	Separation			7

Table 10: Summary of literature on material selection for electric motors.

Search engine	**Search word 1**	**Search word 2**	**Search word 3**	**Search word 4**	**Search word 5**	**Search word 6**	**Search word 7**	**Search word 8**	**Number of hits**
GS	Electrical	PM	Motor	Material	Properties	Recovery	Sustainable	Recyclability	22 600
Oria	Electrical	PM	Motor	Material	Properties				529
Scopus	Electrical	PM	Motor	Material	Properties				45

Table 11: Summary of literature on design for recycling principles for electric motors.

Search engine	**Search word 1**	**Search word 2**	**Search word 3**	**Search word 4**	**Search word 5**	**Search word 6**	**Search word 7**	**Number of hits**
GS	Electrical	Motor	Design	Recycling	Sustainable	Circular	End-Of-Life	18 400
Oria	Electrical	Motor	Design	Recycling	Sustainable			922
Scopus	Electrical	Motor	Design	Recycling	Sustainable			123

Table 12: Summary of literature on life cycle engineering for electrical motors .

Search engine	**Search word 1**	**Search word 2**	**Search word 3**	**Search word 4**	**Search word 5**	**Search word 6**	**Search word 7**	**Number of hits**
GS	Electrical	Motor	PM	Life cycle	Environmental	Sustainable	impact	25 600
Oria	Electrical	Motor	PM	Life cycle	Environmental	Sustainable	impact	6
Scopus	Electrical	Motor		Life cycle	Environmental	Sustainable	impact	7

During the literature review process, the Scopus database was the most widely used due to its advanced search capabilities. The database allowed for searching within titles, abstracts, and keywords, which enhanced the precision of the searches. Additionally, Scopus provided proximity operators such as "w/n" that could be utilized to limit the number of non-relevant words between two desired words, refining the search results. For instance, a search query for "Recycle w/0 techniques" would return matches without any words between "Recycle" and "techniques", making the results more relevant.

The AND operator was used in the main search terms to ensure greater relevance, while w/n and OR operators were utilized in more specific and detailed searches. For example, the OR operator was used in cases where two words covered the same area to look for articles containing at least one of them. W/0 and W1 were used for words that are naturally held together, such as "design w/1 for recycling"

4.3 Qualitative Data Collection

The qualitative data collection for this study was carried out through two primary methods: semi-structured interviews and long-end questions from the survey. These methods were chosen to gain insights from experts in electric motor recycling and industries that use electric motors. They provided valuable information on current recycling methods, and associated challenges, and offered a comprehensive insight into the present-day situation.

4.3.1 Semi-Structured Interviews

Semi-structured interviews were conducted with a purposeful sample of experts in electric motor recycling, including those with experience in recycling electrical and electronic waste or electric motor design. The participants were selected based on their expertise in the field and willingness to participate in the study. An interview guide was developed based on the research questions, and the guide was pilot tested with a small sample of participants to ensure that it effectively elicited the desired information. The interviews were conducted either in person or via video conferencing, depending on the participant's location and preferences. All interviews were audio-recorded and later transcribed for analysis. The interviews can be found in Appendix. !!!

4.3.2 Survey

A survey was designed using an online platform and distributed to industries that use electric motors. The questions aimed to obtain an overview of the thoughts and experiences of recycling electric motors and what companies do after EOL of electric motors. The responses were collected through the online platform and later analyzed to gain further insights into the perspectives and practices of various industries in relation to electric motor recycling. The survey is further described in 4.4.1.

4.4 Quantitative Data Collection

The quantitative data collection for this study was conducted through an online survey, which aimed to gather information on the thoughts, experiences, and practices of various industries in relation to electric motor recycling. This method allowed for the collection of structured data from a larger sample of participants compared to qualitative interviews, providing valuable insights into the broader trends and patterns associated with electric motor recycling practices.

4.4.1 Online Survey Design and Distribution

The online survey was designed using the Nettskjema.no platform to ensure user-friendly and efficient data collection. This platform was also chosen for its ability to anonymize the respondents, protect their privacy and adhere to data protection regulations. Questions were developed to address the respondent's industry sector, the number of electric motors they utilized, their recycling routines, experiences with EOL management of electric motors and perceptions of potential recycling challenges and opportunities. The survey included a total of 13 questions, with a majority being multiple-choice and a few open-ended questions to allow for both quantitative analysis and the gathering of qualitative insights.

The survey was distributed to different industries that use electric motors, including manufacturing, aerospace and energy sector. The industries were selected based on the relevance of electric motor recycling to their operations and the potential for valuable insights to be gained from their experiences. The survey was disseminated through standardised email invitations and was in total sent to 19 different companies. Examples of companies that the survey was sent to include ABB, Alva Industries, Autostore, Equinor and Norske Skog.

In this study, the data collected through interviews and surveys were organized and presented in a manner that facilitated a clear and comprehensive understanding of the research findings. This section describes how the data were presented, including the use of tables and other visual representations.

In this study, a combination of qualitative and quantitative data analysis techniques was employed to gain insights and answer the research questions. Due to the limited amount of available data, simplified methods were utilized for the analysis. This section provides an overview of the methods employed for analyzing the collected data, considering the constraints imposed by the small data sample.

5 Current Practices in Recycling of Electric Motors: Case Study from Stena Recycling

This section explores the current practices in recycling electric motors, based on a case study of Stena Recycling. Recognised for its excellence in offering recycling solutions, Stena Recycling demonstrates significant expertise in the reprocessing of electronic waste, including electric motors. The organisations' relentless pursuit of advancement and innovation in recycling practices makes it a valuable subject for studying the intricacies of current recycling processes. The recycling procedure employed by Stena is categorised into five stages, as illustrated in Figure 18.

Figure 18: Simplified stages in mechanical recycling of electric motor. [60]

5.1 Collection & Sorting

As the preliminary phase of the recycling process, EOL electric motors and other electronic waste are accumulated and transported to recycling facilities. The motors from industries are typically collected in substantial quantities and transported to specialized facilities equipped with containers (see Figure 19), such as Stena Recycling. To optimise the cost-effectiveness of this stage, a substantial accumulation of motors is essential before dispatch.

Figure 19: Simplified stages in mechanical recycling of electric motor [60].

Users that operate with a small number of electric motors deliver their electric motors to recycling collection points, such as Norsirk in Norway. Here, electronic and electric (EE) waste is stored in designated EE cages before being transported to specialised processing facilities. At these facilities, the collected waste is scrutinised and classified based on its constituent materials and inherent value. Electric motors are singled out and channelled to a separate processing division within the Stena Recycling infrastructure for further processing [61].

5.2 Recycle or Reuse

The recycling of electric motors is primarily accomplished through two methods: shredding or disassembling. The choice of recycling method depends on various factors, including the size of the motor, the component being recycled, and ease of disassembly. The degree of disassembly is largely influenced by the method used to fasten the motor components together. For example, epoxy attachments may hinder complete disassembly, but partial disassembly may still be possible. Upon disassembly, certain parts of the electric machine can be reused without further processing, while others need to be remelted into the same raw material or converted into a new alloy. Stena Recycling has stated that the disassembly of electric motors is a time-consuming and challenging process; therefore, as of the current date (April 17, 2023), all-electric motors received at their facilities undergo recycling through a shredding method [61].

The shredding process for electric machines encompasses a series of steps. Figure 20 illustrates the primary stages involved in the shredding process, subsequent to the collection, transportation, and sorting of the motors.

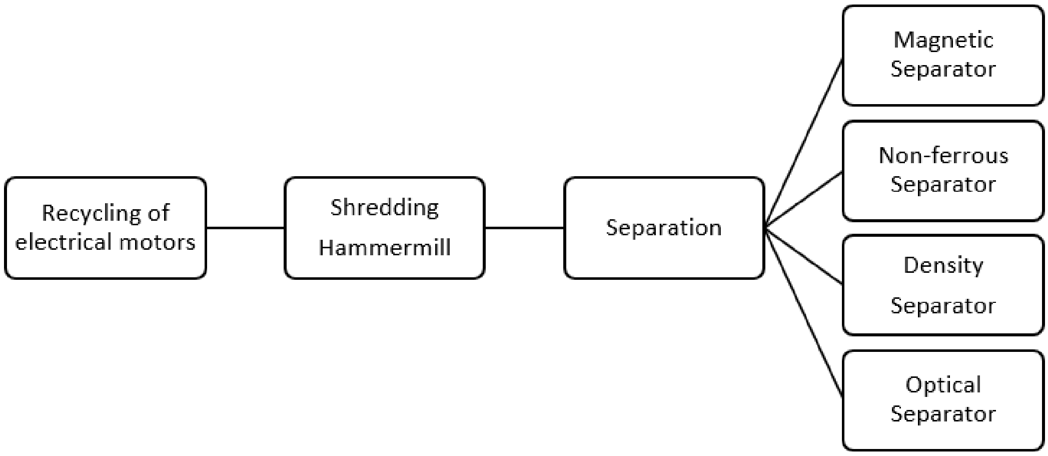

Figure 20: Recycling strategy for electric motors.

5.3 Sorting and Removal of Hazardous Waste

The first step involves sorting the appliances and removing all hazardous waste before any mechanical impact is applied. This step is essential to ensure the safety of workers and prevent any potential environmental harm. Hazardous waste may include substances such as lead, cadmium, mercury, or polychlorinated biphenyls (PCBs), which require special handling and disposal procedures.

For Alva's electric motor, this step is unnecessary, as it does not contain any hazardous materials that cannot be safely handled by the processing methods [61]. Stena has agreements with approved recycling stations that already have completed this step for electric machines containing hazardous waste, allowing Stena to directly start shredding the electric motors.

Stena Recycling has established agreements with approved recycling stations that have already completed the sorting and removal of hazardous waste for electric machines containing such materials. These recycling stations adhere to strict regulations and guidelines for handling hazardous waste. By collaborating with these recycling stations, Stena Recycling can commence the shredding process directly, confident that the hazardous waste has been appropriately addressed in a safe and compliant manner. This collaboration streamlines the shredding process, allowing Stena Recycling to focus on the efficient fragmentation of the electric motors without the need for additional hazardous waste management. It ensures that the subsequent shredding and separation steps can proceed smoothly, optimizing the recycling process and resource recovery.

5.4 Decontamination

This process is carried out in accordance with prevailing legislation and standards to prevent the discharge of hazardous substances into the environment or final fractions. In Norway, the handling and disposal of hazardous waste are regulated by the Norwegian Pollution Control Act and the Regulations on Waste, which require the elimination of potential hazards to human health and the environment. This involves the proper identification, sorting, and storage of hazardous waste prior to its transportation to an authorized treatment or disposal facility. Moreover, the handling and disposal of hazardous waste must comply with specific requirements relating to storage, transportation, and treatment methods to prevent environmental pollution [62].

5.5 Shredding

In a recycling plant line, the shredding process is a crucial step in the recycling of electric motors and other electric waste. The purpose of the shredding process is to break down the materials into smaller fragments, facilitating the subsequent separation of different material fractions. This process involves the use of shredding machines that employ mechanical force to reduce the size and volume of the materials.

The electric motors and other electric waste that have undergone sorting and decontamination are directed to a conveyor belt, which transports them to the shredder. A shredder is typically a robust machine, such as a hammer mill, designed to handle the substantial size and density of the materials. The hammer mill consists of a high-speed rotating rotor equipped with hammers or blades that strike and impact the incoming materials. The force generated by the hammers or blades effectively breaks down the materials into smaller pieces.

The large hammer mill used by Stena Recycling, for example, quickly and efficiently breaks down the electric motors into manageable-sized pieces within a matter of seconds. These pieces still retain a certain level of size and structural integrity, making them suitable for further processing and separation.

After the initial shredding, the resulting fragments can be directed to a secondary shredder with a finer mesh. This secondary shredder further reduces the size of the fragments, achieving the desired level of fragmentation. The finer mesh allows for more precise control over the size and consistency of the shredded materials.

The shredding process serves several purposes in the recycling plant line. Firstly, it facilitates the separation of different material fractions by reducing the size of the materials and increasing their surface area. This enhances the effectiveness of subsequent separation techniques, such as magnetic drum separators and eddy current separators. Additionally, shredding promotes the liberation of valuable materials and components from electric motors, making them more accessible for recovery and recycling.

5.6 Separation

Separation of varied components is the most critical phase in the recycling process of electric motors. his process guarantees that diverse materials including ferrous, non-ferrous, copper, plastics, and aluminum, among others, are duly separated from each other and readied for additional processing. Various technologies and techniques are utilized in the separation process to ensure optimal efficacy and precision. Figure 21 provides a simplified representation of the separation procedure using a magnetic drum and eddy current separator (ECS).

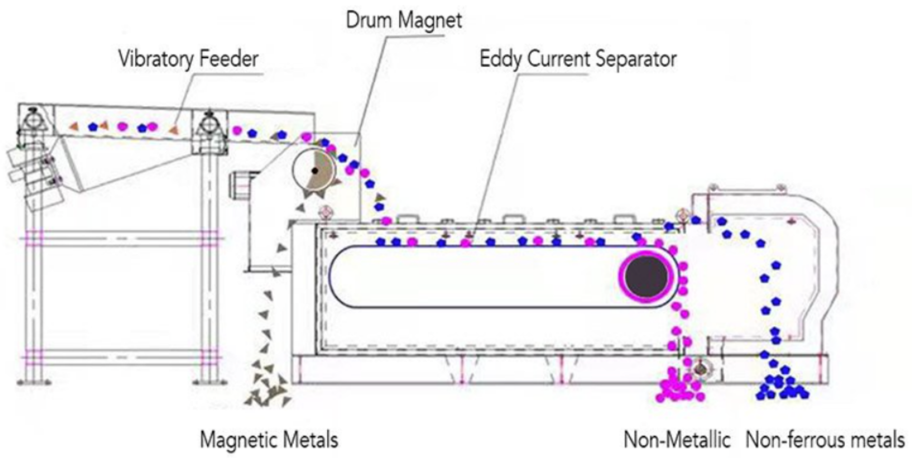

Figure 21: Recycling strategy for electric motors [63].

The separation of electric machines components at Stena Recycling involves the following stages:

1. **Magnetic Drum**: Employing a magnetic drum separator, which comprises a rotating drum made from a magnetic material, typically a permanent magnet, ferromagnetic materials such as iron and steel are attracted and consequently separated from other materials as they pass over the drum. This technique is widely used to segregate ferromagnetic materials from non-ferromagnetic substances, enabling non-ferrous metals to be separated for additional processing. The copper is subsequently separated manually from the other non-ferrous materials [60].
2. **Separation of Non-Ferrous and Plastic Elements**: Remaining non-ferrous and plastic elements are separated based on size into large, medium, and small fractions.
3. **Eddy Current Separator (ECS)**: Typically employed for the separation of non-ferrous metals such as aluminium and copper from other fractions, ECS operates on the principle of electromagnetic induction, thereby generating eddy currents in conductive metals [64]. The ECS consists of a fast rotating magnetic drum, typically powered by an electric motor. As non-ferrous metals come into contact with the rotating magnetic field, eddy currents are induced within these conductive metals. The induced eddy currents, in turn, generate their own opposing magnetic field, resulting in a repulsive force between the non-ferrous metals and the drum. Consequently, non-ferrous metals are separated effectively from other fractions for further processing and recycling [64].
4. **Flotation Process**: The mixed plastic stream undergoes the flotation process. In this process, plastics are introduced into a controlled density liquid, where denser plastics sink while lighter ones float. Subsequently, the plastics are transported to the other side of the tank, thereby separating recyclable plastics from brominated plastics [60].
5. **Optical Separator**: In this process, materials are segregated based on their physical properties, including size, shape, and color. Materials pass through a conveyor belt and are scanned by a camera system that captures multiple images. These images are processed to determine each material's color and shape. Based on this data, the optical separator distributes materials into different streams. One application of optical separation in electric motor recycling is the segregation of aluminium from iron-based metals, which may have been missed during an earlier separation process because it can be challenging to separate them using magnetic separation alone. Optical separation enables aluminium to be distinguished from iron-based metals based on its unique color and other optical characteristics [60].

Table 13 provides a summary of the different separation tools employed in the recycling process of electric motors, along with their respective purposes, advantages, and disadvantages.

Table 13: Overview of Separation Techniques Used in Electric Motor Recycling [60] [61].

Separation Tool	**Purpose**	**Advantages**	**Disadvantages**
Magnetic Drum	Separation of ferromagnetic materials from non-ferromagnetic materials	Effective for separating ferromagnetic materials	Not effective for separating non-ferrous metals
Eddy Current Separator	Separation of non-ferrous metals such as aluminium and copper from other fractions	Effective for separating non-ferrous metals	Difficult to predict and compute the movement trajectory and collection position of metallic particles
Airflow Separator	Separation of light and heavy particles based on density	Low operating cost and high separation efficiency	Wind velocity, particle size, and particle density can be critical influences
Optical Separator	Separation of materials based on physical properties such as size, shape, and colour	Accurate and efficient in separating materials based on unique characteristics	Limited in separating materials that share similar physical properties
Flotation Process	Separation of plastics based on density	Effective for separating plastics based on density	Not effective for separating plastics that have similar densities

Following the separation process, the different fractions are well-organized and primed for a new lifecycle. Stena Recycling's advanced technological processes ensure that the recycling of electric motors is conducted in a highly efficient and sustainable manner [60][61].

5.7 Challenges and Requirements

The process of electric motor recycling entails multiple technological complexities that must be proficiently managed to meet strict material recovery benchmarks, ensuring a substantial proportion of the recycled constituents are viable for reuse. Recycling regulations for Waste Electric and Electronic Equipment (WEEE) are principally directed by the WEEE Directive of the European Union. The directive delineates specific collection, recycling, and reuse targets for electric and electronic waste within EU jurisdictions. As per the WEEE Directive of 2012 (2012/19/EU), the following stipulations were instituted for the recycling and reuse of WEEE [65]:

- A minimum of 85 % by weight of WEEE should be subjected to recycling.
- At least 80 % by weight of WEEE must be reincorporated into the system through recycling, reuse, or energy recovery processes.

Additional details regarding the regulations and standards for electric motor recycling can be located in Section 7.

Stena Recycling has committed to and achieved surpassing these benchmarks, affirming that over 90% of electric motors and other WEEE are recycled [61]. This accomplishment was feasible due to significant investments in advanced technologies focused on the separation and recycling of "fluff". Typically, these technologies integrate mechanical and chemical methodologies to segregate materials and eliminate any contaminants or hazardous substances. "Fluff" refers to a combination of "microscopic" particles formed during the shredding of materials. As the composition of fluff involves a mixture of various materials, the separation of these constituents poses a significant challenge due to the diminutive particle size.

As previously described, Stena Recycling is currently shredding all electric motors. The company prioritizes recycling due to limited time and resources to test individual components for potential reuse [61]. This highlights a potential inefficiency in the recycling process, if certain components can be directly reused, it would be more resource-efficient and environmentally friendly to utilize these components rather than moving immediately towards recycling. Stena Recycling has made it clear that implementing component testing into their process, without associated incentives, is not seen as financially viable. This presents a potential area of responsibility that manufacturers might need to assume if such testing is to be implemented. Manufacturers might be mandated to undertake this responsibility, necessitating significant investments in time, money, and resources, particularly for smaller manufacturers.

Finally, this also highlights a challenge with current regulations. While directives such as the WEEE Directive set clear targets for recycling, there might be a lack of incentives or mandates for the reuse of components [65].

Several strategies might be employed to address these challenges:

- **Innovative technical solutions:** Development of advanced testing tools that can efficiently and accurately determine the ability to reuse components. This could expedite the recycling process and potentially reduce the associated time and cost.
- **Shifts in manufacturer responsibilities:** Introduction of clear and enforceable regulations for component testing and reuse, including specific standards for component reuse and sanctions for non-compliance.
- **Supportive regulatory changes:** Incentives such as tax breaks, grants, or other forms of financial support could encourage manufacturers to invest in component testing and reuse.

In summary, there's a need for an integrated approach to electronic waste management that balances recycling and reuse. Achieving this balance could require innovative technical solutions, shifts in manufacturer responsibilities, and supportive regulatory changes. Further exploration of these issues is therefore recommended to enhance the efficiency and sustainability of the recycling process.

5.8 Partnership Between Stena Recycling and ABB

To enhance recycling processes and facilitate a more robust circular economy, Stena Recycling and, the global technology leader, ABB have established a collaborative relationship. This partnership illustrates a compelling implementation of sustainable practices, where ABB's electric motors are processed effectively at their EOL through Stena's recycling services.

The agreement set in 2021 ensures that substantial industrial clients, such as Yara, participate in this circular economy. ABB sells electric motors to these enterprises, which are later deposited into a container at their EOL, as depicted in Figure 19. Upon the container's filling, Yara notifies Stena of the collection. ABB receives compensation for the returned motors, while Yara benefits from discounted prices on new motors from ABB, thus promoting the sale of new motors and the recycling of old ones.

This partnership amplifies the sustainability of ABB's electric motors. The EOL motors collected from Yara are transported to Stena's recycling facilities, where they are converted into raw materials for the manufacturing of new electric motors. This end-to-end process not only contributes to ABB and Stena Recycling's operational efficiency but also offers value to Yara, providing them with economical options for motor replacements.

The collaboration between ABB and Stena Recycling highlights the potential for strategic alliances to enhance the circular economy, reduce energy consumption, and encourage the use of recycled materials in manufacturing processes. ABB's focus on the circular economy is a critical facet of its sustainability strategy, with this partnership emphasizing its commitment to sustainable practices.

Further underscoring their dedication to sustainability, ABB has taken another significant step by partnering with Boliden to incorporate recycled copper in their highly energy-efficient SynRM IE5 motors. This strategic agreement not only showcases ABB's commitment to the principles of the circular economy but also highlights the substantial potential for energy savings and environmental benefits through the effective recycling of electric motors. The environmental impact of recycling, compared to the traditional mining of raw materials, is remarkable, with energy savings ranging from 75 % to 95 %, depending on the specific material. By embracing this recycling initiative, ABB demonstrates its proactive approach to reducing resource consumption, minimizing waste generation, and contributing to a more sustainable future.

6 Sustainable Development: Economic and Environmental Considerations in Electric Motor Production and Recycling

6.1 Environmental Impacts

To assess the environmental impact of different materials, life cycle assessment (LCA) has been used to compare the effects of primary- and secondary/recycling production. Figure 22 illustrates the life cycle inventory and life cycle impact assessment for materials [66]. In the analysis, there has been a focus on CO_2 emissions, water inputs, land occupation and transformation, and energy use. Although other factors such as toxic emissions and other resource inputs may also play a critical role, these factors have been prioritized based on their importance in determining the overall environmental impact of these processes.

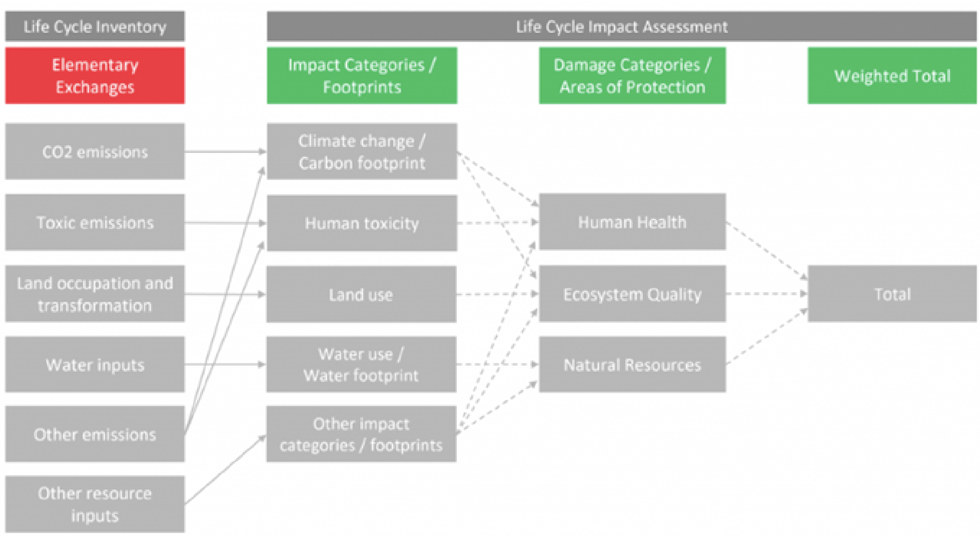

Figure 22: Life cycle assessment for material production
[66]

The embodied energy use associated with both the production and recycling of materials has also been examined, as this factor plays a significant role in determining the environmental impact of these processes. Embodied energy is a calculation of all the energy that is used to produce a material. This includes aspects such as mining, manufacturing and transport [67].

The focus on these key environmental factors and the examination of total energy use associated with electric motor production and recycling aims to provide a comprehensive understanding of the environmental impact of these processes. While other factors may also be relevant, the selected factors are believed to provide valuable insights into the sustainability of these processes and inform future efforts to reduce their environmental impact.

Figure 23 displays the CO_2 emissions associated with the five major material components found in a typical electric motor. The blue bars represent the emissions related to the extraction of these materials, while the orange bars represent emissions related to their recycling. This visual representation provides valuable insights into the environmental impacts associated with both material extraction and recycling in the production of electric motors.

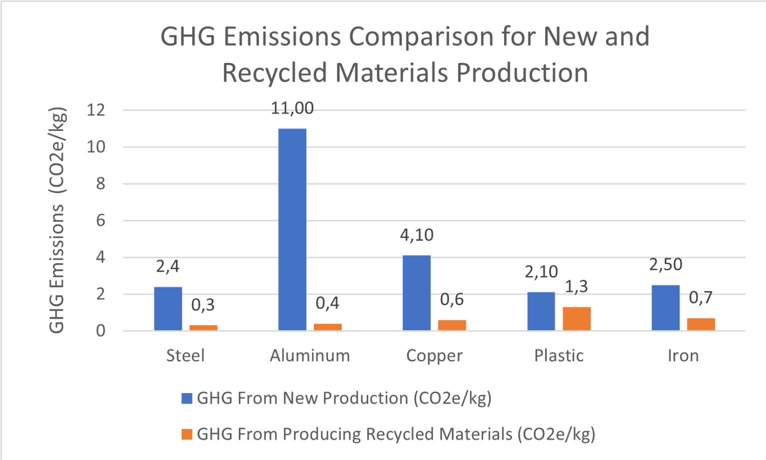

Figure 23: GHG emissions comparison for new and recycled materials production

Figure 24 is an estimate of the embodied energy for both primary and recycled materials, and each material's specific value depends on different factors such as Production process, energy sources, transportation and recycling efficiency.

The embodied energy values presented in the table are estimates based on data collected from various sources. While the analyzed paper, "Climate Benefits of Material Recycling: Inventory of Average Greenhouse Gas Emissions for Denmark, Norway and Sweden", provided valuable information on the embodied energy associated with the production and recycling of materials, it did not cover every material available [68].

Information was gathered from multiple sources to include data for the remaining materials and an average was taken. Due to variations in the data, the values presented in the table may differ slightly from the actual embodied energy values for each material.

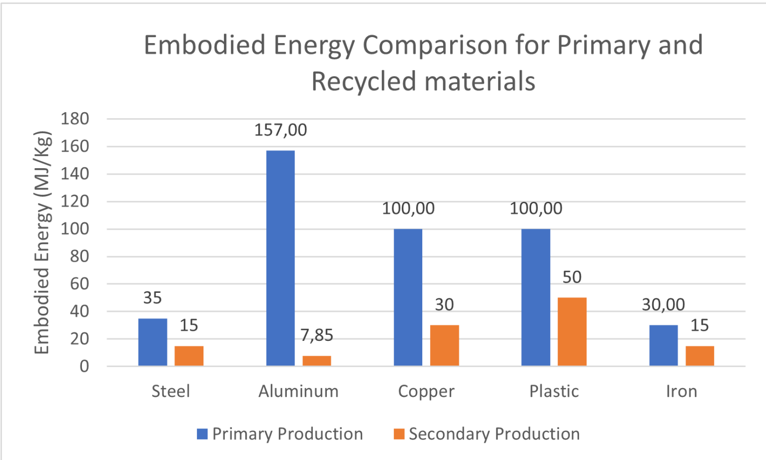

Figure 24: Embodied energy comparison for primary and recycled materials [68].

The environmental impacts of material production and recycling extend beyond greenhouse gas emissions and embodied energy. Factors such as land occupation, transformation, water input, and water pollution also play a critical role in determining the overall sustainability of a material. To provide a clear overview of the differences in these factors between primary and secondary material production, Table 14 presents a concise summary of the main impacts associated with each process.

Table 14: Comparison of environmental aspects in primary and secondary material production.

Aspect	Primary Material Production	Secondary Material Production
Land Occupation	Extensive land occupation due to mining and deforestation	Less land occupation; recycling facilities require less space
Land Transformation	Significant landscape alteration, habitat destruction, soil degradation, and erosion	Lower impact on land transformation; reduced demand for new resource extraction
Water Inputs	High water consumption for cooling, dust suppression, and mineral separation	Generally lower water consumption; water can often be treated and reused within the facility
Water Pollution	Potential Contamination of nearby water bodies due to wastewater from mines and refineries if not managed	Lower risk of water pollution; recycling facilities have more stringent environmental controls and monitoring

These findings indicate substantial environmental benefits associated with the secondary production/recycling, of materials utilized in electric motors when compared to primary production. While both of the production methods have environmental impacts, the data provided indicated that these impacts are significantly mitigated in the context of secondary production. This presents critical implications for the future management of electric motors, signalling a necessity to prioritize recycling and reuse of materials over fresh extraction of materials.

However, it should be noted that there is a need for further research in this field. For instance, a more comprehensive analysis of the total environmental impacts associated with both of these processes would be beneficial. This includes investigating the potential toxic emissions and other resource inputs. Examining additional aspects of the manufacture of electric motors, such as the effect of various design and manufacturing processes on their overall environmental footprint, may also be necessary.

Overall, these findings underscore the importance of a more sustainable approach to the production and recycling of electric motors. This approach could include both technical solutions, such as the development of more advanced recycling technologies and the redesign of motors for easier component reuse, and institutional changes. Institutional changes may include stricter environmental regulations and incentives for sustainable practices. The interplay between technological innovation and institutional frameworks will likely shape the future of sustainable electric motor production.

6.2 Economic Impacts

A simplified economic analysis is conducted to assess the economic implications of recycling versus producing new materials. The analysis primarily focuses on copper, aluminium, and steel - three vital materials for electric motors, chosen due to their significant impact on motor function, performance, and efficiency. Two key considerations in the choice between recycled or new materials are recyclability and cost [69].

Recycling not only saves money and resources but also fosters economic growth by creating new jobs and supporting long-term expansion. The financial benefits of recycling are further demonstrated through real-world examples. Factors such as sustainability goals, technological advancements, and market conditions are projected to influence future trends, thereby stressing the need for accurate data on raw materials and energy prices.

However, this is a simplified analysis which primarily considers raw material and energy costs. It is essential to understand that the economic dynamics of recycling versus new material production are far more complex, with many other important factors. For example, labour costs, technology costs, policy and regulation impacts, and economic scales can significantly affect the choice between secondary and primary materials.

Moreover, the lack of available and reliable data is a limitation of this analysis. The figures used for raw material prices, energy costs, and recycling prices are estimated based on current market conditions and conversations with various recycling companies. However, these figures might not reflect the actual costs due to fluctuations in market conditions and differences in data collection and estimation methodologies across companies. This inconsistency and lack of reliable data could potentially impact the validity of the findings.

Therefore, while this analysis provides a starting point in understanding the economic implications of recycling versus new material production, a more comprehensive approach incorporating a broader range of factors is needed for future research. Specifically, incorporating production and transportation costs, which can significantly affect the overall costs of both processes, is crucial. Additionally, a more rigorous approach to data collection and verification would enhance the accuracy and reliability of the analysis.

While acknowledging these limitations, it is important to note that this analysis still provides valuable insights. It demonstrates the potential economic benefits of using recycled materials over new materials, as indicated by the lower costs of raw materials and energy for recycling. These findings can serve as a basis for further research and contribute to the ongoing discussions on the economic sustainability of recycling.

6.2.1 Direct Costs

An in-depth analysis of the direct and indirect costs associated with the production, gathering, and processing of recycled and original materials is necessary to grasp the economic implications of recycling versus the fabrication of new materials. Although indirect costs are not specifically investigated in this study, it is understood that they have a major influence on whether secondary or recycled materials are used.

Raw Material Cost The prices of primary raw materials were sourced from the London Metal Exchange (LME) website [70]. The prices of raw materials can exhibit variations due to several factors, which may result in discrepancies in the presented figures. These factors can be attributed to Market forces, Exchange rates, Geopolitical factors and production and processing costs. It is challenging to find up-to-date information on raw material prices for recycled materials. Various recycling companies were contacted to obtain better estimates. Table 15 presents the price for both primary- and recycled raw materials. These figures are highly estimated based on the current market conditions (as of May 15, 2023), and recycled materials are currently sold at a 2-3% lower price compared to primary materials. However, it should be noted that these estimates are highly dependent on factors such as material purity, alloy composition, and volume, which significantly influence pricing. Therefore, a margin of error of 15% can be applied to account for these variations [61].

Table 15: Comparison of Estimated Material Prices

Material	Price (Primary)	Price (Recycled)
Aluminium	20.4 NOK/kg	19 NOK/kg
Copper	80.3 NOK/kg	75.2 NOK/kg
Steel	7.4 NOK/kg	3.8 NOK/kg

The prices of recycled materials are generally lower than the primary, which can result in cost savings for manufacturers. However, it is important to consider that these prices are estimates and subject to variations based on factors such as material quality, material availability, and market conditions.

Energy Cost The energy costs in Figure 24 represent the total energy quantity required to produce primary and recycled materials. By utilizing these values, the energy costs can be calculated. According to SSB, the average price of electricity for industrial users in Norway in 2021 was 0.44

Norwegian Kroner per kWh [71]. When converting energy units from megajoules per kilogram (MJ/kg) to kilowatt-hours per kilogram (kWh/kg), the conversion factor is 3.6. This is because 1 kilowatt-hour is equal to 3.6 megajoules. The energy costs for each material are calculated using the following formulas:

$$\text{Energy Quantity [kWh/kg]} = \frac{\text{Embodied Energy MJ/kg}}{\text{Conversion Factor}} \quad (1) \tag{1}$$

$$\text{Cost [NOK/kg]} = \text{Energy Quantity} \times \text{Price per kWh} \quad (2) \tag{2}$$

Table 16 presents the calculated energy costs for 1 kg of each material, highlighting a significant disparity between primary and recycled materials. The energy costs for primary materials are 57% to 95% higher compared to recycled materials. For instance, the total energy cost to produce 100 kg of primary aluminium is 1,920 Norwegian kroner, while the cost for recycled aluminium is 960 Norwegian kroner. This substantial difference illustrates the economic advantage of utilizing recycled materials.

Table 16: Comparison of Energy Costs for Primary and Recycled Materials

Material	Price (Primary)	Price (Recycled)	% Difference
Aluminium	19.20 NOK/kg	0.96 NOK/kg	95.00 %
Copper	12.21 NOK/kg	3.67 NOK/kg	69.93 %
Steel	4.28 NOK/kg	1.83 NOK/kg	57.19 %

6.2.2 Market Forces, Prices, and Demand

The subsequent analysis must understand how market forces, prices, and demand influence the choice between recycled and new materials.

The Influence of Market Forces, Prices, and Demand on Material Selection: Comparing Recycled and New Materials

Market forces, such as supply and demand dynamics, heavily influence the choice between recycled and new materials. The availability, extraction costs, processing costs, market competitiveness, and demand from different industries all have a role in establishing the prices of primary and recycled resources. Industries are incentivised to investigate employing recycled materials when the price of primary raw resources is high due to shortage or rising demand [72]. However, if basic materials are cheap and plentiful, companies may use them instead of recycled content. The growing demand for eco-friendly and sustainable goods may also affect market dynamics. The demand for recycled materials may rise if businesses pay more attention to environmental responsibility and actively encourage using them in their products.

Economic Benefits of Recycling There are several financial advantages to recycling. First, it helps save a lot of money by decreasing the prices of obtaining and processing raw materials. By using recycled resources, factories can save time and money on the main materials' mining, refining, and transport operations. Secondly, recycling is more energy efficient than making new materials from scratch. Primary raw material extraction and processing can be very energy intensive, but recycling can use existing materials, minimising the requirement for such activities [73]. The collection, sorting, processing, and production of recycled materials into new goods all contribute to the recycling industry's ability to provide jobs. The economy benefits from this increase in employment, and the unemployment rate goes down. Lastly, recycling helps the economy by lessening the need to extract new materials and increasing the longevity of existing ones.

Real-World Examples of Economic Advantages Real-World Examples of Economic Advantages Germany's extensive recycling system has boosted the country's economy. Germany can save a lot of money on waste management expenses, create new jobs in the recycling industry, and lessen its need to import raw materials because of its commitment to recycling its packaging trash. The aluminium recycling market in Brazil is mature and robust. Aluminium can recycling rates in the country are among the highest in the world, saving money and resources compared to mining ore [74]. The recycling industry as a whole has benefited greatly from this. The recycling of old automobiles in the United States is a thriving business that has contributed to the country's rising standard of living. Recycling old cars has many benefits, including the conservation of raw materials, the creation of new products and jobs, and the mitigation of environmental damage.

Future Trends in Costs and Benefits Several factors will influence recycling rates and the costs and advantages of producing new materials developed in the future. As businesses and customers alike place a higher value on environmentally friendly goods, it stands to reason that demand for recycled materials would increase as a direct result of this trend. Improved process efficiency and cost-effectiveness due to technological advances can increase recycling's economic appeal [69]. Governments and organisations may support circular economy projects, which might lead to supportive legislation and incentives that further encourage recycling. The costs and advantages of recycling will also be affected by factors including raw material price changes, resource availability, and regional differences in recycling infrastructure and practices. The recycling industry and its associated economy will develop in response to these trends.

7 Regulations and Standards

Regulations and standards play an important role in promoting the recycling of electric equipment, including electric motors. Therefore, the Norwegian, European and international rules and standards are examined to promote a circular economy and resource conservation. This chapter will begin by outlining the relevant directives and laws, such as the WEEE, Restriction of Hazardous Substances (RoHS) and Ecodesign directives, as well as the ISO standard for recycling electric and electronic equipment (EEE). This section will also examine the regulations related to producer responsibility for ensuring the recycling of electric components. Lastly, it will investigate the emerging trend of the "Right to Repair" and the significance of collaboration between stakeholders in promoting progress.

7.1 WEEE-directive

The WEEE Directive (2012/19/EU) is a European Union (EU) legislation that aims to promote the recovery, reuse, and recycling of WEEE to reduce the environmental impact of waste, prevent the negative effects of hazardous substances on human health and the environment, and promote the efficient use of resources [65]. The directive sets out specific requirements for collecting, treating, and disposing of WEEE, including electric motors.

The directive applies to all types of WEEE and establishes a framework for the management of such waste, including the establishment of national collection targets, treatment requirements, and other measures aimed at promoting the efficient use of resources and the protection of human health and the environment.

Regarding electric motors, the WEEE Directive requires that such equipment should be collected separately from other WEEE and treated in an environmental manner. Specifically, the directive sets a target of at least 85% by weight of WEEE to be recovered, and at least 80% of the weight of WEEE to be prepared for reuse and/or recycling, including energy recovery [65].

The directive also requires that manufacturers of electric motors pay for the collection and disposal of their products at EOL. Producers must also take measures to ensure that their products are designed and manufactured to facilitate their reuse, recovery, and recycling. To achieve these goals, the directive sets out a number of specific obligations for producers and other stakeholders in the WEEE management chain to ensure that WEEE is properly collected, treated, and disposed of in an environmentally sound manner. These obligations include [65]:

- Establishment of collection systems: Producers of EEE are required to either individually or collectively establish and finance the collection of WEEE. They must also ensure that WEEE is collected separately from other waste streams and that it is appropriately transported to authorized treatment facilities.
- Provision of information to consumers: Producers are required to provide consumers with information on how to properly dispose their WEEE and must also provide information on the potential environmental impacts of improper disposal.
- Implementation of appropriate treatment methods: Producers and other stakeholders in the WEEE management chain must ensure that WEEE is treated in an environmentally sound manner to minimize its impact on the environment. This may include disassembly, shredding, and other processes to recover valuable materials and components.

The WEEE Directive encourages the creation and application of eco-design principles for EEE to lessen their impact on the environment. Eco-design aims to minimize a product's negative environmental effects throughout its entire life cycle, from manufacturing to disposal. These guidelines include minimizing the use of hazardous substances and promoting energy efficiency. They also include the use of materials and components that are simple to recover and recycle.

The eco-design principles laid out in the WEEE Directive include the use of materials and components that are easy to recover and recycle, the reduction of hazardous substances, and the promotion of energy efficiency. Specifically, the directive requires EEE producers to ensure that their products are designed and manufactured in a way that facilitates their reuse, recovery, and recycling. This includes the elimination or reduction of hazardous substances in EEE and the use of materials that are easy to recover and recycle.

Producers are also required to consider the energy efficiency of their products during the design phase and to provide information to consumers on the energy efficiency of their products. The eco-design principles aim to reduce the environmental impact of EEE throughout its entire life cycle by reducing the amount of waste generated, conserving natural resources, and reducing greenhouse gas emissions associated with EEE production and use.

7.2 RoHS-Directive

The RoHS Directive (2011/65/EU) is an EU legislation that restricts the use of hazardous substances in EEE. The directive applies to all EEE placed on the market in the EU, including electric motors, and sets limits on the use of six hazardous substances [75].

- Lead
- Mercury
- Cadmium
- Hexavalent chromium
- Polybrominated biphenyls (PBBs)
- Polybrominated diphenyl ethers (PBDEs)

Lead and cadmium were commonly used in soldering and surface treatment processes, while PBB and PBDE were used as flame retardants in plastic materials. However, the use of these substances have significantly reduced due to the RoHS Directive and other regulations that have been implemented.

7.3 Ecodesign Directive

(2009/125/EC) is a European Union legislation that sets out specific requirements for the design of energy-related products, including electric and electronic equipment, to improve their environmental performance throughout their entire life cycle [76]. The aim is to reduce the environmental impact of products by promoting the use of eco-design principles and reducing their energy consumption, emissions, and resource use.

The directive requires manufacturers to consider the environmental impact of their products from the design phase, including the selection of materials, energy efficiency, and EOL treatment options.

ISO 14001 is an international standard for environmental management systems that provide a framework for organizations to identify and control their environmental impact [77]. The standard aims to promote sustainable practices and reduce the environmental impact of organization's activities, products, and services.

ISO 14001 requires organizations to develop an environmental management system that includes:

- Environmental policy development
- Planning

- Implementation
- Evaluation
- Improvement

The standard provides a framework for organizations to identify and comply with applicable environmental regulations, reduce their environmental impact, and continuously improve their environmental performance. By implementing this standard, organizations can obtain a certification that is a recognized environmental certification.

Eco-Management and Audit Scheme (EMAS) is another recognized environmental certification. It is a more detailed and ambitious environmental management system compared to ISO 14001 in the following areas:

- Annual publication of an environmental statement that has been reviewed by a third party is required.
- Monitoring of environmental performance using indicators.
- Stricter requirements for compliance with laws and regulations.

EMAS has been introduced in all EU/EEA countries through a regulation dating back to 1995 [78]. In Norway, the regulation is incorporated into the Pollution Control Act, Section 52c.

7.4 Right to Repair

It has been investigated how different countries and regions have taken up the idea of the "Right to repair"

Ulrike Steinhorst and Andreas Türk, researchers at the Department of Environmental Policy at the Freie Universität Berlin, have published a report that shows an overview of the laws and regulations surrounding the right to repair in Europe [79]. According to this report, many countries have introduced rules that give consumers the right to repair their products.

A law in France mandates that producers provide access to technical documentation and replacement parts for up to five years after they stop producing a product [80]. The EU has also introduced regulations that require manufacturers to make spare parts and repair information available for white goods, to increase the lifespan of products and reduce waste [81].

The right for consumers to repair electronics and other equipment on their own or at independent repair shops has been established in several US states. For instance, Massachusetts has enacted legislation requiring manufacturers to give independent repairers access to repair parts and information [82].

In addition to legislation that makes it easier to repair products, there has been an increased focus on this issue. This has led to several manufacturers such as Apple and John Deere being criticized for making it difficult for consumers to repair their products by limiting access to spare parts and repair information.

7.5 Support for recycling initiatives in Norway

In Norway, various support schemes exist through which one can apply for funding to facilitate recycling efforts. Financial support can be sought from agencies such as the Norwegian Environment Agency and Innovation Norway, through programs like the Environmental Technology Scheme and Climate Commitment. The Environmental Technology Scheme provides grants for the development, piloting, and demonstration of new environmental technologies. This scheme is applicable to innovative products or processes that address an environmental issue and is directed towards Norwegian businesses from all industry sectors. For instance, the Environmental Technology Scheme has previously provided grants covering up to 40 % of the costs associated with the development and demonstration of environmental technology [83].

"Klimasats" is a support scheme for municipalities aiming to reduce greenhouse gas emissions and contribute to the transition towards a low-emission society. In the 2023 state budget, NOK 100 million has been allocated for the "Klimasats" initiative.

8 Quantitative Results

8.1 Introduction of Survey

The report presents the results of the survey conducted by the companies. The survey's primary objective was to gain insights into the challenges and opportunities related to the recycling of electric motors and to assess the level of knowledge and awareness among companies regarding this field. The survey aimed to provide valuable insights into companies' current practices, their motivations, and the barriers they face in the recycling process, which can inform future strategies and policies to improve EEE recycling.

8.2 Background of Respondents

A total of 13 questions were included in the survey, which aimed to provide an overview of the sectors the respondents belonged to, the number of electric motors they utilized, their practices and knowledge of recycling processes, and the measures they believed were necessary to make recycling electric motors easier. The survey received nine answers, a response rate of 65%, with respondents representing various industries and company sizes.

The majority of companies that participated in the survey operate in the manufacturing sector, accounting for six of the nine responses. The total overview of the sector distribution and annual production/usage is presented in Figure 25.

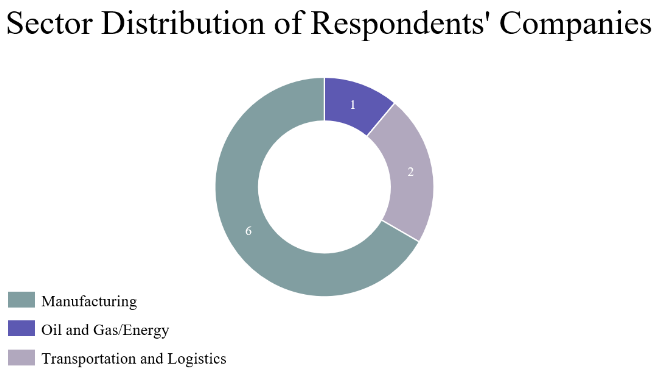

Figure 25: Distribution of Respondents' Companies and Annual Production/Usage of Electric Motors in various sectors.

To better understand the relevance of the topic among the survey participants, the annual production/usage of electric motors was examined. None of the companies reported usage below 50 motors, with six companies reporting between 100-500 electric motors in use. The distribution of these responses is visually depicted in Figure 26.

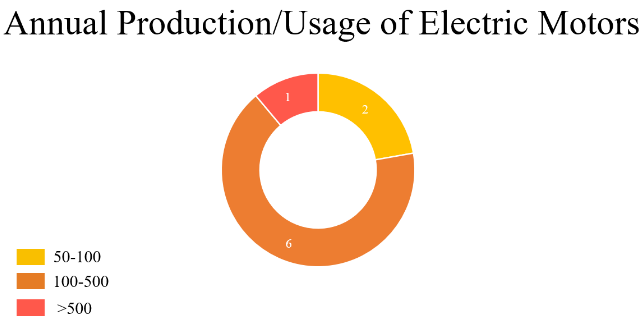

Figure 26: Distribution of Respondents' Companies and Annual Production/Usage of Electric Motors in various sectors.

8.3 Recycling Practices in Companies

Figure 27 illustrates a distribution of how different companies handle the recycling of electrical equipment after its EOL. The data reveals a relatively even distribution, with a slightly larger number of companies having established a recycling plan compared to those without a specific plan for the process. The companies that do not have a recycling plan in place claim that it is not available. However, 56 & of the companies already have a recycling plan in place, demonstrating that this claim is inaccurate. This discrepancy may be attributable to a lack of knowledge or awareness. As shown in Figure 27, among those with a plan in place, the majority send the equipment to a recycling organization for processing.

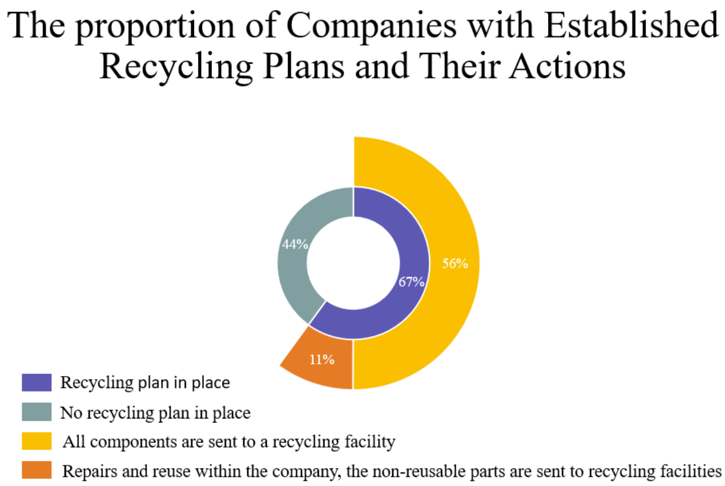

Figure 27: Proportion of companies with established recycling plans.

An initial question at the beginning of the survey aimed to gauge the perspectives of different companies on the reuse and repair of electrical equipment. The majority of respondents indicated that they consider reuse and repair, but the decision depends on costs and time spent on these processes. Only two companies reported always prioritizing reuse and repair over recycling. Three respondents said they always prioritize recycling over reuse. Some companies provided multiple responses, making analysis more difficult. It can be concluded that three out of nine companies send everything directly to recycling, while the remaining six consider direct reuse and repair before sending the equipment for recycling.

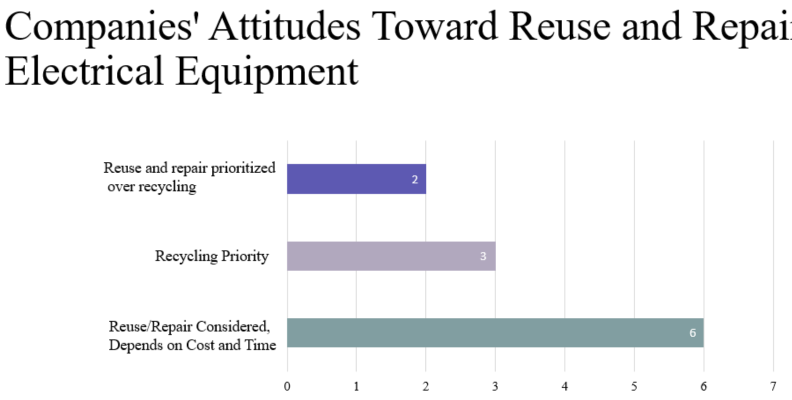

Figure 28: Companies view on reuse and repair of electrical equipment

8.4 Challenges and Barriers to Effective Recycling

Figure 29 shows the challenges or barriers to effective recycling of electric motors. The chart indicated a significant lack of knowledge surrounding the recycling of electric motors. Three respondents attributed this to costs. Initially, payment is received for delivering electrical machines for recycling. Four respondents mentioned the lack of recycling processes. The majority noted that a significant challenge is the lack of knowledge and awareness regarding what is possible and not when it comes to recycling electric motors.

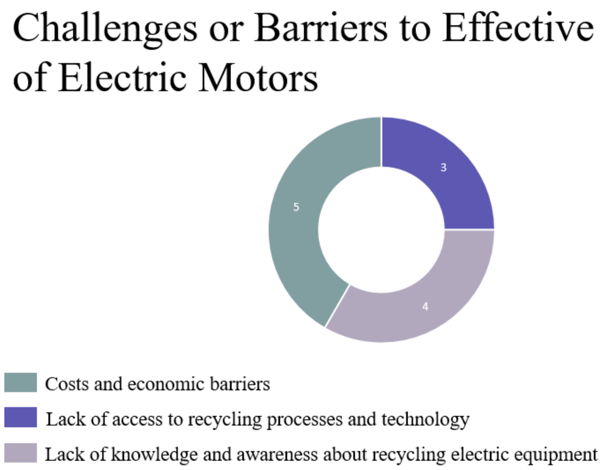

Figure 29: Challenges or Barriers to effective recycling of electric motors

8.5 Opportunities to Improve Recycling

The companies were asked how the recycling of electric motors could be improved. The results are presented in Figure 30, showing that the companies in this question answered several answers. The results indicate that the companies believe they need more practice and awareness on how to handle the recycling of electric motors. Six of the companies also suggested that economic support or incentives from the government would improve recycling. Four companies said that increased access to facilities and technologies may improve recycling. Given that there are already several ways and recycling facilities available, this implies that awareness of these possibilities may be insufficient.

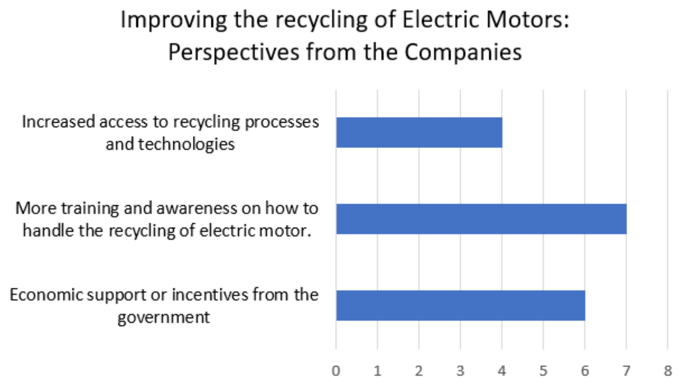

Figure 30: Improving the recycling of electric motors: Perspectives from the companies

The previous question indicates that the majority of companies believe knowledge regarding the recycling of electric motors should be disseminated and taught more broadly. Another question in the survey asked how awareness can be improved, as shown in Figure 31. Here, eight out of nine respondents answered that companies can become more conscious about recycling through economic incentives or advantages. Additionally, six out of nine respondents said that training and raising awareness among employees and managers can make them more conscious of how to handle e-waste, particularly electric motors.

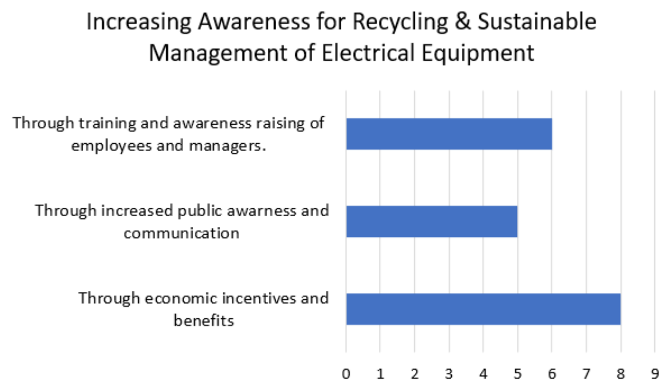

Figure 31: Methods to increase the awareness for recycling and sustainable management of electrical equipment.

8.6 Open Questions

In addition to the multiple-choice questions, some open-ended questions were asked. The number of responses varied, and those who responded provided relatively similar answers. The responses were assessed based on the number of similar answers given.

The first question included which costs the companies had according to the recycling of electric motors and other electrical equipment. Most companies reported that they receive payment for delivering e-waste. They also mentioned that the amount they receive depends on various factors, primarily the recycling value of the different materials. The treatment of electronic waste often requires specialized processes and technologies, resulting in significant costs. Additionally, costs related to collection and transportation affect earnings. By accumulating larger quantities of waste, transportation costs per unit are reduced, thus increasing profitability.

Another question asked was: What factors play a role when your company decides what to do with electrical equipment after its EOL? It appears that all companies evaluate electrical equipment after reaching its EOL. The thoroughness of the evaluation varies among companies. Based on the responses, most consider what is most profitable in terms of both the environment and material earnings. A few respondents stated that they conduct a step-by-step assessment, which involves first examining the condition of the equipment to determine if it can be repaired.

Another area investigated was how a lack of recycling of electrical equipment would impact the company. In this regard, 7 out of 9 respondents stated that the loss of resources would result in economic losses and emphasized the importance of environmental conservation. Failing to recycle waste resources, leads to a loss of value. There is also an increasing focus on sustainability and environmental conservation.

The survey also explored what motivate companies to place an even greater focus on recycling. Three recurring themes emerged:

- Environmental savings
- Value creation
- Economic incentives

Another question asked about the challenges or obstacles companies have encountered concerning the recycling of electrical equipment. Upon analyzing the nine responses, it appears that the most significant challenge is related to having a detailed plan for the recycling process, making it clear what should be done with all components. For example, how a motor should be recycled - whether it should be discarded as a whole, whether parts should be separated as much as possible before being discarded with similar components, or whether it should be discarded based on the materials it consists of. Another challenge with recycling electrical equipment, particularly electric motors, is the ability to reuse components directly. Most companies recycle entire electric motors, even though many parts are functional and can be reused.

8.7 Implications for Policy and Practice

The results from the survey give important insight that can shape future strategies for handling electric and electronic waste (e-waste), specifically focusing on electric motors. In particular, there is a clear need for improved education and communication in this area given the different levels of awareness and knowledge about recycling processes among the surveyed companies.

The survey indicates that there is a serious lack of knowledge about what can and cannot be done when it comes to recycling electric motors. This is despite the fact that a number of companies have recycling plans in place. If this knowledge gap is not closed, recycling strategies may not be implemented effectively, which would prevent the full potential benefits of e-waste recycling from being realized.

In addition to boosting awareness, the findings indicate that economic incentives play a key role in promoting recycling practices. The companies said they would be more inclined to invest in recycling efforts if they were given financial assistance or benefits. This emphasizes the potential for governmental actions like subsidies to motivate businesses to adopt more environmentally friendly practices.

Finally, the survey findings also highlight the possibility of direct reuse and repair of electric motors. While some companies already give this strategy priority, others choose immediate recycling. Increasing the capacity for repair and reuse within businesses could help further reduce waste and conserve resources.

As a result, this study provides a spotlight on a number of relevant topics that can direct toward the development of more efficient e-waste management strategies. A more sustainable and effective method of handling electric motors at the end of their useful lives can be encouraged by addressing the knowledge gaps, financial limitations, and procedural challenges mentioned in this section.

9 Design Criteria for Electric Motors

In this chapter, the primary focus is to establish design criteria for electric motors with the aim of enhancing their recyclability. As the demand for sustainable and eco-friendly practices grows, it is essential to develop criteria that contribute to a circular economy and reduce the environmental impact of EOL electric motors. This chapter will delve into the concepts of design for recycling, raw material recovery, and component reuse opportunities in the context of electric motors. By examining these concepts, the chapter aims to present a set of design criteria that can be adopted by the industry to improve the recyclability of electric motors, thereby promoting sustainable practices and resource conservation.

9.1 Design for X Principles and Their Role in Enhancing Electric Motor Recyclability

The "Design for X" principles, frequently referred to as DfX, are guidelines used in the design of products with the aim of optimizing various aspects of a product's lifecycle. The "X" refers to a particular area, such as manufacturing, maintenance, environment, efficiency, longevity, recyclability and disassembly. Although each of these areas are important to the product lifecycle, the "Design for Recycling" (DfR) is the main area of attention in this chapter. This emphasis is driven by the imperative to protect the environment and effectively use resources throughout a product's lifecycle.

Design for Recycling is a specific DfX principle that focuses on designing products to ease and enhance the recycling process after EOL. This principle plays a critical role to develop design criteria for electric motors, considering the growing environmental concerns surrounding material waste and the limited resources of materials such as copper.

9.1.1 Design for Manufacturing

Design for Manufacturing has become a key area in product development. The primary goal for DfM is to provide a link or integration between the manufacturing process and product design phase. This should contribute to simplifying the design and making it more suitable for manufacturing, which can result in cost reduction and improved efficiency in the production phase. In the context of electric motors, this may involve designing motors in such a way that they can be produced using existing manufacturing lines, mitigating the need for specialized or expensive manufacturing techniques. For the production of electric motors, there are several factors that need to be considered for DfM.

Manufacturing Process Integration: In the design phase of electric motors, it is important to take into consideration the already existing manufacturing lines and processes. This is to avoid the need for specialized or unique manufacturing setups wherever possible. This will result in reducing manufacturing complexity and costs while also potentially increasing the speed of production.

Component Design: The design of each component is very important in DfM as this aims to simplify their complexity and therefore also their manufacturing. Electric motor components often include a multitude of complex components, which should be designed with manufacturability in mind. This includes considering factors such as the ease of machining or molding, the need for special manufacturing techniques, and the implications for assembly and maintenance.

Material selection: The choice of materials is essential to DfM as it can significantly impact the ease of production, cost-effectiveness and quality of the product. In the design process of electric motors, it is crucial to select materials that have a balance between performance requirements and manufacturing considerations. This might involve the evaluation of trade-offs between material properties such as durability, strength, conductivity versus cost, availability and the ease of working with the material in a manufacturing context.

Standardization: To reduce complexity and cost, DfM frequently promotes the use of standardized parts and procedures. In electric motor design, this might mean standardizing certain parts across different motor models to allow for better-streamlined production and easier maintenance.

The principles of DfM do not operate in isolation but instead interact with other designs for X principles. For instance, Design for Environment (DfE) can be considered concurrently with DfM. This ensures that the product is not only designed to be efficient and straightforward to manufacture but also environmentally friendly throughout its lifecycle. Factors related to DfE will be presented in 9.1.3. Efficient implementation of DfM principles can facilitate a more streamlined and cost-efficient production of electric motors. This doesn't just contribute to a more sustainable manufacturing process but also contributes to producing a higher quality product with longer longevity. This promotes more sustainable consumption patterns and waste management strategies for electric motors.

9.1.2 Design for Maintenance

The design for Maintenance (DfMn) is a key principle within the broader " Design for X" methodology especially when recycling is a top priority. The goal with DfMn is to make sure that the product is made in a way that makes it simple to service, repair, and maintain. This can potentially reduce the lifecycle cost of the product and increase its lifespan, contributing to overall sustainability.

Adherence to these principles is crucial for electric motors. An intentional focus on such procedures ensures the ease of repairs and component replacements, thereby extending the useful life of the product. It also aids in preventing the unnecessary recycling of functional components, thereby reducing waste. In addition, regular maintenance is essential to ensure optimal performance. These elements underscore the criticality of various considerations within the area of Design for Maintenance (DfMn).

Ease of Disassembly and Repair: The product should be designed to facilitate easy disassembly for repair. For electric motors, this should involve considerations about how components are connected or fastened and how accessible they are for service personnel. Simplifying disassembly could also reduce the time and cost of repair operations.

Component Durability and Lifespan: The selection of durable materials and components that can withstand the operational stress exerted on them over time is crucial. This may minimize the need for frequent replacements or repairs, thereby enhancing the motor's longevity and reducing maintenance costs.

Standardization: Similar to the DfM principle, standardization plays a significant role in DfMn. The use of standardized components across different motor models can simplify the maintenance process by reducing the number of unique parts that need to be stocked for repairs.

Maintenance Indicators and Diagnostics: Integrating indicators for preventive maintenance or diagnostic capabilities into the motor's design can help to predict and plan for maintenance needs. This might prevent unplanned downtime and enhance the reliability of the motor.

Overall, Design for Maintenance plays a critical role in improving the efficiency and sustainability of electric motors. By considering maintenance requirements during the design phase, it is possible to extend the operational lifespan of the motors, reduce the need for frequent repairs or replacements, and thereby contribute to more sustainable usage patterns of these essential devices.

9.1.3 Design for Environment

Design for Environment (DfEn) is a central principle in the broader Design for X methodology, especially when environmental awareness and sustainability are in focus. The aim of DfEn is to ensure that the product is designed in a way that decreases the environmental impact throughout the entire life cycle, from production to disposal. Designing the electric motors based on the environment will ensure that the environmental impact is minimized, both through the reduction of resource use and emissions in production, and by extending the useful life of the product.

Material selection: The evaluation of which materials to use in components is an important factor within the DfEn. The product should be designed with environmentally friendly materials. For electric motors, this may involve the use of materials with a lower environmental impact in production, or with an ability to be reused or recycled at EOL. If the materials can not be recycled it is important to use resources that are not limited. DfEn entails selecting low impacts materials, that are recyclable and uniform where possible. One example of an electric motor design that uses low-impact materials and energy-efficient manufacturing processes is the permanent magnet motor. These motors use permanent magnets instead of electromagnets to generate the motor's magnetic field, which can result in higher efficiency compared to conventional induction motors. Furthermore, efforts have been made to reduce the use of rare earth metals in these magnets due to their environmental impact and extraction cost.

Selection of Assembly Technique: The choice of assembly technique can affect which materials can be used on the electric motor. A relevant example of DfEn principles applied in the context of electric motors can be seen in the design of many larger motors. These motors are not encapsulated but instead assembled using screws, bolts, and other detachable fasteners. This assembly strategy not only facilitates disassembly but also avoids the use of non-recyclable materials such as epoxy, thereby improving the motor's overall recyclability.

9.1.4 Design for Efficiency

Design for Efficiency (DfE) applies to the optimization of energy and material use in product design and operation. Although efficiency doesn't directly influence the recyclability of a product, it plays a significant role in its overall sustainability by minimizing resource consumption throughout its lifecycle.

Material Efficiency: Material efficiency is also crucial to Design for Efficiency, which seeks to reduce waste and make the most out of resources. This can be achieved through strategies such as material reduction, using recyclable materials, uniform materials where possible, and a minimal number of components. Simplifying assembly methods not only makes the manufacturing process more efficient but also facilitates disassembly for repair and reuse.

Production Efficiency: The simplification of the assembly method used will increase the efficiency of the production process and also makes disassembly easier so that it is easier to repair and reuse components. The use of adhesives such as Epoxy for bonding components is very efficient but it causes challenges during disassembly. It is therefore an important point to consider the balance between production efficiency and after-use value when making decisions.

9.1.5 Design for Longevity

Design for Longevity is a principle that aims to extend the lifetime of a product through enhanced durability and upgradability. Longevity might not directly affect the recycling process, but it significantly contributes to sustainability by delaying the need for replacement, thus reducing waste.

Material selection: The choice of materials is a critical aspect of design for longevity. Employing durable materials that can withstand external influences and maintain their integrity over time is essential. For instance, using corrosion-resistant materials for objects exposed to water can significantly enhance their lifespan.

Modularity: Designing electric motors in modules makes it easier to replace or upgrade components. However, an assembly method that allows the modules to be separated is equally important, otherwise modularity will have no effect. There are associated challenges when considering such a modular system. For example, the risk of unintentional module detachment during the use of electric motors may cause safety concerns and can lead to motor failure or loss of control. Therefore, designing reliable attachment mechanisms is of paramount importance. Techniques such as a secure lock-and-key mechanism can offer more robust connections, ensuring modules remain securely attached even under strenuous operating conditions.

Repairing components: Ensuring easy access to internal components and standardized parts is essential to facilitate the repair of different motors. Simplicity in assembly and disassembly can also ease repair and recycling efforts. For instance, using easy-to-disassemble screw and bolt connections or snap-fit components can facilitate the separation of different materials and components for efficient recycling and maintenance.

Reducing maintenance: Designing electric motors with low maintenance intensity can reduce the risk of failure and thereby extend the product's lifespan. This can be achieved by using an assembly method like encapsulation to protect the components from external stresses. Considering the weight implications of additional components like connectors and fastening mechanisms is crucial, given the weight-sensitive nature of certain applications. Potential solutions may involve the use of lightweight materials and compact fastening mechanisms to minimize weight increases while maintaining secure attachment.

Design for Longevity also inherently incorporates considerations for the product's EOL stage, emphasizing design for easy disassembly, repairability, and recyclability. These considerations make the product lifecycle more sustainable by reducing waste and encouraging reuse and recycling.

9.1.6 Design for Recyclability and Disassembly

Design for Recycling: The Design for Recycling (DfR) principle, as part of the broader Design for X (DfX) methodologies, specifically addresses the EOL phase of products. DfR advocates for designing products in such a way as to facilitate their recycling post-EOL, ultimately promoting material recovery and reducing waste. With respect to electric motor design, DfR considerations should ideally influence the material selection, component design, and assembly methods.

One key strategy for DfR is the use of homogeneous materials or material combinations that are easily separable. This reduces the complexity of the recycling process, and consequently, its cost. For instance, using fewer materials in motor components or employing clear labelling of plastic parts might greatly improve recyclability. However, the selection of materials also have a significant impact on motor performance. Therefore striking the balance between recyclability and functionality can be challenging.

Another approach within DfR is designing components that can be reused in their entirety. For instance, modular motors can allow for the replacement of specific parts, thereby reducing the need for complete motor replacement and contributing to waste reduction.

Design for Assembly and Disassembly: Design for assembly and disassembly (DfA&D) is another important principle, closely related to DfR. It involves designing products to facilitate their disassembly, which can simplify maintenance, repair, and recycling processes. In electric motor design, DfD implies creating a product that can be easily separated into its components at its EOL.

Techniques that enhance the ease of disassembly include the use of modular designs and non-destructive fastening methods, such as screws, bolts, and clips. This approach has been discussed in detail in the previous sections, emphasizing its potential to improve both the product's longevity and its EOL management.

However, DfD also poses challenges, particularly for smaller, high-performance electric motors where compactness and weight are critical factors. For such motors, using fasteners can add to the motor's size and weight, potentially affecting its performance. Therefore, innovative design strategies must be pursued to overcome the challenges without compromising on motor performance or durability.

9.2 Criteria for Sustainable Electric Motor Design

The design of electric motors requires careful consideration of several interconnected factors to be more sustainable. The factors involve a complex relationship between functionality and recyclability, ease of disassembly, and strategic material selection. This section will examine these criteria, illustrating their significance and implications for electric motor design. Based on the Design for X principles that have been examined, it becomes evident that certain factors consistently emerge across various aspects. Among others, these factors include material selection and the employed assembly method in terms of ease of disassembly.

9.3 Criteria for sustainable Electric Motor Design

Achieving sustainability in electric motor design requires careful consideration of multiple interconnected factors. This section will further discuss these factors, illustrating their importance and their implications for electric motor design. Based on the design for X principles that have been examined, it is evident that certain factors are consistently present across most aspects. These factors include, among others, material selection and the assembly method employed in terms of ease of disassembly.

9.3.1 Functionality vs Recyclability

The balance between functionality and recyclability presents a significant challenge in modern engineering design and manufacturing. However, it also creates opportunities for creative and innovative solutions. Industries are struggling with these two interconnected facets of product design and development as sustainability gains traction worldwide.

Functionality, which encompasses elements like ideal performance, dependability, and efficiency, continues to be crucial in any product or system. For instance, to ensure operational safety and efficacy, the design and assembly of electric motors require a high degree of functionality. In high-demand applications like drones, factors like weight, strength, dependability, efficiency, resistance to corrosion, and maintainability are especially important. Concurrently, increasing product recyclability is necessary due to the global movement toward sustainability. Engineering efficient, long-lasting products that are also simple to disassemble and recycle at the end of their useful lives is the aim. The principles of a circular economy, which promotes minimizing waste and maximizing resource optimization, are in line with this vision.

The pursuit of this balance is challenging and it is essential not to compromise product functionality in the quest for recyclability. A highly recyclable electric motor that fails to deliver on performance, safety or reliability offers little value. A high-performance product with low recycling potential might jeopardize sustainability goals by contributing to environmental degradation. Therefore, the challenge is to successfully combine functionality and recyclability while designing and producing products that meet performance standards and take end-of-life processes into account. This integration necessitates a thorough knowledge of the product lifecycle, creative design methods, and perhaps a change in the choice of materials and processes.

In conclusion, the complexity of contemporary product design is exemplified by the relationship between functionality and recyclability. To satisfy both the performance needs of the present and the sustainability requirements of the future, it is necessary to achieve an equilibrium between these factors.

9.3.2 The Impact and Importance of Ease of Disassembly in Electric Motors

The design of electric motors for easy disassembly plays a crucial role in their overall life cycle. It affects areas such as maintenance, upgradeability, recycling and direct reuse.

The ease of disassembling electric motors results in an easier maintenance and replacement process of the components during their life cycle. This can contribute to an extended lifespan of the electric motor, increasing overall efficiency and cutting waste. The components in an electric motor can wear out over time. The overall time and resources required for maintenance decrease with an easily disassembled electric motor, resulting in better cost-effectiveness in the process of disassembly.

In the rapidly evolving world of technology, it is very important to have the ability to upgrade components. This can greatly enhance the electric motors' relevance in the field of electric motors. An electric motor that is designed for easy disassembly allows for the replacement of outdated parts with newer and more efficient ones. This will not only improve the performance of the motor but also its sustainability by extending the lifespan and reducing the need for entirely new motors. An illustrative example of this can be drawn from the scenario where customers require higher performance requirements for electric motors. Instead of withdrawing all electric motors and replacing them with brand new ones, it would be more efficient to upgrade only the necessary components to meet the new requirements. This approach leverages the modularity of the motors, enhancing their adaptability to changing requirements while minimizing waste and resource expenditure.

The ease of disassembly is essential for the effective management of electric motors at EOL. The ability to disassemble an electric motor make material recovery easier, which provides several advantages. For instance, the direct reuse of functional components and recycling of non-functional components contribute to increased resource- and energy efficiency throughout EOL management. By extracting non-functional components and replacing these with functional reused components one can increase the lifespan of the electric motors. The damaged components that are further disassembled into different material groups before recycling can contribute to a lean process. This ensures a reduced necessity for the post-fragmentation material separation process. Each step involved in the recycling process consumes energy and resources, and by minimizing the number of production steps, the environmental impact can be reduced. Additionally, a reduction in steps can minimize material contamination and loss, facilitating the recovery of high-quality materials. Such practices foster a more circular material flow and diminish the reliance on virgin resources.

Alva's electric motor can be partially disassembled, enabling the reuse of different modules even if another part is damaged. For instance, if the rotor module is damaged there is a possibility that the stator module or other components such as bearings still can be reused. However, it is quite challenging to disassemble each module to the extent that its constituent parts can be reused without damaging or altering the materials' properties. This difficulty is primarily due to the use of epoxy resin for bonding, as previously mentioned in section 2.4.1. This results in the scenario where, if a module becomes damaged, the entire module needs to be recycled.

In order to improve resource utilization, recycling effectiveness, and overall sustainability throughout the lifecycle of electric motors, disassembly capability must be increased. However, it is crucial to weigh these benefits against any potential disadvantages, such as any possible effects on motor size, weight, safety, and operational robustness. Therefore, decisions regarding disassembly design should be made holistically, taking into account both short-term functional needs and long-term environmental and resource implications.

The ease of disassembly must be weighed against other functional requirements. For instance, a motor that is simple to disassemble might not be as strong or long-lasting. Additionally, some motor designs might need a higher level of integration and compactness depending on the intended application, which might conflict with how simple it is to disassemble. For instance, the need for lightweight and small motors in drones and other small, mobile applications can make disassembly more difficult. Another important factor is safety, as designs that are simple to disassemble may expose users to risks if they are not properly controlled.

In conclusion, designing electric motors for easy disassembly is a complex task that requires balancing a wide range of functional and life cycle considerations. However, with careful consideration and planning, it is possible to design motors that are not only high-performing and safe but also sustainable and ready for the circular economy.

9.3.3 The Impact and Importance of Material Selection in Electric Motor Design

The material selection has a significant impact on both the motor's operational efficiency and the effectiveness of the recycling process. The selection contributes to shaping the performance and longevity, and overall environmental footprint of electric motors. It is a complex process affected by a variety of factors and aspects that can create trade-offs between different desired outcomes.

Firstly, the choice of material has a direct impact on motor performance characteristics like efficiency, power density, and torque characteristics. For example, the cores of electric motors are usually composed of electrical steel, a soft magnetic material characterized by high permeability and low power loss. These characteristics make it possible to generate magnetic fields effectively, which is essential for motor operation. Similarly, due to their powerful magnetic qualities and high-temperature functionality, rare earth elements (REEs) are frequently used in permanent magnet motors. Although these materials significantly improve motor performance, the environmental and geopolitical ramifications of their extraction raise questions about their sustainability.

However, the design of specialized motors, such as the Alva X60-Kv120 used in applications like drones, requires careful evaluation of supplementary material characteristics. Drone motors must withstand a variety of conditions, necessitating the use of materials with particular properties. One important factor is lightness. Because a lighter motor uses less power to lift and move the drone, reducing the motor's weight directly improves the drone's overall flight efficiency. Longer flight times and higher payload capacities may result from this. Another important factor is water resistance. Drones frequently operate outside and will likely be exposed to bad weather, like heavy rain or high humidity. To ensure operational dependability and longevity, the materials used in the motor should be water- and corrosion-resistant. The materials must also be strong enough to withstand the mechanical strains that are experienced during flight. The motor's rapid rotations as well as the dynamic forces felt during acceleration, deceleration, and direction changes are among them. In summary, a variety of factors, such as weight, water resistance, and mechanical strength, should be taken into account when choosing materials for drone motors. By balancing these variables, motors with high performance and durability may be produced, enhancing drones' operational capabilities.

Electric motor material selections have a variety of environmental effects. First off, the extraction and processing of some materials can have a significant negative impact on the environment. For instance, mining REEs requires a lot of energy, is frequently linked to severe ecological harm, and has a finite supply. This not only prompts questions about sustainability but also leaves supply chains open to geopolitical risks. Second, a key consideration in determining the material's environmental impact is its embodied energy, which refers to the total energy needed for its extraction, processing, and transportation. The overall energy consumption and greenhouse gas emissions linked to the manufacture of motors are increased by materials with high embodied energy. Recycled materials can therefore significantly reduce the embodied energy and, as a result, the environmental impact of the motor. Thirdly, material selections also have an impact on how electric motor EOL management is handled. The composition of used motors has a significant impact on the materials that can be recovered and recycled from them. Certain substances, like the epoxy resin that is used for bonding, as mentioned above, can impede recycling and degrade the quality of the materials that are recovered. This difficulty, along with the rising demand for electric motors, emphasizes how critical it is to use a design for recycling (DfR) strategy.

Design for recycling primarily aims to ease the EOL processing of products, while maximizing material recovery and reducing the environmental footprint. The choice of material is crucial when creating electric motors using this method. While sometimes performing worse than their non-recyclable counterparts, recyclable materials greatly improve the motors' overall sustainability. Design for Recycling prioritizes the practical aspects of the recycling process itself in addition to the environmental effects. Material selections need to be carefully considered not only for their ability to be recycled but also for how easily they disassemble and how materials separate during recycling. If not carefully chosen, using recyclable materials might unintentionally shorten the lifespan of the motor. The frequency of recycling has increased, and more motors are being produced, which might increase energy demand. So, in order to maximize the environmental advantages, the material selection process must strike a balance between performance, durability, and recyclability.

Finally, it is important to remember that material decisions also have social and ethical ramifications. Certain materials can be mined in ways that raise ethical questions about human rights, and recycling procedures can raise similar issues when done improperly. As a result, material selection for electric motors is a multifaceted decision encompassing environmental, economic, social, and ethical considerations. A thorough life cycle assessment (LCA) can offer a structured methodology for evaluating these factors, enabling more sustainable and informed decisions to be made regarding the choice of materials. Manufacturers can minimize these effects where possible by using a well-conducted LCA to fully understand the environmental effects of their material selections, from raw material extraction to EOL disposal.

9.3.4 Establishing Design Criteria for Recycling

The design criteria outlined in Table 17 aim to modify the design of electric motors in a way that better accommodates environmentally friendly recycling techniques. These criteria were established based on the insights gathered in the preceding chapters. "Integrating these criteria into the design phase of electric motors aims to develop a more sustainable design. Such design is anticipated to be more conducive to direct reuse and recycling, aligning with the existing state of design standards and recycling infrastructure

The symbols used in the table are interpreted as follows, in the context of the Alva motor design:

-	The criterion is not met.
◯	The criteria is partially met.
+	The criterion is significantly met but not completely.
++	The criterion is fully met.
x	The criterion is not applicable.

Table 17: Design criteria for Alva

Design for "X"	Design Principle	Criteria	Alva
DfM	Material Selection	Choose recyclable and cost-effective materials	+
	Process optimization	Simplify processes, reduce process steps, suitable for automation.	◯
	Component Simplification and Standardization	Limit the number of unique parts, use standard components.	+
DfA/DfD	Modular Design	Modules that can be upgraded or replaced without replacing the entire system.	+
	Non-destructive Disassembly	Allow disassembly without damaging components.	◯
	Minimizing the Number of Connections	Limit the number of connections between parts.	x
DfMn	Easy Access to Components	Make maintenance parts easily accessible	◯
DfE	Use of Environmentally Friendly Materials	Choose materials with low environmental impact throughout the lifecycle.	+
	Toxicity Reduction	Limit the use of toxic materials, plan for safe disposal and/or recycling.	+
	Use of Renewable or Recycled Materials	Use renewable or recycled materials where possible.	+

Explanation of Grading:

These criteria has received [+] due to the following reasons:

- **Materials:** All materials without epoxy are recyclable.
- **Modular Design:** The motor is partially modular.
- **Environmentally Friendly Materials:** The presence of epoxy prevents this criterion from being fully met.
- **Toxicity Reduction:** Epoxy is a toxic material, however, the remaining materials are within acceptable limits.
- **Renewable Materials:** Epoxy cannot be recycled.

This criterion has received [◯] due to the following reason:

- **Process Optimization:** The process consists of several time-consuming and demanding techniques to achieve the final result.

This criterion has received [x] due to the following reason:

- **Minimizing the Number of Connections:** The use of adhesive bonding to assemble the motor does not facilitate the disassembly process, which is the intention behind this criterion.

To conclude, the assessment indicates that the use of epoxy in Alva's electric motors prevents them from fully meeting the established design criteria aimed at recyclability. The analysis underscores that epoxy is the primary element hindering these motors from satisfying the design criteria. Consequently, exploring potential substitutes for epoxy can significantly increase the sustainability of Alva's motors. By actively pursuing these improvements, Alva could potentially engineer a more environmentally friendly, efficient, and recyclable electric motor, thereby aligning more closely with sustainability goals.

9.3.5 Design Recommendations for Sustainability

In addition to the design criteria that directly influence recyclability, there are several factors that influence the overall sustainability of electric motors. These factors have a significant impact on the product's environmental footprint over the course of its lifecycle, even though they are only loosely related to the recycling process. Therefore, it is crucial to include these factors in the design strategy for environmentally friendly electric motors. The Table 18 presents an extended view of the design principles that can aid in the development of environmentally responsible electric motors and offers a set of design recommendations aimed at enhancing sustainability.

Table 18: Indirect design recommendations for electric motors

Design for "X"	Design Principle	Recommendations
DfMn	Durable and Long-lasting Components	Withstand wear over time, reduce maintenance needs.
DfE	Energy Efficiency	Maximize energy efficiency during normal operation.
DfEn	Life cycle assessment	Designing motors with their full lifecycle in mind, from raw material extraction to waste management.
	Material footprint	Minimizing the use of rare or harmful materials to reduce environmental impact.
DfL	Durable Materials	Selection of durable materials that can withstand stress over time.
	Over-Engineering	Designing for overcapacity to extend the motor's lifespan and reduce the frequency of replacement and recycling.

9.4 Recommended Changes for Alva Industries

Based on the previous analysis and criteria established, it is possible to recommend specific changes to the design of electric motors that may enhance their sustainability and recyclability. The choice of materials, ease of product disassembly, and the balance between a product's functionality and its recyclability are important factors to take into account when applying DfR. The choice of material is crucial because it affects a product's functionality, durability, and recycling potential. The effectiveness of the recycling process is directly impacted by how easy it is to disassemble a product because easier-to-disassemble products can be recycled more quickly and affordably. When EOL treatment options are taken into account during the design stage, the product can be handled in the most environmentally friendly way possible when it comes to EOL.

9.4.1 Material Selection

In terms of material choices for Alva's electric motors, it appears that all materials are recyclable except for epoxy. Epoxy is used to encapsulate the electric motor to protect the components and to attach them to each other. The use of adhesive bonding is probably the best assembly method for electric motors used for applications like drones due to their compact and lightweight design compared to using screws, bolts, or snap-fit solutions. The use of adhesives is also a very sturdy assembly method that provides good protection for the components and ensures the longevity of the motor. Due to the fact that adhesive bonding is the most beneficial assembly method for Alva, it is necessary to examine alternatives that can be used in place of epoxy resins with relatively similar thermal and mechanical properties along with the ease of disassembly and recycling. The polyester resins examined in section 2.5 showed potential for substituting epoxy in electric motors by providing all the thermal (melting point and Tg), physical (weight, adhesion and fluidity) and mechanical (strength and toughness) properties along with recycling convenience. The following list describes a summary of the different materials examined:

Polyurethane (PU): PU appears to be a viable substitute due to its high mechanical strength, thermal stability, and electrical insulating properties. Particularly considering how easily their structure can be altered to achieve thermoplastic properties, making them easier to disassemble and recycle then Epoxy.

Silicone-based Resins: They have exceptional high-temperature tolerance and electrical insulating abilities. Silicone-based resins might be a good replacement for epoxy because of their elasticity, which makes disassembly during recycling easier.

Polyester Resins: Polyester resins have excellent mechanical properties, thermal stability, and electrical insulation, and are frequently used in electric motor applications. They are better suited for recycling because of their linear structure (as opposed to epoxy resins' cross-linked structure).

Polyimide: Polyimide is resistant to high temperatures without suffering much damage because of its exceptional thermal stability and superior electrical insulating properties. They are less difficult to recycle than epoxy resins, despite the fact that the material is highly crosslinked and thermally stable structure.

Bio-based Epoxy Resin: A bio-based epoxy system like VAN-AC-EP/DDM might be a sustainable alternative to traditional epoxy Resin. It contains enhanced energy efficiency, good thermal and mechanical qualities, potential for recycling, and eco-friendly waste disposal. By utilizing a bio-based epoxy one can lower the risk of environmental destruction. This is due to the fact that the material naturally degrade. Alva can compare bio-based epoxy resin to the epoxy they are using today to assess the differences. In this way they can determine if the material can be used without loss of performance.

In order to determine which new adhesive to use it is important to take into consideration the specific requirements of the motors, the trade-offs between different material properties, as well as the feasibility of manufacturing and recycling processes. These options, however, represent a promising starting point for exploring viable epoxy substitutes.

9.4.2 Assembly technique

The selection of an appropriate assembly technique plays a vital role in the design and manufacturing of electric motors. This is because it not only influences the performance and durability of the product but also its recyclability. The most suitable assembly technique for Alva Industries' motors is therefore evaluated. The four assembly methods being considered are press fit, snap fit, threaded fasteners and adhesive bonding.

There are several strategies to make electric motors easier to disassemble. One technique is modular design, where the motor is created as a collection of independent modules that are simple to separate and reassemble. Snap-fit components or detachable fasteners like screws and bolts can help make disassembly easier. In addition, methods like using low-impact or reversible adhesives in place of permanent bonding techniques can also be a solution to ease disassembly.

Adhesive bonding can be an advantage in terms of strength and load distribution, particularly in the case of electric motors that require maintaining structural integrity and minimizing deformations during use. Adhesive bonding proves beneficial with regard to weight savings, a crucial factor for drones, and it can also enhance motor efficiency. By using adhesive bonding, load distribution and structural integrity, which are crucial for effective motor operation, are provided. However, the limitations of adhesive bonding, particularly in relation to recyclability, must be considered. The difficulty of disassembling components joined by this method can hinder the recycling process, potentially resulting in less efficient recycling and increased waste. This is because epoxy is difficult to separate from other materials. Epoxy-contaminated materials, such as copper, will inhibit reduced quality. Additionally, epoxy cannot be reused, resulting in its disposal. Adhesive bonding may pose some challenges in drone applications. The fluctuating temperature conditions and associated thermal stresses can impact the longevity and reliability of the adhesive bond. Additionally, the differences in thermal expansion coefficients between materials can weaken the bond over time. Furthermore, the adhesive bond's potential difficulty in disassembly for recycling or repair raises concerns regarding sustainability. Therefore, careful consideration must be given to selecting alternative assembly techniques that address these challenges effectively while maintaining structural integrity and facilitating recyclability.

threaded fasteners offer assembly flexibility and high load-bearing capacity, making them an ideal choice for electric motors, particularly in drone applications where constant vibrations are anticipated. For maintenance and repair, threaded fasteners offer a great deal of flexibility during assembly and disassembly, which is advantageous for recycling purposes. Additionally, threaded fasteners provide the necessary strength to withstand heavy loads, ensuring reliable motor performance. However, it is important to consider potential challenges associated with threaded fasteners. Precise alignment during application is crucial to prevent damage, and improper fastening can lead to loosening under vibration conditions and thread wear after repeated assembly and disassembly of the electric motor. Another consideration is their susceptibility to corrosion, especially in harsh environments or aquatic settings. Consequently, routine maintenance and inspections are necessary to address these challenges effectively and ensure the continued reliability and longevity of threaded fasteners in drone applications.

Press fit assembly might provide a good balance of strength simplicity and cost-effectiveness, as it does not necessitate additional fasteners. In high-load applications like drone motors, press fit connections provide high mechanical strength, which is essential. Additionally, they offer electrical and thermal conductivity as well as high mechanical strength, both of which are essential for electric motors. Press fit assembly is appealing because it allows for disassembly and repair, which is advantageous for recycling. However, precise tolerance control is required to produce a trustworthy press fit connection, which might make the manufacturing process more difficult. This may result in deformation or damage. It's important to consider the method's restrictions on adjustability after installation because of the tightness, which could be problematic for maintenance and repair.

Lastly, **Snap fit** joints facilitate easy and efficient assembly and disassembly procedures, making them appropriate for repair and recycling processes. In the context of drones, their capacity to dampen and absorb vibrations might be advantageous. Given that it does not require additional fasteners, it can also be cost-effective. Additionally, it can help reduce weight, which is an important factor for drones.

However, compared to permanent joints, snap-fit joints may be more brittle to breakage or damage, have lower load-bearing capacities, and lose effectiveness over time or after repeated assembly and disassembly. For instance, as with the electric motors for drones, snap fit might not be appropriate for applications with high vibrations or temperature variations. Therefore, to ensure adequate flexibility, strength, and durability, careful material selection and design is needed.

Summary

Each assembly technique presents unique benefits and challenges. The choice between these techniques should consider not only their respective strengths and weaknesses but also the specific requirements of Alva Industries' motor applications and the company's sustainability goals. It may also be worth considering a combination of techniques to balance performance, durability, and recyclability. From a recyclability standpoint, both press fit and snap fit assembly techniques seem to be the most advantageous due to their potential for ease of disassembly. With multiple rounds of maintenance, there can also be damage to these fittings, which may lead to parts needing to be replaced more frequently. Damages might happen during use, which is very critical for motors operating in aerospace. However, from a performance and safety perspective, adhesive bonding and threaded fasteners may provide superior strength and load distribution. The chosen assembly technique may vary according to the area for use of the electric motor. Bigger motors situated on the ground may need fewer safety requirements which might make the press fit, snap fit or threaders the preferred option. On the other hand, it is reasonable to use the same technique on all motors to make sure the manufacturing process is effective.

Recommendation of Assembly Technique

For Alva Industries, adhesive bonding seems to be the best assembly technique based on requirements such as performance, dependability, corrosion resistance, safety, weight and efficiency. Despite this, it is important to acknowledge the challenges it presents in terms of maintenance and direct reuse. The exploration of alternative adhesives to epoxy offers a potential approach for simplifying the process. It is noteworthy that the current design allows the replacement of damaged modules, such as the stator and rotor, despite the impossibility of direct reuse of a few individual components of these modules, which are bonded with epoxy resin. From a recycling perspective, the Stena Recycling case study provided evidence that there are no substantial difficulty in shredding electric motors and reprocessing the components into reusable raw materials. The only discarded material in the recycling process is epoxy, constituting a small fraction of the total material content in an electric motor.

Safety, compactness, and weight are paramount considerations in the context of electric motors. Thus, despite its lower recyclability, adhesive bonding has been suggested as the assembly method for Alva Industries. The potential risks associated with motor damage during operation, coupled with competitive demands for lightweight, efficient, and compact motors, guide this decision. This choice is predicated on the expectation that a more recyclable adhesive will eventually be identified and implemented.

This selection is an acknowledgement of adhesive bonding's potential for optimization, even as it presently stands as one of the least recyclable options. However, it also signifies confidence in its potential evolution, with the prospect of more sustainable adhesives in the foreseeable future.

10 Sustainable Management of Electric Motors: A Policy Proposal for Alva Industries

Companies are being urged to support global sustainability initiatives as the world struggles to deal with the growing threats posed by climate change. This chapter presents a thorough recycling policy plan for Alva Industries, concentrating on the EOL management of electric motors, in response to these urgent environmental concerns. Electric motors present a significant opportunity for promoting sustainability and resource conservation because they are a significant part of industrial operations.

This policy has been established as a result of the thorough investigation and analysis carried out throughout this thesis. The aim of this policy is to outline a systematic approach towards the direct reuse and recycling of electric motors. It is primarily designed to guide Alva Industries towards a more sustainable and environmentally friendly practice that not only meets but exceeds the demands of relevant legislation. This policy also aspires to enhance long-term economic efficiency and balance environmental responsibility with business performance.

10.1 Detailed Recycling and Reuse Plan

This section outlines a comprehensive plan for the recycling and reuse of Alva's electric motors. The plan builds upon the process flowchart depicted in Figure 32, which was established during the preliminary work [1]. The process has been developed with the aim of maximizing the lifespan of each component, minimizing waste generated, and guaranteeing the reliable and efficient operation of recycled electric motors.

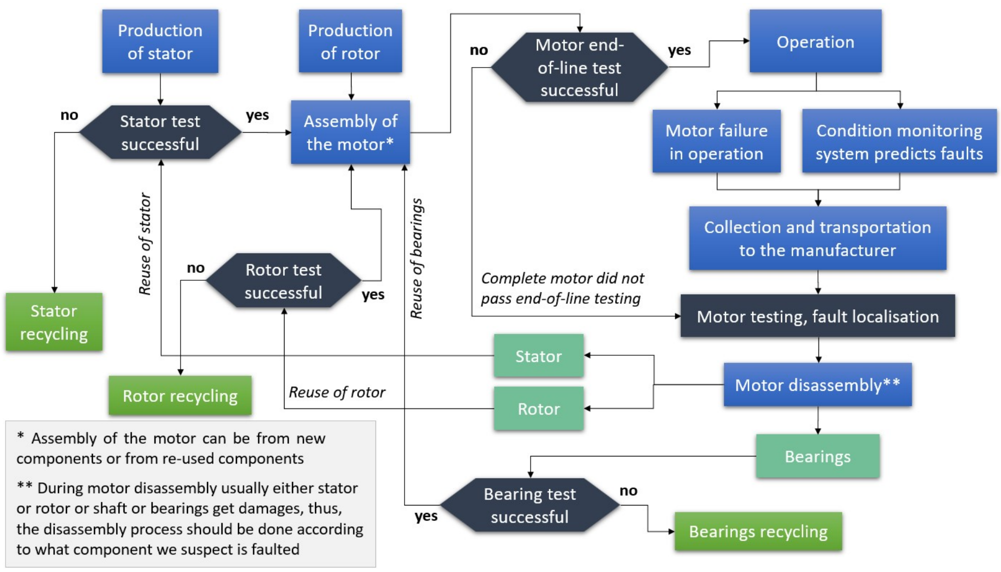

Figure 32: Recycling process for Alva's electrical motors [1].

Motor Failure or Condition Monitoring

The electric motors are taken out of operation due to two reasons: motor failure during operation or when the condition monitoring system predicts faults. At this stage, EOL electric motors need to be collected and transported.

Collection and Transportation Upon the occurrence of motor failure, the motor in question will be removed from operation and tagged for collection. The principal source of these EOL motors will mainly be Alva Industries' own customers, who have purchased and employed the motors within their respective applications and systems.

The collection of the motors will be managed by a specialized team at Alva, where the Sustainability Coordinator acts as the senior authority. This team will be responsible for arranging the collection process from the customers' locations, either through the use of their own personnel or in collaboration with a reliable logistics partner. The collection will be strategically scheduled to ensure larger quantities are collected at once, optimizing the economics of transportation.

For transportation purposes, Alva might enter into an agreement with a third-party transportation company. This company will have the responsibility of conveying the collected motors safely and efficiently to Alva's facility. The selection of the transportation company will be based on their capacity to handle such cargo, their commitment to environmentally-friendly practices and their operational proximity to Alva's clientele. Upon the arrival of the motors at Alva's facility, they will undergo additional testing and fault localization. This will contribute to determining the most appropriate course of action for each individual motor, whether that entails component reuse or complete recycling.

Motor Testing, Fault Localisation and Sorting

At the manufacturer's facility, the motor is tested, and the fault is localised. This step is crucial to determine the next course of action, leading to the disassembly of the motor. These tests may include:

1. **Visual inspection:** This will be the first step in the motor assessment. It involves examining the external condition of the motor for signs of wear, overheating, damage or corrosion.
2. **Vibration Analysis:** This is a predictive maintenance method used to monitor the condition of the motor. Vibrations can indicate issues such as misalignment, imbalance, or bearing problems.
3. **Motor Current Signature Analysis (MCSA):** This non-invasive examination involves examining the motor's current signature to look for any anomalies. It can assist in identifying difficulties such as rotor bar breaks, bearing defects, and power supply problems.
4. **Thermographic Inspection:** Using infrared imaging, it is possible to detect areas of abnormal heat in the motor, which can indicate problems like overloaded circuits, phase imbalance, or issues with the motor windings.

The motors are then sorted based on their functional components (see Figure 33). The purpose of this categorization is to streamline the disassembly process by focusing on motors that have a higher likelihood of having reusable parts. The primary components of the motors are the bearing, the rotor, and the stator. Each of these components can either be functional or non-functional, leading to a total of seven different combinations or categories

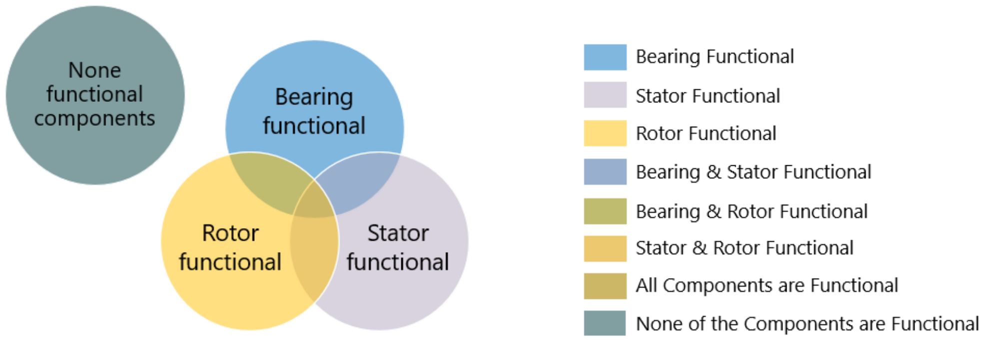

Figure 33: Categorization of Electric Motors Based on Functional Components

There should therefore be seven different bins to sort the motors before disassembling. This will just be a prototype for the sorting system and it should be influenced by the ratio of different types of failures and the capacity to accurately predict the fault location before disassembly. Practical considerations such as space and logistics can also affect the feasibility of the sorting system and may be simplified to only sort in five categories: Bearings, Rotor, Stator, several and none. The size of the bins can also be adjusted based on the number of motors received.

Motor Disassembly and further Sorting

Motor disassembly involves separating the motor into its primary components: the bearing, the rotor, and the stator. Each component is then further tested to decide its future path – recycling or reuse. The stator and rotor cannot be further disassembled, which means that if they have any faults, they are directly sent for recycling and cannot be repaired based on the current design.

Component Testing and Decision Making

Each component - bearing, rotor, and stator - undergoes rigorous testing. If the test is successful, the component is marked for reuse. If the test is unsuccessful, the component goes into a container that will be sent to a recycling facility, such as Stena Recycling, when the container is full.

Bearing Testing: Bearings can be tested for noise, vibration, and temperature rise. Excessive noise or vibration can indicate bearing defects or problems with bearing installation. Temperature testing can help detect issues related to lubrication or excessive load.

Stator Testing: Stator windings can be tested for insulation resistance and polarization index. Other tests include surge tests and high-potential tests to evaluate the integrity of the stator winding insulation. An improper result might indicate problems such as ground faults, inter-turn shorts, or phase-to-phase shorts.

Each test's results are used to decide whether a component can be reused or needs to be recycled. All components that pass these tests are marked for reuse.

Component Reuse or Recycling

Components marked for reuse are assembled with new production parts such as rotors and stators to create a new motor. The reassembled motor then undergoes end-of-line testing. If successful, the motor is put back into operation. If unsuccessful, the motor returns to the testing and fault localisation phase.

On the other hand, components designated for recycling undergo processing by companies such as Stena Recycling. Stena Recycling was selected as a partner for Alva's recycling efforts due to its state-of-the-art facilities, its commitment to ethical and sustainable recycling practices, and its ability to ensure compliance with the WEEE directive, which stipulates that over 80% of the components must be recycled. This alignment with the WEEE directive not only ensures compliance with all relevant legislation and standards but also reflects Alva's commitment to responsible resource management.

By utilizing Stena Recycling, the recycling process aligns with the WEEE directive, ensuring that over 80 % of the components are recycled. This choice also guarantees compliance with all relevant legislation and standards.

This detailed plan ensures that every possible avenue for reuse or recycling is explored for each component of Alva's electric motors, contributing to sustainable and efficient operations.

10.2 Challenges and Benefits

Before implementing such a recycling policy plan, it is crucial to consider the various challenges and benefits of both recycling and direct reuse. This section highlights some of the key factors to facilitate an informed decision on whether it would be profitable for the manufacturer.

Challenges with Direct Reuse

1. **Quality Assurance**: Ensuring that reused components meet quality standards can be a complex task. It involves thorough testing and inspection, which requires time, expertise, and resources.
2. **Inventory Management:** It can be challenging to manage an inventory that includes both new and reused components. This requires precise record-keeping and potentially more storage space.
3. **Volume Requirement:** In order for direct reuse to be economically profitable, a substantial number of EOL motors, or larger motors with costlier components, need to be regularly incoming. This is because the processes of sorting, testing, and refurbishing parts for reuse have fixed costs and require a certain scale to be cost-effective.

Benefits of Direct Reuse

1. **Energy Efficiency:** Reusing components can be more energy-efficient than recycling them since it requires less energy to clean and refurbish a part than to melt it down and remanufacture it.

2. **Economic Development:** Direct reuse can create new jobs and encourage economic development in the manufacturing industries.
3. **Cost Efficiency:** Depending on the specific components and their market value, reuse can be more cost-effective than purchasing new parts or recycling.
4. **Environmental Impact:** Direct reuse can reduce the need for new raw materials, leading to lower environmental impact in terms of resource extraction and waste production

Challenges & Benefits with Recycling

In Table 19, a comparison between the challenges and benefits associated with recycling electric motors is presented. The left column lists the primary challenges, including material loss during the recycling process, energy consumption, and logistical considerations related to transport. Despite these challenges, the right column emphasizes the significant benefits of recycling. These include the conservation of resources, reduction in waste destined for landfills, and potential economic returns. Both of these aspects should be considered when implementing or improving recycling processes for electric motors.

Table 19: Challenges and Benefits of Recycling

Challenges with Recycling	Benefits with Recycling
Material Loss: During the recycling process, some materials may be lost or degraded, reducing the quality and quantity of material available for reuse.	**Conservation of Resources:** Recycling conserves raw materials by reprocessing used motors into new components.
Energy Consumption: Recycling often involves an energy-intensive process which is much higher than for reuse. The energy consumption is still much lower than for primary material production.	**Waste Reduction:** The recycling process returns over 90% of the materials and reduces the amount of waste that ends up in landfills.
Transport and Logistics: Organizing and transporting Electric EOL motors to the recycling facility can pose a logistical challenge.	**Economic Aspects:** Recycling facilities pay money to manufacturers for delivering electric motors.

10.2.1 The Benefits of Implementing a Recycling and Reuse Policy

Implementing a combined strategy of reuse and recycling at Alva offers both immediate and long-term advantages that are environmental, economic and reputational.

Circular Economy: Embracing a strategy of reuse and recycling aligns Alva with the principles of a circular economy, a model that aims to keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of their life. This circular process will minimise waste, reduce resource consumption and promote resource efficiency.

Potential Cost Savings: A reuse and recycling policy can result in significant cost reductions for Alva Industries. The company may be able to save production costs by reusing components because it is frequently less expensive to do so than to create new components from scratch. It may also result in material cost savings. Additionally, the business might drastically reduce waste management expenses with effective recycling. Although a thorough cost-benefit analysis would be necessary to determine an exact estimate of these reductions, it is obvious that there is a significant amount of room for cost savings.

Sustainability Goals: Implementing a combined strategy of reuse and recycling reinforces Alva's commitment to sustainability, providing tangible support for several of the United Nations' Sustainable Development Goals (SDGs). In particular, it aligns with Goal 12, which promotes responsible consumption and production, allowing Alva to make a public commitment to global sustainability initiatives. Additionally, the strategy contributes to combating climate change (Goal 13) by reducing resource extraction and manufacturing emissions, further demonstrating Alva's proactive cooperation towards shared global objectives (Goal 17). Alva shows with this policy that the company not only takes sustainability seriously but also contributes to global efforts against climate change and for responsible consumption This in itself can have a positive impact on Alva's reputation and brand, and it may give the company a competitive edge in a market increasingly concerned with sustainability.

Figure 34: Representation of Aligned Sustainable Development Goals

Customer and Supplier Relationships: Alva's commitment to sustainability and the circular economy may strengthen its relationships with customers and suppliers. Customers are likely to appreciate and support Alva's sustainability efforts as they become more environmentally concerned. Suppliers are likely to also prefer working with companies that follow sustainable business practices.

Industry Relations and Reputation: Alva's commitment to recycling and reuse positions them as an exemplary entity, demonstrating a sense of responsibility towards fostering a more sustainable world. This dedication has the potential to bolster the company's reputation within the industry and potentially influence investors. Moreover, it can positively shape the company's brand image, portraying Alva as a responsible and forward-thinking enterprise.

Competitive Advantage: The implementation of a recycling policy can stimulate innovation for Alva, providing them with a competitive edge. By optimizing the recycling process, they are compelled to reevaluate product design, product life cycles, and waste management in novel ways. This can lead to new business opportunities and set Alva apart from competitors. In an increasingly environmentally conscious market, this can be a crucial factor in acquiring and retaining customers.

10.3 Implementation Plan

In order for a recycling policy to be implemented well for the company, it is important to establish a plan to ensure a comprehensive rollout. The implementation plan was developed based on pertinent research and guidance regarding the recycling process, including insights derived from an article on implementation planning sourced from the Coursera platform[84].

Awareness and Training: The company should launch an internal campaign to educate the employees about the new recycling policy. This should involve workshops, seminars and e-learning modules. It is important that the management attends to these to demonstrate the company's commitment to the recycling policy.

The seminars will cover the overall process and its constituent steps, providing a comprehensive understanding of the recycling process. Workshops, on the other hand, will delve deeper into specific stages for the employees who will be responsible for them, offering detailed insights and practical knowledge.

The e-learning modules are designed to serve as a supplemental resource, providing employees with comprehensive information about the recycling process and enhancing their awareness and competence. The inclusion of an online test following the training period ensures that employees acquire the necessary knowledge.

Throughout the training, employees gain an understanding of the significance of recycling, familiarize themselves with the details outlined in the recycling policy plan, and ascertain their individual responsibilities within the process. The company can further solidify employees' knowledge by implementing an online test after the training period.

Role Allocation: To support the execution of this policy, it is necessary to assign some specific roles and responsibilities. A new role, the 'Sustainability Coordinator', should be introduced to oversee the policy's execution. Existing teams will be assigned tasks related to the recycling process, ensuring that everyone is engaged and responsible. The Sustainability Coordinator will have the overall responsibility for the process, including key tasks such as: Implementing the Recycling Policy, which involves developing and updating the policy, as well as ensuring its compliance across the organization; Training; Partnership management; Monitoring and continuous improvement. As part of their role, the Sustainability Coordinator will also coordinate and lead the other teams involves in the process.

It should be noted that the proposed organizational structure for the recycling process includes additional roles that are essential for ensuring a seamless workflow. While distinct, it is important to acknowledge that certain individuals may assume multiple roles, particularly in the early stages of policy implementation. This approach offers flexibility and scalability to accommodate the expanding recycling processes and the growing volume of electric motors.

In recognition of Alva's current size and with an eye towards its potential growth, an organizational structure for the recycling process has been proposed. It assigns various roles to individuals that will enable a smooth flow in the process, while also allowing for overlap of responsibilities where necessary. An overview of the proposed organizational hierarchy is presented in Figure 35.

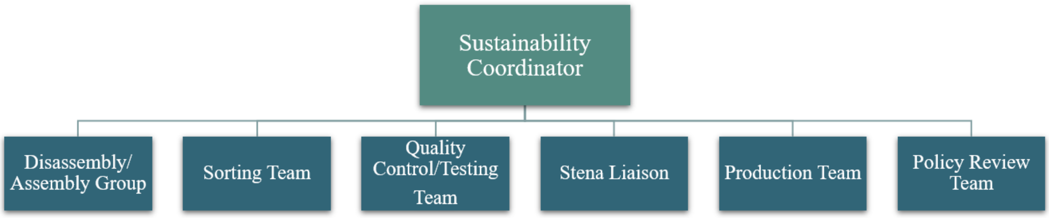

Figure 35: Proposed Hierarchical Structure for Sustainable Recycling Policy

Here are the roles to be fulfilled:

- **Disassembly/Assembly Role:** An individual or a small team will take overall responsibility for the disassembly and assembly of electric motors.
- **Sorting Role:** This responsibility involves handling the sorting of various types of materials for recycling.
- **Quality Control/Testing Role:** This role ensures the quality of the reused components and monitors adherence to necessary standards.
- **Stena Recycling Liaison:** One or several designated employees will maintain communication and collaboration with Stena Recycling.
- **Production Role:** This responsibility involves integrating recycled components into new products.
- **Policy Review Role:** A person or a small group will be responsible for consistently assessing and enhancing the guidelines based on feedback and key performance indicators (KPI's) results. This role requires close work with the Sustainability Coordinator to ensure effective collaboration and alignment with sustainability objectives.

In this structure, while each role is defined, it is understood that one person may take on multiple roles based on the current size of Alva's workforce. As the company grows, these roles can be expanded into teams to accommodate the increased volume and complexity of the recycling process.

Partnership with Stena Recycling: For several compelling reasons, Stena Recycling has been suggested as a strategic partner. Firstly, their strategic location in Hommelvik, Trondheim enables convenient accessibility and seamless communication with Alva.

Stena Recycling's advanced equipment ensures comprehensive and effective material recycling. These machines are able to manage varying volumes and complexity of waste material thanks to this cutting-edge technology. Notably, Alva's dedication to sustainability is in line with Stena Recycling's excellent track record in recycling electric motors, with over 85% of materials being turned into new raw materials.

The dedicated research teams at Stena Recycling focus on continuous improvement and innovation in the recycling process. Their proactive approach to developing new recycling methods and processes that anticipate future demands is evident through initiatives such as the Stena Recycling Lab, where collaborative projects with entrepreneurs, partners, researchers, and students foster the development of cutting-edge recycling technology and products. Through the use of Stena Recycling's specialists, this cooperative method allows for cooperation that goes beyond close proximity. By employing Stena Recycling's knowledge and dedication to innovation, the partnership with Alva not only gives them improved garbage collection, safe transport options, and fewer emissions, but it also helps them gain a competitive edge.

Stena will collect the recyclable components, the schedule of which will be determined based on the duration needed to fill the containers. Therefore, the collection will be done based on orders, and regular meetings will be scheduled between Alva and Stena to better plan and coordinate the collection process once it is established.

Integration of Reused Components: To ensure compliance with ISO 14001's guidance on maintaining an effective environmental management system (EMS), it is proposed that recyclable components undergo thorough testing before reintegrating them into the production line[77]. This proposal demonstrates our commitment to managing potential risks associated with these components while preserving their quality and lifespan.

A quality control system will be established to facilitate this process, aligning with the standard recommendations for continual EMS improvement. Each component will undergo comprehensive testing, and the results will be documented and attached to the corresponding motor, ensuring transparency and instilling confidence in the component's reliability.

In line with ISO 14001:2015 emphasis on effective communication, a system will be implemented to differentiate between new and reused components[77]. This can be achieved by labelling motors with reused components or separating them during sorting. Such measures aim to provide transparency to customers and effectively manage perceptions regarding the use of reused components.

Additionally, each electric motor will be accompanied by a comprehensive document detailing the actions taken, including the testing process, replaced parts, and expected lifespan of the reused components. This proposal aligns with ISO 14001's fundamental principle of providing accurate environmental information, reinforcing our commitment to upholding stringent quality and reliability standards[77].

Monitoring and Evaluation: In line with ISO 14001's principle of continuous improvement, the Sustainability Coordinator along with the Policy Review team not only bears the responsibility to monitor the implementation of the policy and measure its success but also to identify opportunities for improving the recycling process[77]. Improvements can lead to increased recycling rates, improved employee satisfaction, and additional cost savings. Key Performance Indicators (KPIs) will be identified and utilized to measure the success of the recycling policy and to benchmark progress over time. These indicators can be both quantitative and qualitative in nature.

Quantitative KPIs may include:

- **Percentage of Components Recycled:** This can be measured as the total weight or number of components recycled as a proportion of the total weight or number of components processed.

- **Percentage of Components Reused:** Similar to recycling, this can be measured as the total weight or number of components reused as a proportion of the total weight or number of components processed.
- **Waste Reduction:** This can be measured in terms of the total weight or volume of waste avoided through recycling and reusing components.
- **Cost Savings:** The financial savings achieved through the reduction in the need to produce or purchase new components.

Qualitative KPIs may include:

- **Employee Satisfaction:** Feedback from employees regarding the recycling program can be used as a measure of its success and acceptability within the organization.

The policy will be reviewed and adjusted semi-annually to maximize its effectiveness, using the data from these KPIs as a guide for potential improvements. This systematic approach to monitoring and evaluation mirrors the ISO 14001:2015 standard's requirement for environmental performance assessment and continuous improvement.

Timeline: The implementation of the recycling policy does not necessarily have to be time-consuming, but it is challenging to provide an estimate of the duration as it depends on several factors specific to the manufacturer. There has therefore been constructed a tentative timeline for implementing the recycling policy for Alva. A simplified timeline is presented in Figure 36.

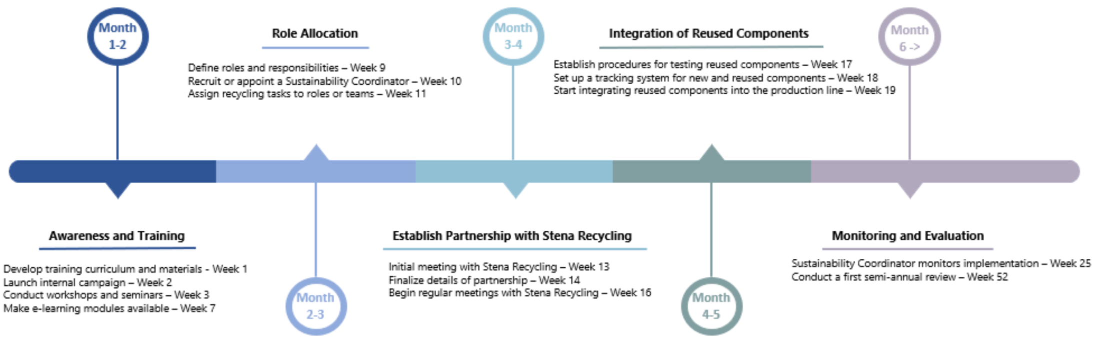

Figure 36: Tentative Timeline for Implementing policy for Alva Industries,

A more detailed time schedule is presented here.

- **Month 1-2: Awareness and Training:**
  - Week 1: Develop training curriculum and materials
  - Week 2: Launch internal campaign to introduce the new policy to employees
  - Week 3-6: Conduct workshops and seminars

- Week 7-8: Make e-learning modules available and encourage all employees to complete them by the end of month 2

- **Month 2-3: Role Allocation:**
  - Week 9: Define roles and responsibilities for the recycling policy
  - Week 10: Recruit or appoint a Sustainability Coordinator
  - Week 11-12: Assign recycling tasks to roles or teams

- **Month 3-4: Establish Partnership with Stena Recycling:**
  - Week 13: Initial meeting with Stena Recycling to discuss partnership
  - Week 14-15: Finalize details of the partnership, including collection frequency and coordination process
  - Week 16: Begin regular meetings with Stena Recycling

- **Month 4-6: Integration of Reused Components:**
  - Week 17: Establish procedures for testing reused components
  - Week 18: Set up a tracking system for new and reused components
  - Week 19 onwards: Start integrating reused components into the production line

- **Month 6 onwards: Monitoring and Evaluation:**
  - Ongoing: Sustainability Coordinator monitors implementation and measures success based on identified KPI's
  - Week 52: Conduct a first semi-annual review of policy effectiveness and make necessary adjustments

10.3.1 Discount Arrangement

Deposit-return Scheme

In order to encourage customers to return EOL electric motors for recycling and ensure continued engagement from customers, it is proposed that Alva Industries consider implementing a discount arrangement similar to the model used by ABB in collaboration with Stena. This might involve Alva providing a financial incentive, such as a discount on new motors, for customers who return their EOL motors for recycling.

A key benefit of this approach is that it might establish a consistent and reliable stream of EOL motors for recycling, thereby improving the efficiency of Alva's recycling operations. Moreover, by offering discounted prices on new electric motors, Alva would be encouraging its customers to participate in a circular economy model, fostering long-term customer relationships and promoting the company's commitment to sustainability. It is recommended that Alva initially pilot the scheme with a limited set of customers to gather data and feedback before rolling it out on a wider scale.

10.4 Feasibility and Risk Assessment

Implementing a new recycling policy can be a complex process that requires planning. To ensure success in the implementation a simplified preliminary feasibility and risk assessment has been conducted in accordance with the guidelines outlined in ISO 14001:2015[77].

10.4.1 Feasibility Assessment

Technical Feasibility: The partnership with Stena Recycling ensures access to cutting-edge recycling technology. Additionally, the plan to train employees and assign clear roles and responsibilities will enable the company to effectively integrate recycling practices into its operations.

Economic Feasibility: Implementing this policy will involve initial costs, including training, hiring and possible equipment purchases. The hope is that the reduction in waste and potential cost recovery through the sale of reused electric motors will make this policy economically feasible in the long run.

Operational Feasibility: The planned awareness campaigns, training programs, and assignment of a dedicated Sustainability Coordinator ensure that the company employees will be ready to put this policy into action.

10.4.2 Detailed Economic Assessment

To fully understand the economic implications of the recycling policy, Alva Industries needs to conduct a detailed cost-benefit analysis, including:

- **Implementation Costs:** These include costs related to training, equipment purchase, changes in logistics, potential hiring of new personnel (e.g., Sustainability Coordinator), and the establishment of partnerships with Stena Recycling.
- **Operational Costs:** Once the policy is implemented, there will be ongoing costs such as maintenance of recycling equipment, regular training updates, and overall management of the recycling process.
- **Savings:** Over time, the recycling approach may result in large financial savings. These can include lower costs for disposing of waste, a decrease in the need for new components due to the reuse of recycled ones, and potential tax benefits, or subsidies associated with sustainable operations.
- **Intangible Benefits:** Although more difficult to measure, the enhanced reputation brought about by implementing sustainable methods might increase client loyalty and possibly boost sales.
- **Potential costs of inaction:** The financial implications of not implementing a recycling and reuse policy should also be considered. Alva can make short-term financial savings by avoiding the implementation and ongoing expenses associated with this policy. However, long-term costs can be very high for the business. Increased waste management costs and lost opportunities by not

utilizing potential subsidies for sustainable operations are some examples. Additionally, as consumers and investors become more environmentally conscious, businesses may experience a decline in sales when they choose to do business with organizations that demonstrate strong sustainability practices. In addition, rejecting this recycling policy can stifle innovation and learning, leading to lost opportunities and reduced market competitiveness.

Given the numerous variables and uncertainties in these factors, it is difficult to set up an estimate for these factors. These variables include market conditions, technological advances, regulatory changes and more. However, it is important to understand that the aim of this policy is not just short-term profitability but long-term sustainability and resilience, which can lead to significant indirect benefits and risk mitigation. Therefore, while it's essential to consider these financial factors, the company should not base their decision solely on immediate costs and revenues. Instead, the focus should be on the strategic value of the recycling policy in terms of its alignment with Alva's commitment to sustainability, its potential to strengthen the brand, and its role in safeguarding the future of the business.

Discount Arrangement

In order to consider the economic implications of the deposit-return scheme, it's essential to balance potential benefits against associated expenses. On one hand, the scheme would necessitate additional expenses related to administration, modifications to purchasing and recycling processes, and provision of discounts on new electric motors. Certain costs, such as administration and alterations to the recycling process, would arise irrespective of this scheme, due to the desired retrieval of EOL motors from customers. Nonetheless, there would be supplementary costs tied to administering this scheme and potential losses related to the provision of discount codes.

However, these costs need to be evaluated against several potential benefits. Firstly, the scheme can lead to cost savings in sourcing EOL motors for recycling, by creating a reliable stream of returned motors. This would reduce the need for and costs of sourcing EOL motors from other suppliers. Secondly, the scheme might generate increased sales of new motors, as customers who return their EOL motors for recycling would receive a discount on their new purchases. This can foster customer loyalty, leading to repeat sales and predictable revenue streams.

A full economic assessment would require data on the current costs of sourcing EOL motors, the expected return rate under the new scheme, and the potential impact on sales of new motors. However, it is hypothesized that, with effective implementation, the benefits of the deposit-return scheme might outweigh the costs, making it a sustainable and profitable initiative for Alva Industries.

10.4.3 Risk Assessment

Despite the promising initial feasibility assessment, it is important to acknowledge potential risks and challenges. The Risk Assessment described is following the setup described by the Norwegian Labor Inspection Authority[85]. There are three simple questions that are the core of the Risk Assessment:

1. What potential risks or hazards might arise?
2. What proactive measures can be taken to prevent these risks from occurring?
3. If a risk does materialize, what actions can be implemented to mitigate and minimize the potential consequences?

In order to comprehensively address and implement appropriate mitigating measures for the risks, it is of paramount importance to holistically consider aspects 1-3. While some risks may occur infrequently, their repercussions may be severe, whereas other more frequent risks may pose comparatively negligible consequences. A risk matrix is an indispensable tool for the evaluation and prioritization of the various potential incidents that have been identified and assessed.

A preliminary risk matrix has been crafted specifically for Alva, serving as an initial point of reference. Risks associated with collaboration, collection, and transportation have been taken into consideration. Concurrently, it is crucial to appraise risks inherent to Alva's processes, including those associated with EOL testing and sorting. Figure 37 and the subsequent list present a simplified rendition of Alva's risk matrix.

- **Collaboration risks**: This includes misunderstandings or arguments over the specifications, procedures, or timetables for recycling between Alva and Stena Recycling. Failure to clearly define roles and commitments in the partnership agreement, resulting in delays or disagreements. This risk is placed within the "Likely" and "Significant" cell of the risk matrix.
- **Collection and transportation risks**: Accidents or incidents may damage functional components, reducing their value. There can occur delays in the process due to transportation. This risk is positioned within the "Likely" and "Significant" cell.
- **Testing:** insufficient quality control measures can contribute to the reuse of faulty or defective parts, introducing potential safety hazards or causing equipment malfunction. This risk is particularly significant as Alva begins to integrate reused components into its manufacturing process, requiring diligent quality maintenance. A key challenge is the accurate identification and documentation of parts' condition and compatibility, essential for correct assembly and preventing compatibility issues when reusing motors. Any oversight in this process, especially due to inadequate or unreliable EOL testing procedures, increases the risk of incorporating unfit components, leading to improper recycling or reuse. Considering these factors, this risk is positioned within the "Likely" and "Moderate" cell of the risk matrix
- **Sorting:** Improper sorting procedures result in the incorrect separation of materials, leading to decreased recycling efficiency or contamination of recyclable materials. This risk is positioned within the " Very likely" and "Moderat" cell.
- **Assembly/Disassembly:** Potential hazards may arise during both the assembly and disassembly of electric motors, posing risks of physical injury or damage to components. Given the continuous nature of these risks, they are placed in the "Very likely" and "Severe" cell.

- **Legal and Regulatory:** Changes in laws and regulations related to waste disposal and recycling can cause unexpected disruptions. It's crucial to stay informed about such changes, therefore this risk is placed in the "Unlikely" and "Significant" cell.

- **Cost Overruns/Delay:** The risk of costs exceeding budgeted amounts or the timeline extending beyond expectations is a perennial concern in projects of this nature. Given that these can occur with reasonable likelihood and have a significant impact, they are positioned within the "Possible" and "Moderate" cell.

- **Personal Injury:** The recycling process, particularly the assembly and disassembly of components, can pose risks of injury. Due to the constant presence of these risks, this is placed in the "Very likely" and "Severe" cell.

- **Technology:** The risk of technological failure or inadequate technological infrastructure is placed within the "Possible" and "Moderate" cell.

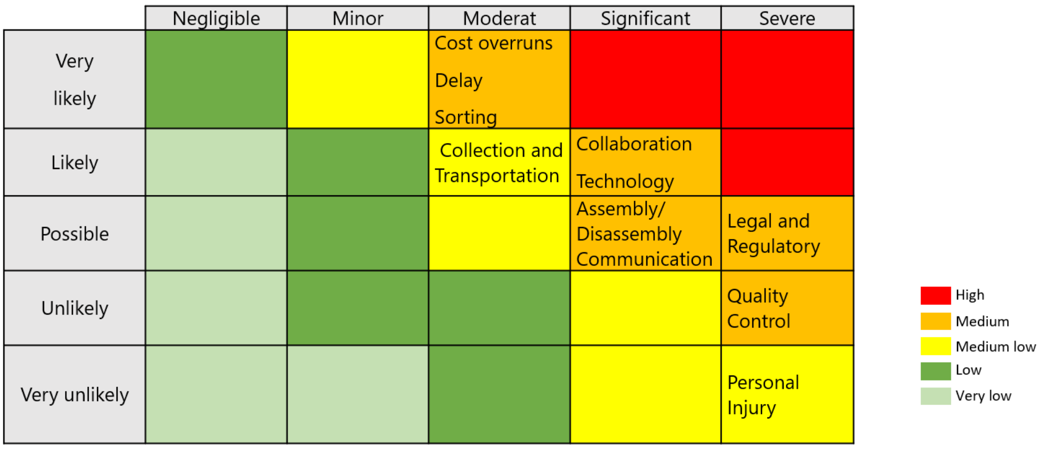

Figure 37: Risk assessment matrix for Alva

The allocation of these risks represents an initial estimation, necessitating further refinement and validation through the incorporation of more precise data or expert input from within Alva and Stena Recycling. Furthermore, regular updates to the risk matrix are crucial as the project advances and additional information is acquired. Currently, the majority of risks are classified as medium. This classification predominantly stems from the ongoing evolution of the process and the imperative to conduct periodic reassessments throughout the implementation phase.

To manage these risks and work towards reducing their likelihood and impact, action plans can be set in place. Here are some proposed risk management strategies:

- **Cost Overruns/Delay:** Regular monitoring of project progress against timelines and budget forecasts can help catch and address potential overruns early.

- **Legal and Regulatory:** Staying updated on changes in relevant laws and regulations, and adapting operational strategies accordingly, will be essential to navigate this risk.

- **Quality Control:** Robust testing and validation procedures, along with comprehensive training of personnel, can help ensure that quality control standards are upheld.
- **Personal Injury:** Rigorous safety protocols, provision of appropriate protective equipment, and regular safety training for staff can mitigate the risks of injury.
- **Assembly/Disassembly:** Adequate safety measures and regular maintenance checks on equipment can help manage potential hazards related to assembly and disassembly.
- **Collaboration:** Clear communication and comprehensive agreement terms can help manage collaboration risks. Regular meetings and open dialogue can ensure that both parties remain aligned.
- **Technology:** Regular maintenance checks, data backups, and investment in reliable technology can help prevent technological failures.
- **Collection and Transport:** Ensuring that vehicles are well-maintained and drivers are appropriately trained and licensed can help to minimize the risks associated with collection and transport.

These risk management strategies form part of a larger risk management plan, and need to be regularly revisited, updated, and refined as the process evolves and further information is obtained.

Design criteria for electric motors Design for X Principles and their role in enhancing electric motor recyclability Design for manufacturing Manufacturing process integration Component design Material selection Standardization Design for maintenance Ease of disassembly and repair Component Durability and lifespan Standardization Maintenance Indicators and diagnostics Design for environment material selection Selection of assembly technique Design for efficiency Material efficiency Production efficiency Energy efficiency in use Design for longevity Design for recyclability and Disassembly Criteria for sustainable electric motor design Material selection easy of Disassembly EOL treatment options Criteria's Recommendation for Alva Industries Assembly technique Material selection Functionality vs recyclability

11 Conclusion

In this thesis, the challenges associated with recycling electric motors were investigated, due to the growing environmental concerns brought on by the increased technological development of electric motors and other electrical equipment. The main goal was to develop a comprehensive policy for reuse and recycling, with a particular focus on Alva Industries. The other goal of this thesis was to develop a set of design criteria for simplifying the recycling of electric motors. This set of criteria has the potential to improve the design process's adaptability, considering recycling, reuse, and repair, thereby leading to increased overall sustainability.

Through a case study and literature review, a deep understanding of existing recycling processes has been achieved. The research identified several significant challenges, including little knowledge about the current recycling process and the design choices that inhibit component disassembly and material decisions. These results highlight the need for redesigning electric motors with sustainability and recycling in mind.

In line with the objectives, it is examined different assembly methods for electric motors. Adhesive bonding emerges as a critical method, notwithstanding its recyclability drawbacks, due to its weight reduction, efficiency enhancement and load distribution in electric motors. The need for a more sustainable solution was looked into a number of recyclable adhesives that might be used without affecting the motor's performance and structural integrity. This challenge underscored the intricate balance that must be achieved between performance and recyclability.

The assessment of the environmental and economic impacts of electric motor production and recycling unveiled potential paths for sustainable development. Importantly, the thesis highlights the necessity of complying with WEEE regulations and standards, a pivotal step towards fostering sustainable practices.

To answer the research question: "What are the necessary steps the industry needs to take in order to prepare for recycling electric motors?", the study shows that the industry must proactively comprehend the existing recycling processes, which can already recycle up to 90% of the materials in electric motors. Despite this potential, our findings suggest that the industry lacks a comprehensive understanding of these processes. Moreover, the industry should consider design criteria for recycling and utilizing recyclable materials and assembly methods, enabling efficient repairs, reuse, and recycling.

In conclusion, the thesis provides valuable insights towards a more sustainable future for electric motors. By balancing performance with recyclability, presenting a comprehensive policy for recycling and reusing, and identifying critical design criteria for recycling, the thesis paves the way towards a more environmentally conscious industry.

11.1 Future Work

Future research should delve deeper into the adhesives to examine if these can both optimize performance and recyclability. An experimental investigation with these adhesives on Alva's electric motor would offer invaluable insights. Exploring alternative assembly techniques that enable simpler disassembly without sacrificing motor functionality would provide a broader perspective on possibilities

The study underlines the urgent need for educating manufacturers and users about the current recycling process and the benefits of recycling electric motors. A more in-depth analysis of the economic and environmental impacts of recycling versus raw material production could help accurately gauge the advantages of recycling and reusing raw materials. This would contribute significantly to the efficiency and sustainability of recycling electric motors.

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Appendix

A Interview Question Templates for Recycling Organizations and Stations

Two templates were created for the questions asked during the interviews. One was designed for recycling stations and the other for recycling organizations

Questions to Recycling Organizations

1. Can you describe the current process for recycling electronic waste, particularly focusing on electric motors?
2. What are the most common materials you find in electric motors that come in for recycling? How do you go about separating these materials?
3. What materials found in electric motors pose the biggest challenges in terms of recycling?
4. What technologies and methods do you use to ensure efficient recycling of electric motors?
5. What are the biggest challenges you face in the recycling process for electric motors?
6. How do you handle hazardous materials that may be found in electric motors?
7. How are recycled materials from electric motors used in the production of new products?
8. How do you assess the cost-effectiveness of current recycling processes for electric motors?
9. How do you see the possibilities for improving the current recycling process for electric motors?
10. Do you repurpose or reuse any components of electric motors directly, or are all materials recycled into new raw materials?
11. How do policy and legislation affect the recycling of electric motors?
12. How do you view the environmental impact of current recycling processes for electric motors?

Questions to Recycling Stations

1. Can you describe the current process for handling electronic waste, especially electric motors?
2. What proportion of the electronic waste you receive is electric motors?
3. What challenges do you face in reception, sorting, and handling of electric motors?

4. How are electric motors handled differently than other electronic waste at your recycling station?
5. How do you cooperate with recycling organizations to ensure that electric motors are efficiently recycled?
6. How do you assess the costs of handling electric motors compared to other electronic waste?
7. How do policy and legislation affect the handling of electric motors at your recycling station?
8. How do you view the environmental impact of handling electric motors at your recycling station?
9. How do you see the opportunities for improving the handling of electric motors at your recycling station?

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