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ANALYSIS OF THE ENVIRONMENTAL IMPACTS OF LOW VOLTAGE CAST IRON INDUCTION MOTOR

Case Study for ABB Motors R&D

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Tämä opinnäytetyö tehtiin ABB Oy, IEC LV Motors Vaasan R&D-osastolle. Opinnäytetyön tarkoituksena oli selvittää elinkaariarvioinnin (LCA) avulla, kuinka sähkömoottorin suunnittelumuutos vaikuttaa ympäristövaikutuksiin, tässä työssä tarkasteltiin kuinka sähkömoottorin jäähdytysripojen madaltaminen vaikuttaa hiilidioksidipäästöihin moottorin elinkaaren aikana.

Opinnäytetyössä tehtiin elinkaariarvioinnit yhdelle ABB:n induktiomoottorille, jonka jäähdytysripoja alkuperäisestä korkeudesta madallettiin 10 mm ja 20 mm. Elinkaariarvioinnit suoritettiin ympäristövaikutusten arviointiohjelma SimaPro:lla. Elinkaariarviointien periaatteet ja puitteet on esitetty ISO 14040 -standardissa, kun taas vaatimukset löytyvät ISO 14044 -standardista. Elinkaariarviointi koostuu neljästä vaiheesta: Tavoitteiden ja laajuuden määrittely, inventaarioanalyysi (LCI), vaikutusarviointi (LCIA) ja tulosten tulkinta.

Molemmissa madalletuissa jäähdytysripakorkeuksissa kaikki muut elinkaaren vaiheet tuottavat vähemmän hiilidioksidipäästöjä verrattaessa alkuperäiseen jäähdytysripakorkeuteen paitsi käyttövaihe. Tuloksista näkee, että jäähdytysripoja madaltaessa käyttövaiheen hiilidioksidipäästöt nousevat, mikä johtuu alentuneesta energiatehokkuudesta. Toimeksiantajalla on mahdollisuus hyödyntää elinkaariarvioinnin tuloksia tutkiessaan tuotteiden optimointimahdollisuuksia sekä uusia tuotteita suunniteltaessa.

Avainsanat elinkaarianalyysi, sähkömoottori, jäähdytysripa, ympäristövaikutus

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ABSTRACT

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This thesis was done for the R&D department, ABB Oy, LV Motors. The purpose of the thesis was to use Life Cycle Assessment (LCA) and understand how a design change in an electric motor influences the environmental impact. Specifically, the case study was to research how reducing the height of the cooling fins of an electric motor affects CO_2 emissions during the life cycle of the motor.

Life cycle assessments were performed using SimaPro for one ABB induction motor with reduced cooling fins from the original height by 10 mm and 20 mm. The principles and framework for life cycle assessments are set out in ISO 14040, while the requirements can be found in ISO 14044. The life cycle assessment consists of four stages: defining goal and scope, inventory analysis (LCI), impact assessment (LCIA) and interpretation of results.

With both reduced cooling fin heights, all other life cycle phases produce less CO_2 emissions when compared to the original cooling fin height except the downstream use phase. The results show that CO_2 emissions from the use phase increase when cooling fins are reduced, which is due to the decreased energy efficiency. The R&D department can utilize the results of the life cycle assessment when investigating the optimization possibilities of products as well as when designing new products.

Keywords Life cycle assessment, electric motor, cooling fin, environmental impact

CONTENTS

TIIVISTELMÄ

ABSTRACT

LIST OF FIGURES AND TABLES

ABBREVIATIONS AND TERMS

1 INTRODUCTION 8

1.1 Case Company 9

1.2 Purpose of this Study 10

1.3 Research Objective and Focus 11

2 BACKGROUND AND THEORY 12

2.1 Sustainability and Circular Economy 12

2.2 Electric Motors 14

2.2.1 Squirrel Cage Induction Motor 16

2.3 Sustainability in the Life Cycle of an Electric Motor 21

2.4 Life Cycle Assessment 22

3 TOOLS AND METHODS 25

3.1 Case Study 25

3.2 Life Cycle Analysis 26

3.2.1 SimaPro as a Tool 27

3.2.2 Modeling in SimaPro 27

3.3 Life Cycle Inventory 29

4 RESULTS AND ANALYSIS 32

4.1 Life Cycle Analysis of a Squirrel Cage Induction Motor 32

4.2 Influence of Design Changes on the Environmental Impact 33

4.3 Influence of Materials on the Environmental Impact of the Motors 41

5 DISCUSSIONS 45

6 CONCLUSIONS AND SCOPE FOR FUTURE WORK 47

REFERENCES 49

LIST OF FIGURES AND TABLES

Figure 1. The Global Goal for sustainable development. (Ministry for Foreign Affairs of Finland, n.d.) 13

Figure 2. Electric motors divided into AC and DC motors. (Rahman, 2022.) 15

Figure 3. Fin cooled induction motor. (ABB, 2019.) 17

Figure 4. Cross-section of induction motor. (ABB, 2019.) 19

Figure 5. Dimension H represents the frame size. (ABB, 2024c.) 20

Figure 6. Life cycle of an electric motor. 21

Figure 7. Four phases of LCA. 23

Figure 8. The original height of cooling fins (40mm). 25

Figure 9. The height of cooling fins is 30mm. 26

Figure 10. The height of cooling fins is 20mm. 26

Figure 11. CO_2 footprint in the lifecycle of a Low Voltage motor. (ABB, n.d.-d.) . 32

Figure 12. Contribution analysis of the motor with original fin height. 33

Figure 13. Distribution of materials on different cooling fin heights. 34

Figure 14. Total environmental impact in Upstream. 37

Figure 15. Total environmental impact in Core. 38

Figure 16. Total environmental impact in downstream distribution. 39

Figure 17. Total environmental impact in downstream use. 40

Figure 18. Total environmental impact in downstream end of life. 41

Figure 19. Distribution on materials and CO_2 footprint (40mm fins). 41

Figure 20. Distribution on materials and CO_2 footprint (30mm fins). 42

Figure 21. Distribution on materials and CO_2 footprint (20mm fins). 42

Figure 22. The motor components contribution to environmental impact in kg CO_2 eq. (Motor with 40mm cooling fins). 43

Figure 23. The motor components contribution to environmental impact in kg CO_2 eq. (Motor with 30mm cooling fins). 43

Figure 24. The motor components contribution to environmental impact in kg CO_2 eq. (Motor with 20mm cooling fins). 44

Table 1. Materials on cast iron induction motor. 29

Table 2. Approximate energy use for production of one motor. (ABB, 2023b.) 30

Table 3. The transportation for the motor components and modules. 30

Table 4. Parameters that have changed due to reduction of cooling fin height. 33

Table 5. Results from SimaPro for motor with 40mm cooling fin height. 35

Table 6. Full LCA analysis for all three different cooling fin heights. (Only total environmental impact shown) 35

Table 7. Upstream and changes between different fin heights on CO_2 emissions. 36

Table 8. Core and changes between different fin heights on CO_2 emissions. 37

Table 9. Downstream distribution and changes between different fin heights on CO_2 emissions. 38

Table 10. Downstream use and CO_2 emissions. 39

Table 11. Downstream end of life and CO_2 emissions. 40

ABBREVIATIONS AND TERMS

ABB	Asea Brown Boveri
BOM	Bill of Materials
CO_2	Carbon Dioxide
D-End	Drive end
IEC	International Electrotechnical Commission
IE	International Energy Efficiency Class
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LV	Low Voltage
M3BP	Cast Iron Squirrel Cage Induction Motor
N-End	Non-Drive end
R&D	Research and Development
SAP	System Applications and Products in Data Processing
SDG’s	Sustainable Development Goals
SIMAPRO	Life cycle Assessment-software

1 INTRODUCTION

Today's growing environmental concerns and an urgent need for sustainable practices, as well as the role of electric motors in mitigating environmental impact, have received significant attention. Electric motors serve as the basis for modern industrial and technological infrastructure and serve as a source of power from home appliances to transportation systems. As the world strives to achieve the ambitious sustainability goals set internationally such as the United Sustainable Development Goals (SDG) and regionally such as the European Green Deal, understanding and improving the environmental footprint of electric motors becomes increasingly important. (International Energy Agency, 2023.)

The United Nations Sustainable Development Goals offer an extensive roadmap for responding global challenges and advancing sustainable development. Three of the 17 SDG's goals are directly related to the sustainability of electric motors: affordable clean energy (SDG7), industry, innovation, and infrastructure (SDG9) and climate action (SDG13). (United Nations, n.d.-b.) Likewise, the European Green Deal sets determined targets for reaching climate neutrality and transitioning to circular economy (European Commission, n.d.-a.). Electric motors play a crucial role in realizing these objectives by enabling energy efficient processes.

Consumption of electric motors is 45% of the world's electricity and the number of motors is expected to double by 2040. It has been estimated that, if all electric motor systems that are currently in operation are replaced with optimized, high-efficiency motors systems, electricity consumption globally could be reduced by up to 10%. (ABB, n.d.-a.)

Two key pillars of improving the sustainability of electric motors are energy efficiency and material efficiency. Improving the energy efficiency of an electric motor is one of the most economical ways to reduce energy-related CO_2 emissions and at the same time combat the growth of energy demand through the savings achieved from efficiency improvements. (Open Access Government, 2023.) Improving the energy efficiency of an electric motor includes optimizing motor design and operational parameters to minimize energy consumption and maximize performance. It will not only reduce operational costs but also reduces the environmental impact related to production and consumption of electricity. Material efficiency includes rational management of resources throughout the life cycle of an electric motor, from extraction of raw materials to end-of-life disposal. Material efficiency is one of the key parts of the circular economy. (International Electrotechnical Commission, 2023.)

This thesis will explore the opportunities how design change in electric motor can influence the environmental impact. By focusing on the reduction of cooling fin height, this study aims to shed light on strategy to improve the sustainability of electric motor technology, assuming that the environmental impacts decrease when using reduced cooling fin height. The thesis will be done for ABB IEC LV Motors, R&D department.

1.1 Case Company

ABB is a global technology leader with over 130 years of experience (ABB, 2023a). The company was formed in 1988 through the merger of ASEA and Brown, Boveri & Cie. ABB is headquartered in Zurich, Switzerland, and the company operates in more than 100 countries and has a diverse portfolio of products and services. Globally ABB has 105 000 employees. ABB is divided in four main business areas which are Electrification, Motion, Process Automation and Robotics & Discrete Automation. ABB is dedicated to fostering innovations that expedite the evolution of industry. (ABB, 2024a.)

IEC LV Motors Division is one of the Motion business areas which produces electrical motors, generators, drives and services as well as mechanical power transmission products and integrated digital powertrain solutions. (ABB, 2024b.)

The sustainability issue is important, and it is high up on the agenda in ABB, like in many other worldwide companies. ABB aims to integrate sustainability into its business model, recognizing that responsible practices are necessary for long-term success. ABB's Sustainability strategy 2030 is built on four fundamental pillars. The first pillar is to enable a low carbon society which means that ABB is collaborating with both customers and suppliers striving to reduce and avoid emissions throughout the value-chain. ABB's objective is to achieve carbon neutrality in their own operations by 2030. Second pillar is to preserve resources where ABB's target is to embed circularity throughout the whole value-chain. Third pillar is to promote social progress, meaning that ABB prioritizes the well-being of employees and advocates social progress globally. Fourth pillar aims to develop culture of integrity and transparency throughout the value-chain. (ABB, 2023a.)

1.2 Purpose of this Study

The purpose of this study is to understand the environmental impact of LV cast iron induction motor and more specifically, the influence of reducing cooling fin height on the environmental impact parameters.

Materials and design choices play a crucial role in determining the environmental impact of an electric motor. Cast iron is one of the oldest materials in engineering and it is generally used as a frame material for motors, it has also both advantages and environmental consequences. While cast iron is cherished for its durability, heat resistance and mechanical properties, production of cast iron includes significant energy consumption and CO_2 emissions. Also, the extraction and processing of raw materials needed for cast iron production can negatively affect the environment. (Panov et al., 2020.)

By focusing on design optimization, it could be possible to reduce environmental impacts connected to the cast iron. One way to reduce the amount of cast iron is to reduce the height of cooling fins. In addition, a more compact design will result in lighter motors, which might potentially lead to energy savings during operation.

Boundary for this case study is that the only impact category investigated is the impacts which produces CO_2 emissions.

1.3 Research Objective and Focus

The case study includes two parts: in the first part the life cycle assessment will be done for the original motor and in the second part the life cycle assessment will be done for the same motor with two different heights of cooling fins. The aim of this research is to investigate whether the current cooling fin design affects the environmental impact of the chosen product, which is M3BP cast iron squirrel cage induction motor. The focus of this study will be on investigating effects of three different heights of the cooling fins. This research focus will form the basis of this thesis.

2 BACKGROUND AND THEORY

The following chapter presents a background and theory of sustainability and circular economy, electric motors, working principles and construction of squirrel cage induction motor, sustainability in the life cycle of an electric motor and life cycle assessment.

2.1 Sustainability and Circular Economy

The United Nations Brundtland Commission has defined sustainability in 1987 as "Meeting the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, n.d.-a.). At its core, sustainability encompasses environmental protection, social equity, and economic well-being (Ministry of the Environment, 2023). Electric motors are present in all industries and applications, serving remarkable potential to support sustainability targets. Efficient operation of electric motors plays a crucial role in reducing energy consumption, mitigating greenhouse gas emissions, and promoting resource conservation (Goman et al., 2021). Therefore, researching how design changes in electric motors affects the environmental impact is essential to foster sustainable practices in production and use.

The circular economy is an economic model which keeps existing materials and products in circulation as long as possible (Ellen MacArthur Foundation, n.d.). Existing materials and products are fully utilized through sharing, leasing, reusing, refurbishing repairing, and recycling. The aim is to minimize resource consumption, waste and environmental impact while maximizing the value of materials and products during their life cycle. Reduce, reuse, and recycle are fundamental principles of the circular economy. (European Parliament, 2023.)

One way to reduce environmental impacts is to use materials efficiently. Material efficiency is closely related to the circular economy. In today's world, natural resources are used faster than they have time to renew, which is why material efficiency is an important topic. The definition of material efficiency is that natural resources are used sparingly, side streams of production are effectively managed, waste is reduced, and materials are recycled. The aim is to reduce the harmful environmental impacts of a product, service, or process during its entire life cycle. (International Electrotechnical Commission, 2023.)

The Sustainable Development Goals (SDGs) are a group of 17 global objectives accepted by all United Nations Member States in 2015 as part of the 2030 Agenda for Sustainable Development. (United Nations, n.d.-b.) All the 17 SDGs are presented in Figure 1. These goals were created to end poverty, protect the planet, and guarantee universal peace and prosperity for all people by the year 2030 (United Nations Development Programme, n.d.).

Figure 1. The Global Goal for sustainable development. (Ministry for Foreign Affairs of Finland, n.d.)

ABB supports the Sustainable Development Goals, focusing on the areas where they can have the greatest impact on the environment, society, and economy (ABB, n.d.-b.). There are four identified SDG's where ABB have the most impact:

- **Affordable and clean energy:** With the portfolio of energy-efficient solutions, automation and electrification, the company provides access to affordable and sustainable energy (ABB, n.d.-b.).
- **Decent work and economic growth:** ABB provides a fair and safe employment, supporting local communities and paying taxes. In this way, the company promotes decent work and economic growth. (ABB, n.d.-b.)
- **Industry, innovation, and infrastructure**: ABB's innovative technologies promote sustainable industrialization and give the opportunity to live more sustainably (ABB, n.d.-b.).
- **Climate action:** ABB reduces its own greenhouse gas emissions and enables customers to reduce their emissions by offering high efficiency products. ABB also supports suppliers and partners in reducing greenhouse gas emissions. (ABB, n.d.-b.)

2.2 Electric Motors

Electric motors convert electrical energy into mechanical energy utilizing electromagnetism to generate motion (Open Access Government, 2023). Electric motors can be divided into different groups according to voltage. Below 1kV is low voltage, 1kV to 35kV is medium voltage and over 35kV is high voltage. (Westberg, 2020.) Electric motors are used to drive for example fans, pumps, or compressors. Electric motors can be different sizes and they are used in many different areas such as industry, residential households, and transport sectors. (Open Access Government, 2023.)

Electric motors operate either with alternating current (AC) or direct current (DC) (Energy Education, n.d.). See Figure 2 for classification of AC and DC motors. In group of AC motors belongs induction motors and synchronous motors and in DC motors group belongs brushless and brushed motors. There are more subgroups for these motors, but they were not considered relevant to add.

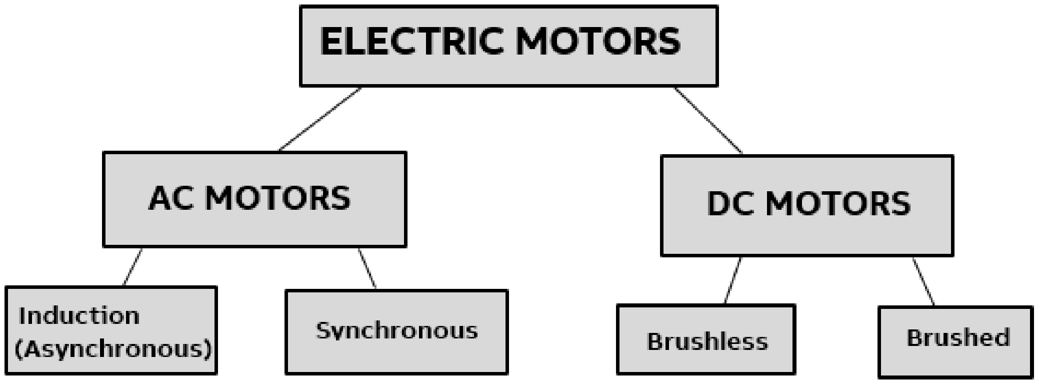


Figure 2. Electric motors divided into AC and DC motors. (Rahman, 2022.)

Electric motors can be divided into natural cooling and forced cooling according to their cooling type. Natural cooling is based on the natural heat dissipation process and forced cooling requires external mechanisms such as fans or coolants to increase the cooling process. (Electricity-Magnetism, n.d.)

ABB’s portfolio encompasses a diverse range of electric motors, including both standard and customized motors which are tailored to specific needs. From powering everyday household appliances with small motors to large industrial motors propelling heavy machinery. (ABB, n.d.-c.)

When selling products in the EU the rules regarding the Ecodesign of electric motors and variable speed drives are mandatory for all manufacturers and suppliers. Energy efficiency is graded according to International Energy efficiency classes (IE), with IE1 denoting the lowest and IE5 the highest level. (European Commission, n.d.-b.)

The efficiency of an electric motor is determined by the ratio of the mechanical output power to the electrical input power. According to existing regulations motors are required to achieve the IE2, IE3 or IE4 efficiency level depending on their rated power and additional attributes. Three-phase electric motors from 0,75kW to 1000kW had to achieve the IE3 level from July 2021. Motors from 75kW to 200kW had to achieve the IE4 level from July 2023. The EU is the first place in the world where the IE4 level is mandatory for some motor categories. (European Commission, n.d.-b.)

2.2.1 Squirrel Cage Induction Motor

The chosen motor for the case study is M3BP IE3 frame size 180 cast iron squirrel cage induction motor. In this chapter, the principle and structure of squirrel cage induction motor will be presented.

The rotor and stator form the core elements of all induction motors, the squirrel cage represents just one approach to harnessing the electromagnetic induction effect. The name “squirrel cage” comes from the unique construction of its rotor that resembles a squirrel cage. (Cavallo, 2020.) Squirrel cage induction motors are commonly used in industry because of their advantages which are low cost, low maintenance costs and robust structure. Squirrel cage induction motors are lightweight, small, and efficiency is high. There are not many parts that should be replaced over motors lifecycle in addition to the bearings. This type of motors has also disadvantages, for example high starting currents and poor starting torque. Common applications for squirrel cage induction motors are for example blowers and fans, pumps, and industrial drives. (PnPn Transistor, n.d.) In Figure 3 two different sizes of the ABB’s fin cooled induction motors are shown.

Figure 3. Fin cooled induction motor. (ABB, 2019.)

The working principle of a squirrel cage induction motor is as follows: Giving a three-phase alternating current to the stator winding, a rotating magnetic field is formed. This rotating magnetic field induces voltage in the rotor bars, thus causing short-circuit currents to flow in the bars. The rotor currents create a self-magnetic field, which interacts with the stator's field. This interaction causes the rotor field to resist its source and it starts to follow the rotating magnetic field. (Electrical 4 U, 2020.)

Once the rotor reaches the rotating magnetic field the current in the rotor drops to zero since there is no longer relative movement between the rotating magnetic field and rotor. During that moment there is no tangential force in the rotor resulting that the rotor slows down for a while. (Electrical 4 U, 2020.)

Cooling fins are extended surfaces of the motor frame which increases the rate of heat transfer from the surface. Extended surfaces are frequently utilized in electric motors to optimize heat transfer by expanding the exchange area. (Soares & Nogueira, 2019.)

Efficient heat dissipation depends on several factors, including effective ventilation, the temperature variance between the motor surface and the surrounding air, and the total heat exchange of surface area including the cooling fins. The geometry of cooling fins plays a crucial role, significantly impacting the area available for exchange. To optimize heat transfer, the construction material of cooling fins should have high thermal conductivity. Energy savings can be contributed if cooling fins are well-optimized. (Soares & Nogueira, 2019.)

The construction of squirrel cage induction motor is shown in Figure 4. The main parts are stator with copper windings, rotor with shaft, D-end and N-end with bearings and frame. Other parts are terminal box with terminals, fan, and fan cover. (ABB, 2019.) Cooling fins are included on the frame.

The stator is a part which surrounds the rotor. The stator contains copper windings looped in between its slots. These windings serve the purpose of conducting the supply current and generating a rotating magnetic field, which interacts with the rotor. (ABB, 2019.)

The rotor is the central rotating part of the motor, which is attached to the shaft. The rotor consists of thin steel laminations and conductive bars that react to the magnetic field, producing torque to rotate the shaft. (ABB, 2019.)

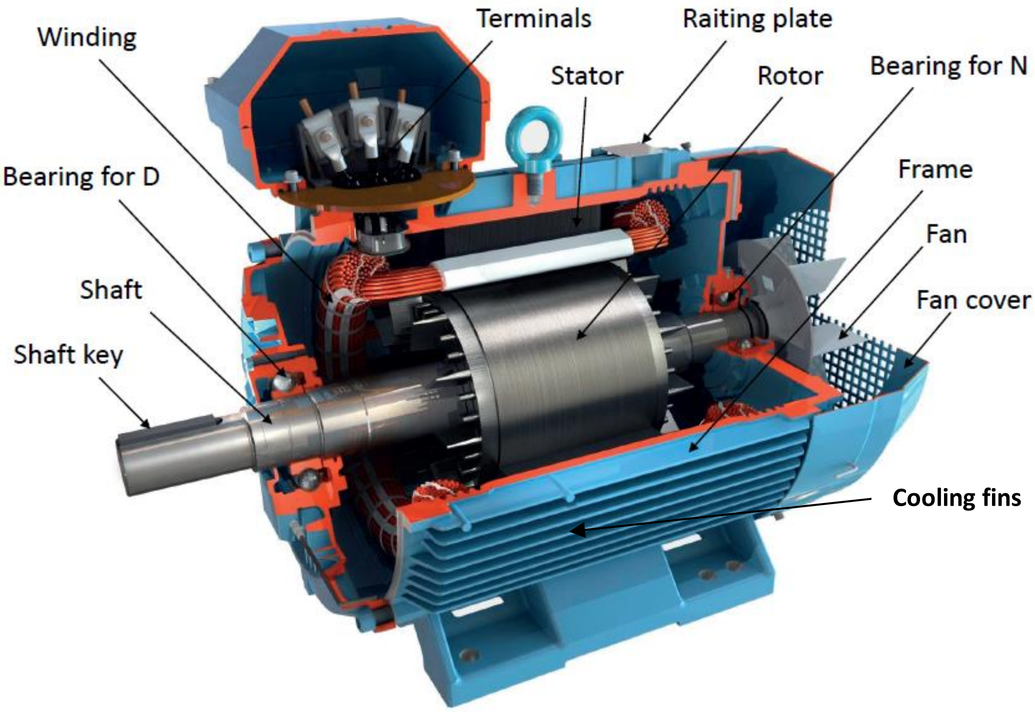


Figure 4. Cross-section of induction motor. (ABB, 2019.)

The shaft is a rotating part which transfers the rotational energy of the rotor to the application that is attached to D-end of the motor. The bearings are the parts that supports the shaft of the motor at both ends decreasing the friction between the shaft and frame. D-end is an abbreviation for drive end of the motor and N-end for non-drive end of the motor. (ABB, 2019.)

The frame covers the core parts of the motor and is made of cast iron or aluminium. Motors with cast iron frames are generally used in heavy industries because of their good endurance against corrosion and chemicals. Motors with aluminium frames are more suitable for lighter applications such as fans and pumps. (ABB, 2019.)

The terminal box is mounted either on top of the motor or on one of it sides. The supply cable is connected to the terminals of the terminal box. (ABB, 2019.)

The fan with the fan cover is attached to the non-drive end of the motor providing heat exchange.

There are various frame sizes and mounting arrangements. Dimension H in Figure 5 demonstrates how size of the motor is defined by the measurement between the lowest part of the motor foot and the center of the shaft. In this thesis the case study has been done for frame size 180 motor which means that dimension H is 180 millimeters.

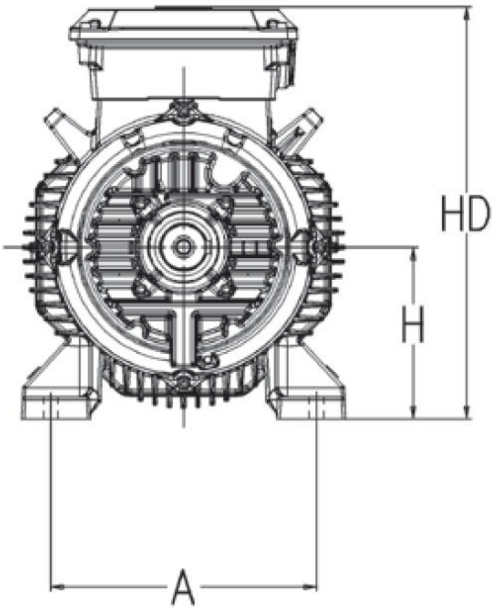


Figure 5. Dimension H represents the frame size. (ABB, 2024c.)

ABB offers three types of mountings: foot mounting, flange mounting and combination of foot and flange mounting. There are 36 different mounting arrangements. (ABB, 2019.)

2.3 Sustainability in the Life Cycle of an Electric Motor

Today, the demand worldwide is growing rapidly for products that contribute to lower carbon emissions and help to build a sustainable future, and an electric motor is no exception. Electric motors consume energy during their long operational lifetime and are therefore of great importance in sustainability transition. To reduce energy consumption which in turn will help in reducing emissions, EU Ecodesign regulation (EU) 2019/1781 is an effective way to improve the environmental performance by setting minimum energy efficiency requirements for low voltage induction motors and variable speed drives (Regulation 2019/1781). However, along with the need to improve the energy efficiency of products, it is equally important to constantly look for opportunities to improve resource efficiency as well. Materials also play a critical role in sustainability, and it is important to ensure that raw materials are available for the near future. As an example, to emphasize the importance of materials, the EU has identified a set of critical raw materials and has recently adopted the Critical Raw Materials Act (European Council, 2024). In this context, it is essential to understand the entire life cycle of an electric motor and scout for opportunities to embed sustainability across the different phases. Figure 6 shows a representation of the life cycle of an electric motor.

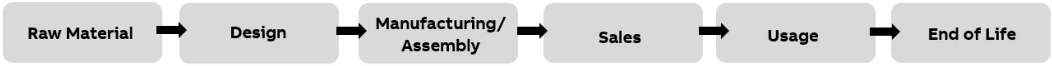


Figure 6. Life cycle of an electric motor.

At the raw material and design phase, considering sustainable raw material alternatives such as recycled, recyclable, bio-based materials and low-carbon alternatives could help in lowering emissions coming from the materials apart from promoting circularity in some cases. Additionally, at the design phase, electric motors can be designed with the optimum usage of sustainable materials without compromising the overall performance of a product. Similarly, in the manufacturing and assembly phase, there is an opportunity to adopt carbon neutral operations in the factory. For an electric motor, the use phase is the longest phase because the motor is usually in operation for several years, in turn contributing a lot to carbon emissions. Therefore, the energy efficiency of the motor plays an important role and higher the energy efficiency, lower the emissions. At the end of life, recycling the motor can contribute to sustainability in a highly positive way.

2.4 Life Cycle Assessment

Life cycle assessment (LCA) is a method used for evaluating the environmental impacts for the whole life cycle of a product, service, or process (Ecochain, 2024b). The international Organization of Standardization defines the main principles for life cycle assessment which are ISO 14040 and ISO 14044. The ISO 14040 standard describes the principles and framework for life cycle assessment while the ISO 14044 states requirements and provides guidelines for life cycle assessment. (Rassõlkin et al., 2020.)

There are four separated stages in life cycle of electric motor: production, distribution, use and end-of-life (Rassõlkin et al., 2020). Each of these stages can have an impact to the environment in different ways. LCA can be used to assess the environmental impact of a product or service from the first to the last stage, or at any stage in between (PRé Sustainability, 2024). The different life cycle models are:

- **Cradle to gate**: The footprint starts from raw materials and ends to the factory gate (PRé Sustainability, 2024).
- **Gate to gate**: The footprint is formed only from manufacturing processes (PRé Sustainability, 2024).
- **Cradle to grave**: The footprint starts form raw materials and ends to the disposal of a product (PRé Sustainability, 2024).

According to ISO 14040 the life cycle assessment consists of four phases, which are goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA)and interpretation (ISO 14040:2006, 2006). As it can be seen in Figure 7, these four phases are dependent on each other.

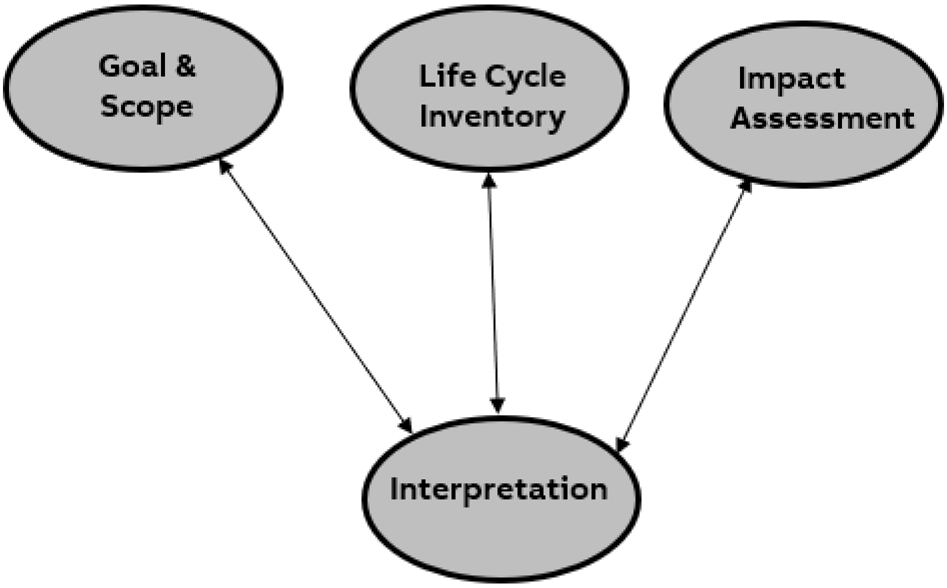


Figure 7. Four phases of LCA.

Goal and Scope Definition: The first step is to define the goal and scope, by creating the base by outlining the purpose of the LCA and the boundaries of the study, this ensures consistent execution. LCA models the life cycle of a product, service, or system. The challenge is to minimize distortion in results because a model is a complex reality that is simplified. This is achieved by carefully defined goal and scope. (PRé Sustainability, 2024.)

Life Cycle Inventory Analysis: The second step examines all the environmental inputs and outputs linked to a product or service. Inputs are resources taken from the environment, like raw materials and energy. Outputs are pollutants and waste released during the life cycle of the product. The life cycle inventory analysis is also known as LCI. (PRé Sustainability, 2024.)

Life Cycle Impact Assessment: The life cycle impact assessment (LCIA) is stage where potential environmental impacts will be evaluated which are identified in the inventory analysis. The environmental impacts from all processes in the life cycle inventory are classified and turned into different environmental themes like global warming and human health. (PRé Sustainability, 2024.)

Life Cycle Interpretation: The interpretation phase finalizes the assessment, ensuring that conclusions are well-justified. The ISO 14044 standard outlines check to validate the data and procedures. (PRé Sustainability, 2024.)

LCAs and Recycling: From sustainability perspective the end-of-life scenario is critical. It is important that the motors will not end up to landfill, as the metals from the motor can be easily recycled and send back the raw materials for circulation. When electric motors reach the end of their useful life, proper recycling is crucial for recovering valuable materials and minimizing the environmental impact. (Ecochain, 2024a.)

3 TOOLS AND METHODS

The following chapter presents the case study, SimaPro as a tool and how to model with the software, also life cycle inventory is presented.

3.1 Case Study

This study was limited to only one ABB motor where the cooling fin height was reduced from the original 40 mm height to 30 mm and 20 mm. The environmental impact was studied using the life cycle assessment software SimaPro. The chosen motor for this case study was M3BP IE3 frame size 180, 2-pole cast iron squirrel cage induction motor with 37 kW output power.

Figure 8 demonstrates how the original fin height (40mm) looks like, and Figure 9 shows the difference when 10mm has been reduced from the original 40mm fin height. In Figure 10 the cooling fin height has been reduced 20mm from the original height.

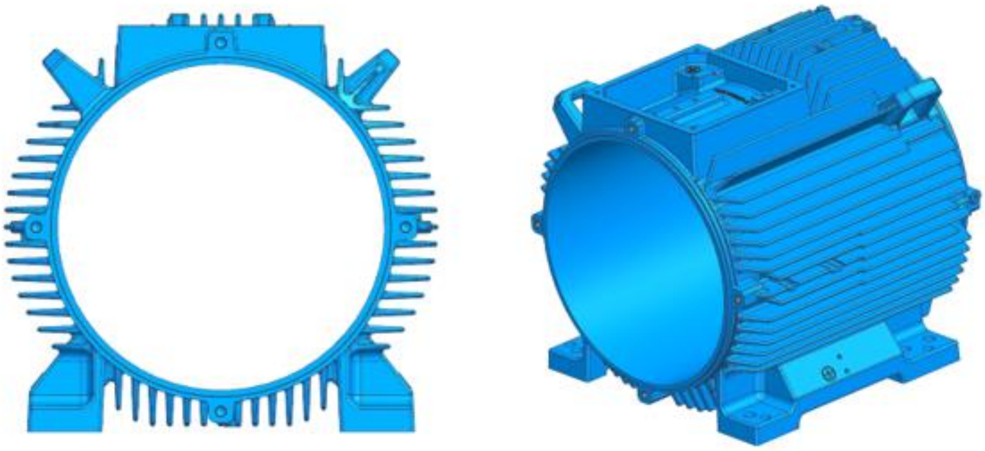


Figure 8. The original height of cooling fins (40mm).

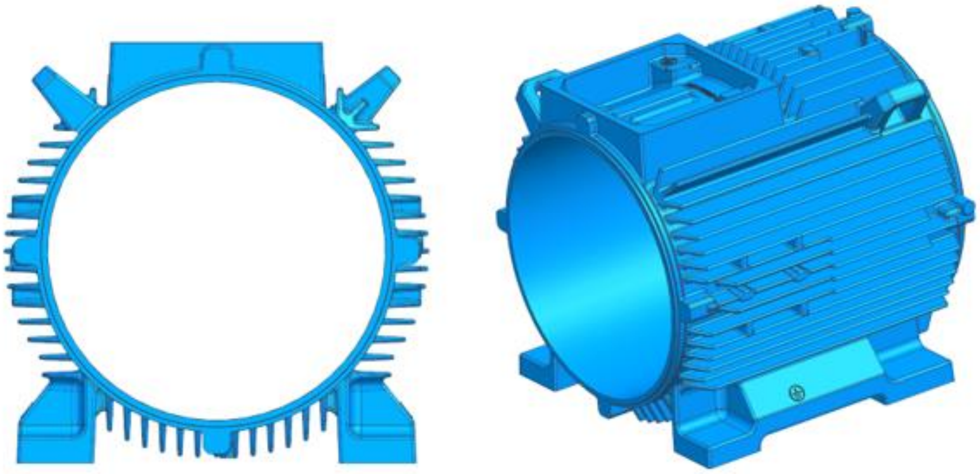


Figure 9. The height of cooling fins is 30mm.

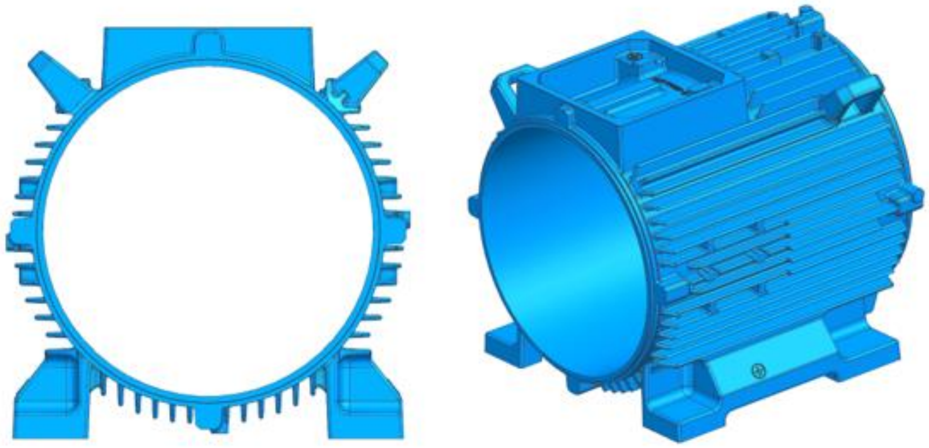


Figure 10. The height of cooling fins is 20mm.

3.2 Life Cycle Analysis

The next sections present the LCA tool SimaPro and briefly about modeling with the tool in question. Also, the method that has been followed is presented.

3.2.1 SimaPro as a Tool

SimaPro stands out as a world-leading life cycle assessment software. For example, it can facilitate the identification of improvement opportunities by locating environmental hotspot areas and enable comparison of products for both internal and external purposes. (Westberg, 2020.)

SimaPro includes a variety of LCI databases, including Ecoinvent, which provide a comprehensive information on materials, construction processes, and more. There are several different types of Ecoinvent datasets: GLO, RoW, ReR and country specific. The GLO datasets provide the global average obtained from international datasets, while the RoW datasets represents areas not covered by Ecoinvent and ReR stands for the European average. (Westberg, 2020.)

3.2.2 Modeling in SimaPro

The database used in SimaPro was Ecoinvent 3, also secondary data was from the same database. The impact assessment method that was used for displaying the results of the LCA is Environmental footprint 3.1, this method is adapted and includes normalization and weighting set.

By using the normalization set, all the impact category indicators have the same unit, this way it is easier to compare the results. The weighting set is a method where the results of impact category indicator are multiplied by weighting factors and added together with the total or individual score. (SimaPro, 2022.)

In this study the system function of the electric motor is the transformation of electrical energy into mechanical energy. The functional unit is the reference unit for assessing the performance of the service delivered by a product to its users. The primary purpose of the functional unit is to provide a reference, the inputs and outputs of which can be evaluated within the framework of LCA (Singha & Westberg, 2024).

The functional unit is defined as the provision of mechanical power by electric motor with 37 kW nominal power for 6500 hours a year for 20 years of service life. The reference flow in this study is determined as the quantity of motors.

Information of capital goods are left outside of system boundaries because they cannot be directly allocated to the production of reference product. These capital goods are information about buildings, machinery, internal transport packaging, tools, and infrastructure. Selected Ecoinvent datasets has general information on capital goods. (Singha & Westberg, 2024.)

A cut-off rule of 1% has been applied if necessary. This means that the included inventory data (excluding inventory data for processes that are explicitly outside the system boundary) must together produce at least 99% of the results of any environmental impact categories. 99% of the mass of the product and 99% the life cycle energy consumption of the product has also been taken account. (Singha & Westberg, 2024.)

The assumptions and allocations used in the LCA are briefly presented in the following.

- **Procurement of raw material:** Acquiring information about raw material procurement is difficult, therefore general data was used from SimaPro for this phase of life cycle.
- **Production:** Data for energy use in the production site is obtained from the energy audit report. The data from production is primary data.
- **Transportation:** Transportations from end-suppliers to production site at ABB and from ABB to the customer were only taken account in terms of transportation.
- **Use:** The motor is assumed to be in use for 6500h per year for 20 years.
- **End-of-life:** All non-recyclable materials are assumed to be incinerated.

3.3 Life Cycle Inventory

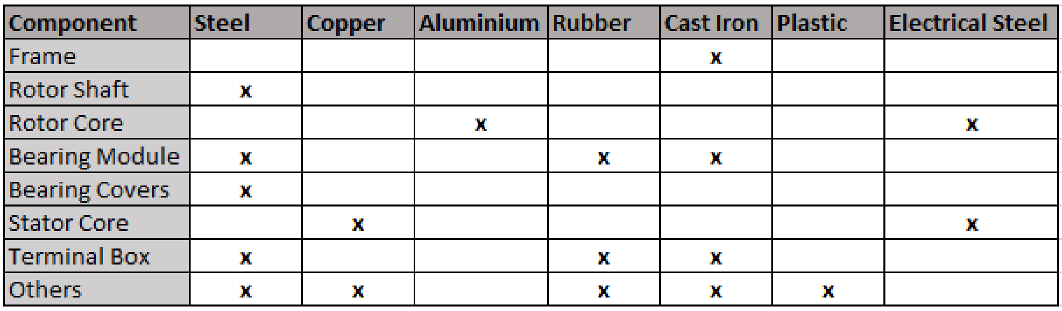
Both primary and secondary data are used in this LCA. ABB has provided site specific foreground data. Primary data such as electricity, heat, water, and waste collected from ABB's production are from 2022. Bill of materials (BOM) are from internal SAP software; this is a list of all components and assemblies organized by level and this list forms the final product. Each item is matched with its code, weight, quantity, and supplier. The bill of materials was processed, adding material, surface area and other weight data, extracted from technical drawings. (Singha & Westberg, 2024.)

Google Maps was used for calculating the road distances between the supplier and ABB where the capital of the country in question was calculated with the distance to the production site in Vaasa, Finland. Marine distances were calculated by using "sea-distances.org". (Singha & Westberg, 2024.)

Motor Manufacturing: The motor used in this study is manufactured at IEC LV Motors, Vaasa production site. Some of the components come from suppliers and some are assembled from raw materials in production site.

Materials in the Motors: Materials used for the motor are stated in Table 1. The total weight of the motor is 229,35kg. Most of the weight of the motor consists of electrical steel and cast iron.

Table 1. Materials on cast iron induction motor.



Component	Steel	Copper	Aluminium	Rubber	Cast Iron	Plastic	Electrical Steel
Frame					x		
Rotor Shaft	x						
Rotor Core			x				x
Bearing Module	x			x	x		
Bearing Covers	x						
Stator Core		x					x
Terminal Box	x			x	x		
Others	x	x		x	x	x	

Motor Production: Data relating to energy and water use was obtained from ABB's internal material. The total energy and water use for 2022 is divided by the number of motors produced that year. Data relating to energy and water use can be seen in Table 2.

Table 2. Approximate energy use for production of one motor. (ABB, 2023b.)

Energy Source	Amount	Unit
Electricity	128,767	kWh
Distric Heating	82,537	kWh
Diesel	0,156	kg
Wates Consumption	416,35	kg

Transportation Scenarios: Transportation of the motor components (Table 3.) is separated by mode of transportation and supplier country. Due to confidential information, the distance of transportation is defined as short, medium, and long. The destination for all components and modules is IEC LV Motors factory Vaasa, Finland.

Table 3. The transportation for the motor components and modules.

Component/Module	Mode of Transport	Distance
Frame	Ship+Truck	Long
Rotor Core	Truck	Medium
Rotor Shaft	Truck	Short
Stator	Truck	Medium
Bearing Module	Ship+Truck	Long
Bearing Covers	Truck	Medium
Terminal Box	Ship+Truck	Long
Packaging	Truck	Short
Other	Ship+Truck	Short+Long

Module named Other includes components and smaller modules such as fan module and fan cover module.

Use Phase: The use of the motor is assumed to be in Germany, being the average country in Europe. The general European medium voltage electricity mix from Ecoinvent is used in SimaPro.

End-of-life Scenario: Approximately 97% of electric motor is made from different metals. Regarding this type of motor, all the metal is recyclable. The end-of-life scenario assumed to be a waste scenario with 95% recycling and 5% to landfill. It is assumed that the transport distance from the place of use to the place of disposal is 50km by truck. Stena Recycling in Sweden and ABB are collaborating by offering a take back model for customers to recycle their old motors and replace them with a new more energy-efficient motors (ABB, 2022).

4 RESULTS AND ANALYSIS

The following chapter will answer the research questions. The environmental impact of the IE3 M3BP frame size 180 cast iron squirrel cage induction motor is presented in this chapter from different perspectives.

4.1 Life Cycle Analysis of a Squirrel Cage Induction Motor

Figure 11 shows how CO_2 footprint is distributed from design phase to end-of-life phase. Most of the CO_2 emissions come from the use phase of the motor. This shows how just a small increase in energy efficiency can make a huge impact to the environment. The use phase dominates the impact because usually expected lifetime of an electric motor is between 15 and 30 years, during this time it needs energy to work, due to this the CO_2 emissions are high.

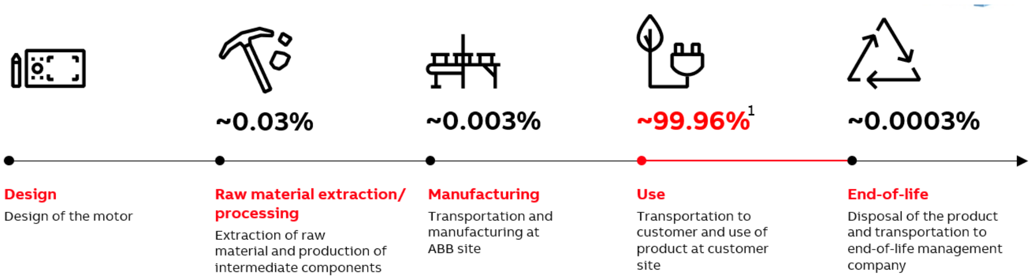
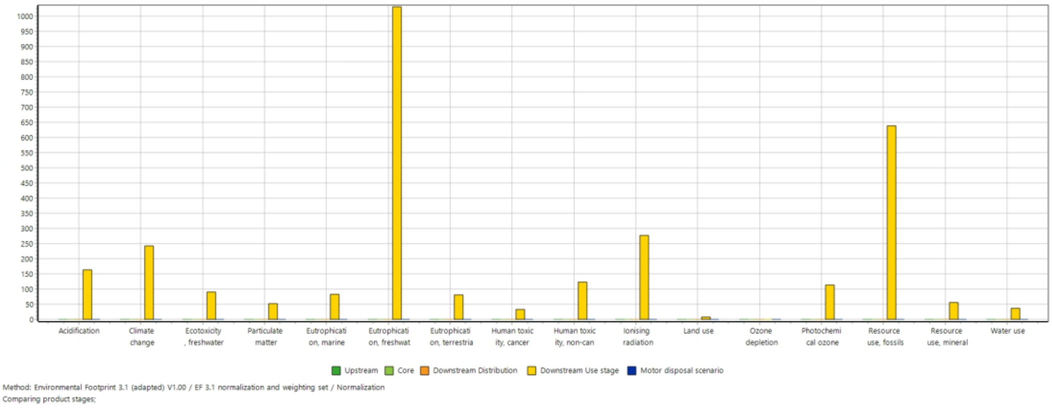


Figure 11. CO_2 footprint in the lifecycle of a Low Voltage motor. (ABB, n.d.-d.)

To highlight the critical factors, a contribution analysis was performed for the motor with the original fin height that shows the environmental impact of the individual processes in the lifecycle of the motor. The contribution analysis in Figure 12 shows that the downstream use stage has by far the biggest impact on all categories. Furthermore, for the resource use, fossil is the biggest category.



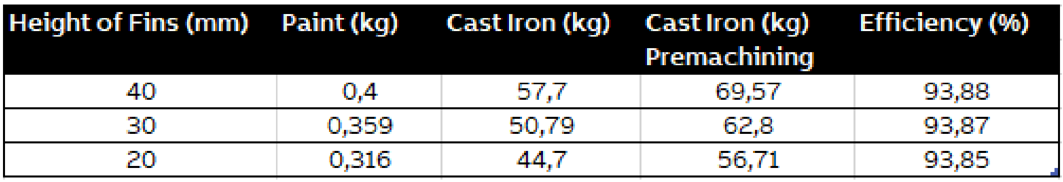
Method: Environmental Footprint 3.1 (adapted) V1.00 / EF 3.1 normalization and weighting set / Normalization
Comparing product stages;

Figure 12. Contribution analysis of the motor with original fin height.

4.2 Influence of Design Changes on the Environmental Impact

The original height of cooling fins is 40 mm, the study was also done for 30mm and 20mm fins by using the SimaPro software. Table 4 presents which parameters have changed when cooling fin height is reduced.

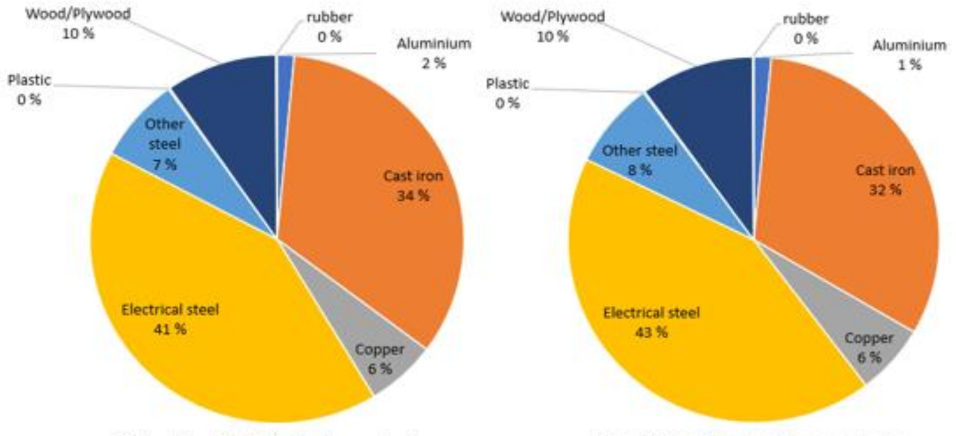
Table 4. Parameters that have changed due to reduction of cooling fin height.



Height of Fins (mm)	Paint (kg)	Cast Iron (kg)	Cast Iron (kg) Premachining	Efficiency (%)
40	0,4	57,7	69,57	93,88
30	0,359	50,79	62,8	93,87
20	0,316	44,7	56,71	93,85

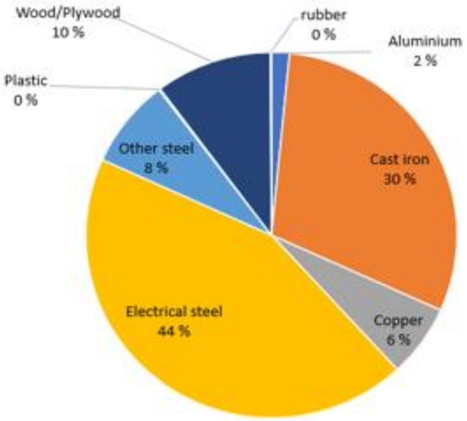
The amount of cast iron has decreased due to reduction of cooling fin height, also amount of pre machined cast iron is reduced. When the amount of cast iron is lower, the amount of paint decreases as the surface area gets smaller. Energy efficiency decreases 0,01 – 0,03% depending on the height of the fins.

Figure 13 presents how materials are distributed on motors with different fin heights. Parts that include cast iron are end-shields, terminal box, and frame. The pie chart shows that motor with the original 40 mm fin height is made 34% of cast iron, 30 mm fin height 32% of cast iron and 20 mm fin height 30% of cast iron.



Original fin height_including packaging

30 mm fin height_including packaging

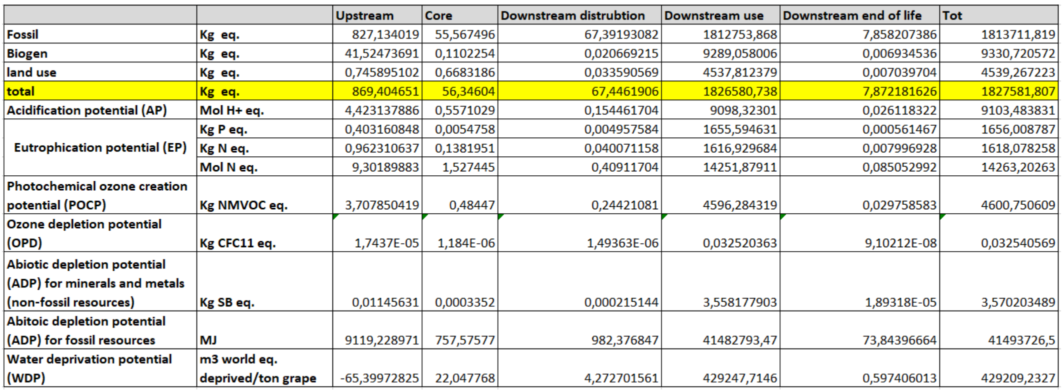


20 mm fin height_including packaging

Figure 13. Distribution of materials on different cooling fin heights.

The full LCA analysis for the original motor exported from SimaPro can be seen in Table 5, including also other impact factors that are not being discussed in this thesis. All the other tables and figures present only the CO_2 emissions since that is the only impact factor in the scope of the case study.

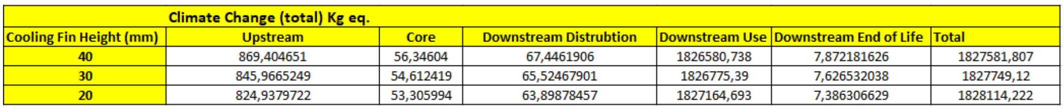
Table 5. Results from SimaPro for motor with 40mm cooling fin height.



		Upstream	Core	Downstream distrubtion	Downstream use	Downstream end of life	Tot
Fossil	**Kg eq.**	827,134019	55,567496	67,39193082	1812753,868	7,858207386	1813711,819
Biogen	**Kg eq.**	41,52473691	0,1102254	0,020669215	9289,058006	0,006934536	9330,720572
land use	**Kg eq.**	0,745895102	0,6683186	0,033590569	4537,812379	0,007039704	4539,267223
total	**Kg eq.**	869,404651	56,34604	67,4461906	1826580,738	7,872181626	1827581,807
Acidification potential (AP)	**Mol H+ eq.**	4,423137886	0,5571029	0,154461704	9098,32301	0,026118322	9103,483831
Eutrophication potential (EP)	**Kg P eq.**	0,403160848	0,0054758	0,004957584	1655,594631	0,000561467	1656,008787
	Kg N eq.	0,962310637	0,1381951	0,040071158	1616,929684	0,007996928	1618,078258
	Mol N eq.	9,30189883	1,527445	0,40911704	14251,87911	0,085052992	14263,20263
Photochemical ozone creation potential (POCP)	**Kg NMVOC eq.**	3,707850419	0,48447	0,24421081	4596,284319	0,029758583	4600,750609
Ozone depletion potential (OPD)	**Kg CFC11 eq.**	1,7437E-05	1,184E-06	1,49363E-06	0,032520363	9,10212E-08	0,032540569
Abiotic depletion potential (ADP) for minerals and metals (non-fossil resources)	**Kg SB eq.**	0,01145631	0,0003352	0,000215144	3,558177903	1,89318E-05	3,570203489
Abitoic depletion potential (ADP) for fossil resources	**MJ**	9119,228971	757,57577	982,376847	41482793,47	73,84396664	41493726,5
Water deprivation potential (WDP)	**m3 world eq. deprived/ton grape**	-65,39972825	22,047768	4,272701561	429247,7146	0,597406013	429209,2327

Table 6 present the full LCA analysis for all three cooling fin heights where the total CO_2 emissions are shown.

Table 6. Full LCA analysis for all three different cooling fin heights. (Only total environmental impact shown)



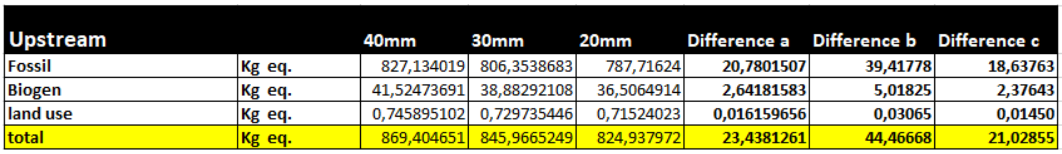
	Climate Change (total) Kg eq.					
Cooling Fin Height (mm)	**Upstream**	**Core**	**Downstream Distrubtion**	**Downstream Use**	**Downstream End of Life**	**Total**
40	869,404651	56,34604	67,4461906	1826580,738	7,872181626	1827581,807
30	845,9665249	54,612419	65,52467901	1826775,39	7,626532038	1827749,12
20	824,9379722	53,305994	63,89878457	1827164,693	7,386306629	1828114,222

It can be seen from the full LCA results that the total CO_2 emissions are higher on the motors which have reduced cooling fin heights. The only stage where the emissions are higher on motors with reduced cooling fins is the downstream use. The explanation for this phenomenon is that energy efficiency is slightly lower on motors with reduced cooling fins.

Tables 7-11 shows what the changes on CO_2 emissions are between different cooling fin heights. Difference a is the difference between 40mm and 30mm, difference b is the difference between 40mm and 20mm and difference c is the difference between 30mm and 20mm. These tables are the same as Table 3 but cut into more detailed pieces.

The upstream stage covers all the components, maintenance of bearings, packaging and waste coming from the production.

Table 7. Upstream and changes between different fin heights on CO_2 emissions.



Upstream		40mm	30mm	20mm	Difference a	Difference b	Difference c
Fossil	Kg eq.	827,134019	806,3538683	787,71624	**20,7801507**	**39,41778**	**18,63763**
Biogen	Kg eq.	41,52473691	38,88292108	36,5064914	**2,64181583**	**5,01825**	**2,37643**
land use	Kg eq.	0,745895102	0,729735446	0,71524023	**0,016159656**	**0,03065**	**0,01450**
total	Kg eq.	869,404651	845,9665249	824,937972	**23,4381261**	**44,46668**	**21,02855**

In the upstream stage the CO_2 emissions decreases in line with the reduction of cooling fins. The main impact comes from the components and the materials used for producing these components. Approximately 16,5% of CO_2 emissions comes from the waste from production. Figure 14 shows the same results as Table 7.

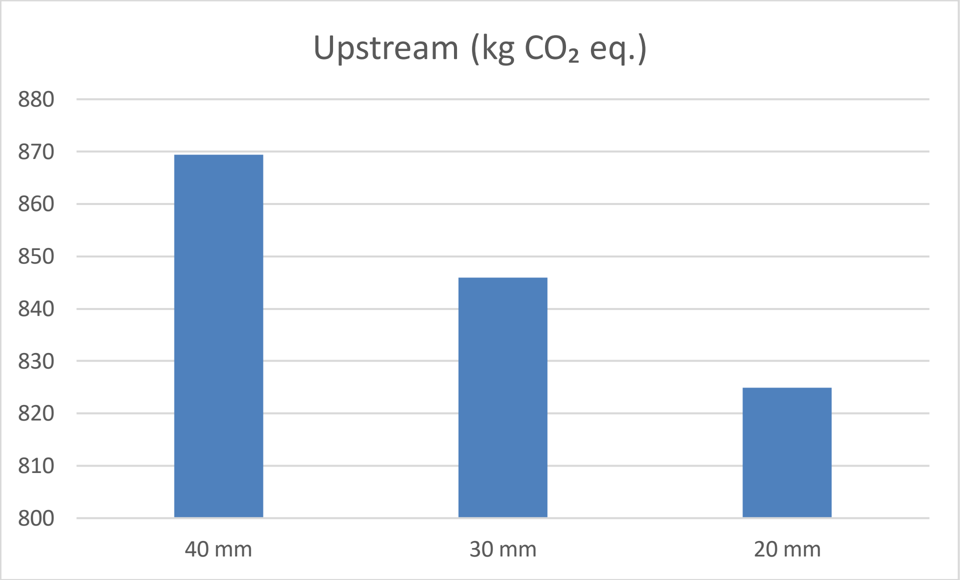


Figure 14. Total environmental impact in Upstream.

The core stage covers burden of waste coming from production, energy and water use, internal transportation, and transportation of components to ABB.

Table 8. Core and changes between different fin heights on CO_2 emissions.

Core		40mm	30mm	20mm	Difference a	Difference b	Difference c
Fossil	Kg eq.	55,567496	53,857439	52,571605	**1,710057**	**2,99589**	**1,28583**
Biogen	Kg eq.	0,1102254	0,1069622	0,1041545	**0,0032632**	**0,00607**	**0,00281**
land use	Kg eq.	0,6683186	0,6480177	0,630235	**0,0203009**	**0,03808**	**0,01778**
total	Kg eq.	56,34604	54,612419	53,305994	**1,733621**	**3,04005**	**1,30643**

In the core stage the biggest impact on CO_2 emissions is the transportation of components to ABB. CO_2 emissions are lower on motors with reduced cooling fins, reason is that the frames made of cast iron are lighter in weight and that affects to the CO_2 emissions of transportation. Figure 15 presents the same results as Table 8.

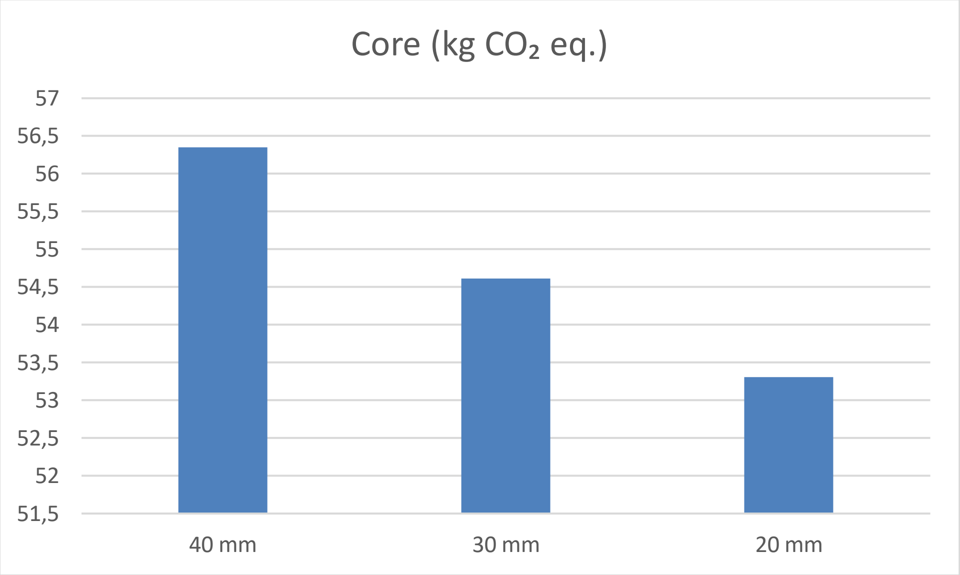


Figure 15. Total environmental impact in Core.

The downstream distribution stage covers transport and burden of packaging waste and transportation to customer.

Table 9. Downstream distribution and changes between different fin heights on CO_2 emissions.

Downstream Distribution		40mm	30mm	20mm	Difference a	Difference b	Difference c
Fossil	Kg eq.	67,39193082	65,4719651	63,84737872	**1,91996572**	**3,54455**	**1,62459**
Biogen	Kg eq.	0,020669215	0,020080375	0,019582126	**0,00058884**	**0,00109**	**0,00050**
land use	Kg eq.	0,033590569	0,032633529	0,031823726	**0,00095704**	**0,00177**	**0,00081**
total	Kg eq.	67,4461906	65,52467901	63,89878457	**1,92151159**	**3,54741**	**1,62589**

In the downstream distribution stage, the biggest impact comes from the transportation to the customer. Figure 16 shows the same results as Table 9.

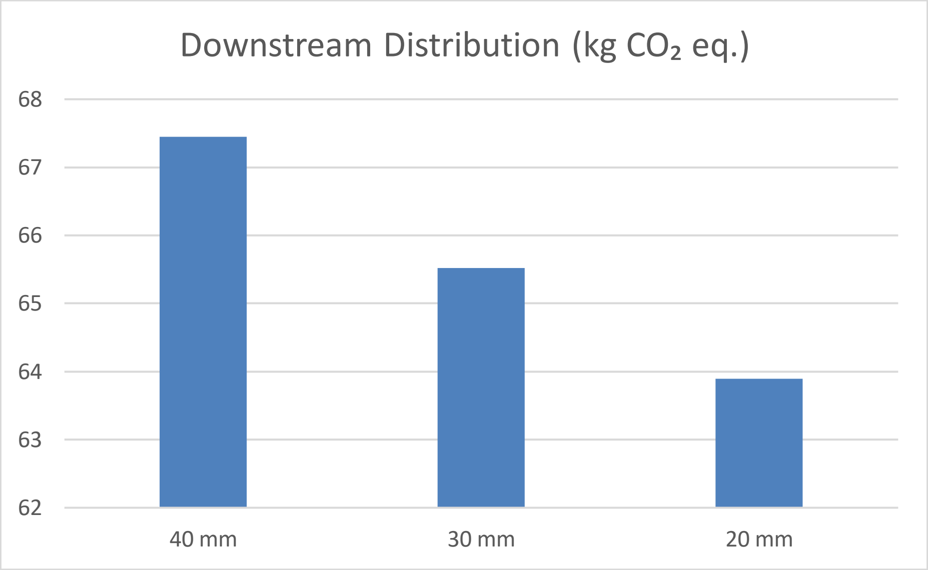
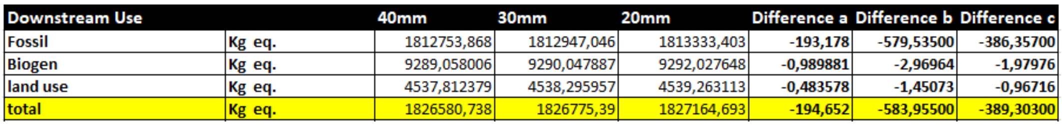


Figure 16. Total environmental impact in downstream distribution.

The downstream use phase covers the energy use stage and refurbishment and maintenance.

Table 10. Downstream use and CO_2 emissions.



Downstream Use		40mm	30mm	20mm	Difference a	Difference b	Difference c
Fossil	Kg eq.	1812753,868	1812947,046	1813333,403	-193,178	-579,53500	-386,35700
Biogen	Kg eq.	9289,058006	9290,047887	9292,027648	-0,989881	-2,96964	-1,97976
land use	Kg eq.	4537,812379	4538,295957	4539,263113	-0,483578	-1,45073	-0,96716
total	Kg eq.	1826580,738	1826775,39	1827164,693	-194,652	-583,95500	-389,30300

In the downstream use phase emissions comes from the energy use stage. The result was as expected, the motor is running 6500h per year for 20 years. Figure 17 presents the same results as Table 10.

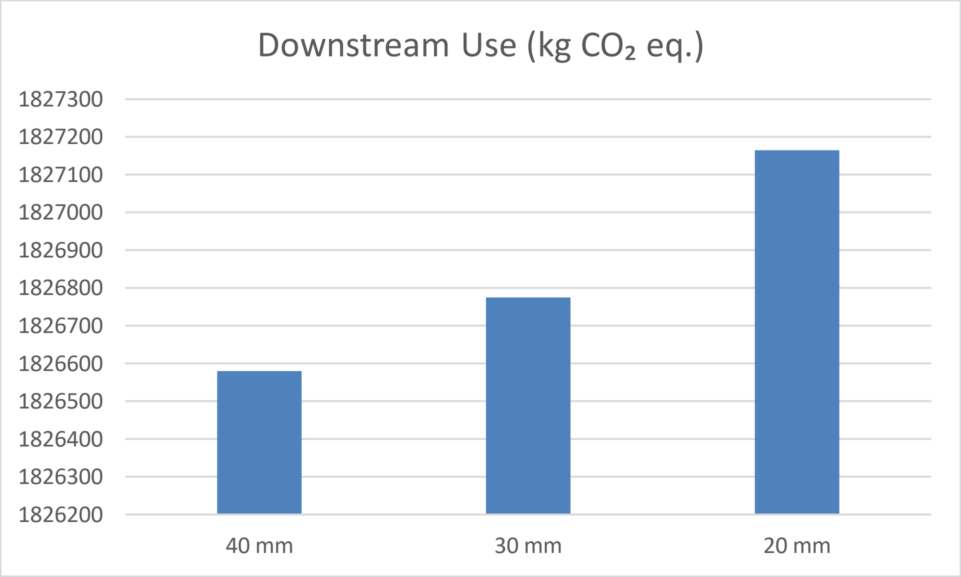
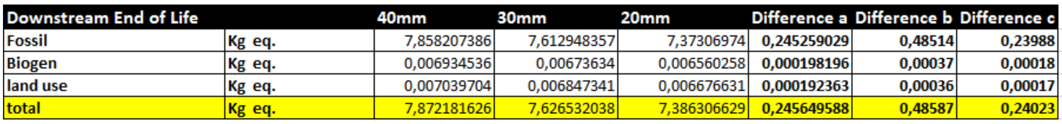


Figure 17. Total environmental impact in downstream use.

The downstream end-of-life stage covers the motor disposal scenario which has been explained in section 3.3.6.

Table 11. Downstream end of life and CO_2 emissions.



Downstream End of Life		40mm	30mm	20mm	Difference a	Difference b	Difference c
Fossil	Kg eq.	7,858207386	7,612948357	7,37306974	**0,245259029**	**0,48514**	**0,23988**
Biogen	Kg eq.	0,006934536	0,00673634	0,006560258	**0,000198196**	**0,00037**	**0,00018**
land use	Kg eq.	0,007039704	0,006847341	0,006676631	**0,000192363**	**0,00036**	**0,00017**
total	Kg eq.	7,872181626	7,626532038	7,386306629	**0,245649588**	**0,48587**	**0,24023**

The downstream end-of-life stage covers the motor disposal scenario which is explained in section 3.3.6. The emissions come from recycling the motor and from using the ABB's take-back model which includes the transportation of the end-of-life-motor to Stena Recycling. Figure 18 shows the same results as Table 11.

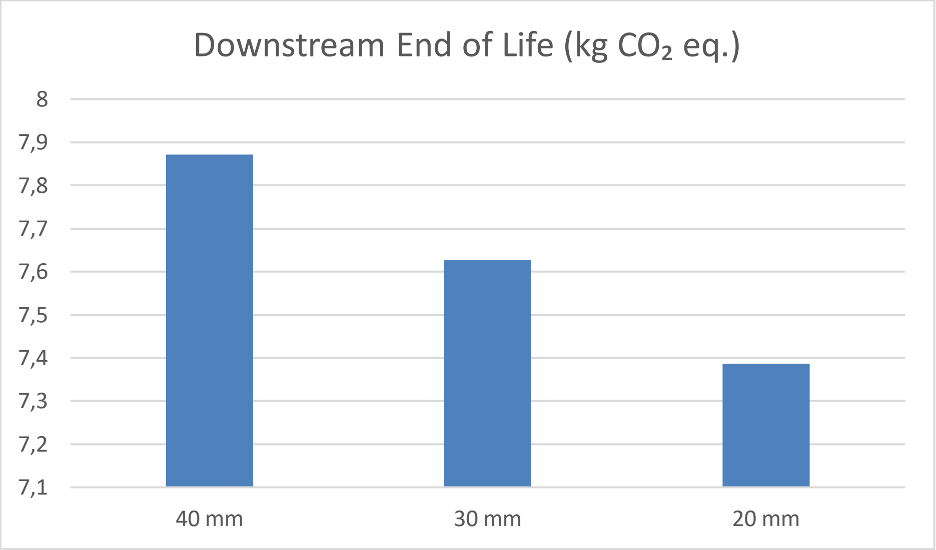


Figure 18. Total environmental impact in downstream end of life.

4.3 Influence of Materials on the Environmental Impact of the Motors

Figures 19, 20 and 21 demonstrate how materials used in the motor affects the CO_2 footprint. The most relevant parameter is the impact of cast iron, the difference is 4% between 40 mm and 20 mm. It can be seen how just a small reduction in material can affect the environmental impact.

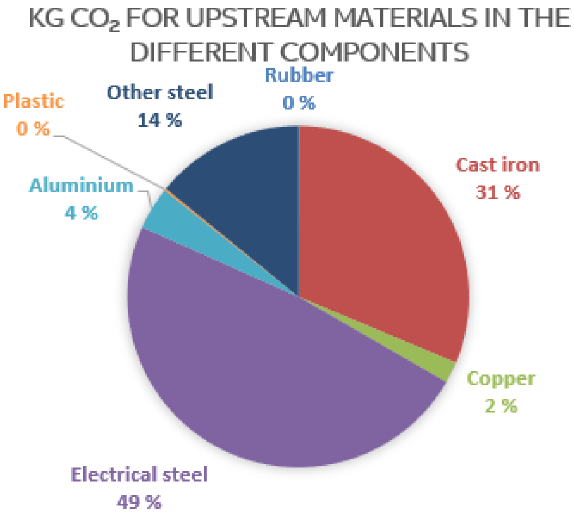


Figure 19. Distribution on materials and CO_2 footprint (40mm fins).

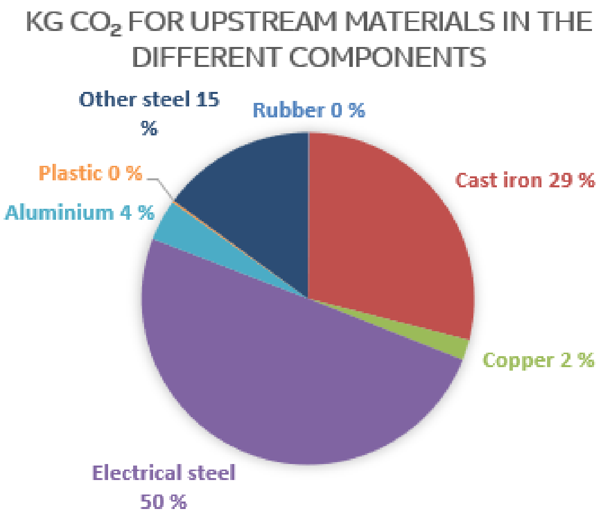


Figure 20. Distribution on materials and CO_2 footprint (30mm fins).

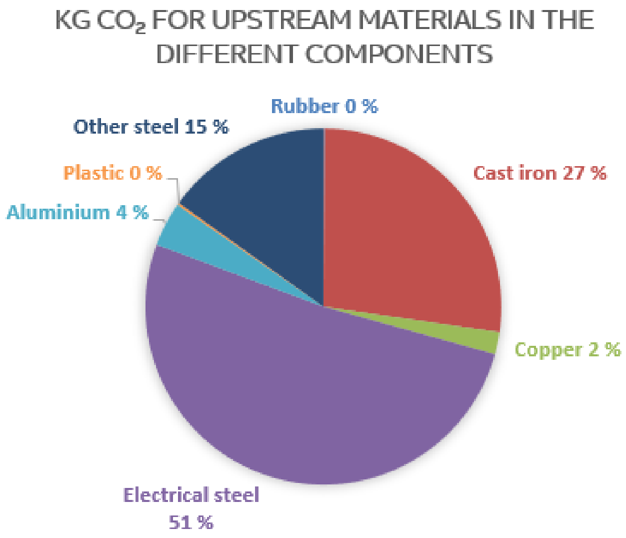


Figure 21. Distribution on materials and CO_2 footprint (20mm fins).

Figures 22, 23 and 24 present the contribution of components to the environmental impact. The greatest contributor of environmental impact is the stator (28-29% depending on cooling fin height) followed by the frame (24-27% depending on cooling fin height).

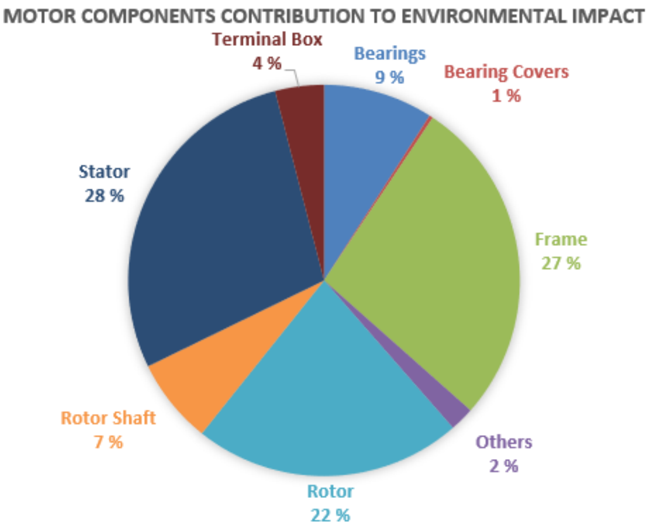


Figure 22. The motor components contribution to environmental impact in kg CO_2 eq. (Motor with 40mm cooling fins).

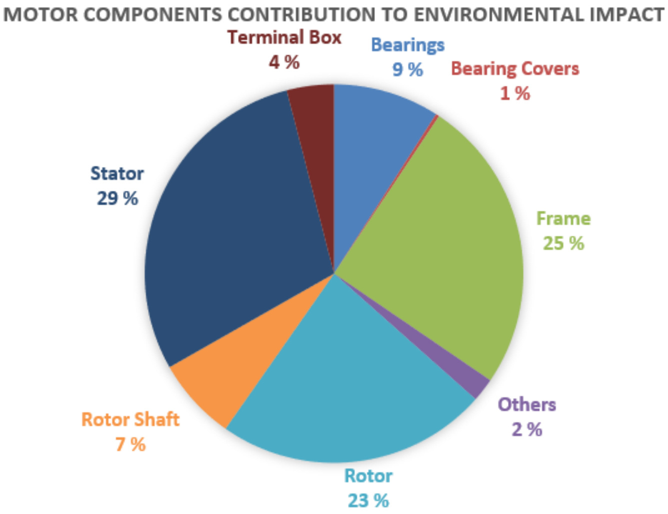


Figure 23. The motor components contribution to environmental impact in kg CO_2 eq. (Motor with 30mm cooling fins).

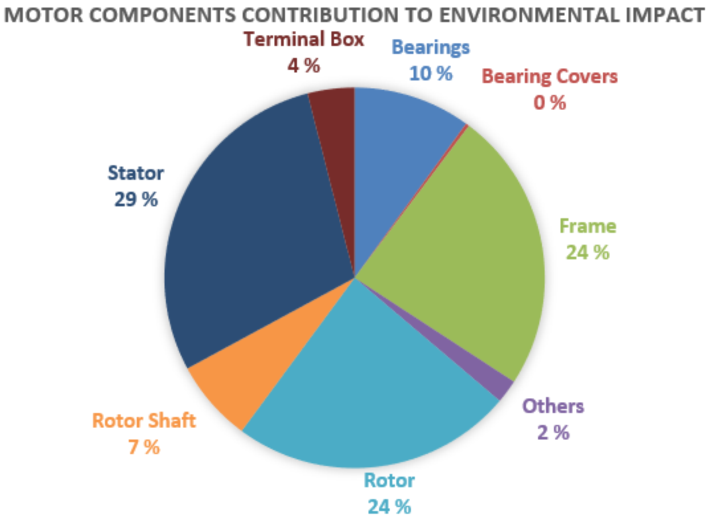


Figure 24. The motor components contribution to environmental impact in kg CO_2 eq. (Motor with 20mm cooling fins).

5 DISCUSSIONS

A life cycle assessment is a good way to get an overall picture of the environmental impacts of a motor during its life cycle. The purpose of this case study was to find out how reducing the cooling fin height affects the environmental impact. SimaPro was used for the LCA study and different assumptions were made while performing the LCA.

The case study reviews the entire life cycle of the motor starting from upstream and ending to down-stream end of life, this model is called cradle to grave. On the other hand, customers are interested in the emissions coming from upstream and core phases, this is called the cradle to gate model. Thus, this model completely omits the biggest environmentally burdening phase, the use phase.

From cooling performance perspective, reducing the cooling fins requires that temperature of the motor remains tolerable, a balance needs to be found between reducing the cooling fins and temperature rise of the motor. Reducing the cooling fin height to be reasonable, the design should be optimized that the obstacles in the airflow path are minimal.

The cast iron used for the motor consists of 56% iron scrap, 30% low-alloyed steel and 14% pig iron (Singha & Westberg, 2024). Although the use of virgin raw materials in the production of electric motors is still common, it causes significant sustainability challenges. The transition to 100% recycled or even partly recycled materials, the adoption of sustainable mining practices and following the circular economy principles are important steps towards reducing the environmental impact associated with virgin raw materials.

As it can be seen from the results, reducing the cooling fin height slightly lowers the energy efficiency. When there is a need to increase the energy efficiency of an electric motor by design, it is often achieved by choosing the right grades of materials and by changing the amount of different materials such as copper, electrical steel and aluminium. However, depending on the additional amount of materials, it should be noted that an increase of materials has their own environmental impacts, and it adds weight to the motor, which also has an impact on the environment.

Performance and other effects such as temperature rise of the motor must be considered in addition to environmental impacts when making changes in the design.

6 CONCLUSIONS AND SCOPE FOR FUTURE WORK

Based on the results in this thesis, some conclusions can be drawn. From the life cycle phases of the motor, the downstream use phase causes most of the environmental impacts. The result was predictable, as the use phase may last several decades with the motor running at 6500h per year used in the LCA calculations. Also, the country where the motor is assumed to operate has an impact due to the mix of electricity used in the country.

Reducing the cooling fin height has a decreasing effect on the environmental impact at all phases on the life cycle of the motor except the use phase. In the use phase, CO_2 emissions increase at both reduced fin heights. The reason for this is a decrease in energy efficiency of 0,01-0,03% from the original fin height, even such a small difference in energy efficiency has a surprisingly big impact on CO_2 emissions.

Reducing the cooling fin height affects the amount of frame material, in this case cast iron. In the upstream phase, reduction of the environmental impact is in line with the reduced cooling fins, due to the decrease of the frame material. It can be seen in the results that electrical steel produces the most CO_2 emissions, followed by cast iron. When looking at the results at the component level, the stator forms the most CO_2 emissions, followed by the frame. The stator is the heaviest component of the motor, followed by the frame.

By reducing the height of the cooling fins, the amount of paint decreases due to the smaller surface area, as well as the easier painting access to the gaps between the fins. The density between cooling fins causes a lot of scrap costs in painting, if cooling fins are reduced or thinned scrap costs will also reduce.

In the future, it would be interesting to study other motor components as well, and their impact to the environment. In this study only the environmental impacts were studied in more detail, it would be interesting to study other impact categories, as well.

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